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Characteristics of a cw chemical HF laser operating by using a new oxidising-gas production technique

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Abstract. **The energy and spectral characteristics of an HF laser operating by using a new method of obtaining the oxidising gas based on a two-region mixing are studied experimentally. The investigation involved redistribution of the overall amount of the rare-gas diluent (helium) delivered to the laser between the gas generator (the first mixing region) and the subsonic parts of the nozzles of the nozzle unit (the second mixing region). In this case, the temperature in the gas generator was maintained constant and the experiments were conducted under conditions when either the mass flow of atomic fluorine or the pressure in the gas generator were maintained constant. It was shown that upon a nearly full transfer of helium from the first mixing region to the second one in the constant-pressure regime in the gas generator, the laser output power increased by 70 %, while in the regime of a constant mass flow of atomic fluorine, the output power increased by 14 % along with a simultaneous increase in the specific energy extraction by 40 %. The lasing region was found to lengthen by no less than 35 %.**

Keywords: *chemical laser, oxidising gas, active medium.*

1. Introduction

The active medium in cw chemical HF/DF lasers (HF/DF CCLs) is produced during nozzle unit-effected mixing of the jets of an oxidising gas containing atomic fluorine, which are formed in a nozzle unit, and a secondary fuel (hydrogen or deuterium molecules) followed by the initiation of the pump reaction $F + H_2 \rightarrow HF(v) + H$ or $F + D_2 \rightarrow DF(v) + D$ in the cavity [$HF(v)$ и $DF(v)$ are the molecular reaction products in an excited vibrational state; and v is the vibrational quantum number]. In many respects, the properties of the active medium are determined by the properties of the oxidising gas, which should contain a maximum number of fluorine atoms (they play the role of active centres in the initiation of the pump reactions), a minimum number of by-products [they are deactivators of the working molecules $HF(v)$ and $DF(v)$], and should be as cool as possible (to reduce the relaxation rate of the working molecules in the active region and improve the conditions for the production of inversion). The oxidising gas is produced in a special gas generator.

There are several different ways of obtaining the oxidising gas. One of them involves using an external energy source (typically, an arc discharge). In this case, the gas generator is a plasmatron with a mixing chamber [1], in which a fluorine-containing compound dissociates under the action of high temperature with the production of atomic fluorine and by-products. Among the methods based on the use of external energy sources is the dissociation of fluorine-containing compounds under the action of electric discharges of other types – high-frequency [2], glow [3], and microwave [4] discharges. The method of obtaining the oxidising gas with the help of an external energy source is simple and minimises the amount of by-products. Its main disadvantage is the high energy consumption, which may be a problem in the case of high-power lasers (especially in mobile systems).

Another method for obtaining the oxidising gas uses an auxiliary exothermal chemical reaction, which proceeds in a gas generator. This method does not require an external energy source and is therefore autonomous. At present there are two variants of implementation of this approach. The first one uses the reaction of molecular fluorine with nitric oxide: $F_2 + NO \rightarrow NOF + F$. This variant is realised in subsonic CCLs and is described in Ref. [5]. However, the low reaction rate and insignificant thermal effect of the reaction result in low degrees of dissociation of molecular fluorine, which is responsible for rather moderate energy characteristics of the laser. In the second (traditional) variant [6], the gas generator is a combustion chamber, to which the initial reagents – the primary fuel, the fluorine-containing oxidiser, and the rare-gas diluent – are delivered through a mixing head. The oxidiser-to-primary fuel flow rate is set at an above-stoichiometric level. When this condition is fulfilled, the excess free fluorine contained in the combustion products, which are the oxidising gas, will completely or partly dissociate owing to the rise of the mixture temperature (up to $T = 1800 - 2000$ K) due to the heat released during combustion.

It is known [7, 8] that the efficiency of the HF/DF laser strongly depends on the translational temperature T of the active medium. When this temperature exceeds 600 – 650 K, the population inversion is suppressed and lasing is quenched. To reduce the translational temperature, a certain amount of an inert diluent (helium or nitrogen), which fulfils the function of a thermal ballast, is added to the oxidising

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gas. In the traditional variant of oxidising-gas production, all inert diluent (normally helium) is supplied to the combustion chamber, from which the diluent, heated to the dissociation temperature of the fluorine-containing oxidiser, is transported in mixture with fluorine atoms and combustion products via the nozzle to the cavity. A drawback of this method is the heating of the entire inert diluent to the dissociation temperature of the fluorine-containing oxidiser, which involves a virtually useless consumption of a part of the initial reagents and is accompanied by the production of an additional amount of deactivators – unexcited DF(0) or HF(0) molecules.

