

METHOD OF MEASURING VIBRATIONAL
TEMPERATURES IN THERMODYNAMICALLY
NONEQUILIBRIUM GAS FLOWS

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UDC 621.375

A numerical calculation is made of the integral radiation of CO₂ molecules in the 2.7- and 4.3- μ m bands and of CO molecules in the 4.7- μ m band when the vibrational temperatures significantly exceed the rotational and translational temperatures.

The development of modern nonequilibrium physicochemical kinetics led to the creation of reliable optical diagnostic methods for the mechanism and kinetics of the elementary processes in vibrationally nonequilibrium chemically reacting fluxes of molecular-gas mixtures.

Extensive – and in many cases exhaustive – information on the distribution of individual chemical components over the vibrational degrees of freedom may be obtained on the basis of measurements of the instantaneous radiation intensities in the corresponding vibrational – rotational bands. However, for the direct determination of instantaneous populations (temperatures) of the vibrational energy levels, it is necessary to establish theoretical, calculational relations of the radiation and absorption characteristics in the chosen region of the IR spectrum with a nonequilibrium distribution of molecules over the vibrational levels. Note that this approach to the determination of the vibrational-distribution parameters is associated with difficulties of applying traditional methods of measuring the vibrational temperatures of optically thin layers, introducing impurities which radiate in the visible spectral range, and converting intensities and so on to the conditions characteristic of thermodynamically nonequilibrium gas flows [1].

A method of measuring vibrational temperatures of carbon dioxide on the basis of theoretical relations of the radiative characteristics of the medium with the distribution of molecules over the vibrational degrees of freedom was realized experimentally and theoretically in [1, 2] for nonequilibrium supersonic fluxes containing CO₂, and also theoretically in [3, 4] for carbon dioxide in the active medium of CO₂ lasers. The method described in [3] allows only the vibrational temperature of the asymmetric mode of CO₂ to be determined, and requires it to be assumed that the temperatures of the remaining modes equal the translational temperature.

In measuring the vibrational temperatures of CO₂ in accordance with [1, 2], simultaneous recording of the spontaneous and stimulated radiation intensity of the investigated medium is necessary.

Below, a method based on measurements of the spontaneous IR radiation intensity is developed for the measurement of the instantaneous vibrational temperatures of radiating molecules in the conditions of thermodynamically nonequilibrium supersonic fluxes. To this end, there is a theoretical consideration of the radiation process of a molecular gas in the given conditions, and spectral and integral (over the band) radiation intensities I_ω for widely distributed molecules active in the IR range (carbon monoxide and dioxide in the 4.7-, 4.3-, and 2.7- μ m bands) are calculated. The calculations are made for conditions in which the vibrational temperatures considerably exceed the translational and rotational temperatures, as is characteristic for vibrationally nonequilibrium supersonic fluxes.

The distribution of CO molecules over the vibrational levels is assumed to be of Boltzmann type, with the vibrational temperature T_v^3 . According to [5, 6], the distribution of CO₂ molecules over the vibrational levels is described by two vibrational temperatures T_v^3 and T_v^2 determined by the populations in the asymmetric, symmetric, and deformational modes.

The radiation intensity of a homogeneous isotropic medium of molecular gas due to transitions from the

quantum state ν' to ν'' , neglecting scattering of the radiation, is determined by the relation [7]

$$I_\omega d\omega = 2hc^2\omega^3 \frac{1 - \exp(-K_\omega X)}{g'N''/g''N' - 1} d\omega, \quad (1)$$

where ω is the wave number of the transition; K_ω ($\text{atm}^{-1} \cdot \text{cm}^{-1}$), absorption coefficient for the transition ν' to ν'' ; X ($\text{atm} \cdot \text{cm}$), optical path length; N'' , g'' and N' , g' , population and statistical weight of the upper and lower level, respectively.

