MEASUREMENT OF THE TEMPERATURE OF GAS MEDIA CONTAINING CARBON DIOXIDE BY THE LASER-PROBING METHOD

S. P. Vagin and Yu. A. Yakobi

UDC 536.5:621.378.325

Measurements of the temperature by means of the vibrational–rotational absorption (amplification) spectrum of carbon dioxide under equilibrium and nonequilibrium conditions are compared with independent thermocouple measurements and computed values.

Gas media containing carbon dioxide are used extensively in modern engineering. Primarily combustion chambers of hydrocarbon propellants as well as the CO_2 lasers which have recently received extensive development can serve as examples. Since the media mentioned are often nonequilibrium, their thermal state is characterized not only by a translational temperature, but also by a vibrational temperature which can be determined by means of the intensity of vibrational-band radiation or absorption [1, 2]. The translational temperature is often determined by contact methods (thermocouples, for instance). However, these latter substantially distort the gas medium. Best known of the optical methods is the temperature determination by means of the Doppler spectrum line broadening. However, it is correct only at low pressures and high temperatures. Thus, for $P = 1$ atm and $T_g = 300$°K the collisional broadening is 30-50 times greater than the Doppler broadening [3]. Since Doppler broadening is proportional to $\sqrt{T_g}$, the situation does not change substantially even at temperatures on the order of several thousands of degrees.

The translational temperature can also be determined by optical recording of the population distribution over the rotational levels [4, 5], since these latter are practically always in equilibrium with the translational motion [6]. However, ordinary methods of recording the radiation or absorption spectra require the combination of a large aperture and high resolution in this case. As is known, the requirements mentioned are contradictory [7]. The problem is simplified substantially when the rotational absorption spectrum is investigated by using a frequency-tunable CO_2 laser which will assure a high monochromatic density of the probing radiation for a large number of rotational transitions [8]. The question of the accuracy of the method mentioned remains open, since it was compared only with other optical methods in research performed earlier, which could not be standards, since the measurements were only performed in nonequilibrium media [8, 9]. In this connection, we performed measurements in both equilibrium and nonequilibrium media under those conditions when the thermocouple measurements on the cuvette walls could assure sufficiently accurate pinpointing of the temperature. A very essential factor is also the spectrum scanning rate, which is ordinarily executed within a time on the order of seconds or even minutes that is fraught with the drift of parameters of the medium under investigation and of the measuring channel.

The diagram of the experimental setup is presented in Fig. 1. A CO_2 laser tunable in the 9.4-10-μm spectral range and assuring an intensity on the order of 1 W at individual lines was used as the radiation source. Complete scanning of the vibrational–rotational band was accomplished in 10^{-3} sec. A specimen of the generation spectrum is represented in Fig. 2. The absorption (amplification) coefficient was measured by a comparison scheme in which the light beam from the laser 1 was divided by the germanium plate 2 into two beams, one of which fell directly on the cooled gold-doped germanium photodetector 3, while the other fell on an analogous photodetector 5 after passing through the gas cuvette 4. Part of the radiation was drawn off by the divider plate 6 to the entrance slit of the infrared monochromator 7 tuned to one of the known lines. Spectrum sweeps were simultaneously delivered to the two-beam oscilloscope 13 from the photodetectors 3 and 5 to measure the absorption. The sweeps were photographed and processed to determine the absorption coeffecients at all the lines of the band being scanned. To pinpoint the spectrum, a signal from the photodetector 8 was supplied to one of the oscilloscope inputs. A 0.5-m-long Kovar tube of 0.008-m inner diameter was used

---

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 1, pp. 5-10, July, 1978. Original article submitted January 13, 1978.

