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Effect of the method of secondary-fuel supply on the characteristics of a cw chemical HF laser with a three-jet nozzle array

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Abstract. **The effect of the angle of secondary-fuel injection into a flow of oxidising gas and pressure of an active medium on the energy and spatial characteristics of a cw chemical HF laser with a three-jet nozzle array are experimentally studied. It is shown that the intensification of reagent mixing at the output of the nozzle array with the three-jet nozzle – nozzle – injector scheme due to the secondary-fuel injection at an angle of 20° to the direction of oxidising-gas flow enables one to reach a maximum of specific output energy, with the mass hydrogen flow lowered by 20 % compared to the case of parallel injection. This is accompanied by a 12 % increase in the specific output energy and a 15 % shortening of the lasing region. The output energy as large as 50 % of the maximum value can be reached at the static pressure of the active medium of about 13 Torr, which enables one to increase the pressure at the output of a diffuser by a factor of two when evacuating exhausted reaction products into the environment.**

Keywords: *chemical laser, nozzle array, output characteristics.*

1. Introduction

Our studies of the methods of increasing the length of the lasing region in supersonic cw chemical HF lasers [1 – 3] showed that nozzle arrays with a three-jet scheme of reagent mixing offer the greatest promise for solving this problem. In this scheme, a jet of a separating inert gas (secondary or additional diluent, namely, helium) is injected between the jets of oxidising gas (containing fluorine atoms) and secondary fuel (hydrogen molecules) and supplied into a laser cavity. A detailed experimental study of a bench kilowatt cw chemical HF laser with a three-jet nozzle array using the nozzle – nozzle – injector scheme demonstrated key advantages of this mixing scheme, such as a high specific output power ($N_{\Sigma} = 225$ J g^{-1}) and a large length of the lasing region ($\Delta x_{\rm L} = 12.5$ cm) [1]. The energy characteristics obtained in the experiments are far from the limiting values (according to calculations, the specific output energy may reach 300 J g^{-1}). Because of this, their improvement calls for a further study. In particular, for the cw chemical HF laser mentioned above, with a superposed collector for secondary-fuel supply, the simplest method of increasing the specific output laser energy is the intensification of mixing by injecting hydrogen jets at an angle to the direction of the flow of fluorine atoms.

The energy parameters of a cw chemical HF laser are strongly dependent on the static pressure $p_{\rm s}$ in the lasing region. This pressure is caused by the necessity of proving efficient mixing of supersonic reagent jets in a time comparable to the relaxation time of vibrational energy stored in the active medium (AM) and obtaining an accessible length of the lasing region.

Despite the fact that the pumping reaction $F + H_2 \rightarrow HF(\upsilon) + H$ ($HF(\upsilon)$ is an excited molecule and υ is the vibrational quantum number) has a rather high rate, the pressure in the AM is rather low because of a high relaxation rate of $HF(\upsilon)$ molecules and, as a rule, it is not higher than 5 – 7 Torr. This limits the pressure at the output of a diffuser through which exhausted reaction products are discharged into the environment. For ground-based lasers, this limitation is critical because it assumes application of special devices (usually, ejectors), whose presence considerable increases the total mass flow of gases required for the operation of this laser and sharply decreases its specific output energy.

To proceed into the region of higher working pressures without a substantial loss of specific output laser energy, one should also use intensified reagent mixing. It is evident that this will shorten the length of the lasing region (in comparison with the parallel hydrogen injection [1]). In our opinion, the three-jet mixing scheme has certain potentialities for increasing the AM static pressure because an additional diluent lowers its translational temperature, which should favour a decrease in the rate of vibrational energy relaxation.

Here, we report results of the experimental estimation of the effect of the method of secondary-fuel supply on the spatial and energy characteristics of a cw chemical HF laser with a three-jet nozzle array and on the pressure in its AM.

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2. Experimental setup and the measuring system

The experiments were carried out on a bench setup equipped with technological systems, which provide tests of a cw chemical HF laser in various operating modes, changing, in accordance with a given program, both the mass flow of any reagent and the position of the optical cavity axis relative to the edge of the nozzle array [4]. The working reagents represented gaseous fluorine (oxidiser), deuterium (primary fuel), hydrogen (secondary fuel), and helium [primary (He) and secondary (He^*) diluents], which were used in the molecular proportion $D_2:F_2:He:H_2:He^* = 1:\alpha_1:\psi_1(\alpha_1-1):\alpha_2(\alpha_1-1):\psi_2(\alpha_1-1)$).

