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Problems in the development of autonomous mobile laser systems based on a cw chemical DF laser

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***Abstract*. The problems involved in designing autonomous mobile laser systems based on high-power cw chemical DF lasers, whose mass and overall dimensions would make it possible to install them on various vehicles, are discussed. The need for mobility of such lasers necessitates special attention to be paid to the quest for ways and means of reducing the mass and size of the main laser systems. The optimisation of the parameters of such lasers is studied for various methods of scaling their systems. A complex approach to analysis of the optical scheme of the laser system is developed.**

Keywords: *cw chemical DF laser, optical scheme of the laser system, optimisation of laser parameters.*

1. Introduction

The first fundamental results on the studies of various types of chemical lasers were obtained under the supervision of N.G. Basov at the Lebedev Physics Institute of the USSR Academy of Sciences [1–3]. It was at his initiative that work was started at the Energomash Research and Production Association on the development of high-power hydrogen fluoride cw chemical lasers (cw HF lasers). This association was chosen because its staff had a considerable experience in the development of various types of gas-dynamic devices and in the use of various types of fluorine- and fluoride-based oxidants for liquid fuel for rocket engines. The Astrofizika Research and Production Association and the State Institute of Applied Chemistry also took part in this work. At present, experimental samples of cw HF lasers with the output power ranging from a few kilowatt to 400 kW have been fabricated and tested at the Energomash.

In recent years, considerable interest has been evinced in the cw DF laser because a variety of problems can be solved with the help of this laser whose radiation propagates easily through the Earth atmosphere under different climatic conditions [4–6]. The potentialities of the cw DF laser were demonstrated during the testing of laser devices MIRACL [7] and THEL [8], although very little information is available about them. The range of applicability of the cw DF laser can be extended considerably by making it mobile, i.e., by mounting this laser on various vehicles like trucks, ships, aircrafts, etc. The aim of this work is to use the results of the experimental investigation of the cw HF laser (whose construction is basically identical to that of the cw DF laser) to study the possibilities of creating autonomous mobile laser systems based on cw DF lasers of various power, with the exhaust of laser gas flows to the atmosphere. Keeping in mind the need for transporting such systems, special attention must be paid to find out ways of reducing their mass and overall dimensions as far as possible. To compare the characteristics of various versions of the cw DF laser, we assumed that lasing occurs for 50 s.

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2. Approach to the problem of laser output power scaling

Fig. 1 shows the schematic of an autonomous cw DF laser, indicating the basic parts that determine its autonomous operation under the surrounding atmospheric conditions: the gain-gas generator (GGG) consisting of a combustor (with a combustor injector), a nozzle array and a laser chamber, an optical cavity, and the pressure recovery system consisting of a supersonic diffuser and a gas-jet ejector with the stream-gas generator (SGG). The atomic fluorine flow required for the chemical pumping reaction $F + D_2 \rightarrow DF^*(v) + D$ in the laser chamber was created by burning a mixture of C_2H_4 and NF_3, diluted with helium, in a combustor.

One of the basic ways of increasing the output power of the cw DF laser is the scaling (increase) of the area of the nozzle array exit of the GGG (Fig. 2). This can be done in two ways: by forming the active medium by several GGGs or by using a multisection nozzle array in a single GGG. In both these approaches used for scaling, the experience gained during the designing of cw HF lasers can be quite helpful. At the Energomash, many scientists and engineers were involved in the development of a medium-size cw HF laser with a nozzle array exit size of 100×400 mm and a nozzle spacing of 7.5 mm (Fig. 2a), capable of generating up to 30 kW output power by using a stable resonator, as well as a large-size cw HF laser with a nine-section nozzle array (spacing 6 mm, overall nozzle array exit size $400 \times 9 \times 155$ mm) with an output power up to 400 kW (Fig. 2b). Such a division of the nozzle array into sections along its length with a height 155 mm of the vanes in each section was caused by the impossibility of ensuring the strength of the

