EFFECTS OF PRESSURE RATIO ON POPULATION INVERSION IN THE DF CHEMICAL LASER CAVITY

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INTRODUCTION

The chemical laser can generate high power laser beam in the megawatt range, so that it can be used for manufacturing processes in industries as well as for military purposes. Laser operation takes place via transitions between different energy levels of an atomic or molecular system. Therefore, there always have to be the excited atoms or molecules in the laser system, which are usually created by use of a light source like diode or lamp. But the chemical laser makes use of the only chemical reaction in order to generate the excited atoms or molecules at a high temperature. It is the advantage to help the considerable amount of chemical energy from the chemical reaction to form the excited atoms or molecules, which makes the chemical laser have considerably high efficiency of energy transformation and generate high power laser beam. They are expanded through a supersonic nozzle and form a low vacuum environment (5~10 torr). After this, an intense laser beam is formed through the reaction of F with H_2 or D_2. Although the chemical laser has the advantage of high-energy transformation efficiency, the expansion process through a supersonic nozzle is particularly needed to keep the unstable excited state of atoms or molecules in pretty long time. It causes the complicated flow patterns in the laser cavity like strong shock and expansion waves. And the mixing process between F and H_2 or D_2 is occurred in this complex supersonic flow field. The active mixing rate is a key factor to produce a high power laser beam.

There have been several experimental as well as analytical or numerical studies that examined HF and DF chemical lasers. The approximate theories characterizing diffusion flames and premixed systems were founded as a study of the chemical laser by Emanuel [1]. His results revealed the parametric behavior of the system and exhibited phenomena and influence of *j*-shifting on the performance. In 1980s, Driscoll [2,3] achieved experiments and numerical simulations to demonstrate the ability of a new supersonic ramp nozzle design to accelerate mixing in a DF chemical laser via the reactant surface stretching mechanism. It revealed a possible mechanism by which trip jets caused reactant surface stretching could make mixing enhanced.

The purpose of the present study is to describe the effects of the pressure ratio of D_2 injector to supersonic nozzle on population inversion in the DF chemical laser cavity. As mentioned before, the study of the enhancement of the population inversion is so important because it is the heart of generating high power laser beam. This investigation is going to examine the variations of the mixing and reacting phenomena with the D_2 injection pressures as shown in Fig.1. To calculate the gas flow developments, the governing equations are non-dimensionalized and a fully conservative unsteady implicit and 2nd order TVD schemes [4] are used with the finite volume method (FVM).

GOVERNING EQUATIONS

As schematized in Fig.2, the current paper deals with supersonic flow and chemical reaction in the DF chemical laser cavity. These phenomena are governed by Navier-Stokes equations and species equations that remarkably affect the thermo-physical properties. The model dealt with in this study is that in the upper section, the uniform mixing flow (F, F_2, HF and He) comes into the DF chemical laser cavity through the supersonic nozzle at $M = 5.0, P = 2.40\, torr, T = 169.37K$, and in the lower section, the sonic D_2 flow streams into it at $T = 239.61K$ as shown in Fig.2. There is a nozzle base between the supersonic nozzle and D_2 injector with the height of 1.6 mm, which also plays an important role in the chemical species mixing. In the present study, an 11-species (including DF molecules at various excited states of energies), 32-step chemistry model is adopted for he DF reaction in the DF chemical laser cavity.

BOUNDARY CONDITIONS

In this analysis of the DF chemical laser cavity, the boundary conditions have to be applied to upper and lower walls, inlet and outlet as shown in Fig.2. At upper and lower walls, the symmetric condition is imposed since the physical domain is a part of the nozzle array. At the outlet, the outflow condition of the 1st order extrapolation is used, because the flow moves at the supersonic speed. Finally, at the inlet the boundary conditions at the supersonic nozzle and the D_2 injector are given in Table 1 and the adiabatic conditions are applied at the nozzle base. Under the above conditions, the physical domain is divided into a 301×151 grid system after many preliminary calculations with different grid sizes.

