Detonations and Thermoacoustic Modes in a Flow through RDC

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1. Introduction

There has been increased activity of pressure gain combustion (PGC) research over the past few years, including a resurgence of interest in the rotating detonation combustor (RDC). Prior studies of RDCs have claimed promising benefits for the future of detonation based pressure gain combustion including (i) a notable increase in total impulse over pulsed detonation combustors [1], (ii) an increase in fuel efficiency [2], (iii) an increase in the total pressure in the combustor due to detonation [3], (iv) a rise in thermal efficiency [4,5]. However, some details of its operation are yet to be better understood. Although significant progress has been made, much work remains in properly understanding the various modes and combustion dynamics present in these devices.

Rotating detonation combustors are known to exhibit various modes of operation, and multiple modes can coexist at certain combinations of reactants mixtures [6]. The periodic modes can be detected through pressure measurements. Fast Fourier transforms can be performed on high-speed pressure measurements to identify periodic modes present during operation. High-speed imaging that can either be performed from the exhaust side of the combustor or from the side through a transparent outer combustor wall helps in identifying the mode of operation. Spectral Proper Orthogonal Decomposition (SPOD) serves as an empirical method to extract modes from combustion data gathered using high-speed imaging [7]. These methods can be used to analyze the internal combustion dynamics of the RDCs at varying frequencies and identify co-exiting modes.

SPOD is a form of proper orthogonal decomposition that extracts modes that are coherent in both space and time. This is in contrast to standard POD which only extracts modes coherent in space [7]. The temporal coherence results in modes that correspond to particular frequencies. In the context of a RDC, SPOD can be used on high-speed imaging to extract visuals of the operating modes of the combustor as various modes of differing frequencies exist throughout a test at different times.

RDCs can operate in modes other than the ideal detonative mode where a single or multiple rotating detonation waves rotate at or near the theoretical Chapman-Jouget (CJ) wave speed and peak pressure. A hollow RDC, with a back wall or with an open upstream port (a flow-through RDC) can also operate in a thermoacoustic deflagrative mode. In this mode, thermoacoustic instabilities exist at or near the theoretical CJ frequency, without the presence of a rotating detonation wave [6]. In this geometric configuration transverse modes are present due to the absence of an obstructing center-body which are part of the geometry of an annular RDC. In addition, a combination of detonation and thermoacoustic modes modes can coexist. The analysis of these different modes in a flow through RDC configuration are the subject of this investigation.

2. Methodology

The flow through rotating detonation combustor investigated here is depicted in Fig. 1. The main combustion chamber consists of an open cylinder, with no internal structures. In the flow-through configuration, a reduced diameter inlet cylinder at the forward end is open to the atmosphere, allowing entrained air to mix with the combustion reactants and products. Air is injected radially inwards into the combustor through an injection slot whose area can be adjusted. As air flows out of the plenum through the circumferential injection slot it mixes with the fuel jets that are injected axially through 120 injection holes. The mixture of ethylene and air is ignited using a spark plug or a pre-detonator. After ignition, depending on reactant conditions, an azimuthally traveling detonation wave is formed. Incoming fresh reactants are consumed by the travelling detonation wave, while high pressure and temperature products behind the detonation wave expand and exhaust outwards through the open combustor exit. The detonation wave is self-sustaining as long as reactants continue to flow.
Static pressure is measured in the air and fuel plenums and inside the combustor using the following transducers: air plenum pressure sensor (OMEGA PX359), fuel plenum pressure sensor (OMEGA PX359), and combustor pressure sensor (OMEGA PX359). The combustor pressure sensor is offset from the combustor for durability in a capillary tube averaged pressure (CTAP) arrangement. Dynamic pressure is measured in the combustor via Piezotronics brand piezoelectric pressure transducers (PCB 113B24) sampled at 1 MHz. These PCB pressure transducers are placed at equal axial positions with 120° azimuthal separation.

A Phantom v1610 high-speed camera is used to capture high-speed imaging, positioned aft-looking-forward to RDC. The camera operates at a constant f-stop of f/3.5, a minimum frame rate of 45,000 frames per second, and an exposure time of 10 μsec for all test cases providing clear visualization thus providing data for analysis of the combustion wave modes.

