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Scalable chemical oxygen – iodine laser

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Abstract. **The problem of scaling chemical oxygen – iodine lasers (COILs) is discussed. The results of experimental study of a twisted-aerosol singlet oxygen generator meeting the COIL scalability requirements are presented. The energy characteristics of a supersonic COIL with singlet oxygen and iodine mixing in parallel flows are also experimentally studied. The output power of ~7.5 kW, corresponding to a specific power of 230 W cm^{-2}, is achieved. The maximum chemical efficiency of the COIL is ~30 %.**

Keywords: *chemical oxygen – iodine laser (COIL), scaling, twisted-aerosol singlet oxygen generator, laser power, chemical efficiency.*

1. Introduction

To develop a highly efficient industrial chemical oxygen – iodine laser (COIL) based on small-scale laboratory setups, one needs scalable research models allowing one to develop lasers with higher output power without reducing the specific characteristics and efficiency. One of the problems in increasing the scale of devices is the requirement of a high gas velocity in the singlet oxygen generator (SOG).

In the present paper, we discuss the problem of scaling of COILs and present the results of experimental studies of a twisted-aerosol SOG (TA SOG) and a laser model that we used to create a COIL with an average output power of 50 kW [1].

2. On scaling of COILs

The simplest way to fabricate a COIL with a high output power is to design modules that can be composed in one cavity to achieve a required power. Figure 1 presents the schemes of gas flows in supersonic COILs, which, to a first approximation, determine the possibility of scaling by using modules.

If the admissible gas velocity in a SOG is smaller than at the nozzle inlet, then, for gas flow rate matching, the SOG must have a larger cross section area than the nozzle inlet. This situation, which is typical, for example, for droplet and jet SOGs [2, 3], is illustrated in Fig. 1a. An increase in the scale of a device leads to an increase in the losses of oxygen during its transportation and to a larger difference between the lengths of the central and peripheral trajectories of gas particles. In this case, the relaxation of the nonequilibrium flow creates inhomogeneities in the available energy density, as well as in the gain coefficient and temperature. This results in a lower laser efficiency. This is especially pronounced when the pressure in the flow increases, which is desirable because the COIL output power in this case can be increased without changing its dimensions and the gas exhaust can be designed simpler.

Figure 1b shows a scheme of flows in a supersonic COIL that is ideal for scaling and is characterised by equivalent gas velocities in the SOG and at the entrance to the subsonic part of the nozzle. In this case, the trajectories of all gas particles have the same lengths. Under these conditions, we can be sure that an increase in the laser scale does not worsen the specific energy characteristics and efficiency and can even improve them due to a higher efficiency of the cavity with a longer gain length.

What gas velocity in a SOG allows one to realise this scheme of flows? To minimise losses in the total pressure in a gas path, the nozzle Mach number M at which the supersonic flow is stable must be minimal. Based on this, the Mach number is, as a rule, chosen to be $M \approx 2-3$ [4, 5]. In this case, the flow velocity at the entrance to the nozzle array ranges from 50 to 120 m s^{-1}. Almost for all known SOGs [6], this gas velocity in the reaction zone cannot be achieved due to injection of the solution into the laser volume, and, hence, the maximum gas velocity in SOGs in laser experiments usually does not exceed 20 m s^{-1}. Today, the only one SOG in which the gas velocity in the reaction zone can exceed 50 m s^{-1} is the TA SOG developed previously in the Russian Federal Nuclear Centre – All-Russian Research Institute of Experimental Physics (RFNC – VNIIEF) [7].

Below, we present the results of experiments with a COIL model designed based on a TA SOG according to the scheme shown in Fig. 1c, which is maximally close to the ideal scheme of Fig. 1b. Under these conditions, the specific energy characteristics obtained with a kilowatt-power COIL model can be completely transferred to larger-scale devices, which was proved by creating a modular system with an average output power of 50 kW [1]. As was expected, the efficiency of this laser increased due to a higher efficiency of the cavity with a longer gain length and a larger dimension along the flow.

