Numerical Study of H_2+CO Turbulent Combustion with Supersonic Coflow in Confined Geometries

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1 Introduction

The successful flight test of X-51A opened new era of powered hypersonic flight for practical applications. A technology that distinguishes X-51A from previous scramjet flight test is the dual-mode Scramjet (DMSJ) engine. DMSJ engine starts at ramjet mode and transit to scramjet mode accelerating from supersonic launch speed and to hypersonic crusing condition. The DMSJ engine employs complex regerative cooling system that would be more useful for a reusable. More affordable concept of hypersonic propulsion for expendable systems would be the dual combustion ramjet (DCR) has been suggested by Billig [1] which have been applied for HyFly program. Though its flight tests were not sufficiently successful yet due to non-combustion related problems, the concept seems to be still promising expecially for expendable systems. Regardless of the long time researches and developemnt, many of the related works on DCR is classified and little has known publically.

The dual combustion ramjet (DCR) has two flow paths, gas generator (GG, or fuel-rich ramjet combustor) and supersonic main combustor. The schematics of DCR operation is summarized in Fig. 1. Liquid fuel is pre-burned in GG with the air compressed to subsonic speed. The pre-burned fuel, mostly composed of hydrogen and carbon-monoxide, is delivered to the supersonic combustor at high speed, then consumed by the combustion with supersonic main flow. It is consided that turbulent shear layer is the major mechaism of fuel-air mixing and combustion in this system. In the present study the characteristics of the supersonic turbulent reacting shear layer is investigated at elevated enthalpy condition with confinement effects to undestand the the combustion dyanmics and stabilities.

2 Theoretical Modeling and Computational Methods

The flowfield is assumed as to be axi-symmetric for affordable computation. The coupled form of the multi-component chemically reactive system, fluid dynamics, and turbulent transport equations can be summarized in a conservative vector form as follows.

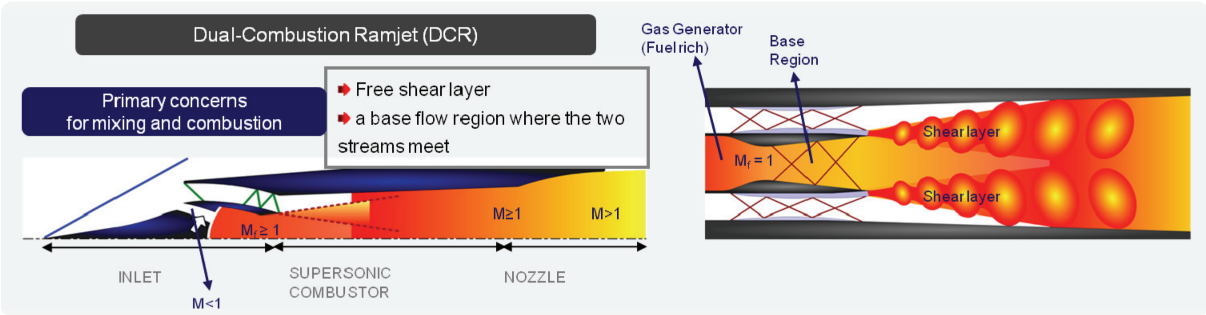

Figure 1. Schematics of the flow features in a Dual Combustion Ramjet (DCR) and the supersonic combustion flow field in DCR.

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}=\frac{\partial \mathbf{E}_v}{\partial x}+\frac{\partial \mathbf{F}_v}{\partial y}+\mathbf{W} \tag{1}$$

where,

$$\mathbf{Q}=\begin{bmatrix}\rho_k\\ \rho u\\ \rho v\\ \rho e\\ \rho k\\ \rho\omega\end{bmatrix},\ \mathbf{E}=\begin{bmatrix}\rho_k u\\ \rho u^2+p\\ \rho uv\\ (e+p)u\\ \rho uk\\ \rho u\omega\end{bmatrix},\ \mathbf{F}=\begin{bmatrix}\rho_k v\\ \rho uv\\ \rho v^2+p\\ (e+p)v\\ \rho vk\\ \rho v\omega\end{bmatrix},\ \mathbf{W}=\begin{bmatrix}\omega_k\\ 0\\ 0\\ 0\\ S_k\\ S_\omega\end{bmatrix},\ \mathbf{E}_v=\begin{bmatrix}-\rho_k u_k^d\\ \tau_{xx}\\ \tau_{xy}\\ \beta_x\\ \mu_k\partial k/\partial x\\ \mu_k\partial\omega/\partial x\end{bmatrix},\ \mathbf{F}_v=\begin{bmatrix}-\rho_k u_k^d\\ \tau_{yx}\\ \tau_{yy}\\ \beta_y\\ \mu_k\partial k/\partial y\\ \mu_k\partial\omega/\partial y\end{bmatrix} \tag{2}$$

