Since evaporation occurs nonuniformly with the diminution of the particle radius, the vapor distribution over the section can have a certain profile at the end of the mixing zone. The solution of this problem requires a separate examination. The authors are grateful to A. M. Prokhorov for turning their attention to the questions considered in the paper, and for discussing these questions.

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NUMERICAL INVESTIGATIONS OF THE INFLUENCE OF FRICTION ON THE MAGNITUDE OF LOSSES IN A NOZZLE CASCADE OF A GASDYNAMIC CO_2–N_2–He LASER

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UDC 621.373.826.038.823

Sets of short nozzles (nozzle cascades) with small critical sections [1] are used to obtain strongly nonequilibrium gas flows in gasdynamic CO_2 lasers. The gas viscosity plays a relatively large part in such apparatus. The friction-caused losses in gasdynamic lasers (GDL) were determined by numerical methods in [2, 3]. It was assumed in both papers that the interactions between different kinds of vibrations in the gas molecules and the nozzle surface are simultaneously subject to the same regularities. However, multiatomic molecules have a complex spatial structure as a rule, which should generally result in different relaxation rates for their vibrational degrees of freedom on the boundary of contiguity of two phases. The question of the possible practical utilization of these phenomena was discussed in [4]. Later, in [5] a mathematical model of CO_2 molecule relaxation on the surface of aqueous aerosol particles [4] was proposed for utilization in the analysis of physical processes in GDL.

Zhukovskii. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 61-65, November-December, 1979. Original article submitted December 1, 1978.

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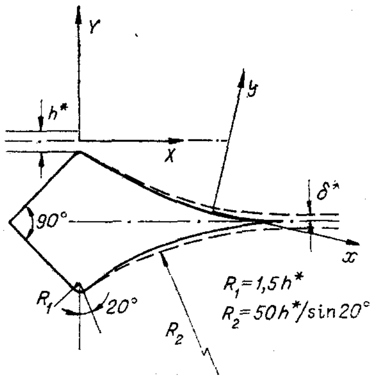

Fig. 1

A three-component mixture of the gases taken in the ratio $\xi_1:\xi_2:\xi_3$ = 0.05:0.25:0.7 (ξ_i is the molar concentration of the i-th mixture component) is considered as the working medium in this paper for the following values of the stagnation parameters (conditions in the fore-chamber): $p_0 = 1.013\cdot10^6$ Pa stagnation pressure and T_0 = 1900°K stagnation temperature.

The nozzle cascade is assumed comprised of identical plates whose shape is determined by the known mode of the inviscid flow kernel (the characteristic dimensions are indicated in Fig. 1), and by the calculated boundary layer displacement thickness $\delta^* = \int\limits_0^{\hat{H}/2}\left(1-\frac{\rho u}{\rho_e u_e}\right)dY$, where H is the transverse nozzle section. Under the mentioned conditions in the fore-chamber and a height of h^* = 2 mm for the minimum section of an individual nozzle in the cascade (the Reynolds number $Re^* = 1.22\cdot10^4$ is calculated by means of the flow parameters in the minimum section), the concept of a thin boundary layer is applicable, according to which the role of viscosity is substantial near the wall (boundary layer), while the flow parameters in the remaining part experience only indirect influence. Inviscid flow is considered in a one-dimensional approximation, where the flow to the section in which its velocity reaches the "frozen" speed of sound [6], is assumed equilibrium.

The reaction scheme [7] from which the transitions $N_2(1) + CO_2(00^00) \rightleftarrows N_2(0) + CO_2(11^10, 03^10)$ are excluded is taken as basis. For the flow parameters, nozzle shape, and collision transition probabilities [8] used in the computations, the asymptotic method of solving the kinetic equations [9-11] permits the unique selection of a mathematical nonequilibrium flow model. The general equations obtained in [10] have the following form for the considered mixture of the gases CO_2—N_2—He:

a) For an inviscid flow core

$$\rho U F(X) = \text{const},$$

$$\rho U\frac{dU}{dX} = -\frac{dp}{dX},\quad \frac{U^2}{2} + \frac{\varkappa}{\varkappa-1}\frac{p}{\rho} + \frac{\varepsilon_K}{\bar{m}} = h_0,$$

