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Rotating Detonation Combustor Research at the University of Cincinnati

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Abstract Rotating detonation combustors (RDC) are at the forefront of pressure gain combustion (PGC) research. The simplicity in design and the ease of assembly makes it a promising technology that could be integrated into existing combustor architectures. This is, however, coupled with the considerable complexities of the detonation-based flow field, and the associated modes and coupling mechanisms. The current paper is an overview of the research done at the University of Cincinnati to address some of the challenges and questions pertaining to the physics of RDC operation. Issues such as combustor geometry, injection schemes and mixing, varied reactants behavior and modes of RDC operation are discussed. The effects of pressurization of the combustor, along with other detonation enhancement strategies are also deliberated upon. When appropriate, parallels are drawn to the phenomena of high frequency combustion instabilities to address the similarities in observations between the two fields.

Keywords Rotating detonation engine · Combustion instability · Detonation

1 Introduction

The supersonic combustion phenomenon of detonation produces a pressure increase of 13–55 in gases [1] across the wave due to the shock wave linked to the combustion front. This detonative mode of combustion is theorized to provide the highly sought after pressure gain (or more specifically, the gain in stagnation pressure, according the AIAA Pressure Gain Combustion Technical Committee) across the component. Although pulsed detonation combustors (PDCs) were once the widely investigated type of pressure gain combustion (PGC)

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systems, the majority of recent research has migrated to rotating detonation combustors (RDCs). The higher power density [2], the lack of a need to regulate periodic ignition and fuel/oxidizer injection, as opposed to a PDC, and the steadier exit flow profile [3] circumvents the notable issues besetting PDCs. Despite the considerable progress made to date on the different facets of RDCs, substantial research is still warranted to ascertain the physics and apply RDCs as a real-world, power-generation device.

Until recently, the probable efficiency increases afforded by RDCs, due to detonative burning [4], remained a figment of numerical or analytical solutions, with studies claiming the following benefits: (i) a notable increase in total impulse over pulsed detonation combustors [3], (ii) an increase of up to 9% in fuel efficiency [5], (iii) an increase of 15% in the total pressure in the combustor due to detonation [6], (iv) a rise of 5% [7] and 1.6% [8] in thermal efficiency, and (v) a 14% increase in power plant efficiency over conventional J class turbines [9]. However, a handful of experimental investigations have now supported the theoretical promulgations of increased efficiency of the detonation cycle. For instance, in their rocket engine configuration, while noting the issue of unoptimized combustors, Frolov et al. have shown that RDCs do indeed have a higher efficiency—by 7–13%—than the corresponding deflagrative combustors [10]. Wolański has estimated a reduced SFC—by 5%—when RDCs were integrated into their unoptimized GTD-350 helicopter engine [11]. In the USA, AFRL's research into an open looped, turbine-integrated RDC resulted in an increased turbine factor—defined as the ratio of the energy extracted by the turbines to the total fuel energy input to the system—with RDCs, as opposed to deflagrative combustors [12]. These advancements have tentatively proven the efficacy of RDCs to provide the required step-change increase in gas-turbine and rocket engine efficiency.

In this regard, at the University of Cincinnati (UC), various aspects of PGC have been researched since 2003. During the last 5 years, emphasis has been placed on RDC operation at different conditions of geometry, injection and mixing, reactants, pressurization, modes, detonation enhancing strategies, and the associated effects on noise, emissions and heat transfer. We have also shown the possibility of attaining rotating detonations in a hollow combustor, as opposed to the traditional annular RDC designs. This concept was subsequently extended to successfully demonstrate rotating detonations in a flow-through, hollow combustor with significant air entrainment. It is emphasized here that a few researchers studying rocket engines (both liquid propellant engines and solid motors) have observed "detonation-like" [13–17] tangential waves spinning around the rocket combustion chamber at thousands of Hertz. Note that it is a common occurrence for multiple tangential waves to co-exist inside the rocket combustor at certain conditions, just like in RDCs, and are referred to as 1T (first tangential spin), 2T (second tangential spin), etc. These "high-frequency instabilities" (HFI) in rocket engines, characterized by "shock-fronted" waves have been a source of constant adversity to the development of rocket engine programs, mainly due to the lack of understanding of the fundamental behavior of the complex combination of combustion and fluid dynamics. This has traditionally led to a highly demanding and economically detrimental process of trying to treat the rocket-specific symptoms of the high-frequency instability by adopting a trial-and-error process [18]. To exemplify, The F-1 engines for the Saturn V program had to be subject to over 2000 full-scale test runs to detect and avoid the intrinsic (starts only after injection of reactants and subsequent ignition) instabilities [19]. Ariane 5 is another rocket that experienced significant HFI events in its Viking engines [20, 21]. The primary reason behind not considering detonation physics to explain HFI in rocket engines seems to be attributed to the rather large mismatch between the ideal CJ model-predicted wave speeds and peak pressures, and the measured values, when such an effort was undertaken [17, 22]. However, this mismatch can now be explained by recent findings

