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LES Investigation of Thermally Choked Mode Combustion Characteristic of the Dual Combustion Ramjet Engine

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Abstract

Numerical study is carried out to investigate the combustion characteristics of the Dual Combustion Ramjet (DCR) engine. In this study, the two different combustion modes were achieved by differences in initial internal energy. These two combustion modes result from the interplay of compressibility effects, turbulent motion, pressure waves, and heat addition. The choice between modes depends on the level of heat addition and the presence of pressure wave interactions. It is inferred that mode control based on ignition sources is feasible in DCR. The ignition source could potentially involve a micro-pulse detonation engine, known for its capability to provide a high-energy supply.

Keywords: *Dual Combustion Ramjet, Non-premixed Supersonic turbulent combustion, Thermal-choking, Chemical Explosive Mode Analysis*

1. Introduction

The successful flight test of X-51A opened a new era of powered hypersonic flight for practical applications. A technology that distinguishes X-51A from previous scramjet flight tests is the dual-mode ramjet (DMR) engine using liquid fuel. The DMR engine starts at thermally choked ramjet mode at supersonic launching speed and then accelerates to hypersonic cruising condition, operating at scramjet mode. The DMR could have a practical flight range and time by the use of liquid fuel. The liquid fuel flows through the regenerative cooling passage, and then the superheated fuel is injected into the combustor at the gas phase. While the DMR would be attractive for reusable systems, dual combustion ramjet (DCR) by Billig et al. [1] would be a more affordable concept for an expendable system. Fig. 1 is the schematics for DCR operation. A part of the incoming air is compressed to subsonic conditions for very fuel-rich combustion in the gas generator. The pre-burned fuel is delivered to the supersonic combustor at high speed. The high-temperature gaseous fuel mixes with the supersonic air and burns quite easily. Thus, the fuel-air mixing at the supersonic turbulent shear layer is the key factor of the combustion in the DCR engine, as well as in the rocket-based combined cycle (RBCC) engine.

There have been many studies [2-5] on coaxial combustors to understand the compressibility effects and the overall structure of supersonic combustion. However, among the studies on supersonic combustion using the co-flow of fuel and air, few studies can be related to the combustion of DCR [6-9]. Regardless of long-time research, the role of turbulence structures in supersonic combustion characteristics has been understood recently by the advances in computing capabilities and visualization techniques. In the present study, the behavior of the supersonic turbulent combustion in DCR is examined to perceive the stability in combustion dynamics by means of 3-dimensional high-resolution numerical analysis.

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2. Dual Combustion Ramjet Model

2.1. Operating Conditions and Configurations of DCR

Pre-burning of heavy hydrocarbon liquid fuel with a small amount of air would be a brilliant idea to burn the fuel in supersonic flows. It is known that the optimum air ratio is approximately 1:3 for the pre-burner and the main supersonic combustor. Therefore, the equivalence ratio in the pre-burner is greater than 3.0 to maintain the equivalence ratio less than 1.0 in the main combustor. In this circumstance, the pre-burned gas mainly contains carbon monoxide and hydrogen of nearly same volumetric ratio with exit temperature around 1,000 K. The cracked fuel composition at such high temperature improves the combustion efficiency drastically even in the harsh condition for combustion in supersonic flow.

The coaxial fuel and stream for supersonic combustion is contemplated for by assuming the pre-burning of heavy hydrocarbon fuel, C_nH_{2n}. The final product at the exit of the pre-burner comprises of $CO+H_2+1.88N_2$, assuming the equivalence ratio of 3.0 in the pre-burner. For simplicity, the pre-burned fuel is injected into the supersonic combustor through the sonic nozzle at static temperature and pressure of 1,200K and 0.2 MPa, respectively, and the air ($O_2+3.76N_2$) flows through the diffuser inlet at Mach 2.0 with the same static temperature and pressure. This condition roughly corresponds to the flight Mach number 6 at altitude of 20~30 km depending on the intake design and performance.

Accounting to the realistic engine size, the fuel port radius R (2.54 cm) with the lip thickness R, separating fuel and air stream, the main combustor radius 3R and the length of the main combustor 100R are presumed. The exit radius of 4R is assumed for the combustor. The Fig. 1 illustrates the flow conditions and configurations in detail.

From the previous study with 2-dimensional parametric simulation [10], it has been known that the length of the constant area combustor leads to the combustion mode transition from typical supersonic shear layer combustion to the thermal choking mode. In thermal choking mode, due to the coupled effect of the compressibility and turbulent flame structure, the combustion efficiency was found to be greatly enhanced especially in the L_C=90 case. Therefore, the constant-area combustor length (L_C) of 90 R is employed for the present simulation.

