# ASPECTS OF SELECTING THE MODE OF MIXING IN $CO_2 + N_2 + H_2O$ GASDYNAMIC LASERS

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Recommendations are made with regard to selection and organization of operating modes in gasdynamic lasers, viz., the mixing of excited nitrogen with a $CO_2$ + $H_2O$ mixture.

Inversion of populations in gasdynamic $CO_2$ lasers with selective excitation and mixing in a supersonic stream occurs as a result of a two-stage process. In the first stage fast cooling during acceleration in the supersonic nozzle produces a stream of nitrogen which is frozen with respect to vibrational degrees of freedom, in the second stage the stored vibrational energy is transmitted in a resonance mode to the upper laser level of $CO_2$ molecules being injected into the supersonic stream. In a gasdynamic laser with mixing, moreover, an inversion of populations occurs also in the binary mixture $CO_2 + N_2$ [1, 2], but an efficient extraction of energy from the resonator requires, as has been correctly mentioned [2, 3], a catalyst which will increase the rate of deactivation of the lower laser level as the latter becomes populated during emission. Helium or water vapor are usually added as the catalyst. It has been found that the requirements with respect to organization of the mixing mode are quite different depending on whether $H_2O$ or He molecules serve as the catalyst. This is due to the following reasons:

1) a $CO_2 + H_2O$ mixture is discharged at a much higher velocity than a $CO_2$ + He mixture;

2) the ratio of flow rates of emitting component to nitrogen is usually much lower with a $CO_2 + H_2O$ mixture than with a $CO_2$ + He mixture as that component;

3) injection of the light gas ($CO_2$ + He) into the supersonic nitrogen stream causes an acceleration and, consequently, an additional cooling of the resultant stream, while injection of the heavy gas ($CO_2 + H_2O$) causes a deceleration and some recovery of the temperature.

In this study the aspects of selection of the mixing mode in gasdynamic $CO_2 + N_2 + H_2O$ lasers will be numerically analyzed. The gain and the specific energy output have been calculated on the basis of the quasi-one-dimensional formulation in the instantaneous-mixing model [4, 5] (with the rate constants of the relaxation process involving $H_2O$ and the equations of vibrational kinetics taken from a reference book [1]). An analysis of the results leads to the following conclusions.

Temperature Dependence. The calculated temperature dependence of the gain and of the specific energy output shown in Fig. 1 indicate that with moderate concentrations of water vapor, despite the decreasing gain $\alpha$ at temperatures $T_0 \gtrsim 2000$°K, the specific energy output W/G continues to increase up to ~3500°K and reaches ~140 J/g.

A comparison with calculated data on gasdynamic $CO_2 + N_2$ + He lasers with mixing reveals that up to nitrogen stagnation temperatures $T_0 \lesssim 2000$°K the specific energy output is almost the same whether water vapor or helium has been used as the catalyst. As the temperature increases to $T_0 \gtrsim 2000$°K, the specific energy output in a gasdynamic $CO_2 + N_2 + H_2O$ laser increases at a decreasing rate because of appreciable losses due to deactivation of the upper laser level and because of the increasing population of the lower laser level. The calculations shown in Fig. 1 were made for a profiled "fast" expansion nozzle with an $h^* = 1$ mm high critical section and an areas ratio $A/A^* = 30$. The $CO_2 + H_2O$ stream was mixed at a Mach number $N_{Ma} = 3$ of the main stream. The translational temperature at the exit from such a nozzle at $T_0 = 3500$°K is rather high ($T \sim 600$°K). As further calculations have revealed, however, an additional expansion of the gas with its attendant cooling to room temperature improves neither the gain nor the specific energy output: at moderate concentrations of water

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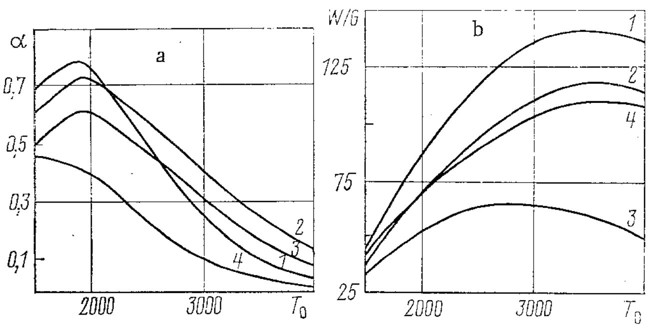

Fig. 1. Dependence of the gain $\alpha$, $m^{-1}$ (a) and of the specific energy output W/G, J/g (b) at the nozzle outlet on stagnation temperature $T_0$, °K, of nitrogen under a pressure of 10 atm in the plenum chamber; $CO_2$ content in the resultant stream 5% in all operating modes, $H_2O$ content: 1) 1%; 2) 5%; 3) 15%; 4) 0.

vapor the temperature $T_{12}$ of symmetric and deformation vibration modes remains fixed upon further expansion, while increasing the concentration of water vapor by 2-5% or more causes the loss of vibrational energy to increase due to relaxation of the upper laser level.