More efficient is reduction of the temperature of the active medium by feeding an additional amount of a cold inert diluent, for instance helium, directly to the region of the pump reaction (located behind the combustion chamber); the diluent is injected between the jets of the oxidising gas and the secondary fuel [9]. The additional diluent lowers the translational temperature of the active medium directly in the region of generation of laser radiation, which exerts a favourable effect on the energy laser characteristics. However, the realisation of this method complicates the design of the nozzle unit, which now contains the device for feeding the additional inert diluent. Attempts to use in full measure the additional inert diluent as the thermal ballast have failed, because a part of helium mixes with the cold secondary fuel owing to diffusion.

The aim of our work is to investigate the characteristics of an HF laser with the aid of a new method of obtaining the oxidising gas. This method involves two-region mixing and is distinguished by the absence of heating of the bulk (or of the entire quantity) of the inert diluent to the dissociation temperature of the fluorine-containing oxidiser. The essence of the method is that the high-temperature mixture prepared in the gas generator (in the first mixing region), which contains fluorine atoms, as well as the cold inert diluent are delivered in the form of separate jets to the input of subsonic parts of the nozzles of the nozzle unit (to the second mixing region). In the supersonic parts of the nozzles, these jets mix under chemically nonequilibrium conditions for a frozen composition of the mixture. As a result, the concentration of fluorine atoms remains virtually invariable, while the amount of reagents required for the production of the unit flow rate of atomic fluorine becomes smaller and the temperature of the oxidising gas fed to the active region decreases.

2. Experimental

We studied the characteristics of the HF-CCL by the new method of obtaining the oxidising gas on a test setup consisting of the HF laser, the systems for feeding the working reagents (F_2, D_2, H_2, He) and recording the parameters of the operating regime, and also the measuring system.

In the gas-dynamic path of the HF laser (Fig. 1), special injector (*4*) in the form of a perforated stainless steel tube 6 mm in diameter with bores 0.5 mm in diameter is located between the combustion chamber of gas generator (*1*) and the input part of slotted nozzles (*3*) of nozzle unit (*4*). The injector is intended for the injection of additional (secondary) inert diluent (He^* atoms) into every 3-mm wide slotted nozzle. The bores are arranged in three rows and are spaced at 5 mm in every row, the pitch corresponding to the

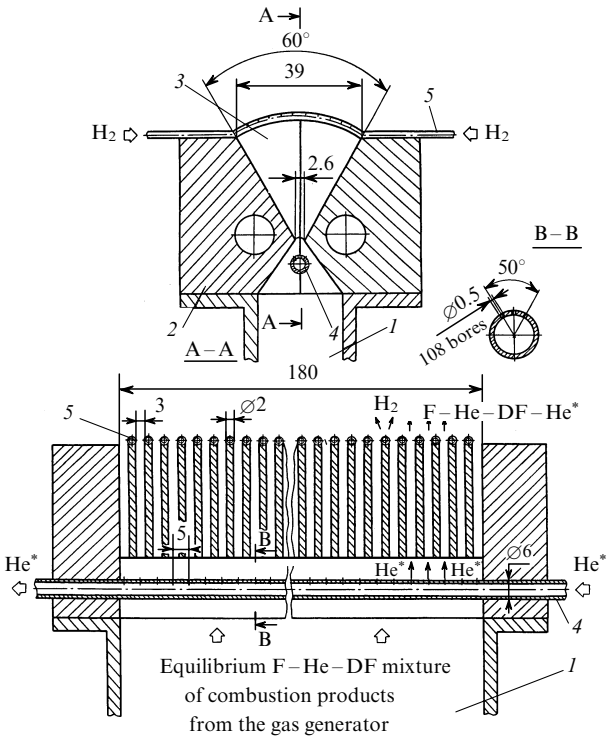

Figure 1. Scheme of the HF laser (the dimensions are given in millimetres): (*1*) combustion chamber of the gas generator; (*2*) nozzle unit; (*3*) supersonic nozzle; (*4*) special injector for the injection of additional inert diluent (helium); (*5*) tube for feeding the secondary fuel (hydrogen).

spacing of the nozzles (the injector contains 108 bores). The angle between the axes of two adjacent bores is equal to 25°. According to this arrangement, two streams are delivered to the region between the input to the subsonic part of the slotted nozzle and its critical section: the equilibrium mixture of mixed high-temperature ($T \sim 1800 - 2000$ K) combustion products (F, DF, and part of He atoms) from the gas generator and the additional low-temperature ($\sim$300 K) inert diluent (He^* atoms) from the special injector. The flow in the supersonic part of every slotted nozzle, which is attended with the mixing of these two streams, is chemically nonequilibrium in character [10]. Consequently, the density of free fluorine atoms remains virtually invariable and the oxidising-gas temperature decreases as a result of flow mixing in the nozzle, which should favour a decrease of the temperature of the active medium and an improvement of the energy laser characteristics.