In this paper, we investigate the combustion characteristics in the L_C=90 combustor with different combustion regimes (the supersonic shear layer combustion and the thermal choking mode combustion). In the supersonic shear layer combustion mode, the combustor temperature is initialized as 1,200 K (case 1). The thermal choking mode combustion is triggered by initializing the initial temperature of 3,200 K (case 2) which may be initiated by employing the micro-pulse detonation engine as an ignitor.

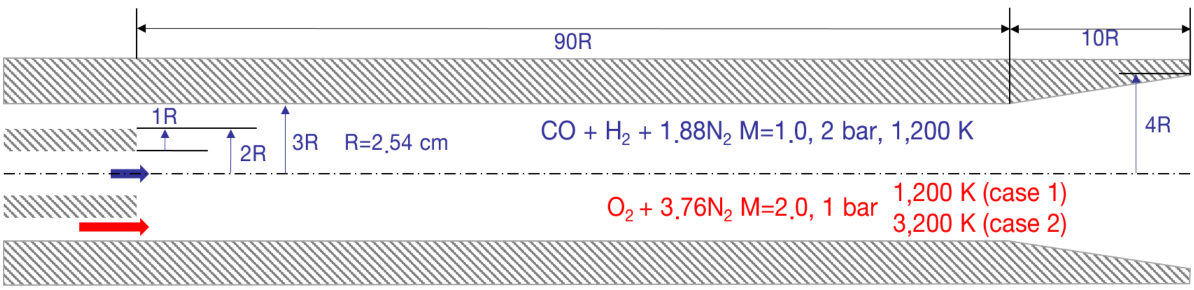

Fig 1. Configuration and flow conditions of DCR supersonic combustor

2.2. Numerical Modeling of DCR

The coupled form of the multi-species chemically reacting system, 3-dimensional fluid dynamic, and the turbulent transport equation can be summarized in the conservative vector form as follows.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial y}+S \tag{1}$$

$$Q=\begin{bmatrix}\rho_i\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho k\\ \rho\omega\end{bmatrix}\ E=\begin{bmatrix}\rho_i u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (e+p)u\\ \rho uk\\ \rho u\omega\end{bmatrix}\ F=\begin{bmatrix}\rho_i v\\ \rho vu\\ \rho v^2+p\\ \rho vw\\ (e+p)v\\ \rho vk\\ \rho v\omega\end{bmatrix}\ G=\begin{bmatrix}\rho_i w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ (e+p)v\\ \rho wk\\ \rho w\omega\end{bmatrix} \tag{2}$$

$$E_v=\begin{bmatrix}-\rho_i u_i^d\\ \tau_{xx}\\ \tau_{xy}\\ \tau_{xz}\\ \beta_x\\ \mu_k\,\partial k/\partial x\\ \mu_\omega\,\partial\omega/\partial x\end{bmatrix}\ F_v=\begin{bmatrix}-\rho_i v_i^d\\ \tau_{yx}\\ \tau_{yy}\\ \tau_{yz}\\ \beta_y\\ \mu_k\,\partial k/\partial y\\ \mu_\omega\,\partial\omega/\partial y\end{bmatrix}\ G_v=\begin{bmatrix}-\rho_i w_i^d\\ \tau_{zx}\\ \tau_{zy}\\ \tau_{zz}\\ \beta_y\\ \mu_k\,\partial k/\partial z\\ \mu_\omega\,\partial\omega/\partial z\end{bmatrix}\ S=\begin{bmatrix}S_i\\ 0\\ 0\\ 0\\ 0\\ S_k\\ S_\omega\end{bmatrix} \tag{3}$$

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. To take into account the turbulent eddy motion, the Menter's shear stress transport (SST) model is used with DDES with improved wall-modeling capability (IDDES). The governing equation was solved in a fully coupled manner using a fully implicit formulation. The convective fluxes are discretized by a multi-dimensional fifth-order accurate oMLP scheme and modified Roe scheme (RoeM). Viscous fluxes are discretized by a central difference scheme. The second-order implicit time integration is used with sub-iterations for time-accurate computation. The computational domain (43 million grid) is decomposed into 181 sub-domains and calculated with the MPI parallelized RPL3D in-house code [11-13]. Detailed information on the numerical methodologies utilized within the in-house code can be found in previous research conducted by our group[14-25].

3. Combustion Characteristics in DCR

Figure 2 displays the instantaneous plots of various parameters, including pressure, temperature, Mach number, pressure gradient, mixture fraction, scalar dissipation rate (χ), Takeno flame index (FI), and heat release rate, for both supersonic shear layer combustion mode (case 1) and thermal choking mode (case 2).

