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Numerical simulation of a high efficiency combustion-driven HF laser with preheated fuels

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Abstract. **We report a simulation calculation of the processes proceeding in a nozzle array and an optical cavity of a combustion-driven cw HF chemical laser with preheated fuels. Investigation results demonstrate that fuel preheating can dramatically improve the output characteristics of combustion-driven HF chemical lasers. The available output power and specific output power are improved by ~13% and ~46%, respectively, when fuels are preheated to 1200 K. It is shown that the fuel consumption in the combustor is reduced by ~36%, which allows one to improve the performance of combustion-driven HF lasers and make them more compact due to fuel preheating.**

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

1. Introduction

HF/DF chemical lasers have a history of about 50 years. They have been successfully used in many applications, including ground-based platforms [1–3] and space-based platforms [4–7]. As is well known, the large laser volume is the principal problem limiting the further development of combustion-driven continuous-wave DF/HF chemical lasers (DF/HF-CWCLs), which is mainly caused by huge gas-jet ejectors and a large fuel storage system. An effective method for reducing the volume of gas-jet ejectors is to increase the pressure in the optical cavity, i.e. to increase the total pressure in the combustor [8–10]. But no effective method has been found to reduce the volume of the fuel storage system.

In 1975, an experimental investigation aimed at improving the performance of DF/HF-CWCLs by fuel preheating was carried out by the Air Force Weapons Laboratory [11]. For a HF chemical laser with a fuel mixture of $(D_2-F_2-He)+H_2$, a He diluent was electrically heated to 810 K from room temperature before entering the combustor, to compensate for the D_2 and F_2 flow rates required to maintain the same fluorine dissociation fraction and fluorine flow rate to the cavity. The experimental results showed that the peak power of the laser was increased by about 15% compared to that at room temperature, due to a 22-percent reduction of DF (the strongest deactivator) in the optical cavity, which means less fuel consumption to produce the same output power.

This investigation triggered the development of more compact DF/HF-CWCLs by reducing the amount of fuel needed through fuel preheating, especially after problems related to fast ablation of nozzle throats during long-term operation at a high combustor total pressure had been solved successfully [12–14].

Our research team is carrying out a research into a new type of DF/HF-CWCLs, which are more compact and exhibit better performance characteristics. At the first stage, fuel preheating has been studied theoretically to analyse its potential for compact DF/HF-CWCLs [10]. Calculation results show that the required total mass of laser fuels was reduced by about 43% and the specific power was increased by about 74.2% when fuels were preheated to 1300 K.

But only theoretical calculations cannot provide enough guidance for the engineering design of compact DF/HF-CWCLs with preheated fuels, and experimental tests are very expensive, which makes it desirable to perform relevant numerical modelling before experiments.

In this paper, we employed the CHMBER and RANDON calculation programme (C-R) [15,16] to investigate the characteristics of HF-CWCLs with preheated fuels. In addition, we calculated the small-signal gain and line intensity distribution in the optical cavity, output power, specific output power and chemical efficiency of lasers at different preheating temperatures. This numerical modelling is an essential part of our research program, and this paper presents important intermediate research results, which will provide a theoretical support for our experimental tests at the next stage. Thus, all the laser operation regimes and parameters in our simulation are set as needed in our future experiments in order to compare the experimental results with those obtained in the simulation.

2. Description of the calculations

Our investigation is based on a HF-CWCL with a fuel mixture of $(D_2-F_2-He)+H_2$, and nozzles of 2.1 mm in length, 0.076 mm in width, whose area ratio is 20.5 [17]. It was assumed that the initial reactants are in the molecular ratio of $n_{D_2}:n_{NF_3}:n_{He} = 1:1.003:5.683$. The coefficient α, which denotes the NF_3 excess coefficient, is equal to 1.55 [10], and the primary dilution ratio is $\Psi_p = 10.34$ [10]. The optical path length in the optical cavity is assumed equal to 100 cm, and the absorption ($a_{1,2}$) and reflection ($r_{1,2}$) coefficients of a highly reflecting mirror (a_1, r_1) and an output mirror (a_2, r_2) are set to be $a_1 = 0$, $r_1 = 1$ and $a_2 = 0.02$, $r_2 = 0.85$. Given that NF_3 is easily dissociated at high temperature, in our calculation the pre-

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heating temperature of NF_3 is 300–550 K, while that of D_2 and He is 300–1200 K. The initial temperature of the secondary fuel H_2 and walls of fuel nozzles is assumed equal to 300 K. The initial total pressure in the combustor is 0.9 bar, and the stagnation pressure of H_2 is set to be 0.6 bar. The simulation process is shown below.