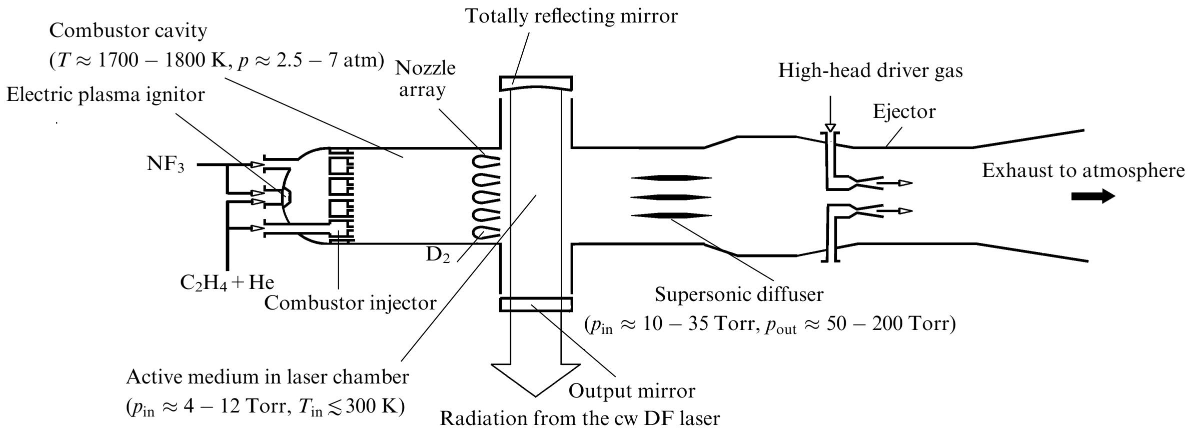

Figure 1. Schematic of the cw DF laser.

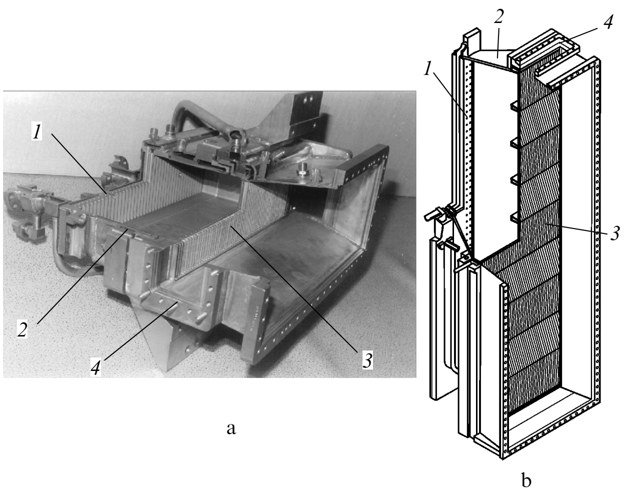

Figure 2. General view of (a) GGG of a medium-size cw HF laser and (b) a large-size cw HF laser with nine-section nozzle array: (*1*) combustor injector; (*2*) combustor housing; (*3*) nozzle array; (*4*) laser chamber window for laser radiation extraction.

array and the uniformity of deuterium flow into the laser chamber for vanes of height 400 mm arranged perpendiculary to the optical axis (see Fig. 2a).

Taking into account the results of these developments, we consider the problems associated with designing autonomous mobile systems based on cw DF lasers with different output powers and exhaust to the atmosphere. As an example, we consider three versions of the cw DF laser in which an unstable resonator was used to obtain highly collimated laser radiation:

1. based on a single medium-size GGG module (~ 15 kW);
2. based on two assemblies (with four medium-size GGG modules in each), placed one over the other (~ 160 kW);
3. based on one large-size nine-section GGG (~ 300 kW).

3. Gain-gas generator

To choose the operating regime for the GGG in the cw DF laser, a series of calculations was made in which the radiation intensity at various vibrational–rotational transitions of the DF molecule (1–0, 2–1, 3–2, and 4–3) and the gas-dynamic parameters were determined by solving self-consistently the system of equations describing the gas-dynamic and radiative processes occurring in the active medium assuming quasi-steady lasing. Because the calculations were time-consuming, gas-dynamic computations were based on Navier–Stokes equations in the narrow-channel approximation [9, 10]. As a result of the theoretical analysis of the energy parameters of the cw DF laser taking into account the operational characteristics of the fuel components, we chose an optimised molar fuel composition $C_2H_4 : NF_3 : He : D_2 = 1 : 6 : 33 : 90$. The spacing of the slot nozzle array was taken equal to 6 mm, as in a large-scale GGG. When such an array is used, we considered that it is expedient to maintain a low pressure of the active medium (~ 4 Torr) at the inlet to the laser chamber because it allows one

(a) to increase the length of the lasing zone along the gas flow;

(b) to lower the level of optical inhomogeneities in the active medium;

(c) to reduce the consumption of expensive deuterium; and

(d) to decrease the amount of toxic products in the exhaust gases.