The secondary fuel (H_2 molecules) is fed through a layon collector formed by 37 perforated injector tubes with an outer diameter of 2 mm and bores 0.35 mm in diameter (20 bores in every tube). The injector tubes are attached to the edges of the slotted nozzles; the bore axes make an angle of 20° with the flow direction of the oxidising gas (the F–He–DF–He^* mixture) emanating from the nozzles. The output section of the nozzle unit measures 180 × 39 mm.

We used in experiments a stable two-mirror closed spherical resonator with extraction of laser radiation through a 2-mm opening in one of the mirrors. Copper spherical mirrors of size 9 × 9 cm with a radius of curvature of 5 m and a polished reflective surface (with the reflectivity $r = 0.98$) were used. To take into account the radiation

absorption losses, each mirror was fitted with four chromel–copel thermocouples. The mirrors were mounted in special holders placed on an optical table accommodated in a pressure chamber. The table was equipped with a drive mechanism to ensure the possibility of smooth variation of the position of the optical resonator axis relative to the exit section of the nozzle unit of the HF laser accommodated in the same pressure chamber. The resonator length (the distance between the mirrors) was 1 m. The output window of the pressure chamber was made of a plate of calcium fluoride 16 cm in diameter.

The power of laser radiation generated in the closed resonator was measured by the method [11] with an accuracy of ±7 %. The power of laser radiation extracted through an opening 2 mm in diameter was measured by devices of two types: a Model 201 (Coherent Radiation, USA) calorimeter and an MG-30 pyroelectric detector with an accuracy of ±10 %. The laser radiation spectrum was recorded with an IR spectrometer on the basis of an IKM-1 monochromator. The accuracy of measurements of the relative intensities of spectral lines did not exceed ±5 %.

As reagents, we employed fluorine gas (the oxidiser), deuterium (the primary fuel), helium (the primary and secondary diluents), and hydrogen (the secondary fuel) in the $D_2:F_2:He:H_2:He^* = 1:\alpha:\psi_1(\alpha-1):\alpha_2(\alpha-1):\psi_2(\alpha-1)$ molar ratio, where $\alpha = n_{F_2}/n_{D_2}$; $\psi_1 = n_{He}/(n_{F_2})_{free}$; $\alpha_2 = n_{H_2}/(n_{F_2})_{free}$; $\psi_2 = n^*_{He}/(n_{F_2})_{free}$; $(n_{F_2})_{free} = n_{F_2} - n_{D_2}$; n is the number of moles of the corresponding reagent.

We focused our attention in the study on the measurement of the dependences of the energy characteristics of the HF laser on the amount of helium, which was successively withdrawn from the gas generator (from the first mixing region) and directed to the special injector for delivery to the subsonic parts of the nozzles of the nozzle unit (to the second mixing region). In this case, the overall degree of dilution of the fuel mixture $\psi_\Sigma = \psi_1 + \psi_2 \sim 13$ was maintained invariable (close to the optimum for the HF laser with the use of the traditional method of obtaining the oxidising gas [12]). The dimensionless coefficients ψ_1 and ψ_2 assumed the following respective values: the degree of primary dilution $\psi_1 = 13$ (100 %), 5.3 (40 %), 2.6 (20 %), 0.65 (5 %) and the degree of secondary dilution $\psi_2 = 0$ (0 %), 7.7 (60 %), 10.4 (80 %), 12.35 (95 %).

