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Possibilities of improving the performance of an autonomous cw chemical DF laser by replacing the slot nozzles by the ramp ones in the nozzle array

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***Abstract*. The results of a comparative numerical study of the performance of an autonomous cw chemical DF laser are obtained by simulating the processes in the nozzles and laser cavity where several configurations of slot and ramp nozzle arrays are employed. Three-dimensional Navier – Stokes equations solved with the Ansys CFX software are used to describe the reacting multicomponent flow in the nozzles and laser cavity. To investigate lasing characteristics, a supplementary code is developed and is used to calculate the radiation intensity in the Fabry – Perot resonator, taking into account its nonuniform distribution along the aperture width and height. It is shown that the use of the nozzle array consisting of ramp nozzles, which, in contrast to the slot nozzles, provide enhanced mixing of the reactants makes it possible to improve the laser performance in the case of a high-pressure (more than 15 Torr) active medium.**

Keywords: *gain generator, autonomous cw DF chemical laser, nozzle array, three-dimensional flow, Navier – Stokes equations.*

1. Introduction

An efficient way for improving the energy characteristics of hydrogen fluoride cw chemical lasers (CCLs) is to intensify the mixing of supersonic flows of the oxidant (containing atomic fluorine) and the secondary fuel in the laser chamber. This is generally obtained by perturbing the flow, as a result of which the contact area of the neighboring oxidant and secondary fuel jets increases. Since these jets outflow through a periodic structure of small nozzles, which form a nozzle array, various geometric features of the nozzle configuration can be considered as the main source of such perturbations. Typical examples of these configurations are arrays with HYLTE nozzles [1], TRIP nozzles [2], and deflector and ramp nozzles [3]. The main drawback of all these arrays is that they are much more difficult to fabricate in comparison with the conventional slot nozzle array. This drawback is not so significant for only the ramp nozzle array. Here, the reagent mixing surface is increased due to the introduction of protrusions ('ramps') into the slot nozzle; these ramps are located directly after the nozzle throat with their height gradually increasing up to the nozzle array exit plane (NEP).

Some versions of the ramp-nozzle array configuration were proposed in [3] and [4], where the reagent mixing dynamics in the laser chamber was investigated and the small-signal gain was measured for DF CCLs. Such studies do not give full picture of the processes occurring in the active medium, because they do not analyse the lasing regime and thus do not allow one to estimate the energy characteristics of such a laser. At the same time, along with the absolute values of the lasing characteristics, their relative change with respect to those obtained with a nozzle array of another configuration (for example, slot configuration) are also of practical interest. This problem can be solved numerically instead of carrying out expensive experiments. In this paper, we report the results of such a study.

Using the standard methods of numerical simulation of the physicochemical processes occurring in the nozzles and in the active medium filling the optical cavity, we performed a comparative analysis of the influence of ramps in the oxidant and secondary fuel nozzles on the change in the lasing characteristics of DF CCLs. To make the comparison more objective, we considered the processes occurring at different pressures in the active medium. It should be noted that, when a slot nozzle array is used, the optimal pressure in the active medium is generally low (about 4 – 5 Torr); an increase in pressure significantly slows down the reagent mixing, because the diffusion (the main mixing mechanism) is hindered at higher pressures. As a result, the production rate of vibrationally excited DF(υ) molecules decreases, while the negative influence of their vibrational – translational relaxation becomes more significant. At the same time, CCLs with a high-pressure active medium have a significant advantage: more favourable conditions for ejecting exhaust components into the ambient atmosphere. In particular, some aspects of designing an HF(DF) CCL for aircraft location at different altitudes (12 – 18 km) were considered in [5]. In this case, an increase in the pressure of the active medium (formed using a slot nozzle array) made it possible to recover the exhaust flow static pressure at the diffuser output to the environmental level. As a result, gas-jet ejectors were excluded, and the design of the laser system was significantly simplified. However, it turned out

