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Economical generation regime of a supersonic continuous-wave chemical DF laser

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Abstract. **We have performed experimental and computer-aided theoretical studies of the effect of the dilution degree ψ_2 of a secondary fuel (deuterium) by an inert gas (helium) on the output characteristics of a supersonic cw chemical DF laser with a flat nozzle array, constructed in accordance with the nozzle–nozzle reagent mixing scheme. It is shown that an increase in the dilution degree in the range of $0 \leqslant \psi_2 \leqslant 20$ leads to a monotonous increase in the lasing zone length (a decrease in the radiation load on the resonator mirrors) and a drop in the laser specific energy output. With an increase in the optical path length (a decrease in the threshold gain), the sensitivity of the laser energy characteristics to the dilution degree decreases. Consequently, for a high-power DF laser (with a long nozzle array) with partial replacement of expensive deuterium with cheaper helium, a potential possibility for the implementation of an economical generation regime with acceptable specific energy output is achieved. The conditions for the implementation of this regime are identified.**

Keywords: *supersonic cw chemical DF laser, secondary fuel, inert diluent, dilution degree, energy characteristics, lasing zone length, economical generation regime.*

1. Introduction

In the past few years, undoubted progress has been made in the development of solid-state lasers – disk [1] and fibre [2] ones. Nevertheless, supersonic HF/DF cw chemical lasers (HF/DF CWCLs) remain the most powerful (at a level of megawatts). They exhibit unique advantages – high energy potential and operation in autonomous regime that does not require external energy sources (only regular refuelling with fuel components is necessary). Excess heat is carried away by exhaust gases. With the ability to operate in different regimes (overtone HF laser, HF laser, DF laser, and DF–CO_2 laser), CWCLs generate radiation in a wide range of infrared wavelengths: $\lambda \approx 1.32–1.34$ μm (2–3 lines) , 2.71–2.91 μm (8–9 lines), 3.75–4.18 μm (12–15 lines), and 10.6 μm. Technological power plants based on fuelled CWCLs are mobile and can be transported to the place of use. The durability of the CWCL operation makes it possible to implement repetitively pulsed lasing with a high pulse power for several minutes.

Thanks to these advantages, high-power HF/DF CWCLs can find practical application in the development of a number of new technologies. Among these technologies are those that provide solutions to the problems of cleaning up space debris [3] and preventing meteoric danger [4]; launching small satellites without using a launch vehicle (laser rocket engine) [5]; lightning protection of particularly valuable ground objects [6]; reduction of thermal radiation defocusing on the track during its transportation to the impact zone (formation of conductive channels in the atmosphere with minimal resistivity) [7]; development of systems for cleaning water [8] and solid [9] surfaces from a wide range of contaminants; remote cutting of metal structures located in hard-to-reach places in emergency situations of man-made hazards (fires in oil and gas wells, emergencies at chemical industry enterprises and nuclear power facilities) and in the aftermath of various disasters [10]; cutting multilayer energy-saving packages of glass, ceramics and composite materials along an arbitrary path at room temperature [10]; spatial sweep of a series of high-frequency optical discharges in the air during ignition of the sprayed combustible mixtures [11]; elimination of laser-plasma shielding of the affected object and a significant increase in the efficiency of energy input into the target, as well as providing local energy release in space and time, reducing energy consumption due to switching to the regime of target material ablation; and the implementation of the radiation impact on the affected object, which combines laser and high-voltage pulses during their propagation in space (combating terrorists, protecting particularly important objects from penetrations).

However, these lasers have certain disadvantages. It is known [12] that characteristic of supersonic HF/DF CWCLs are generation regimes with multiple excess of the volume flow rate of the secondary fuel (H_2 or D_2) above that of the oxidising gas ($F + F_2 + He$) compared to the stoichiometric ratio of the flow rates of these reagents [excess ratio of secondary fuel (deuterium) $\alpha_2 = n_{D_2}(n_{F_2} - n_{H_2}) = 10 - 12$].