Species conservation equations for eight reacting species (O, O_2, H, H_2, OH, H_2O, CO, CO_2) and inert assumed nitrogen (N_2) are considered with momentum and energy equations. The combustion mechanism is taken from Singh and Jachimowski [2]. Two-equation Menter's shear stress transport (SST) model is used with DES (detached eddy simulation) extension to enhance the eddy capturing characteristics at separated flow region while preserving the RANS characteristics at boundary layer. The governing equations were solved in fully coupled manner using fully implicit formulation. The convective fluxes are discretized by the Roe's flux difference splitting (FDS) method and viscous fluxes are handled by a central difference scheme. The computational code has been used used for a supersonic combustor studies[3] and currently extended to multi-dimensional fifth order accurate scheme with wavelet-extended multi-dimensional limiting process (O-MLP) scheme [4]. The second order implicit time integration is used with sub-iterations for time accurate computation. The code is parallelized by OpenMP for the optimum performance in multi-core SMP (shared memory processors) machines. More details on modeling issues and numerical approaches are addressed in the previous works [2,3].

3 Combustor Configuration and Operational Conditions

In this study an elevated enthalpy flow conditions in Table 1 is considered as a preliminary step of studying the flame stability and combustion dynamics in DCR. Two schematic configurations of DCR main combustor are pltted in Fig. 2 Combustor 1 is composed of coaxial fuel and air flow in a constant area duct followed by divergent section, while Combustor 2 has a divergence angle from the beginning of the combustor. All other flow variables and computational conditions remain same during the entire computational time.

Table 1: Flow conditions for the supersonic combustion flow field in DCR.

		T (K)	P (bar)	Composition
Air	M=2.0	1,200 K	1 bar	$O_2+3.76N_2$
Fuel	M=1.0	1,200 K	2 bar	$CO+H_2$
Grid	2,201x201(main combustor) + 81x81(Air intake) + 61x61 (fuel nozzle)			
Comp. Cond.	1”=2.54 cm, Pr_t=0.9, Sc_t=0.4, MLP			

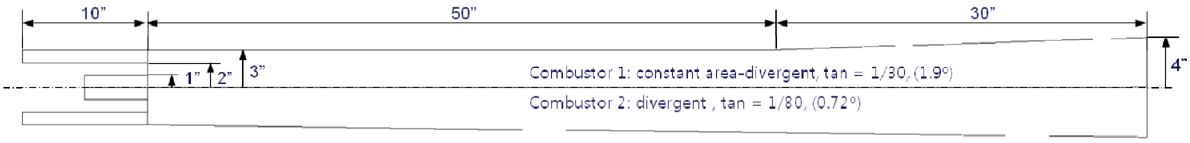

Figure 2. Computational domain of the supersonic combustion flow field in DCR: (upper) model Combustor 1 with constant area duct followed by a diverging duct, (lower) model Combustor 2 with divergent duct.

4 Results and Discussions

Figure 3 is the instantaneous flow field for the two combustors. The turbulent combustion characteristics in supersonic shear layer is clearly captured with fine structures of various levels of eddy motions in the the constant area section of the Combustor 1. In this configuration flame is lifted off more than 20 cm and the combustion accous downstream. In the meanwhile, combustion is not fully accomplished in the Combustor 2. Only a weak combustion is observed at downstream of the combustor. It is considered that flame lift off distance seems to be greater than the entire combustor length for this configuration and conditions. The only reason on the flame stability and lift-off distance is the flow expansion caused by a small divergence angle, since all the flow and computational conditions are maintained same while Combustor 2 simulation is started from the stabilized results of Combustor 1. As a result, flow Mach number in the Combustor 1 is around 1.0, while it is much higher in Combustor 2. Further discussion on the exapsnion effects on the flow parameters and flame stability will be addressed during the presentation.

The turbulent wall boundary layer is considered as not being important for the turbulent flame structure, but could be important to account for the compressibility effect on the turbulent combustion. It is shown in the results thqt the wall boundary layers are captured in RANS mode that is appropriate to avoid the higher resolutions required to resolve near wall turbulence by LES. The multi-dimensional limiting process (O-MLP) scheme is revealed to contibute greatly in capturing the small eddy motions compared with one-dimensional higher order scheme, resulting higher combustion efficiency at the same conditions.

