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INFLUENCE OF RADIATION INTENSITY AND PARAMETERS OF THE MEDIUM ON THE DEPTH OF COOLING AND THE CHANGE IN THE INDEX OF REFRACTION DURING THE ADSORPTION OF RADIATION WITH λ = 9.2-10.6 μm BY WATER VAPOR

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UDC 539.196+546.214

The possibility of cooling molecular gases by laser radiation has recently attracted the interest of many investigators [1-5]. A decrease in the temperature of the medium in the channel of an actuating laser beam leads to the formation of a thermal converging lens and, as a consequence, to self-focusing of the laser beam [5]. One of the gases absorbing the radiation of a CO_2 laser with a wavelength λ = 9.2-10.6 μm most intensely is water vapor. It was assumed earlier that the adsorption of the energy of radiation with λ = 9.2-10.6 μm by water vapor leads to heating of the medium in the beam channel and the formation of a diverging thermal lens [2]. The possibility of cooling of a medium containing water vapor upon the action of a radiation pulse with λ = 9.2-10.6 μm and a duration less than the time of V–T relaxation of deformation vibrations of H_2O molecules was demonstrated only recently [6]. Here the cooling mechanism is analogous to the mechanism of cooling of a gas of diatomic molecules upon resonance absorption of radiation in the P branch of a vibrational–rotational transition discussed earlier [7].

In the present paper, on the basis of analytic relations obtained, we analyze the influence of the intensity of the actuating radiation and the parameters of the medium containing water vapor on the depth of cooling and the change in the index of refraction during the absorption of radiation of a CO_2 laser in vibrational–rotational transitions of H_2O molecules.

It is well known that the radiation of a CO_2 laser with a wavelength λ = 9.2-10.6 μm is absorbed, depending on its frequency, by water vapor both in the purely rotational band of the vibrational ground state and in vibrational–rotational transitions of the deformation mode ($0 \to \nu_2$) [8]. In the present work we consider only those radiation frequencies of a CO_2 laser which are absorbed in the $0 \to \nu_2$ band of the H_2O molecule for a medium consisting of the gases H_2O, O_2, and N_2. We recall that cooling of the gas in this case is possible only under the action of radiation with a frequency in resonance with the frequency of a line of a vibrational–rotational transition for which the rotational energies of the upper (E_j'') and lower (E_j') levels satisfy the inequality $E_j'' < E_j'$ [6].

As usual, we assume that the width of the line of the radiation acting on the medium is considerably less than the width of the spectral absorption line. We shall carry out the analysis for $\tau_I \gg \max(\tau_{R\text{-}T}, \tau_{V\text{-}V})$, where τ_I, $\tau_{R\text{-}T}$, and $\tau_{V\text{-}V}$ are the characteristic times of induced transitions and of rotational–translational (R–T) and intramodal vibrational–vibrational (V–V) exchanges, respectively. In this case the distribution of H_2O molecules over the rotational levels can be taken as a Boltzmann distribution with a translational temperature T, while the change in the state of the medium over times $t < \tau_T, \tau_c$ (τ_T and τ_c are the heat-conduction and convection times) under the action of radiation with λ = 9.2-10.6 μm can be described by the system of equations [6]

$$\frac{d\varepsilon_1}{dt} = \frac{p}{kT}[L_{31}W_{31} - L_{12}W_{12}]; \tag{1}$$

$$\frac{d\varepsilon_2}{dt} = \frac{p}{kT}\left[\frac{k_\nu I \mu^2}{\rho^2 N_A^2 \gamma_1 h\nu_I} + 2L_{12}W_{12} + 2L_{32}W_{32} - L_{24}W_{24}\gamma_2 - (\varepsilon_2 - \varepsilon_{20})W_{20}\right]; \tag{2}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 9-16, November-December, 1986. Original article submitted November 4, 1985.