This circumstance is due to the following reasons: 1) from the gas-dynamic viewpoint, this excess provides the possibility of attaining the estimated outflow regime, i.e., the coordination of pressures in the sections of the secondary fuel and oxidising gas nozzles (in this case, the interaction of jets is accompanied by the formation of compression shockwaves of minimal intensity); 2) from the thermodynamic viewpoint, the presence of a significant excess of cold hydrogen (or deuterium) in the chemical reaction zone of pumping seems to be favourable since, having a high heat capacity, it serves as a 'thermal ballast' and prevents excessive growth of the static temperature in the chemical reaction zone of pumping and the resulting effect of lasing breakdown; and 3) from the molecular and kinetic viewpoint, the excess of the secondary fuel contributes to an increase in the frequency of collisions of

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its molecules with the oxidiser F atoms, which intensifies the chemical reaction of pumping $F + D_2 \rightarrow DF(v) + D$ or $F + H_2 \rightarrow HF(v) + H$ and provides complete combustion of fluorine in the lasing zone.

Obviously, the function of the 'thermal ballast' can be performed not only by the secondary fuel molecules, but also by the molecules of an inert diluent (for example, helium) introduced into the jet of the secondary fuel. In this case, an increase in the content of the inert diluent in the reagent mixing zone due to partial dilution of the secondary fuel with helium can positively affect the laser's output characteristics as a result of a noticeable increase in the lasing zone length and a decrease in radiation load on the resonator mirrors without a significant reduction in both the laser power and its specific energy output, especially in the DF CWCL variant, when the molecular masses of deuterium and helium coincide.

And, finally, the potential possibility of significant reduction costs during the testing of high-power DF CWCLs seems to be quite important. The fact is that the cost of the secondary D_2 fuel is quite high. In the world market, it is about \$5,000 per kilogram, and in the domestic market – about \$2,500. For typical generation regimes of such a laser, the cost of deuterium is almost an order of magnitude higher than the total cost of all other reagents, which leads to a very high start-up cost.

Given the role of the secondary fuel noted above, the start-up cost when conducting the DF CWCL bench tests can be significantly reduced by diluting the secondary flow with an inert diluent, such as helium, without significantly reducing the laser energy. Indeed, when replacing deuterium with helium, condition 1) is not violated, since, due to the same molecular weight of the reagents, the gas-dynamic regime of the secondary flow in the nozzles does not change too much (only in the case of differences in viscosity coefficients and heat capacities). To fulfil condition 3), large values of the secondary fuel excess coefficient ($\alpha_2 = 10-12$) are not required, since smaller α_2 values are sufficient for complete combustion of fluorine, even with the laminar diffusion nature of jet mixing. Moreover, the secondary flow diffusion into the oxidising gas when diluted with helium will be more intense due to the high diffusion capacity of the latter.

With allowance for these circumstances, an attempt is made of a systematic comprehensive (experimental and computer-aided theoretical) study of the conditions for the implementation of an economical generation regime for a supersonic DF CWCL by replacing part of the expensive secondary fuel (deuterium) with a cheaper inert diluent (helium).

2. Conditions for conducting experiments

The object of our study is a bench model of a supersonic DF laser (active medium generator) of autonomous type with an estimated power of $N \sim 5$ kW, equipped with a flat nozzle array (*7*) made according to the 'nozzle–nozzle' reagent mixing scheme (Fig. 1). It comprises 34 wedge-shaped nozzles for the supply of the secondary fuel (deuterium), between which 33 profiled nozzles are located for the supply of the oxidising gas ($F + F_2 + HF + He$ mixture) from the atomic fluorine generator (*6*). The material of the nozzles is BrKh-08 bronze. The step of nozzle placement is 7.5 mm, and the output cross section size of the nozzle array is 250 × 28 mm. The nozzle array is water-cooled.

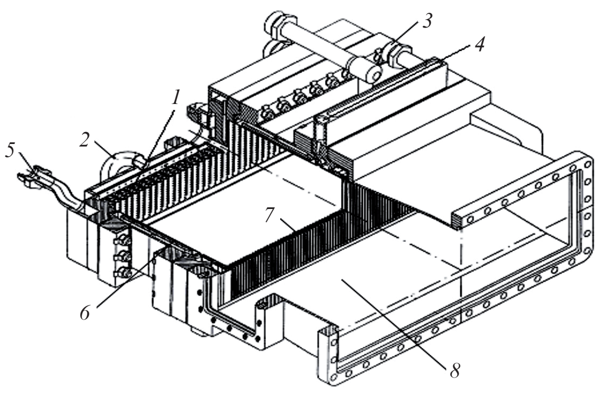

Figure 1. General view of the active medium generator of the DF CWCL bench model with a flat nozzle array according to the nozzle–nozzle mixing scheme:
(*1*) injector head; (*2*) oxidant supply (fluorine); (*3*) coolant supply (water); (*4*) supply of a mixture of secondary fuel (deuterium) and inert diluent (helium He^*); (*5*) supply of a mixture of primary fuel (hydrogen) and inert diluent (helium He); (*6*) combustion chamber of the atomic fluorine generator; (*7*) nozzle array; (*8*) laser chamber (resonator cavity).