3. Twisted-aerosol singlet-oxygen generator

In experiment, we used a SOG called in the literature 'twisted-aerosol singlet-oxygen generator' (TA SOG) [8]. Previously, we demonstrated a TA SOG model ensuring stable highly efficient

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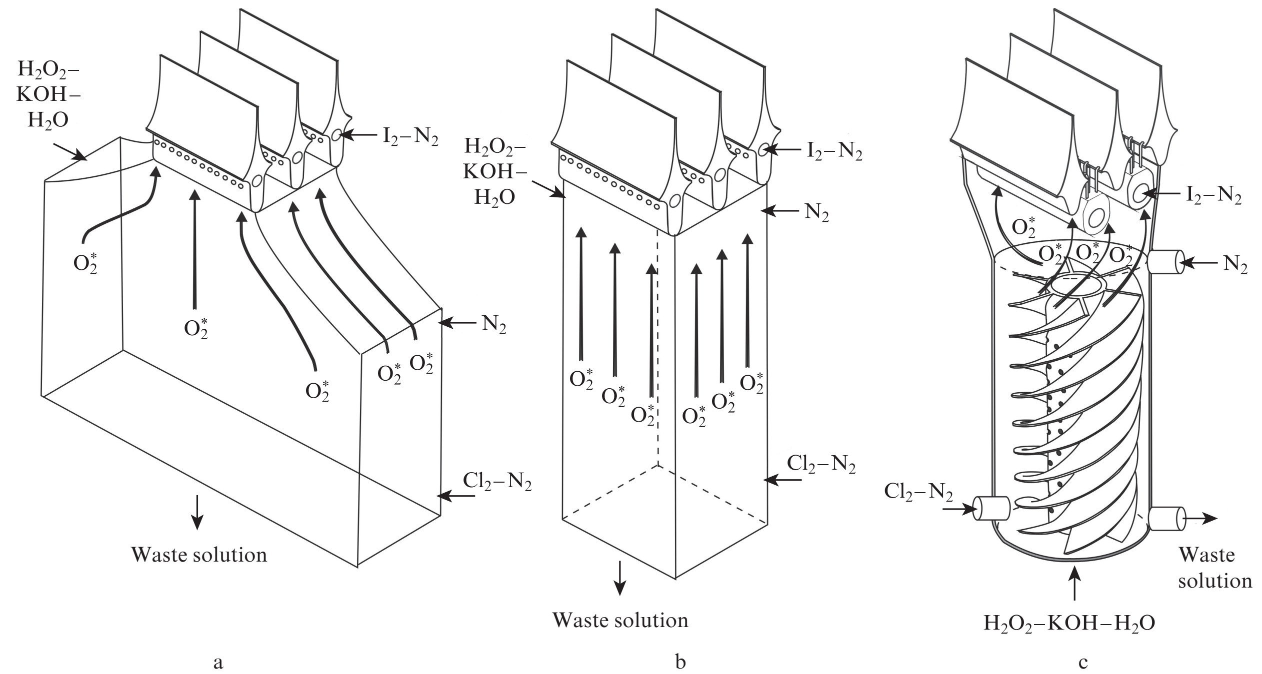

Figure 1. Possible schemes of gas flows in supersonic COILs with low (a) and high (b) gas velocities in the SOG, as well as with the use of a TA SOG (c).

operation and an aerosol-free outflow with a velocity exceeding 100 m s^{-1} [7]. The new more efficient TA SOG model used in the present work is distinguished by an increased (from 51 to 76 mm) diameter of the reaction zone. The area of the reactor cross section in the plane perpendicular to the gas velocity vector is 17.8 cm^2.

The experiments were performed according to the standard scheme [7], in which chlorine was mixed with nitrogen approximately in the proportion 1:2 before entering the SOG and the gas velocity in the reaction zone was controlled by changing the area of the critical cross section of the nozzle at the SOG exit (12, 15, and 18 cm^2). We used an alkaline solution of 35% hydrogen peroxide with the alkali concentration [KOH] = 5 mol L^{-1} and a flow rate of ~1.2 L s^{-1}. Changing the area of the exit nozzle cross section and mixing the second buffer gas (nitrogen) into the flow entering the nozzle, we were able to change the gas velocity in the TA SOG from 30 to 100 m s^{-1} and even higher.