$$U\frac{d\hat{\varepsilon}_\alpha}{dX} = q_\alpha,\quad \alpha = 1,\ 2;\ 3;\ 4,$$

$$\hat{\varepsilon}_{1,2} = 2\sum_{i=1}^{2}\left[\exp\left(\frac{\Theta_i}{T_{1,2}}\right)-1\right]^{-1},\quad \hat{\varepsilon}_\alpha = \left[\exp\left(\frac{\Theta_\alpha}{T_\alpha}\right)-1\right]^{-1},\quad \alpha = 3;\ 4,\tag{1}$$

$$q_{1,2} = n(\varphi_1 - 3\varphi_2),\quad q_3 = n(\varphi_2 + \xi_2\varphi_3),\quad q_4 = -\xi_1 n\varphi_3,$$

$$\varphi_1 = \left(\sum_{i=1}^{3}\xi_i\langle g\sigma(2\to0)\rangle_{1-i}\right)(1-\beta_2)(\hat{\varepsilon}_{02}-\hat{\varepsilon}_2),$$

$$\varphi_2 = \langle g\sigma(3\to\Sigma)\rangle\left[\beta_3\beta_2^{-3}(1+\hat{\varepsilon}_3)\left(\frac{\hat{\varepsilon}_2}{2}\right)^3 - \hat{\varepsilon}_3\left(1+\frac{\hat{\varepsilon}_2}{2}\right)^3\right],$$

$$\varphi_3 = \langle g\sigma(4\to3)\rangle_{1-2}(\hat{\varepsilon}_3 - \hat{\varepsilon}_4),$$

$$\langle g\sigma(3\to\Sigma)\rangle = \gamma\sum_{i=1}^{3}\xi_i\langle g\sigma(3\to1,2)\rangle_{1-i} + \sum_{i=1}^{3}\xi_i\langle g\sigma(3\to2)\rangle_{1-i},$$

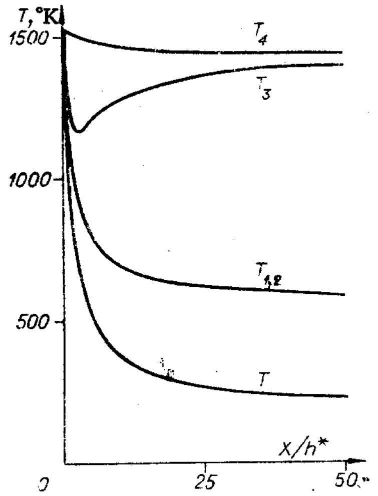

Fig. 2

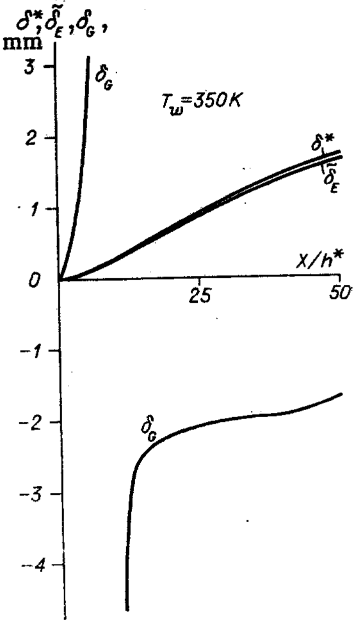

Fig. 3

$$\beta_i = \exp\left(\frac{\Theta_i}{T}\right),\ \gamma = \left[\left(1+\frac{\hat{\varepsilon}_2}{2}\right)^2 - \beta_1\beta_2^{-2}\left(\frac{\hat{\varepsilon}_2}{2}\right)^2\right]^{-1},$$

where F(X) is the cross-sectional area of the inviscid stream core, $\varkappa$ is the adiabatic index in the "frozen" flow [6], $\varepsilon_K = k\sum_{i=1}^{2}\xi_i\sum_l \Theta_{li}\hat{\varepsilon}_{li}$ is the mean energy of vibrational motion per single molecule, $\bar{m} = \sum_{i=1}^{3}\xi_i m_i$ is the mean molecular weight of the mixture, h_0 is the stagnation enthalpy referred to unit mass of gas, Θ_α, Θ_{li} is the characteristic temperature of the l-th vibrational mode in molecules of the i-th species;