The experiments were conducted on a bench. To form the working medium, traditional reagents were used: gaseous fluorine (oxidiser), hydrogen (primary fuel), helium (inert diluent), and deuterium (secondary fuel), which comprise the fuel composition $[H_2 + \alpha F_2 + \psi(\alpha - 1)He] + \alpha_{2\Sigma}(\alpha - 1) \times [(1 - C_{He})D_2 + C_{He}He^*]$, where $\alpha = n_{F_2}/n_{H_2}$ is the oxidiser excess ratio; $\psi = n_{He}/(n_{F_2} - n_{H_2})$ is the factor of fluorine dilution by helium in the atomic fluorine generator; $\alpha_{2\Sigma} = n_{D_2}(n_{F_2} - n_{H_2} - n_{He^*})^{-1}$ is the total excess coefficient of deuterium and helium flowing with deuterium in relation to free, conditionally molecular fluorine; n_i is the number of moles of the ith reagent; i are reagents F_2, H_2, He, D_2, and He^*; and C_{He} is the mass fraction of helium in the deuterium jet. The values of the α, ψ, and $\alpha_{2\Sigma}$ coefficients in our experiments and calculations were chosen to be close to optimal in terms of attaining the maximum specific output energy $N_\Sigma = N/m_\Sigma$ (N is the laser radiation power and m_Σ is the total mass flow rate of the fuel mixture). The pressure in the atomic fluorine generator was kept constant at a level of $p_c = 0.09$ MPa, corresponding to a maximum generation power of the laser model under study.

The active medium generator is installed in a low-pressure chamber designed to separate the gas jet flowing from the nozzle array in the free jet regime from the external medium. The pressure chamber is connected to vacuum tanks with a total volume of 600 m^3, into which the waste products of the reaction are fed. Inside the pressure chamber, a laser resonator is placed, which is moved by a remotely controlled motorised translation stage.

During the tests, the mass fraction of the inert gas (helium He^*) in the secondary fuel jet (deuterium) was varied in the range $0 \leqslant C_{He^*} \leqslant 0.8$, which corresponded to a change in the degree $\psi_2 = C_{He} \times (1 - C_{He})^{-1}$ of deuterium dilution with helium from 0 to 4. The laser operating parameters (pressure in the atomic fluorine generator, temperatures at various points along the cooling path, and mass consumption of reagents), as well as the laser radiation power were measured. The latter was measured by the closed resonator method using a mirror calorimeter with zero transparency according to the technique of work [13] with an error of ±7%. The mirror calorimeter was a stable resonator formed by two uncooled spherical mirrors with diameters of 86 mm and curvature radii of 5 m, made of polished bronze. The generation energy was determined from the temperatures of the resonator mirrors, measured by means of four soldered differential chromel–copel thermocouples mounted on the mirrors. The mirror calorimeter operation time (generation process duration) corresponded to the test duration and constituted ~40 s. It was determined using a low-inertia photodetector of FS-1 type, to which part of radiation was fed through a hole of 2 mm in diameter, located at the centre of one of the mirrors. In each test, the optimal location x_c^{opt} of the resonator optical axis was determined, at which the generation power was maximal.

3. Conditions for numerical calculations

The numerical analysis was conducted as follows, based on a set of mathematical models of the processes occurring in the elements of the gas-dynamic path of a DF CWCL developed at Russian Scientific Centre 'Applied Chemistry' together with Peter the Great St. Petersburg Polytechnic University [14]. The chemical composition and stagnation temperature of the oxidising gas flow at the exit from the atomic fluorine generator (at the entrance to the nozzle array) were determined by means of thermodynamic calculation from the given values of the oxidiser excess coefficient $\alpha = 1.73$, the degree of fluorine dilution by helium $\psi = 9$, and the pressure in the combustion chamber of the atomic fluorine generator $p_c = 0.09$ MPa.