The flow rates of chlorine and buffer gases were determined by a conventional method from the pressures measured at the outlet orifices with known cross sections. The concentration of singlet oxygen (SO) $O_2(a^1\Delta)$ was determined using a photometric method based on measuring the intensity of spontaneous IR emission of oxygen at the wavelength $\lambda = 1270$ nm. The photodetector was calibrated by a method similar to the method described in [9]. The chlorine utilisation at the TA SOG exit measured by the absorption at $\lambda = 365$ nm in a special cell with an error of ~20% was 84%–88%.

Figures 2 and 3 show some experimentally measured characteristics of the new TA SOG model. The observed increase in the yield of singlet oxygen (at the same chlorine flow rates) with increasing gas velocities is related to smaller relaxation

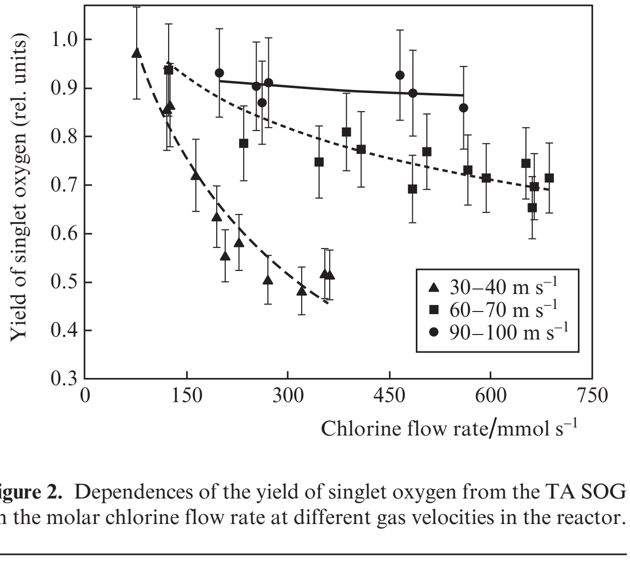

Figure 2. Dependences of the yield of singlet oxygen from the TA SOG on the molar chlorine flow rate at different gas velocities in the reactor.

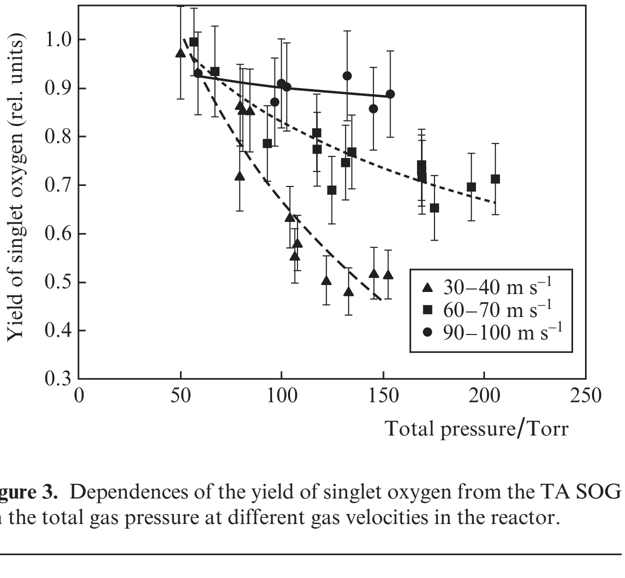

Figure 3. Dependences of the yield of singlet oxygen from the TA SOG on the total gas pressure at different gas velocities in the reactor.

losses during its transport. All the data are presented for regimes acceptable for laser experiments, when the SOG output is aerosol-free.

