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Efficient chemical oxygen – iodine laser with a high total pressure of the active medium

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***Abstract*. A new concept of obtaining a high total pressure of the active medium of a chemical oxygen – iodine laser (OIL) is proposed and verified. The nozzle unit of the laser consists of the alternating vertical arrays of cylindrical nozzles to produce high-pressure nitrogen jets, plane slotted nozzles for the flow of $O_2(^1\Delta)$ oxygen, and vertical arrays of cylindrical nozzles to inject the $N_2 - I_2$ mixture between the first two streams. For a molar chlorine flow rate of 39.2 mmol s^{-1}, the output power was 700 W and the chemical efficiency was 19.7 %. The combined use of the ejector nozzle unit proposed to obtain the active medium and a super-sonic diffuser allows a significant simplification of the exhaust active medium system of the OIL.**

***Keywords*:** *oxygen – iodine laser, singlet oxygen, supersonic flow, ejector.*

1. Introduction

Increasing the gas-flow stagnation pressure in the resonators of gas-dynamic or chemical lasers is important for the efficient ejection of the exhaust laser gas to the atmosphere [1]. The increase in pressure should not be accompanied by the appreciable reduction in the output power and the efficiency of the laser system. This problem is especially important for an oxygen – iodine laser (OIL) because of a relatively low pressure in the generator of singlet oxygen (GSO).

The total pressure in the OIL was raised to 100 Torr upon a strong dilution of oxygen by helium (1:6) in a Verti-COIL laser operated with a disk generator of $O_2(^1\Delta)$ [2]. However, the high gas density in the GSO reaction zone causes the removal of a large amount of the solution aerosol and thereby prevents the attainment of a high total pressure.

The new way to prepare the high-pressure active medium was proposed in Refs [3, 4]. The nozzle unit consists of conic nozzles for the $N_2 - I_2$ mixture flow and slotted or cylindrical nozzles for the $O_2(^1\Delta)$ flow. The conic nozzles produce a supersonic $N_2 - I_2$ flow and the oxygen nozzles form the flow of oxygen with a sound velocity and a pressure of about 10 Torr. However, this scheme is inherently inconsistent.

Indeed, to obtain a high total pressure at a static pressure of ~ 10 Torr, the $N_2 - I_2$ flow with a high supersonic velocity should be generated. The gas-dynamic lowering of the $N_2 - I_2$ flow temperature results in the condensation of molecular iodine in the nozzles. This drawback may be remedied in the nozzle unit which generates the flow of pure N_2 with a high expansion ratio and the $N_2 - I_2$ flow with a low expansion ratio.

Therefore, the new nozzle unit incorporates the nozzles of three types intended respectively for a high-pressure flow of pure nitrogen and low-pressure flows of $O_2(^1\Delta)$ and an $N_2 - I_2$ mixture. This nozzle unit operates on the principle of a gas ejector in which the low-pressure $O_2(^1\Delta)$ and $N_2 - I_2$ flows are mixed with the high-pressure nitrogen flow.

The aim of this work was to demonstrate the operating capacity of the new nozzle unit for an OIL.

2. Description of the OIL with a novel nozzle unit

The schematic diagram of the OIL with an ejector nozzle unit is given in Fig. 1. The OIL consisted of a jet GSO, a nozzle unit, a mixing chamber, and an optical resonator.

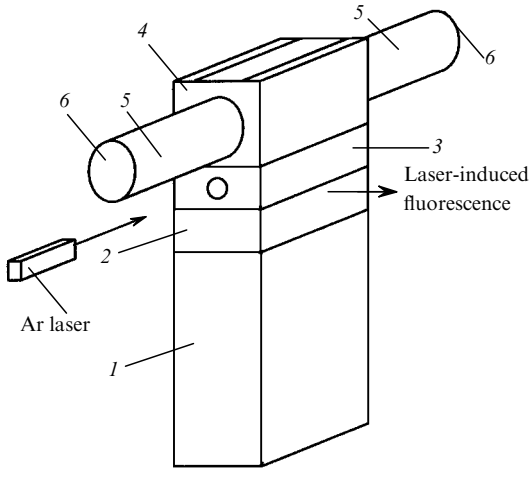

Figure 1. OIL schematic:
(*1*) jet generator of singlet oxygen; (*2*) nozzle unit; (*3*) mixing chamber; (*4*) active region of the resonator; (*5*) tunnels; (*6*) optical resonator mirrors.

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The jet GSO of the vertical type was described in detail elsewhere [5]. The initial transverse dimension of the mixing chamber was 50 mm along the optical axis and 15 mm in height; the angle between the flow axis and the walls of the mixing chamber was 2°. The gas flow from the mixing chamber entered the active region of the OIL resonator.

