COMPARATIVE ANALYSIS OF SUBSONIC AND SUPERSONIC FAST FLOW-THROUGH ELECTROIONIZATION CO LASER

V. A. Gurashvili, A. V. Dem'yanov, S. A. Zhdanok,
I. V. Kochetov, A. K. Kurnosov, and A. P. Napartovich

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A comparative analysis of the energy and gas-dyanmic characteristics of electroionization carbon monoxide lasers with sub- and supersonic flow of the active medium is made.

Together with the development of pulsed CO-EIL, in the last four years much effort has gone into the development of fast flow-through electroionization CO lasers in which the working body is cooled to cryogenic temperatures and the discharge zone and the resonator are combined [1, 2]. Two schemes are usually studied: with sub- and supersonic flow velocity. In the first case the working mixture is cooled in special cooling units at the inlet into the gas-discharge chamber of the CO-EIL; in the second case the working body is cooled by means of adiabatic expansion in a supersonic nozzle. This paper is devoted to the theoretical analysis of electroionization (EI) CO lasers with sub- and supersonic flow velocity of the active medium in the discharge.

The mathematical model of a fast flow-through CO laser is analogous to that of a pulsed carbon monoxide laser described in [3, 4], the only difference being that the system of equations of vibrational kinetics employed in there is supplemented by equations from one-dimensional gas dynamics:

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = 0, \tag{1}$$

$$\rho u \frac{d}{dx}\left(c_p T - \frac{u^2}{2}\right) = jE(\eta_T + \eta^*), \tag{2}$$

$$G = \rho u F = \text{const}, \tag{3}$$

$$p = \rho r T, \tag{4}$$

where u is the flow velocity of the gas; ρ, gas density; p, static pressure; T, temperature; j, current density; E, electric field intensity; η_T, relative fraction of the pump power expended on direct heating of the active medium; η^*, ratio of the specific heating power owing to vibrational relaxation to the specific pump power; c_p, heat capacity at constant pressure; G, mass flow rate of the gas; F, cross section of the channel; $r = R/\mu$; R, universal gas constant; and μ, molecular weight of the mixture.

The quantity η^* is determined by the kinetics of vibrational energy exchange in the gas; in this work it was found by solving the complete system of kinetic equations describing e − V, V − V, and V − T processes.

For a supersonic laser the calculations were performed for parameters of the active medium that are close to those realized experimentally in [2]. It was assumed that the mixture of CO and N_2 gases with the starting density N = 0.5 amagats and at a temperature of 80 K flows into a gas-dynamic channel with a constant cross section; the starting Mach number equals 3. In carrying out the calculations with a high starting temperature of the active medium the mass flow rate was held equal to the previous value. The length of the discharge zone along the flow, like in [2], equaled 15 cm. In the calculations the constant gain method (the threshold gain $\Gamma = 2.5 \cdot 10^{-3}$ cm^{-1}) was employed, and the resonator was combined with the part of the discharge zone where $g \geq \Gamma$ (g is the gain). It was assumed that the pump power per cubic centimeter remains constant along the flow. In studying the character-

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A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 55, No. 1, pp. 37-41, July, 1988.

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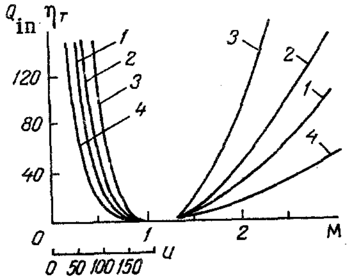

Fig. 1

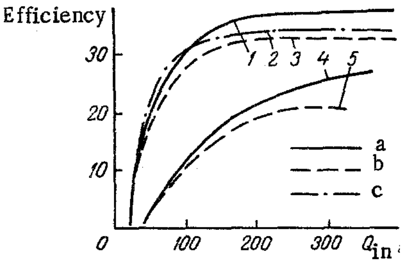

Fig. 2

Fig. 1. Limiting energy input versus the starting velocity of the gas: 1) $CO:N_2 = 1:9$, T = 80 K; 2) $CO:N_2 = 1:9$, T = 120 K; 3) CO:He = 1:9, T = 80 K; 4) CO:Ar = 1:9, T = 80 K. The scale at the bottom for the starting gas flow velocity u corresponds to the mixture $CO:N_2 = 1:9$, T = 80 K. $Q_{\text{in}}\eta_T$, J/g; u, m/sec.