in the field of RDCs, where the rotating detonation wave speed and peak pressure across all the facilities worldwide always exhibit varying levels of deficiencies from the expected ideal C-J values [23–28]. The rationale behind attributing the Rayleigh heat addition criterion to explain HFI processes in rocket engines is because there are oftentimes, clearly linear processes that tend to operate at very similar frequencies [17, 29–31]. This is seen as symmetric sinusoidal pressure oscillations at high frequencies [32–36]. The problem arises when the same process is also used to explain the patently nonlinear, non-isentropic detonation-like processes that are also categorized under the umbrella of high frequency instabilities [37, 38]. Clayton et al. [22] deliberates on this conundrum of trying to explain their observation of "rotating detonation-like waves" in their rocket engines as follows: "Regardless of whether the phenomenon is called a detonative or an acoustical disturbance, it is believed that the definition of the parameters controlling it requires understanding of the generating and sustaining mechanisms for steep-fronted combustion-supported pressure waves sweeping about the periphery of circular cross-section chambers". Therefore, the implications of detonation dynamics in annular / hollow combustors are not only of paramount importance to the field of RDCs, but also to high frequency combustion instabilities. The current paper is oriented towards presenting a brief review of the work done to date, at UC, on annular, hollow and flow-through RDCs (Fig. 1).

2 Geometry-Based RDC Variations

Detonation was widely regarded as a one-dimensional combustion wave even after almost half a century after its discovery as the Chapman-Jouguet theory of modified Rankine-Hugoniot equations with "zero reaction width thickness" was able to accurately predict the
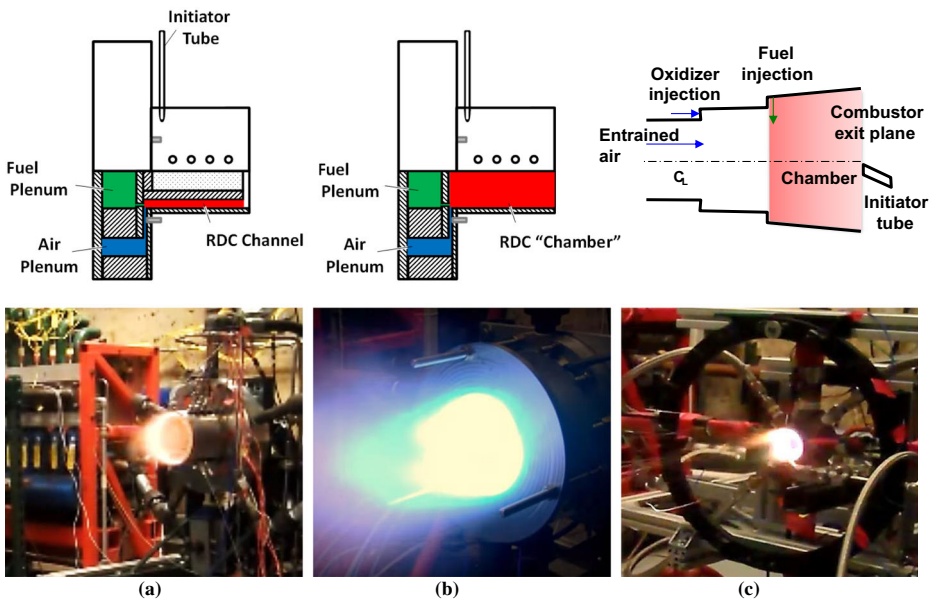