b) For flow in the boundary layer which is assumed laminar on the plate surface

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0,\ \rho u\frac{\partial u}{\partial x} + \rho v\frac{\partial u}{\partial y} = -\frac{dp}{dx} + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right),$$

$$c_p\left(\rho u\frac{\partial T}{\partial x} + \rho v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \mu\left(\frac{\partial u}{\partial y}\right)^2 + u\frac{dp}{dx} - \rho\sum_{i=1}^{2} c_i R_i \sum_l \Theta_{li} q_{li}, \tag{2}$$

$$\rho u\frac{\partial\hat{\varepsilon}_\alpha}{\partial x} + \rho v\frac{\partial\hat{\varepsilon}_\alpha}{\partial y} = \frac{\partial}{\partial y}\left(\frac{\lambda_\alpha}{c_{v\alpha}}\frac{\partial\hat{\varepsilon}_\alpha}{\partial y}\right) + \rho q_\alpha,\quad \alpha = 1, 2; 3; 4,$$

where c_i, R_i are, respectively, the mass concentration and the gas constant of the i-th component of the mixture.

The boundary layer equations (2) are written in an (x, y) coordinate system coupled to the nozzle surface, and the inviscid flow equations are in a (X, Y) coordinate system whose origin is at the center of the minimum nozzle section (see Fig. 1). The contribution to the magnitude of the transfer coefficients of the resonance and rapid inelastic (Fermi resonance in CO_2) energy exchanges is not taken into account.

Two kinds of boundary conditions are considered for (2):

$$y = 0,\ u = v = 0,\ T = T_{1,2} = T_w,\ \left(\frac{\partial T_3}{\partial y}\right)_w = \left(\frac{\partial T_4}{\partial y}\right)_w = 0,$$
$$y \to \infty,\ u \to u_e,\ T \to T_e,\ T_\alpha \to T_{\alpha_e},\quad \alpha = 1, 2; 3; 4; \tag{3}$$

$$y = 0,\ u = v = 0,\ \left(\frac{\partial T}{\partial y}\right)_w = \left(\frac{\partial T_\alpha}{\partial y}\right)_w = 0, \tag{4}$$
$$y \to \infty,\ u \to u_e,\ T \to T_e,\ T_\alpha \to T_{\alpha_e},\quad \alpha = 1, 2; 3; 4.$$

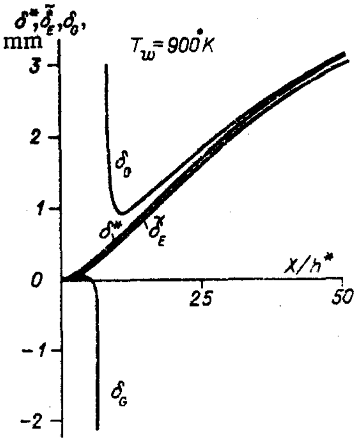

Fig. 4

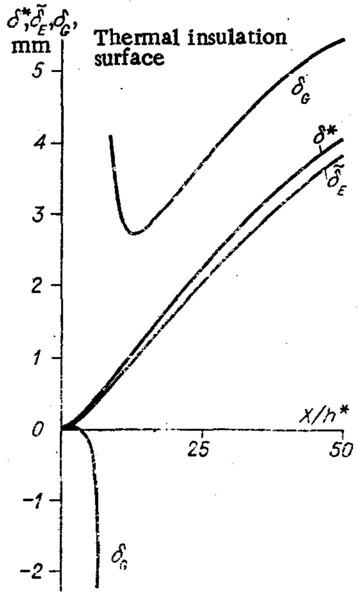

Fig. 5

As is shown in [9-11], the use of the gasdynamics equations in a multitemperature approximation corresponds to the transition to a rougher method of description as compared with the particular case of monatomic gases, which requires a more careful relation to the boundary condition formulation. However, for closely interrelated Fermi resonances of the symmetric and deformation vibrations in CO_2 and very rapid relaxation of these latter, the use of the mathematical models of a catalytic (3) and heat insulated surface (4) is allowable. In contrast to [4], it is assumed additionally in the conditions (3) that the vibrational degrees of freedoma of N_2 do not take part in the energy exchange with the nozzle surface.

