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Calculation of the mixing chamber of an ejector chemical oxygen–iodine laser

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***Abstract*. Gas parameters are calculated at the outlet of the mixing chamber of an ejector chemical oxygen–iodine laser with a nozzle unit consisting of nozzles of three types, which provides a total pressure of the active medium that substantially exceeds a pressure in the generator of singlet oxygen. This technique of forming the laser active medium substantially facilitates the ejection of the exhaust gas to the atmosphere by using a diffuser and single-stage vacuum systems based on water circulating pumps.**

Keywords: *chemical oxygen–iodine laser, mixing chamber, ejector.*

1. Introduction

A chemical oxygen – iodine laser (OIL) is the first chemical laser operating on electronic transitions at 1.315 μm in the near-IR region. The input working components of the laser are hydrogen peroxide, a solution of potassium hydroxide (an alkali), chlorine, and iodine. The reaction yields absolutely nontoxic products, such as potassium salt and water.

The ease and cheapness of obtaining the active medium, the weak absorption of OIL radiation in the atmosphere [1 – 4], and its efficient interaction with materials [5] ensure a variety of applications of this laser. The advent of low-loss quartz fibres [2, 6] further expanded the technological applications of OILs. Among the most important technological problems solved with the help of OILs is first of all the remote robot-assisted laser dismantlment of obsolete radioactive equipment of nuclear power facilities [6, 7], which provides the minimum pollution of the environment. Note also the underwater repair of ship hulls, the cutting of thick blanks of steel and aluminium, the welding of aluminium automobile bodies, etc. [5]. The more efficient (compared to a CO_2 laser) interaction of OIL radiation with metals [5] provides, in particular, twice as high an efficiency in cutting steels.

The dimensions, the weight, and the energy expenditures of the discharge system of the exhaust active medium determine to a large extent the technical efficiency of a chemical OIL. The efficiency of the discharge system of the exhaust active medium depends on the specific power per unit evacuation capacity of the pump system (W s litre^{-1} or J litre^{-1}). A typical value of this parameter for the existing lasers is 1 J litre^{-1}.

There exist two possibilities to increase this parameter: increasing the stagnation pressure of the supersonic flow of the active medium in the resonator and the pressure recovery in the diffuser [8] or employing a subsonic flow of the medium with a high static pressure and low losses of the total pressure [9].

In Ref. [10], the total pressure of the medium in a chemical OIL with a disk generator was raised to nearly 100 Torr by preliminary diluting chlorine with helium in the proportion of 1 : 6. However, the high gas density in the reaction region favours the development of instabilities in the liquid film, the generation and the capture of the aerosol of the working solution, and produces additional diffusion resistance to the chlorine mass transfer to the disk surfaces. Therefore, this method allows one to increase the pressure recovered in the diffuser only within certain limits. A subsonic OIL permits relaxing the requirements on the pump system and raising the specific power up to 3.1 J litre^{-1} [11], but the small length of the amplification region in this laser results in a substantial increase in the radiation load on the mirrors. Moreover, the exhaust pressure in subsonic lasers remains relatively low to enable the use of economic single-stage pump systems.

To increase substantially the total and recovered pressures, in papers [12, 13] a new ejection technique of preparing the active medium of an OIL was proposed. This technique allows one to extend the gain region and to increase substantially the recovered flow pressure by rising simultaneously the static pressure and the Mach number in the resonator. In this case, energy transfer and the attainment of a high total pressure are provided by different gas components.

In this case, some nozzles of the nozzle unit inject small-sized oxygen jets with a sonic or slightly supersonic velocity and a moderate static pressure (for instance, 10 Torr) into the mixing region, while the other nozzles form supersonic high-pressure jets of nitrogen (or another buffer gas) with a small admixture of iodine vapour. If the total momentum of the nitrogen jets far exceeds that of the oxygen jets, the total pressure of the fully mixed gas will be virtually determined by the nitrogen flow, whose total pressure and Mach number are free parameters.

However, specific internal contradictions are inherent in this design. In fact, the necessity of using nitrogen with a

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high total pressure and a low static pressure in the mixing chamber involves the use of nozzles with a high Mach number. The static temperature of gas jets at the outlet of these nozzles proves to be extremely low, while the degree of supersaturation of the iodine vapour can amount to 5–10 orders of magnitude, which is favourable for condensation of the iodine vapour. To prevent condensation of the iodine vapour, nozzles with the Mach number close to unity should be used.