Pressure Dependence. The dependence of the gain and the specific energy output on the stagnation pressure of the main stream (nitrogen) in a gasdynamic laser is shown in Fig. 2. The decreasing of the specific energy output with increasing pressure can be explained not only by the acceleration of relaxation processes in the mixing zone but also by the dynamics of the gain variation $\alpha(P_0)$. The gain increases linearly with the pressure within the range of the Doppler line contour, but at pressures $P_0 \gtrsim 6$-10 atm, at which the line contour becomes a collisional one, the gain $\alpha$ does not increase with the pressure and is determined only by the difference between the vibrational temperature $T_3$ and $T_{12}$, at a given translational temperature and a given composition of the gas mixture. As the pressure increases, both temperatures $T_3$ and $T_{12}$ decreases because of accelerating thermalization processes and this determines the intricate trend of the $\alpha(T)$ relation.

Dependence on the Concentration of Components. Concentrations of water vapor in the resultant stream on the order of 1% are sufficient for effective deactivation of the lower laser level. At higher concentrations of water vapor there occurs additional losses due to the deactivation of the upper laser level, but the degree of inversion and the magnitude of the specific energy output remain significant (e.g., above 50 J/g at a nitrogen stagnation temperature of 2000°K) up to ≈10% $H_2O$ concentrations.

Just as in the case of injection of a $CO_2$ + He mixture [5], in this case the optimum concentration of $CO_2$ molecules in the resultant stream is determined not so much by the relaxation processes as by the quality of the resonator. Thus the gain $\alpha$ is already on the order of 1 $m^{-1}$ with $\xi_{CO_2} = 5\%$ in the stream and increases almost linearly as $\xi_{CO_2}$ increases to 15-20%. Attainment of a still higher gain is, naturally, linked with an increase of relaxation losses. At $T_0 = 2000$°K, e.g., an increase of $\xi_{CO_2}$ from 5 to 15% results in a decrease of the specific energy output from 85 to 65 J/g.

Mixing Geometry. The optimum mixing (or, more precisely, admixing [2]) site for a $CO_2$ + $H_2O$ mixture is located much farther downstream than for a $CO_2$ + He mixture. This is due to an appreciable recovery of the translational temperature and a filling of the lower laser level during mixing of nitrogen and $CO_2$ streams at a high temperature. According to calculations, the optimum Mach number of the main stream at the mixing site should be higher than 5.

Effect of Gasdynamics. Because of the large difference between the velocities of the injected stream and the main stream in a gasdynamic $CO_2$ + $N_2$ + $H_2O$ laser within the mixing zone, there occurs an appreciable recovery of temperatures which worsens the lasing characteristics of the device. According to two-dimensional calculations for laminar viscous mixing in such a laser [3], a change in the injected stream to main stream velocity ratio from 1 to 1/2 will result in reducing the gain by almost one half.

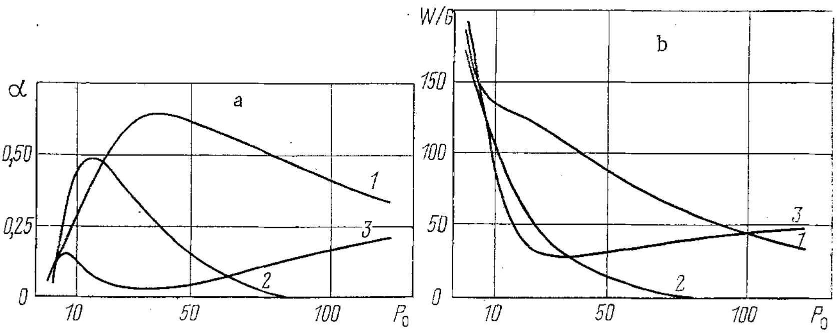

Fig. 2. Dependence of the gain $\alpha$, $m^{-1}$ (a) and of the specific energy output W/G, J/g (b) at the nozzle throat on the stagnation pressure $P_0$, atm, of nitrogen; temperature in the plenum chamber 3000°K, composition of the gas after mixing: 1) $0.94\ N_2 + 0.05\ CO_2 + 0.01\ H_2O$; 2) $0.9\ N_2 + 0.05\ CO_2 + 0.05\ H_2O$; 3) $0.95\ N_2 + 0.05\ CO_2$.

