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PROBLEM OF A PISTON IN A RELAXING GAS

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The possibility of obtaining an oscillatory inversion of population in $CO_2 + N_2 +$ He mixtures behind nonstationary shock waves is studied.

In [1-5] the possibility of obtaining an inversive population in gases consisting of multiatom molecules by means of thermal methods of pumping. In particular, inversion between the oscillatory levels (04°0-00°1) and (20°0-00°1) of the CO_2 molecule behind stationary shock waves is considered. Below we use the motions of an ideal, non-heat-conducting, perfect gas in the case of the problem of a symmetric piston moving in a $CO_2 + N_2 +$ He mixture. For the analysis of oscillatory relaxation, we use the kinetic Anderson model [3, 5].

In a gaseous medium at rest, let the initial instant of motion of a piston obey the law $r_p = \lambda_p t^\delta$, where λ_p, $\delta = \text{const}$. A shock wave is formed in front of the piston [6]; this wave excites oscillatory relaxation leading to an inversive population of the oscillatory levels of CO_2 molecule.

According to the Anderson model [3, 5], the oscillatory levels of CO_2 and N_2 molecules group into two "modes." This is based on the characteristic feature of the CO_2 molecule, which manifests itself in the fact that the strain oscillations ν_2 and the symmetric oscillations ν_1, which very rapidly come into equilibrium with them, have a shorter relaxation time than the asymmetric oscillations ν_3. On the other hand, thanks to the almost equal disposition, the asymmetric oscillations ν_3 rapidly exchange energy with the oscillatory level of the N_2 molecule. Such a feature of the CO_2 and N_2 molecules allows us to unite the oscillations ν_1 and ν_2 into "mode" I, and the oscillations ν_3 and ν into the "mode" II.

Since the lower oscillatory levels are of the major interest, in the case of calculations the model of the harmonic oscillator

$$\frac{dE_I}{dt} = \frac{E_I(T) - E_I(T_I)}{\tau_I} \tag{1}$$

remains valid, analogously for E_{II}, where τ_I, τ_{II} are the characteristic relaxation times; T is the translational temperature. The values τ_I and τ_{II} are certain effective values determined according to the rule of "parallel resistance" [3, 5]. The oscillatory temperatures T_I, T_{II} can be found, using the relations for the quantities E_I, E_{II}:

$$E_I = C_{CO_2} R_{CO_2} \left\{ \frac{\theta_1}{[\exp(\theta_1/T_I) - 1]} + \frac{2\theta_2}{[\exp(\theta_2/T_I) - 1]} \right\}, \tag{2}$$

$$E_{II} = C_{CO_2} R_{CO_2} \frac{\theta_3}{[\exp(\theta_3/T_{II}) - 1]} + C_{N_2} R_{N_2} \frac{\theta}{[\exp(\theta/T_{II}) - 1]}.$$

Here C_{CO_2}, R_{CO_2} are the mass fraction and the gas constant for CO_2; C_{N_2}, R_{N_2} are determined analogously to N_2; $\theta_i = h\nu_i/k$ are the corresponding characteristic temperatures. When computing the level populations in "modes" I and II, we take as valid the Boltzmann distribution over the levels within the "modes" [3-5].

The movement of the gas will be described by Eqs. (1) and (2) in combination with the equations of conservation of mass, momentum, and energy, which can be taken in the form

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial r} + j\frac{\rho u}{r} = 0,$$

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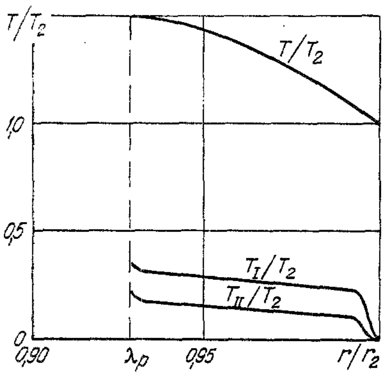

Fig. 1

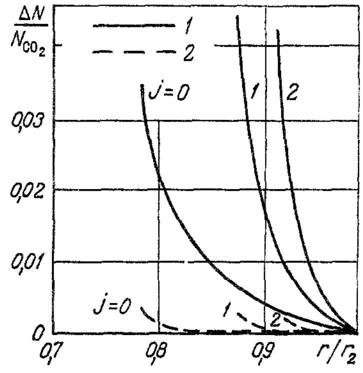

Fig. 2

Fig. 1. Temperature profiles for $j = 2$, $\delta = 1$.