The radiation intensity for the vibrational-rotational transition ($\nu_i + k_i \nu_j J'' \rightarrow \nu_i \nu_j J'$) may be written, in the absence of thermodynamic equilibrium between the vibrational and translational-rotational degrees of freedom according to Eq. (1), in the form

$$I_\omega^{i,j} = A_\omega^{i,j} \mathcal{L}_\omega^{i,j}, \quad (2)$$

where $A_\omega^{i,j} = 1 - \exp(-K_\omega^{i,j} X)$ is the spectral absorptivity, and

$$\mathcal{L}_\omega^{i,j} = 2hc^2\omega^3 \left\{ \exp \left[\sum_i \theta_i^i k_i / T_i^i + \left(\frac{hc}{k} \right) \frac{\omega - \omega_0^{i,j}}{T_r} - 1 \right] \right\}^{-1} \quad (3)$$

is a limit function. The superscripts i and j denote characteristics of the active (radiating) and passive mode, respectively; ν , vibrational quantum number; k , change in vibrational quantum numbers in the transition; J , rotational quantum number; $J'' - J' = 0 \pm 1$; ν_i, ν_j , set of vibrational quantum numbers of the active and passive modes; θ_i, T_i , and T_r , characteristic temperature of the mode, the vibrational temperature, and the rotational temperature; $\omega_0^{i,j}$, wave number at the center of the band of the given vibrational transition.

In conditions of thermodynamic equilibrium, the limit function corresponds to the Planck blackbody radiation function.

The vibrational-rotational bands are determined by the set of transitions ($\nu_i + k_i \nu_j \rightarrow \nu_i \nu_j$), the vibrational components of the band, where the quantum numbers of the active and passive modes take values of 0, 1, 2, etc.

In low-pressure conditions ($P_t = 10^{-1} - 10^{-4}$ atm), characteristic for thermodynamically nonequilibrium supersonic fluxes, the distance between adjacent rotational components of the band exceed the width of the individual lines by 1-3 orders of magnitude [1]. In the given conditions, neglecting the overlap of rotational lines, the spectral radiation intensity of the band is determined by summing over the quantum numbers of the active and passive modes

$$I_\omega = \sum_{i,j} A_\omega^{i,j} \mathcal{L}_\omega^{i,j}. \quad (4)$$

The important feature of the radiation of an attenuated vibrationally nonequilibrium molecular gas is the sharp change in radiation intensity over the spectrum. The low rotational temperatures, practically coinciding with the translational temperature ($T_r = T = 100 - 400^\circ \text{K}$ [5, 6]) are due to the increased population of the low rotational levels and, hence, the high radiation energy in transitions between these states. On the other hand, at low pressure ($P_t = 10^{-1} - 10^{-4}$ atm), the degree of broadening of the rotational lines is negligible, and in the intervals between adjacent lines the gas practically does not radiate.

The characteristic spectral range of the change in radiation intensity for the given values of pressure and temperature $\Delta\omega' = 10^{-2} - 10^{-4} \text{ cm}^{-1}$ [1]. In practice, to ensure the necessary sensitivity of optical systems in conditions of high time resolution, it is necessary to record radiation in spectral ranges comparable with the width of the vibrational-rotational band ($100 - 500 \text{ cm}^{-1}$), including a considerable number of rotational lines. Therefore, to calculate the radiation in the vibrational-rotational band, it is necessary to average values of I_ω in the spectral range $\Delta\omega = 1 - 10 \text{ cm}^{-1} \gg \Delta\omega'$. The characteristic spectral range of limit-function variation exceeds $50 - 100 \text{ cm}^{-1}$. Taking into account that the sharp frequency dependence of I_ω is mainly determined by the absorptivity A_ω , the averaged radiation intensity may be written in the form

$$\langle I_\omega \rangle = \sum_{i,j} \langle A_\omega^{i,j} \rangle \mathcal{L}_\omega^{i,j}. \quad (5)$$

The absorptivity $\langle A_\omega^{i,j} \rangle$ is averaged on the basis of the band model [7, 8]. The averaged absorptivity of the $4.3\text{-}\mu\text{m}$ band of carbon dioxide in conditions of disequilibrium between the vibrational and translational-rotational degrees of freedom was determined in [1, 4, 9-11]. In the present work, in accordance with the above assumptions, the calculation of the radiation intensity is based on the nonoverlapping-line model, ac-

ording to which $\langle A_{\omega}^{i,j} \rangle = W_{\omega}^{i,j}/d_{\omega}^{i,j}$, where $W_{\omega}^{i,j} = \int_{-\infty}^{\infty} [1 - \exp(-K_{\omega}^{i,j}X)] d\omega$ is the equivalent linewidth; $d_{\omega}^{i,j}$ is the distance between adjacent rotations lines in the vibrational component of the band [8].