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Table 1. Linear parameters for two configurations of a ramp nozzle array

Array configuration	Parameters/mm							
	D	H	L_1	L_2	h_1	h_2	D_1	D_2
Version proposed in [3]	5.46	1.25	4.3	2.3	0.13	0.085	2.3	1.5
Version proposed in this study	7.5	1.5	6	1.8	0.4	0.12	4.6	1.5

that for the aforementioned location altitudes an increase in pressure in the active medium reduces significantly (when a slot nozzle array is used) the specific power of the laser. In this study, we considered the fundamental possibility of attaining higher values of specific power for a ramp nozzle array at elevated pressures (much above 5 Torr), which ensure ejection of exhaust components into atmosphere in a wide range of altitudes (from 8 km and more) without gas-jet ejectors.

2. General statement of the problem

To determine the lasing characteristics of DF CCL, we performed a numerical simulation of the gas flow in the supersonic nozzles and laser chamber based on solving the system of three-dimensional Navier–Stokes equations, taking into account the processes of chemical pumping, vibrational relaxation and vibrational exchange between DF molecules, and the induced emission in a plane-parallel Fabry–Perot resonator. The numerical calculations were carried out for two configurations of the ramp nozzle array, differing by the step of the nozzles, ramp width, throat size, and the nozzle lengths (Table 1). Figure 1 shows a fragment of ramp nozzle array, which was proposed in [3] (configuration 1 below). A specific feature of this array is fairly small values of the nozzle step D and the width of the throats $h_{1,2}$; hence, they may be technologically inconvenient. Taking this into account, an alternative version of a ramp nozzle array with an enlarged nozzle step (configuration 2 below) was proposed.

Since the ramp nozzle array configurations analysed here have a periodic structure, the three-dimensional description of the gas flow in the nozzles and laser chamber can be reduced to the consideration of one nozzle period along the z axis and one ramp half-period along the y axis (Fig. 1b). The resulting domain was discretised by a hexahedral grid; the grid in the laser zone was constructed so that the distance between neighbouring points in all three dimensions remained the same. Thus, the grid sizes in the transverse cross section of the laser zone for configurations 1 and 2 were, respectively, 36×160 and 30×150 points. The number of grid points in the flow direction (x axis) was varied, depending on the active-medium width.

The boundary conditions at the inlet of the oxidant nozzle included the pressure, temperature, and oxidative gas composition as produced in the combustion chamber, which were determined from the thermodynamic calculation of the fuel composition $C_2H_4 + 5.5NF_3 + 38He$ (such a composition was used in [3]). The calculation yielded the equilibrium temperature $T_0 = 1800$ K and the following mass fractions of the components: $C_F = 0.133$, $C_{HF} = 0.141$, $C_{He} = 0.256$, $C_{CF_4} = 0.309$, and $C_{N_2} = 0.138$. The pressure at the input of the oxidant nozzle was assumed to be 10 atm (also according to [3]). To analyse the lasing characteristics of DF CCL at lower pressures in the active medium, we also performed calculations for pressures of 5 and 2 atm in the combustion chamber. The temperature T_0 and pressure p_0 at the input of the secondary fuel nozzle were taken to be, respectively, 500 K and 3 atm for all calculations; the mass fractions of the components were $C_{D_2} = 0.406$, $C_{He} = 0.594$. To take into account the recombination of atomic fluorine on the oxidant nozzle walls, the latter were considered as absolutely catalytic. The temperature of the nozzle walls was assumed to be 500 K.

The resulting system of equations, which includes the equation of continuity, the Navier–Stokes equations, the equation for the energy, and the transport equations for the individual gas mixture components, with the boundary conditions described, was solved using the Ansys CFX software. The processes of the chemical and vibrational kinetics of the DF molecule were described using the package of rate constants [6], supplemented with the processes of multi-quantum vibrational relaxation of the DF molecule.