RESULT AND DISCUSSION

Now, a special attention is paid to the effects of pressure ratio of D_2 injector to supersonic nozzle on population inversion in the DF chemical laser cavity. The pressure ratio is directly connected with the D_2 mass flow rate at the D_2 injector; as the pressure ratio increases twice, the mass flow rate of D_2 from the D_2 injector also increases twice, that is the former is proportional to the latter. When the mass fraction and the temperature are kept up at the inlet as presented in Table 1, this proportionality between the pressure ratio and the mass flow rate is preserved according to the equation of state. This study is carried out in such a way that the consumption of F atom, the production of the excited DF molecules in the flow direction are measured through the numerical simulation explained in the above section, which are closely related to the power of the DF chemical laser system. In this study, the system of equations based on the Navier-Stokes equations and species equations was solved and particularly the excited molecules, DF(i) were assumed to be composed of species which have different energy states. The excited DF molecules from DF(0) to DF(4) were used for this numerical simulation as HF system applied by King and Mirels [5]. As mentioned before, the inlet conditions are keeping constant. But the D_2 injector pressure condition changes from 48 torr to 388 torr. Finally, before the numerical results are discussed, it is noted that the flow in the chemical laser cavity is laminar as analogously discussed by Masuda *et al.* [6]. The reason is that the Reynolds number based on the size of the D_2 injector (0.3 mm) and the injection conditions is only of the order of 10^3.

In the following, the results obtained with the current code developed here would be presented and discussed to analyze the effects of pressure ratio of D_2 injector to supersonic nozzle on the phenomena occurred in the DF chemical laser cavity.

Fig.3 illustrates the effects of D_2 injector pressures on the Mach contours. A strong expansion is observed to occur near the supersonic nozzle outlet as soon as D_2 is injected, since D_2 injection pressure is much higher than the static pressure of fluorine mixture. And the recirculation zone is generated around the nozzle base between the D_2 injector and supersonic nozzle. In the present study, two values of the pressure of the D_2 injector were used with 192 torr and 388.64 torr; 192 torr is 80 times as high as the pressure at the supersonic nozzle exit (2.4 torr) and 388.64 torr is 162 times. The peculiar differences between 192 torr and 388.64 torr cases are the height of the Mach disc and the inclined angles of shock wave surfaces behind the Mach disc as shown in Fig.3. As the pressure of the D_2 injector increases, stronger shock wave influences flow field much more and stronger reflected shock wave is also built up. Hence the pattern of the shock wave reflection can be shown more clearly with the increase of the pressure of the D_2 injector. The analogous analysis is deduced from the temperature contours plotted in Fig.4, which reveals that the strength of the reflected shock wave becomes higher with the pressure ratio, though it is getting weaker as the flow runs downstream. And the positions of the maximum temperature are moved with the pressure ratio; in the 192 torr case, it is located near the recirculation zone while in the 388.64 torr case, at the intersection of the upper symmetric line and the first reflected shock wave. It is caused by the difference of the patterns of the shock wave reflection with the pressure ratio. Also the maximum temperature in the 388.64 torr case (~800 K) is higher than that in the 192 torr case (~700 K), from which it is respected that as the pressure ratio becomes higher, the chemical reaction is more activated that the DF excited molecules will be produced much more and the population inversion will be occurred greatly. However, this prediction is not true as seen in Figs.5, 6 and 7. In the upstream, the excited DF(3) molecules are produced more in the 388.64 case. But it is observed that in the downstream their amount in the 192 torr case is more than that in the 388.64 torr case. This phenomenon is also figured out in Fig.6, which shows the excited DF(2) and DF(3) mass distributions with respect to longitudinal distance x from the nozzle exit plane. The absolute amount of DF(2) and DF(3) is more within 6~10 cm range from the nozzle exit in the 388.64 torr case than in the 192 torr case. Thereafter this situation is reversed so that the amount of the DF excited molecules in the 192 torr case increases and is more than that in the 388.64 torr case. Actually the end mirrors in the laser cavity are positioned at both sides of the cavity and the width of the valid area to generate the laser beam is approximately 6 cm from the position (1~2 cm apart from the nozzle exit). Consequently the phenomena within 7~8 cm from the nozzle exit plane is most important in the laser system. The patterns of the population inversion in this range are magnified and redrawn in the right upper section of Fig.6 to show their detailed shapes. The population inversion becomes higher in the 192 torr case, which is the most important parameter to determine the power of laser beam. Therefore, it is concluded that the low pressure ratio can make the laser beam intenser in this situation. And it is said that as the pressure ratio increases, the consumption of F atom increases due to the strong chemical reaction near the inlet, which results from higher temperature environment caused by the strong shock wave interaction. The wiggling pattern in the F atom mass distribution is given rise to by the reflection of the shock wave.