For clarity of presentation of the results, we used the parameter $\bar{\Psi}_1 = [\psi_1/(\psi_1)_0] \times 100\ \%$ – the percentage of the inert diluent in the gas generator (in the first mixing region), where ψ_1 and $(\psi_1)_0 = 13$ are the degrees of primary dilution with and without the delivery of helium to the special injector, respectively. The laser operating mode for $\bar{\Psi}_1 = 100\ \%$ (when all helium was delivered to the gas generator) was adopted as the reference regime. The characteristics of precisely this regime were compared with all other regimes. The test conditions, which were conducted for a constant temperature in the gas generator, were prescribed proceeding from two requirements: as the amount of helium delivered to the special injector was increased, maintained constant was either the mass flow of atomic fluorine (m_F = const, with characteristic values of 5.11 and 6.21 g s^{-1}) or the pressure in the gas generator (P_c = const, at characteristic levels of 0.12 and 0.14 MPa). The secondary-fuel excess factor α_2 and the total mass flow of the reagents m_Σ were also maintained constant: $\alpha_2 \sim 10$ and $m_\Sigma \sim 30$ g s^{-1}, while the oxidiser excess coefficient α was varied in the range from 1.53 to 2.55.

3. Experimental results

We now turn to the analysis of the results obtained. In a special series of experiments we determined the optimal distance x_c of the optical resonator axis from the output section of the nozzle unit, which was equal to 13 mm when no helium was supplied to the special injector and to 17.5 mm with this supply. The displacement of the optimal position of the optical axis along the flow in the latter case is an indirect indication that the lasing region widened by no less than 35 %.

3.1 Energy characteristics of laser radiation

Figure 2 shows three groups of the dependences of laser radiation characteristics on the percentage of the inert diluent in the gas generator, with each dependence obtained for two values of the mass flow of atomic fluorine. All these dependences [$N = f(\bar{\Psi}_1)$, $N_\Sigma = f(\bar{\Psi}_1)$ and $N_F = f(\bar{\Psi}_1)$] reflect the growth of laser radiation energy with decreasing the percentage of helium in the first mixing region (down to $\bar{\Psi}_1 = 20\ \%$). In particular, the power of laser radiation N and the specific energy extraction per mass flow of atomic fluorine N_F increase by 10 % – 12 % (Figs 2a and 2c), while the specific energy extraction per total mass flow of the reagents N_Σ increases by 32 % – 35 % to attain a value of 226 J g^{-1} for $m_F = 5.11$ g s^{-1} [Fig. 2b, curve (*1*)]. On further lowering of $\bar{\Psi}_1$ to 5 %, all energy characteristics were observed to decrease [Fig. 2, curves (*1*)]. However,

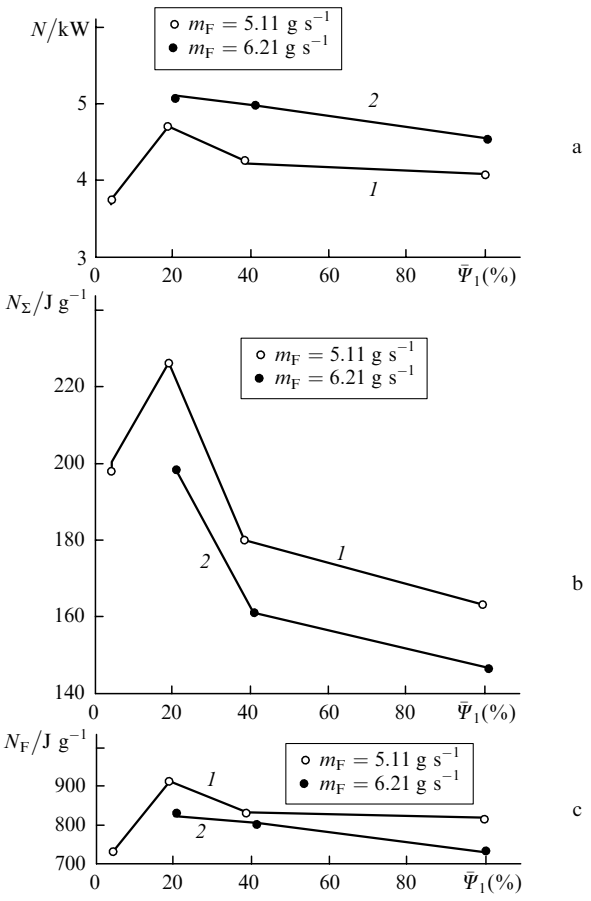

Figure 2. Dependences of the laser radiation power N (a) and specific energy extractions N_Σ (b) and N_F (c) on the relative fraction of the inert diluent in the gas generator for m_F = 5.11 and 6.21 g s^{-1}.

while the laser radiation power N for $\bar{\Psi}_1 = 5\,\%$ is 13 % lower than its value in the reference regime (for $\bar{\Psi}_1 = 100\,\%$), the specific energy extraction N_Σ exceeds the reference level by 15 %. In this case, the amount of molecular fluorine required to produce one gram of atomic fluorine is 1.8 times smaller, the amount of deuterium is three times smaller, and the amount of deuterium fluoride [the relaxant of the working HF(υ) molecules] is also tree times smaller. The last-mentioned circumstance is highly important from the standpoint of operating a practical laser facility, because it permits reducing the supply of reagents, improving the weight-dimensioning specifications of the facility storage system, lowering the facility cost, and improving its operational safety.