This contradiction can be eliminated by using special additional nozzles for injecting the necessary amount of iodine vapour into the flow, which form transonic velocity jets with a low consumption of nitrogen as the carrier gas. In this case, the high-pressure jets should contain only pure nitrogen. The parameters of the fully mixed gas can be estimated with the help of the method used to calculate gas ejectors operating in the critical mode [14].

A fragment of the plastic nozzle unit [15, 16] investigated experimentally is shown in Fig. 1. Oxygen with a total pressure of ~ 30 Torr comes from the generator of singlet oxygen to the mixing chamber through plane slotted nozzles. High-pressure jets, whose total pressure may exceed the atmospheric one, are injected through cylindrical channels of the unit. Cylindrical tubes serve to inject the iodine vapour with a buffer gas with a small Mach number.

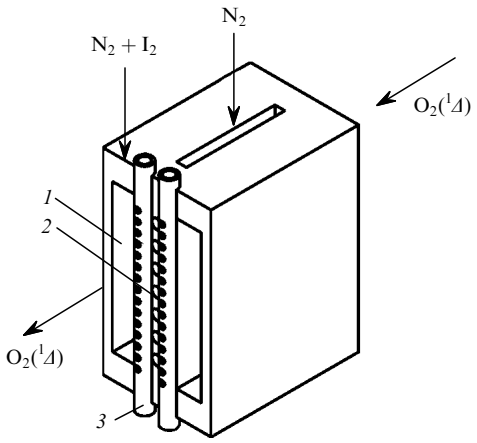

Figure 1. Fragment of the ejector nozzle unit: (*1*) slits for oxygen; (*2*) cylindrical channels for the ejection of nitrogen; (*3*) perforated tubes for the $N_2 + I_2$ mixture.

By using such a nozzle unit, we built a supersonic ejector OIL with a chemical efficiency of 19.7 %, a pressure in the Pitot tube of over 100 Torr, and a total pressure of the active medium of about 220 Torr.

2. Calculation procedure

We assume that all the nozzles are sonic, with the total critical cross section areas F_{0i} ($i = 1, 2, 3$). We neglect the nonuniformity of the flows at the nozzle outlet related to the existence of boundary layers. Because the total area of all the nozzles is far less than the area of the chamber cross section, the free jets expand to occupy flow areas E_i, accelerate, and occupy the entire chamber cross section ($F_1 + F_2 + F_3 = F$). As this takes place, the static pressures in the jets become equal, $P_i = P$. The plane in which the outlet nozzle sections are located cannot be employed to calculate the gas parameters, because the pressure distribution in the bottom regions of the nozzle unit is unknown. For this reason, the plane where all the jets mix together and the static pressures become equal is adopted as the initial flow section. In this case, neglecting the occurrence of the so-called barrels, shock waves, and transverse momentum components, we will assume that the free expansion of the jets occur adiabatically. Evidently, this approach will result in some underestimation of the loss of the total pressure, the static temperature, and in some overestimation of the recovered pressure behind the shock wave. However, as shown below by a specific example, this overestimation is insignificant.

Let us introduce the notation: $R = 8.314 \times 10^7$ erg $K^{-1} \times mol^{-1}$ is the universal gas constant; k_i are the adiabatic indices; T_{0i} are the stagnation temperatures; P_{0i} are the stagnation pressures; m_i are the molar gas masses [subscripts $i = 1 - 5$ at the parameters imply that a given parameter is related to high-pressure nitrogen (1), oxygen (2), nitrogen with iodine vapour (3), fully intermixed gases at the outlet of the mixing chamber (4), and to fully intermixed gases behind the pressure shock measured by the Pitot tube (5)];

$$m_3 = \frac{254P_I + 28P_N}{P_I + P_N}$$

is the molar mass of the nitrogen–iodine vapour mixture; P_I is the partial iodine vapour pressure; P_N is the nitrogen pressure in the chamber employed to measure the iodine vapour density by the absorption method; $G_i = 10^{-3} m_i g_i$ is the mass flow rate of a gas in g s^{-1};

$$g_i = 1.333 \cdot 10^6 \left[\left(\frac{k_i}{m_i R T_{0i}} \right) \left(\frac{2}{k_i + 1} \right)^{(k_i+1)/(k_i-1)} \right] P_{0i} F_{0i} \quad (1)$$