Fig.7 represents the distributions of the excited DF molecules with respect to longitudinal distance *x* from the nozzle exit plane. These distributions are closely related to the population inversion. Better environment that can generate high power laser beam is formed in the 192 torr case which gives the clear view to distinguish each energy state in the wide range. However, in the 388.64 torr case, the population inversion is occurred only in the short range (~4 cm) and this inversion is also weak.

To generate the laser beam in the chemical laser system and to keep the excited state longer, the supersonic expansion is used. The high pressure of the D_2 injector causes the strong shock wave reflection, so it is difficult for the population inversion to be occurred. And this strong shock wave reflection pattern can be deduced from Fig.5, which reveals that the DF(3) distribution along the longitudinal direction in the 192 torr case is smoother than that in the 388.64 case.

CONCLUSION

The DF chemical laser employs a chemical reaction to produce a population inversion. It offers the possibility of operation without an electrical input. All the required energy could be produced in the chemical reaction. One simply mixes chemical agents (D_2 and F) and allows them to react. In the present study, consumption of F atom and production of the excited DF molecules were numerically measured in order to investigate the effects of the pressure ratio of D_2 injector to supersonic nozzle on population inversion in the DF chemical laser cavity. The conservative equations for this analysis were formulated and numerically solved.

The power of the DF chemical laser system is determined by the amount of the excited DF molecules in the laser cavity. When it is not sufficient, the environment to produce the high power laser beam is not built up. Further results showed that

1. As the pressure ratio of D_2 injector to supersonic nozzle decreases, it is easier to produce the nonequilibrium situation of a population inversion, which is made by some method that D_2 molecules and F atoms are mixed and expanded through supersonic nozzle, and then the excited DF molecules with high-lying energy levels are produced.
2. The increase of the D_2 injector pressure aids the reflection of the shock wave to be stronger in the DF chemical laser cavity. It is unfavorable to produce the population inversion in order to generate the laser beam in the DF chemical laser system.
3. The domain to generate the laser beam is limited only to the region where the population inversion occurs. As the pressure ratio decreases, the region becomes wider and better environment to generate the laser beam is formed because the effect of the reflection of shock wave on the flow and reaction fields is reduced.
4. The rate of consumption of F atom which is used as the oxidizer in the DF chemical laser system is not an indicator to inform the rate of production of the excited DF molecules.

ACKNOWLEDGEMENT

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Table 1 DF chemical laser inlet conditions

	Upper Nozzle		D_2 Injector	
Mach Number	5.0		1.0	
Temperature (K)	169.37		239.61	
Pressure (torr)	2.40		388.64	
			192.00	
Species	F	0.3071	D_2	1.0
Mass Fraction	F_2	0.0340		
	HF	0.3191		
	He	0.3398		

