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Analysis of the possibility of designing more compact DF lasers driven by combustion of preheated fuels

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Abstract. **We report a theoretical calculation of the processes proceeding in the combustor of combustion-driven cw DF/HF chemical lasers with different mixtures of fuels preheated to high temperatures. Calculation results demonstrate a great effect of the preheating temperature on the yield of F atoms and strongest deactivator, on the primary dilution ratio Ψp and on the estimated specific power. When fuels are preheated to about 1300 K, the specific power is improved by about 74.2%, and the total mass of the fuel is reduced by about 43%, which makes it possible to realise a more compact and efficient design of combustion-driven cw DF/HF chemical lasers at elevated combustor pressures. Fuel preheating can facilitate the development of chemical lasers and high-power lasers based not only on airborne and space-borne platforms, but also on mobile ground-based platforms.**

Keywords: *chemical lasers, combustion-driven lasers, fuel preheating, compactness.*

1. Introduction

Combustion-driven cw DF/HF chemical lasers are representatives of high-energy lasers [1]. DF/HF laser programmes resulted in several multi-100-kW and MW-class systems including BDL, NACL, MIRACL and Alpha [2]. The ground-based DF tactical high-energy laser (THEL) is a laser developed for military use, whose mobile version (MTHEL) is intended to shoot down incoming rockets, artillery and mortars. Despite the highest performance in terms of the laser power output per unit of reactants, the MTHEL programme was postponed in 2006, because of the laser system bulkiness. Then, the research focus turned to the development of solid-state lasers (SSLs) in order to design a compact and efficient high-power laser; however, the results proved to be not so satisfactory.

It was pointed out by Carroll [1] in 2011 at the 42nd AIAA Conference on Plasma Dynamics and Lasers that if space-based platforms are ever again seriously investigated, we will likely see an HF or DF system considered because of the tremendous power-to-weight advantage.

The two main factors resulting in a large laser volume are huge gas-jet ejectors and a large fuel storage system. An effective method for decreasing the dimensions of gas-jet ejectors is an increase in the pressure in the optical cavity. A high-pressure active medium creates more favourable conditions for ejecting exhaust components into the ambient atmosphere [3], especially when designing an DF(HF) chemical laser for aircraft location at different altitudes (12 – 18 km) [4]. In this case, an increase in the pressure of the active medium 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. In 2011, Bashkin et al. [3] demonstrated the theoretical possibility of improving significantly the lasing characteristics of an autonomous DF laser using a ramp nozzle array (instead of a slot one) to form the active medium of an airborne laser at altitudes of about 8 km, with ejection of exhaust components into the ambient atmosphere without gas-jet ejectors.

When clearing the near-Earth space from space debris fragments (SDFs) with the help of a space-borne laser station (SBLS) equipped with an autonomous DF/HF chemical laser [5], the required mass of laser fuel components will be limited in order to ensure that the total mass of the SBLS does not exceed the carrying limit of its carrier rocket. Therefore, if the required mass of laser fuel components can be greatly reduced in some way, the SBLS can be more compact and the possibility of launching such a SBLS using a carrier rocket can be significantly improved.

To make combustion-driven DF/HF chemical lasers more compact and to improve their performance, fuel preheating had been tried by the Air Force Weapons Laboratory long before 1975 [6]. In work [6], He diluent was heated to 810 K from room temperature before entering the combustor, and the peak power of the laser was increased by about 15% compared to that at room temperature, which meant less fuel consumption to produce the same output power.

In this paper, the effect brought by fuel preheating is investigated theoretically. A theoretical and systematic calculation is made of the processes proceeding in the combustor of combustion-driven cw DF/HF chemical lasers with different fuel systems when fuels are preheated to high temperatures. In this case, the total pressure in the combustor is set to be high (20 bar), which will result in a favourable high-pressure active medium in the optical cavity with an acceptable gain length. Theoretical calculations show that the required total mass of laser fuel components is greatly reduced and a much higher specific power is obtained due to fuel preheating, which makes it possible to design more compact and efficient combustion-driven cw DF/HF chemical lasers.