The three-jet nozzle array, which was worked off in detail on a test bench, is shown in Fig. 1a. It has 33 profiled slotted supersonic nozzles (*1*) for oxidising-gas (fluorine atoms) supply and 34 wedged nozzles (*2*) for secondary-diluent (He^* molecules) supply. Type I device for secondary-fuel (H_2 molecules) supply has the following design: in each nozzle (*2*) for the secondary diluent, a wedged element with an injector is installed, which is made in the form of a perforated tube 1 mm in diameter (*3*). The secondary fuel is supplied through 13 holes in the tube, which are 0.3 mm in diameter and spaced 2 mm apart. The hole axes are parallel to the direction of the oxidising-gas flow from nozzles (*1*) (the angle between the axes is $\gamma = 0$).

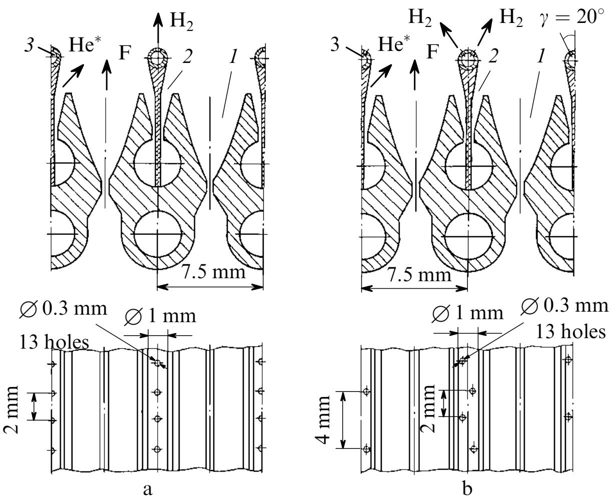

Figure 1. Schematic diagrams of three-jet nozzle arrays with type I (a) and II (b) devices of secondary-fuel supply: (*1*) oxidising-gas nozzle; (*2*) secondary-diluent nozzle; (*3*) perforated tube for secondary-fuel supply.

As shown in our previous studies of a cw chemical HF laser with a radially divergent two-jet nozzle array [5], the injection of secondary fuel at an angle of 20° to the direction of the oxidising flow causes an increase in energy characteristics by approximately 20 % in comparison with the case of parallel injection. If this regularity is also valid for a laser with a three-jet nozzle array, it is feasible to increase its specific output energy. For an experimental verification of this assumption, we developed and fabricated a modified device (type II, Fig. 1b) for secondary-fuel supply, in which hydrogen is injected from 13 holes 0.3 mm in diameter, which are arranged in the staggered order with a 2-mm step. The axes of holes in tubes (*3*) are oriented at the angle $\gamma = 20°$ to the direction of the oxidising-gas flow from nozzles (*1*). In both nozzle arrays, the nozzle–nozzle–injector mixing scheme is realised.

The energy (the output radiation power N and the specific output energy N_Σ) and spatial (the length of the lasing region Δx_L) characteristics of the cw HF chemical laser were measured by the double slit cavity method [6]. The measuring system consisted of two independent closed cavities, whose optical axes were mutually parallel and spaced apart by $\Delta x = 3.5$ cm in the direction of the AM flow. The cavities had rectangular apertures with height 9 cm and width 4 and 3 cm. Highly reflecting spherical mirrors with 5-m radius of curvature were made of polished copper. Each mirror was equipped with four chromel–copel thermocouples. The laser radiation power was determined from the increase in mirror temperature during the lasing time, which was specified by a mechanical shutter place between the AM and the cavity mirrors. Radiation outcoupled through the opening of the first cavity (here and below, the cavities are number in the flow direction) was directed onto a quick-response MG-30 detector, and its output signal was recorded by an oscillograph for determining the lasing time. The output laser power was measured by this method with an error of ± 7 %.