 0021-8944/86/2706-0796$12.50 © 1987 Plenum Publishing Corporation

$$\frac{d\varepsilon_3}{dt} = \frac{p}{kT}\left[-L_{31}W_{31} - L_{32}W_{32}\right]; \tag{3}$$

$$\frac{d\varepsilon_4}{dt} = \frac{p}{kT}L_{24}W_{24}\gamma_1,\ \varepsilon_5 = \varepsilon_{50}(T); \tag{4}$$

$$C_p\frac{dT}{dt} = J,\ J = \frac{k_\nu I}{\rho} - \left(\gamma_1\sum_{j=1}^{3}\Theta_j\frac{d\varepsilon_j}{dt} + \gamma_2\Theta_4\frac{d\varepsilon_4}{dt}\right),$$
$$\varepsilon_j = [\exp(\Theta_j/T_j) - 1]^{-1}r_j,\ C_p = \frac{R}{\mu}\left(\frac{7}{2} + \frac{1}{2}\gamma_1\right), \tag{5}$$
$$\varepsilon_{j0} = \varepsilon_j(T),\ W_{pq} = \sum_{i=1}^{3}W_{pq}^{i}\gamma_{is}$$
$$L_{pq} = \varepsilon_p^{l_p}(\varepsilon_q + 1)^{l_q} - \varepsilon_q^{l_q}(\varepsilon_p + 1)^{l_p}\exp\left(\frac{l_q\Theta_q - l_p\Theta_p}{T}\right).$$

Here p, ρ, and T are the pressure, density, and translational temperature of the gas; μ is the molecular weight of the mixture; Θ_j and Tj are the characteristic and local vibrational temperatures of the j-th mode while rj is the multiplicity of its degeneracy; k is the Boltzmann constant; h is Planck's constant; R is the universal gas constant; N_A is Avogadro's number; W_{pq} is the rate constant of intermolecular V−V' exchange while W_{pq}^{i} is the rate constant of intramolecular V−V' or V−T exchange in a collision with an i-th partner (i = 1, 2, and 3 correspond to the gases H_2O, O_2, and N_2; p(q) = 1, 2, 3, 4, and 5 correspond to symmetric, deformation, and asymmetric types of vibrations of the H_2O molecule and vibrations of O_2 and N_2 molecules); γ_i is the molar fraction of the i-th component in the mixture; l_q is the number of vibrational quanta lost or gained by mode q in V−V' exchange; I is the intensity of the actuating radiation while γ_I is its frequency; k_ν is the absorption coefficient.

As numerical calculations of the complete system of equations (1)-(5) carried out in [6] showed, in the absorption of CO_2 laser radiation by water vapor the inequalities $|\Delta T| \ll T_0$ and $|\Delta p| \ll p_0$ are valid ($\Delta T = T - T_0$ and $\Delta p = p - p_0$; here and later the index 0 refers to the parameters of the undisturbed medium at t = 0).

Under conditions when overlapping of spectral lines at adjacent frequencies is absent, while the detuning is $\Delta\nu = |\lambda_I^{-1} - \lambda_0^{-1}| < 0.3\ \text{cm}^{-3}$ (λ_I and λ_0 are the wavelength of the actuating radiation and the wavelength corresponding to the line center of the absorbing transition), the absorption coefficient for the $0 \to \nu_2$ band can be represented in the form

$$k_\nu = C_k p T^{-3} H_V(\nu)\prod_{j=1}^{3}[1 - \exp(-\Theta_j/T_j)]\left[\exp\left(-\frac{E_{j'}}{kT}\right)\sqrt{A_{V'}B_{V'}C_{V'}} - \exp\left(-\frac{\Theta_2}{T_2} - \frac{E_{j''}}{kT}\right)\sqrt{A_{V''}B_{V''}C_{V''}}\right],$$

where C_k is a constant; Ej' and Ej'' are the rotational energies of the H_2O molecule in the ground (000) and in the excited (010) vibrational states, while $A_{V'}$, $B_{V'}$, $C_{V'}$, $A_{V''}$, $B_{V''}$, and $C_{V''}$ are the rotational constants for these states; $H_V(\nu)$ is the Voigt function. The maximum value of ε_2 ($\varepsilon_2 > \varepsilon_{j'}$, $j \neq 2$) is reached upon saturation of the absorbing transition. From the condition $k_\nu = 0$ we have

$$\Theta_2/T_2 = \Delta E_j/(kT_0). \tag{7}$$

Since $\Delta E_j \equiv E_{j'} - E_{j''} = k\Theta_2 - h\nu_I/k$ ($h\nu_I/k \simeq 1352°K$, $\Theta_2 = 2300°K$), from (7) we obtain the maximum attainable value of T_2:

$$T_{2\max} = 2{,}47T_0. \tag{8}$$

The kinetic equations (1)-(4) can be linearized when the conditions $\max(\varepsilon_j) \ll 1$ and $\max \times (\varepsilon_{j_0}) \ll 1$ are satisfied. For the realization it is necessary that $\Theta_2/T_2 \leqslant \ln 10$ or $T_2 \leq 1000°K$. Using (8), we find the limit on T_0 for which the linearization is valid: $T_0 \leq 400°K$. In this case

$$\frac{d\varepsilon_1}{dt} = -\varepsilon_1\left(\frac{E_{31}}{\tau_{31}} + \frac{1}{\tau_{12}}\right) + \varepsilon_2\frac{E_{12}}{\tau_{12}} + \varepsilon_3\frac{1}{\tau_{31}}; \tag{9}$$

$$\frac{d\varepsilon_2}{dt} = \frac{1}{\tau_I}\frac{k_\nu}{k_{\nu 0}} + \varepsilon_1\frac{2}{\tau_{12}} - \varepsilon_2\left(\frac{1}{\tau_{24}} + \frac{\varepsilon_{20}}{\tau_{20}} + \frac{1}{\tau_{20}} + 2\frac{E_{12}}{\tau_{12}} + 2\frac{E_{32}}{\tau_{32}} + \varepsilon_4\frac{E_{24}}{\tau_{24}}\right); \tag{10}$$

$$\frac{d\varepsilon_3}{dt} = \varepsilon_1\frac{E_{31}}{\tau_{31}} + \varepsilon_2\frac{E_{32}}{\tau_{32}} - \varepsilon_3\left(\frac{1}{\tau_{31}} + \frac{1}{\tau_{32}}\right); \tag{11}$$

$$\frac{d\varepsilon_4}{dt} = \varepsilon_2 \frac{\gamma_1}{\gamma_2 \tau_{24}} - \varepsilon_4 \frac{\gamma_1}{\gamma_2} \frac{E_{24}}{\tau_{24}}, \quad \varepsilon_5 = \varepsilon_{50}(T). \tag{12}$$

Here $k_{v0} = k_v(t=0)$; $\tau_{pq}^{-1} = \frac{p_0}{kT_0} W_{pq}(T_0)$ $(p = 1, 2, 3; q = 0, 1, 2)$;

$$\tau_{24}^{-1} = \frac{p_0}{kT_0} W_{24}(T_0)\gamma_2; \quad \tau_I^{-1} = \frac{k_{v0} I T_0 k}{p_0 h\nu_I \gamma_1}; \quad E_{pq} = \exp\left(\frac{\Theta_q - \Theta_p}{T_0}\right).$$

An analysis of data on the rate constants of V–V' and V–T processes in an $H_2O-O_2-N_2$ mixture showed that the fastest processes are V–T relaxation of the energy of deformation vibrations in the H_2O molecule and V–V' exchange through the channel $H_2O(010) + O_2(V = 0) \rightarrow H_2O(000) + O_2(V = 1)$. Therefore, at $t < \min(\tau_{20}, \tau_{21})$ we can assume that $\varepsilon_1 = \varepsilon_{10}(T_0)$ and $\varepsilon_3 = \varepsilon_{30}(T_0)$. For ε_j, $\varepsilon_{j_0} \ll 1$ we can, with good accuracy, take $\varepsilon_j = \exp(-\Theta_j/T_j)$ and $\varepsilon_{j_0} = \exp(-\Theta_j/T_0)$. Then, since $A_{V'}B_{V'}C_{V'} = A_{V''}B_{V''}C_{V''}$, we represent the absorption coefficient for the $0 \rightarrow \nu_2$ band in the form

$$k_v = k_{v0} \frac{1 - \varepsilon_2 \exp[(E_{j'} - E_{j''})/(kT_0)]}{1 - \varepsilon_{20} \exp[(\varepsilon_{j'} - \varepsilon_{j''})/(kT_0)]}. \tag{13}$$