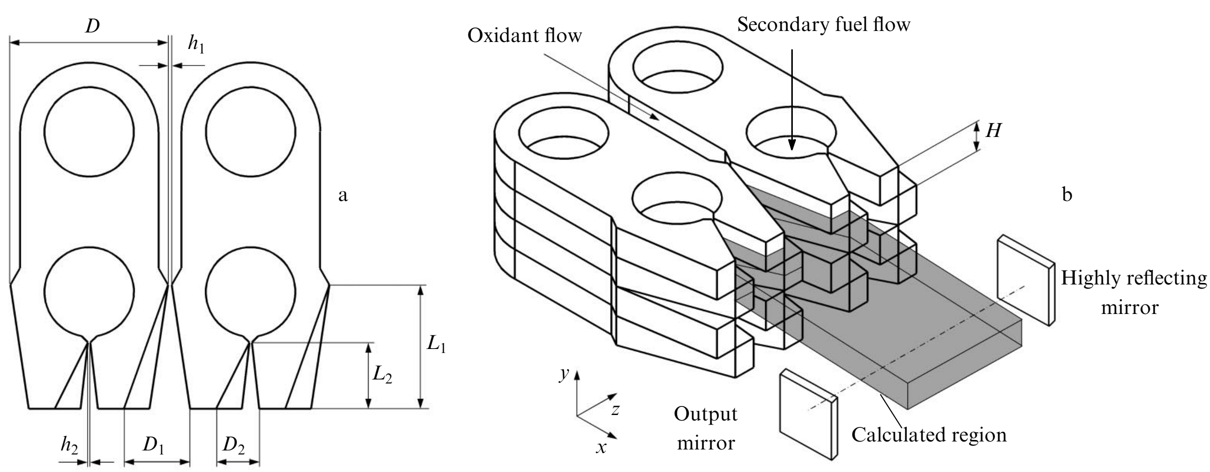

Figure 1. (a) Fragment of a ramp nozzle array with the main geometric parameters and (b) a schematic diagram of supplying components into the laser chamber.

The small-signal gain on different vibrational–rotational transitions of the P branch of the DF molecule was calculated under assumption of the rotational equilibrium [6]. In the case of Fabry–Perot resonator, the necessary condition for lasing in some $\upsilon \to \upsilon - 1$ band of the DF molecule in some cross section, oriented perpendicularly to the flow direction (x axis), is the excess of the gain on a vibrational–rotational transition, averaged over the nozzle array period, above the threshold value. When lasing occurs, the gain $G_{\upsilon-1,j}^{\upsilon,j-1}$ on this transition decreases to the threshold value $g_{\rm th}$:

$$G_{\upsilon-1,j}^{\upsilon,j-1}(x,y) = \frac{1}{h_z}\int_0^{h_z} g_{\upsilon-1,j}^{\upsilon,j-1}(x,y,z)\mathrm{d}z$$

$$= g_{\rm th} \equiv \frac{1}{L_{\rm a}}\ln\frac{1}{\sqrt{r_1 r_2}}, \qquad (1)$$

where $L_{\rm a}$ is the active-medium length along the CCL optical axis (in our case, along the z axis); r_1 and r_2 are the reflectances of the cavity mirrors; h_z is the nozzle period along the z axis, and $g_{\upsilon-1,j}^{\upsilon,j-1}(x,y,z)$ is the local value of the small-signal gain on a specified vibrational–rotational transition of the DF molecule.

The lasing characteristics of the output laser radiation were estimated from the nozzle array power flux (the ratio of the lasing power to the area of the NEP) and the specific power (the ratio of the lasing power to the total mass flow rate of the components). In this statement of the problem the nozzle array power flux can be obtained from the expression

$$P_{\rm las} = \frac{1}{L_{\rm a} h_y}\int_{x_0}^{x_*}\int_0^{h_y} I_{\rm out}(x,y)\mathrm{d}x\mathrm{d}y, \qquad (2)$$