2. Calculation method

In this paper, we have performed two series of calculations concerning the fuel preheating. The first series was designed

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to test the correctness of our calculations by comparing them with the reported experimental data [6]; in the calculations we used the following fuel mixture: $(D_2 + F_2 + He) + (H_2 + He^s)$, where $(D_2 + F_2 + He)$ was the fuel used in the combustor, and $(H_2 + He^s)$ was the fuel used in the optical cavity. The purpose of the second series was to analyse the influence of fuel preheating on the equilibrant output parameters of the combustor.

In classical combustion-driven DF/HF chemical lasers [7], the combustor acts as a fluorine generator, in which fluorine atoms are produced from fluorine-containing compounds (NF_3 or F_2) by thermal dissociation and then flow into the optical cavity through the nozzle array. The operating condition of the combustor determines the dissociation rate of NF_3 and the yield of fluorine atoms, which, in turn, affects the lasing environment in the optical cavity and the output performance of the laser.

When fuels are preheated to different high temperatures, the processes in the combustor of combustion-driven cw DF/HF chemical lasers with five different fuel systems are calculated based on the energy conservation equation. In these calculations, the commonly used fuel system $(C_2H_4 + NF_3 + He^p) + (D_2 + He^s)$ [8] is described in detail as below, where $(C_2H_4 + NF_3 + He^p)$ are the fuels in the combustor with He^p as a primary diluent, and $(D_2 + He^s)$ are the fuels in the optical cavity with He^s as a secondary diluent.

It was assumed that the initial reactants in the combustor are determined by the molecular ratio $C_2H_4 : NF_3 : He = 1 : 4\alpha : 6\Psi_p(\alpha - 1)$, where α is the NF_3 excess coefficient and Ψ_p is the primary dilution ratio. The fuels flow into the combustor after being preheated to temperature t_0. Thus, the external energy brought into the combustor can be calculated as follows:

$$Q_0 = (H^o_{t_0} - H^o_{298.15})_{C_2H_4} + 4\alpha(H^o_{t_0} - H^o_{298.15})_{NF_3}$$
$$+ 6\Psi_p(\alpha - 1)(H^o_{t_0} - H^o_{298.15})_{He^p}. \quad (1)$$

Here, $(H^o_{t_0} - H^o_{298.15})_i$ is the enthalpy change of 1 mole of the ith component from 298.15 K to temperature t_0, whose value can be calculated according to the American NIST standard database [9].

In the combustor there occur the following the chemical reactions:

exothermic reaction,

$$C_2H_4 + 4NF_3 \rightarrow 2CF_4 + 4HF + 2N_2, \quad (2)$$

dissociation reaction,

$$4\alpha NF_3 \rightarrow 4\alpha\Big[\frac{1}{2}N_2 + 3\alpha_F F + \frac{3}{2}(1 - \alpha)F_2\Big], \quad (3)$$

where α_F is the dissociation rate of NF_3.

The thermal balance of the above chemical reactions is found from the equations

$$Q_{exo} = [2\Delta_f H^o(CF_4) + 4\Delta_f H^o(HF) + 2\Delta_f H^o(N_2)] -$$
$$- [\Delta_f H^o(C_2H_4) + 4\Delta_f H^o(NF_3)], \quad (4)$$

$$Q_{dis} = (\alpha - 1)[12\alpha_F \Delta_f H^o(F) + 6(1 - \alpha_F)\Delta_f H^o(F_2)$$
$$+ 2\Delta_f H^o(N_2)] - 4\Delta_f H^o(NF_3). \quad (5)$$

Here, $\Delta_f H^o(i)$ is the standard enthalpy (in kJ mol^{-1}) of the ith component, which is given by the American NIST standard database [9]:

$\Delta_f H^o(CF_4) = -930$; $\Delta_f H^o(HF) = -272.55$;

$\Delta_f H^o(N_2) = \Delta_f H^o(F_2) = 0$; $\Delta_f H^o(C_2H_4) = 52.47$;

$\Delta_f H^o(NF_3) = -132.09$; $\Delta_f H^o(F) = 79.39$;

$Q_{exo} = -2474.31$ kJ mol^{-1} (the sign '-' indicates the heat release); and $Q_{dis} = (\alpha - 1)(952.68\alpha_F + 528.36)$ kJ mol^{-1}.