Under the assumptions made, the system (9)-(12) has the analytic solution

$$\varepsilon_2 = k_1 \exp(\lambda_1 t) + k_2 \exp(\lambda_2 t); \tag{14}$$

$$\varepsilon_4 = \varepsilon_{40} + \frac{\gamma_1}{\gamma_2 \tau_{24}} \left\{ \left(\frac{C}{B} - \varepsilon_{20} \right) t + \frac{k_1}{\lambda_1} [\exp(\lambda_1 t) - 1] + \frac{k_2}{\lambda_2} [\exp(\lambda_2 t) - 1] \right\},$$

$$\varepsilon_1 = \varepsilon_{10}(T_0), \quad \varepsilon_3 = \varepsilon_{30}(T_0),$$

$$k_1 = \frac{\tau_I^{-1} + \lambda_2 (C/B - \varepsilon_{20})}{\lambda_1 - \lambda_2}, \quad k_2 = \frac{\tau_I^{-1} + \lambda_1 (C/B - \varepsilon_{20})}{\lambda_2 - \lambda_1}, \tag{15}$$

$$\lambda_{1,2} = -A/2 \pm \sqrt{A^2/4 - B}, \quad A = \tau_I^{-1} B_0/A_0 + \tau_{20}^{-1} + \tau_{24}^{-1}(1 + E_{24}\gamma_1/\gamma_2),$$

$$B = E_{24}\tau_{24}^{-1}(\tau_{20}^{-1} + \tau_I^{-1} B_0/A_0)\gamma_1/\gamma_2, \quad B_0 = \exp\left(\frac{E_{j'} - E_{j''}}{kT_0}\right),$$

$$C = E_{24}\tau_{24}^{-1}(\tau_I^{-1}/A_0 + \varepsilon_{20}\tau_{20}^{-1})\gamma_1/\gamma_2, \quad A_0 = 1 - B_0\varepsilon_{20}.$$

Integrating (5) with allowance for (13)-(15), we obtain an expression for the change in the translational temperature in the adsorption zone:

$$\Delta T = \frac{h\nu_I \gamma_1 N_A}{\mu C_p \tau_I} \left\{ \left(\frac{1}{A_0} - \frac{B_0}{A_0} \frac{C}{B} \right) t - \frac{B_0}{A_0} \left[\frac{k_1}{\lambda_1} (\exp(\lambda_1 t) - 1) + \frac{k_2}{\lambda_2} (\exp(\lambda_2 t) - \right. \right.$$

$$\left. \left. - 1) \right] - \frac{R}{\mu C_p} [\Theta_2 (\varepsilon_2 - \varepsilon_{20})\gamma_1 + \Theta_4 (\varepsilon_4 - \varepsilon_{40})\gamma_2] \right\}. \tag{16}$$

Knowing the temperature change, it is easy to determine how the index of refraction n varies in the regime of kinetic cooling. Let the length τ_p of a pulse of actuating radiation and the size of the beam be such that the condition $\tau_p \ll a/c_0$ is satisfied [a is the characteristic radius of the beam, $c_0 = \sqrt{\varkappa RT/\mu}$, and $\varkappa = (7 + \gamma_1)/(5 + \gamma_1))$, or $a/c_0 < \tau_p \ll \tau_T$. In this case the variation of n is determined by the equation

$$\delta n = -(n_0 - 1)\delta T/T_0. \tag{17}$$

The focal length of the thermal lens formed in this case is [9]

$$L_f = \lambda_I/\delta n. \tag{18}$$

First let us consider the absorption of CO_2 laser radiation by pure water vapor. The main laws obtained in this case are also valid for an $H_2O-O_2-N_2$ mixture. For pure water vapor ($\gamma_1 = 1$) Eq. (16) takes the form

$$\Delta T = \frac{0{,}25 A_0 \Theta_I}{B_0 + A_0 C_I} \left\{ C_I \frac{t}{\tau_I} + \left(\frac{\Theta_2}{\Theta_I} - \frac{B_0}{B_0 + A_0 C_I} \right) \left[\exp\left(-\frac{t}{\tau_I} \frac{B_0 + A_0 C_I}{A_0} \right) - 1 \right] \right\}, \tag{19}$$