is the molar flow rate of a gas in mmol s^{-1}; $C_i = (R/m_i)[k_i/(k_i - 1)]$ ($i = 1, 2, 3$) are the specific heat capacities at constant pressure; Q^* is the heat release in the flow due to the condensation of the admixture of water vapour in oxygen jets, the quenching of singlet oxygen and excited iodine atoms; $Q = Q^*/(G_1 C_1 T_{01})$ is the heat release measured in units of the enthalpy of the ejecting gas, which corresponds to $\eta_q = Q^*/(G_2 C_2\, 34.7\,\mathrm{K})$, the fraction of quenched $O_2(^1\Delta)$; 34.7 K is the temperature difference in pure oxygen when heated due to the relaxation of one percent of $O_2(^1\Delta)$;

$$A_i = \left[\frac{2RT_{0i}k_i}{m_i(k_i + 1)} \right]^{1/2}$$

is the critical velocity of the ith flow; $\lambda_i = V_i/A_i$ is the velocity coefficient; $M_i = V_i/V_{i,s}$ is the Mach number; V_i is the gas velocity; $V_{i,s}$ is the velocity of sound; $X = T(\lambda)/T_0 = 1 - (k-1)\lambda^2/(k+1)$ is a gas-dynamic temperature function;

$$\pi(\lambda) = \frac{P(\lambda)}{P_0} = \left[1 - \frac{(k-1)\lambda^2}{k+1} \right]^{k/(k-1)} \equiv X^{k/(k-1)}; \quad (2)$$

$$q(\lambda) = \frac{F_0}{F(\lambda)} = \left(\frac{k+1}{2} \right)^{1/(k-1)} \lambda \left[1 - \frac{(k-1)\lambda^2}{k+1} \right]^{1/(k-1)} =$$

$$= \left(\frac{k+1}{2} \right)^{1/(k-1)} \left[\frac{(1-X)(k+1)}{k-1} \right]^{1/2} X^{1/(k-1)} \equiv q(X)$$

is a gas-dynamic function of the flow area; $Z(\lambda) = \lambda + 1/\lambda$.

The conditions that the jets combine and their pressures are equal have the form

$$P_{01}\pi(\lambda_1) = P_{02}\pi(\lambda_2) = P_{03}\pi(\lambda_3) \equiv P, \tag{3}$$

$$F_1 + F_2 + F_3 = \frac{F_{01}}{q(\lambda_1)} + \frac{F_{02}}{q(\lambda_2)} + \frac{F_{03}}{q(\lambda_3)} = F \tag{4}$$

and allow one to determine the parameters of the gas jets in the new nozzle unit.

Assuming that

$$X_1 \equiv 1 - \frac{(k_1 - 1)\lambda_1^2}{(k_1 + 1)} \tag{5}$$

and using expression (2), we express X_2 and X_3 in terms of X_1:

$$X_2 \equiv 1 - \frac{(k_2 - 1)\lambda_2^2}{k_2 + 1} = X_1^{j1}\left(\frac{P_{01}}{P_{02}}\right)^{(k_2-1)/k_2} \equiv X_2(X_1), \tag{6}$$

$$X_3 = X_1^{j2}\left(\frac{P_{01}}{P_{03}}\right)^{(k_3-1)/k_3} \equiv X_3(X_1), \tag{7}$$

where

$$j_1 = \frac{k_1(k_2 - 1)}{(k_1 - 1)k_2}; \quad j_2 = \frac{k_1(k_3 - 1)}{(k_1 - 1)k_3}.$$

Substitution of these values in Eqn (4) gives the equation for the determination of X_1:

$$F(X_1) \equiv \frac{F_{01}}{q(X_1)} + \frac{F_{02}}{q(X_2(X_1))} + \frac{F_{03}}{q(X_3(X_1))} - F = 0. \tag{8}$$

The solution X_1^* of this equation determines $X_2^* = (X_1^*)^{j_1} \times (P_{01}/P_{02})^{(k_2-1)/k_2}$, $X_3^* = (X_1^*)^{j_2}(P_{01}/P_{03})^{(k_3-1)/k_3}$, the jet velocity coefficients $\lambda_i = [(1 - X_i^*)(k_i + 1)/(k_i - 1)]^{1/2}$, the Mach numbers $M_i = \{2\lambda_i^2/[X_i^*(k_i + 1)]\}^{1/2}$, the static pressure $P = P_{01}(X_1^*)^{k_1/(k_1-1)}$, the static temperatures $T_1 = T_{0i}X_i^*$, and the total areas $F_i = F_{0i}/q_i(X_i^*)$ of the jets of the same type.