We studied a small-scale cw chemical HF laser (designed for obtaining an output power of 5–6 kW) with the nozzle array of size 25 cm × 2.8 cm in the output cross section. The laser was arranged in a low-pressure chamber, which separated the free gas-dynamic flow outgoing from the laser from the environment. The gas-dynamic pattern of this flow is determined to a large extent by the interaction of the flow with the environment, i.e., an edge effect. In the case of a rather long (~ 10 cm) AM, a small (2.8 cm) height of a nozzle blade gives no way of using the method proposed in Ref. [7] for eliminating the edge effect. Because of this, we used special means in the experiments on the study of the pressure effect (see Fig. 2). To decrease the pressure gradient in the AM along the height of the nozzle array, we mounted (by analogy with Ref. [8]) rigid boundary walls with the opening angle corresponding to the opening angle of the oxidising-gas nozzles (*2*). To weaken the effect of viscosity in the supersonic AM flow past the boundaries, we used a special gas-dynamic device forming jets of a cold gas that are parallel to the wall. Two rigid walls (*5*) (Fig. 2) bound the AM flow 14.5 cm long, beginning from the edge of the nozzle array and directed downward the flow, and separate it from the environment of the low-pressure chamber where the laser is arranged. At a distance of 2.5 cm from the edge of the nozzle array, two groups of injectors (*4*) are

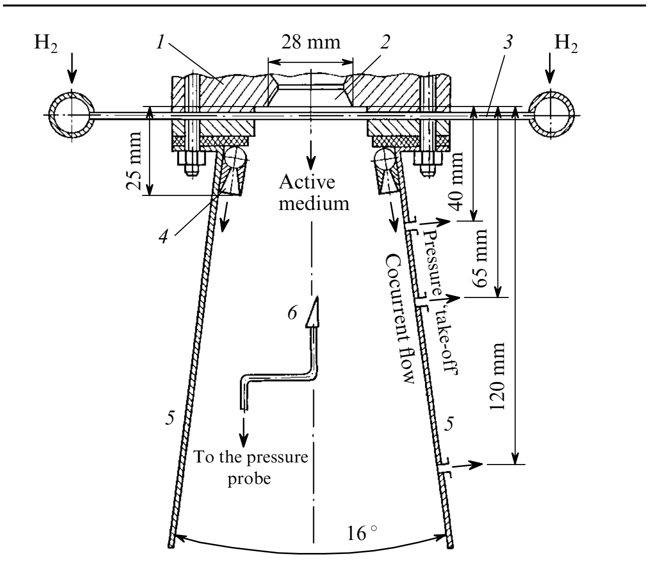

Figure 2. Schematic diagram of the device with bounding walls: (*1*) nozzle array; (*2*) oxidising-gas nozzle; (*3*) perforated tube for secondary-fuel supply; (*4*) injector of cocurrent flow; (*5*) bounding walls; (*6*) probe-sampler of static pressure.

arranged, each of the containing 42 axially symmetric nozzles for injecting an $H_2:N_2$ mixture in the mass proportion 50:50. To 'take off' static pressure from the periphery region of the AM flow, three drain holes 0.5 mm in diameter are made in one of the walls at distances of 4, 6.5, and 12 cm from the output section of the nozzle array.

The static pressure in the central region of the AM flow was measured by an uncooled plane–wedge type probe-sampler using the technique [9]. The probe-sampler (*6*) was positioned on a movable platform, which was mounted in the low-pressure chamber. In the course of experiments, the platform was discretely translated relative to the edge of the nozzle array in the flow direction. We used IKD6TDa probes (± 3 % error), which provided the determination of static pressure with an error not worse than ± 10 %.

3. Experimental results

We performed comparative studies of the cw chemical HF laser with two different devices (types I and II) of secondary-fuel supply. They included three stages. At the first stage, we varied the mass flow of secondary fuel and determined the effect of the method of secondary-fuel supply on the specific output energy. At the second stage, the energy characteristics and the AM length were estimated. At the third stage, we studied the effect of pressure in the AM.

In all the experiments, the chemical composition of fuel in the generator of atomic fluorine was fixed and corresponded to dimensionless coefficients $\alpha_1 \simeq 1.85$ and $\psi_1 \simeq 8.5$. The summary mass flow of reagents at the first and second stages was held close to the nominal (calculated) value $m = 30$ g s^{-1}. At the third stage, it was varied from the nominal to the maximum value $m_{max} = 60$ g s^{-1}. In these experiments, the mass flow of gases injected through the gasdynamic device was increased in proportion (from 30 to 60 g s^{-1}). In accordance with the results of previous studies [1], the secondary-dilution factor ψ_2 was taken close to the optimum value: $\psi_2 = 3 - 5$.