Fig. 1 Schematic and successfully operating **a** 6"annular RDC, **b** 6" hollow RDC, and **c** flow-through 3D-printed hollow RDC (UC studies)

peak pressures and wave speeds of the phenomenon. This perception, however, was altered in 1926 when Campbell and Woodhead [39] reported the three-dimensional phenomenon of spinning detonations, which move helically in a tube with stationary premixed reactants [40]. Due to intense research over the next several decades, several discoveries were made, the most important of which is the true nature of detonations: the complex three-dimensional interaction between Mach wave, incident wave, transverse wave and the reaction zone that together form what is now called the 'detonation cell' [41]. Thus, spinning detonations were responsible for the new outlook on detonation waves, and naturally have been researched extensively; however, there are still outstanding issues and questions to be answered. One such researcher that investigated the complex phenomenon was Voitsekhovskii et al. [42]. Since a comprehensive analysis of spinning detonations required detonation tubes of considerable length, depending on the mixture used (even up to 10 m [16]), Voitsekhovskii et al. proposed "fixing" the detonation wave in a stationary frame of reference, which could potentially alleviate the demanding facility requirements. He reasoned that a premixed mixture of the required reactants, when fed into an annular chamber (to enforce the required helical path) at the required inlet velocity (so as to balance the spinning detonations' axial velocity in a stationary premixed tube) the transverse waves composing the detonation wave could be fixed in the laboratory frame, thereby lending it to be studied easier. However, since such a premixed injection was prone to intense flash back events, he resorted to experimentally testing the next best configuration—non-premixed reactants that are continually fed into an annular chamber, or, in other words, what we now know to be a rotating detonation combustor. Voitsekhovskii's intention seems to not have been to create a pressure gain device, but rather to efficiently study spinning detonations. The annular cross-section that is characteristic of almost all RDCs is due to this origin.

Hence, there appears to be no stringent physics-based rule that dictates RDCs should be annular. A hollow RDC is lighter than an annular combustor of similar dimensions due to the absence of the inner-body. While this forecasts positive implications to the usage of a hollow rotating detonation combustor, we are left with an important unanswered question: if rotating detonation waves can be produced in both a hollow and an annular combustor, what is the physical mechanism responsible for its production and continued sustenance? Furthermore, under what conditions does an ordinary combustor become a rotating detonation combustor and vice versa, and is it something that can be controlled? In fact, if rotating detonation waves can be produced in a hollow combustor that are of equal strength (in terms of pressure and velocity) to the waves produced in an annular combustor, it would be better to resort to the hollow combustor design due to heightened heat transfer to the annular walls. Since it is well known that a planar detonation in a tube with the same mixture concentration gets progressively weaker, and eventually fails when the tube diameter is reduced below a critical value of detonation cell size [41], logic dictates that we move away from the annular designs that have been the singular signature of rotating detonation combustors until now.

Some of the above questions have been addressed through the research performed at UC. We have extensively tested both annular [43] and hollow [44] configurations, utilizing a variety of reactants (discussed next). Pictures acquired from high-speed imaging of the RDC aft-end (looking into the combustor) are presented in Fig. 2a (annular) and b (hollow). The first image in both the sub-sections (a and b) denote the initial blast wave entering the combustor from the pre-detonator. Note that ignition of an RDC appears to be a minimal concern, since a variety of energy deposition methods, ranging from pre-detonator [45], through low and high energy spark plugs [46], to blast wires [47] have been used to initiate RDCs, with similar success. Our investigation into the functioning of pre-detonators revealed that the energy deposited by this method is smaller than the required energy to
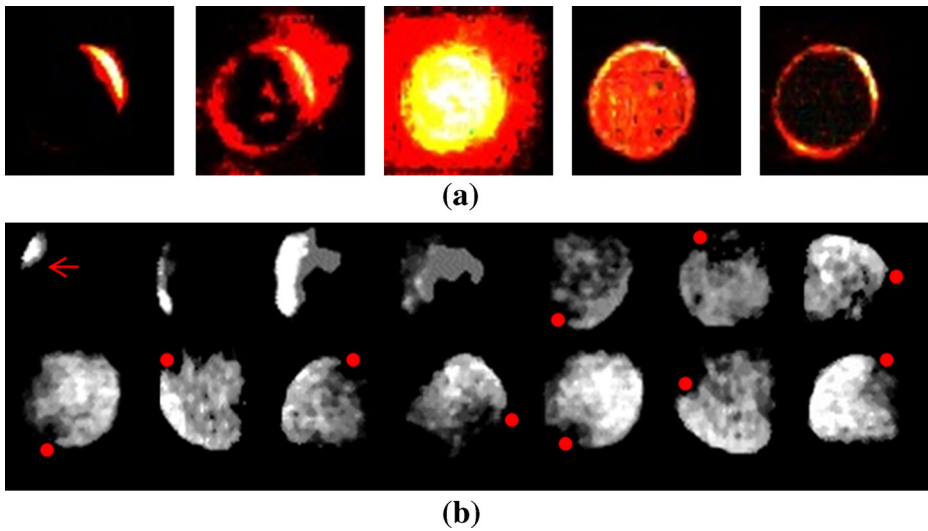
(a)