where x_0 and x_* are the coordinates corresponding to the beginning and end of the lasing zone along the flow direction; h_y is a half period of ramps along the y axis; and $I_{\rm out}(x,y)$ is the total intensity of the output laser radiation at the point (x, y), which, in turn, is determined by the expression

$$I_{\rm out}(x,y) = \sum_{\upsilon=1}^{4} I_{\upsilon-1}^{\upsilon}(x,y)$$

$$\times \frac{t_1\sqrt{r_2} + t_2\sqrt{r_1}}{(1-r_2)\sqrt{r_1} + (1-r_1)\sqrt{r_2}}\ln\left(\frac{1}{\sqrt{r_1 r_2}}\right). \qquad (3)$$

Here, $I_{\upsilon-1}^{\upsilon}(x,y)$ is the laser intensity in the vibrational $\upsilon \to \upsilon - 1$ band in the cavity and t_1 and t_2 are transmittances of the cavity mirrors.

The corresponding value of the specific power is determined as:

$$E_{\rm las} = \frac{P_{\rm las}}{(\dot{m}_0/S)}, \qquad (4)$$

where $\dot{m}_0/S$ is the mass flow rate of the components per unit area S of the NEP.

When determining the threshold gain (1) and the output radiation intensity (3), we assumed that the reflectance r_1 of the highly reflecting mirror in the cavity is 99.4 %, the output mirror reflectance r_2 is 90 %, and the loss coefficient for the mirrors is 0.6 %. The active-medium length $L_{\rm a}$ was assumed to be 40 cm.

To estimate the effect of the presence of ramps in the oxidant and secondary fuel nozzles on the change in the lasing characteristics, we also considered DF CCL versions with an equivalent slot nozzle array; all other input data were retained the same. The equivalent slot array is considered to be a nozzle array in which the sizes of the throat sections and the expansion ratios of the oxidant and secondary fuel nozzles are the same as for the initial ramp nozzle array.

3. Calculation of the laser intensity

Generally, the laser intensity field is obtained by solving the system of Navier–Stokes equations. In this system, the equation for energy and the transport equations for vibrationally excited DF molecules contain source terms, which describe the changes in the energy of the system and in the concentrations of DF molecules at individual vibrational levels due to the removal of the laser energy from the active medium as a result of lasing [6, 7]. These source terms cannot be taken into account in the system of equations solved by the Ansys CFX software, because they contain laser intensity values that are unknown beforehand; special numerical methods must be applied to determine them. Therefore, using this program for simulating the processes occurring in the active medium, one can consider only the amplification regime.

Since the development of a numerical model that would make it possible to solve the system of three-dimensional Navier–Stokes equations simultaneously with the calculation of the laser intensity field is a fairly difficult problem, we propose a simpler (in terms of implementing) approach, which allows one to determine the intensity field from the calculated fields of gas flow parameters. This approach is based on the assumption that the effect of the laser energy removal from the active medium on the flow field in this medium is negligible. In other words, the production and transport of emitting DF(υ) molecules and the other mixture components in the cavity occurs in the fields of the momentum, temperature, and pressure, which are determined beforehand and correspond to the amplification regime. Hence, the Ansys CFX software can be used during the first stage of the calculations. The general form of the transport equations for vibrationally excited DF(υ) molecules, which are solved during the second stage, is as follows:

$$\rho U_j \frac{\partial C_{\rm DF}(\upsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_{\rm DF}\frac{\partial C_{\rm DF}(\upsilon)}{\partial x_j}\right)$$

$$+ \dot{w}_{\rm DF}(\upsilon) + \dot{w}_{\rm rad}(\upsilon), \qquad (5)$$

$$\dot{w}_{\rm rad}(\upsilon) = \frac{W_{\rm DF}}{N_{\rm A}}\left[\frac{g_{\upsilon,j+1}^{\upsilon+1,j} I_{\upsilon,j+1}^{\upsilon+1,j}}{h\nu_{\upsilon,j+1}^{\upsilon+1,j}} - \frac{g_{\upsilon-1,j'+1}^{\upsilon,j'} I_{\upsilon-1,j'+1}^{\upsilon,j'}}{h\nu_{\upsilon-1,j'+1}^{\upsilon,j'}}\right], \qquad (5.1)$$