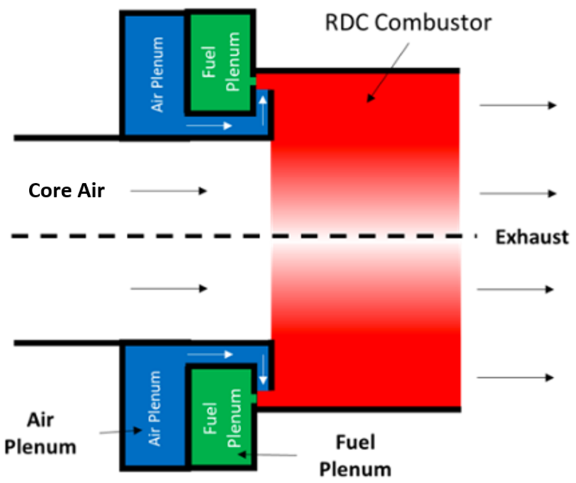
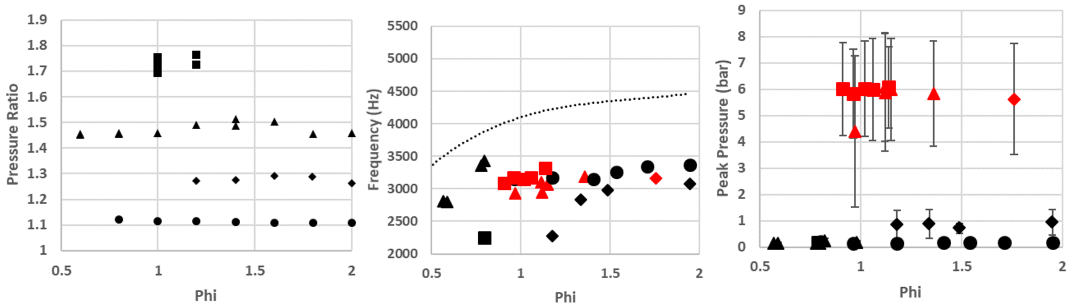


Figure 1: Flow through RDC.

3. Results and Discussion

A series of tests have been conducted with the flow-through RDC with air flow rates ranging from 0.2 to 0.5 kg/sec and equivalence ratios from 0.5 to 2.0. The air and fuel mass flows were measured through FlowMaxx sonic nozzles. Fig. 2 shows the operating map, the wave frequency, and the peak pressures. The symbols in each figure represent the dominant mode of operation. Squares represent detonative modes, diamonds represent thermoacoustic modes, and circles deflagrating cases. The operating map in Fig. 2a shows that stable detonations were obtained at the higher flow rates for equivalence ratios between 1 to 1.2. At a flow rate of 0.4 kg/sec transitional behavior was observed with thermoacoustic modes transitioning to stable detonations. At a flow rate of 0.3 kg/sec, only thermoacoustic modes were detected and at even lower flow rates only weak thermoacoustic waves transitioning to deflagrations occurred. In all cases, the wave frequency was 75-80% of Chapman-Jouguet frequency (Fig. 2b). The mean peak pressures are shown in Fig. 1c with detonation pressure reaching up to 8 bar while the thermoacoustic and deflagration cases have low pressures (Fig. 2c).



(a) (b) (c)

○ 0.2

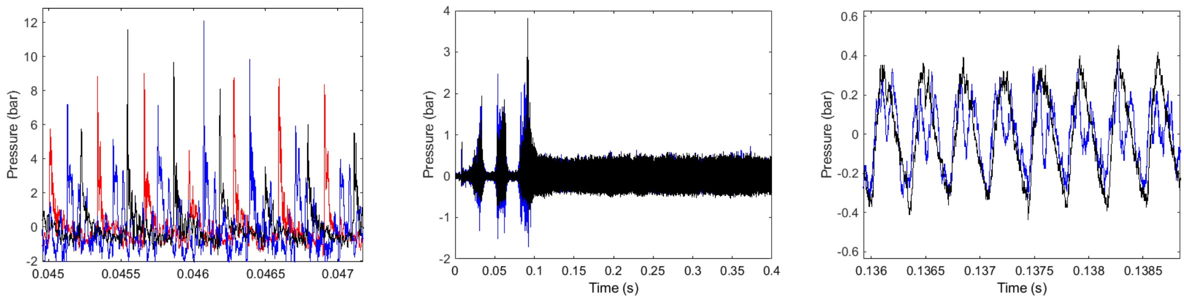
◊ 0.3

Δ 0.4

□ 0.5

black = thermoacoustic and deflagrations

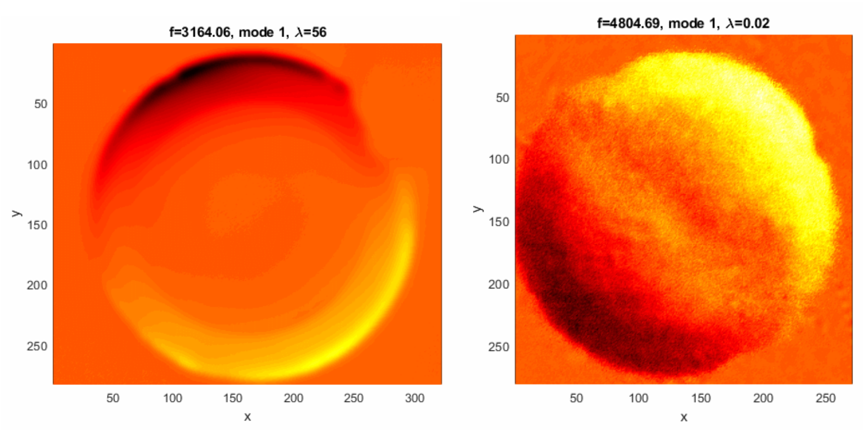
Figure 2: Operational map, frequency, and peak pressure of RDC in flow through configuration.