Chemically nonequilibrium flow of the oxidising gas in oxidising nozzles was calculated by a finite-difference method based on the use of the 'narrow channel' approximation. The material of the walls of the nozzle array was considered totally catalytic with respect to the recombination reaction of atomic fluorine, and their temperature was assumed to be equal to 300 K, which corresponded to experimental conditions using intensive water cooling of the nozzle array.

The parameters $(1-C_{He})D_2 + C_{He}He^*$ of the secondary fuel flow at the nozzle array exit were also calculated in the framework of the 'narrow channel' approximation. In this case, the fuel stagnation pressure was selected during calculations so that the static pressures in the reagent jets at the nozzle side exit (at the entrance to the resonator) coincided with each other, which corresponded to the calculated outflow regime of the secondary fuel and oxidising gas into the resonator cavity (laser chamber).

The processes in the laser chamber and the CWCL output characteristics were calculated using a technique based on the 'narrow channel' approximation for a multicomponent gas mixture in the presence of chemical reactions, vibrational relaxation, and coherent radiation.

At the final calculation stage, the effect on the laser energy characteristics of atomic fluorine losses in the combustion chamber of the atomic fluorine generator, stipulated by recombination in the boundary layers on the cooled chamber walls, was taken into account. To this end, the values of energy characteristics determined by calculating the flow in the resonator cavity were multiplied by the coefficient $(1 - \delta C_F)$, which was calculated, unlike the case of adiabatic flow in the combustion chamber, using the relation

$$\delta C_F = \frac{C_F^{ad} - \bar{C}_F}{C_F^{ad}},$$

where δC_F is the loss factor of fluorine atoms on the cooled walls of the combustion chamber of the atomic fluorine generator; C_F^{ad} is the equilibrium mass concentration of atomic fluorine under adiabatic conditions;

$$\bar{C}_F = \frac{1}{g}\int_0^1 \rho u C_F \mathrm{d}\bar{y}$$

is the specific consumption of atomic fluorine at the exit from the combustion chamber; ρ and u are the density and velocity of the oxidising gas; C_F is the concentration of fluorine atoms; $g = m_c/(HB)$ is the density of the mass flow rate of gas in the combustion chamber; m_c is the mass flow rate of the reagents through the combustion chamber; H and B are the height and width of the combustion chamber, respectively; and $\bar{y} = y/H$ is the relative transverse coordinate.

Even though the described complex of mathematical models should be attributed to low-dimensional models, the validity of the approach used to calculate the energy characteristics of an HF/DF CWCL equipped with flat nozzle arrays of the nozzle–nozzle type was repeatedly demonstrated by comparing the results of calculations with experimental data.

4. Results and discussion

The results of experiments are presented in Table 1, and the results of calculations are shown in Figs 2 and 3. In considering them, we should emphasise quite satisfactory (within 10%) agreement between the calculated and experimental values of the specific energy output N_Σ. Certain increase in the difference of the results, which occurs with a strong dilution of the secondary fuel (deuterium) with helium ($C_{He} \approx 0.75$, $\psi_2 \approx 3$) is apparently due to the fact that in this case the resonator mirrors with a diameter of 86 mm do not completely cover the lasing zone, and therefore the measured value of N_Σ turns out somewhat underestimated (see Table 1, Test No. 2).

Satisfactory agreement between the calculated and experimental data makes it possible to use the results of calculations to interpret the obtained dependences of the DF CWCL output characteristics on the degree of dilution of the secondary fuel with helium and to analyse its effect on the laser parameters that are not measured in the experiment.

Table 1. Operating parameters and energy characteristics of the DF CWCL supersonic model with different degrees of the secondary fuel (deuterium) dilution with helium.

Test number	C_{He}	p_c/MPa	α	ψ	$\alpha_{2\Sigma}$	x_c^{opt}/mm	N_Σ/J g^{-1}	N/kW
1	0	0.89	1.76	8.8	11.5	36.5	135.4	4.8
2	0.75	0.87	1.75	8.9	11.5	43.5	88.4	3.1
3	0.51	0.92	1.79	8.2	10.8	40.5	119.7	4.3
4	0.25	0.93	1.75	8.8	11.4	36.5	120.2	4.3