For the conditions of thermodynamically nonequilibrium supersonic fluxes, there may be significant collisional and Doppler mechanisms of spectral line broadening. The line contour is described by the Voigt function when both these broadening mechanisms are taken into account [7]. The equivalent width for the Voigt line contour may be determined with an error of not more than 8% using the dependence [12]

$$W_F = [W_L^2 + W_D^2 - (W_L \cdot W_D/SX)^2]^{1/2}, \quad (6)$$

where $W_L = W_L(u_L)$, $W_D = W_D(u_D)$ are the equivalent linewidths with purely collisional and Doppler contours; $S = \int_{-\infty}^{+\infty} K_{\omega} d\omega$ is the integral absorption coefficient of the line. The dimensionless parameters $u_L = SX/2\pi\gamma_L$, $u_D = SX/\sqrt{\pi}\gamma_D$ characterize the optical path length at the line center with collisional and Doppler contours; γ_L and γ_D are the corresponding halfwidths of the line.

The integral absorption coefficient of the line corresponding to the rotational transition $J' \rightarrow J''$ and belonging to the vibrational component of the band $\vartheta' \rightarrow \vartheta''$ in thermodynamically nonequilibrium conditions is given by the relation [7]

$$S_{\vartheta',J' \rightarrow \vartheta'',J''} = \frac{N_{\vartheta',J'}}{N_{\vartheta'}} \frac{\omega_{\vartheta',J' \rightarrow \vartheta'',J''}}{\omega_{\vartheta' \rightarrow \vartheta''}} S_{\vartheta' \rightarrow \vartheta''} (R_{J' \rightarrow J''})^2 \frac{1 - g_{\vartheta',J'} N_{\vartheta'',J''} / g_{\vartheta'',J''} N_{\vartheta',J'}}{1 - g_{\vartheta'} N_{\vartheta''} / g_{\vartheta''} N_{\vartheta'}} (1 - g_{\vartheta'} N_{\vartheta''} / g_{\vartheta''} N_{\vartheta'}), \quad (7)$$

where $R_{J' \rightarrow J''}$ is the rotational-transition matrix element; $S_{\vartheta' \rightarrow \vartheta''}$ is the integral absorption coefficient of the vibrational transition ($\vartheta' \rightarrow \vartheta''$) [6, 7]

$$S_{\vartheta' \rightarrow \vartheta''} = \frac{8\pi}{3hc} \frac{N_{\vartheta'}}{P} \omega_{\vartheta' \rightarrow \vartheta''} \beta_{\vartheta' \rightarrow \vartheta''}^2 (1 - g_{\vartheta'} N_{\vartheta''} / g_{\vartheta''} N_{\vartheta'}), \quad (8)$$

$\beta_{\vartheta' \rightarrow \vartheta''}$ is the vibrational-transition matrix element. In practice, the value of $S_{\vartheta' \rightarrow \vartheta''}$ is determined on the basis of Eq. (8), taking account of experimental measurements of the absorption coefficient of the band in normal conditions ($P_t = 1$ atm, $T = 293^\circ\text{K}$). In normal conditions, the integral absorption coefficient of the whole band is determined by the vibrational transition $0 \rightarrow 1$ in the first excited state

$$\sum_{\vartheta'} S_{\vartheta'' \rightarrow \vartheta'} = S_{0 \rightarrow 1}.$$

