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AMPLIFICATION RATIO ON CO_2 GASDYNAMIC LASERS BEHIND NOZZLES OF WEDGE AND PROFILED GEOMETRIES.

2. MEASUREMENT RESULTS. COMPARISON OF EXPERIMENTAL AND CALCULATED DATA

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The optimum content of the components and parameters of the mixture are determined experimentally and the efficiencies of the nozzle apparatus are compared. The influence of local inhomogeneities on the amplification is estimated and satisfactory agreement between experimental and calculated data is noted.

In a homogeneous gasdynamic laser (GDL) the active medium is formed by the rapid expansion of the preheated and compressed working mixture in a supersonic nozzle. The achievement of supersonic stream velocities imposes very strict demands on the profiling of the flow channels. Heat release due to the relaxation of vibrationally excited CO_2 and N_2 molecules in the resonator creates the inhomogeneity in the supersonic stream characteristic of the active media of GDL, to which are added gasdynamic inhomogeneities, the source of which is, for example, incorrectness of the profiling of the flow channel [1].

The influence of these factors can be estimated by numerical calculations, making certain simplifications in solving the problem of the state of the active medium moving in the resonator. In the present work we used the well-known scheme of [2] for calculating CO_2 GDL for a gas mixture of 10% CO_2 + 45% N_2 + 45% He which expanded through a nozzle with a wedge geometry [3] and having the stagnation parameters $T_0 \simeq 1200$-2200°K and $P_0 = 1.5$ MPa. The vibrational modes of CO_2 and N_2 molecules were described within the framework of the model of a harmonic oscillator and it was assumed that relaxation of the deformation and symmetrical modes of carbon dioxide proceeds jointly, i.e., the corresponding temperatures are equal, while the relation $\theta_1 = 2\theta_2$ is satisfied for the characteristic temperature θ_1 of the vibrational level. The presence of equilibrium of rotational and translational degrees of freedom was also assumed, while variation of the chemical composition and effects of viscosity and heat conduction were ignored. The kinetic constants were chosen on the recommendations of [1]. The system of relaxation equations for vibrational levels of CO_2 and N_2 was solved jointly with the equations of one-dimensional gasdynamics [4]. The amplification ratio for a weak signal was calculated for the P(20) transition of the 00°1-10°0 band of the CO_2 molecule at the center of the line with allowance for the Doppler and collisional mechanisms of broadening.

For the case of the flow of an inverted medium in a resonator channel of constant cross section the gasdynamic parameters and amplification were calculated with allowance for the presence of an oblique compression shock inclined at a 13° angle to the vector of the oncoming stream; the angle of inclination was determined from an analysis of thermograms of gas flow behind a nozzle with a wedge geometry [3]. It was assumed that as the gas passes through the compression shock there is a change in the density and translational temperature of the gas, while the internal degrees of freedom of the molecules relax far more slowly than the translational ones, i.e., they are "frozen in." The kinetic and gasdynamic equations were integrated by the method of streamlines using the known pressure distribution for four stream filaments: boundary ($y_1 = 15$ mm), axial ($y_4 = 0$), and two intermediate ones (y_2 and y_3); the

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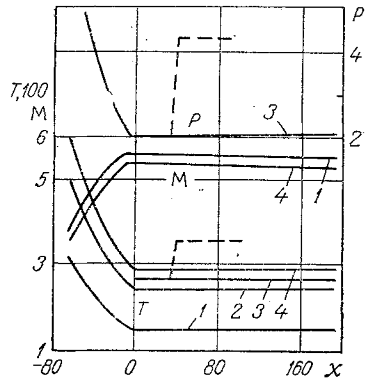

Fig. 1. Results of a calculation of gasdynamic parameters along a supersonic GDL channel x (mm) (pressure P (kPa), Mach number M, temperature T (°K)): 1) T_0 = 1200 °K; 2) 1800; 3) 2000; 4) 2200. Parameters behind the shock are given by dashed lines.