As a result of reactions (2) and (3), the concentrations of the reaction products achieve an equilibrium at an adiabatic temperature T_0. The heat needed to heat reaction products from room temperature up to the adiabatic temperature T_0 can be calculated as follows:

$$Q_{temp\,up} = 2(H^o_{T_0} - H^o_{298.15})_{CF_4} + 4(H^o_{T_0} - H^o_{298.15})_{HF} + 2\alpha$$
$$\times (H^o_{T_0} - H^o_{298.15})_{N_2} + 12\alpha_F(\alpha - 1)(H^o_{T_0} - H^o_{298.15})_F + 6(1 - \alpha_F)$$
$$\times (\alpha - 1)(H^o_{T_0} - H^o_{298.15})_{F_2} + 6\Psi_p(\alpha - 1)(H^o_{T_0} - H^o_{298.15})_{He^p}. \quad (6)$$

Then the energy conservation equation in the combustor can be written in the form

$$(1 - \eta_h)Q_{exo} + Q_0 = Q_{dis} + Q_{temp\,up}, \quad (7)$$

where η_h is the heat loss coefficient caused by heat transfer between reaction products and combustor walls. In our calculations, it is assumed that $\eta_h = 0.2$, according to previous experimental data [10].

In the optical cavity, F atoms and D_2 are reactants of the pump reaction

$$F + D_2 \rightarrow DF(v = 1\text{–}4, J) + D, \Delta H = -128 \text{ kJ mol}^{-1}, \quad (8)$$

and D_2 is always in excess in order to make full use of F atoms, so that F atoms, which are almost completely reacted, determine the output power of lasers in accordance with the empirical formula

$$P\,(\text{kW}) = \eta_{las} \times 128 n_F\ (\text{mol s}^{-1}), \quad (9)$$

in which $\eta_{las} = 10\%$–20% (we assumed in our calculations that $\eta_{las} = 10\%$), and n_i is the mole flow rate of the ith component.

The equilibrant output parameters of the combustor determine the lasing environment in the optical cavity. To increase the yield of F atoms, while keeping the equilibrium temperature T_0 at about 1900 K (in order to maintain the dissociation rate of NF_3 above 95%), it is assumed in our calculation that all the external energy brought into the combustor by fuel preheating is used to dissociate NF_3 such that to increase the fluorine inflow while keeping $n_{C_2H_4}$ and n_{He} unchanged. Thus, in the F-atom generator, P_0, T_0, Ψ_p and α_F are almost kept unchanged in order not to destroy the lasing environment in the optical cavity, and the only variables are n_{NF_3} and α. All the calculation results presented below are obtained by the programmes written by us based on the above calculation method.

3. Results of calculations

3.1. Checking the correctness of calculations

The purpose of the experiments in paper [6] was to measure the power loss due to the deactivation of DF, by heating He electrically to reduce D_2 and F_2 flow rates required to obtain the same fluorine dissociation fraction and fluorine flow rate to the cavity. In our calculations, the initial chemical composition of the fuel in the combustor is assumed to be $n_{F_2}:n_{D_2}:n_{He} = 0.1647:0.1109:1.265$, the total pressure is 1.6479 bar, and only He is heated, in accordance with the experimental conditions of Ref. [6]. Comparison of the main results of our calculations and the experiments data from [6] is shown in Fig. 1, in which the normalised value of n_{DF} is the ratio of the amount of DF obtained with heated He to that obtained with He at room temperature.

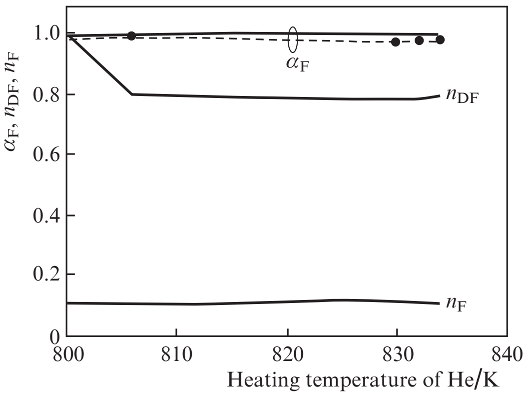

Figure 1. Comparison of the main results of our calculations (solid curves) with experimental data (points) from [6]; n_{DF} is the normalised value and n_F is measured in mol s^{-1}.

