Parallel Numerical Simulation of Shear Coaxial LOX/GH_2 Jet Flame in Rocket Engine Combustor

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Key Words: Combustion, Rocket engine

1. INTRODUCTION

Liquid rocket engines are used in a number of launch vehicles worldwide. In these rocket engines, e.g. LE-7A engine of H-2A, Space Shuttle Main Engine (SSME) and Vulcain engine of ARIANE 5, liquid oxygen (LOX) and gaseous hydrogen (GH_2) are injected through coaxial injectors (a schematic is shown in Fig.1). Although the injector design is a critical component of the combustion device, the processes associated with LOX/GH_2 injection, such as atomization, mixing and combustion, are still not well understood. The methodology of injector design, therefore, mostly relies on a time-consuming and costly trial-and-error. In order to reduce the development cost for future or improved rocket engines, a large part of such trial-and-error phase must be eliminated.

A lot of works has been conducted both numerically [1-3] and experimentally [4] on the LOX/GH_2 injection and combustion, which provided an improved understanding of the processes in liquid rocket engine combustion chambers. Despite these efforts, many basic phenomena, such as turbulent mixing and combustion, is still far from being understood to a satisfactory level.

For recent years, numerical simulation has been becoming a powerful tool in combustion research. Due to the rapid improvement of computer resources, a time-dependent three-dimensional simulation of actual size flame with detailed chemistry and transport models has been enabled. Our research group succeeded in capturing a turbulent hydrogen jet lifted flame using the direct numerical simulation (DNS) approach [5,6]. In the study, important and interesting features of the flame have been revealed by analysis of simulated flowfield data. We believe that this kind of huge and detailed simulation will give us a good understanding also for the case of LOX/GH_2 jet flame in rocket engines.

In the present study, we will aim to clarify the detail structure of a shear coaxial LOX/ GH_2 jet flame in rocket engine combustor by means of the detailed numerical simulation. In this extended abstract, a preliminary result by an axisymmetric numerical simulation with detailed chemistry and fine resolution mesh is shown for a single shear coaxial injector element which follows the experiment by Mayer and Tamura [4]. By the analysis of the simulated flame, fundamental features of LOX/GH_2 jet flame are explored. To reduce the required computing time accompanying with the time-dependent simulation with fine resolution mesh and detailed chemistry, our combustion simulation code is fully parallelized. The parallel performance exceeds 50 GFLOPS using 83 processors on the Central Numerical Simulation System (CeNSS) installed at Institute of Aerospace Technology (IAT), JAXA.

2. NUMERICAL METHOD

The governing equations are the Navier-Stokes equations in an axisymmetric form. Eight chemical species (H_2, O_2, OH, H_2O, H, O, H_2O_2 and HO_2) are assumed and 18 reactions model by Petersen and Hanson [7] is employed. The numerical flux function is given by the AUSM-DV scheme [8] with the 2nd order MUSCL interpolation. The viscous terms are evaluated with

2nd order difference formulae. The time integration method is 1st order Euler explicit method.

The equation of state employed in the present simulation is Soave-Redlich-Kwong equation of state (SRK EoS) which is a cubic equation of state for predicting pressure-volume-temperature behavior of dense fluid at high pressure environment [9]. The nonideality of thermodynamic properties under high pressure conditions is expressed by departure functions [9]. The speed of sound is also derived from SRK EoS. The viscosity and thermal conductivity are calculated by the method based on the extended corresponding state principle by Ely and Hanley [10,11].

3. PARALLEL IMPLEMENTATION

Parallel computation is implemented by the domain decomposition strategy, and carried out using 83 processors on the CeNSS installed at IAT, JAXA. The entire computational domain is decomposed into 83 domains as shown in Fig.2. Boundary values are exchanged between neighboring domains by the Message Passing Interface (MPI). The total performance of parallel computation exceeds 50 GFLOPS.

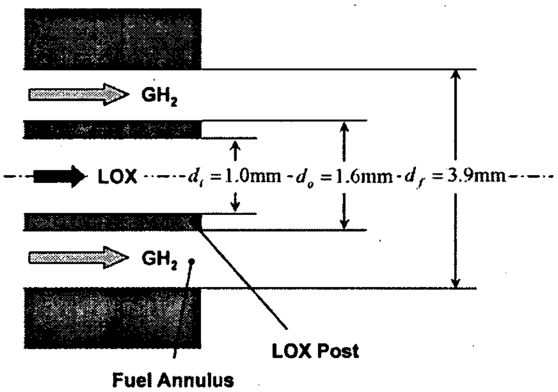

Fig.1 A schematic of shear coaxial injector.