The distribution of molecules over the vibrational levels, in the absence of equilibrium between the vibrational degrees of freedom in the harmonic approximation, may be written in the form

$$N_{\vartheta}^{i,j} = Q_{\vartheta}^{-1} g_{\vartheta} \prod_{i,j} \exp(-\theta_{\vartheta}^{i,j}/T_{\vartheta}^{i,j}), \quad (9)$$

where $Q_{\vartheta} = Q_{\vartheta}(T_{\vartheta}^{i,j})$ is the vibrational statistical sum. Rapid rotational relaxation leads, in the conditions of molecular lasers, to the establishment of equilibrium between the translational and rotational degrees of freedom [5, 6]. Therefore, the distribution of molecules over the rotational levels is of Boltzmann type, with the temperature $T_R = T$:

$$N_{\vartheta}^{i,j}(J) = N_{\vartheta}^{i,j} Q_R^{-1} (2J+1) \exp(-E_r^{i,j}(J)/kT), \quad (10)$$

where $Q_R = (k/hc)(T/B_0)$ is the rotational statistical sum; B_0 , rotational constant; $E_r^{i,j}(J)$, rotational energy. At low gas temperatures, the anharmonicity of the molecules, expressed in cm^{-1} , is comparable with the width of the vibrational component of the band. The rotational-line spectral distribution in the vibrational component of the band is largely determined by the interaction of the vibrations and rotations of the molecule. To take these factors into account, the vibrational and rotational energy must be determined using the empirical relations [7]

$$E_{\vartheta}^{i,j} = h \sum_i \left[\nu_{i,j} \left(\vartheta_{i,j} + \frac{r_{i,j}}{2} \right) + \sum_{i',j'; i' \leq j'} \kappa_{i',j'} \left(\vartheta_{i,j} + \frac{r_{i,j}}{2} \right) \left(\vartheta_{i',j'} + \frac{r_{i',j'}}{2} \right) \right], \quad (11)$$

$$E_r^{i,j} = J(J+1) \left[B_0 + \sum_{i,j} \alpha_{i,j} \left(\vartheta_{i,j} + \frac{r_{i,j}}{2} \right) \right],$$

where $\nu_{i,j}$, $\kappa_{i,j}$, $\alpha_{i,j}$ are empirical constants characterizing the frequencies of normal molecular oscillation, the anharmonism and interaction of various types of vibration, and the interaction between the molecular

vibration and rotation, respectively; $r_{i,j}$ are the multiplicities of the degeneracy of the corresponding mode [13].

Thus, Eqs. (2)-(11) allow the radiation and absorption of the molecular gas to be calculated in conditions of disequilibrium between the vibrational and rotational-translational degrees of freedom.

Calculations were carried out for three vibrational-rotational bands: the basic 4.7- μm band of carbon monoxide and the "parallel" (corresponding to transitions between vibrational states with the same polarization index of the deformational mode l) 4.3- and 2.7- μm bands of carbon dioxide. The 4.3- μm band is formed by transitions within the asymmetric mode $\Delta\vartheta_3 = 1$, and has a structure similar to the bands of diatomic molecules. The 2.7- μm band of CO_2 is formed by the transition ($\Delta\vartheta_1 = 1, \Delta\vartheta_3 = 1$) and ($\Delta\vartheta_2 = 2, \Delta\vartheta_3 = 1$) from levels associated with Fermi resonance.

For CO_2 molecules, the modes 1, 2, and 3 correspond to symmetric, deformational, and asymmetric oscillation types. In the 4.3- μm band, mode 3 is active and modes 1 and 2 are passive; in the 2.7- μm band, modes 1 and 3 or 2 and 3 are active.

In the case of diatomic molecules, the dependence of the integral absorption coefficient of the rotational lines in the vibrational component of the band on the rotational quantum number may be transformed, depending on the wave number, using a relation derived from Eq. (11):

$$m' = B_0/\alpha \pm 1/\alpha \sqrt{B_0^2 - \alpha(\omega - \omega_0)}; B_0 = B_0 - \alpha(\vartheta + 1), \quad (12)$$

$m' = J' + 1$ for the R branch and $m' = -J'$ for the P branch.