In combination with equations of conservation of mass, energy, and angular momentum, these data allow one to determine all the parameters of a fully mixed gas.

Let us introduce a new notation:

$$n_1 = \frac{G_3}{G_2}; \quad n = \frac{G_2}{G_1}; \tag{9}$$

$C_4 = (G_1C_1 + G_2C_2 + G_3C_3)/(G_1 + G_2 + G_3)$ is the heat capacity of the mixed gas; $C^{(14)} = C_4/C_1$; $C^{(12)} = C_2/C_1$; $C^{(13)} = C_3/C_1$; $t_2 = T_{02}/T_{01}$; $t_3 = T_{03}/T_{01}$;

$$m_4 = \frac{g_1m_1 + g_2m_2 + g_3m_3}{g_1 + g_2 + g_3} \tag{10}$$

is the molar mass of the mixture; and

$$k_4 = 1 + \frac{g_1 + g_2 + g_3}{g_1/(k_1 - 1) + g_2/(k_2 - 1) + g_3(k_3 - 1)} \tag{11}$$

is the adiabatic index of the mixture.

In this notation, the law of conservation of mass has the form:

$$G_4 = G_1[1 + n(1 + n_1)],$$

$$g_4 = \frac{1000G_4}{m_4} = \frac{1000G_1[1 + n(1 + n_1)]}{m_4}. \tag{12}$$

From the law of conservation of energy

$$\frac{G_1C_1T_{01} + G_2C_2T_{02} + G_3C_3T_{03}Q^*}{G_1C_1T_{01}} = \frac{G_4}{G_1}C^{(14)}\frac{T_{04}}{T_{01}}$$

$$= [1 + n(1 + n_1)]C^{(14)}\frac{T_{04}}{T_{01}} = 1 + n\left(t_2C^{(12)} + n_1t_3C^{(13)}\right) + Q$$

we obtain

$$T_{04} = \frac{T_{01}\left[1 + n(t_2C^{(12)} + n_1t_3C^{(13)}) + Q\right]}{1 + n(1 + n_1)C^{(14)}}, \tag{13}$$

and from the law of conservation of momentum

$$\frac{G_4A_4Z_4k_4}{k_4 - 1} = \frac{G_1A_1Z_1k_1}{k_1 - 1} + \frac{G_2A_2Z_2k_2}{k_2 - 1} + \frac{G_3A_3Z_3k_3}{k_3 - 1}$$

it follows that

$$Z_4 \equiv \left(\lambda_4 + \frac{1}{\lambda_4}\right)$$

$$= \frac{G_1A_1Z_1k_1/(k_1 - 1) + G_2A_2Z_2k_2/(k_2 - 1)}{G_4A_4k_4/(k_4 - 1)}$$

$$+ \frac{G_3A_3Z_3k_3/(k_3 - 1)}{G_4A_4k_4/(k_4 - 1)}, \tag{14}$$

or

$$\lambda_4^2 + Z_4\lambda_4 + 1 = 0.$$

The solution of Eqn (14) has two roots: one for a fully mixed supersonic flow ($\lambda_4 > 1$) and the other for the flow behind the front of a direct shock wave ($\lambda_5 = 1/\lambda_4 < 1$), where

$$\lambda_4 = \frac{Z_4}{2} + \left(\frac{Z_4^2}{4} - 1\right)^{1/2}; \tag{15}$$

$$\lambda_5 = \frac{Z_4}{2} - \left(\frac{Z_4^2}{4} - 1\right)^{1/2}. \tag{16}$$

By introducing the notation

$$X_4 \equiv 1 - \frac{(k_4 - 1)\lambda_4^2}{k_4 + 1},$$

we obtain

$$T_4 = T_{04}X_4, \tag{17}$$

$$q_4(X_4) \equiv \left(\frac{k_4 + 1}{2}\right)^{1/(k_4-1)}\left[\frac{(1 - X_4)(k_4 + 1)}{k_4 - 1}\right]^{1/2}X_4^{1/(k_4-1)},$$

$$X_5 \equiv 1 - \frac{(k_4 - 1)\lambda_5^2}{k_4 + 1},$$

$$q_5(X_5) \equiv \left(\frac{k_4 + 1}{2}\right)^{1/(k_4-1)}\left[\frac{(1 - X_5)(k_4 + 1)}{k_4 - 1}\right]^{1/2}X_5^{1/(k_4-1)}.$$