The effect of pressure in the gas generator on the energy characteristics of the HF laser for a helium percentage $\bar{\Psi}_1 = 20\,\%$ and 40 % is illustrated in Fig. 3. In the pressure variation ranges investigated, $P_c = 0.088 - 0.148$ MPa (for $\bar{\Psi}_1 = 20\,\%$) and $P_c = 0.122 - 0.163$ MPa (for $\bar{\Psi}_1 = 40\,\%$), we observed a smooth, almost linear increase in laser radiation power with increasing pressure (Fig. 3a).

The obtained dependences allowed us to describe the variations of energy characteristics of the laser throughout the helium percentage ($\bar{\Psi}_1$) range investigated (from 5 % to 100 %) at the pressures $P_c = 0.123$ and 0.136 MPa in the gas generator. They are plotted in Fig. 4. For $P_c = 0.123$ MPa, for instance, in the course of lowering $\bar{\Psi}_1$ from 100 % to 5 % we observed a growth of the laser radiation power N from 3.2 to 5.5 kW, which corresponds to the absolute rise by 70 % in power [Fig. 4a, curve (*1*)]. This result appears to be highly significant, for this is precisely the result that demonstrates the high energy efficiency of the new method of producing the oxidising gas.

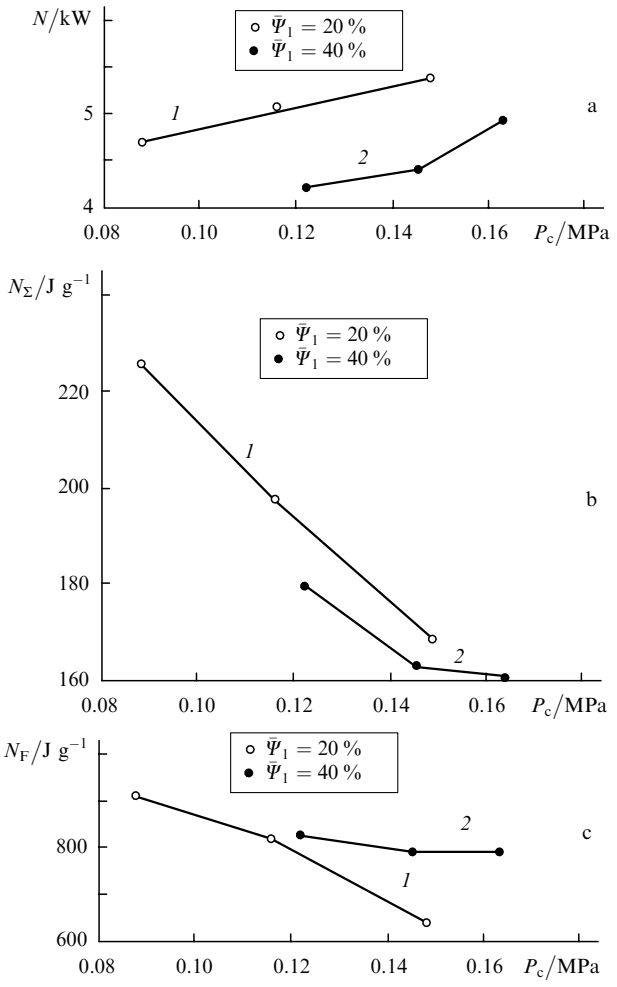

Figure 3. Dependences of the laser radiation power N (a) and specific energy extractions N_Σ (b) and N_F (c) on the pressure in the gas generator for $\bar{\Psi}_1 = 20\,\%$ and 40 %.

