



Combustion oscillation study in a kerosene fueled rocket-based combined-cycle engine combustor

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ABSTRACT

This study reports the combustion oscillation features in a three-dimensional (3D) rocket-based combined-cycle (RBCC) engine combustor under flight Mach number (M_{flight}) 3.0 conditions both experimentally and numerically. Experiment is performed on a direct-connect ground test facility, which measures the wall pressure along the flow-path. High-speed imaging of the flame luminosity and schlieren is carried out at exit of the primary rocket. Compressible reactive large eddy simulation (LES) with reduced chemical kinetics of a surrogate model for kerosene is performed to further understand the combustion oscillation mechanisms in the combustor. LES results are validated with experimental data by the time-averaged and root mean square (RMS) pressure values, and show acceptable agreement. Effects of the primary rocket jet on pressure oscillation in the combustor are analyzed. Relation of the high speed rocket jet oscillation, which is thought to among the most probable sources of combustion oscillation, with the RBCC combustor is recognized. Results reveal that the unsteady over-expanded rocket jet has significant impacts on the combustion oscillation feature of the RBCC combustor, which is different from a thermo-acoustics type oscillation. The rocket jet/air inflow physical interactions under different rocket jet expansion degrees are experimentally studied.

1. Introduction

Rocket-based combined-cycle (RBCC) engines subtly combine the advantage of high thrust/weight ratio of rocket engines with high specific impulse of air-breathing engines, have shown great potential for future space transportation [1]. RBCC is one of the most promising propulsion systems for SSTO and TSTO as it owns satisfactory performance in full range of its ballistic trajectory. It is most likely to be used for the next generation of hypersonic RLVs and fast responding aerospace planes [2,3].

Unfortunately, some problems remain to solve before its large scale engineering applications, one of which is the combustion oscillation observed in both ground tests and free-jet wind tunnel experiments. An improved understanding of the combustion instability along with a predictive capability is desired for the development of RBCC engines. Experimental study of combustion instability in an air-breathing engine has been conducted to explore the combustion oscillation mechanism and control methods [4]. Thermo-acoustic instability and the ensuing flow oscillation in a scramjet located at the AFRL have been studied [5]. The analysis was based on a quasi-one-dimensional treatment of unsteady flow motions, and the main features of the

oscillatory flow in both isolator and combustor were simulated. The mechanism responsible for driving flow oscillation was identified as the acoustic-convective interaction between the fuel injections and the flame zones. Acoustic disturbance originating from the flame zones causes oscillation in fuel mass fraction at the injections, which is then convected downstream to affect the heat release in the flame zones. Thermo-acoustic instability inside an ethylene-fueled scramjet with a cavity has been studied experimentally [6]. Pressure oscillation with frequencies from 100 Hz to 500 Hz inside the flow-path was measured. The observed phenomena may be attributed to the acoustic feedback loops between the shocks and the flame zones, and to the acoustic-convective feedback loops between the fuel injections and the flame zones. Combustion instabilities in an ethylene-fueled scramjet combustor have been investigated [7]. Experiments have demonstrated that the thermo-acoustic type oscillation with a broad frequency range exists for the cases with quasi-steady thermal choking or fixed shock trains. However, for the cases with a transient thermal throat, a deflagration-to-detonation type low frequency oscillation can be formed. A series of comparative experiments focusing on the combustion oscillation in a single-side expansion scramjet combustor with cavities have been conducted [8]. The global equivalence ratio, the fuel

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Nomenclature*Acronyms*

3D	Three-dimensional
RBCC	Rocket-Based Combined-Cycle
LES	Large Eddy Simulation
RMS	Root Mean Square
SSTO	Single Stage to Orbit
TSTO	Two Stage to Orbit
RLV	Reusable Launch Vehicle
AFRL	Air Force Research Laboratory
RANS	Reynolds–Averaged Navier–Stokes
DES	Detached Eddy Simulation

Variables

M_{flight}	Flight Mach number (Dimensionless)
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p_{e-exp}	Exit pressure of the third combustor in the experiment (atm)
p_{b-exp}	Back pressure of the third combustor in the experiment (atm)
p_{e-LES}	Exit pressure of the third combustor in the LES (atm)
p_{b-LES}	Back pressure of the third combustor in the LES (atm)
n	The order of oscillation frequency (Dimensionless)
$\bar{a}$	The longitudinally-averaged speed of sound between the fuel injection and flame zone (m/s)
$\bar{M}$	The longitudinally-averaged Mach number between the fuel injection and flame zone (Dimensionless)
L_{if}	The length scale between the fuel injection and flame zone (m)
f_{if}	The characteristic frequency between the fuel injection and flame zone (Hz)
T	The time period of one pressure oscillation cycle (ms)

injection scheme, and the fuel type all play a role.