The optical resonator was formed by two mirrors with a radius of curvature of 5 m spaced at 63 cm. The length of the active part of the resonator along the flow was 45 mm. To prevent the condensation of iodine vapour on the mirrors and to force out the stagnation regions from the tunnels, a nitrogen flow was applied outward the mirrors. The mixing chamber and the optical resonator were made of Plexiglas to allow a visual observation of the mixing range of the gas flows.

A segment of the ejector nozzle unit is shown in Fig. 2. Oxygen flowed into the mixing chamber through seven plane slits 15 mm long and 2.5 mm wide located in the nozzle unit and evenly spaced at 6.5 mm. The high-pressure (primary) nitrogen flowed into the mixing chamber through 56 cylindrical channels one millimetre in diameter arranged in eight rows. The mixture of the secondary nitrogen with iodine vapour heated to 70°C was injected into the mixing chamber through 240 holes 0.5 mm in diameter drilled in 14 thin-walled nickel tubes, which were located between the oxygen and nitrogen nozzles. The gas jets from each of the nozzle arrays expanded freely and mixed together in the mixing chamber. This nozzle array operates on the principle of a supersonic gas ejector [6] wherein the pressure in the mixing chamber may far exceed the total pressure in the GSO.

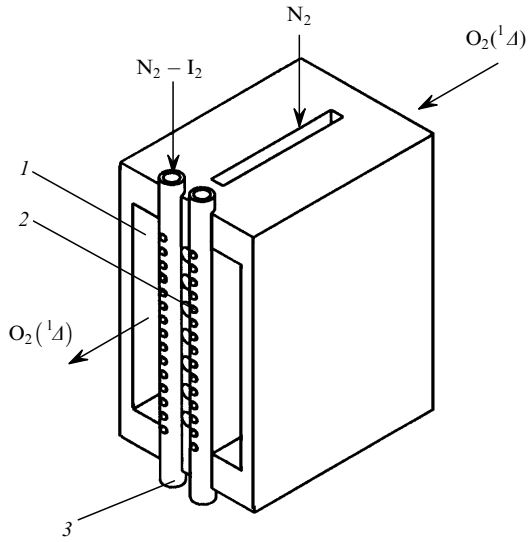

Figure 2. Segment of the ejector nozzle unit:
(*1*) slits for oxygen, (*2*) cylindrical holes for the primary nitrogen, (*3*) perforated tubes for the $N_2 - I_2$ mixture.

The active medium was pumped out with a mechanical AVZ-125 pump. A tank with a volume of 4 m^3 pre-evacuated to a pressure of less than 1 Torr was opened to achieve a higher gas-mixture flow rate for a short time. The pressure p_1 in the GSO, the pressure p_2 in front of the oxygen nozzles, in the resonator p_3, and in the total-pressure tube p_4 were measured during the laser action. The opening for measuring the pressure p_3 was located below the optical axis at the geometrical centre of the active region of the resonator. The imlet of the total-pressure tube was located at the centre of the outlet of the resonator and at 2.25 cm from the optical axis. The Mach number M of the flow in the resonator was estimated from the relationship $p_4/p_3 = 166.7M^7/\left(7M^2-1\right)^{2.5}$ and the total pressure p^* of the gas flow in the resonator from the relationship $p^* = \left(1 + 0.2M^2\right)^{3.5} p_3$ [6]. It was assumed that the total output laser power was $W = W_1(T_1 + T_2)/T_1$ and the chemical efficiency of the laser was $\eta_c = W/(M_{Cl} \times 90.4\ \text{J mmol}^{-1})$, where W_1 is the measured power of the radiation passing through the mirror with a higher transmittance T_1, T_2 is the transmittance of the second mirror, and M_{Cl} is the chlorine flow rate (in mmol s^{-1}).

3. Preliminary gas-dynamic tests of the nozzle unit

The initial tests of the ejector nozzle unit for the OIL involved determining the parameters of the gas flow in the resonator region when rare gases were admitted with nominal flow rates. The 'cold' tests were accomplished through the GSO at a room-air flow rate of 40 mmol s^{-1} (without admission of the alkaline solution of hydrogen peroxide) and a distance between the cut of the nozzle unit and the optical axis of 64 mm. For zero flow rates of primary and secondary nitrogen ($M_{NP} = 0, M_{NS} = 0$), the pressure in front of the oxygen nozzles was $p_2 = 17$ Torr. For $M_{NP} = 500$ mmol s^{-1} and $M_{NS} = 0$, the pressure p_2 increased to 27 Torr. Simultaneously, the pressures $p_3 = 8$ Torr and $p_4 = 87$ Torr were recorded. In this case, the pressure of the primary nitrogen in front of the nozzles was about 1.9 bar.