where $C_{\rm DF}(\upsilon)$ is the mass fraction of DF molecules at a vibrational level; $\dot{w}_{\rm DF}(\upsilon)$ is the source term, which describes the change in the concentration of DF molecules at this level (as a result of chemical pumping, vibrational–vibrational exchange, and vibrational–translational relaxation); and $\dot{w}_{\rm rad}(\upsilon)$ is a source term, which describes the change in the concentration of these molecules under induced emission.

The equations for the other (nonradiative) components in the active medium are recorded similarly. The boundary conditions for these equations also use the previously calculated (in the first stage) concentrations (mass fractions) of the components in some cross section near the NEP. To solve these equations in the finite-difference approximation, which yields a system of algebraic equations, we used the matrix sweep method. The intensity entering Eqn (5) was calculated proceeding from threshold condition for lasing in the Fabry – Perot resonator (1).

It should be noted that the neglect of the effect of radiation extraction from the active medium on the change in its temperature may introduce some error into the calculation of the radiation intensity and, therefore, the lasing characteristics. We estimated this error using the previously developed software that solves two-dimensional Navier – Stokes equations in the slender-jet appro-ximation [8], where a planar slot nozzle array was considered. This software allowed us to implement both the standard technique for determining the intensity and the new method proposed here. The ratios of the components in the oxidant flow and the cavity parameters were assumed to be the same as in Section 2. Several cases were considered, where the pressure at the NEP was varied from 5 to 9 Torr and the helium mass fraction in the secondary fuel flow was in the range from 0 to 0.6. The calculations showed that the largest error in determining intensity is observed near the laser zone boundary, and the maximum error in determining the nozzle array power flux ($\sim 15\,\%$) corresponded to a long (above 10 cm) lasing zone. The value of the nozzle array power flux was determined with a higher accuracy when the lasing zone was relatively short (less than 7 cm), which was provided by increasing the pressure at the NEP and decreasing the helium mass fraction in the secondary fuel flow. Thus, in the problems considered here, where the length of the lasing zone is assumed to be relatively small, our approach can be definitely used to calculate the lasing characteristics

4. Results

The calculation model proposed in this study was tested in the following way: the obtained values of the small-signal gain were compared with the corresponding experimental data [3]. The measurements [3] were performed on three vibrational – rotational transitions of the DF molecule [$P_2(6)$, $P_2(8)$, and $P_3(7)$], using a ramp nozzle array (configuration 1). The main purpose of these tests was to make sure that the kinetic model used [6] adequately describes the processes occurring in the active medium. Note that the multi-quantum relaxation rate constants of DF(υ) molecules are absent in this kinetic model; therefore, we performed their fitting. Fairly good agreement with the experiment for the maximum gain was obtained on the assumption that the multi-quantum relaxation rate of DF(υ) molecules is smaller by a factor of 5 than the corresponding single-quantum relaxation rate. Despite some differences in the values of the amplification zone width obtained within this kinetic model, further modification of the individual rate constants of the pumping and relaxation processes occurring in DF molecules, aimed at increasing the calculation accuracy, was not performed because of large computational expenditures.

The obtained distributions of the small-signal gain along the active-medium flow (x axis) are shown in Fig. 2, which also presents (for qualitative comparison) similar distributions obtained by considering a gain generator with an equivalent slot nozzle array. The calculated gain distributions were plotted taking into account the gain value averaged over the transverse cross section of the active medium (yz plane). The gain values obtained in the case of a slot nozzle array are easy to explain by the high pressure in the active medium (much above 5 Torr): the diffusion is significantly hindered in this case and, correspondingly, the production rate of DF(υ) molecules is also reduced.