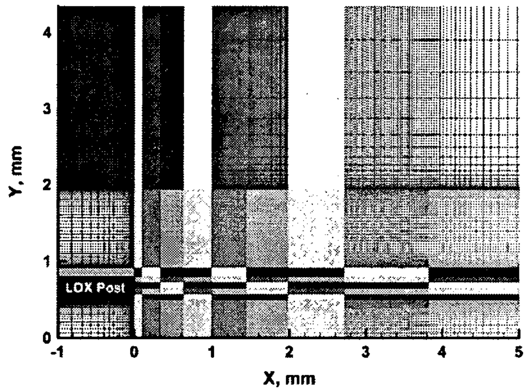

Fig.2 Computational mesh near the LOX post tip.

Table 1 LOX/GH$_2$ injection conditions

Chamber pressure	10 MPa
Oxygen injection velocity	30 m/sec
Oxygen injection temperature	100 K
Hydrogen injection velocity	300 m/sec
Hydrogen injection temperature	300 K

4. FLOW CONDITIONS

The present simulation is conducted for a single shear coaxial injector element which follows the experiment by Mayer and Tamura [4]. The dimensions of the LOX/GH$_2$ injector are shown in Fig. 1. The injection conditions are summarized in Table 1. In Fig.2, the computational mesh employed in the present simulation is shown for the region near the injector exit. The computational domains consist of the LOX injector, the hydrogen annulus, and the combustion chamber. The diameter and length of combustion chamber are 40 and 400 mm, respectively. The overall mesh size is 571×401 points along the axial and radial directions, respectively. To resolve a thin reaction layer and a shear layer, grid points are clustered in the wake of LOX injector post. 161 grid points are used to cover the LOX post thickness of 0.3 mm in the radial direction. The grid spacing at the LOX post wall is 1μm. In the axial direction, grid points are distributed with the stretching factor of 1.02.

The boundary conditions are as follows: The velocity distributions at injector inlets are assumed to be a fully developed turbulent pipe flow velocity profiles. At the exit boundary, the non-reflection condition is imposed [12]. The LOX injector post and combustion chamber walls are assumed to be no slip and isothermal wall. The wall temperatures of LOX injector post and combustion chamber are assumed to be 500 and 300 K, respectively.

5. RESULTS

In the present study, simulation is conducted for about 1msec, and a stable flame is successfully obtained through the simulation. Figure 3 shows the instantaneous contours of temperature at 0.5msec. The stoichiometric line (solid black line) is also shown in the temperature contours. The flame is attached to the LOX post tip, and the hot product gas completely separates the hydrogen and oxygen streams. This result is consistent with the experimental study by Mayer and Tamura [4], and results of LES by Oefelein and Yang [1,2]. The shear layer shed from the outer rim of the LOX post tip becomes unstable and generates a series of vortices. These vortices interact and coalescence with their neighboring vortices in the hydrogen stream side while convecting downstream. Developed vortices impinge directly onto the flame, and the thickness of the flame becomes very thin at the flow downstream region. As indicated by the study of Juniper et al. [13], a hydrogen/oxygen flame is quite resistant to flow straining. Also in our simulation, no local extinction is observed when a strong straining due to vortices occurs.

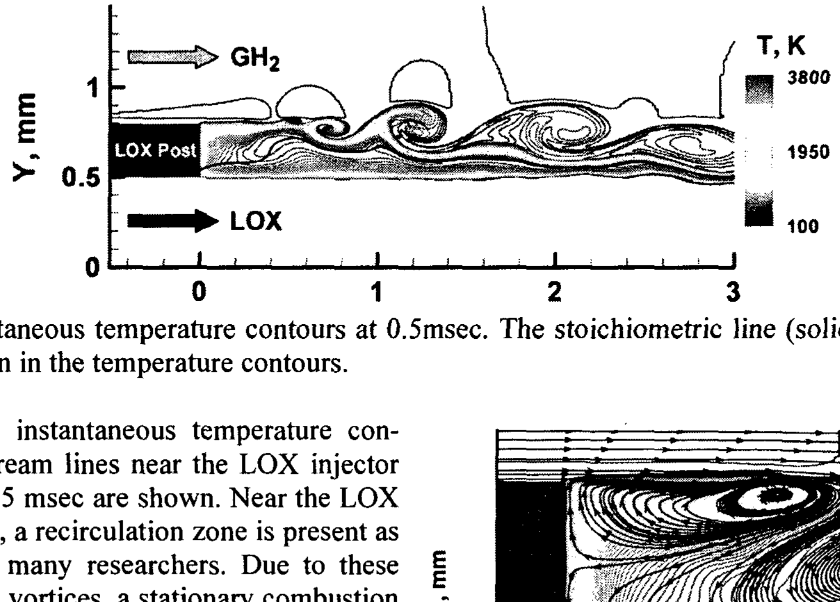

Fig.3 Instantaneous temperature contours at 0.5msec. The stoichiometric line (solid black line) is also shown in the temperature contours.