One can see from Fig. 1 that in our calculations, n_F and α_F are virtually constant, while n_{DF} decreases by about 21.5% when He is preheated to about 800 K. The experimental results [6], showing a 22% reduction in DF, confirm the correctness of our calculations.

3.2. Analysis of the influence of fuel preheating on the output characteristics of DF lasers

For the fuel system (C_2H_4 + NF_3 + He^p) + (D_2 + He^s) of combustion-driven chemical DF lasers, we performed a numerical analysis of the equilibrant output parameters of the combustor at different preheating temperature based on our calculations. Furthermore the calculations made it possible to assess the potential capabilities of combustion-driven HF/DF chemical lasers. The following results were obtained.

Figure 2 presents the initial fuel composition entering the combustor, which was determined by the thermodynamic calculation at different preheating temperatures (see Section 2). Because NF_3 is easily dissociated at a high temperature, in calculations the preheating temperature of NF_3 is limited to 550 K, while that of C_2H_4 and He are varied from 300 to 1300 K. Preliminary tests showed that stainless steel 310s can withstand a high temperature of 1300 K and can be used for fuel preheating. The total pressure in the combustor is 20 bar. One can see that the amount of the fluorine source (NF_3) increased with increasing preheating temperature, while the amount of C_2H_4 and He remains unchanged, consistent with the description in Section 2.

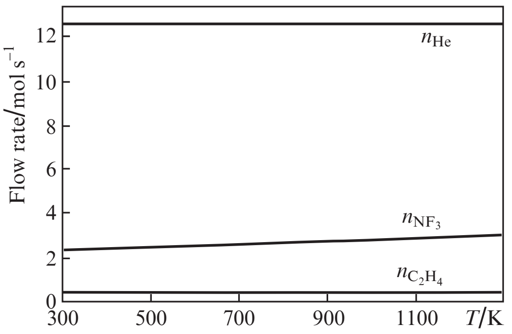

Figure 2. Initial fuel composition entering the combustor at different preheating temperatures T.

Additional He is used to produce a cooling film in the nozzle throats, which form an array that prevents the throats from the deformation due to ablation. The structure of the nozzle array with a cooling film (described in detail in our patent [11]) is shown in Fig. 3; the cooling film is quite necessary when lasers operate at a high combustor pressure, because in this case water-cooling alone cannot prevent nozzle throats from accumulated-ablation deformation, which was observed in real tests.

Figure 4–8 show the main results of our calculations of the output parameters of the combustor, which were obtained by varying the preheating temperature in the range from 300 to 1300 K. (The term ‘normalised’ in the figures means the ratio of the mentioned parameter of preheated fuel components to its value at room temperature.) These results demon-

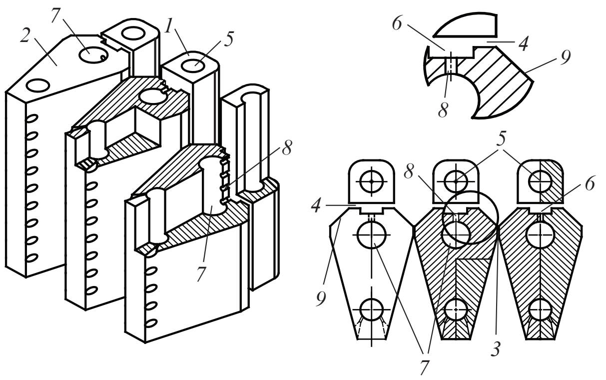

Figure 3. Structure of the nozzle array with a cooling film: (*1*) section before contraction; (*2*) section of throat and expansion; (*3*) throat; (*4*) cooling-film slit; (*5*) cooling-water channel; (*6*) buffer chamber; (*7*) throat-gas supply cavity; (*8*) microholes; (*9*) diversion section wall.

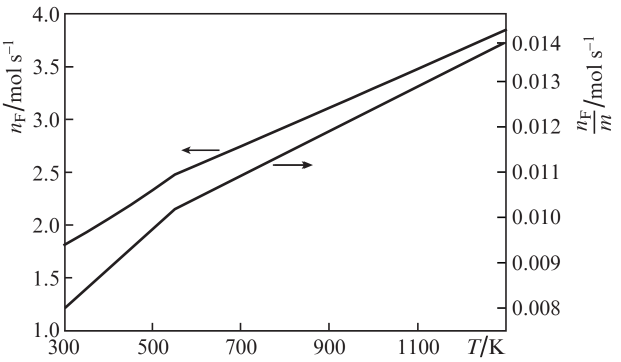

Figure 4. Dependences of n_F on the preheating temperature T (m is the total mass of fuel components).

strate clearly three characteristic features arising from the fuel preheating.