Fig. 2. Efficiency versus the energy input; the mixture is $CO:N_2 = 1:9$ [subsonic (a), supersonic (b), supersonic with expansion ($S/S_0 = 2$) (c)]: 1, 2, 3) T = 80 K; 4, 5) 120 K. Efficiency, %.

istics of the subsonic laser the mass flow rate and the pump power were reduced approximately by an order of magnitude.

As is well known, many experimental works [5, 6] indicate that the direct heating of the gas in the discharge ($\eta_T \gtrsim 0.2$) for $E/N \lesssim 1\cdot 10^{-16}$ V·cm² is significant. The mechanism of this heating has never been fully clarified. In fast-flow CO lasers heating in the flow increases (for subsonic flow) or decreases (for supersonic flow) the flow velocity. Under certain conditions of heating this can cause "locking" of the flow. The critical energy input for which "locking" of the flow occurs can be evaluated as follows. If in the equation of continuity for the energy the interaction of the vibrational and translational degrees of freedom is neglected, then one easily derives

$$\frac{T_2^*}{T_1^*} = 1 + \frac{Q_{\text{in}}\eta T}{T_1^* c_P}, \tag{5}$$

where

$$T^* = T + \frac{u^2}{2c_P}; \quad Q_{\text{in}}\cdot\eta_T = \int_{l_1}^{l_2} \eta_T \frac{jE}{\rho u}\,dx.$$

If the starting and final Mach numbers M_1 and M_2 are given, then, substituting T_1* and T_2 with the help of (5), we find $Q_{\text{in}}\eta_T$. In the limiting case $M_2 = 1$ this expression assumes the simple form

$$Q_{\text{in}}\,\eta_T = \frac{\left(\frac{R}{M}\right)\gamma T_1^*\left(\frac{1}{M_1} - M_1\right)^2}{2(\gamma+1)(\gamma-1)}.$$

Figure 1 shows $Q_{\text{in}}\eta_T$ as a function of M_1. The curves shown in Fig. 1 correspond, for subsonic flow, to $M_2 = 0.9$, while for supersonic flow $M_2 = 1.3$. One can see from the figure that if $\eta_T = 0.25$ (which corresponds to the parameters $E|N \approx 0.5\text{-}0.6\cdot 10^{-16}$ V/cm² [5, 6]), then the limiting energy input for $M_1 = 3$ (u = 550 m/sec) equals 430 J/g, while for $M_1 = 0.27$ (u = 50 m/sec) and $M_1 = 0.55$ (u = 100 m/sec) it equals 700 and 110 J/g, respectively. The computational results presented in this work were obtained for $\eta_T = 0.25$.

Figure 2 shows the efficiency versus the energy input. In a CO laser with a subsonic active medium the relative heating of the gas owing to vibrational relaxation is higher and at T = 80 K equals approximately 10 and 5% of the pump energy with a specified energy input of 100 and 400 J/g. For supersonic flow these losses are virtually independent of the specific energy input and for the same starting temperature equal approximately 3% of the pump

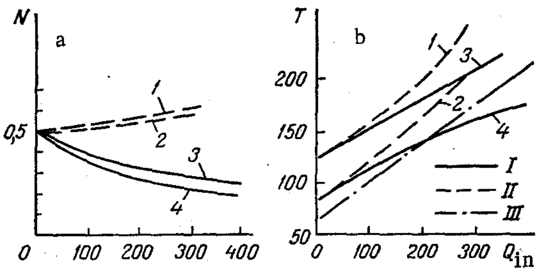

Fig. 3

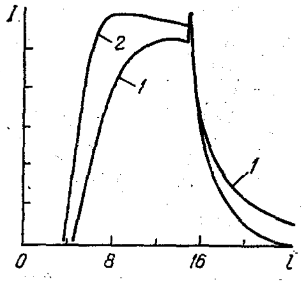

Fig. 4

Fig. 3. Gas density (a) and the gas temperature (b) at the outlet from the discharge zone versus the energy input. The mixture is $CO:N_2 = 1:9$: I) subsonic; II) supersonic; III) supersonic with expansion ($S/S_0 = 2$); 2, 4) T = 80 K; 1, 3) T = 120 K. N, amagats.