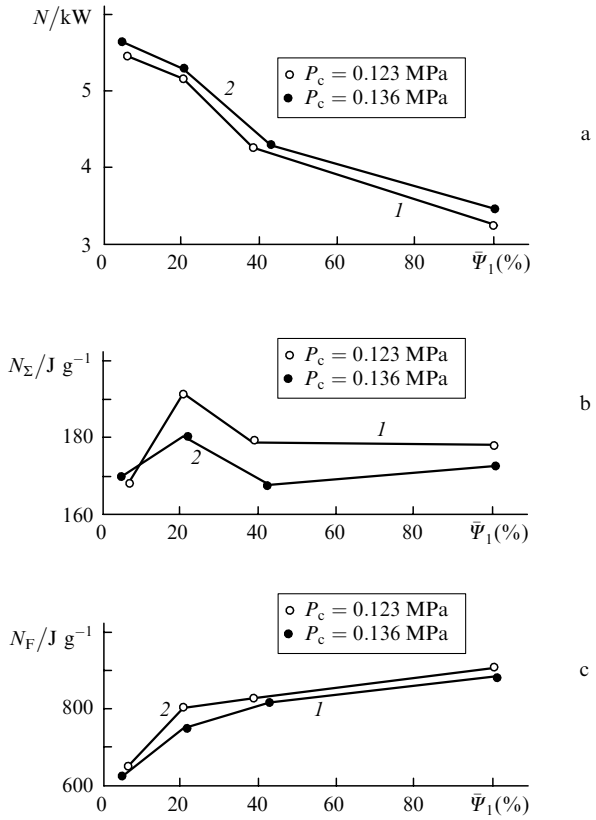

Figure 4. Dependences of the laser radiation power N (a) and specific energy extractions N_Σ (b) and N_F (c) on the relative fraction of the inert diluent in the gas generator for $P_c = 0.123$ and 0.136 MPa.

The specific energy extraction N_Σ in the range where $\bar{\Psi}_1$ varies from 100 % to 20 % increases slightly (by 8 %) with the subsequent, also small (by 12 %) decrease in the range where $\bar{\Psi}_1$ varies from 20 % to 5 % [Fig. 4b, curve (*1*)]. That is, N_Σ actually does not undergo any significant changes. As the percentage of helium $\bar{\Psi}_1$ decreases, the specific energy extraction N_F decreases: for $\bar{\Psi}_1 = 5\,\%$ it amounts to about 70 % of its value for $\bar{\Psi}_1 = 100\,\%$. With decreasing $\bar{\Psi}_1$, the N_F-decay rate increases to attain its maximum in the interval $\bar{\Psi}_1 = 20\,\% - 5\,\%$ (Fig. 4c). This behaviour of the function $N_F = f(\bar{\Psi}_1)$, taking into account the invariance of the amount of diluent per unit mass flow of free fluorine ($\psi_\Sigma = 13$ for $\bar{\Psi}_1 = 100\,\%$ and $\psi_\Sigma = 14$ for $\bar{\Psi}_1 = 5\,\%$), for the same pressure and stagnation temperature in the gas generator testifies, under the conditions of the temperature lowering of the oxidising flow in its mixing with the cold additional (secondary) helium in the nozzle cavity, to the existence of significant losses of atomic fluorine. These losses may be related both to high thermal losses in the gas generator and possibly to the design of the special injector for helium injection into the second mixing region. In

separate experiments it was found that the losses of atomic fluorine in the special injector (in experiments employing a blind tube to model it) resulted in additional ($\sim 15\,\%$) losses in laser radiation power.

Figures 5a and 5b show the experimental and calculated dependences of the laser radiation power $N = f(\bar{\Psi}_1)$ and specific energy extraction $N_F = f(\bar{\Psi}_1)$ for a pressure $P_c = 0.123$ MPa in the gas generator. They diverge significantly, the discrepancy becoming greater as the percentage of the primary diluent becomes smaller. It is pertinent to note that the calculated dependences do not take into account the additional losses of atomic fluorine. That is why they represent an estimate of the maximum attainable laser energy characteristics, i.e., an upper estimate. This estimate shows that an almost complete transfer of helium from the first mixing region to the second one (i.e., for $\bar{\Psi}_1 = 5\,\%$) would have resulted in a four-fold rise in laser radiation power N [curve (*1*) in Fig. 5b] and in a 1.6-fold rise in specific energy extraction N_Σ [curve (*1*) in Fig. 5b]. However, the substantial losses of atomic fluorine, which took place in our experiment, did not allows us to realise so high a potential in full measure.

Consider the possible reasons for the losses of atomic fluorine and estimate their effect. We determine the change of the duration of stay of combustion products $t = L_c/U$ in the gas generator (L_c is the length of combustion chamber and U is the flow velocity of combustion products), to begin with. The results of an estimative calculation show that, as the percentage of helium $\bar{\Psi}_1$ decreases, the time t lengthens compared to the reference-mode time t_0 to increase by about a factor of 2.2 for $\bar{\Psi}_1 = 5\,\%$ (Fig. 5d), which testifies directly to a substantial increase of the thermal losses in the gas generator.