(b)

Fig. 2 Aft-end high speed images of clockwise-moving detonation wave obtained by 'looking into' **a** an annular RDC, and **b** hollow RDC (red dot signifies the leading part of the detonation wave) [44]

produce direct detonation initiations in chosen mixtures by an order of magnitude, leading to the conclusion that all RDC initiation processes are due to a complex deflagration-to-detonation transfer (DDT) mechanism that is yet to be clearly understood [45]. Using a windowed cross-correlation algorithm [48], we found that despite this apparent randomness in RDC initiation, there is a rigid statistical coherence (depending on flow rates and backpressure) in the time it takes (within an order of magnitude) for the DDT process to develop into sustained rotating detonations [49]. All the other frames (for both annular and hollow RDC) indicate this complex process of DDT (distinguished by deflagrative combustion – darker images) that precedes stable detonation wave propagation, following the initial ignition from the pre-detonator. Unsurprisingly, the detonation wave structure is markedly different in our hollow combustor [44], as seen by a sectoral region of intense combustion defining the detonation wave, whereas the annular combustor has the traditional almost-planar detonation wave. The leading front of the detonation wave in the hollow combustor is, however, distinct and is marked by a preceding red dot. This suggests that closer to the wall the wave speed is higher than the radially inward location, owing to the dependence of linear velocity on radius. These results correlate well with the detonation structure acquired by Tang et al. [50], numerically, in a hollow RDC with the same reactants: hydrogen and air.

As noted before, one should expect a hollow combustor to be able to produce stronger and faster detonations due to the absence of various wall-dependent losses (heat quenching, area divergence, etc. [41]). This inference is strengthened from our observations on annular RDC operation and its dependence on annulus width—shorter widths tended to produce narrower operating maps [51]. For the hollow configurations we tested [52], this is confirmed to be true, as the highest peak pressures recorded in a hollow combustor were significantly higher than that observed in an annulus at the same flow rates—a similar behavior has also been noted by Hansmetzger et al. [53]. This behavior is exemplified in Fig. 3, which shows the pressure-time traces from three azimuthally distributed PCB piezoelectric sensors (near
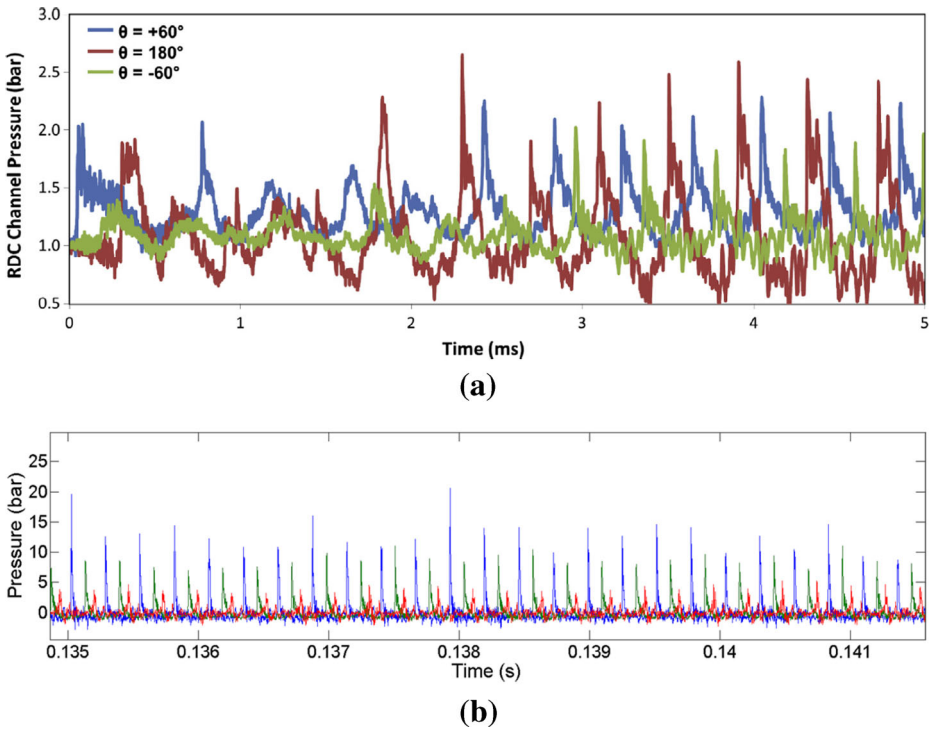
(a)