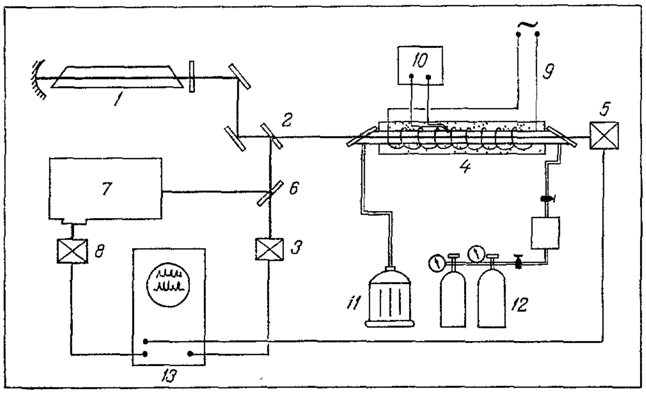

Fig. 1

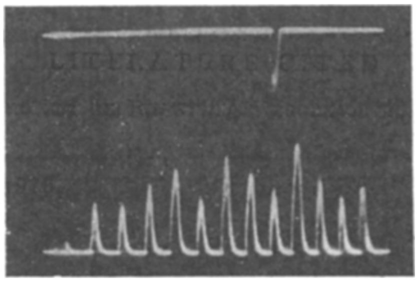

Fig. 2

Fig. 1. Diagram of the experimental setup.

Fig. 2. Oscillogram of the combined recording of the radiation spectrum of the tunable CO_2 laser and the signal at the extracted frequency from the monochromator.

as the cuvette. The tube was heated by the spiral 9 wound uniformly on its surface and was carefully heat insulated. The surface temperature was checked by the thermocouple 10. The high value of the ratio between the tube length and diameter and the good heat insulation permit considering the temperature identical along the tube (and constant along the diameter as well in the case of thermal heating). The tube was evacuated by the pump 11, after which the initial relationship between the beam intensities was recorded. Then the gas mixture containing the CO_2 was released from the tanks 12 and heated to several hundred degrees.

The weak signal index of absorption (amplification) at the center of a line broadened by the combined effect of collisions and the Doppler effect can be written in the following form for the P branch [10]:

$$\alpha_\nu = \frac{\lambda_J^2 A(\ln 2)^{1/2}}{8\pi^{3/2}\Delta\nu_D}\,\frac{2hcB}{kT_g}\,(2J+1)\exp\left[-\frac{hcBJ(J+1)}{kT_g}\right]\times$$

$$\times\left\{N_1 - N_2\exp\left[\frac{2JhcB}{kT_g}\right]\right\}H(a,\ 0), \tag{1}$$

$$a = (\Delta\nu_c/\Delta\nu_D)(\ln 2)^{1/2}.$$

The collisional broadening $\Delta\nu_C$ was calculated in conformity with [11], and the Einstein coefficient was assumed equal to 0.21 $\sec^{-1}$ [12].

The quantity $2hcB/k$ is 56.3°K for $J \simeq 50$; hence, $\exp(2JhcB/kT_g)$ differs slightly from one for small J and temperatures $T_g \geq 400$°K. The error in replacing the exponential by one is less than 1%. Taking the logarithm of (1), we obtain

$$\ln\left[\frac{\lambda_0^2\alpha_\nu L}{\lambda_J^2(2J+1)}\right] = -\frac{hcBJ(J+1)}{kT_g} + \ln K_0, \tag{2}$$

where

$$K_0 = \frac{A(\ln 2)^{1/2}\lambda_0^2 L}{8\pi^{3/2}\Delta\nu_D}\,\frac{2hcB}{kT_g}\,H(a,\ 0)\{N_2 - N_1\}.$$

Using a method analogous to [8], we determine the translational temperature from the slope of the root-mean-square line drawn as a function of $J(J+1)$ by means of the experimentally measured values of $\ln[(\lambda_0/\lambda_J)^2(\alpha_\nu L/(2J+1))]$. It is quite essential that (2) permit determination of the temperature without relying on information about the CO_2 molecule concentration and the optical-path length. Results of scanning the spectrum for $T_g \approx 380$°K are shown in Fig. 3 as an illustration. The experimental points lie well on a line, which confirms the presence of an equilibrium population of the system of rotational levels as had been assumed in the derivation of (1).