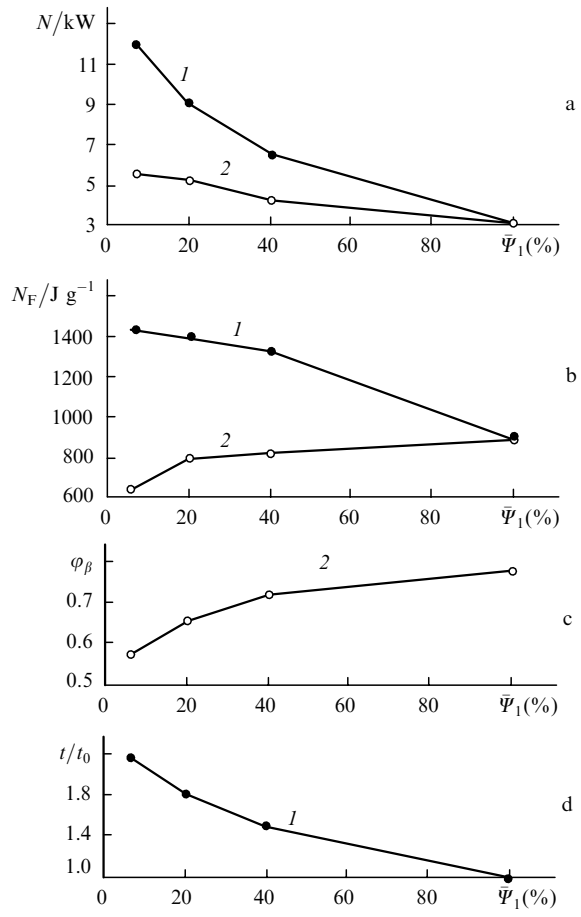

Figure 5. Calculated (*1*) and experimental (*2*) dependences of the laser radiation power N (a), specific energy extraction N_F (b), pressure coefficient φ_β (c), and relative duration of stay of combustion products t in the gas generator (d) on the relative fraction of the inert diluent in it; $P_c = 0.123$ MPa.

Let us now estimate the real thermal losses on the basis of available experimental data. To do this, we will use the pressure coefficient $\varphi_\beta = \mu(\beta_{exp}/\beta_{th})$, where β_{exp} and β_{th} are the experimentally measured and calculated [13] flows of the consumption complex and μ is the nozzle discharge coefficient (for minimal thermal losses, $\varphi_\beta = 0.96 - 0.98$). On analysing the results of these estimates, which are represented in the form of the function $\varphi_\beta = f(\bar{\Psi}_1)$ in Fig. 5c, we arrive at the following conclusions. First, the functions $\varphi_\beta = f(\bar{\Psi}_1)$ and $t/t_0 = f(\bar{\Psi}_1)$ behave in a diametrically opposite manner. This fact is indication that the increase of the duration of stay of combustion products in the gas generator with decreasing the percentage of helium in the first mixing region results in a significant rise of the thermal losses in it. Second, the curve $\varphi_\beta = f(\bar{\Psi}_1)$ is hardly different from the curve $N_F = f(\bar{\Psi}_1)$ in Fig. 4c. This circumstance means that the chief cause for the lowering of specific energy extraction N_F (and its associated laser radiation power N) is the reduction of the amount of atomic fluorine delivered to the region of active-medium formation due to its recombination. This recombination arises from high thermal losses (low values of φ_β equal to 0.56–0.72) and an almost two-fold increase of the time of contact of atomic fluorine with catalytically reactive walls of the gas generator, which is made of a copper alloy. Obviously, the increase of the growth rate of thermal losses and the duration of stay of combustion products in the gas generator with decreasing the percentage of helium delivered through the mixing head accounts also for the growth of the difference between the experimental and calculated plots of the functions $N = f(\bar{\Psi}_1)$ и $N_F = f(\bar{\Psi}_1)$ (Figs 5a and 5b).