Fig. 4. Intensity of the radiation versus the distance along the flow for energy input Q_{in} = 190 J/g and a starting temperature of 120 K: 1) supersonic; 2) subsonic. I, relative units; ℓ, cm.

energy. The absolute heating of the gas in the subsonic laser, however, turns out to be smaller, which leads to somewhat better energy characteristics. According to the curves shown in Fig. 2, increasing the starting temperature of the gas from 80 to 120 K increases the lasing threshold with respect to the pump energy by approximately a factor of 2.5 and lowers the efficiency. Figure 2 shows for a supersonic laser the computational results for an expanding channel, whose degree of expansion equaled $S/S_0 = 2$. Such strong expansion insignificantly increases the efficiency owing to some drop in the temperature of the gas.

The computed curves of the density of the active medium and its translational temperature at the outlet from the discharge zone versus the specific energy input are presented in Fig. 3.

As regards the computed lasing spectra for the two CO laser schemes studied, it turns out that for the same starting temperatures and specific energy inputs they are very close and their short wavelength boundaries are identical.

Increasing the starting temperature of the gas shifts the short wavelength boundary of the lasing spectrum toward higher vibrational transitions. Thus, for example, in the subsonic scheme the short wavelength boundary of the spectrum shifts from the transition $v = 6 \rightarrow v = 5$ to the transition $v = 7 \rightarrow v = 6$ when the starting temperature is raised from 80 to 120 K and the specific energy input equals 190 J/g.

This result can be explained by the effect of the gas temperature on the value of the Trinor number ($v_T \sim T$), which characterizes the region of vibrational quantum numbers v with a power-law decay of the distribution function of CO molecules over vibrational energy levels (the "plateau" region), since it is precisely the start of the "plateau" that corresponds to the short-wavelength boundary of the lasing spectrum [7].

In the mathematical model employed here the lasing spectrum was determined by the method of constant gain. In this method the lasing spectrum at each point of the flow is assumed to be independent; moreover, as one can see from Fig. 3, the gas temperature along the gas flow changes by 100-200 K. If the resonator allows for efficient "mixing" of the radiation between different regions of the gas flow, then because of the difference in the temperature the maximum gain will be obtained on different vibrational—rotational transitions. Other methods for finding the lasing intensities, in which a real resonator is described more accurately, can give different computed spectra. The fact that reabsorption in the wings of the lines of the P and R branches of the CO molecule can affect the vibrational—rotational lasing spectrum already for the densities of the active medium employed in the calculations should be taken into account [8].

Thus, the question of the detailed vibrational—rotational lasing spectrum in a fast flow CO electroionization laser requires further theoretical study.

A significant difference between the two schemes of the CO-EIL studied in this work is that the variation of the gas density along the flow is different. In the supersonic scheme with an energy input of 400 J/g the gas density increases by less than 20%, while in the subsonic scheme the gas density under the same conditions drops by a factor of 2.5 (Fig. 3). This, first of all, causes E/N to vary significantly along the gas flow and therefore requires that special measures be taken to maintain the stability of the discharge. Second, such a strong change in the gas density can affect the divergence of the laser radiation. These questions require special theoretical and experimental study.

We also note that after the gas flow leaves the discharge zone the drop in the lasing intensity occurs over a time determined by V—V exchange. The distributions of the radiation intensity along the flow, calculated for the two CO laser schemes studied in this work, were obtained for the case when the downstream boundaries of the discharge zone and the resonator coincided. The curves in Fig. 4 show that some optimization of the efficiency is possible by increasing the resonator length and placing the resonator somewhat farther downstream relative to the discharge zone.

The analysis performed in this work showed that for identical energy inputs, gas temperatures and density, the efficiency of the subsonic laser is somewhat higher than that of the supersonic laser. The long residence time of the gas in the discharge zone in the subsonic laser leads to low values of $(E/N)_{cr}$, corresponding to contraction of the discharge, and thereby an increase in the relative fraction of the energy going directly into heat. The sharp differential of the gas density (a factor of 2-3) in the discharge zone of a subsonic laser presents a definite difficulty from the viewpoint of discharge stability and quality of the laser radiation.

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