To determine the stagnation pressure, the gas flow rate

should be expressed in terms of the gas-dynamic functions $q_i(X_i)$:

$$G_4 = 1333\left[\left(\frac{k_4 m_4}{RT_{04}}\right)\left(\frac{2}{k_4+1}\right)^{(k_4+1)/(k_4-1)}\right]^{1/2} P_{04} F q_4(X_4),$$

where

$$P_{04} = \frac{G_4}{1333 F q_4(X_4)}\left[\left(\frac{k_4 m_4}{RT_{04}}\right)\left(\frac{2}{k_4+1}\right)^{(k_4+1)/(k_4-1)}\right]^{-1/2}, \tag{18}$$

$$P_4 = P_{04} X_4^{k_4(k_4-1)}. \tag{19}$$

In this case, the gas stagnation pressure behind the direct pressure shock is determined from the expression

$$P_{05} = \frac{P_{04} q_5(X_5)}{q_4(X_4)}, \tag{20}$$

while the Mach numbers and the velocity coefficients are related by the well-known expression

$$M_{4,5} = \lambda_{4,5}\left[\frac{2}{X_{4,5}(k_4+1)}\right]^{1/2}. \tag{21}$$

Expressions (1)–(12) provide the solution of the problem in hand.

3. Calculation of a specific nozzle unit

Numerical simulation allows one to estimate the effect of various factors on the pressure recover. A nozzle unit 15 mm in height and 50 mm in length, whose fragment is shown in Fig. 1, was used in experiments with an oxygen–iodine laser and allowed attaining a pressure of over 100 Torr in the Pitot tube for an output laser power of 700 W and a chemical efficiency of 19.7 % [15]. The nozzle array for the injection of high-pressure nitrogen consisted of 56 cylindrical openings 1 mm in diameter (eight rows, seven openings in a row, a total area $F_{01} = 0.44$ cm^2). Oxygen was injected through seven 2.5-mm wide slits with an overall area $F_{02} = 2.625$ cm^2 and the iodine vapour with nitrogen – through 210 cylindrical openings with diameters of 0.5 mm and $F_{03} = 0.41$ cm^2.

The initial cross section of the mixing chamber was 7.5 cm^2. To compensate for the growing boundary layers at the walls, the channel expanded with the help of wide walls located at an angle of 2°. At the outlet, the chamber height was 18 mm and its area was 9 cm^2. The actual cross sectional area of the mixing chamber, taking into account the boundary displacement layer, is unknown and necessitates refinement.

In 'cold' test runs of the nozzle unit, a similar mixing chamber with closed sidewalls was used instead of a resonator chamber with tunnels for mirrors to achieve a more correct comparison. In experiments, pure nitrogen was injected through the iodine nozzles and air was injected instead of oxygen. The following gas parameters were obtained: $g_1 = 515$ mmol s^{-1}, $g_2 = 39.2$ mmol s^{-1}, $g_3 = 11$ mmol s^{-1}, $T_{01} = T_{02} = 290$ K, $T_{03} = 335$ K, $k_i = 1.4$, $P_4 = 9$ Torr, $P_{05} = 79.2$ Torr, and $M_4 = 2.55$.

Although the geometrical parameters of the nozzles are known, the presence of boundary layers in them reduces the areas of the outlet cross sections by an unknown value. For this reason, to compare calculations with the result of experiments for the same gas mass flow rates, corrections should be introduced into the areas of oxygen and nitrogen nozzles. The iodine nozzles are openings in nickel tubes with a wall thickness of 0.1 mm and are not 'encumbered' with boundary layers.

For the stagnation pressures measured, a correction of this type gives $F_{01} = 0.38$ cm^2, $F_{02} = 1.65$ cm^2. The results of calculations for a fully mixed gas with accounting for the heat release upon condensation of water vapour in the air jets (the partial pressure of the water vapour was assumed to be equal to 2 % of the air pressure) depend on the acting cross section of the mixing chamber (upon subtraction of the boundary layer area).