Fig. 2. Inversive populations in the case of $\delta = 1$ for different symmetries: 1) $\Delta N = N_{04^\circ 0} - N_{00^\circ 1}$; 2) $\Delta N = N_{20^\circ 0} - N_{00^\circ 1}$.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0,$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial r} - \frac{1}{\rho}\left(\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial r}\right) = 0,$$

$$h = \frac{\gamma}{\gamma - 1}\frac{p}{\rho} + E_{\mathrm{I}} + E_{\mathrm{II}}, \tag{3}$$

where $j = 0$, 1, 2 for the plane, cylindrical, and spherical cases.

We shall consider the motion of the gas at time instants when the energy enclosed by the oscillatory degrees of freedom is less than the work of the piston:

$$A > U = \sigma_j \int\limits_{r_p}^{r_2} (E_I + E_{II})\rho r^j dr, \tag{4}$$

where $\sigma_j = 2\pi j + (j - 1)(j - 2)$; r_2 is the radius of the shock wave. The work of the piston is

$$A = \sigma_j \int\limits_0^t pur^j dt.$$

For the time instants when inequality (4) holds we can seek the solution, using the method of linearization with respect to the small parameter $\varepsilon = U/A$. After linearization of Eqs. (1)-(3) we find that the system for the principal terms decomposes into two. The solution of the gasdynamic equations is furnished by the automodel functions describing the flow from the piston. This problem is well studied [6, 7]. The relaxation of oscillatory energies can here be considered on a given field of flow.

In Figs. 1 and 2 we have presented the results of a typical calculation in the case of $\delta = 1$. The velocity of the shock wave $D = 2100$ m/sec, the temperature behind the jump $T_2 = 1200$ K, while the mole fractions of the mixture $\alpha_{CO_2} = 0.02$, $\alpha_{N_2} = 0.38$, $\alpha_{He} = 0.6$. For the adiabatic index of the mixture we took the expression

$$\gamma = \frac{1 + \alpha}{\alpha}, \quad \alpha = \frac{3}{2}\alpha_{\mathrm{He}} + \frac{5}{2}(\alpha_{\mathrm{CO_2}} + \alpha_{\mathrm{N_2}}).$$

In Fig. 1 we have shown the variation of the translational temperature T and the oscillatory temperatures T_I, T_{II} behind the shock front. The more rapid growth of T_I is clearly seen, while T_{II} grows more slowly. This result reflects the rapid population rise of oscillatory levels in "mode" I. In Fig. 2 we have shown the inversions between the levels (04°0-00°1) and (20°0-00°1) of the CO_2 molecule.

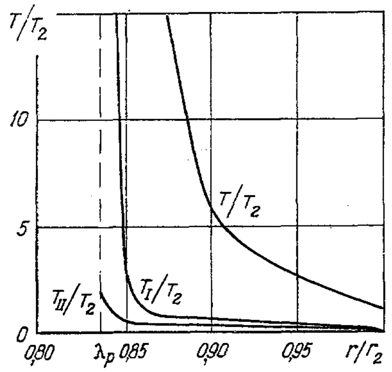

Fig. 3

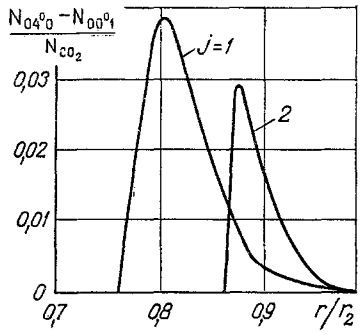

Fig. 4

Fig. 3. Temperature profiles for $j = 2$, $\delta = 0.55$.

Fig. 4. Typical inversive populations in the case of $\delta = 0.55$.

If we increase the ratio $\alpha_{CO_2}/\alpha_{N_2}$, while the He content is left the same, then we observe a somewhat stronger growth of the temperatures T_I and T_{II}. A reduction of the He content in the case of an unchanged velocity of the shock wave leads to an increase in the inversion. We also note that lower values of inversion correspond to larger values of γ.