For the CO molecule, $\alpha = -1.75 \cdot 10^{-2} \text{ cm}^{-1}$ [6]. In the CO_2 molecule, the symmetric type of oscillation reacts most strongly with the rotation: $|\alpha_3| > |\alpha_1|$, $|\alpha_2|$ ($\alpha_1 = -5.8 \cdot 10^{-4}$, $\alpha_2 = +4.5 \cdot 10^{-4}$, $\alpha_3 = -3.07 \cdot 10^{-3} \text{ cm}^{-1}$) [7]. Hence, Eq. (12) is also valid for carbon dioxide, with $\alpha = \alpha_3$ and $\vartheta = \vartheta_3$. The rotational constants B_0 of the CO and CO_2 molecules are 1.91 and 0.393 cm^{-1} , respectively.

In the CO_2 bands corresponding to deformational-mode polarization index $l > 0$, the Q branch is present. In conditions characteristic for thermodynamically nonequilibrium supersonic fluxes ($u_L, u_D \gg 1$), the radiation intensity of the whole Q branch corresponds to the radiation of one rotational line of the P and R branches [14]. Therefore, the radiation in the Q branches of the CO_2 -band vibrational components is disregarded in the present work.

The vibrational states of CO_2 with $l \geq 1$ are doubly degenerate, $g_\vartheta = 2$. In the vibrational state of CO_2 characterized by the deformational-mode polarization index $l = 0$, rotational levels with a definite parity of the quantum number J are populated. Therefore, in transitions between vibrational states with $l = 0$ half the rotational lines are absent from the spectrum, and the remaining lines have double the intensity. Accordingly, transitions from each level of the multiplets of symmetric and deformational CO_2 modes (vibrational states with $\vartheta_{12} = \vartheta_2 + 2\vartheta_1 = \text{const}$) are considered separately in the present work.

For carbon-monoxide molecules, the square of the rotational-transition matrix element $(R_{J' \rightarrow J''})^2$ is proportional to $|m'|$ in the first approximation, for the "parallel" CO_2 bands, $(R_{J' \rightarrow J''})^2$ is proportional to $|(m')^2 - (l')^2| : |m'|$ [7]. In the harmonic approximation, the square of the vibrational-transition matrix element $\beta_{\vartheta' \rightarrow \vartheta''}^2$ is proportional to $(\vartheta' + 1)$ for CO and $(\vartheta_3 + 1)$ for the 4.3- μm band of CO_2 [7]. For the 2.7- μm band, which is a superposition of two types of vibrational transition, the square of the matrix element is determined by the transition with the least change in the number of vibrational quanta, i.e., $\Delta\vartheta_1 = 1, \Delta\vartheta_3 = 1$, and hence is proportional to $(\vartheta_1 + 1)(\vartheta_3 + 1)$ [15]. The effect of the interaction between vibration and rotation on the matrix elements is neglected.

The collisional half-widths of the rotational lines of the CO and CO_2 molecules are assumed to be the same, within the limits of each band (4.7, 4.3, and 2.7 μm) and to correspond to the measurement of γ_L in transitions to the first vibrationally excited state of these molecules. Extrapolation of γ_L over the temperature is achieved by means of the theoretical dependence $\gamma_L \sim T^{-1/2}$. Nitrogen is assumed to be the component mainly responsible for the line broadening of the CO and CO_2 broadening. In accordance with [15], $\gamma_L = 0.06 \text{ cm}^{-1}$ for $P_t = 1 \text{ atm}$ and $T = 293^\circ \text{K}$ for the 4.7- μm band, and $\gamma_L = 0.07 \text{ cm}^{-1}$ for the 2.7- μm and 4.3- μm bands. The radiation of isotopic CO and CO_2 molecules is neglected.

The integral absorption coefficients assumed in the calculations are as follows: $273 \text{ atm}^{-1} \cdot \text{sec}^{-2}$ for the 4.7- μm band of CO [16], 2700 for the 4.3- μm band of CO_2 [7], and 25.7 and 39.3 for the 2.7- μm band for the transitions ($00^\circ 0 \rightarrow 02^\circ 1$) and ($00^\circ 0 \rightarrow 10^\circ 1$), respectively [17].