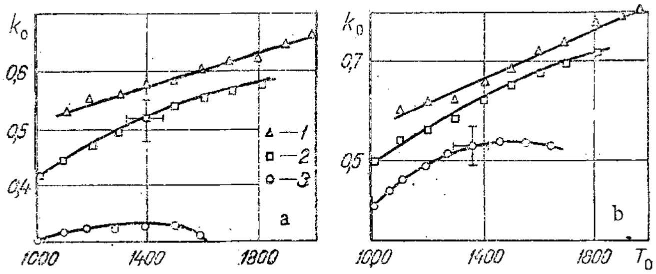

Fig. 2. Amplification k_0 (m^{-1}) as a function of stagnation temperature T_0 (°K) for a channel design with a nozzle of wedge geometry (N_2/He = 1): a) x = 10 mm; b) 144; 1) 10% CO_2; 2) 15; 3) 5.

distance between any neighboring stream filaments is 5 mm. The parameters were calculated under the condition that in the subsonic part of the nozzle the adiabatic index γ is taken from data on the equilibrium heat capacity, while in the supersonic part it is taken from the heat capacity with "frozen-in" vibrational degrees of freedom of the molecules. It should be noted that the relaxation processes taking place behind an oblique compression shock result in a change in γ, which was taken into account in the numerical calculations.

The results of calculations of the gasdynamic parameters — the static temperature T and pressure P and the Mach number — along the stream of the active medium are presented graphically in Fig. 1. The values of P and T with allowance for the oblique compression shock are also plotted here for the conditions of the intermediate stream filament y_2 for T_0 = 1800°K. It is characteristic that the presence of an oblique compression shock results in an increase in the pressure behind the shock by about 2.0 times and in the temperature by 1.3 times (from 270 to 350°K); similar results were obtained for the other three stream filaments analyzed. According to [5], the region of static pressures of ~2 kPa is the limiting region for the action of mechanisms of spectral-line broadening, for P_{st} > 2 kPa the line profile is due to collisional processes, and for P_{st} < 2 kPa the Doppler mechanism prevails, this being in the region of collisional broadening, which in our case occurs behind the shock, and a decrease in amplification is expected owing to the increase in density and translational temperature.

The main experimental results on the measurement of amplification were obtained on a CO_2 GDL installation using a pulsed periodic scheme of measurement [3]. This scheme allows one to measure the amplification along or across the stream of active medium at any number of points chosen in advance. We investigated $CO_2 + N_2 + He$ mixtures in a wide range of stagnation parameters: T_0 = 1000-2100°K and P_0 = 1-2 MPa. The stagnation temperature was varied by varying the inductive reactances in the plasmatron supply circuit, while different mixture

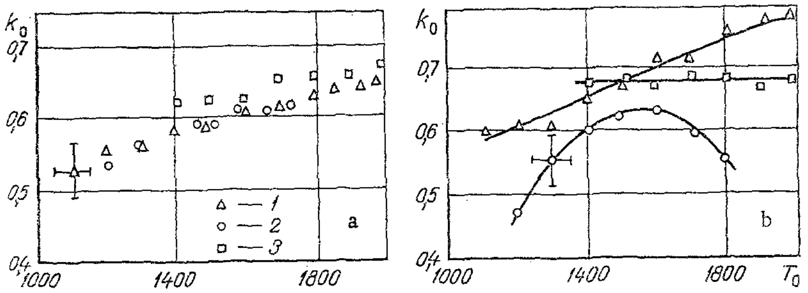

Fig. 3. Amplification k_0 (m^{-1}) as a function of stagnation temperature T_0 (°K) for a channel design with a nozzle of wedge geometry (10% CO_2): a) x = 10 mm; b) 144 mm; 1) $N_2/He = 1$; 2) 2; 1/2.

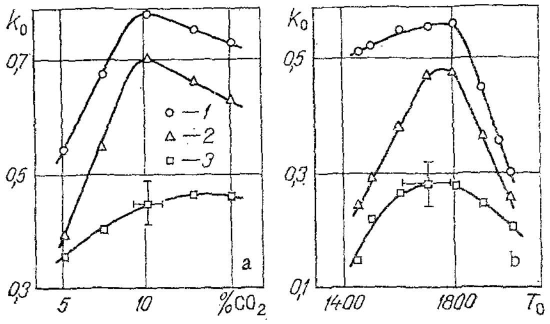

Fig. 4. Amplification k_0 (m^{-1}) as a function of molar content of CO_2 (% CO_2) and stagnation temperature T_0 (°K): a) channel design with a profiled nozzle ($N_2/He = 1$; $T_0 = 1200$°K): 1) x = 144 mm; 2) 100; 3) 10; b) design with a nozzle array (10% CO_2; $N_2/He = 1$): 1) x = 122 mm; 2) 79; 3) 35.

compositions were provided by mounting the appropriate critical-drop washers on the supply lines of the components, and they were also monitored by the method described in [6].

It should be emphasized that the amplification ratio for a weak signal being measured in our tests represents a quantity averaged over the probing distance, as well as the fact that possible mechanisms of attenuation of the probe beam, such as the absorption of radiation in stagnant zones of the supersonic GDL channel [7] and others, were not taken into account in the analysis of the experimental results.

