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Longitudinal pulsed detonation instability in a rotating detonation combustor

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A B S T R A C T

The peculiar phenomenon of longitudinal pulsed detonation (LPD) in a rotating detonation combustor (RDC) is studied using hydrogen–air mixtures, by utilizing: (i) two air injection schemes having different inlet areas, and (ii) a convergent nozzle assembly with different spacers that affixes to the RDC exit. By varying the air injection pressure ratio and the backpressure, the regime of occurrence and the mechanism of this pulsed detonation instability are investigated. Immense evidence to suggest that LPD is caused by a peculiar detonation initiation mechanism enabled by a reflected shock wave from the RDC exit is discovered through an ensemble axial pressure profile analysis. Distance–time plots show that a single cycle of the pulsed detonation has two components: a fast-moving axial forward decaying detonation wave (with 75% of the ideal detonation speed) and a slower reflected detached shock wave (with 30% of the ideal speed). When the weak reflected wave comes in contact with the fresh reactants at the RDC headwall, another strong axial detonation is produced, thereby continuing the cycle without external ignition. LPD is also found to have three diverse facets, namely, inception, sustenance and operating frequency. For similar backpressures, the two air injection schemes have completely different operating regimes, leading to the inference that while backpressure is necessary for the onset of the pulsed detonation instability, by virtue of enabling reflected shock waves from the exit, lower air injection pressure ratio dictates the sustenance of the instability. A narrow band of injection pressure ratios, between 1.4 and 1.85, under back-pressurized RDC operation has high proclivity to produce sustained periodic longitudinal pulsed detonations in the combustor. Above this range, stable rotating detonation is preferred, and below this range, the operation is distinguished by the mixed presence of both rotating and pulsed detonations for a given test point, finally breaking down into chaotic instability for lower pressure ratios. The frequency of the pulsed detonation operation is found to depend on the initial combustor pressure and equivalence ratio, with higher frequency observed with an increase in backpressure and equivalence ratio.

1. Introduction

Combustion is broadly classified into two types: deflagration and detonation. When the combustion wave travels with subsonic velocity in the reactant mixture it is a deflagration wave. In detonation, the combustion wave is coupled to a shock wave and travels faster than the sound speed in the mixture. Detonation, due to its inherent linkage to a shock wave, produces pressure ratios of 13–55 [1] across the detonation wave. This property of enabling a pressure gain by a detonation wave could be profitably used in a detonation combustor [2]. Pulsed detonation combustor (PDC) and rotating detonation combustor (RDC) are the two prominent detonation devices. PDC is characterized by relatively larger size, periodic reactants injection and purge using valves, and highly pulsating (of up to 100 Hz) exhaust pressures [3]. It is prohibitive to increase the frequency of operation, *f*, beyond 100 Hz due to the mechanical limitations imposed on valves assembly. RDCs on the other hand are smaller than a PDC of comparable mass flow and have continuous reactants fill into the combustor. Depending on the mass flow rate and the geometry [4,5], the RDC can have one or more detonation waves propagating continuously inside the chamber. Though the preferred operating mode of RDC is to have the eponymous rotating detonation inside the chamber, it has been observed by a few prior studies [4,6–12] that at certain geometries and mass flow rates, the RDC transitions from housing a continuous rotating detonation to producing axial pulsed detonation inside the combustion chamber, like the PDC.

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Nomenclature

f	frequency (Hz)	P_C	time-averaged combustor pressure before ignition (bar)
Φ	equivalence ratio	P_A	time-averaged air plenum pressure before ignition (bar)
$\dot{m}_a$	air flow rate (kg/s)	x	axial distance from RDC headwall (cm)
t	time (s)		
P_R	average pressure ratio across air inlet before ignition		

This pulsation, which was first observed in an RDC and named as longitudinal pulsed detonation (LPD) by Bykovskii et al. [6], is an intriguing phenomenon because it occurs in the absence of any mechanical valves to actuate the reactant flow, which is tantamount to a PDC of the simplest design. Additionally, the frequency of the pulsation is noted to be in thousands of Hertz [6,8,9,12], which, once again, betters the operating frequency of any known PDC by more than an order of magnitude.