At the first stage, the new molecular ratio of fuels was calculated in accordance with the method from Ref. [10] when fuels were preheated to different high temperatures t. Then, the primary equilibrant output parameters of the combustor (mass percent $\partial_i^{(t)}$ of ith equilibrant components, total temperature T_0, total pressure P_0, specific heat ratio γ and molecular weight w of the mixture) with fuels preheated to different high temperatures were obtained by CEA (Computer Programme for Calculation of Complex Chemical Equilibrium Compositions) [18]. The flow rate $\dot{m}_i^{(t)}$ of equilibrant components (i = DF, F, F_2, N_2, He) at different preheating temperatures t can be calculated by using the equation

$$\dot{m}_i^{(t)} = \partial_i^{(t)} \left\{ c\, \frac{p_0 A^*}{\sqrt{RT_0/w}} \left[\gamma \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)(\gamma-1)} \right]^{1/2} \right\}, \qquad (1)$$

where c is the mass flow coefficient, A^* is nozzle throat's area, and $R = 8.314\ \mathrm{J\ mol^{-1}\ K^{-1}}$ is the gas constant.

At the second stage, in order to obtained the same flow rate of F atoms at the exit of the combustor at different preheating temperatures, as that at room temperature, instead of P_0 we used

$$p_0^{(t)} = p_0 \frac{\partial_{\mathrm{F}}^{(t)}}{\partial_{\mathrm{F}}^{300\,\mathrm{K}}}, \qquad (2)$$

to provide an equality $\dot{m}_{\mathrm{F}}^{(t)} = \dot{m}_{\mathrm{F}}^{300\,\mathrm{K}}$, with other parameters in Eqn (1) being unchanged. Then, the new equilibrant output parameters of the combustor (with a total pressure of $p_0^{(t)}$) at different preheating temperatures were again calculated by CEA.

With the new fuel molecular ratio, the primary diluent ratio Ψ_{p} was gradually decreased with increasing preheating temperature. In order to keep Ψ_{p} stable to minimise its influence on the lasing environment in the optical cavity, the additional primary diluent He can be used as a cooling film [12] at the throats of the nozzle array to prevent nozzle throats from accumulated ablation. In our calculations, He was added to the equivalent components of the combustor directly, because there were no cooling film slits in this 2D simulation structure.

At the third stage, the C-R programme was used to calculate independently the flows in oxidant/secondary fuel nozzles and optical cavity, respectively.

3. Results of simulations

The main results of our calculations are shown as below. We proceed from the fact that the mass flow rate of F atoms, produced in the combustor, and the primary diluent ratio remain unchanged with the rise of the preheating temperature.

The main operating parameters of the combustor are shown in Fig.1. One can see that along with the rise of the preheating temperature from 300 K to 1200 K, the NF_3 excess coefficient increases from 1.55 to 2.07 due to an increase in the concentration n_{NF_3}, and the total fuel mass flow rate in the combustor needed to produce the same amount of F atoms is reduced by ~36%, which is quite favorable to improve the specific output power of lasers.

Figure 2 shows that the peak value of the total radiation intensity inside the cavity slightly increases (by ~2.8% at 1200 K in comparison with that at 300 K) with increasing

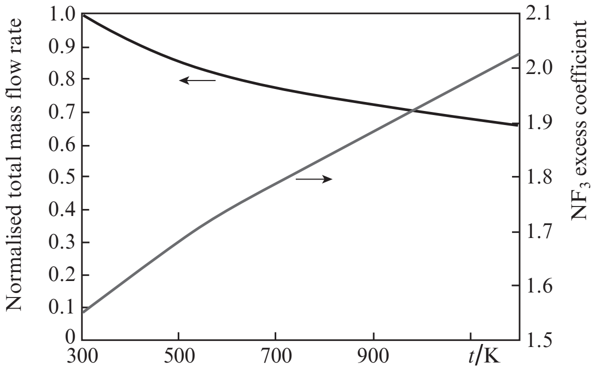

Figure 1. Main operating parameters of the gas in the combustor as functions of the preheating temperature t.