The calculations were carried out for damped shock waves, when $\delta < 1$. The results of one of the calculations are presented in Figs. 3 and 4, where $j = 1$; 2, $\delta = 0.55$. Variations in the composition of the mixture and in the acceleration of the shock wave had almost no influence on the magnitude of inversion between the levels (04°0–00°1), while the inversion of the levels (20°0–00°1) does not in fact occur.

Analogous calculations were carried out for cylindrical and plane shock waves. The character of variation of inversions does not change; we only observe an increase in the maximum of the inversive populations: the maxima of inversions of the levels (04°0–00°1) lie within the limits $(0.3\text{–}1.0)\cdot 10^{-1}$, while those of inversions of the levels (20°0–00°1) lie within the limits $(0.1\text{–}1.0)\cdot 10^{-2}$.

The accuracy of the calculations presented above is largely determined by the reliability of the constants being used. Regrettably, no reliable experimental data on oscillatory relaxation of CO_2 at temperatures above 1000 K exists so far. In the given investigation we did not find the conditions which are optimal for shock-formed inversions. However, it is not very likely that in the case of optimization the order of inversions would be increased for $CO_2 + N_2 + He$ mixtures in comparison with the results just presented.

NOTATION

p, pressure; ρ, density; u, velocity of the medium; γ, adiabatic index; E_I, E_{II}, oscillatory energy per unit mass of the mixture for modes I and II; C_i, mass fraction of component i; R_i, specific gas constant for component i; α_i, mole fraction of component i; ν_1, ν_2, ν_3, ν, fundamental oscillatory frequencies for CO_2 and N_2; λ_p, δ, θ_i, constants.

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HEAT LOSSES IN THE PLENUM CHAMBER OF A GASDYNAMIC LASER BY SIMULATION IN A SHOCK TUBE

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It is shown that the heat losses in the plenum chamber of gasdynamic laser simulated in a shock tube do not significantly affect the operating conditions of the laser apparatus under investigation.

Experience in the use of shock-tube techniques in high-temperature gas dynamics in chemical physics has served as the basis for developing pulsed gasdynamic laser systems which practically completely simulate the working conditions in stationary apparatuses with thermal pumping and with subsequent adiabatic expansion of the working mixture in a nozzle [1]. Using the shock wave, we can heat a previously prepared working mixture of gases, fairly rapidly and uniformly over the volume, to a temperature of thousands (or even tens of thousands) of degrees. Using the reflection of the shock wave from the closed end of the tube, we can easily similate the necessary "static" state of the gas in the plenum chamber of the stationary apparatus; the final state of the apparatus after two shock compressions is uniquely specified by velocity of the shock wave and the initial gas pressure. If in the end face of the shock tube we mount a supersonic nozzle with a critical cross section much smaller than the cross section of the main channel of the tube, the final state of the gas will differ little from the state behind the reflected plane wave.

However, the final state of the gas in the plenum chamber of a gasdynamic laser may vary with time as a result of heat losses to the walls of the apparatus. At the same time, the output characteristics of the gasdynamic laser (amplification factor, power output) depend substantially on the thermodynamic state of the working medium, and in particular on the gas temperature in the plenum chamber. From the data shown in Fig. 1 it can be seen that a 10% change in the temperature of the working gas results in a change of 5-7% in the amplification factor, which inevitably affects the operating conditions of the laser apparatus.

The purpose of the present study is to determine the amount of the heat losses in the plenum chamber of a gasdynamic laser with mixing, simulated in a shock tube, and to estimate the effect of these losses on the parameters of the system.

We consider the heat losses into the end face and the lateral surface of the shock tube, starting from the time $t = 0$, when the shock wave is reflected from the end face. Suppose that the temperature of the tube walls is T_0 and the temperature of the gas behind the front of the reflected shock wave is T_1. The motionless gas behind the front of the reflected shock wave, moving at velocity D, will be considered a semibounded body, and the temperature at its boundary will be taken to be T_0; this leads to results which are somewhat too high, since we have not taken account of the thermal resistance of the shock-tube walls. Then [3] the amount of heat transferred in time t through the end face and the lateral surface can be written as follows:

$$\Delta Q_T = \frac{1}{2}\sqrt{\pi\lambda c_p\rho}\,(T_1 - T_0)\,d^2\sqrt{t}, \quad \Delta Q_C = 2\sqrt{\pi\lambda c_p\rho}\,(T_1 - T_0)\,Ddt\sqrt{t}.$$

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