(b)

Fig. 3 Pressure profiles from three azimuthally placed high-speed PCB dynamic pressure sensors showing rotating detonations in **a** annular RDC for $\dot{m}_a = 0.1$ kg/s at $\Phi = 1.03$ (H$_2$-air) [45], and **b** hollow RDC for $\dot{m}_a = 0.4$ kg/s at $\Phi = 1.4$ (C$_2$H$_4$-air) [52]

the headwall) for annular (a) and hollow (b) configurations. Annular geometries tend to curtail peak detonation pressures below 3 bar as can be seen in the represented figure (note that we have seen a maximum of 8 bar for this annular geometry), whereas the peak pressure routinely exceeds 1 bar when the RDC is run without an inner wall. A similar drastic change in detonation behavior is also noted in the breadth of the operating regime and wave speed, especially for ethylene-air mixtures. A study at UC utilizing multiple annular widths in a conventional RDC failed to produce "proper" detonations, but exhibited rotating waves at sub-sound speeds [54], as seen in Fig. 4a. Premixed ethylene-air mixtures also produced similar propagation at acoustic speeds in another facility [55], which is highly suggestive of quasi-detonations [41]. Other studies [16, 27] have used ethylene-air-oxygen mixtures in a large combustor (around 500 mm diameter), but still failed to achieve the high wave speed that is required of detonations. However, when we integrated an obstacle to the headwall of a hollow RDC to force the fresh reactants towards the combustor wall, detonations of considerable speed were observed in ethylene-air mixture. Certain operating points exhibited speeds upwards of 95% of the ideal Chapman-Jouguet speed for a given global equivalence ratio, as seen in Fig. 4b. To our knowledge, this is the first time rotating detonations of this speed and magnitude have been attained in a non-premixed mixture of ethylene-air. A major part of this shortcoming could be attributed to the probable quenching effect of the narrow annular walls; a predicament that is removed in a hollow combustor. However, numerical simulations show vast regions of deflagrative burning (wasteful) at the RDC central axis [50,
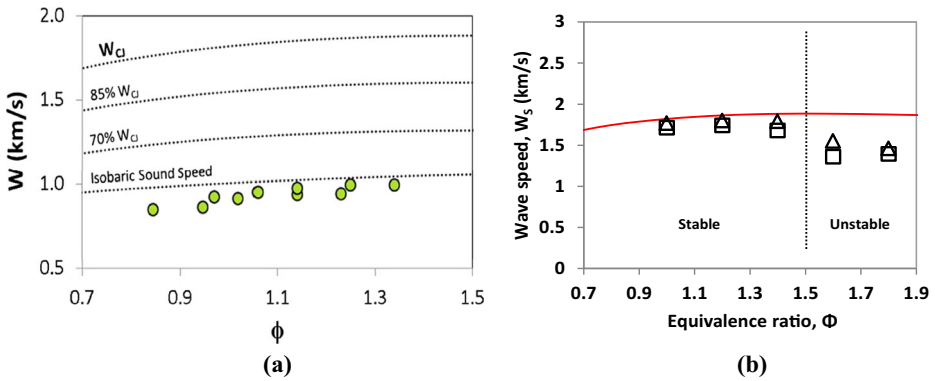
Fig. 4 Dependence rotating wave's speed on the equivalence ratio of C2H4-air mixtures in **a** annular RDC [54], and **b** hollow RDC [52]

56] that could reduce the potential benefits of RDCs. At the same time, one could postulate that due to the products expansion along all three-dimensions, pre-burning of fresh reactants by burnt products might be lower than an annular RDC. Further analyses are required to understand these competing effects in a hollow RDC. At present, it could be posited that it is unlikely that the vast majority of the observed high frequency combustion instabilities and RDC dynamics are due to two completely different mechanisms, to the significant overlap in qualitative and quantitative similarities [23, 52]. Knowing this can perhaps help in designing combustors that work with the preferred type of combustion mode—either the conventional deflagration, or the more efficient, but prohibitive detonations.