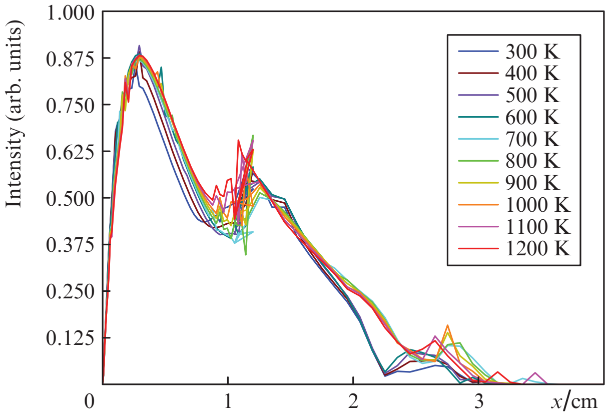

Figure 2. (Colour online) Total radiation intensity inside the cavity as a function of distance x to the nozzle array exit plane at different preheating temperatures t.

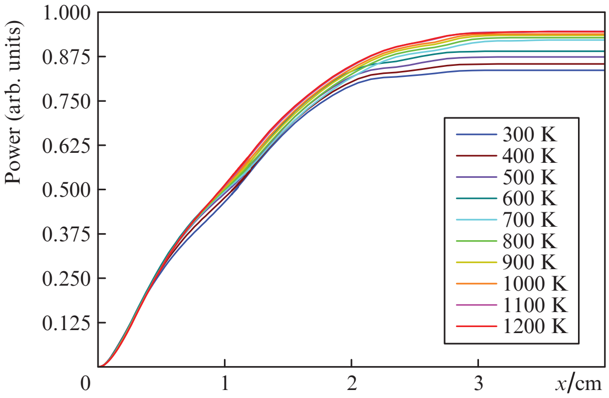

Figure 3. (Colour online) Output power vs. distance x at different preheating temperatures.

preheating temperature, and the lasing zone length (~2 cm) exhibits almost no obvious change, beginning at ~0.22 cm away from the nozzle array exit plane and up to ~2.25 cm.

Figure 3 demonstrates that the output power increases with increasing preheating temperature and exhibits a ~13-percent increase when fuels are preheated to 1200 K. Figure 4 shows that the specific output power is improved with increasing preheating temperature, and a ~46-percent increase in the specific output power is obtained when fuels are preheated to 1200 K, which means that much less fuels are needed in the combustor to produce the same laser output power.

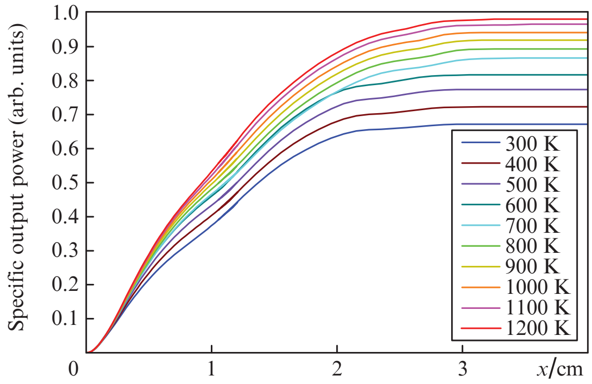

Figure 4. (Colour online) Specific output power vs. distance x at different preheating temperatures.

The output characteristics of the investigated HF laser were obtained under the condition that same amount of F atoms was produced in the combustor at different preheating temperatures. Thus, the probable reasons for the improvement of the output power and specific output power are as follows.