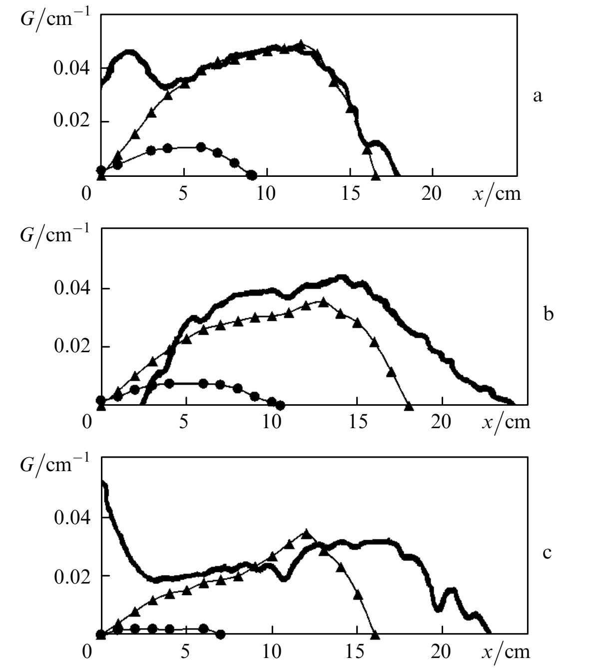

Figure 2. Distribution of the small-signal gain G on the vibrational – rotational transitions (a) $P_2(6)$, (b) $P_2(8)$, and (c) $P_3(7)$ of the DF molecule for AMGs with a ramp nozzle array [(bold line) experimental data and (▲) the calculation results] and an equivalent slot nozzle array [(●) calculation results].

Thus, this testing allowed us not only to choose the appropriate kinetic model of the processes occurring in the active DF CCL medium but also to make sure of the efficiency of a ramp nozzle array in the gain generator design by comparing the gain properties of the active medium.

The comparative estimation of the influence of the ramp and slot nozzle array configurations on the DF CCL lasing characteristics included the calculation of the fields of output laser radiation intensity using the technique proposed. In the case of both ramp and equivalent slot nozzle arrays six versions were considered, which differed by the array configuration (either '1' or '2') and the pressure in the combustion chamber (10, 5, or 2 atm), which was set as a boundary condition at the oxidant nozzle input. When plotting the dependences of the lasing characteristics on the pressure in the active medium, the characteristic value of the latter was taken to be equal to the pressure in the oxidant flow core at the NEP, because it remained practically the same for both ramp and slot arrays. For the aforementioned pressures at the oxidant nozzle input the corresponding pressures in the flow core at the NEP were 29, 16, and 8 Torr (configuration 1) and 45, 23, and 10 Torr (configuration 2). For comparison, the pressures in the core of the secondary fuel flow at the NEP were ~ 13 and 20 Torr for configurations 1 and 2, respectively. The distributions of the output radiation intensity over the aperture width and height (within one half-period of the active medium along the y axis) for the ramp nozzle array are shown in Fig. 3.

It can be seen that an increase in the pressure in the active medium leads to a less uniform intensity distribution over the aperture height, which indicates that turbulent mixing of the oxidant and secondary fuel dominates over laminar mixing. Note also that lasing is observed mainly within 2 cm from the NEP. Despite the small length of the lasing zone (which is smaller than that for the equivalent slot nozzle array by a factor of almost 3), the intensity turned out to be almost an order of magnitude higher. This circumstance imposes rather strict requirements to the quality of the cavity mirrors, whose radiation resistance must be not lower than 30 kW cm^{-2} (proceeding from the peak intensities in the plots). A practical solution of this problem was proposed in [2], where mirrors with a radiation resistance of 60 kW cm^{-2} were fabricated for a DF CCL, the nozzle array of which consisted of TRIP nozzles. Thus, we can conclude that it is quite realistic to prepare mirrors with a necessary radiation resistance for the DF CCL working modes under consideration.