Note also that the output power increases quite insignificantly (by ~ 10 %) as the pressure is increased from 4 to 12 Torr.

The experimental studies performed at the Energomash showed that by improving the nozzle array design and selecting appropriately the gas flow composition in a medium-size CCL, the amplitude of the periodic small-scale phase distortions of the laser radiation wave front after passing 1 m of the active medium at a pressure ~ 4 – 5 Torr can be lowered to a level not exceeding $\lambda/50$ [11]. The method of self-compensation for periodic phase distortions was used in large-scale nine-section GGG [12, 13]. For this purpose, the vanes were inclined to the optical axis at an angle of ~ 5°, and the sign of this angle was reversed for neighbouring sections. As a result, the amplitude of the periodic small-scale phase distortions in a large-size GGG was lowered to $\lambda/40$ per metre length of the active medium [11]. Therefore, when a multipass scheme with an effective length 5–6 m along the optical axis of the active medium of a cw DF laser is used, the phase distortions produced during one pass of the beam do not prevent the attainment of a beam divergence close to the diffraction limit.

4. Specific features of the optical scheme of laser systems

While calculating the laser system parameters, we should take into account the fact that the optical resonator is just a part of its optical scheme. As an example, Fig. 3 shows a simplified basic optical scheme of a laser system, providing the efficient action of laser radiation at quite large distances. Fig. 4 shows the basic optical schemes of the unstable resonator for the three versions of the cw DF laser proposed in Section 2. While calculating the energy parameters for all versions, the unstable resonator was replaced by a Fabry–Perot resonator to ensure a considerable decrease in the time required for calculations. A comparison of the results of calculations for both types of resonators was made by equating their output coupling factors: $1 - r = 1 - 1/M_{\rm res}^2$, where $M_{\rm res}$ is the magnification coefficient of the unstable resonator. Such a comparison is a certain approximation for estimating the output power of a laser with the unstable resonator, but the dependence of the power on the output coupling factor for the unstable resonator and the Fabry–Perot resonator will obviously remain the same.

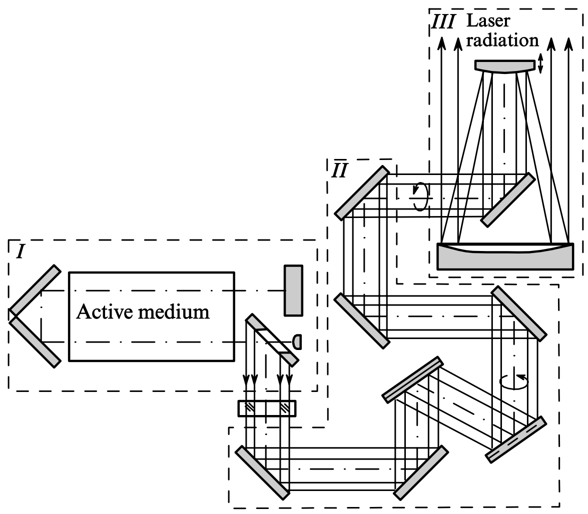

Figure 3. Simplified optical scheme of a cw DF-laser facility providing the propagation of radiation at large distances: (*I*) unstable resonator filled with active medium, (*II*) scheme for matching the shape and size of apertures at the unstable-resonator output and the entrance to the laser beam–director telescope, (*III*) laser beam–director telescope for obtaining laser beam with required aperture and its pointing and focusing to the object of action.

The most efficient optical scheme for the first nozzle array was the scheme with a Z-shaped optical axis (1/Z-version). For the second and third arrays, two schemes were considered: the two-pass (2/2 and 3/2 versions) and four-pass (2/4 and 3/4 versions) (here and below, the first digit indicates the cw DF-laser version number and the second digit corresponds to the number of passes of the laser beam through the active medium). The feedback factor r (reflectivity) for the resonator was varied in calculations. The loss