The hollow RDC concept can be extended to a flow-through RDC, which does not have a headwall (see Fig. 1c). We measured a temperature increase to up to 1200 K within an operating time of about 4 s, for annular RDC [57], which suggests that the major components of a conventional RDC (outer body, inner body and the injection elements) need to be actively cooled. With this in mind, a flow-through RDC was made (using additive manufacturing) with the headwall shaped in a way to entrain significant amount of atmospheric air [58, 59]. Such a design allowed us to attain prolonged RDC operation, since only one wall element had to be cooled. Hydrogen-oxygen-air mixtures were used to attain rotating detonations that propagate at about 10 kHz. This result is a successful proof-of-concept, and lays the foundation for detailed research in the future to characterize detonation dynamics in a flow-through configuration.

3 Effects of Injection and Mixing on RDC Behavior

The presence or absence of detonations inside an RDC is primarily dependent on the reactants (next section), injectors and the associated mixing produced by the latter, given the geometry of the combustor Detonation waves, by virtue of the high peak pressures, tend to produce considerable backpressure that causes localized occlusion of the injectors. This process reduces the amount of fresh mixture for the next lap of detonations, thereby causing the wave to fail due to the prohibitive feedback loop [60]. Additionally, the local equivalence ratio is predicated on the mixing produced by these injectors, and takes importance in sustaining detonations since they cannot propagate below an equivalence ratio of 0.5, due to the
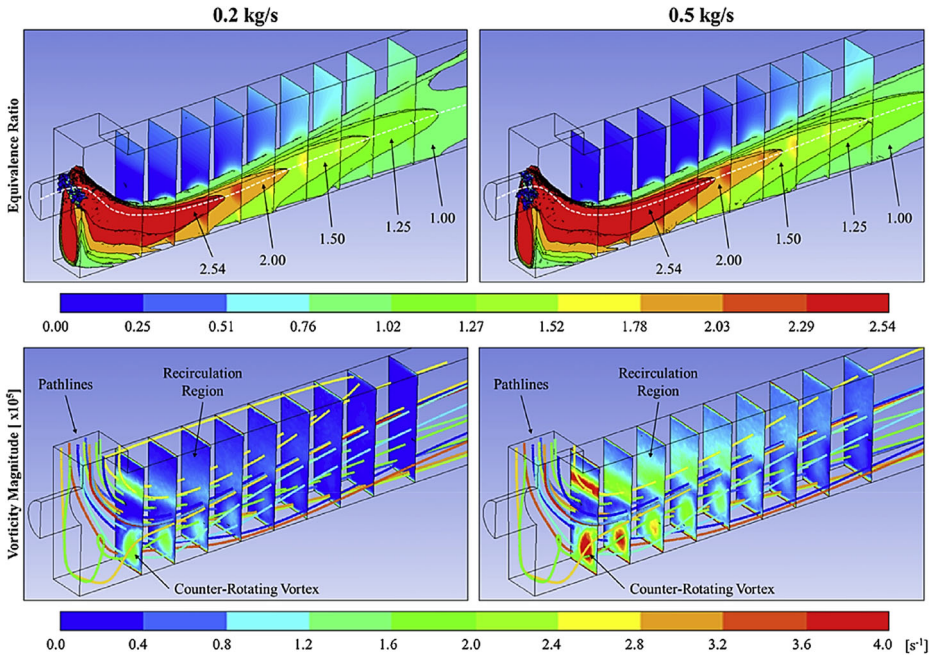
Fig. 5 a Gas sampling probe locations at the flow-through hollow RDC exit plane, **b** average NOx ppm measured at the four locations across multiple tests (same conditions), and **c** temperature contour plot from a numerical study on the same design showing almost cold-flow conditions at the RDC center (UC study [61])

quenching produced by heat transfer to the surroundings [41]. Thus, proper RDC operation requires focused attention on both injection at the headwall and mixing in the combustor. At UC, considerable focus has been directed towards both. Shown in Fig. 5 are contour plots of local equivalence ratios and vorticities inside the channel of our annular RDC, for two air flow rates of 0.2 kg/s and 0.5 kg/s (both at stoichiometric equivalence ratio). Fuel is injected axially through axisymmetric holes and air is injected radially inward through the rectangular slot. It can be seen that there are very high gradients in mixing, as seen by the equivalence ratio varying from very lean conditions (close to 0.25) to very rich (greater than 2.29). There are also strong re-circulation zones and counter-rotating vortices within the small annular section. These findings suggest that the global equivalence ratio is notably different from the local one, thereby imparting significant variations in upstream conditions for detonation wave propagation through the region. This variation not only causes fluctuations in detonation strength, but also produces considerable variations in the combustion emissions depending on the spatial location.