3.1 Effect of the amount of secondary fuel

In the experiments at the first stage, we successively used type I and II devices for secondary-fuel supply and measured the dependences of the output laser power on the coefficient α_2, which was varied in the range $\alpha_2 = 4 - 14$. The corresponding normalised dependences for the specific output energy $\bar{N}_\Sigma$ of the cw HF laser are presented in Fig. 3. One can see that they differ: for type II device, the specific output energy reaches a maximum at $\alpha_2 = 11$; for type I device, the maximum is observed for $\alpha_2 = 13$. In other words, the intensification of reagent mixing at the output of the nozzle array due to secondary-fuel injection at the angle $\gamma = 20°$ to the direction of the oxidising-gas flow enables one to reach a maximum specific output energy at a mass hydrogen flow that is decreased by 20 % in comparison with the case of parallel injection ($\gamma = 0$).

This result is evident. Under the conditions of diffusion reagent mixing (which is realised in the case of parallel hydrogen injection), an excess of secondary fuel favours an increase in collision frequency for collisions of its mo-lecules with oxidiser atoms and increases the rate of chemical pumping. For intensified mixing, the effect is reached faster, which enables one to decrease the amount of hydrogen.

Although both functions $\bar{N}_\Sigma = f(\alpha_2)$ have maxima in the region of α_2 variation studied by us, on the whole, the specific output energy changes weakly with variations in the mass flow of secondary fuel. In particular, a twofold decrease in hydrogen mass flow in comparison with the optimum value, which corresponds to the factors $\alpha_2 = 11$ and 13, leads to the decrease in specific output energy by 15 % and 20 %, respectively. A similar feature is typical of a cw chemical HF laser with a two-jet nozzle array [9].

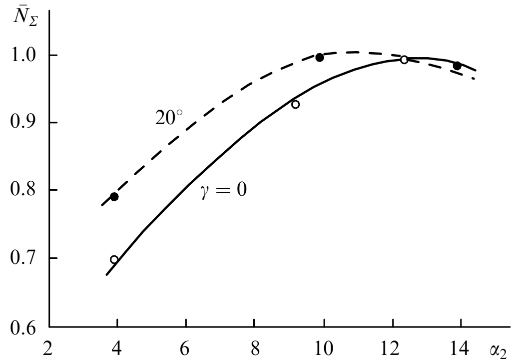

Figure 3. Normalised dependences of the specific output energy $\bar{N}_\Sigma$ of the cw chemical HF laser with type I (solid curves) and II (dashed curves) devices of secondary-fuel supply on the coefficient of secondary-fuel excess α_2 for different angles γ.

3.2 Energy characteristics of radiation and the AM length

In the experiments at the second stage (each of them was 40–50 s long and included four-five regimes, which differed only in the position of the optical cavity axis), the laser cavity was translated, which allowed us to determine the energy contribution of different parts of the AM and simultaneously find the length of the lasing region. The results of these experiments are presented in Table 1. One can see from it that the maximum specific output power of the laser with type II device of secondary-fuel supply is 12 % higher in comparison with the laser using type I device. Note that in the latter case the specific output energy ($N_\Sigma = 163$ J g^{-1}) exactly corresponds to the values obtained by us earlier in Ref. [1] in similar conditions. This gives evidence of a good reproduction of experimental results and supports their reliability. Note that the specific output energy was increased at the cost of decrease in the length of the lasing region (see Table 1).

Table 1. Comparative spatial and energy characteristics of the cw chemical HF laser with two types of devices for secondary-fuel supply

Device type	N/kW	N_Σ/J g^{-1}	Δx_L/cm
I ($\gamma = 0$)	5.67	163	10.9
II ($\gamma = 20°$)	6.33	183	9.3

3.3 Effect of pressure in the AM

The distributions of static pressure p_s along the AM flow for different mass reagent flows are presented in Fig. 4. The pressures in fixed sections of the central region of the AM and the cocurrent flow adjacent to the bounding walls were found to be identical (bold and empty circles on the curve for $m = 30$ g s^{-1}). This effect has an important consequence for practice: because it is extremely undesirable to place pressure probe-samplers in a laser cavity in the experiments on lasing, the pressure p_s in the AM (at least at the distances $x \geqslant 4$ cm) can be judged from the results of measurements in the cocurrent flow near the boundary walls.

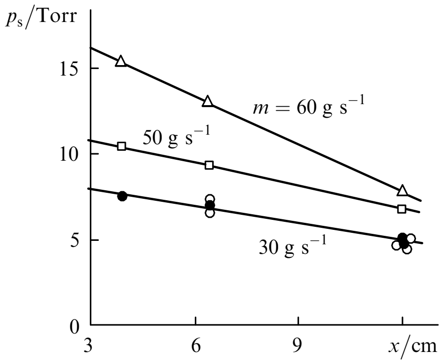

Figure 4. Distribution of static pressure p_s in the direction of the AM flow, measured by the probe-sampler in the central region of the flow (solid circles) and in the cocurrent flow near the wall of a bounding plate (empty circles) for different mass flows m.