The first feature (Figs 4 and 6) consists in an increase in the yield of F atoms with increasing preheating temperature T (Fig. 4), i.e. the total mass of fuels needed to produce 1 mole of F atoms is greatly reduced (Fig. 6), by about 43%, when the preheating temperature reaches 1300 K.

The second feature is that the yield of the strongest deactivator (HF), which, according to the chemical reaction rate equation [10], deactivates excited DF molecules at a rate of about three orders of magnitude higher than the other components, is reduced enormously (Fig. 5). At $T \sim 1300$ K, the ratio n_{HF}/n_F was decreased by about 53%, which means the weakening of deactivation and the stretching of the lasing zone length in the optical cavity, both of which are very important for improving the output power of lasers and reducing the load on the cavity mirrors.

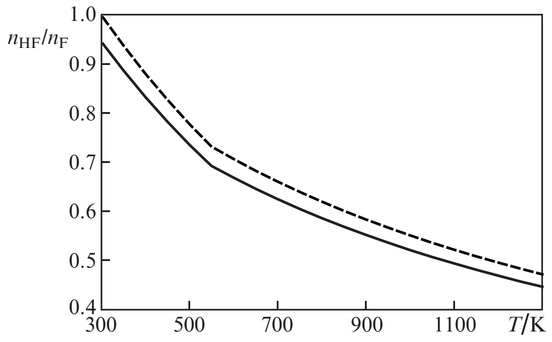

Figure 5. Dependences of n_{HF}/n_F on the preheating temperature T (dashed curve is the normalised ratio).

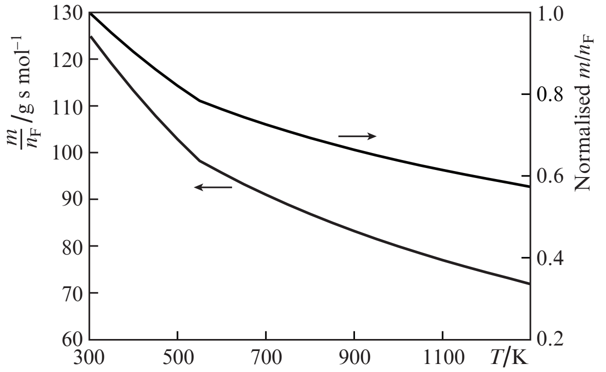

Figure 6. Dependences of m/n_F on the preheating temperature T.

The third feature is very useful for combustion-driven chemical lasers with a cooling film. A simple way to make the laser compact is to increase the working pressure in the combustor. However, there arise problems related to the fast ablation of the nozzle throat, which is intolerable from the point of view of increasing the service life of the laser. In our calculations, the working pressure in the combustor was increased to 20 bar, and a cooling film was introduced as described in paper [11] to avoid ablation of the nozzle throat. The calculation results show that the primary dilution ratio Ψ_p follows a downward trend with increasing preheating temperature. In order to keep the output parameter Ψ_p of the combustor unchanged and to minimise the influence on the lasing environment in the optical cavity, one can use reduced primary diluents (ΔHe in Fig. 7) as a cooling film at the throat of the nozzle array, which can protect the nozzle throat from ablation and help the laser to run longer.

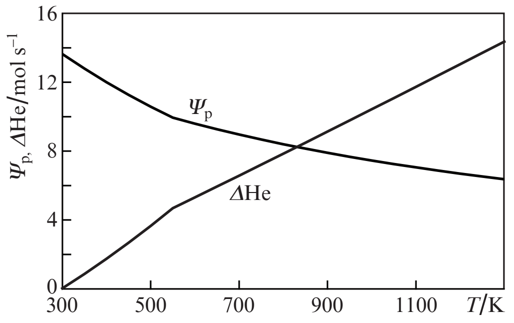

Figure 7. Dependences of the primary dilution ratio Ψ_p and ΔHe on the preheating temperature T (ΔHe is the He flow rate required to maintain Ψ_p constant in the combustor).