A flow-through RDC was tested at four locations at the exit plane to reveal that NOx emissions is almost zero at the central axis region, but about 35 ppmv as we move towards the combustor wall (see Fig. 6a and b [61]. The observed disparity was explained by a numerical simulation of the same device, which showed that the rotating detonation wave mostly "hugged" the wall (see Fig. 6c) due to the presence of high fuel content near the wall (radially injected fuel jets were pushed towards the wall by the axial air crossflow [58, 59]). Moving forward, this uncertainty in mixing in the combustor needs to be dealt with, for reliable application of RDCs. Furthermore, we also tested a partially premixed RDC in
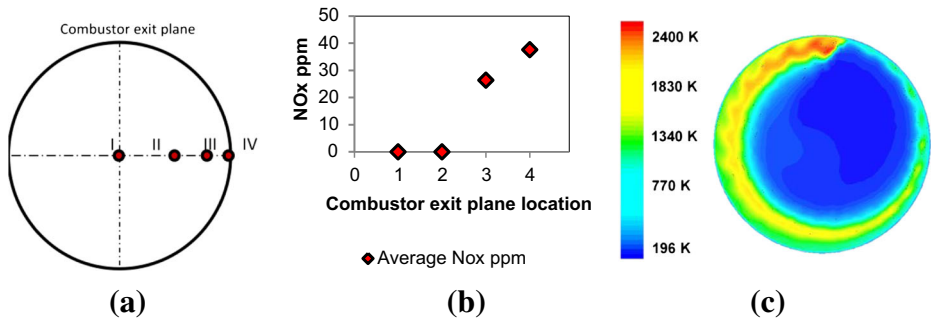
Fig. 6 Flow field of the baseline geometry [63]

which hydrogen was introduced from a separate manifold, whereas air and ethylene were introduced, premixed, in another manifold [62]. Using this method of fuel blending, with hydrogen supply shut-off midway the test, rotating detonations were established in ethylene-air mixtures in a smaller annulus width (which did not promote detonations with ethylene, when non-premixed), furthering the claim that mixing is a very important element in RDC design.

We established that lower injection areas and higher pressure ratios (from the injector to the combustor) contribute to an optimal injector design—both parameters contribute to higher fluidic impedance [18], thereby mitigating the effects of the downstream detonation wave in disturbing the plenum [64]. Subsonic air injection produces highly chaotic detonation wave propagation characterized by periodic failure and re-ignition of the detonation wave, because of the pressure waves from detonations propagating upstream [65]. Additionally, a higher number of fuel injection holes with smaller diameter were found to sustain detonations better than a lower number of fuel injection holes with a bigger diameter (despite the total injection area being the same) [43]. The former tends to produce and sustain detonations throughout the duration of continued fuel supply, even at the lean limits of operation, whereas the latter is characterized by abrupt cessation of detonations ("pop-outs") at the lean limits [43]. A high-speed chemiluminescence study by a different group supports our findings and found that this variation in performance is due to the lack of fresh mixture between two fuel holes, thereby causing the detonations to consume products gases instead of the unburnt reactants, which is necessary for it to sustain [66]. The effect of injectors on RDC performance is more pronounced in a backpressurized RDC, which obviously tends to globally un-choke the reactants supply. We found the mode of detonations itself to be dependent on the pressure ratio across the injectors. Rotating detonations were observed when the pressure ratio is greater than 1.85, whereas the azimuthal phenomenon of longitudinal pulsed detonation almost purely preferred ratios between 1.4 and 1.85, with lower pressure ratios producing highly chaotic detonation wave propagation in a backpressurized RDC [23]. This further emphasizes the importance of injection elements in an RDC environment. Due to the complexity of the processes involved, it is recommended that numerical simulations be used to benchmark the performance of a given injector design, before experimental testing. Some of our other numerical investigations are given in Refs [67–70], where particular emphasis is placed on analyzing non-premixed injection feeds from separate plenum, which is characteristic of an actual RDC As shown by Gaillard et al. [71, 72], the detonation wave structure and dynamics are significantly altered when the injection elements are not idealized to be premixed.