First of all, the longitudinal (along the x coordinate) distributions of the small-signal gain g inside the cavity followed an upward trend when the preheating temperature went up. It can be seen from Fig. 5 that the peak values of g were increased by ~47.5%, ~66.1% and 274%, respectively for the transitions $v = 1 \rightarrow v = 0$, $v = 2 \rightarrow v = 1$ and $v = 3 \rightarrow v = 2$ of the HF molecule. The lasing zone length inferred from the longitudinal distributions of g was about 1.9 cm, from ~0.29 cm to ~2.2 cm away from the nozzle array exit plane, which is almost consistent with the data obtained from Fig. 2.

Secondly, the mass fraction of the strongest deactivator of excited molecule of HF(v) – molecular DF – in the optical cavity was greatly reduced with increasing preheating temperature (Fig. 6): from 0.2858 at t = 300 K to 0.1621 at t = 1200 K, which is a ~43.3-percent reduction, meaning the weakening of deactivation to the excited HF(v) molecules.

Thirdly, the mass fraction of excited HF(v) molecules increased enormously with increasing preheating temperature (Fig. 7). The peak values of the mass fractions of HF($v = 1$), HF($v = 2$) and HF($v = 3$) increased by about 33%, 44% and 15%, respectively, when fuels were preheated to 1200 K, which is quite advantageous for improving the output power.

The chemical efficiency of the laser depends on the preheating temperature. The chemical efficiency of the laser was improved considerably from ~10% at t = 300 K to ~15% at t = 1200 K, which is a satisfactory improvement of 50% (Fig. 8).

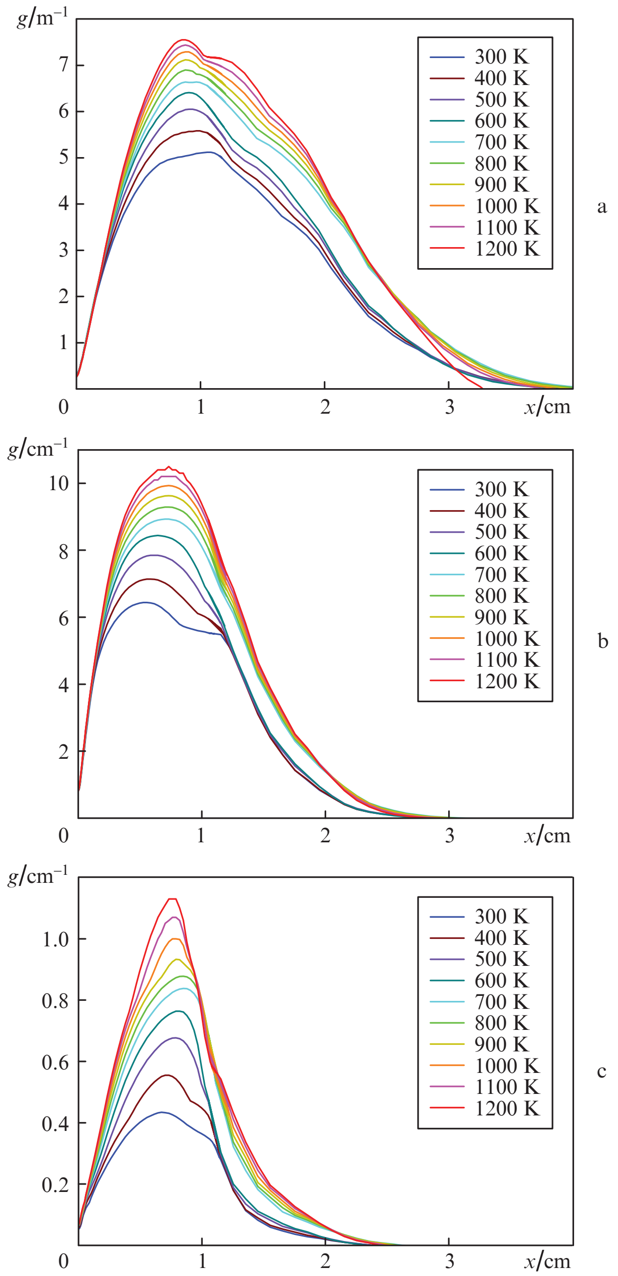

Figure 5. (Colour online) Longitudinal distributions of the small-signal gain g inside the cavity at different preheating temperatures t for the transitions (a) $v = 1 \rightarrow v = 0$, (b) $v = 2 \rightarrow v = 1$ and (c) $v = 3 \rightarrow v = 2$.