An increase in mass flow is accompanied by an increase in static pressure in the AM flow and the rate of its decrease downward the flow (the curves for $m = 50$ and 60 g s^{-1}). It is likely that the latter fact is caused by the gas flow expansion in the plane of reagent mixing (in the direction along the nozzle array) that is not precluded by the bounding walls. One can see from the distributions in Fig. 4 that the static pressure inside the cavity nevertheless varies. Because of this, we propose to use its integrated characteristic, namely, the weight-average pressure

$$\bar{p}_s = \frac{N_1 p_s' + N_2 p_s''}{N_1 + N_2},$$

where N_1 and N_2 are the powers of radiation formed in the first and second cavities; p_s' and p_s'' are the static pressures in the sections of the AM flow that pass through the optical axes of the first and second cavities.

The dependence of the normalised specific output energy on the pressure $\bar{p}_s$ is shown in Fig. 5. It was obtained for the cw HF laser with type II device for secondary-fuel supply. The form of the dependence $\bar{N}_\Sigma = f(\bar{p}_s)$ gives evidence of two specific features. First, in spite of the intensified reagent mixing, the dependence in the pressure range under study is close in form to the theoretical dependence for the laser with the diffusion mixing mechanism [10]: $\bar{N}_\Sigma \sim \bar{p}_s^{-1}$. Second, a 50 % decrease in the specific output energy with respect to the maximum value ($N_\Sigma^{\max} = 183$ J g^{-1}) makes possible laser operation at a higher (by a factor of 1.6) AM pressure ($\bar{p}_s \sim$ 13 Torr).

As for the possibility of recovering the total pressure of the AM flow in a cw chemical HF laser with a three-jet nozzle array, it can be estimated on the basis of data from Refs [8, 11]. Using the dependence obtained in Ref. [8], one can determine the pressure at the diffuser output p_d for the laser parameters realised in our experiments. According to our estimates, to the maximum specific output energy corresponds the pressure $p_d \sim 75$ Torr. A 50 % decrease in N_Σ in comparison with the maximum value makes possible a twofold increase in pressure up to ~ 150 Torr. A further recovery of pressure up to atmospheric using a gas ejector requires the compression degree $\varepsilon_1 \sim 10$ in the first case and

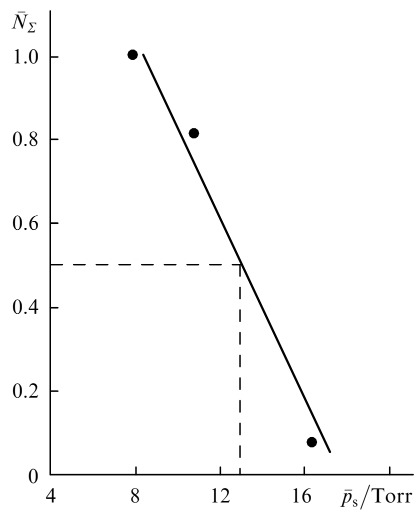

Figure 5. Dependences of the normalised specific output energy $\bar{N}_\Sigma$ of the cw HF chemical laser on the weight-average static pressure inside the laser cavities $\bar{p}_s$.

$\varepsilon_2 \sim 5$ in the second one, which requires the ejection coefficients $n_1 = 13.3$ and $n_2 = 6.4$. Using these data, which were taken from Ref. [11], one can estimate the required mass flow of the ejecting gas and find conditions for obtaining a compromise between the pressure of a gas flow exhausted into the environment and the specific output power of the cw chemical HF laser.

4. Conclusions

The results of our experiments show that the intensification of reagent mixing in a cw chemical HF laser with a three-jet nozzle array using the nozzle – nozzle – injector scheme due to secondary-fuel injection at an angle of 20° to the direction of the oxidising-gas flow makes it possible

(1) to reach a maximum specific output power at the hydrogen mass flow decreased by 20 % with respect to the value for parallel injection;

(2) to increase the specific output energy by 12 %, with the length of the lasing region being decreased by 15 %;

(3) to increase the pressure inside the laser cavity by a factor of 1.6, with a twofold decrease in the specific output power.

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