Our experiments demonstrated a stable operation of the TA SOG at a chlorine flow rate up to 680 mmol s^{-1}, a gas pressure up to 200 Torr, and a gas velocity up to 100 m s^{-1}. Owing to the high velocity and density of the gas in the TA SOG, the specific productivity exceeded 20 mmol s^{-1} cm^{-2} of singlet oxygen with its yield of $\sim$70% (or 38 mmol s^{-1} cm^{-2} of chlorine). No one of the known SOG in the world has similar characteristics [6].

4. Experimental study of the energy characteristics of a COIL with the TA SOG

The energy characteristics of a supersonic COIL with the new TA SOG module were studied at the test setup whose photograph made during the experiment is given in Fig. 4. The laser design is described in our previous papers [10, 11].

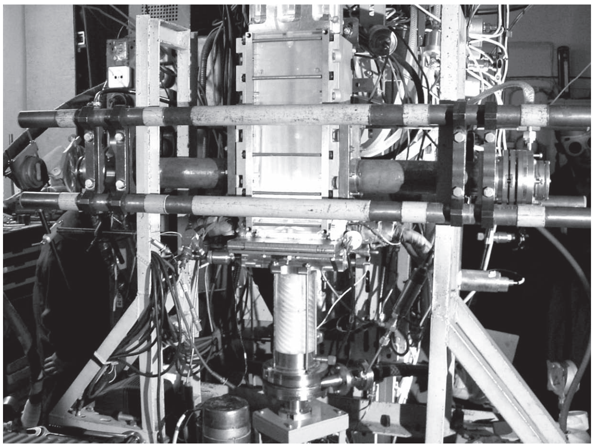

Figure 4. Photograph of the test setup during the laser experiment.

The lasing experiments were performed with supersonic nozzles 15 cm wide for three heights of the critical cross section (8, 10, and 12 mm). We used the scheme of mixing of energy-carrying (singlet oxygen and nitrogen) and emitting (mixture of iodine and nitrogen vapours) gases in parallel flows. The iodine – nitrogen mixture was injected into the supersonic region of the singlet oxygen flow (Fig. 1c), at a distance of 2 mm from the nozzle critical cross section, by thin tubes disposed in nine lines. The tubes were joined in a stern of a wing-shaped injector positioned in the subsonic part of the nozzle. This scheme ensured the minimal gas-dynamic perturbations upon mixing of the working gas mixture components, had an active laser medium extended along the gas flow (up to 15 – 20 cm), and demonstrated excellent results previously in a mixing gas-dynamic laser [12]. When used in COILs, this scheme of mixing allows one to completely prevent the interaction of singlet oxygen with iodine in the region of high gas densities and to reduce the losses of singlet oxygen during its transport and mixing.

We used a stable plane-spherical cavity with reflectances of 99.5% and 96% for the highly reflecting and output couplers, respectively. The optical diameter of the mirrors was 50 mm, and the curvature radius of the highly reflecting coupler was 10 m. The experimental results are listed in Table 1. The total output power (the sum of powers emitted through both mirrors of the cavity) and the chemical efficiency of the laser as functions of the chlorine flow rate for different nozzles are shown in Figs 5 and 6.

An increase in the height of the nozzle critical cross section was accompanied by an increase in the gas velocity in the TA SOG and by a decrease in the total pressure at the nozzle inlet, which lead to a higher efficiency of the TA SOG and lower relaxation losses of singlet oxygen. An increase in the laser power corresponded to an increase in the chlorine flow

Table 1. Results of lasing experiments.

