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Variation of population inversion and gain characteristics with D_2 injection angle in DF chemical laser cavity

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Abstract

Nowadays, a chemical laser has been developed not only for a strategic military purpose, but also as a manufacturing tool in industrial usage due to its high power lasing characteristics. In order to increase the laser beam power in the chemical laser systems, the mixing efficiency of fuel and oxidant should be improved, since more excited molecules are followed by high mixing efficiency. Basically, the production of a lot of excited molecules in the laser cavity results from the high mass flow rates of fuel and oxidant based on efficient mixing and chemical reaction. Therefore, in order to supply higher mass flow to the chemical laser cavity, a radial-expansion nozzle array was used and examined here, not a planar nozzle array which has been widely employed until now. The laser beam generation in this system is achieved by mixing F atoms from supersonic nozzle with D_2 molecules ejecting from holes of round-bended supply lines which are distributed in zigzag configuration, which would extend the reaction zone. Consequently, more excited molecules are expected to be produced, so the intensity of population inversion will be higher.

Since the two-stream injection angle was considered to influence the performance of supersonic combustor, the effects of D_2 injection angles against the main F flow on mixing enhancement, population inversion and gain characteristics were numerically investigated in this study. The results were discussed by comparison with three cases of D_2 injection angles such as 10°, 20° and 40° against the main flow direction. As the injection angle increases, two counter-balancing effects were observed.

Keywords: DF chemical laser; Population inversion; Gain; Injection angle; Supersonic combustor

1. Introduction

A chemical laser is known to employ a chemical reaction to produce a population inversion and to offer the possibility of operation without any electrical input. All the energy required for lasing can be produced in the chemical reaction in which D_2 molecule reacts with atomic fluorine. Therefore, a mixing process of one species with another in the chemical laser is so important as to produce excited atoms or molecules, eventually the population inversion occurs.

The mixing process in the chemical laser used to mainly depend on such parameters as pressure ratio of injector to supersonic nozzle [1], species compositions [2,3] and geometric designs [4]. Among them, it is very difficult to change the geometric design parameters in experiments, so that the numerical simulation is likely to play a significant role in this regard. In the chemical laser, the supersonic mixing and its subsequent chemical reaction take place. Consequently, an enhancement in mixing rate is highly desirable. In this respect, the injection or colliding angle of two species is one of the most important factors to affect mixing rate and reaction efficiency [5,6]. By the same reasoning, the angle of injection of D_2 molecules and F atoms in DF chemical laser system is expected to make considerable effects on population inversion.

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Nomenclature

c	speed of light (2.99792458×10^8 m/s)
C_i	mass concentration of ith species (kg/m^3)
C_{pi}	specific heat at constant pressure of ith species (J/kg K)
E, F, G	inviscid flux vectors
E_v, F_v, G_v	viscous flux vectors
e_i	internal energy of ith species (J/kg)
e_t	total internal energy (J/kg)
h_i	enthalpy of ith species (J/kg)
I	intensity (W/m^2)
J	Jacobian
k	thermal conductivity (J/m K s)
M	Mach number
n_i	ith species molar concentration (mol/m^3)
N_A	Avogadro number (mol^{-1})
P	mixture pressure (Pa)
Q	conservative state vector
R_u	universal gas constant (J/kmol K)
S	source vector
T	temperature (K)
t	time (s)
u, v, w	velocities (m/s)
x, y, z	Cartesian coordinates (m)
Y_i	ith species mass fraction
W_i	ith species molecular weight (kg/kmol)

Greek symbols

α	gain coefficient (cm^{-1})
ξ, η, ζ	generalized curvilinear coordinates
$\hbar$	Planck's constant ($6.6260755 \times 10^{-34}$ J s)
κ	Boltzmann constant (5.670×10^{-8} W/m^2 K^4)
ρ	density (kg/m^3)
τ_{ij}	stress tensor
ν	transition frequency (s^{-1})
ω	transition frequency, ν/c (cm^{-1})

Subscripts

i, j, k	space indices
J	rotational quantum number
ref	reference state
v	vibrational quantum number

Superscript

–	non-dimensional quantities

The laser cavity, which is located in chemical laser, comprises mirrors and injectors of chemical species. In order to generate high lasing power, it is necessary to supply larger amount of chemical species through nozzles. However it is difficult to fabricate many injection holes on the nozzle base enough to supply high mass flow rate. In order to meet these requirements, nowadays, the radial-expansion nozzle array system has been developed and used.

As explained above, the most important factor in designing the radial type nozzle block is a mixing enhancement so as to increase the power of the chemical laser beam. Therefore, in the present study, the population inversion and gain characteristics, which are directly related to the rate of mixing and laser power in this laser system, are numerically studied with a variation of injection angles as one of the important geometric design parameters.

There are lots of numerical and experimental studies regarding the chemical laser. Galaev et al. [7] described the dependence of output power of a CW chemical HF laser with an inhomogeneous distribution of small-signal gain in the active medium on the reflection coefficient of output mirror in the cavity. Also a numerical and experimental method was developed for determination of the properties of active media of lasers, and was applied to determine the energy and amplifying characteristics of a compact HF laser with a radial-expansion nozzle array and to predict the parameters of a large-scale laser. A simple model for a steady flow HF chemical laser was formulated by Broadwell [8], in which the excited state formation rate was limited by the H_2–F mixing rate. However, its simple analytic prediction for lasers was markedly different from the experimental observations. The flow field experiments on a DF chemical laser were conducted by Driscoll and Tregay [9]. The data on the reaction zone structure for laminar mixing were obtained when the mixing was augmented by the gas jet injection at the reactant interface. An experimental investigation was made of the operational characteristics of a self-contained supersonic CW chemical HF laser by Galaev et al. [10], which used a three-jet array with reagent jets spatially separated by helium jets. It was revealed that this type of nozzle array increased the energy characteristics of the laser by a factor of 1.20–1.35 and the length of the active medium by a factor of 1.4–1.7, and at the same time reduced the level of optical inhomogeneity by 30%.

Unlike other laser systems such as solid state laser, semiconductor laser, organic dye laser, etc., the power of chemical laser is predominantly determined by the rate of mixing. Therefore, the optimal conditions, which make it higher and the laser beam more intense, should be sought for improving the chemical laser performance.

In this study, the dependence of population inversion and gain characteristics on variations of D_2 injection angles was numerically investigated in a DF chemical laser cavity in view of the mixing and beam power enhancement. The selected injection angles were 10°, 20° and 40° against the main flow direction. In order to predict chemical as well as thermo-chemical flow development, the governing equa-