Special attention was turned to comparing the temperature measurements performed simultaneously by the method of laser probing along the axis and by the thermocouple on the tube wall. Errors associated with the thermocouple are determined by the heat efflux along the thermocouple thermoelectrodes, by the change in the resistance of the loop, by the inertia of the object being measured, and by the accuracy class of the mea-

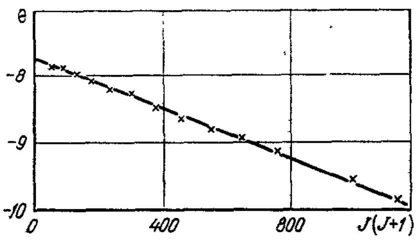

Fig. 3. Dependence of experimentally determined values of $\theta = \ln[(\lambda_0/\lambda_J)^2 (\alpha_\nu L/(2J+1))]$ as a function J(J + 1) at the gas temperature $T_g = 380$°K.

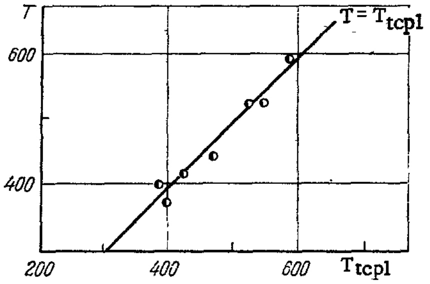

Fig. 4

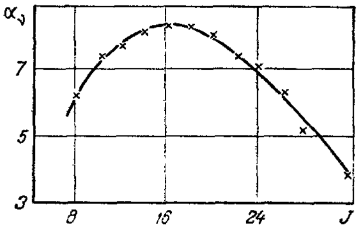

Fig. 5

Fig. 4. Comparison of the temperature values (°K) measured by the thermocouple and the laser-probe method.

Fig. 5. Dependence of the gain α_ν (rel. units) on the quantum number J in a discharge plasma at $T_g = 345$°K.

suring instrument, which equals one in our case. In order to diminish these errors in the present research, the thermocouple thermoelectrodes were laid out along the tube surface and maintained at the same temperature as the wall. Calibration was executed without a subsequent change in the loop resistance, and the temperature measurement and reading were performed by reaching a system of thermal equilibrium. Taking account of the above, the error in the thermocouple measurements lies within 2% limits. The upper bound of the value of the difference between the geometric and the effective optical lengths of the tube, because of edge effects, yields $\Delta L/L \simeq 2d/L \simeq 2\%$. The greatest error is associated with processing the oscillograms (5%). Temperatures measured by the thermocouple (abscissa axis) and by the laser-probe method (ordinate axis) are compared in Fig. 4. The line bisects the angle formed by the coordinate axes. The spread in the results lies within 5% limits, which corresponds to the above-mentioned possible sources of error.

A nonequilibrium (lasing) medium produced by an electrical discharge in a CO_2-N_2-He mixture with the partial pressure ratio 1 : 3 : 5 for a 10-torr total pressure, was the object of investigation in the second stage of the research. The metal tube was hence replaced by water-cooled glass. The discharge current I was varied between 10 and 30 mA. In Fig. 5 we present the characteristic dependence of the gain as a function of the rotational quantum number J. Since the dependence of α_ν on J has a maximum whose location is determined by the temperature T_g, this latter can be determined directly from the value of the rotational quantum number corresponding to the maximum gain. As follows from (1),

$$J_{\max} \simeq \sqrt{\frac{kT_g}{2hcB}} - \frac{1}{2} \simeq 0.95\sqrt{T_g} - \frac{1}{2}. \qquad (3)$$

However, we used more exact computations performed by means of graphs of the kind presented in Fig. 3.

On the other hand, the translational temperature on the tube axis can be determined from the heat-conduction equation [4]

$$Q = (T_g - T_w)\, 18.9\lambda_\Sigma(T_g). \qquad (4)$$

The quantity λ_Σ was calculated by means of the formula presented in [13], while the wall temperature T_w was assumed equal to the temperature of the cooling water. An experimental determination of the rotational (translational) temperature was performed by the laser-probe method. Values of the translational temperature were substituted into (1), which was then solved for the population of the upper level characterized by the vibrational temperature in order to determine the vibrational temperature.