h^* /mm	M_{cold}	S_1^* /cm^2	Chlorine flow rate /mol s^{-1}	Flow rate of nitrogen 1 /mol s^{-1}	Flow rate of nitrogen 2 /mol s^{-1}	Total flow rate /mol s^{-1}	p_1 /Torr	T_1 /K	Iodine flow rate /mol s^{-1}	Flow rate of nitrogen 3 /mol s^{-1}	p_2 /Torr	T_2 /K	p_{stat} /Torr	M_{res}	W /kW	η_{chem} (%)
8	2.4	10.9	0.077	0.156	0.187	0.420	42	390	0.0040	0.019	120	380	3.8	2.3	1.15	16.5
			0.134	0.239	0.269	0.642	62	380	0.0039	0.018	117	380	5.8	2.2	1.31	10.8
			0.227	0.168	0.457	0.852	83	370	0.0039	0.018	117	380	–	–	2.30	11.3
			0.374	0.164	0	0.538	55	330	0.0039	0.019	122	390	–	–	3.88	11.5
			0.374	0.258	0	0.632	61	340	0.0041	0.019	123	380	5.3	2.3	3.80	11.3
10	2.2	13.9	0.078	0.165	0.178	0.421	33	370	0.0042	0.020	129	390	6.7	1.8	1.95	27.8
			0.126	0.254	0.252	0.632	46	370	0.0042	0.020	129	390	9	1.8	2.46	21.7
			0.212	0.178	0.446	0.836	63	360	0.0042	0.020	130	390	12.3	1.8	2.97	15.6
			0.344	0.325	0	0.669	51	330	0.0042	0.020	130	390	10	1.8	4.74	15.3
			0.347	0.326	0	0.673	51	330	0.0042	0.020	129	390	–	–	4.22	13.5
			0.348	0.326	0.350	1.024	74	350	0.0042	0.020	128	390	–	–	4.48	14.3
12	2.1	16.9	0.353	0.326	0.160	0.839	55	400	0.0046	0.020	134	380	–	–	5.42	17.1
			0.400	0.758	0.184	1.342	85	410	0.0038	0.017	129	380	–	–	6.02	16.7
			0.411	0.325	0.280	1.016	64	400	0.0046	0.021	134	380	–	–	5.39	14.6
			0.433	0.753	0.184	1.370	87	410	0.0038	0.017	124	380	–	–	5.90	15.1
			0.436	0.470	0.176	1.082	70	400	0.0047	0.022	140	380	13.2	1.8	6.30	16.1
			0.470	0.760	0.184	1.414	90	410	0.0043	0.019	129	380	–	–	6.02	14.7
			0.483	0.639	0.265	1.387	88	410	0.0039	0.018	119	390	–	–	7.53	17.3

Notes: h^* is the height of the nozzle critical cross section; M_{cold} is the Mach number of the nozzle calculated from its geometric dimensions for cold nitrogen; S_1^* is the area of the nozzle critical cross section (the area of the injector critical cross section is $S_2^* = 0.59$ cm^2); nitrogen 1 and 2 are buffer gases; nitrogen 3 is the iodine-carrier gas; p_1 and p_2 are the gas pressures at the nozzle and injector inlets, respectively; T_1 and T_2 are the temperatures at the nozzle and injector inlets, respectively, calculated by the measured pressures p_1 and p_2, the flow rates of gases, and the area of the flow cross section in the point of measurement of pressures; p_{stat} is the static gas pressure in the cavity; M_{res} is the Mach number of the gas flow in the resonator estimated by an isentropic formula using the ratio of p_{stat} to the effective stagnation pressure of the mixture of main and injected gases, calculated by the instantaneous mixing model; W and η_{chem} are the COIL output power and chemical efficiency, respectively; dashes in the table mean that the corresponding parameters were not measured.

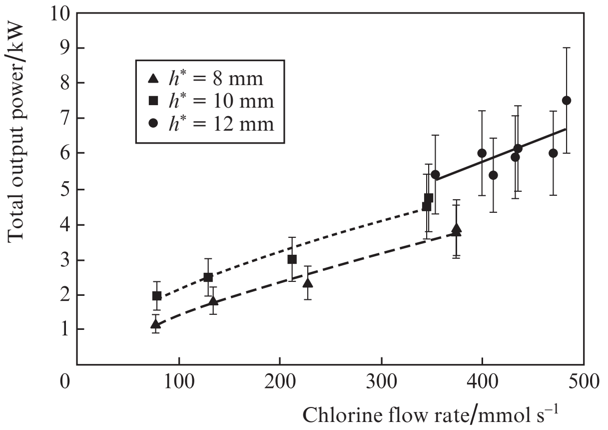

Figure 5. Dependences of the total output power of a supersonic COIL on the molar chlorine flow rate at different heights h^* of the nozzle critical cross section.