$$\Theta_I = h\nu_I/k, \quad C_I = \tau_I/\tau_{20}.$$

Differentiating (17) with respect to t and equating the derivative to zero, we find that the maximum depth of cooling, determined by the expression

$$\Delta T_{\max} = \frac{0{,}25 A_0 \Theta_I}{B_0 + A_0 C_I}\left\{\frac{A_0 C_I}{B_0 + A_0 C_I}\ln\left[\frac{\Theta_2}{\Theta_1}\left(1 + \frac{B_0}{A_0 C_I}\right) - \frac{B_0}{A_0 C_I}\right]\right.$$
$$\left. + \left(\frac{\Theta_2}{\Theta_I} - \frac{B_0}{B_0 + A_0 C_I}\right)\left[\frac{A_0 C_I}{(B_0 + A_0 C_I)\,\Theta_2/\Theta_I - B_0} - 1\right]\right\}, \tag{20}$$

is reached at $t = t_0$, where

$$t_0 = \frac{A_0 \tau_I}{B_0 + A_0 C_I}\ln\left[\frac{\Theta_2}{\Theta_I}\left(1 + \frac{B_0}{A_0 C_I}\right) - \frac{B_0}{A_0 C_I}\right]. \tag{21}$$

We find the time of existence of the effect of kinetic cooling from the solution of the transcendental equation $\Delta T = 0$.

To test the validity of the analytic solutions obtained, we compared the results of a numerical calculation of the dynamics of the variation of the translational temperature of water vapor under the action of CO_2 laser radiation with λ = 9.4-10.6 μm by the method of [6] with the results of calculations of the function $\Delta T = f(t)$ from Eq. (19) in a wide range of gas parameters (p_0, T_0) and radiation intensities. Good agreement was obtained for all values of p_0 and I down to $T_0 \leq 6000°K$. In Fig. 1 such a comparison is given for radiation with λ_I^{-1} = 1066.036 cm^{-1} and I = 500 MW/cm^2, absorbed in the $000(10_{38}) \rightarrow 010(9_{09})$ transition of the H_2O molecule for $p_0 = 10^{-3}$ MPa and T_0 = 600 and 900°K (curves 1 and 2); the dashed lines are the calculations from Eq. (19) and the solid lines are the numerical calculations.

Now, on the basis of the solutions obtained, let us analyze the dependence of $\Delta T_{\max}$ and t_0 on the intensity of the actuating radiation and the parameters of the gas. First we consider the limiting case of a "weak field." Here $\tau_{20} \ll \tau_I$. In this case $\Delta T_{\max}$ is defined by the equation

$$\Delta T_{\max} = -0.25\frac{k_{v0} I T_0^2 k}{p_0^2 W_{20}}\left[\frac{\Theta_2}{\Theta_I} - 1 - \ln\left(\frac{\Theta_2}{\Theta_I}\right)\right] \tag{22}$$

and is reached at

$$t_0 = \frac{kT_0}{p_0 W_{20}}\ln\left(\frac{\Theta_2}{\Theta_I}\right). \tag{23}$$

From (22) and (23) it follows that $\Delta T_{\max}$ is proportional to the intensity of the actuating radiation, while t_0 does not depend on the intensity and decreases with an increase in the frequency of the actuating radiation.

The dependence of $\Delta T_{\max}$ on the parameter of the medium (p_0 and T_0) is determined by the term $k_{v0}T_0^2/(p_0^2 W_{20}(T_0))$. First we analyze this dependence for the Doppler profile of the spectral absorption line,

$$H_\nu(\nu) = \exp(-\alpha/T_0),\ \alpha = \frac{(\Delta\nu)^2 \mu_1 c^2}{2\nu_0^2 R},$$

where c is the speed of light in a vacuum; ν_0 is the frequency corresponding to the line center of the absorbing transition. Using (6) and taking $A_{V'}B_{V'}C_{V'} = A_{V''}B_{V''}C_{V''}$, as before, we can represent the expression for $\Delta T_{\max}$ in the form

$$\Delta T_{\max} = -f(T_0)\frac{0{,}25 C_k k I}{p_0}\sqrt{A_{V'}B_{V'}C_{V'}}\left[\frac{\Theta_2}{\Theta_I} - 1 - \ln\left(\frac{\Theta_2}{\Theta_I}\right)\right],$$
$$f(T_0) = \frac{\exp(-\alpha/T_0)}{T_0 W_{20}(T_0)\left[\exp(-E_{j'}/kT_0) - \exp(-\Theta_2/T_0 - E_{j''}/kT_0)\right]}. \tag{24}$$