Since the expansion angle of the channel was not specially selected to exactly compensate for the boundary layers, the calculations were performed for several cross sections of the chamber. Of course, such a procedure is not quite correct, since it replaces the action exerted on the flow by the sidewalls with a boundary layer and an unknown pressure distribution along the walls. The results of calculations are given in Table 1. One can see that they disagree with experimental results.

Table 1.

F/cm^2	P_4/Torr	P_{04}/Torr	P_{05}/Torr	M_4	T_4/K
7.5	5.71	534	100.3	3.65	80
8.0	5.17	535	94.5	3.72	78
8.5	4.71	536.9	89.3	3.79	76
9.0	4.32	537.7	84.6	3.85	74

We assumed that upon the formation of an ensemble of free jets in the space between the tubes for the injection of iodine vapour (see Fig. 1), shock waves are produced, which are responsible for the formation of a direct shock and a subsonic flow. In this case, the critical section for the ejected gas are not 56 cylindrical openings, but the slits between the tubes (the overall area of the slits is $F_{01}^* = 1.2$ cm^2). The stagnation pressure P_{01}^* in the space between the tubes is determined from the conservation condition for the gas flow rate: $F_{01}P_{01} = F_{01}^* P_{01}^*$, or $P_{01}^* = P_{01}F_{01}/F_{01}^*$. Assuming that $F_{01}^* \approx 1.2$ cm^2 and $P_{01} = 1220$ Torr, we find the gas stagnation pressure in the space between the tubes $P_{01}^* = 386.25$ Torr. The results of calculations in this case are given in Table 2.

Table 2.

F/cm^2	P_4/Torr	P_{04}/Torr	P_{05}/Torr	M_4	T_4/K
7.5	8.96	233.3	92.9	2.77	116
8.0	8.06 (14.65)	235 (121.5)	87.8 (85.5)	2.85 (2.04)	112 (188)
8.5	7.3	235	83.2	2.91	109
9.0	6.76	236	79.36	2.96	107

One can see that the results of calculations of the gas parameters for the effective channel area $F = 7.5 - 8.5$ cm^2 do not differ quite strongly from those obtained experimentally and that the total pressure loss in the space between the tubes for the injection of iodine vapour lowers only slightly the pressure P_{05} in the Pitot tube (by about 7 %–8 %).

This model allows one to elucidate several important questions, such as how the recovered pressure is influenced by the molecular weight and the adiabatic index of the ejecting gas, and also by the heat release in the mixing chamber upon addition of the iodine vapour. In particular, Table 2 presents in parentheses the gas parameters in the case of a heat release corresponding to a 22.5 % relaxation of singlet oxygen. One can easily see that the gas heating only slightly affects the pressure P_{05}, because it does not alter the momentum of the gas flow. Table 3 illustrates the role of the molecular weight and the adiabatic index of the ejecting gas for the same molecular flow rate equal to 515 mmol s^{-1}.

Table 3. ($F = 8$ cm^2, $F_{01}^* = 1.2$ cm^2)

Gas	P_4/Torr	P_{04}/Torr	P_{05}/Torr	M_4	T_4/K
He	4.85	50.8	35.16	2.17	118
Air	8.06	235	87.8	2.85	112
Ar	7.03	220	92.8	2.97	77
CO_2 ($k = 1.35$)	10.25	327	112	2.89	118
Xe	13.8	270	142.9	2.62	93

To maximise the recovered pressure, one should use heavier gases. To attain a deeper cooling of the medium, gases with the highest adiabatic index should be used.

4. Conclusions

A technique for calculating the mixing chamber of an ejector chemical oxygen–iodine laser is outlined, which involves injection of gas mixtures with critical pressure drops in the nozzle array consisting of nozzles of three types. Simple one-dimensional calculations provide a reasonably good agreement between the parameters of a fully mixed gas and parameters realised in experiments and allow one to make preliminary estimates of the expected flow parameters using different ejected gases. The ejector technique for preparing the active medium of a laser allows one to obtain the recovered pressures that far exceed the oxygen pressure in the generator and to simplify the system for the ejection of the exhaust active medium in the atmosphere.

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