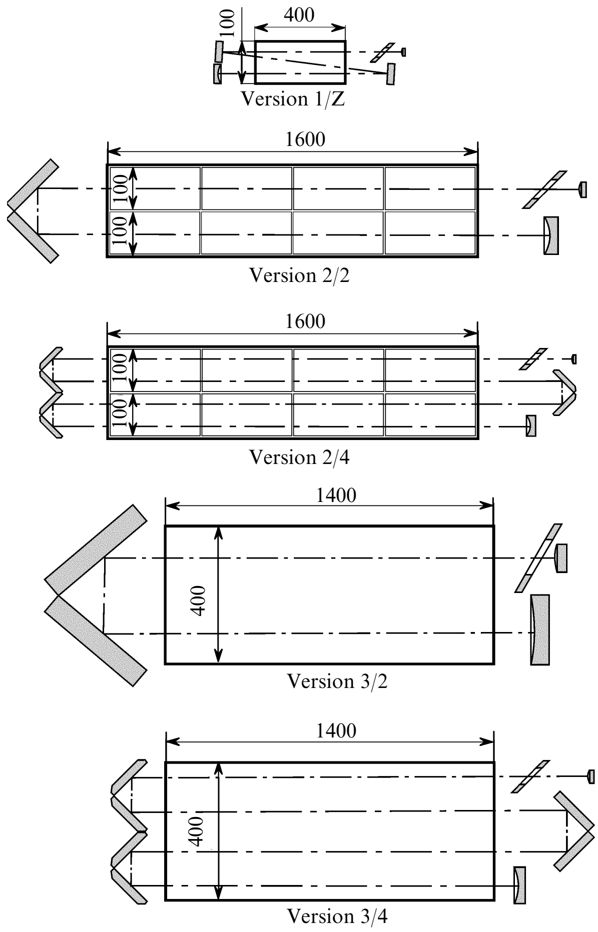

Figure 4. Optical schemes of unstable resonators for the three versions of the cw DF laser with different sizes of nozzle array exit area in GGG. (In order to eliminate parasitic resonators between corner reflectors in the 2/4 and 3/4 schemes, small detunings are introduced at their corners, which can easily be calculated using the geometrical optics methods.) All sizes in the schemes are given in millimetres.

factor in each mirror for all resonator schemes was assumed to be equal to 0.4 %. Because of the very low pressure of the active medium, nonresonance losses in it were neglected.

In the investigation of the power performances directly at the laser output, the objective criterion for comparison of various unstable-resonator schemes is the output power P_0 per square centimetre of the nozzle array exit area (nozzle array power flux P_0/S). Fig. 5a shows the dependences of P_0/S on r, each of which has its own maximum at a certain value $r_{\max}$. It is this maximum that is usually sought in the experiments.

In this work, we shall be guided by two criteria while choosing an optical scheme of the unstable resonator for the laser facility based on a cw DF laser using the laser beam–director telescope. These criteria are the attainment of the maximum axial intensity of the focused laser beam in the far field, and the confinement of the radiation load at the resonator mirrors to an ultimate value determined by the radiation strength of these mirrors.

The far-field radiation intensity for any version is directly proportional to the nozzle array power flux P_0/S and inversely proportional to the square of beam divergence angle θ at the exit of the laser beam–director telescope. For the most commonly used Cassegrain scheme of the laser beam – director telescope, the output beam aperture has the shape of a ring. In this case, despite the recommendations to use unstable resonators with essentially asymmetric radiation extraction in order to increase the power at the resonator exit, we consider that it is more expedient to use an unstable resonator with a symmetric extraction of radiation to avoid power losses in matching the apertures at the resonator output [14] and at the input of the laser beam – director telescope. For the linear magnification used in the scheme shown in Fig. 3, the relative areas of the ring aperture of a beam at the output of unstable resonators and the laser beam – director telescope, which correspond the output coupling factor $1-r$ of the equivalent Fabry – Perot resonator, are identical.

Since $1/\theta^2 \sim 1-r$, each version of the optical scheme of the unstable resonator can be characterised by a dimensionless parameter determining the relative brightness of laser radiation,

$$B(r) = \frac{(1-r)P_0(r)}{P_{0\,\max}^{(2/2)}},$$

where $P_{0\,\max}^{(2/2)}/S$ is the maximum nozzle array power flux for all the versions considered above (Fig. 5a). Using this parameter, we can compare different design versions of cw DF-laser facilities. A conical optical scheme can be used in principle for varying the relative area of the annular aperture for the beam outcoming from the resonator. However, this would complicate the optical scheme considerably and would lead to additional aberration distortions and to a considerable increase in the local radiation load on conical optical elements; hence, we do not consider this case here.