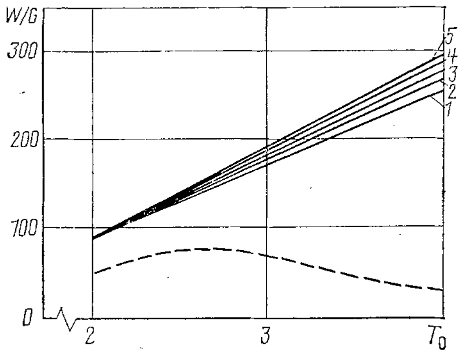

Fig. 3. Dependence of the specific energy output W/G, J/g, on the stagnation temperature $T_0$, kK, of nitrogen; Mach number of the main stream at the mixing site $N_{Ma,N_2} = 5$ for all mixing modes, composition of the gas after mixing $0.9\ N_2 + 0.1\ CO_2$. Mach number of injected stream $N_{Ma,CO_2}$ and temperature in the plenum chamber $T_{0CO_2}$: 1) $N_{Ma,CO_2} = 1$ and $T_{0,CO_2} = 300$°K; 2) $N_{Ma,CO_2} = 2$ and $T_{0,CO_2} = 390$°K; 3) $N_{Ma,CO_2} = 3$ and $T_{0,CO_2} = 575$°K; 4) $N_{Ma,CO_2} = 4$ and $T_{0,CO_2} = 830$°K; 5) $N_{Ma,CO_2} = 5$ and $T_{0,CO_2} = 1160$°K. Dash line: distribution at $N_{Ma,N_2} = 3$, $N_{Ma,CO_2} = 1$ and $T_{0,CO_2} = 300$°K.

In selective gasdynamic $CO_2 + N_2 + He$ lasers the deceleration of streams can be decreased by mixing [6] either by an increase of the helium content in the injected stream or by a lowering of the Mach number of the main stream at the admixing site.

A different method has been proposed for a gasdynamic $CO_2 + N_2 + H_2O$ laser [7], namely, preheating and additional acceleration of the $CO_2$ gas. Indeed, since the flow rate of $CO_2 + H_2O$ mixture is 5-10% of the flow rate of nitrogen, the additional loss on heating the $CO_2$ gas is small ($\lesssim$5-6%). Meanwhile, by heating the $CO_2$ gas from 300 to 1500°K, one can increase the velocity of discharge from the supersonic nozzle by a factor of 4.5 at least, from 270 to 1400 m/sec, while maintaining the same density and temperature of the auxiliary stream within the admixing zone. It must be noted that the stream of $CO_2$ gas is entirely at equilibrium along the auxiliary channel from the plenum chamber to the injection site, which means that the lower laser level of the injected $CO_2$ gas is in equilibrium with the translational temperature and thus is unpopulated.

The calculated specific energy output from such a variant of a gasdynamic laser with selective heating of both the exciting component and the emitting component is shown in Fig. 3, the data here corresponding nearly optimum conditions. An analysis of these data reveals that at a nitrogen stagnation temperature $T_0 = 4000$°K, e.g., heating of the emitting component with an additional energy loss of ≈2-3% (referred to the energy loss on heating the nitrogen) will increase the specific energy output by more than 15% so that the absolute magnitude of the specific energy output can reach something of the order of 300 J/g.

The results of calculations presented here thus indicate that the optimum mixing mode in a gasdynamic laser with water vapor as the catalyst for deactivation of the lower laser level differs appreciably from the optimum mode with helium as the catalyst. In a gasdynamic $CO_2$ + $N_2$ + $H_2O$ laser, moreover, mixing modes with low relaxation losses and high specific energy output are attainable.

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## NOTATION

$T_0$, stagnation temperature of the main stream; $P_0$, stagnation pressure of the main stream; $\alpha$, weak-signal gain; W/G, specific energy output; $\xi$, molar concentration; $T_i$, vibrational temperatures of $CO_2$; $N_{Ma,N_2}$, Mach number of the main stream at the mixing site; $N_{Ma,CO_2}$, Mach number of the injected stream at the mixing site; and $T_{0,CO_2}$, temperature in the plenum chamber of the injected stream.

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