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INFLUENCE OF SUPERSONIC FLOW HEATING ON THE GAIN OF A CARBON DIOXIDE GASDYNAMIC LASER

S. A. Losev and V. N. Makarov

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The statement of the problem in the present article is the same as in our preceding work [1], namely optimization by the method of configurations with respect to initial conditions, composition, and nozzle geometry. The transition to dimensionless variables shows that the optimization parameters in the given problem are p_0, T_0, ξ_i, λ, and β_j, where p_0 and T_0 are the initial pressure and initial temperature; ξ_i denotes the mole fractions; $\lambda = p_0 l$ (l is a characteristic length); and β_j denotes parameters determining the dimensionless function A/A_*, where A and A_* are the nozzle cross sections at an arbitrary point and at the geometrical critical point, respectively. In [1] we adopted as β_j the values of the derivatives at certain fixed mesh-points $\bar{x}_j = x_j/L$, where $\bar{x}$ is the dimensionless distance along the x axis, referred to the nozzle length L. Quadratic approximation was applied to determine A/A_* between the mesh-points. We take $l = L$, so that for plane-parallel flows $\beta_j = \alpha_j L = \frac{2\,\mathrm{tg}\,\theta_j}{h_*} L$, where θ_j denotes the slope angles of the nozzle contour at the points $x_j = \bar{x}_j L$; and h_* is the height at the critical cross section of the nozzle. We consider fixed values of the initial pressure p_0, so that T_0, ξ_i, α_j, and L can be taken as the optimization parameters [1]. Unlike [1], the parameters α_j ($j = 1, 2$) can assume negative values.

The results of optimization with respect to the indicated parameters as a function of the initial pressure p_0 are given in Fig. 1 for a $CO_2 + N_2 + He$ mixture. These results show that following the large expansion of the supersonic flow in the geometrical critical zone of the nozzle a certain downstream constriction is observed in the optimal regime, i.e., α_1 and α_2 can assume negative values. For small initial pressures ($p_0 < \bar{p}_0$) we have $\alpha_1 > 0$ and $\alpha_2 < 0$, i.e., flow constriction must occur closer to the nozzle exit, and for large initial pressures ($p_0 > \bar{p}_0$) we have $\alpha_1 < 0$ and $\alpha_2 > 0$, i.e., constriction is observed in the middle part of the supersonic flow region of the nozzle. For pressures $p_0 \approx \bar{p}_0$ we find that $\alpha_1 \sim 0$ and $\alpha_2 \sim 0$, i.e., after the initial expansion and parabolic transition ($\alpha_0 > 0$) the flow cross section remains practically invariant up to the optimum distance L. For the

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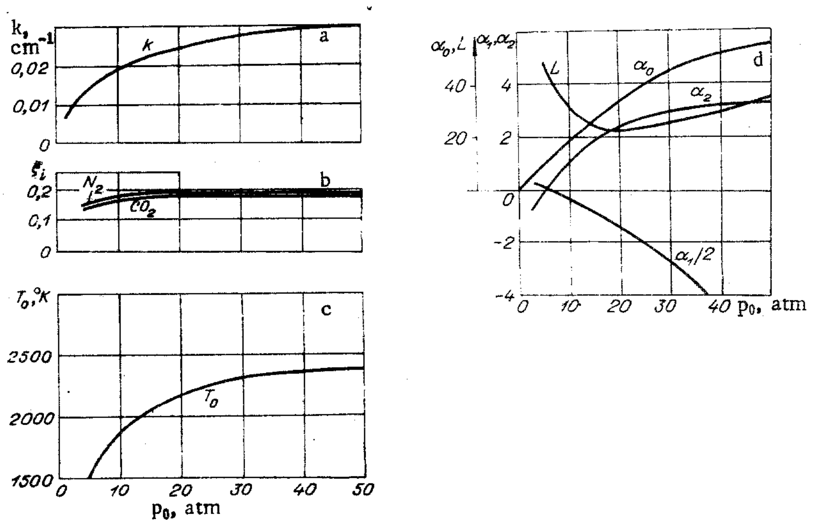