In Fig. 2 we present the experimental results (for a channel design with a wedge nozzle) on measurement of the amplification ratio k_0 at the channel axis ($y_4 = 0$) for mixtures with a ratio $N_2/He = 1$ for different carbon dioxide contents: 5, 10, and 15 mole %. The curves are plotted as a function of the stagnation temperature T_0 for different distances x from the nozzle cut. The greatest amplification is achieved for a mixture with a CO_2 content of ~10%, with a decrease in CO_2 content in the mixture to 5% resulting in a sharp decrease in k_0 (almost twofold at small distances from the cut) while an increase in CO_2 to 15% has a slight effect on the amplification, especially at large x and in the region of temperatures $T_0 \geqslant$ 1300-1400°K. The relatively low values of k_0 for $T_0 \leqslant 1200$°K are explained by the low population of the upper laser level 00°1 of the CO_2 and N_2 molecules (v = 1) at this temperature (for a mixture with 5% CO_2 this is aggravated by the low concentration of CO_2 molecules). With an increase in T_0 the amplification grows owing to the increase in the population of the upper laser level. A decrease in k_0 with an increase in CO_2 concentration to 15% is noted for the investigated range of T_0 over the entire length of the supersonic channel. An increase in amplification along the stream is observed for all the mixtures, although at a distance of x = 65 mm on the channel axis there is an interaction of two compression shocks running off from the point of transition of the nozzle into a channel of constant cross section [3].

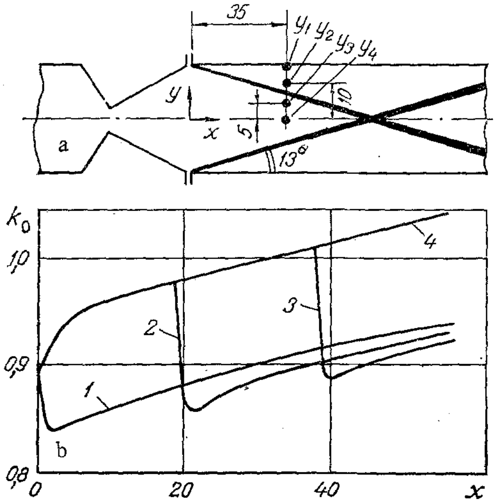

Fig. 5. Diagram of flow in a GDL channel (nozzle of wedge geometry) and points of amplification measurement; y) coordinate along height of channel, mm; x) distance from cut of nozzle unit, mm (a) and results of a calculation of the amplification k_0 (m^{-1}) along the stream x (mm) with allowance for oblique compression shocks, $T_0 \approx 1800°K$, $p_0 = 1.5$ MPa, 10% CO_2, $N_2/He = 1$, P_{20}: 1) for stream filament y_1; 2) y_2; 3) y_3; 4) y_4 (b).

The results of optimization experiments on the N_2 and He content in the mixture are presented in Fig. 3, where the amplification k_0 is shown as a function of the ratio N_2/He (1, 2, and 1/2) with a constant carbon dioxide content of 10%. The results are given for two measurement points, at distances x = 10 mm from the nozzle cut and x = 144 mm. It is seen from Fig. 3a that none of the mixtures has a significant advantage in amplification at a slight distance from the nozzle cut. The advantage of mixtures with $N_2/He = 1$ is revealed at a rather large distance x = 144 mm from the nozzle (Fig. 3b); they have a higher amplification ($k_0 \approx 0.75\ m^{-1}$ at $T_0 = 1800°K$) than mixtures with an enriched nitrogen content ($N_2/He = 2$, $k_0 \approx 0.6\ m^{-1}$) or helium content ($N_2/He = 1/2$, $k_0 \approx 0.65\ m^{-1}$). This is connected with the fact that for a content of $N_2/He = 1$ there is a resonance transfer of vibrational energy from nitrogen to the upper laser level 00°1 of the CO_2 molecule, on the one hand, while helium efficiently empties the lower laser level 10°0 of the CO_2 molecule, on the other hand. With a considerable decrease in the He content in the mixture ($N_2/He = 2$) the decay of amplification is connected with the inadequately efficient depopulating of the lower laser level 10°0 of CO_2, while an He excess ($N_2/He = 1/2$) causes intensive emptying of the upper laser level. A similar result on the optimization of helium mixtures (an optimum at ~40% He) was obtained in [8]. For mixtures with $N_2/He = 2$ a maximum amplification is observed in the region of $T_0 \approx$ 1500-1600°K ($k_{0\ max} \approx 0.60\ m^{-1}$), mixtures with $N_2/He = 1/2$ have an almost constant amplification in a rather wide range of $T_0 \approx$ 1400-2000°K, while mixtures with the optimum content of $N_2/He = 1$ show an increase in amplification with an increase in stagnation temperature up to $T_0 \approx 2000°K$.

