LOCAL COOLING OF A GAS INDUCED BY ABSORPTION OF CW RADIATION ON AN INTERMODE TRANSITION

A.B. Vasil'ev, O.M. Vokhnik, A.V. Kolchin, P.V. Milyaev, E.V. Perestoronina, and V.A. Spazhakin

State University, Moscow

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In this paper we discuss a mechanism of stationary radiation-diffusion cooling of molecular gases induced by absorption of CW IR–radiation on an intermode vibrational transition. It is shown for the first time that nonmonotonic stationary spatial distributions of temperature and density are formed in gases of few-atom molecules upon exposure to a light beam. We also analyse some characteristics of such distributions. It is shown that a local decrease of temperature may be induced in the mixtures of $CO_2 : N_2 : He\ (H_2O)$ *by absorption of a focused radiation of a* CO_2*-laser.*

The short-time "kinetic" cooling of molecular mixtures of CO_2:N_2:H_2O by a pulsed radiation of a CO_2–laser attracts much attention in connection with the possibility of heat focusing of a laser beam into the atmosphere.[1–3] However, during the time of vibrational–translational ($V–T$) relaxation of the upper level of CO_2 such cooling is changed by heating, what makes its practical implementation difficult. Stationary mechanisms of cooling of molecular gases by the IR-radiation were discussed in Refs. 4 and 5. Thus far, no consideration has been given to the conditions of forming the stationary temperature distributions.

In this paper we investigate the new possibility of forming stationary temperature distributions with the minimum in the region occupied by a beam due to absorption of radiation on an intermode transition from an excited vibrational level when the cooling is due to the $V–T$ processes and the spatial transfer of energy is due to diffusion of molecules excited to the level of a mode with large quantum.

At low temperatures ($T \sim 300$ K), taking into consideration that the rate of $V–T$ exchange at lower level τ^{-1}, as a rule, significantly exceeds the effective rate of $V–T$ relaxation of the upper state γ, the following system of equations was used to describe the basic processes:

$$D\Delta_r n_1 - \gamma\, n_1 - wn_1 + wn_2 = 0, \qquad (1)$$

$$wn_2 - wn_1 + (n_2 - n_0\upsilon) / \tau = 0, \qquad (2)$$

$$\Lambda\Delta_r T + E_2(n_2 - n_0\upsilon) / \tau + E_1\, \gamma\, n_1 = 0, \qquad (3)$$

$$n_1(R) = 0,\ \ T(R) = T_0. \qquad (4)$$

Here $\Delta_r = \dfrac{d^2}{dr^2} + \dfrac{1}{r}\dfrac{d}{dr}$ is the radial component of the Laplacian operator; D is the diffusion coefficient; $\Lambda = \lambda/k$; λ is the heat conductivity; k is the Boltzmann constant; n_1, n_2, E_1, and E_2 are the population densities and energies (in K) of the upper and lower levels; n_0 is the population density of the ground state ($n_0 \gg n_i$, $i = 1,\ 2$); $\upsilon = \exp(-E_2/T)$; and R is the radius of a medium.

The radiation of molecular lasers, as a rule, is multimode (and multifrequency), therefore it was assumed that at low pressures the radiation interacts with all particles occupying levels 1 and 2, and the radial distributions of the form $w = w$ for $r \le a$ (region I) and $w = 0$ for $r > a$ (region II) were used for the rate of stimulated transitions.

Equations (1) – (3) were reduced to dimensionless form of the variables $r' = r/l_D$, $T' = T/T_0$, and $n_i' = n_i/n_0$ and of the parameters $l_D = (D/\gamma)^{1/2}$, $w' = w/\gamma$, $\kappa = E_1 n_0 D/\lambda T_0$, $\tau' = \tau\gamma$, $\varepsilon = E_1 / E_2$, $a' = a/l_D$, and $R' = R/l_D$. These equations were solved separately for regions I and II with subsequent joining of the obtained solutions and their derivatives at the boundary of a beam for $r = a$. So the substitution of Eq. (2) in Eq. (3) and of Eq. (3) in Eq. (1) for region I leads to the fourth–order differential equation.

$$\Delta_{r'} F = \mu,\ \ F = \Delta_{r'} T' - \nu T',\ \ \mu = \kappa\vartheta\Gamma\,(1 - \varepsilon^{-1}),$$

$$\nu = (1 + w'\tau')^{-1}\,(1 + w' + w'\tau'),\ \Gamma = (1 + w'\tau') / w', \qquad (5)$$

that admits of sequential integration on the assumption that $\vartheta = \vartheta_0 = \exp(-E_2/T_0)$. The solution of Eqs. (5) $F = A_0 \ln r' + \mu r'^2 / 4 + A_1$ becomes simpler: $A_0 = 0$ because the singularity at $r' = 0$ has been removed. Then the solution of the modified Bessel equation in system of Eqs. (5) is found simply as the sum of corresponding solutions of homogeneous and inhomogeneous equations.