The free expansion of nitrogen jets with a high initial pressure is accompanied by their acceleration to supersonic velocities. The fall of the nitrogen pressure from 1.9 bar to 8 Torr in the region of expansion of the nitrogen jets is accompanied by the appearance of strong shock waves and a decrease in the total pressure. By increasing the flow rate of the secondary nitrogen to 11 mmol s^{-1}, we obtained pressures $p_3 = 9.3$ Torr and $p_4 = 92$ Torr; which gives $M = 2.7$. The above gas dynamic parameters are realised due to the mixing and the interaction of all the three flows. These data allow an estimate of the absolute flow velocity in the mixing chamber as $U \approx 600$ m s^{-1}. An additional admission of nitrogen with a flow rate of 15 mmol s^{-1} through each of the tunnels for mirrors caused p_3 to rise to 10.4 Torr and p_4 to 111 Torr. The increase in p_2 from 17 to 27 Torr is explained by the choking of the air flow through the oxygen nozzles by the expanding supersonic jets of the primary nitrogen. The critical cross section for the air flow from the oxygen sleets is realised at some distance from the nozzles, and its cross section is smaller than the geometrical cross section of the slits for the oxygen.

Therefore, the velocity of the oxygen flow in the mixing chamber will be equal to the 'local' sound velocity some distance downstream the nozzle unit. The rise of the static pressure p_3 and the recovered pressure p_4 during the admission of nitrogen through the tunnels for mirrors is explained by the appearance of a sequence of weak oblique compression shocks in the main supersonic flow. The 'cold' tests described above demonstrated the feasibility of form-

ing a high-pressure flow in the resonator region with the aid of an ejector nozzle unit with a simple nozzle geometry.

4. Estimate of the flux mixing efficiency

The second stage of the investigation of the gas flow formed by the ejector nozzle unit was a qualitative observation of the efficiency of mixing of the three flows in the mixing chamber. The challenge was to determine the distance to the nozzle unit at which a relatively uniform distribution of the iodine concentration is formed along the optical axis. We observed this distribution in the mixing chamber by the method of laser-induced fluorescence (LIF).

The distribution of the molecular iodine is visualised in this method from the yellow emission of the iodine molecules which were excited to the $B\,^3\Pi$ state by a 5145-Å argon laser [7].

The visualisation was accomplished in a tailor-made mixing chamber equipped with windows to inject the argon laser radiation and record the LIF in the direction perpendicular to the flow axis and to the argon laser beam (see Fig. 1). The argon laser radiation beam 3 mm in diameter was directed perpendicular to the flow midway between the walls of the mixing chamber. The LIF was recorded with a Kodak photographic film through an optical filter rejecting the scattered radiation of the argon laser. The distribution pattern of molecular iodine was recorded under conditions close to laser experimental conditions.

In these experiments, the flow of singlet oxygen $O_2(^1\Delta)$ from the GSO was replaced with a nitrogen flow. The rates of primary- and secondary-nitrogen flow through the oxygen nozzles were varied in the 200–400 and 20–40 mmol s^{-1}ranges, respectively. Under these conditions, the Mach number of the flow varied from 1.7 to 2 and the pressure p_3 from 10 to 20 Torr. The lower Mach numbers and the higher static pressures p_3 are explained by the stronger effect of boundary layers in the channel with a constant cross section.

At a distance of 50–60 mm from the nozzle unit, the LIF intensity distribution observed visually under the above-specified conditions was virtually uniform along the optical axis. The LIF pattern for specific conditions (M_{NP} = 400 mmol s^{-1}, M_{NS} = 40 mmol s^{-1}, nitrogen flow through the oxygen nozzles at a rate of 40 mmol s^{-1}) is given in Fig. 3. Therefore, for the given nozzle unit, the concentration of molecular iodine is rather uniformly distributed along the optical axis in the region located at a distance of 50 – 60 mm from the source (i.e., in a time $\sim 10^{-4}$ s).

This suggests that the iodine component of the flow in laser experiments will also mix at the same distance from the nozzle unit. Because the iodine vapour injection takes place in the region between the jets of primary nitrogen and $O_2(^1\Delta)$, one may expect a rapid turbulent mixing of the three flows issuing from the nozzle unit. The high flow-mixing rate is explained by the presence of large initial tangential discontinuities in the gas-dynamic parameters of the mixed flows.