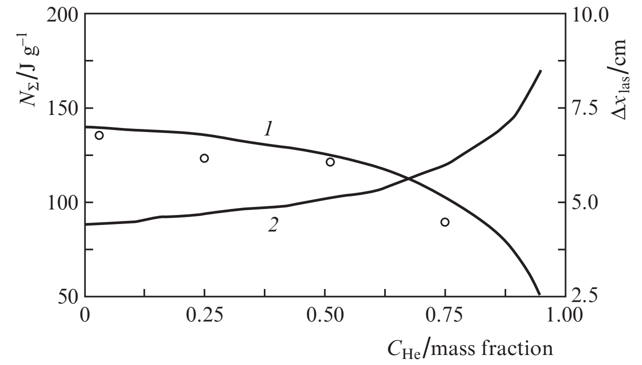

Figure 2. Dependences of (*1*) the specific energy output and (*2*) lasing zone length on the mass fraction of helium in the secondary fuel jet (deuterium) (points are the result of the experiment, solid curves are the results of calculation).

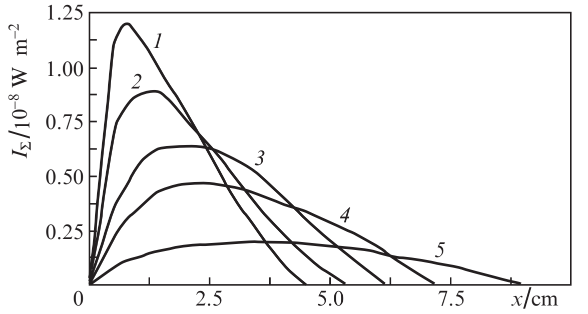

Figure 3. Distributions of the DF CWCL total radiation intensity along the lasing zone at C_{He} = (*1*) 0, (*2*) 0.50, (*3*) 0.75, (*4*) 0.85 and (*5*) 0.95.

It can be seen from Fig. 2 that an increase in the helium content in the secondary fuel jet, as expected, leads to a monotonous increase in the lasing zone length Δx_{las}. In this case, the maximum value of the radiation intensity I_Σ decreases, and the position of the function $I_\Sigma(x)$ maximum is shifted downstream from the exit section of the nozzle array (Fig. 3). These effects are stipulated by the fact that, with an increase in the degree of dilution of the secondary fuel with helium, the rate of deuterium diffusion into the oxidising gas flow decreases. This, in turn, leads to a decrease in the rate of pump reactions $F + D_2 \rightarrow DF(v) + D$, and consequently, to a decrease in the production rate DF(v) of vibrationally excited molecules in the flow and a decrease in the growth rate of the thermodynamic temperature of the mixture. Ultimately, the radial load on the resonator mirrors turns out significantly reduced.

The recording of laser emission spectra has not been carried out within the framework of this study. However, based on obvious physical considerations, it can be assumed that a decrease in the growth rate of the thermodynamic temperature of the mixture with increasing helium content in the jet of secondary fuel should leads to a shift of the spectral lines into the short-wavelength spectral range (to a decrease in the rotational quantum numbers of transition levels) and to a decrease in their number and intensity. This assumption is confirmed by spectral measurements in experiments with CWCLs, in which an inert diluent was fed directly into the region of the active medium formation, also performing the function of the 'thermal ballast' [15].

As for the specific energy output, as can be seen from Fig. 2, an increase in the helium content in the secondary fuel jet is accompanied by a monotonous decrease in N_Σ. Important, however, is the fact that up to sufficiently high dilution degrees ψ_2 ($\psi_2 \sim 3$, $C_{He} \sim 0.75$), despite the very substantial deuterium dilution with helium (replacing about 75% of secondary fuel mass with an inert gas), the described effects are relatively weak: the N_Σ value in the range of $0 < C_{He} < 0.75$ decreases by no more than 20%, while the lasing zone length Δx_{las} increases by about 30% compared to the case of no diluent in the deuterium jet.

With a further increase in the dilution degree ψ_2 ($3 \leqslant \psi_2 \leqslant 20$; $0.75 \leqslant C_{He} \leqslant 0.95$), there is a rapid increase in the lasing zone length (more than twice) and a sharp decrease in the specific energy output (see Fig. 2), which makes these regimes ineffective in terms of attaining high laser energy characteristics.