The specific output power (Fig. 8) was estimated according to Eqn (9), which related the output power with the parameter n_F. Note that the specific power of lasers follows an upward trend with increasing preheating temperature because n_F/m rises to supply more F atoms. At 800 and 1300 K, the specific power increased by about 44% and 74.2%, respectively, which is a significant progress in con-

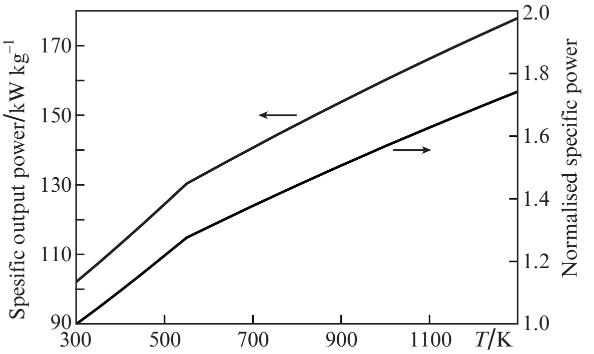

Figure 8. Estimated specific power at different preheating temperatures T.

structing compact combustion-driven chemical lasers. Our research group is currently working on a miniproject, whose aim is to study the effect of preliminary heated fuels on the output parameters of chemical lasers.

4. Conclusions

Our theoretical analysis of the effect of fuel preheating on the characteristic parameters of combustion-driven HF/DF chemical lasers allows the following conclusions.

(i) The yield of F atoms increases with increasing preheating temperature. At $T = 1300$ K, the total mass of fuels needed to produce F atoms is reduced by about 43% and the specific power is increased by about 74.2%, which is an advantage in designing more compact combustion-driven HF/DF chemical lasers.

(ii) The yield of the strongest deactivator (HF molecules) is reduced enormously with increasing preheating temperature, indicating the stretching of the lasing zone length in the optical cavity, which is important for improving the output power of lasers and reducing the load on the cavity mirrors.

(iii) The primary dilution ratio $\Psi_{\rm p}$ follows a downward trend with increasing preheating temperature. The reduced primary diluent He can be used as a cooling film at the throat of the nozzle array, which can keep the output parameter $\Psi_{\rm p}$ of the combustor unchanged and minimise the influence on the lasing environment in the optical cavity, as well as protect the throat from ablation and increase the service life of the laser.

The results obtained demonstrated a theoretical possibility of ensuring compactness and improving significantly the lasing characteristics of a combustion-driven DF laser using fuel preheating. However, to make the laser compact in practice, more factors effecting the performance need to be considered, such as the best preheating temperature, optimised cooling-film flow rate, feasible and innovative heating, which we plan to implement by using the numerical simulation and experiments in the near future.

References

1. Carroll D.L. *42nd AIAA Plasmadynamics and Lasers Conf.*, **3012**, 1-21 (2011).
2. Horkovich J.A. *AIAA Paper*, **2006**, 3753 (2006).
3. Bashkin A.S., Gurov L.V., Kurdyukov M.V. *Kvantovaya Elektron.*, **41** (8), 697 (2011) [*Quantum Electron.*, **41** (8), 697 (2011)].
4. Bashkin A.S., Parfen'ev M.V., Semenov S.N., in *Proc. RPE Energomash*, **24**, 344 (2006).
5. Avdeev A.V., Bashkin A.S., Katorgin B.I., Parfen'ev M.V. *Kvantovaya Elektron.*, **41** (7), 669 (2011) [*Quantum Electron.*, **41** (7), 669 (2011)].
6. Hyde J.C., Hurlock S.C. *Advanced Chemical Laser Nozzle Concept* (Springfield, 1975).
7. Spencer D.J. *Int. J. Chem. Kinetics*, **1**, 439 (1969).
8. Bashkin A.S., Gurov L.V., Katorgin B.I., Petrova S.N., Polinovsky D.V. *Kvantovaya Elektron.*, **38** (5) 429 (2008) [*Quantum Electron.*, **38** (5) 429 (2008)].
9. http://webbook.nist.gov/chemistry/.
10. Gross R.W., Bott J.F., Yin H.M. (Eds) *Handbook of Chemical Lasers* (New York: Wiley, 1976).
11. Chinese Patent 2015105296444 (2016).