It is seen from (24) that for the Doppler mechanism of broadening of a spectral line, $\Delta T_{\max}$ decreases in proportion to the increase in p_0 and increases with an increase in T_0 (the same dependence $W_{20}(T_0)$ as in [6] is taken for the determination of $f(t_0)$).

In the case of collision broadening of the spectral line,

$$H_\nu(\nu) = \frac{\alpha_1 \sqrt{T_0}\, p_0 b_c(T_0)}{b_c^2(T_0) p_0^2 + 4(\Delta\nu)^2},\ \alpha_1 = \frac{2\nu_0}{c}\sqrt{\frac{2R}{\pi\mu_1}},$$

where $b_c(T_0)$ is the coefficient of collision broadening (in accordance with [10] we shall take $b_c(T_0) \sim T_0^{-0.62}$),

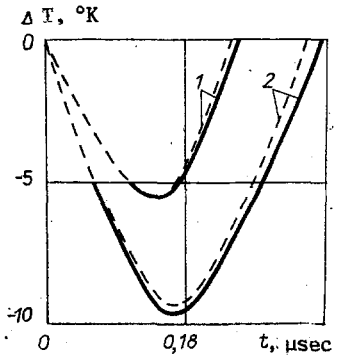

Fig. 1

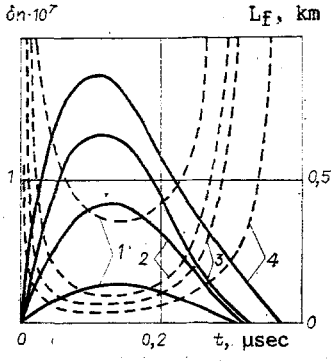

Fig. 2

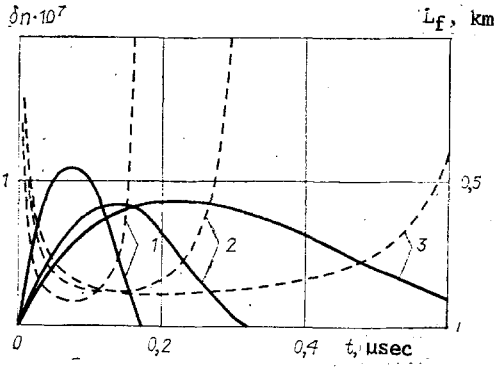

Fig. 3

$$\Delta T_{\max} = -f_1(T_0, p_0)\,0{,}25\,C_k k\alpha_1 \sqrt{A_{V'}B_{V'}C_{V'}}\left[\frac{\Theta_2}{\Theta_I} - 1 - \ln\left(\frac{\Theta_2}{\Theta_I}\right)\right], \tag{25}$$

$$f_1(T_0, p_0) = \frac{b_c(T_0)}{\sqrt{T_0}\,W_{20}(T_0)\left[b_c^2 p_0^2 + 4(\Delta\nu)^2\right]\left[\exp\left(-\frac{E_{j'}}{kT_0}\right) - \exp\left(-\frac{k\Theta_2 + E_{j''}}{kT_0}\right)\right]}.$$

An analysis of $f_1(T_0, p_0)$ shows that in resonance absorption of the radiation, when $b_c p_0 \gg 2|\Delta\nu|$ and the representation (6) is valid, $\Delta T_{max} \sim p_0^{-2}$, i.e., it decreases faster with an increase in pressure than for a spectral line with a Doppler profile ($\Delta T_{max} \sim p_0^{-1}$). At the same time, in absorption in the wings of lines ($b_c p_0 \ll 2|\Delta\nu|$), ΔT_{max} does not depend on pressure (it must be noted, however, that the description of the profile of a collision-broadened line by a Voigt profile is not always competent, and a special analysis is required in each concrete case). In this case the temperature dependence of ΔT_{max} is similar to the dependence $\Delta T_{max} = f(T_0)$ for the Doppler broadening mechanism. The time in which ΔT_{max} is reached for both these cases is determined by the time τ_{20} of V–T relaxation of the energy of deformation vibrations of the H_2O molecule.