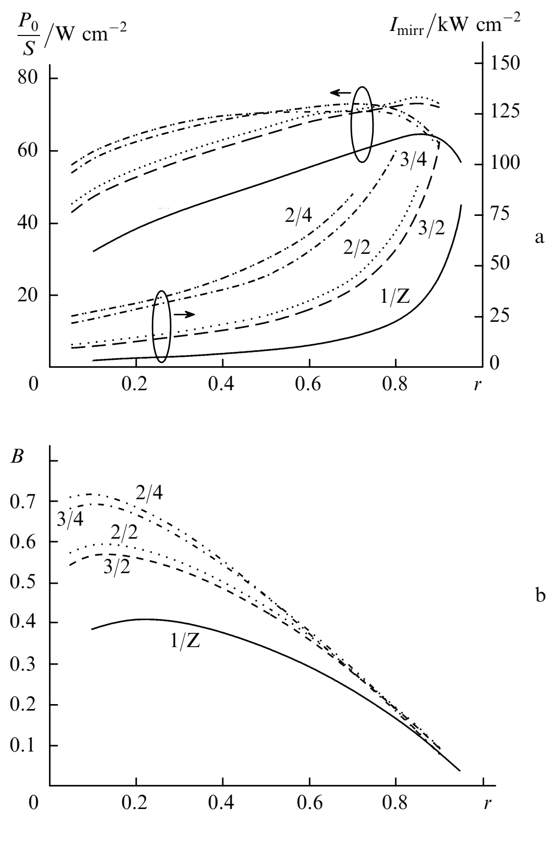

Figure 5. Dependences of nozzle array power flux P_0/S, intensity I_{mirr} at the most loaded mirror (a), and relative axial intensity of laser radiation in the far field B (b) on the feedback factor r of the resonator for different versions of the cw DF-laser design.

The dependences $B(r)$ shown in Fig. 5b have maxima $B_{\max}$ at the corresponding values of $r_{\rm opt}$. A comparison with Fig. 5a shows that the maximum axial intensity $B_{\max}$ of radiation in the far field in a certain version of a laser facility with an unstable resonator is attained for output coupling factors $1-r_{\rm opt}$, which differ significantly from values of $1-r_{\max}$ for which the power at the resonator output is maximum. For this reason, in a laser facility with an unstable resonator and a laser beam – director telescope, it is impossible to aim only at attaining the maximum power at the unstable resonator output.

As for the ultimate radiation load on resonator mirrors, the mirrors with a multilayer dielectric coating can withstand, according to [15], a load up to 60 kW cm^{-2}. Assuming a considerably smaller ultimate load (25 kW cm^{-2}) for reliably operating mirrors, we can estimate the limiting admissible output coupling factor $1-r_{\rm lim}$ of the resonator from the curves depicted in Fig. 5a. Table 1 contains the unstable-resonator feedback factors $r_{\max}$, $r_{\rm opt}$, and $r_{\rm lim}$ obtained in this way. The real feedback factor $r_{\rm res}$ can obviously be determined from the relation $r_{\rm res} = \min\{r_{\rm opt}, r_{\rm lim}\}$, which corresponds to $M_{\rm res} = 1/\sqrt{r_{\rm res}}$.

Table 1. Performance the cw DF laser with different unstable-resonator schemes.

Version	$r_{\max}$	$r_{\rm opt}$	$r_{\rm lim}$	$M_{\rm res}$	$P_{0\,\max}S^{-1}$/ W cm^{-2}	$B_{\max}$	$\frac{P_{\rm res}}{P_{0\,\max}}$	$P_{\rm res}$/kW
1/Z	0.86	0.22	0.81	2.1	65	0.41	0.62	16
2/2	0.85	0.13	0.48	2.8	75	0.59	0.69	166
2/4	0.70	0.10	0.05	4.5	73	0.72	0.77	180
3/2	0.85	0.14	0.54	2.7	73	0.57	0.69	282
3/4	0.70	0.105	0.12	3.1	71	0.69	0.82	326

The quantity $P_{\rm res}$ characterises the total laser power at the unstable-resonator output with the coefficient $M_{\rm res}$ from Table 1. The ratio $P_{\rm res}/P_{0\,\max}$ determines the power losses in such an unstable resonator as compared to the maximal power $P_{0\,\max}$ at the output of a Farby – Perot resonator. It follows from Table 1 that the loss $1- P_{\rm res}/P_{0\,\max}$ amounts from 18 % to 38 %; however, the axial radiation intensity in the far field for $r = r_{\rm res}$ nevertheless exceeds its value when the maximum output power is reached (for $r = r_{\max}$) by a factor of 3 – 4. Table 1 also shows that versions 2/4 and 3/4 ensure the maximum values of $B_{\max}$.