Equations (1) and (2) were integrated numerically by using a finite-difference method [12] for the boundary layer equations (2) and an ordinary finite-difference scheme of second-order accuracy [6] in the case of (1). Individual program fragments [13] were used in the computation program.

The results of the computations are represented in Figs. 2-5. The change in the vibrational temperatures $T_{1,2}$ T_3, T_4 and the gaskinetic temperature T along the nozzle in the inviscid stream core is shown in Fig. 2. Friction results in insignificant heating of the antisymmetric mode in CO_2 and of the vibrations in N_2 in the models under consideration of heterogeneous relaxation on the nozzle surface. This explains the negative values of the thickness of the vibrational energy losses $\delta_E = \int_0^{H/2} \frac{\rho u}{\rho_e u_e}\left[1 - (\xi_1\Theta_3\hat{\varepsilon}_3 + \xi_2\Theta_4\hat{\varepsilon}_4)/(\xi_1\Theta_3\hat{\varepsilon}_{3e} + \xi_2\Theta_4\hat{\varepsilon}_{4e})\right]dY$ (the quantity $\tilde{\delta}_E = \delta_E + \delta^*$ is displayed in Figs. 3-5 for convenience). Negative values of the loss thickness of the weak signal gain $\delta_G = \int_0^{H/2}\left(1 - \frac{G}{G_e}\right)dY$ (line P20) at a 350°K wall temperature indicate an additional formation in the area of the viscous flow of population inversions of the lasing levels in the CO_2 molecules. This effect is related to the "cooling" of the deformation and symmetric modes in CO_2 near a cold surface, and the advantageous absence of direct interaction with the wall from the remaining vibrational degrees of freedom of the molecules. Destruction of the antisymmetric mode energy level in CO_2 and the vibration energy level in N_2 by the population occurs principally because of the intermodal exchanges with other vibrations which are of slight effect in the boundary layer.

As follows, from Figs. 3-5, the losses in the gain coefficient and the boundary layer thickness are maximal for nozzles with heat insulated walls, where the viscosity diminishes the gain coefficient at the nozzle exit up to 6.6%. The gain coefficient in nozzles with cooled walls increases 20-22% for T_W = 350°K as compared with the inviscid approximation, and the boundary layer is thinner. Vibrational relaxation processes on the nozzle surface affect the losses substantially.

The author is grateful to V. M. Kuznetsov for useful discussion of the results of the research.

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SYMMETRY PROPERTIES OF THE DIFFUSION TENSOR IN THE THEORY OF NEW PHASE FORMATION

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UDC 539.196.198

The classical theory of the growth of a new phase with phase transitions of the first kind [1-5] is based on a consideration of the diffusion of the new phase seed in the space of their dimension through a potential barrier which occurs because of the competition between the volume and surface energies. In a number of cases, it turns out to be necessary to characterize the seed by two or more variables rather than one. Thus, in the most popular problem of mixture condensation, the natural variables are the numbers of molecules of the mixture components in the seed, and in different problems of the theory of cavitation it is expedient to use the density [6] or rate of growth [7] of the seed as variables in addition to the dimension, finally, the seed temperature [8] plays the part of an additional parameter in taking account of the incomplete thermal equilibrium between the seed and the medium.

The evolution of a nonequilibrium distribution function $f(\mathbf{x}, t)$ of the seed-characterizing parameters $\mathbf{x} = \{x_i\}$ is determined by the multidimensional Fokker–Planck equation

$$I_i = \varphi(\mathbf{x}) \sum_j D_{ij}(\mathbf{x}) \frac{\partial}{\partial x_j}\left(\frac{f(\mathbf{x}, t)}{\varphi(\mathbf{x})}\right), \quad \frac{\partial f}{\partial t} + \sum_i \frac{\partial I_i}{\partial x_i} = 0, \tag{1}$$

*Deceased.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 65-71, November-December, 1979. Original article submitted September 5, 1978.

 0021-8944/79/2006-0708$07.50