In the case 1, the combustion occurs in the form of a turbulent lifted flame. It starts at the interface where the velocity gradient between air inflow and fuel inflow is large, and supersonic combustion occurs along the turbulent mixing layer. In this mode, the pressure and temperature gradually rise after the continuous shock wave starting from near the injector lip, and combustion occurs continuously in the shear layer region further downstream.

Notably, in case 2, the pressure and temperature are considerably higher compared to case 1, and the flow velocity downstream of the thermally choked region becomes subsonic. The contour of the pressure gradient reveals that while the initial shock wave structure is similar, pressure waves resulting from the interaction between combustion and turbulence are observed at the midsection of the combustion chamber, occasionally developing into shock waves. By the close examination of the pressure-developing process of the combustor, it is found that there are pressure wave interactions generated by the turbulence motion with heat addition at the middle of the combustor therefore maintaining the thermal choking mode of combustion.

In conclusion, the two combustion modes are achieved due to the compressibility effect and the coupling phenomenon of turbulent motion. It is considered that the mode difference occurs depending on the pressure wave, enhanced turbulent motion, and the level of heat addition. Furthermore, we performed a Chemical Explosive Mode Analysis (CEMA) analysis to better understand the flame structure according to the combustion mode. In this simulation, we found that the combustion efficiency is improved in thermal choking mode.

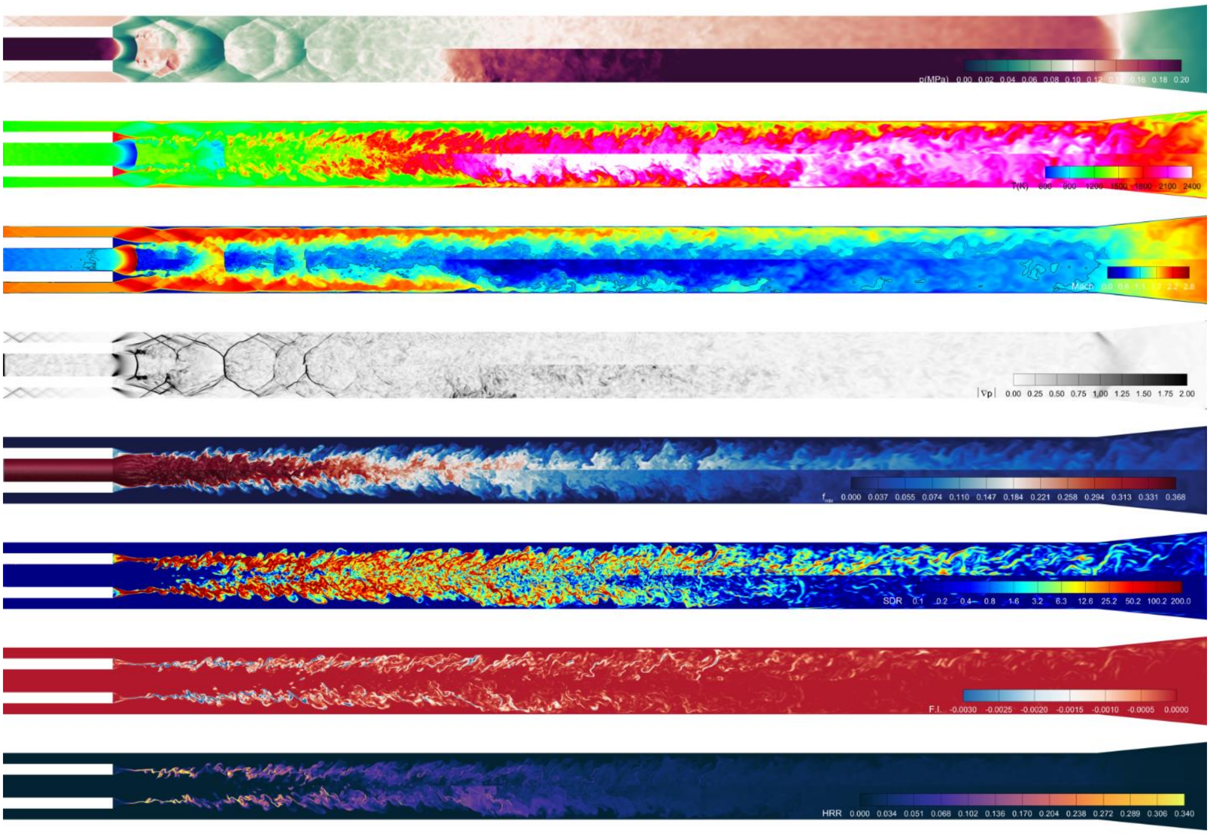

Fig 2. Instantaneous plots of case 1(upper) and case 2(lower)

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