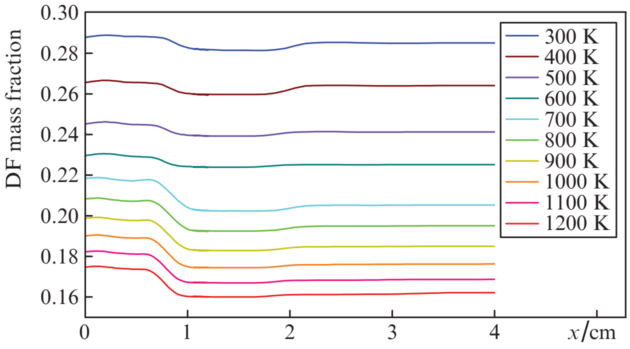

Figure 6. (Colour online) Longitudinal distributions of the mass fraction of DF at different preheating temperatures t.

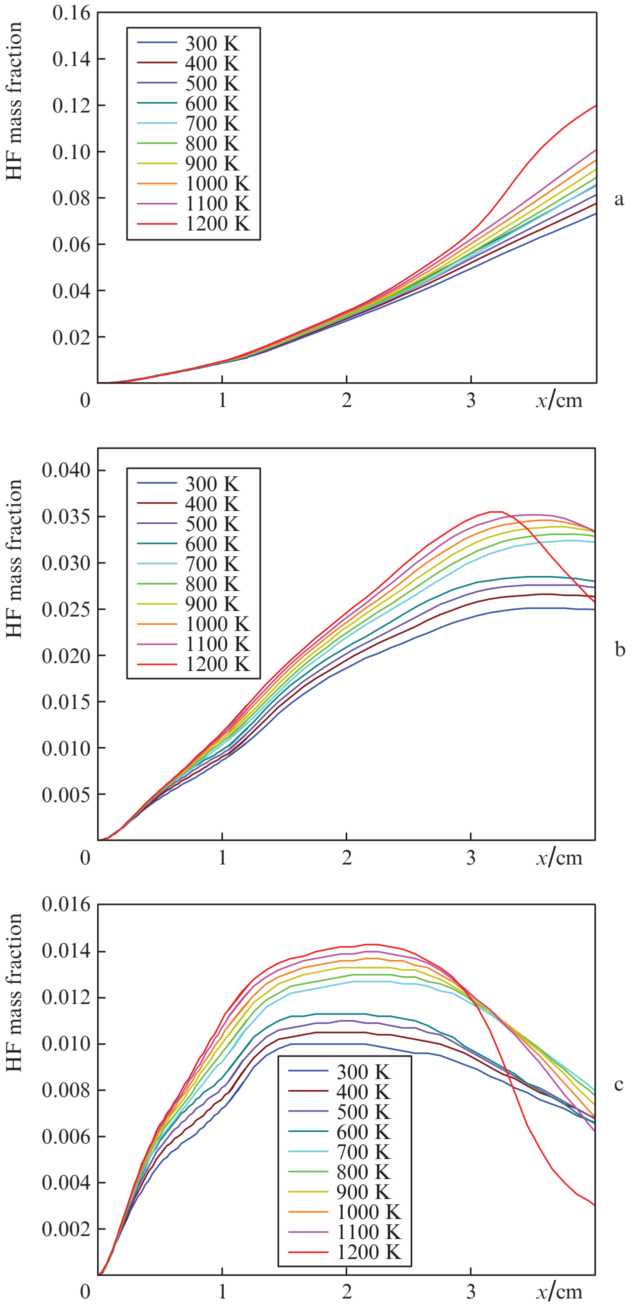

Figure 7. (Colour online) Longitudinal distributions of the mass fraction of excited molecules of (a) HF(v = 1), (b) HF(v = 2) and (c) HF(v = 3) at different preheating temperatures t.