5. Laser experiments with the ejector nozzle unit

Despite the attainment of high Mach numbers in the mixing chamber and the rapid mixing of the flows, the question of the dissociation efficiency of molecular iodine and of the efficiency of conversion of the energy stored in $O_2(^1\Delta)$ to

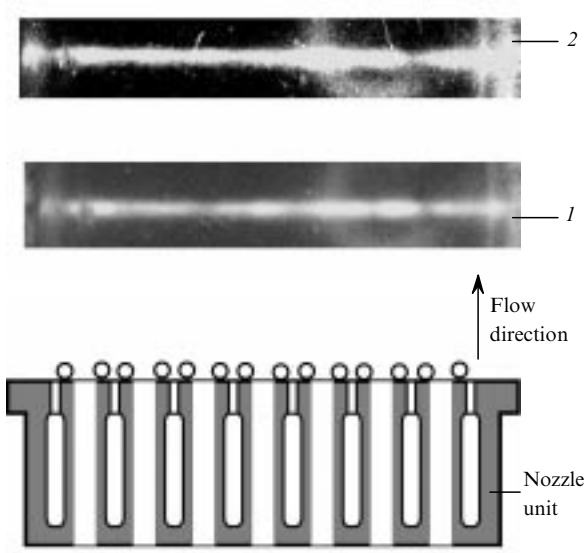

Figure 3. LIF pattern in the mixing chamber at distances of 37 (*1*) and 62 mm (*2*) from the nozzle unit.

radiation is still an open question. The strong gas-dynamic mixture cooling may indeed result in a premature condensation of iodine molecules and the rapid mixing may cause a lowering of local concentrations of $O_2(^1\Delta)$ and I_2 and of the I_2 dissociation rate. All these may result in a low gain coefficient and a low laser efficiency. The answers to these questions were to be provided by direct laser experiments.

The laser experiments with the ejector nozzle unit were conducted under the following conditions: the chlorine flow through the GSO at a rate of 39.2 mmol s^{-1}, the flow rate of primary nitrogen of 400 mmol s^{-1}, the flow rate of secondary nitrogen of 40 mmol s^{-1}, and the nitrogen flow through each of the mirror-harbouring tunnels at a rate of 20 mmol s^{-1}. The initial distance between the nozzle unit and the optical axis was 89 mm. For a zero iodine flow rate ($M_I = 0$), $p_2 = 28.5$ Torr, $p_3 = 7.8$ Torr, and $p_4 = 97$ Torr. With an increase in iodine flow rate and intensification of the chemical processes in the active medium, the pressure p_3 increased and p_4 decreased.

The peak output power was attained for an iodine flow rate $M_I \sim 0.68$ mmol s^{-1}. For the mirrors with transmittances $T_1 = 0.94\,\%$ and $T_2 = 0$, it was 603 W, which corresponds to a chemical efficiency $\eta_c = 17\,\%$. In this case, the pressure p_3 increased to 11.9 Torr and the pressure p_4 dropped to 81 Torr. The difference between these pressures and those obtained for a zero iodine flow rate is supposedly related to the heat release in the gas flow.

We conducted simultaneously the video recording of luminescence in the mixing region. We found that the bright yellow luminescence of iodine molecules disappeared at a distance of 50–60 mm from the nozzle unit. The luminescence of iodine molecules in the region of its intense dissociation to atoms caused by excitation of molecular iodine to the $B\,^3\Pi$ state in collisions with $O_2(^1\Delta), O_2(^1\Sigma)$, and $I(^2P_{1/2})$ iodine atoms [8] characterises the activity of this process. Therefore, the active dissociation of molecular iodine under the above conditions takes place within the same distance as does the mixing of the $O_2(^1\Delta)$ and $N_2 - I_2$ flows.

In this connection the separation of the nozzle array from the optical axis was set at 64 mm. Lower $O_2(^1\Delta)$ losses

Table 1. Results of the test runs of a supersonic OIL with an ejector nozzle array.

Test run No.	p_2/Torr	p_3/Torr	p_4/Torr	M	p^*/Torr	M_I/mmol s^{-1}	T_1 (%)	T_2 (%)	W/ W	η_c (%)
1	32.8	9.47	98.3	2.9	300	0	0	0	0	0
2	32.4	10.7	102	2.62	214	0.54	0.94	0.18	604	17.0
3	32.4	10.9	102	2.62	227	0.65	0.94	0.18	660	18.6
4	32.6	11	101	2.6	220	0.68	0.94	0.18	673	18.9
5	33	11.2	101	2.57	211	0.73	0.94	0.18	643	18.1
6	32.5	10.9	100	2.6	218	0.74	0.94	0.18	700	19.7
7	32.5	11.3	100	2.55	210	0.85	0.94	0.18	657	18.5
8	32.9	11.4	100	2.5	200	0.74	0.94	0	598	16.8
9	33	11.3	102	2.55	205	0.76	1	0	618	17.4
10	32.5	11.4	101	2.5	200	0.75	1.3	0	563	15.8
11	32.7	11.4	102	2.55	207	0.75	1.7	0	565	15.9
12	33	11.4	102	2.55	207	0.77	1.7	0.94	489	13.7
13	33	11.3	103	2.55	205	0.77	1.7	1.3	405	11.4
14	32.9	11.1	101	2.55	204	0.76	1.7	1.7	0	0