3.2 Spectral power distributions of laser radiation

In the laser operation with a closed resonator, the number of spectral lines ranges up to fifteen, $P_0(6-13)$ in the $1 \to 0$ band and $P_1(6-12)$ in the $2 \to 1$ band, and the wavelength range is 2.707–3.096 μm. The processing of the oscillation spectra obtained under the constraint that the mass flow of atomic fluorine was constant ($m_F = 5.11$ g s^{-1}) allowed us to trace the behaviour of the most intense spectral lines $P_0(7,8)$ and $P_1(6-8)$ (Figs 6b and 6c). As the relative fraction $\bar{\Psi}_1$ of the diluent decreases, the degree $\bar{\Psi}_2$ of secondary dilution increases, the relative radiation powers of the $P_0(8)$ and $P_1(7,8)$ lines decrease monotonically to the relative power level $N_J/N = 0.05 - 0.1$. The power of the $P_0(7)$ line initially decreases and then, beginning with $\bar{\Psi}_1 = 20\,\%$, increases sharply. The relative power of the $P_1(6)$ line is almost invariable throughout the $\bar{\Psi}_1$ variation range. The distribution of spectral radiation power over the vibrational bands (Fig. 6a) is diametrically opposite for each of the bands. In this case, for $\bar{\Psi}_1 = 20\,\%$ the fraction of laser radiation power confined in the $2 \to 1$ band is largest (53.5 %) and in the $1 \to 0$ band is lowest (46.5 %). The spectrum-averaged rotational quantum number $J_m = \sum J_i N_i / \sum N_i$ (J_i and N_i are the rotational quantum number and the power of the ith spectral line) is also minimal for $\bar{\Psi}_1 = 20\,\%$ (Fig. 6d). This behaviour of the

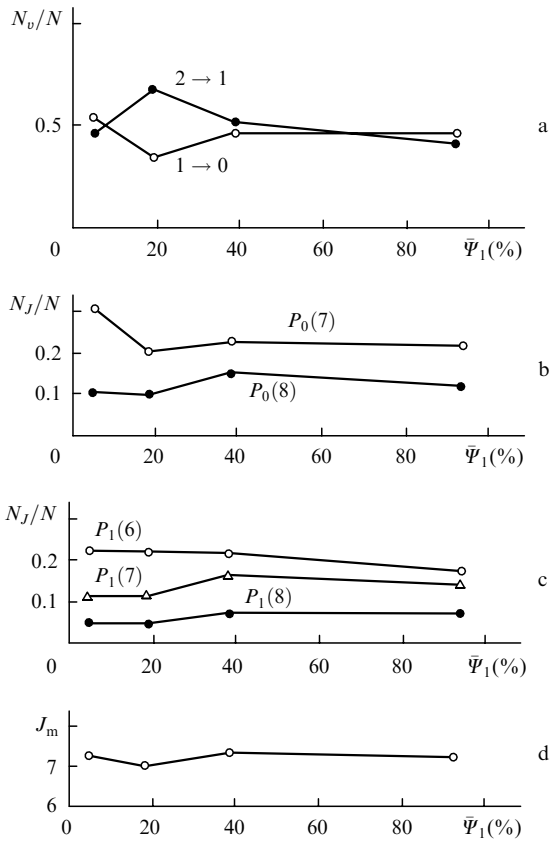

Figure 6. Spectral power distributions of the laser radiation in the vibrational bands N_υ/N (a) and in separate rotational transitions N_J/N (b, c) as well as the spectrum-averaged rotational quantum number J_m (d) as functions of the relative fraction of the inert diluent in the gas generator for $m_F = 5.11$ g s^{-1}.

spectral characteristics may be due to the fact that the temperature is minimal when the percentage of the inert diluent is $\bar{\Psi}_1 = 20$ % (when about 80 % of the total flow rate of helium is delivered to the special injector of helium). In this case, the conditions for the formation of inversion are more favourable, which accounts for the highest gain in the energy characteristics of the HF laser [curves (*1*) in Fig. 2].

4. Conclusions

By using a new method of obtaining the oxidising gas, we achieved a significant increase (by a factor of 1.4–1.7) in the energy characteristics of an HF laser. The high efficiency of the method has been demonstrated, which involves the reduction of the amount of initial working reagents required for the production of one gram of atomic fluorine and as well as of their combustion products, which are the relaxants of the working HF(υ) molecules. We have determined why it has not been possible to improve the energy characteristics of the small-scale laser version (designed for a flow rate $m_\Sigma \sim 30$ g s^{-1}) by more than a factor of 1.4–1.7). Among the underlying reasons are the losses of atomic fluorine caused by the high level of thermal losses in the combustion chamber of the gas generator and the long duration of stay of combustion products in it. Further improvement of the laser energy characteristics calls for a geometrically larger-scale (designed for a flow rate $m_\Sigma = 150 - 200$ g s^{-1}) model. Its design should correspond to the utmost the proposed way of obtaining the oxidising gas and exhibit the lowest possible losses of atomic fluorine due to the reduction of the relative fraction of thermal losses.

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