Using the intensity distributions obtained by considering the ramp and slot nozzle array, one can calculate the corresponding values of nozzle array power flux and specific power. Figure 4 shows the dependences of these parameters on the pressure in the active medium. It can be seen that at active-medium pressures below 10 Torr a change from the slot nozzle configuration to the ramp nozzle barely affects the lasing characteristics and leads only to an increase in the radiation loads on the cavity mirrors because of the differences in the lasing-zone length. However, with an increase in pressure up to 45 Torr this change increases significantly the nozzle array power flux, which varies relatively weakly in the case of a slot nozzle array. Due to the increase in the nozzle array power flux and, correspondingly, increase in

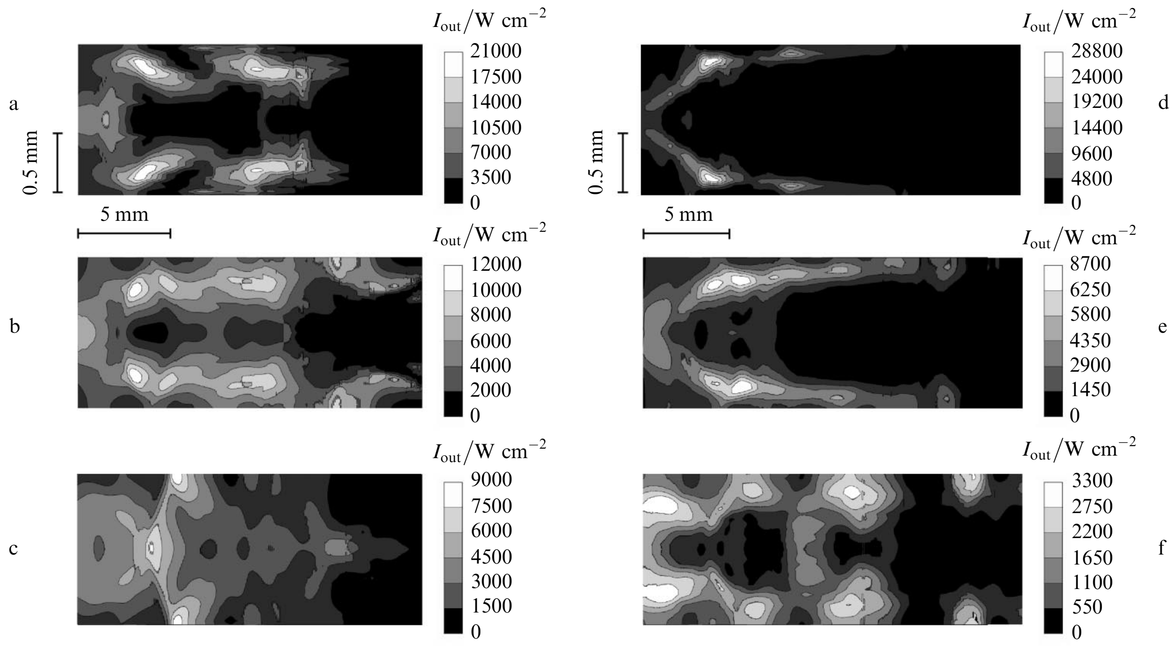

Figure 3. Distributions of the total intensity of the DF CCL output radiation for gain generators with ramp nozzle arrays of configuration (a – c) 1 and (d – f) 2. The corresponding characteristic pressures in the active medium are (a) 29, (b) 16, (c) 8, (d) 45, (e) 23, and (f) 10 Torr.