(a) (b) (c)

Figure 3: Pressure traces: (a) Stable detonation; (b) Transient detonation-thermoacoustics; (c) Thermoacoustics

Figure 3 shows pressure traces as a function of time for three cases: stable detonation (Fig. 3a), transient mode where the operational mode switches between detonations and thermoacoustic waves (Fig. 3b), and Fig. 3c with a thermoacoustic wave. In the first case, stable detonation wave propagation occurs immediately following ignition and the direction of rotation is conserved till the end of the test. This is indicated by the pressure peaks that reach up to 12 bar and a regular pattern of black, red, and blue peaks that are measured by the circumferentially located pressure transducers. In the second case, transition between detonations and thermoacoustics occurs three times at the beginning of the test, followed by stable low pressure thermoacoustic waves as illustrated in Fig. 3c. These waves are characterized by a sinusoidal shape with low amplitude and centered on zero pressure.



(a) (b)

Figure 4: SPOD analysis of the dominant modes of: (a) stable single wave detonation; (b) Transverse thermoacoustic wave

High speed videos were obtained visualizing the combustion chamber from the back side through the open exhaust. The high-speed videos were analyzed using spectral proper orthogonal decomposition analysis (SPOD) of the Nyquist-satisfied broadband luminescence data. The single wave mono-directional mode is seen at a frequency of 3164 Hz in Fig. 4a. The detonative mode has the highest modal energy from the SPOD analysis. The detonation front is seen to be very thin radially, hugging the wall. Lowest air flow rate mostly produces Rayleigh thermoacoustic oscillations that are barely discernable from the high-speed video due to a very low relative luminescence. Fig. 4b shows the extracted modal behavior using SPOD which picks out the acoustic oscillations as a distinct peak in the spectra and shows the non-stationary transverse acoustic mode.

A spatiotemporally algorithm was developed to track the brightest pixel in each frame of high-speed videos generating a three-dimensional space-time diagram enabling to attain a broad overview of the combustor dynamics (Fig. 5 left). The detonation wave trajectory is shown from the ignition moment and the transition to detonation occurs within the first 150 frames (3 msec) after ignition. In this case of a stable single wave detonation, the rotating detonation wave appears as a “sliver” always adhering to the outer wall of the combustor (Fig. 5 right).

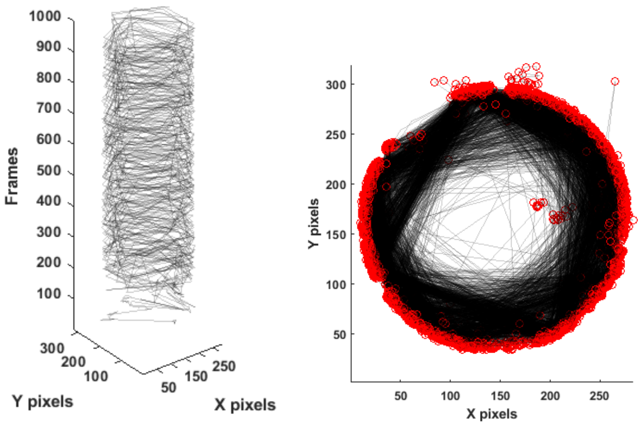


Figure 5: Spaciotemporal diagram of the detonation wave trajectory of a single wave stable detonation wave propagation.

Figure 6 depicts a transitional case when both thermoacoustic waves and detonations transition from one mode to the other and back. The algorithm gives insight into the link between thermoacoustic radial and tangential oscillations and rotating detonation (Fig. 6 left). Immediately following ignition a transverse acoustic mode is initiated and after ~400 frames (9 msec) slowly start rotating into a spinning acoustic mode [8], which eventually gathers speed, thereby ending in rotating detonations at ~1000 frames (22 msec). However, the transition fails and spinning thermoacoutic waves reappear before a final transition to stable detonations at ~1500 frames (33 msec). This process appears to be a DDT occurring in 3-D. Fig. 6 right shows the combined detonation mode with the circumferential red circles at the combustor wall, while the thermoacoustic mode is dispersed inside the combutor.

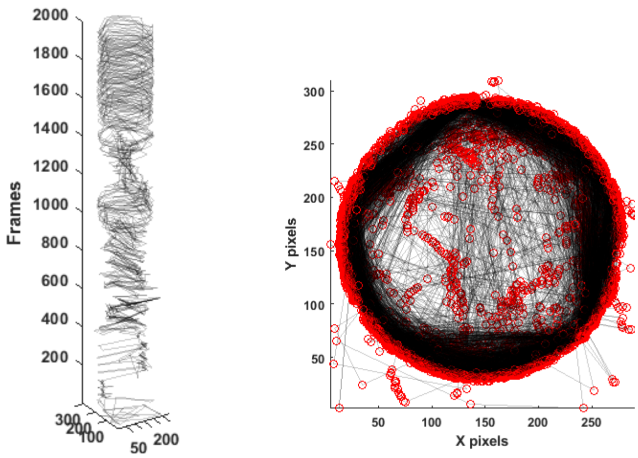


Figure 6: Spaciotemporal diagram of a transitional case when thermoacoustic waves transition to stable rotating detonation.

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