However, the cause behind the onset and sustenance of LPD has not yet been deliberated in detail in literature. Bykovskii et al. [6,7] established that LPD onsets in an RDC operating with H_2–air when the chamber width is dropped below a threshold value which in turn may influence the detonation cell-width of a given mixture. LPD also occurs for RDC operation with relatively lower chamber pressure and substandard mixing with subsonic air injection [6]. In terms of equivalence ratio, Φ, Bykovskii et al. discovered that the LPD mode demarcates the regions of deflagrative combustion and detonative combustion at lean and rich limits of H_2–air operation, for their RDC setup [7]. They measured the frequency of pulsations to be around 1.6 kHz. Frolov et al. [8] noted the existence of LPD for H_2–air mixtures in their larger RDC with a diameter of 406 mm. LPD was found to occur at $f \approx 1$ kHz at higher air injection gap width. While a specific case of LPD was discussed for an operating case with the higher injection area and a convergent nozzle (and hence presumptively a choked RDC exit leading to subsonic air injection), it is unclear if they observed the phenomenon without a choked exit. Simultaneous azimuthal pulsations in the RDC are also noted by Wang et al. [9] during their RDC operation with vitiated air. It could be speculated that heat addition may have caused a choked exit in the RDC. While Frolov et al. used ion probes in their study and Wang et al. used pressure sensors in theirs, both concurred that the instigation for LPD started downstream, near the RDC exit. Additionally, the presence of the LPD mode is also observed in ethylene–hydrogen–air mixtures in an RDC with convergent nozzle by St. George et al. [10], indicating that the instability is reactant mixtures independent. Driscoll et al. [11] have observed LPD at lean operating conditions for H_2–air mixtures with a convergent nozzle, and thus, once again, subsonic air injection. Finally, a preliminary discussion on LPD as one of the prominent instabilities in a back-pressurized RDC is discussed by Anand et al. [12], where for a given restricted exit area of an RDC, LPD was found to occur only below a critical Φ. Hence, from literature, it is clear that LPD has high propensity to occur for subsonic air injection, and for operation near the lean boundary.

Furthermore, liquid rocket engines are known to be susceptible to "high-frequency instabilities", the fundamental mechanics of which are yet to be clearly understood. Interestingly, "longitudinal instability", which is characterized by axially traveling pressure pulses between the injection head and the nozzle throat at $f \geqslant 1000$ Hz are a prominent subset of the high-frequency instabilities in rocket engines, and are not comprehensively explained, despite the considerable research into the phenomenon during 1950–80s [13]. Male et al. [14] visually captured the onset of "longitudinal shocks" moving within the thrust chamber at $f \approx 1000$ Hz when fuel transition was effected from furfuryl alcohol to JP-3. Hybrid modes of operation with both the longitudinal and other high-frequency instability – lateral oscillations at $f \approx 6000$ Hz – were also recorded. The shock waves were found to occur with a maximum pressure ratio of 2.8, with the highest recorded pressure peak of ≈44 bar. Highly uniform rocket chamber erosion was observed near the injectors for operations with the longitudinal instability. A nonlinear analytical method to model this instability, based on its "shock wave characteristics" was developed by Lores and Zinn [15], while conceding the model's shortcomings in predicting the triggering of the instability. Commendable work was done by Berman et al. [16,17] in subsequent articles in visually characterizing this longitudinal instability. Berman and Cheney [17] recorded the presence of "intermittent shock-type axial instability" around 1000 Hz upstream of the nozzle throat when the total reactants flow rate was lowered beyond a critical value, for a constant head pressure drop (pressure ratio across injectors). Moreover, the instances of tests producing these instabilities were lowered progressively when the nozzle throat area is gradually increased. Using a novel moving slit photography technique, their partially transparent rocket engine revealed a process consisting of an upstream moving shock wave with gradually increasing strength, which eventually impinges on the injector head (with an absolute velocity of 1005 m/s), and almost instantaneously initiates a highly luminous downstream propagating shock wave (absolute velocity of 1433 m/s). Berman et al. also observed that the presence and strength of this longitudinal instability is a function of the angle of convergence of nozzle throat (amplifier and reflector), injector type, and chamber length, finally concluding that while the chamber pressure (predicated by flow rate and throat area) had a significant influence on this instability, the head pressure drop across the injectors was the driving factor. In synopsis, the above-mentioned sources on rocket engine combustion instability implicitly attribute the phenomenon in rocket thrust chambers to be caused due to periodic explosions.

Thus, this pulsed detonation instability in an RDC is of paramount importance, because: (1) it could commence research into truly valve-less PDCs with an increase in frequency by at least an order, (2) it is imperative to understand this significant instability, if practical employment of RDCs is ever to be realized, and (3) understanding the kinship between the longitudinal instabilities in rotating detonation engines and rocket engines would greatly further the development of both propulsive devices. Since this phenomenon has been observed sporadically through the literature, and since there has not been any substantial theory describing the mechanism yet, the current paper aims to address LPD through a systematic parametric investigation of RDC operation at lean equivalence ratios of H_2–air mixtures, utilizing two air injection areas and varied levels of backpressures.

2. Experimental methodology

The current research is performed at the Detonation Engines Test Facility in the Gas Dynamics and Propulsion Laboratory at the University of Cincinnati for RDC operation with H_2–air