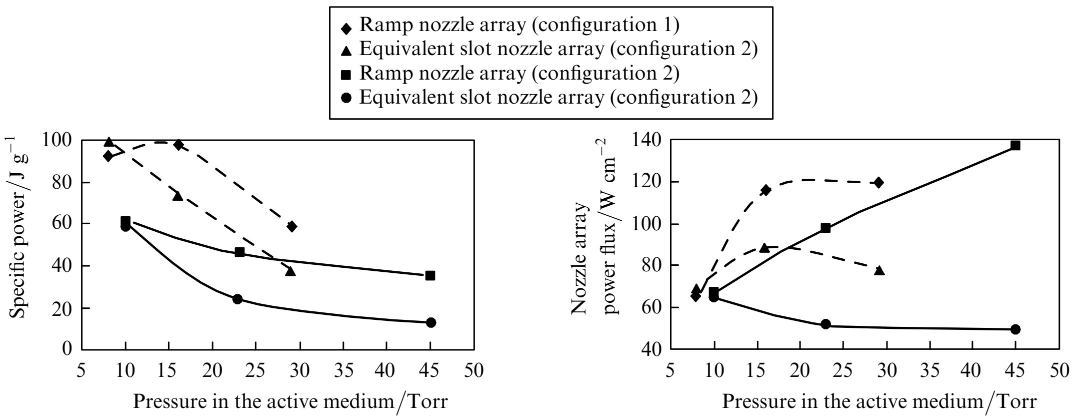

Figure 4. Dependences of the specific power and nozzle array power flux on the pressure in the DF CCL active medium.

the mass flow rate of the mixture, the specific power for the ramp nozzle array turned out to be much higher. As follows from Fig. 4c, for the array of configuration 2 an increase in pressure (at least to 45 Torr) causes a decrease in the specific power by less than 40 %, whereas the use of an equivalent slot nozzle array reduces the specific power by a factor of more than 3.

The fundamental possibility of using DF CCLs for aircraft location at altitudes of about 8 km, where the exhaustion of components into the ambient air would occur without gas-jet ejectors, can be estimated based on expression (6) (which was found to be in good agreement with experiment in [2]). This expression sets a relationship between the mixture mass flow rate per nozzle array exit plane unit area, $\dot{m}_0/S$, and the pressure at the diffuser output, $p_{\rm out}$:

$$p_{\rm out} = 5.14(\dot{m}_0/S)\sqrt{\frac{T_0}{W}}\sqrt{\frac{2}{\gamma-1}}\left(\frac{\gamma+1}{2\sqrt{\gamma}}\right)^{\frac{\gamma+1}{\gamma-1}}. \qquad (6)$$

Here, the total temperature T_0, the mixture molar mass W, and the adiabatic index γ correspond to the values at the input of the active zone.

Having equated the pressure at the diffuser output in (6) to the ambient pressure, which is 267 Torr at the altitude under consideration (8 km), one can determine the minimum mass flow rate of the mixture, when the pressure restored in the diffuser will be not lower than the aforementioned value. On the assumption that $T_0 = 1800$ K, $W = 11$ g mol^{-1}, and $\gamma = 1.5$, we find that $\dot{m}_0/S =$ 1.8 g cm^{-2} s^{-1}). For the DF CCL operation regimes considered here, the obtained values of mixture mass flow rate turned out to exceed the aforementioned ones in three cases (Figs 3a, 3d, 3e). For these versions the values of the mixture mass flow rate per nozzle array exit plane unit area were, respectively, 2, 3.8, and 2.2 g cm^{-2} s^{-1}. Having generalised the results obtained, we can conclude that the use of ramp nozzle arrays in aircraft-location DF CCLs yields relatively high specific energy parameters.

5. Conclusions

A simplified approach to the calculation of the DF CCL intensity was proposed and substantiated. This approach deals with both two- and three-dimensional flow fields in the resonator cavity and thus makes it possible to consider the versions of active-medium formation using nozzle arrays of arbitrarily complex configurations (ramp, HYLTE, etc.).

The results obtained demonstrated a theoretical possibility of improving significantly the lasing characteristics of an autonomous DF CCL using a ramp nozzle array (instead of a slot one) to form the active medium of an aircraft-location laser at altitudes of about 8 km, with ejection of exhaust components into the ambient atmosphere without gas-jet ejectors.

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