References

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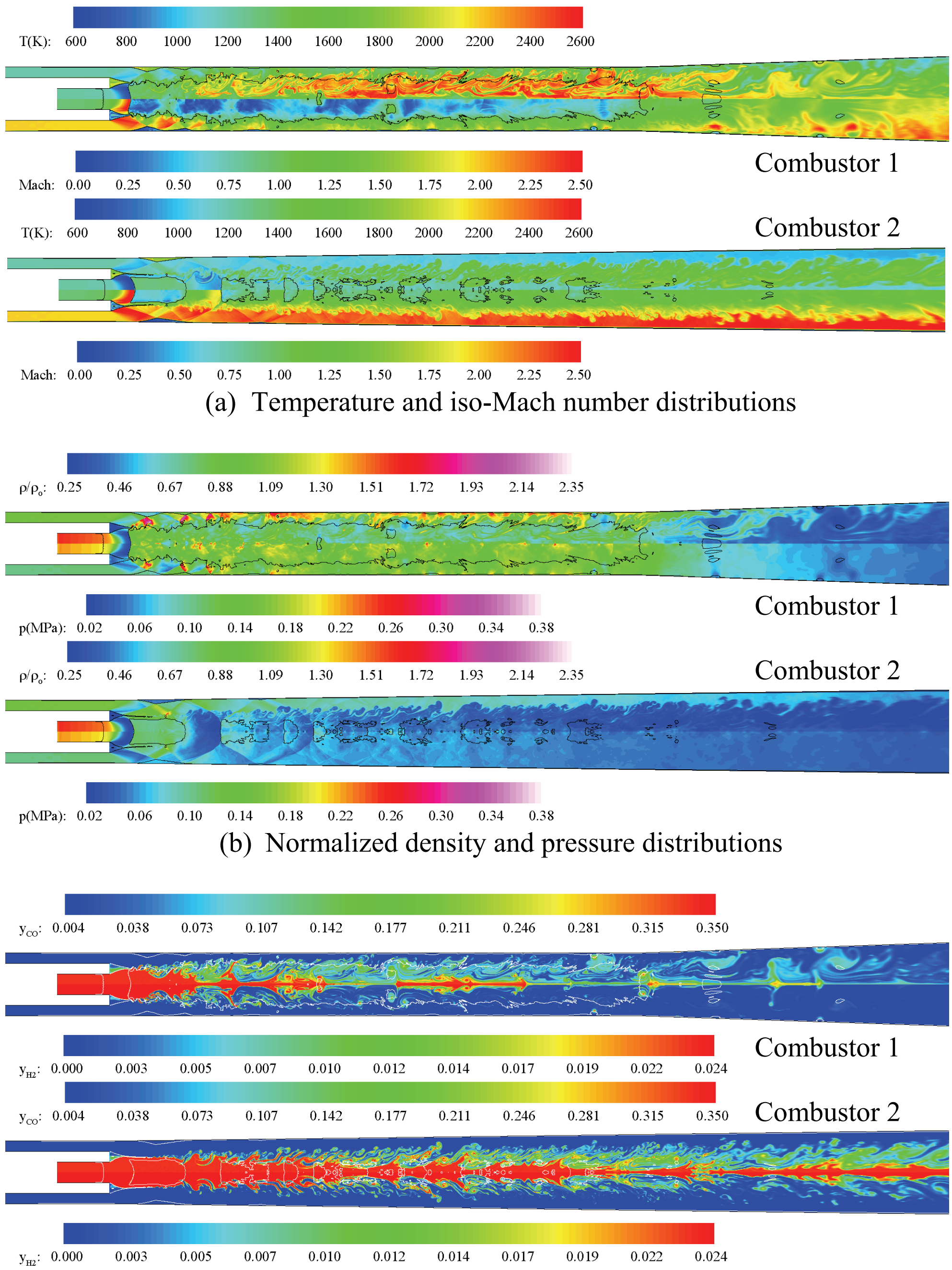

(a) Temperature and iso-Mach number distributions

(b) Normalized density and pressure distributions

(c) Fuel (CO and H_2) mass fraction distributions

Figure 3 Instantaneous flow structures in combustor 1 (upper) and combustor 2 (lower) overlaid with sonic line (M=1.0, black solid curves).