upon its quenching and lower losses of atomic iodine upon its condensation were anticipated to occur at this distance. The results of experiments are collected in Table 1. A maximum output power of 700 W for a chemical efficiency of 19.7 % was attained in the test run No. 6. It is somewhat lower than the maximum output of 798 W of the chemical laser with a slit nozzle for the same chlorine flow rate through a similar GSO [5] and a dilution of the active medium with room-temperature nitrogen.

6. Discussion of the results

A new technique of preparing the active medium of a chemical OIL with a high total pressure has been proposed, elaborated and tested. The nozzle unit which realises this technique comprises nozzles of three types. The slit nozzles are intended to obtain the flow of $O_2(^1\Delta)$ with a Mach number $M \sim 1$, the cylindrical nozzles serve to generate a high-pressure nitrogen flow, and the small-dimension nozzles located in between are employed to inject the $N_2 - I_2$ flow with a relatively low Mach number. Preliminary 'cold' test runs are demonstration that this ejector nozzle unit with a simple nozzle geometry makes it possible to produce a supersonic active medium in which the total pressure far exceeds the oxygen pressure in the GSO. The observations of the LIF of molecular iodine and its luminescence in the presence of $O_2(^1\Delta)$ showed that the complete mixing of the flows and the termination of iodine dissociation occur virtually simultaneously at a distance of 50–60 mm from the nozzle unit for a gas velocity of ~ 600 m s^{-1}.

The qualitative picture of physicochemical processes at the origin of the mixing zone is supposedly as follows. The $O_2(^1\Delta)$ jet flows from the slits into the mixing chamber for a pressure higher than the critical one, which is approximately equal to $p_2/2 \approx 15$ Torr. In this case, it comes in contact with the $N_2 - I_2$ mixture immediately. The expanding jet of high-pressure primary nitrogen deflects the $N_2 - I_2$ jets toward the oxygen flow and compresses them.

The local iodine vapour density in the unmixed $N_2 - I_2$ flow is $[I_2]_0 \approx [I_2]_1(M_{NS} + M_{NP} + M_{Cl})/M_{NS}$ (where $[I_2]_1$ is the iodine density in the totally mixed flow). Since $(M_{NS} + M_{NP} + M_{Cl})/M_{NS} \approx 10 \gg 1$, the molecular iodine density at the origin of the mixing zone of the $N_2 - I_2$ and oxygen flows is well above its average density. In the region where these two flows come in contact with each other, there occurs a rapid dissociation of molecular iodine. Owing to strong tangential discontinuities of the gas-dynamic parameters, there occurs a turbulent mixing of the three flows and their gas-dynamic cooling due to the high-pressure nitrogen flow.

It is likely that the dissociation of iodine follows the course of mixing under the situation produced, i. e., the dissociation moderates as the flows mix and the local densities of iodine and oxygen lower. In a totally mixed flux, the dissociation of iodine is virtually terminated in a time it takes the mixture to traverse the resonator. It is evident that an incomplete dissociation of molecular iodine should be expected under these conditions. The optimisation of this process invites further investigation.

A maximum output power of 700 W and a chemical efficiency of 19.7 % were attained in an OIL with an ejector nozzle unit and a 5-cm long active region in the resonator. In this case, in the resonator was 10.9 Torr and the pressure at the resonator outlet was 100 Torr. For the above pressures, the flow Mach number in the resonator was $M = 2.6$. The total pressure of the flow in the resonator calculated from these data is $p^* = 218$ Torr. Conceivably this calculation may slightly overestimate the values of M and p^* because the question of how much the nitrogen flow from the resonator tunnels affects the structure of the main flow remains an open question.

The use of the ejector nozzle unit to obtain the active medium in combination with the installation of the supersonic diffuser allows a significant simplification of the exhaust active medium system of the OIL. The high degree of dilution of the active medium with nitrogen (1:11) and the low relative heat release favour the operation of the supersonic diffuser.

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