5. Pressure recovery system

The main elements of the pressure recovery system are a supersonic diffuser, in which a supersonic laser gas flow is transformed into a subsonic one with simultaneous recovery of static pressure, and a gas-jet ejector playing the role of a steam-jet pump for the exhaust of the flow from the supersonic diffuser exit to the atmosphere. Minimisation of the supersonic diffuser length at a conserving efficiency of static pressure recovery in the

Table 2. Main performance parameters of three versions of the cw DF laser for autonomous mobile laser facilities operating for 50 s.

Characteristics	GGG versions						
	Single medium-size module	Eight medium-size modules		Large-size module with nine-section nozzle array			
Laser output power/kW	15	160	160	300	300	300	300
Number of ejector stages	1	2	2	1	1	2	2
Oxidiser for SGG	O_2	O_2	O_2	H_2O_2	O_2	H_2O_2	O_2
Mass of resonator, GGG, diffuser, ejector, and SGG/t	0.6	3.6	3.6	3.7	3.7	3.7	3.7
Design of tanks and accessories	standard	standard	special	special		special	
Total mass of FSSS/t	2.4	13.2	6.4	9.9	12.4	7.6	9.3
Mass of components with bottles and tanks for GGG/t	0.5	3.4	1.6	2.3	2.3	2.3	2.3
Mass of components with bottles and tanks for SGG/t	1.2	6.5	4.5	7.2	9.7	4.9	6.6
Mass of accessories and pipes/t	0.7	3.3	0.3	0.4	0.4	0.4	0.4
Mass of supporting frame*/t	0.6	3.4	2	2.7	3.2	2.3	2.6
Total mass of laser/t	3.6	20.2	12	16.3	19.3	13.6	15.6
Laser overall dimensions (length×width×height)/m	5.8 × 2.0 × 2.5	8.9 × 3.9 × 2.9		8.1 × 3.2 × 3.0		9.3 × 3.2 × 3.0	

*The mass of the supporting frame is assumed to be 20 % of the mass of the entire equipment installed on it.

exhaust flow is ensured by using a multichannel design of the gas flow part.

The ejector for a mobile system must obviously be simple in design (i.e., must operate without cooling) and must consume available inexpensive and nontoxic fuel components for the SGG, which would be convenient for maintanance and would ensure admissible mass and size characteristics of the fuel storage and supply system (FSSS). The latter is determined by the ejector efficiency (the ratio of the flow rates of the low-head driven gas to the high-head driver gas), which is the higher, the higher the pressure and temperature of the high-head driver gas and the smaller its molar mass. The maximum temperature (~ 1100– 1200 K) of the high-head driver gas is determined by the temperature stability and high technological state of the materials used; it is not expedient to elevate the initial pressure of this gas above 50 – 60 atm in order to avoid undesirable condensation of water vapour constituting the main part of the high-head driver gas, which will occur upon a deeper cooling to the required level during expansion in supersonic nozzles of the ejector. An analysis carried out taking into account the above considerations shows that the most suitable compositions ensuring the best convenience in operation with most favourable mass and overall dimensions of the FSSS for the SGG operation are $C_2H_5OH - O_2$(gaseous) $- H_2O$ and $C_2H_5OH - H_2O_2 - H_2O$.

For lasers with an output power of 160 and 300 kW, it is expediant to employ a combination of eight two-stage ejectors. The multichannel nature of the ejection system facilitates the reduction of its length, while the presence of two stages makes it possible to considerably reduce the cmass flow rate of fuel composition for the SGG. For a moderate laser power (~ 15 kW), a simple one-stage ejector can be used since the mass of the facility is small as compared to the load-carrying capacity of vehicles (Table 2).

6. Fuel storage and supply system, and mass, and overall dimensions for three versions of the cw DF laser for autonomous mobile laser systems

Gaseous component are fed to the GGG and SGG directly from bottles under an initial pressure up to 250 atm, except for bottles with NF_3 (90 atm) and C_2H_4 (up to 100 atm) in view of special operating features of these components, while liquid components are supplied to the SGG by displacing them from tanks by gaseous nitrogen. Apart from standard bottles made from alloyed steel, the possibility of using in the FSSS of special bottles made of high-strength stainless steels and titanium alloys and manufactured at space-industry plants is also considered.