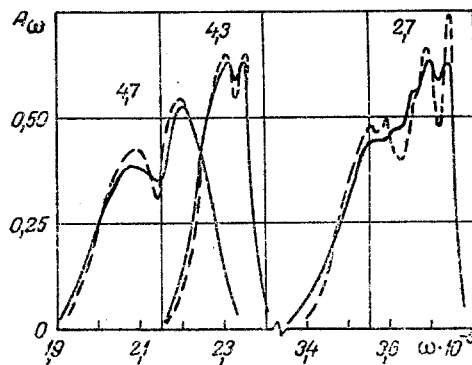


Fig. 1. Experimental (continuous curve) and calculated (present work, dashed curve) values of the spectral absorptivity. Experimental values of $\langle A_\omega \rangle$ are taken from [20] for the 4.3- μm band ($P_t = 0.0622$ atm, $X = 0.475$ atm·cm), from [18] for the 2.7- μm band ($P_t = 0.921$ atm, $X = 1.17$ atm·cm), and from [19] for the 4.7- μm band ($P_t = 1.0$ atm, $X = 20$ atm·cm). The equilibrium gas temperature is 1200°K. $\omega \cdot 10^{-3}$, cm^{-1} .

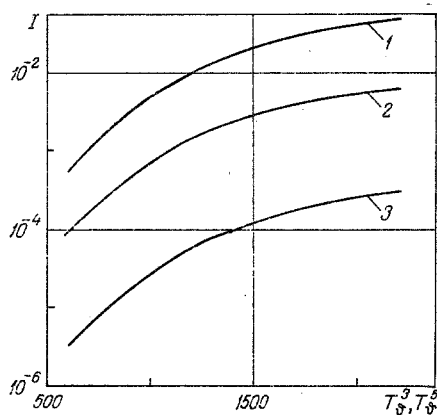


Fig. 2

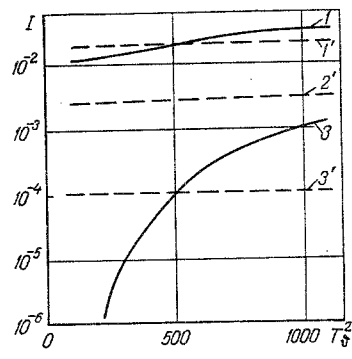


Fig. 3

Fig. 2. Radiation intensity of CO_2 and CO vibrational-rotational bands with different active-mode temperatures. The optical path length $X = 10^{-2}$ atm·cm, pressure $P_t = 5 \cdot 10^{-2}$ atm, temperature $T_v^2 = 500^\circ\text{K}$, $T = 300^\circ\text{K}$. I , $\text{W}/\text{sr} \cdot \text{cm}^2$; T , $^\circ\text{K}$.

Fig. 3. Radiation intensity as a function of vibrational temperature T_v^2 and gas temperature T . The mass path length $X_\rho = 1.12 \cdot 10^{-5}$ g/ cm^2 , which corresponds to $X = 10^{-2}$ atm·cm at $T = 300^\circ\text{K}$; $T_v^2 = 1500^\circ\text{K}$, $P_t = 5 \cdot 10^{-2}$ atm; curves 1 and 3 are for $T = 300^\circ\text{K}$ and curves 1' and 3' for $T_v^2 = 500^\circ\text{K}$.

The averaging interval for the absorptivity is 5 cm^{-1} . In the calculation, the vibrational levels of modes with quantum numbers up to 5-20 are considered. The contribution to the radiation made by rotational levels with a population amounting to 10^{-5} of the population for a maximum-populated rotational level of the basic vibrational state is taken into account.

The results of comparing the calculated spectral absorptivity for the 4.7-, 4.3-, and 2.7- μm bands of the CO and CO_2 molecules in conditions of thermodynamic equilibrium with the experimental data of [18, 19] are given in Fig. 1. The good agreement of experiment and calculation indicates that the system realized here for the determination of the spectral absorptivity and hence the radiative characteristics of the gas is correct.