In Fig.4, instantaneous temperature contours and stream lines near the LOX injector post tip at 0.5 msec are shown. Near the LOX injector post, a recirculation zone is present as reported by many researchers. Due to these recirculation vortices, a stationary combustion is sustained, and the maximum temperature within the recirculation zone reaches about 3750K, which is almost identical to the adiabatic flame temperature of hydrogen/oxygen at stoichiometric condition.

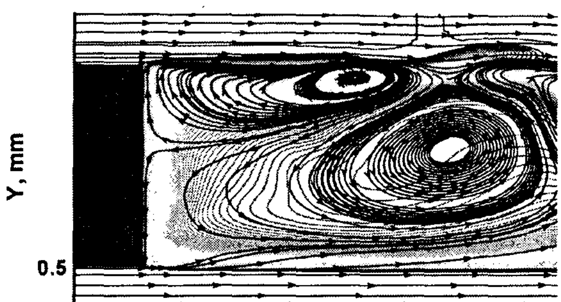

Fig.4 Instantaneous temperature contours and stream lines near the LOX injector post tip at 0.5 msec.

In Fig.5, the vortical structure of flowfield is summarized. The instantaneous vorticity contours and the power spectral densities of radial velocity oscillation at three different axial locations along the mixing layer are shown. Probe locations where temporal signals are stored are also indicated in the figure. In the present simulation, the dominant frequencies are 450, 147 and 97.7 kHz at each probe location, respectively. As the flow convecting downstream, the dominant frequency decreases to around 100 kHz. The corresponding Strouhal numbers are 0.45, 0.147 and 0.097 at each probe location, respectively. We note that the Strouhal number is defined based on the LOX Post thickness (0.3 mm) and the mean inlet velocity of hydrogen stream (300 m/sec). According to the two-dimensional simulation conducted for the backward facing step flow [14], the Strouhal number of dominant oscillation decreases toward the flow downstream and reaches almost constant value of O(0.1). The result of present simulation, therefore, is consistent with the tendency observed in the backward facing step flow.

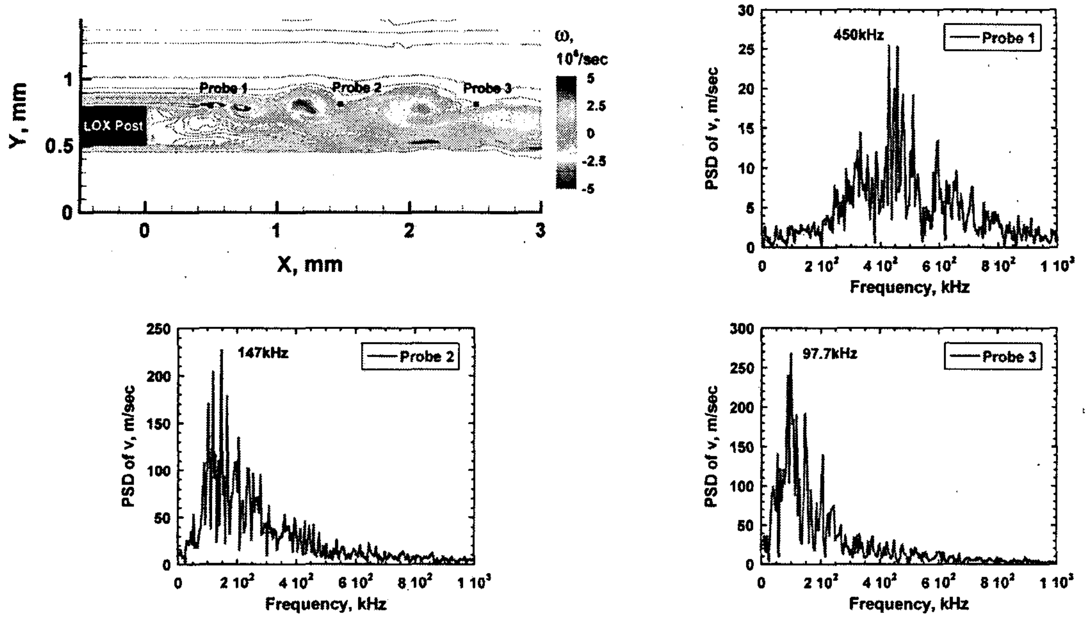

Fig.5 Instantaneous vorticity contours, and frequency spectra of radial velocity oscillation at three different axial locations along the mixing layer.

4. SUMMARY

An axisymmetric simulation with detailed chemistry and fine resolution mesh is conducted for the LOX/GH_2 jet flame in rocket engine combustor. A preliminary result is shown for a single shear coaxial injector element. The fundamental features of the LOX/GH_2 coaxial jet flame is explored by the analysis of simulated flame.

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