The main performance parameters and mass and overall dimensions of the cw DF laser are given in Table 2. It can be seen that, in all versions, the main contribution to the total mass of the laser comes from the FSSS; consequently, the use of special design of tanks, bottles, and accessories instead of standard designs will lead to a significant gain. For the eight-module version, this gain is ~ 40 % (12 t instead of 20 t); for this reason, in the version with an output power of 300 kW, we considered the possibility of using the bottles, tanks and accessories only with the special modification. Considering the latter version as an example, we see that the best results for the given output power can be obtained with a two-stage ejector. The use of H_2O_2 instead of gaseous O_2 leads to an insignificant gain (~ 2 t); a larger gain (~ 4 t) can be attained in the version with O_2 where a one-stage ejector is replaced by a two-stage ejector.

The general view of the cw DF-laser design version with an output power ~ 300 kW shown in Fig. 6 demonstrates the possibility of its location on vehicles with reasonable overall dimensions (even when a two-sage ejector is used), e.g., on a trailer truck with a load-carrying capacity not

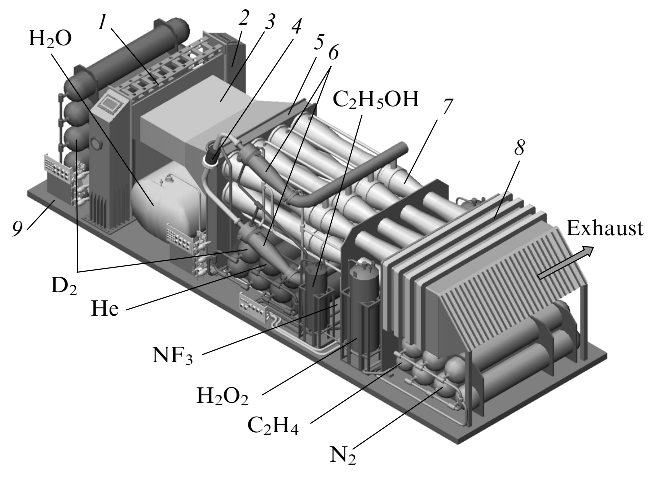

Figure 6. Design of the cw DF laser based on a single large-size GGG with a nine-section nozzle array, using H_2O_2 in the SGG: (*1*) large-size GGG; (*2*) unstable-resonator optical unit; (*3*) supersonic diffuser; (*4*) reactor for decomposition H_2O_2; (*5*) adapter chamber; (*6*) SGG; (*7*) two-stage ejectors; (*8*) muffler; (*9*) load-carrying frame.

exceeding 16 t. The pressure recovery system uses only one multichannel supersonic diffuser to which an assemble of eight two-stage ejectors (two rows with four ejectors in each) is connected through an adapter chamber.

7. Conclusions

Various methods are considered for scaling the cw DF laser components for a facility intended for complex studies of laser radiation propagation through the atmosphere and for working out the criteria ensuring the effective use of the laser radiation over large distances (of the order of several kilometers). Optimisation of optical schemes and the choice of rational thermodynamic and gas-dynamic parameters as well as the principles of designing basic cw DF laser systems proved that the mass and overall dimensions of these facilities with high output powers ($\sim$ 160 and 300 kW for a lasing time of 50 s) permit their location on almost all available vehicles: trailer trucks, ships, aircrafts, and so on. The cw DF-laser version with an output power of $\sim$ 300 kW is preferable for promising laser facilities since it ensures much higher power as compared to the multi-module version ($\sim$ 160 kW) for practically the same mass and overall dimensions. However, it is expedient to use the multimodule version for designing a demonstration laser facility during an extremely short time and with minimal possible expenditures since the testing can be mainly made on a single module with power $P_0 \approx 15$ kW.

Note that for the doubled operating life, the mass of the laser increases only by $\sim$ 50 %, while its overall dimensions increase by $\sim$ 20 – 30 %. Considerable potentialities for reducing the mass and overall dimensions lie in the reserves of the vehicle on which the laser facility is mounted (the use of water, kerosene instead of alcohol and electric power supply in the case of a ship, kerosene in the case of aircrafts, etc.).

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