In Fig. 4 we present the results of experiments on determining the amplification for a nozzle with a profiled geometry and for a nozzle array [3]. Just as in the case of a nozzle with a wedge geometry, k_0 first grows with an increase in CO_2 concentration from 5 to 10% (Fig. 4a), while a further increase in CO_2 concentration (mixtures with $\geqslant$10% CO_2) results in a decrease in k_0. At the same temperatures ($T_0 = 1200°K$) the amplification is 1.3 times higher for a design with a profiled nozzle than for a wedge nozzle, which is connected with the better organization of the stream in the channel of constant cross section.

The amplification measured in the case of a channel design with a nozzle array, in the temperature range T_0 = 1400-2000°K, and at different distances from the cut of the array is presented in Fig. 4b. The clearly expressed optimum in stagnation temperature, $T_{0\ opt} \approx$ 1600-1800°K, which agrees with the results of [6], is obvious. It is characteristic that slight amplification ($k_0 \approx 0.30\ m^{-1}$) is achieved at the distance x = 35 mm in a wide temperature range. The value of k_0 grows monotonically along the stream to $k_0 \sim 0.57\ m^{-1}$ so that the amplification zone expands. The reason for the low values of k_0 is the rhomboid structure of the oblique shocks running off from the numerous rims of the individual vanes of finite thickness. The gasdynamic inhomogeneities formed in the supersonic stream contribute to density fluctuations and cause an increase in the static temperature, which adversely affects the population inversion between the main laser levels. Dissipation of the shocks takes place along the stream; they weaken, and even at distances on the order of 100 calibers (a caliber is the distance between the centers of adjacent nozzles) the density fluctuations do not exceed 1% [9]. In our case fluctuations in the stream at small distances ($x \leqslant 35$ mm) are so strong that they can entirely suppress the amplifying properties of the active medium at low temperatures ($T_0 \leqslant 1400$°K).

To estimate the influence of oblique compression shocks on the amplification we ran an additional experiment with a channel design using a nozzle of wedge geometry. We measured k_0 at a distance x = 35 mm from the nozzle cut: Two measurement points were located in the zone of the undisturbed stream ($y_4 = 0$ and $y_3 = 5$ mm) and one in the stream behind the shock ($y_2 = 10$ mm). A diagram of the oblique shocks and the measurement points is presented in Fig. 5a. We investigated an optimum mixture of 10% CO_2 + 45% N_2 + 45% He with the stagnation parameters $T_0 \simeq 1800$°K and $P_0 \simeq 1.4$ MPa. The same amplification $k_0 = 0.91\ m^{-1}$ was measured at the measurement points y_4 and y_3, located in one zone of the stream, while $k_0 = 0.76\ m^{-1}$ at the point y_2. Thus, a decrease of ~16% in the amplification behind the compression shock was noted experimentally.

Calculations of the gasdynamic parameters made for a concrete case (see Fig. 1) showed that in this variant the width of the spectral line is determined mainly by the collisional broadening mechanism ($P_{st} > 2$ kPa), with a decrease in amplification takine place behind the shock, as shown in [5].

Values of the amplification k_0 calculated by the method presented above for the conditions of our experiment are presented in Fig. 5b. The constant increase in amplification for any of the stream filaments analyzed is due to the slow rate of the relaxation processes for helium mixtures, thanks to which both the inversion and the amplification grow continuously along the stream of active medium, while the sharp decrease in k_0 is explained by the pressure rise in the shock and the collisional mechanism of broadening of the spectral line connected with it. At x = 35 mm the calculated values of the amplification are $k_0 = 1.01\ m^{-1}$ (ahead of the shock) and $k_0 = 0.90\ m^{-1}$ (behind the shock) for stream filament y_2, which is in satisfactory agreement with the experimental results.

NOTATION

T_0, stagnation temperature, °K; P_0, stagnation pressure, Pa; θ_i, characteristic temperatures of levels, °K; y, coordinate along height of channel, mm; γ, adiabatic index; T, T_{st}, static temperature, °K; P, P_{st}, static pressure, Pa; M, Mach number; k_0, amplification ratio for a weak signal, m^{-1}; x, distance from cut of nozzle unit, mm.

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