Numerical studies trying to understand the combustion instability in air-breathing engines also have been performed. A single-step chemical reactive LES has been used to study the combustion instability in a two-dimensional dump combustor [9]. Results showed that vortex structures may induce unsteady heat release and provide energy to acoustic waves. A transverse injection of hydrogen has been considered in a scramjet and the detailed resolution of the flow and flame dynamics was featured [10]. It was found that much of the flow unsteadiness relates not only to the cavity, but also the intrinsic unsteadiness of the flow. Interactions between the unsteady flow and flame evolution may cause large excursions of flow oscillation. Large flow disturbance can be generated by the shear layer instability, which is triggered by the interactions with the shock waves. A single-step chemistry model LES has been used to investigate the oscillating flow in a 3D dump combustor, and a mode-by-mode analysis of Rayleigh criterion was presented by the proper orthogonal decomposition tool [11]. The HyShot II scramjet mounted in the high enthalpy shock tunnel Göttingen (HEG) has been studied numerically by RANS and LES with detailed and reduced chemistry models [12]. LES was used to elucidate the flow, mixing, self-ignition and the subsequent combustion processes, which revealed a complicated flow pattern dominated by the transverse jet-in-cross-flow and the associated fuel/air mixing and self-ignition. The intermittent formation of hot spots generates an oscillating self-ignition zone, which participate in forming the unsteady features.

Other types of thermo-acoustic coupling system have also been widely studied in [13–17], etc. For the other types of combustion oscillation in scramjets, the periodic fluid dynamic also plays an important role [18]. The Richtmyer-Meshkov instability has been observed in the shear layers of fuel injection jet [19–22]. Micka has found that flame oscillates between the cavity stabilized location and the jet-wake stabilized location in a model scramjet combustor for intermediate air stagnation temperatures [23,24]. It has been found that the oscillation does not occur at a fixed frequency and is not coupled with any acoustic mode, but the upstream auto-ignition reactions assist the flame propagation and control the actual flame fluctuations.

Amongst these works, none is directly related to combustion instability in RBCC combustors. Due to the highly unsteadiness associated with combustion oscillation, a combined study of both experiment and numeric is desired with air inlet, isolator, main strut, primary rocket, and combustor all included in the RBCC engine. The aim of this study is to demonstrate the ability of LES in predicting combustion oscillation and to clarify the effects of primary rocket jet on

the combustion oscillation of RBCC combustor. In our previous work [25], the phenomena of unsteady combustion in this configuration have been studied. The LES solver and its validation, the methodology for meshing, initialization and boundary condition specifications have been described. The current work is an extension of that one, but emphasizes more on the combustion oscillation features and the underlying driving mechanisms. Experimentally measured high-speed flame luminosity and schlieren images are also used for analysis. Effects of primary rocket jet on the combustion features of the RBCC combustor is presented, and the self-sustained combustion oscillation mechanism is recognized.

2. The experimental facility

Details about the ground test RBCC engine have been provided in the previous work [25]. For brevity, we just give some descriptions on the optical measurements in the test. The combustion region at the exit of the primary rocket is imaged through a silica window providing a visible zone of 200 mm in length and 40 mm in height. A high-speed video camera with a sample rate of 10000 f/s and a resolution of 800×912 pixels is used to record the flame luminosity images. As preliminary analysis has indicated that the nozzle of the primary rocket is indeed works at an over-expansion status, the flow speed just at its exit is not very high. This is also verified by the Mach number distribution in Fig. 6 of Ref. [25]. Therefore, this sample rate is thought to be enough for capturing the transient flame dynamics in the observed window-region. The acquisition frequency for the schlieren system is 8000 f/s, which uses a laser light and a shuttle time of 10 μ s.

For the measurement of pressure signals, 31 wall flush-mounted transducers are distributed along the flow-path to record the wall pressure at a sample rate of 2000 Hz. A large amount of ground tests [25–27] have indicated that combustion oscillation in the current or similar RBCC combustors is a low frequency type of the order of 200 Hz. Therefore, the 2000 Hz pressure acquisition rate is capable to record and obtain the right frequency spectrum. The air stagnation temperature is monitored by a K-type thermocouple locates just at the entrance of the isolator, which is around 707 K in our simulated $M_{flight} = 3.0$. The total pressure is 0.8 MPa, and the air mass flow rate is 4.67 kg/s. Mach number at the isolator entrance is about 1.7. Liquid kerosene is used as the secondary fuel, which is injected perpendicularly to the flow by two pylons embedded in front of the primary combustor at an equivalence ratio of 0.67. Kerosene is injected at 300 K under a plenum pressure of 3.1 MPa through totally 40 injector holes at both sides of the two pylons, leading to an injection velocity about

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