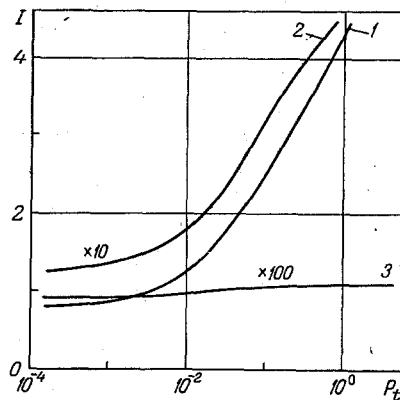


Fig. 4. Dependence of radiation intensity of 4.3- (1), 4.7- (2), and 2.7- μm (3) bands of gas on P_t , atm, $X = 10^{-2}$ atm·sec, $T = 300^\circ\text{K}$, $T_{\text{v}}^3 = T_{\text{v}}^5 = 1500^\circ\text{K}$, $T_{\text{v}}^2 = 500^\circ\text{K}$.

This allows consideration to proceed to the radiative characteristics of gases in conditions where thermodynamic equilibrium is absent. Some results of the present investigations are shown in Figs. 2-4.

In Fig. 2 the integral radiation intensity of the 4.3- (1), 2.7- (3), and 4.7- μm (2) bands is shown as a function of the vibrational temperatures T_{v}^3 and T_{v}^5 characterizing the active-mode population. It follows from these results that the radiation intensity of vibrationally nonequilibrium gas depends sharply on the active-mode vibrational temperatures. Change in the vibrational temperatures of CO_2 (T_{v}^3) and CO (T_{v}^5) from 600 to 1500°K leads to change in the radiation intensity I by almost two orders of magnitude.

The dependence of the integral radiation intensity of the 4.3- and 2.7- μm bands on the vibrational temperature of symmetric and deformational CO_2 modes (curves 1 and 3, respectively) is shown in Fig. 3, together with the dependence of the integral radiation intensity of the 4.3-, 4.7-, and 2.7- μm bands on the translational temperature of the gas (curves 1', 2', and 3').

The radiation intensity of the 2.7- μm band depends sharply on the vibrational temperature of the symmetric and deformational CO_2 modes, which are active in the given case. The dependence of the radiation intensity of the 4.3- μm band, for which the symmetric and deformational modes are passive, on the vibrational temperature T_{v}^3 is significantly weaker. With increase in the temperature T_{v}^3 from 100 to 1000°K , the radiation intensity of the 4.3- μm band rises by a factor of ≈ 4 . This increase is determined by the appearance of new spectral lines in the 4.3- μm band, corresponding to the excited states of the symmetric and deformational modes.

It follows from the data of Fig. 3 that the radiation intensity of the vibrational-rotational bands is practically independent of the translational and hence the rotational temperature. This important conclusion allows the deviation of the rotational distribution from thermodynamic equilibrium to be disregarded.

In Fig. 4 the radiation intensity of the given bands is shown for different gas pressures. A characteristic feature of reabsorbed radiation is a strong dependence on the gas pressures. It is evident from the data of Fig. 4 that for an optical path length $X = 10^{-2}$ atm·sec there is significant reabsorption of radiation in the 4.3- and 4.7- μm bands.

The data given in Figs. 2-4 allow the radiation intensities of the 4.3-, 2.7-, and 4.7- μm bands to be compared, and allow the extent to which their radiation affects the gas parameters to be determined. The main conclusion of this work is that the dependence of the radiation intensity of the vibrational-rotational bands in thermodynamically nonequilibrium conditions is determined mainly by the vibrational temperatures of the active and, to a lesser degree, passive modes. This assures the reliability and high accuracy of the experimental method of determining vibrational temperatures on the basis of recording the IR-radiation intensity of the vibrationally nonequilibrium gas.