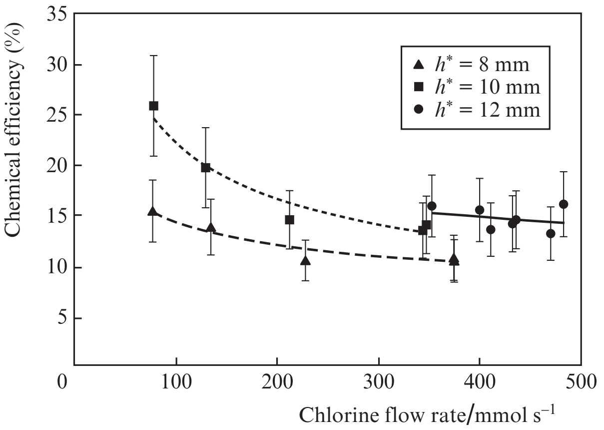

Figure 6. Dependences of the chemical efficiency of a supersonic COIL on the molar chlorine flow rate at different heights h^* of the nozzle critical cross section.

rate. It should be noted that, in all the experiments, we used the same tube injector of iodine, which was previously developed for a nozzle with the critical cross section height 3.8 mm [10, 11]. With increasing the height up to 8–12 mm, we had to increase the distance between the output edges of the injector tubes, which worsened the conditions for mixing iodine with singlet oxygen and decreased the laser efficiency. Nevertheless, the maximum output power and the chemical efficiency of the COIL turned out to be rather high, despite the fact that the laser cavity length along the gas flow was only 50 mm.

The maximum COIL power was ~7.5 kW at a chlorine flow rate of ~480 mmol s^{-1}, a gas velocity in the reactor of ~100 ms, and a gas pressure at the nozzle inlet ~90 Torr, which corresponded to the power normalised to the cross section area of the gas flow in the cavity of about 230 W cm^{-2}. The maximum chemical efficiency of the COIL was ~30% at a chlorine flow rate of ~80 mmol s^{-1} and a gas pressure at the nozzle inlet of ~35 Torr.

The COIL power may be even higher provided that the dielectric antireflection coating are not destroyed by the laser radiation. The simplest estimates show that, even at the laser output power of only 4 kW, the average intensity of radiation incident onto the cavity mirrors is ~10 kW cm^{-2}. This means that the intensity in hot spots may achieve 30–50 kW cm^{-2}. The dielectric coatings cannot withstand such high intensities. Thus, the antireflection coatings were partially destroyed at a laser power exceeding 3 kW.

5. Conclusions

Thus, we discussed the problem of scaling of COILs. It is shown that, when increasing the scale of a COIL, it is possible to retain its specific power and efficiency if the gas velocity in the SOG reaction zone is no lower than 50–120 m s^{-1}. A TA SOG model satisfying these requirements is presented.

Our experiments have demonstrated a stable operation of the TA SOG model at a chlorine flow rate up to 680 mmol s^{-1}, a flow rate of hydrogen peroxide alkaline solution of 1.2 L s^{-1}, a gas pressure up to 200 Torr, and a gas velocity in the reactor up to 100 m s^{-1}. The maximum specific productivity of the TA SOG exceeded 20 mmol s^{-1} cm^{-2} of singlet oxygen with its yield of about 70% (38 mmol s^{-1} cm^{-2} of chlorine). These characteristics are unachievable for world-known SOGs.

The energy characteristics of a supersonic COIL with the TA SOG are studied. At a gas pressure at the nozzle inlet of ~90 Torr, we achieved the maximum COIL output power of ~7.5 kW, which corresponded to a normalised power of 230 W cm^{-2}. The maximum chemical efficiency of the COIL was ~30% at a gas pressure at the nozzle inlet of ~35 Torr.

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