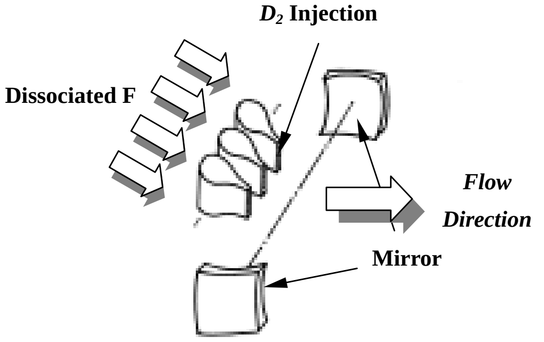


Fig. 1 Supersonic diffusion DF chemical laser cavity

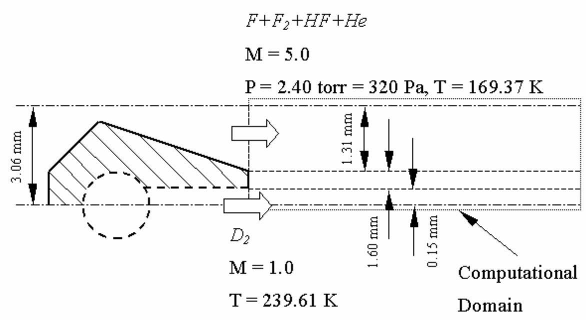
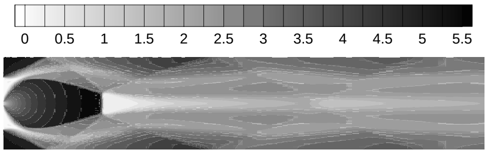
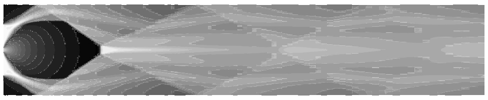


Fig. 2 A schematic of the DF chemical laser cavity

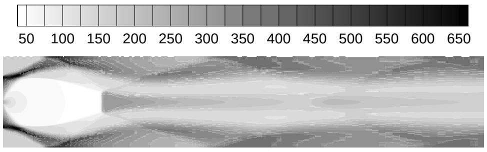


(a) $P_{D2\ Injector}$ = 192 torr

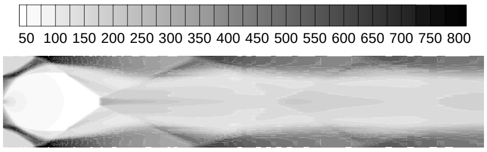


(b) $P_{D2\ Injector}$ = 388.64 torr

Fig. 3 Effects of D_2 injector pressures on the Mach contours

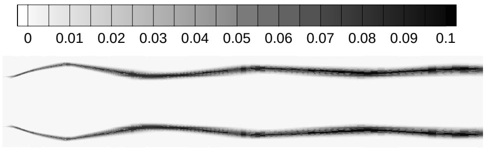


(a) $P_{D2\ Injector}$ = 192 torr

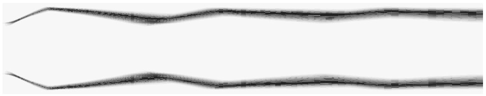


(b) $P_{D2\ Injector}$ = 388.64 torr

Fig. 4 Effects of D_2 injector pressures on the temperature contours



(a) $P_{D2\ Injector}$ = 192 torr



(b) $P_{D2\ Injector}$ = 388 torr

Fig. 5 Effects of D_2 injector pressures on the DF(3) mass fraction contours

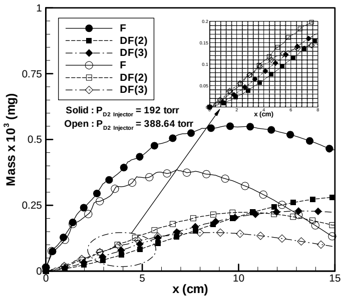
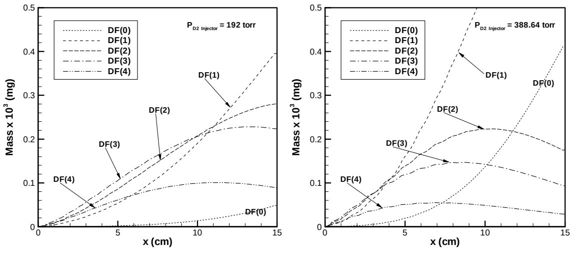


Fig. 6 Comparison of F, DF(2) and DF(3) mass distributions with respect to longitudinal distance *x* from the nozzle exit plane



(a) $P_{D2\ Injector}$ = 192 torr (b) $P_{D2\ Injector}$ = 388.64 torr

Fig. 7 Distributions of the excited DF molecules with respect to longitudinal distance *x* from the nozzle exit plane