Now let us consider the case of a "strong field," when $\tau_I \ll \tau_{20}$. Here the maximum cooling is determined by the equation

$$\Delta T_{\max} = 0{,}25\Theta_I \frac{A_0}{B_0}\left\{\frac{A_0}{B_0}C_I \ln\left[\frac{B_0}{A_0 C_I}\left(\frac{\Theta_2}{\Theta_I} - 1\right)\right] - \left(\frac{\Theta_2}{\Theta_I} - 1\right)\right\}. \tag{26}$$

In the limit as $C_I \to 0$ (the absorbing transition is saturated), (26) takes the form

$$\Delta T_{\max} = -0{,}25\,(\Theta_2 - \Theta_I)\left[\exp\left(\frac{\Theta_2 - \Delta E_j}{kT_0}\right) - 1\right]\varepsilon_{20}. \tag{27}$$

For $\Theta_I = 1400°K$ ($\lambda_I = 10^{-3}$ cm) and $T_0 = 300°K$, from (27) we have $\Delta T_{max} = -16°K$. From (27) it is seen that for a "strong field" ΔT_{max} increases with an increase in T_0 and does not depend on pressure. Since $k\Theta_I \simeq k\Theta_2 - \Delta E_j$, from (26) it follows that $\Delta T_{\max} \approx (\Theta_2 - \Theta_1)\left[\exp\left(\frac{\Theta_I}{T_0}\right) - 1\right]$, i.e., the depth of cooling increases with an increase in the radiation frequency (ν_I). In this case the time in which ΔT_{max} is reached is determined by the expression

$$t_0 = \frac{\Theta_I p_0}{I k_{\nu 0} T_0} \ln\left\{\left[\exp\left(\frac{\Delta E_j}{kT_0}\right) - \varepsilon_{20}\right]\frac{(\Theta_2 - \Theta_I)\,kT_0^2 k_{\nu 0} I}{\Theta_I^2 p_0^2 W_{20}(T_0)}\right\}\left[\exp\left(\frac{\Delta E_j}{kT_0}\right) - \varepsilon_{20}\right]. \tag{28}$$

From (28) it is seen that the time in which the maximum depth of cooling is reached decreases with an increase in the radiation intensity. By analogy with the case of a "weak field," we can show that for a spectral line with a Doppler profile, t_0 decreases with an increase in p_0 in proportion to $\ln(\alpha/p_0)$, where α is a function of T_0. For the collisional mechanism of spectral line broadening, when $b_c p_0 \gg 2|\Delta\nu|$, t_0 decreases with an increase in p_0, while $t_0 \sim p_0^{-1}$ for absorption in the line wings ($b_c p_0 \ll 2|\Delta\nu|$). An analysis of Eq. (28) shows that t_0 decreases with an increase in temperature in the temperature range where $dk_{\nu 0}/dT_0 > 0$.

Now let us consider the influence of the radiation intensity and the water vapor content in the $H_2O-N_2-O_2$ mixture, close in composition to the humid atmosphere ($\gamma_2 = 0.2$), on the