4. Discussion

For fuels to be preheated, two feasible methods are considered: electrical heating and pre-combustor heating.

In the case of electrical heating, as a heat accumulator we used a coil pipe heated by a low-power electrical current for a long time. When the laser operates, fuels to be preheated pass through the coil pipe, and the heat stored in the coil pipe is then transferred to these fuels, preheating them to a desired temperature.

The result of a preliminary electrical preheating test showed that stainless steel 310s can withstand the high temperature of 1300 K, and can be used to preheat fuels. The heat energy Q stored in the coil pipe made of 100-kg stainless steel (310s) can be calculated to be $Q = Cm\Delta t = 0.5\times100\times10^3\times1000$ K $= 5\times10^7$ J, where $C = 0.5$ J g^{-1} K^{-1} is the specific heat of steel 310s, and $t = 1000$ K is the change in the accumulator temperature during its heating. It is assumed that the temperature of the coil pipe is reduced from 1300 K to 1200 K when the heat energy of about 5×10^6 J is released to preheat laser fuels, which is enough to preheat them to a desired temperature.

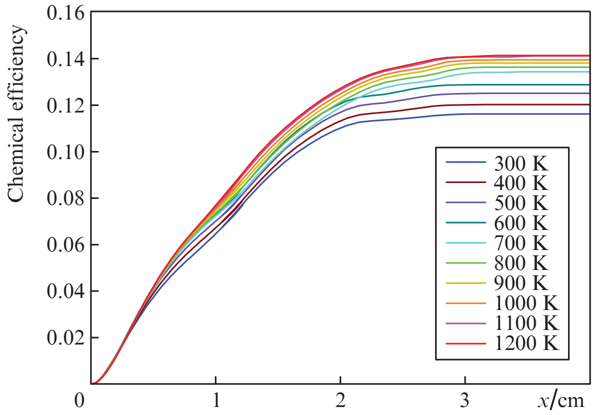

Figure 8. (Colour online) Chemical efficiency at different preheating temperatures t.

But it takes a long time to store enough heat in the coil pipe, and the time for the heat to transfer from the coil pipe to fuels is very short, because fuels flow fast; therefore, this electrical heating is useful for short-term operation rather than long-term operation.

For long-term operation, pre-combustor heating is quite suitable. Fuels (ethyl, alcohol, etc.) combust with the oxidant (oxigen extracted from the compressed air) to produce a high temperature. Laser fuel pipes go through the pre-combustor, and the high temperature gas in the pre-combustor preheats laser fuels to a desired temperature. The preheated fuels then flow into the combustor. The gas in the pre-combustor can be emitted directly into the atmosphere after experiments, and no ejector is needed, which is quite in favor of the compactness of the laser.

Compared to the fuel mass saved by preheating (~36%), and the reduction of the corresponding exhaust emission volume and weight, the cost, weight and volume of the preheating system with either of this two methods are quite small, demonstrating that fuel preheating can contribute greatly to the progress towards the compactness and perfection of DF/HF-CWCLs. The purpose of the simulation in this paper is to prove theoretically that fuel preheating can decrease the size of DF/HF-CWCLs and greatly improve their performance, in order to provide enough theoretical guidance for the subsequent experimental design and implementation.

A DF/HF-CWCL with preheated fuels is being rebuilt based on a small combustion-driven DF/HF laser, and we are now applying for a patent about the fuel preheating methods. More details about the preheating methods can be seen in our patent after its publishing.

5. Conclusions

The following conclusions can be drawn as a summary of the results of our investigation into the effect of different fuel preheating temperatures on the output parameters of a combustion-driven HF chemical laser.

It has been shown that fuel preheating can improve the output characteristics of combustion-driven HF chemical lasers. The available output power and specific output power have been improved by ~13% and ~46%, respectively, when fuels are preheated to 1200 K. At the same time, the fuel consumption in the combustor is reduced by ~36%, which makes it possible to improve the performance of combustion-driven HF lasers and make them more compact due to fuel preheating.

Further experimental investigation into the effect of fuel preheating on the performance of combustion-driven HF lasers will be conducted in the near future.

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