LITERATURE CITED

1. N. N. Kudryavtsev, S. S. Novikov, and I. B. Svetlichnyi, "Method and results of experimental determination of CO₂ vibrational temperature in nonequilibrium fluxes using the model of vibrational-rotational bands," *Dokl. Akad. Nauk SSSR*, 231, No. 6, 1419-1421 (1976).
2. N. N. Kudryavtsev, S. S. Novikov, and I. B. Svetlichnyi, "Experimental determination of temperature of 00°1 level of carbon dioxide molecule in nonequilibrium flux of a CO₂ + N₂ + H₂(He) mixture," *Fiz. Goreniya Vzryva*, 13, No. 2, 205-212 (1977).
3. S. Bihl, J. P. Fouassier, and R. Joeckle, "Calcul de l'emission infrarouge de milieu laser CO₂," *J. Quant. Spectr. Rad. Transfer*, 12, No. 8, 819-927 (1974).
4. L. P. Bakhir and Yu. V. Orevchenko, "Determining CO₂-molecule vibrational-level populations in gas-dynamic lasers by the methods of IR spectroscopy," *Zh. Prikl. Spektrosk.*, 30, No. 1, 44-56 (1979).
5. S. A. Losev, *Gasdynamic Lasers* [in Russian], Nauka, Moscow (1977).
6. J. D. Anderson, *Gasdynamic Lasers. An Introduction*, Academic Press, New York-San Francisco-London (1976).
7. S. S. Penner, *Quantitative Molecular Spectroscopy and Gas Emissivities*, Addison-Wesley (1959).
8. R. M. Gudi, *Atmospheric Radiation* [Russian translation], IL, Moscow (1966).
9. J. P. Hodgson, "The nonequilibrium emissivity of carbon dioxide near 4.3 μ ," *Aeronat. Research Current Paper*, No. 1116, 3-26 (1970).
10. S. A. Losev, "Infrared radiation of carbon dioxide in nonequilibrium conditions," *Tr. Inst. Mekh. Mosk. Gos. Univ.*, No. 43, 79-86 (1976).
11. B. A. Khmelinin and Yu. A. Plastinin, "Radiative and absorptive properties of H₂O, CO₂, CO, and HCl molecules at temperatures of 300-3000°K," *Tr. TsAGI*, No. 1656, 102-146 (1975).
12. C. D. Rodgers and W. Williams, "Integrated absorption for Voigt profiles," *J. Quant. Spectr. Rad. Transfer*, 14, No. 4, 319-326 (1974).
13. C. P. Courtoy, "Le spectre de C¹²O₂¹⁶ entre 3500 et 8000 cm⁻¹ et les constantes moléculaires de cette molécule," *Can. J. Phys.*, 35, 608-648 (1955).
14. N. I. Ostroukhova and G. V. Shlyapnikov, "Infrared radiation of molecular gas in Q branch," *Teplofiz. Vys. Temp.*, 16, No. 2, 279-281 (1978).
15. M. P. Lisitsa and V. L. Strizhevskii, "Temperature dependence of intensities of vibrational-rotational absorption bands of gases in the case of Fermi resonance," *Opt. Spektrosk.*, 7, No. 4, 478-484 (1959).
16. P. Varanasi and S. Sarangi, "Measurement of intensity and nitrogen-broadened widths in the CO fundamental at low temperatures," *J. Quant. Spectr. Rad. Transfer*, 15, No. 6, 473-483 (1975).
17. H. D. Downing, L. P. Brown, and R. H. Hunt, "Line intensities of CO₂ in the 2.7- μ m region," *J. Quant. Spectr. Rad. Transfer*, 15, No. 3, 205-211 (1975).
18. W. Malkmus, "Infrared emissivity of carbon dioxide (2.7 μ m band)," *J. Opt. Soc. Am.*, 54, No. 4, 751-758 (1964).
19. M. M. Abu-Ramia and C. L. Tien, "Measurement and correlations of infrared radiation of carbon monoxide at elevated temperatures," *J. Quant. Spectr. Rad. Transfer*, 6, No. 2, 143-167 (1966).
20. D. E. Burch and D. A. Gryvnak, "Laboratory investigation of the absorption and emission of infrared radiation," *J. Quant. Spectr. Rad. Transfer*, 6, No. 3, 229-241 (1966).
21. R. M. Huffaker, "Current research on infrared radiation from rocket exhaust," *J. Quant. Spectr. Rad. Transfer*, 8, No. 1, 87-98 (1968).