In region II Eq. (2) becomes identically zero and the solution of Eq. (1) is written in terms of the Bessel functions of imaginary arguments $I_0(r')$ and $K_0(r')$, and integral (3) is given by a sum of $I_0(r')$, $K_0(r')$, and fundamental solution of the equation $\Delta_{r'} T' = 0$, i.e., $T' = B_0 \ln r' + B_1$.

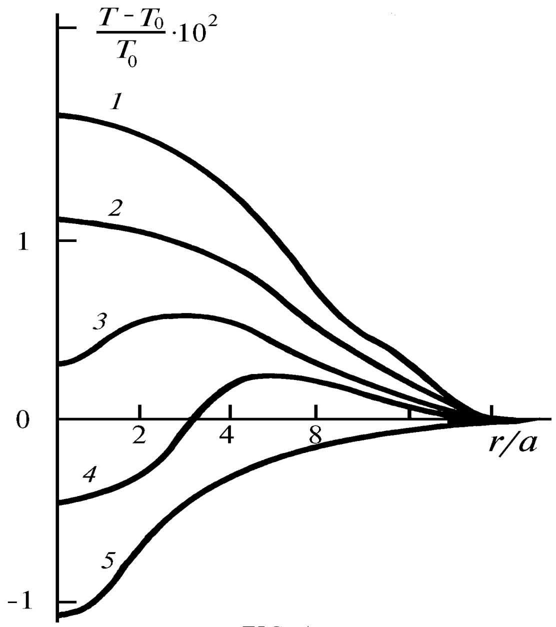

FIG. 1.

Distributions of $T(r)$ that were calculated according to the derived analytical relations, are shown in Fig. 1. In our calculations we used the values of the parameters that were close to those of few-molecule gases (CO_2, N_2O, and CS_2) at pressures $p \sim 0.1 - 1$ Torr with insignificant additions of H_2O (H_2, He): $\kappa = 5$, $\varepsilon = 1.5$, $w' = 10$, $\tau' = 0.3$, and R/a = 10. The radial translational temperature distribution was $l_D / a = 0$(*1*), 1(*2*), 1.5(*3*), 2(*4*), and 5(*5*).

It can be seen from the figure that as the effective diffusion length l_D / a increases, heating of a medium is changed by its cooling; moreover, this transformation occurs through nonmonotonic stationary temperature distributions. For the above–mentioned parameters when $l_D \geq 1.3\,a$ lowered temperature zone starts to form on the axis of a beam in a heated medium. A further increase when $l_D \geq 1.8\,a$ leads to absolute cooling of the near–axis zone while heating of the peripheral zone keeps, and then (for $l_D \geq 3.5\,a$) to cooling of the whole medium. For the fixed parameters l_D, a, and R ($l_D > a$) the differences of T and n_1 from their equilibrium values decrease almost linearly with increase of κ, increase with increase of ε, and for $R \gg a$ depend weakly on the value of R. We note that these differences increase exponentionally with rise in T_0 due to increasing equilibrium population density of lower level. With formal increase of T_0 to 600 K the temperature drop is about 10 K, and it is about 10^2K when $T_0 \sim E_2$ and $a = R$.

Only the parameter κ depends explicitly on the concentration of molecules N and on the heat conductivity λ; moreover, at a low concentration of additions at low T_0 $N \approx n_0$ for $\lambda = Dc_{\mathrm{v}} n_0 m$ (c_V is the specific heat and m is the mass of molecule) this dependence disappears and $\kappa = kE_1/T_0 c_{\mathrm{v}} m$, i.e. an individual variation of n_0 (for fixed l_D) engenders a consistent alteration of positive and negative sources of heat without disturbing the temperature distribution.

Below we analyse the characteristics of nonmonotonic stationary temperature distributions (3) and (4) which were first found under conditions of interaction of IR-radiation with molecular gases. The value of r'_m corresponding to the maximum value of T'_m can be easy determined from the condition $dT'/dr' = 0$ and, for example, is given by the transcendental correlation when $a \ll l_D \ll R$ and $\omega \approx \tau^{-1} \gg \gamma$,

$$r'_{\mathrm{m}} H(r'_m, R') = (1 - \varepsilon^{-1})\, a' H(a', R'), \tag{6}$$

where $H(r', R') = I_1(\mathrm{r}') + I_0(R')\, K_1(r') / K_0(R')$.

From Eq. 6 it follows that r_m may significantly exceed a and does not depend on κ. The equality $r_m = R$ specifies the condition of transition to the cooling of the whole medium. When it is met the energy exchange with a wall goes only by transmission of vibrational quanta without heat conduction; moreover, such regime is stable with respect to the fluctuations of radiant power.

Thus, the proposed mechanism of radiation cooling due to diffusion outflow of vibrational quanta is capable of forming stationary zone of lowered temperature in the region occupied by a beam and even may cause the cooling of the whole medium. Due to absorption of radiation by the P–branch of transition the cooling will intensify as a result of "additional" transfer of rotational quanta.[4]

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