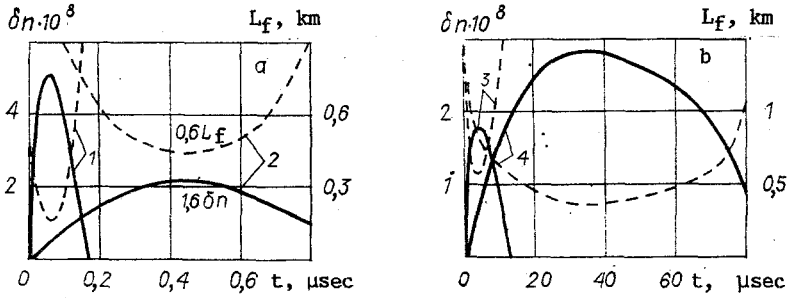

Fig. 4

change in the index of refraction and the focal length of the converging thermal lens formed in the beam channel for $\tau_I \simeq \tau_{20}$. In making the calculations we took $W_{20}^{H_2O}$ as $2 \cdot 10^{-11}$ cm³/sec in accordance with the data of [11, 12] for $T_0 = 300°K$. For all the other rate constants of V–T and V–V' exchange we took the same values as in [6]. All the molecular constants needed to determine the amplification ratio were determined for radiation with $\nu_I = 1066.037$ cm^{-1}, corresponding to the R2 [$00^01 \rightarrow 10^00$] generation line of the CO_2 laser, which is absorbed in the $000(10_{38}) \rightarrow 010(9_{09})$ transition of the H_2O molecule. It is obvious that the results obtained are also qualitatively correct for other frequencies of radiation absorbed by water vapor in transition with $Ej'' < Ej'$. The influence of the intensity of the actuating radiation on the dynamics of the variation of n and of the quantity L_f is shown in Fig. 2, where we give the functions $\delta n(t)$ and $L_f(t)$ (solid and dashed lines) for the $H_2O-N_2-O_2$ mixture ($\gamma_1 = 0.05$, $\gamma_3 = 0.75$, $\gamma_2 = 0.2$) with $p_0 = 0.01$ MPa and $T_0 = 300°K$ for I = 100, 400, 700, and 10^3 MW/cm² (curves 1-4). It is seen that the optical power of the thermal lens that forms increases with an increase in the intensity of L_f reaches a minimum at $t = t_0$, and then ($t > t_0$) it increases and reaches infinity at the time of $\Delta T = 0$.

A change in intensity leads to a change not only in L_f but also in the time interval during which L_f is less than a certain assigned value, such as the Rayleigh length L_p ($L_p = 2a^2/\lambda_I$) at which diffraction effects start to appear. An increase in the content of water vapor in the $H_2O-N_2-O_2$ mixture leads to a decrease in the time τ_{20}, and hence a shortening of the time of existence of the state of the medium with $\Delta T < 0$. The time interval during which $L_f > 0$ (a converging lens) decreases in this case, naturally, although the minimum value of L_f (in the range of $\gamma_1 = 0.001$-0.1) varies insignificantly. This is reflected in Fig. 3, where the variation of δn and L_f (solid and dashed lines) is shown for the medium $H_2O-N_2-O_2$ ($\gamma_2 = 0.2$) with $p_0 = 0.01$ MPa and $T_0 = 300°K$ for different contents of water vapor in the mixture, $\gamma_1 = 0.1$, 0.05, and 0.01 (curves 1-3). The intensity of the actuating radiation was assumed to be 400 MW/cm².

In the propagation of CO_2 laser radiation in the atmosphere, γn and L_f will also vary as a function of the altitude of the path above the earth's surface. To determine this influence, we calculated the time variation of δn and L_f for radiation with $\nu_I = 1066.037$ cm^{-1} and I = 400 MW/cm² at altitudes H = 0, 15, 30, and 45 km. The water vapor content in the atmosphere was taken as 1%. The necessary data on the parameters of the atmosphere (p_0, T_0) for these altitudes were taken from [13]. The results of the calculations are given in Fig. 4a and b, where 1-4 are the functions $\delta n(t)$ and $L_f(t)$ (solid and dashed lines) for H = 0, 15, 30, and 45 km. It is seen that the optical power of the thermal lens that forms decreases with an increase in H, while the duration of the existence of a lens with $L_f > 0$ increases.

For $L_f \leq L_p$ the self-focusing effect due to the absorption of water vapor by CO_2 laser radiation can compensate for diffractional divergence. For radiation with $\lambda_I = 10^{-3}$ cm this condition is satisfied for beams with $a \geq \sqrt{L_f \lambda/2}$. Thus, for H = 0 with the values of γ_1 and I under consideration, suppression of diffractional divergence can be achieved for beams with $a \geq 4$ cm for $\tau_p = 1.5$ μsec, and by increasing the radiation intensity it can be achieved for narrower beams and for longer values of τ_p.

Thus, the results obtained indicate the possibility of reducing the energy losses in the transmission of CO_2 laser radiation through the humid atmosphere in pulses of a certain length.

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