TABLE 1. Values of the Gas Temperature Magnitude T_g (°K) Measured in the Gas-Discharge Plasma, of the Population of the Upper Lasing Level $N_{00^01} \cdot 10^{-15}$ cm^{-1}, and of the Vibrational Temperature T_V (°K) of the Level 00^01 of the CO_2 Molecule as a Function of the Discharge Current I (mA) [T is the value of the gas temperature obtained from (3) (°K)]

T_g	T	N_{00^01}	T_V	I	E
300	340	1,29	1100	10	92
345	379	1,39	1200	20	82
415	417	1,48	1400	30	74

Results of comparing the temperature values on the tube axis, obtained from optical measurements and from (4), as well as the values of the vibrational temperature and of the upper lasing level population are presented in Table 1. The degree of agreement obtained showed the admissibility of using (4) for CO_2 lasers of coaxial construction. Direct utilization of the laser-probe method is directly necessary in CO_2 lasers of orthogonal construction. The information hence obtained (rotational and vibrational temperatures, weak-signal gains, and magnitude of the vibrational energy flux suitable for conversion into coherent radiation) is extremely important for the optimization of flow through lasers [14].

Therefore, the method of measuring the translational temperature of gas media, based on fast scanning of the vibrational–rotational CO_2 absorption spectrum by using a frequency-tunable CO_2-laser, assures satisfactory accuracy. The error does not exceed several percent.

The translational temperature of a gas mixture under conditions characteristic for coaxial CO_2 lasers can be determined to an accuracy on the order of 10% by using (4).

NOTATION

P, pressure of the gas medium; T_g, gas temperature; N_2, N_1, upper and lower vibrational level temperatures; $H(a, 0)$, value of the Voigt function at the center of the line; $\Delta\nu_D$, $\Delta\nu_c$, Doppler and collisional line broadening; λ_0, λ_J, lasing transition wavelengths; J, rotational quantum number; A, probability of spontaneous radiation; B, rotational constant; α_ν, index of absorption (amplification) of the weak signal at the center of the line; h, Planck's constant; c, speed of light; k, Boltzmann constant; d, L, tube diameter and length; Q, power liberated in the gas per unit length of the discharge; I, E, electrical field current and intensity, respectively; λ_Σ (T_g), coefficient of thermal conductivity of gas mixture; T_w, wall temperature of the discharge tube.

LITERATURE CITED

1. A. A. Mikaberidze, V. N. Ochkin, and N. N. Sobolev, J. Quant. Spectrosc. Radiat. Transfer, 12, 169 (1972).
2. R. Bleekrode, IEEE J Quant. Electron., QE-5, 57 (1974).
3. R. I. Soloukhin and Yu. A. Yakobi, Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1974).
4. S. S. Vasil'ev and A. E. Sergeenkova, Zh. Fiz. Khim., 40, 2373 (1966).
5. M. Z. Novgorodov, V. N. Ochkin, and N. N. Sobolev, Zh. Tekh. Fiz., 40, 1268 (1970).
6. E. V. Stupachenko, S. A. Losev, and A. I. Osipov, Relaxation Processes in Shock Waves [in Russian], Nauka, Moscow (1965).
7. A. I. Zaidel', G. V. Ostrovskaya, and Yu. I. Ostrovskii, Technique and Practice of Spectroscopy [in Russian], Nauka, Moscow (1976).
8. P. V. Avizonis, Appl. Phys. Lett., 7, 23 (1973).
9. N. N. Kudryavtsev, S. S. Novikov, and I. B. Svetlichnyi, Fiz. Goreniya Vzryva, No. 2 (1977).
10. S. S. Penner, Quantitative Molecular Spectroscopy and Gas Emissivities, Addison-Wesley (1959).
11. S. A. Losev and V. N. Makarov, Kvant. Elektron., No. 7 (1974).
12. E. T. Gerry and D. A. Leonard, Appl. Phys. Lett., 8, 227 (1966).
13. S. Mathur and S. C. Saxena, Appl. Sci. Res., 17, 155 (1967).
14. Laser Focus, No. 11, 14 (1977).