The calculations have also shown that an increase in the dilution degree ψ_2 in the region $C_{He} \geqslant 0.5$ leads to a noticeable decrease in the already relatively low (compared to a HF CWCL) small-signal gain, and hence to a decrease in the degree of active medium saturation in the resonator during the DF CWCL operation in the generation regime. This circumstance is very significant for small-size models of the CWCL type we study, which, due to the short optical path length ($L_{opt} = 0.25$ m), has a rather high threshold gain factor $g_0 = 0.21$ m^{-1} (when the product of the reflection coefficients of the resonator mirrors $r_1 r_2 = 0.9$). Therefore, along with the dependences of the output characteristics on the degree of deuterium dilution with helium obtained for the small-size DF CWCL model we have studied, similar dependences for a DF CWCL with a lower threshold gain (for large-size models) are of considerable interest

In the present work, such dependences were numerically obtained by varying the optical path length in the range $0.25 \leqslant L_{opt} \leqslant 2$ m. Since the reflection coefficients of the resonator mirrors were fixed, this situation corresponded to a change in the threshold gain g_0 from 0.21 to 0.026 m^{-1}.

The calculation results indicate both the possibility of a substantial (almost 1.5 times) increase in the CWCL specific energy output at the expense of a decrease in the threshold gain factor (Fig. 4) and a decrease, with increasing L_{opt}, in the sensitivity of laser energy characteristics towards the degree of deuterium dilution with helium (Fig. 5). The latter circumstance may be important in the development of high-power DF CWCLs, in which a high degree of active medium saturation in the resonator is provided.

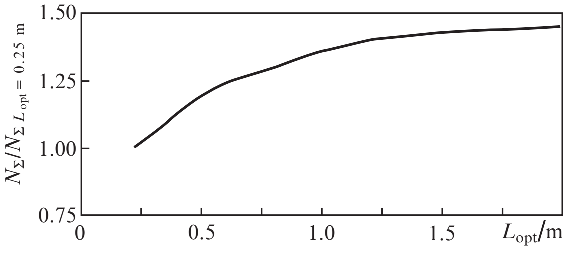

Figure 4. Dependence of the DF CWCL relative specific energy output on the optical path length in the absence of the secondary fuel (deuterium) dilution with helium.

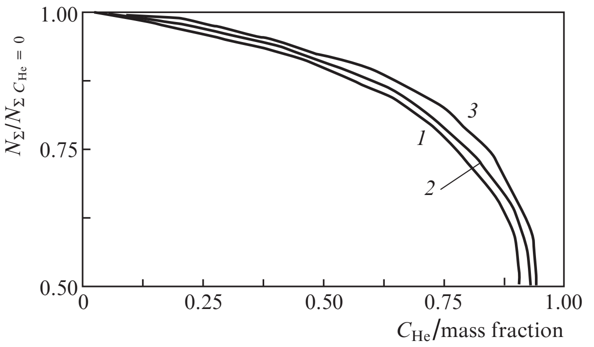

Figure 5. Dependences of the DF CWCL relative specific energy output on the dilution degree of the secondary fuel (deuterium) with helium at L_{opt} = (*1*) 0.25, (*2*) 1 and (*3*) 2 m.

5. Conclusions

Calculations and experiments have shown that, in the case of dilution (partial replacement) up to 75 mass % of the expensive secondary fuel (deuterium) by a much cheaper (almost 20 times) inert diluent (helium), the DF CWCL power and specific energy output change slightly, the lasing zone length increases, while the radiation loads on the resonator mirrors are reduced. As the length of the laser nozzle array increases in the direction of the resonator axis (lowering the threshold gain), the sensitivity of the specific energy output to the degree of deuterium dilution with helium decreases. Consequently, choosing from compromise considerations the degree of deuterium dilution with helium will reduce the start-up cost of a high-power DF CWCL with acceptable levels of energy characteristics and thus provide a more economical generation regime, which is especially important when conducting a large amount of bench tests for developing a laser design.

As for the actual DF CWCL operating conditions, the following can be noted here. As a result of many years of efforts, the technology of working with DF lasers of various power levels, including systems of multikilowatt and megawatt classes, has been reliably perfected in bench conditions. Based on the experience gained, several specific projects have been proposed for their use in ground-based [16], aviation [17] and space-based [18] systems, in which the problem of operating a laser with toxic exhaust products (HF and DF) has been successfully solved. In the first case, by using a special exhaust system that includes a gas ejector and adsorbers [13], whilst in the second and third cases – by scattering in the atmosphere and space.

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