Fig. 1

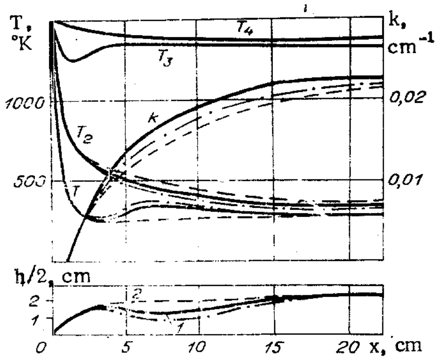

Fig. 2

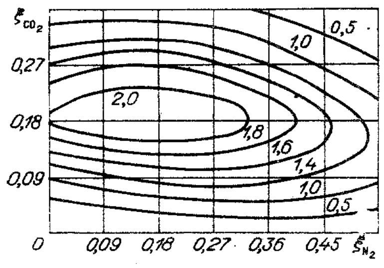

Fig. 3

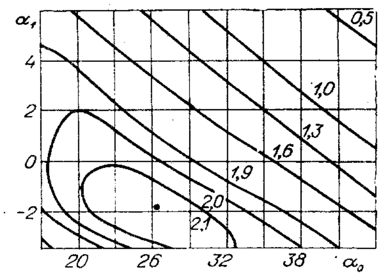

Fig. 4

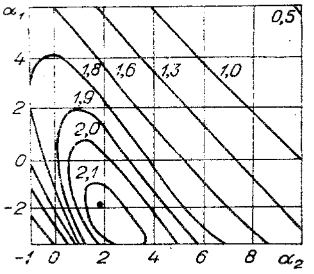

Fig. 5

mixture CO_2+N_2+He it turns out that $\bar{p}_0 \sim 6$ atm. We note that the slope angles in constriction and subsequent expansion of the flow are much smaller (by more than one order of magnitude) than the initial flare angle of the nozzle, i.e., $|\alpha_1/\alpha_0| < 1/10, |\alpha_2/\alpha_0| < 1/10$.

The role of the observed flow constriction is brought to light by inspection of the distribution curves for the translational and vibrational temperatures in the optimal flow regime for, say, $p_0 = 15$ atm (Fig. 2). We first attempt to explain the necessity of constriction. We consider the nonoptimal contour 2 of length L without constriction, where the ratio A/A_* of the exit to the critical cross section of the nozzle and the value of α_0 are the same as for the optimal nozzle 1. These nozzles differ to a great extent in the constriction zone. It turns out that the values of the vibrational temperature for the ν_3-mode of CO_2 and N_2 (T_3 and T_4) are frozen in along the interval up to the transition to constriction. Therefore, the small variation of the contour after T_3 and T_4 have ceased to vary cannot have a significant effect on their values in the subsequent part of the nozzle, i.e., the values of T_3 and T_4 in this part do not depend as strongly on the shape of the contour as does the value of the vibrational temperature of the ν_2-mode for CO_2 (T_2). The value of T_2 in the zone where the nozzle contour can be varied without appreciable influence on the values of T_3 and T_4 continues to relax, so that with flow constriction (i.e., upon transition from nozzle 2 to nozzle 1) the translational temperature T increases somewhat, thereby increasing the relaxation rate of the lower lasing level and widening the difference between T_3 and T_2. On the other hand, if a contour with greater than the optimal constriction is taken, the upper lasing level begins to relax. The absolute value of the net increase attained in the gain k in going from nozzle 2 to nozzle 1 is small.

The weak dependence of the optimum gain k on the values of α_1 and α_2 indicates that a further increase in the number of defining parameters α_i ($i \geq 3$) will yield only a small increase in the optimum k, so that the parameters α_0, α_1, and α_2 are sufficient for the statement of the optimization problems.

In setting up the appropriate experiment it is important to have quantitative data on the behavior of the parameters near the optimum values. A good idea of that behavior is afforded by relief maps of the optimization surface with respect to two parameters, for example, for the composition of the gas the mole fractions ξ_{CO_2} and ξ_{N_2} (the remainder being the mole fraction of helium; Fig. 3); the initial flare-angle parameter α_0 and the quantity α_1 (Fig. 4); or the quantities α_1 and α_2 (Fig. 5), which characterize the profile of the rest of the nozzle ($p_0 = 15$ atm in Figs. 3-5). In each case all the remaining parameters besides those plotted are assigned their optimum values. It is evident in Fig. 3 that the gain near the optimum is more sensitive to the CO_2 content than to the N_2 content.

The most indicative relief map of the required surface from the viewpoint of the stated problem is provided by the variables (α_0, α_1) and (α_1, α_2). It is seen in Figs. 4 and 5 that the equal-gain levels "extend" along the lines $A/A_* =$const. It can be shown that in the coordinates (α_0, α_1) the locus of points at which the ratio A/A_* has a constant value is determined by the relation $\alpha_0 = \bar{\alpha}_0 - 4(\alpha_1 - \bar{\alpha}_1)$, while in the coordinates (α_1, α_2) it is determined by the relation $\alpha_1 = \bar{\alpha}_1 - 2(\alpha_2 - \alpha_2)$ (where $\bar{\alpha}_0, \bar{\alpha}_1$, and $\bar{\alpha}_2$ are the values of these variables at the optimum point). The indicated results show that the surface relief is smooth in the vicinity of the optimum.

The presence of constrictions in the supersonic flow, of course, can generate (primarily for large values of h_* and, accordingly, large slope angles of the nozzle contour) strong shock waves and undesirable restructuring of the flow pattern. Such constriction therefore requires careful analysis of the flow inhomogeneity. In essence the investigated effect is associated with heating of the gas in the supersonic flow region, and the optimum values of α_j promote the best temperature and pressure distribution of the supersonic flow. In this sense, the foregoing results are extremely general insofar as the required temperature increase of the gas can be effected by alternative methods (hot-gas injection, electric heating, etc.) using a nozzle without constriction. The required preheating can also be realized by means of a system of weak shock waves (oblique compression shocks) by a procedure similar to Blackman's [2].

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