4 Dependence of Detonation Wave Dynamics on Reactants

Detonations are complex three-dimensional events comprising the interaction of an incident shock wave, the associated reflected wave and a Mach stem. This interaction produces the widely observed 'triple point', which can be traced as a detonation wave moves across a mixture [41]. Such a tracing results in characteristic diamond-shaped cellular structures, and is now accepted to be a tenet of detonation propagations in most mixtures. Highly reactive mixtures like those of hydrocarbon-oxygen tend to produce smaller cells—characterized by the transverse cell width—in comparison to the less reactive mixtures like those composed of hydrocarbon-air [41]. Therefore, cell size (λ) has been used as a direct consequence of the propensity to detonate a given mixture. Hence, geometric constraints of a given device (annulus width in an RDC) dictate the possibility of producing rotating detonations in a mixture of choice. Therefore, the interdependence between RDC geometry and the reactants used is of foremost importance. Multiple facilities, including UC, have produced rotating detonations in hydrogen-air mixtures [73]. This is less complicated than attaining the same in ethylene-air mixtures due to the high reactivity of hydrogen. As described earlier, we have obtained rotating detonations in both hydrogen [43] and ethylene [52], albeit requiring the usage of a hollow combustor for the latter. The resulting wave speeds and peak pressure for the detonation wave through ethylene-air mixture is noted to be a significant improvement over existing results from literature. However, when an annular RDC was used, the wave speed was barely above the isobaric sound speed [54], similar to the finding from another facility [55], suggesting that less detonable mixtures are indeed affected by the width of the channel annulus. The results obtained at UC suggests that hollow configurations might be more prone to sustain rotating detonations when the mixture is less detonable, i.e. the whole combustor (diameter) can be used to produce detonations instead of just the annulus (width). This could negate the requirement of having prohibitively large RDCs in order to detonate fuels with very low detonability. For instance, the cell size of detonations through methane-air mixtures at stoichiometric conditions is about 0.3 m, which would require a minimum annulus width of similar dimension. This issue could be bypassed by using a hollow RDC with a diameter of 0.3 m. It is emphasized here that the above-mentioned claims are preliminary and result from our initial findings, and considerable research is required to test these issues further.
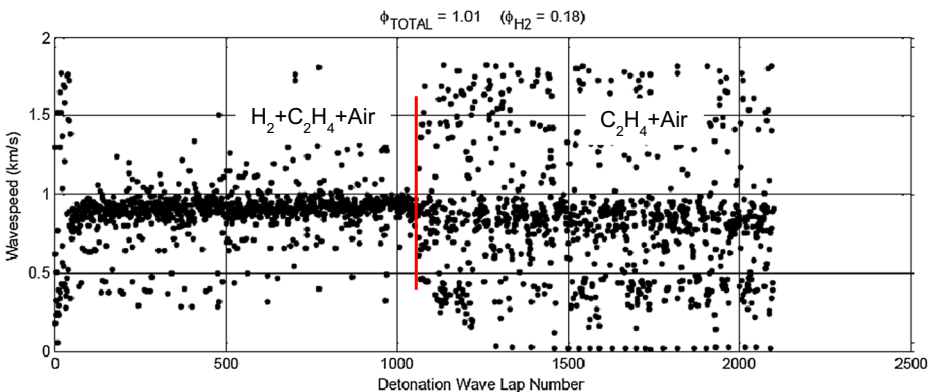

Fig. 7 Rotating detonation wave speed per lap with hydrogen-blended ethylene air mixture, and purely ethylene-air mixture, in a single test point [62]

There are other ways to bypass the issue of reactant detonability: i) use fuel-blends to assist detonation sustenance, or ii) use oxygen enriched air to significantly lower the detonation cell size. Both these methods have been investigated at UC. First, hydrogen was added to premixed ethylene-air mixtures to initially ignite rotating detonations [62]. This fuel-blended mixture was then converted to purely premixed ethylene-air by weaning off hydrogen which produced a sustained rotating detonation with high instability (refer wave speed per detonation lap plot in Fig. 7). A similar study was performed by another research group with a fuel blend of propane and hydrogen that yielded similar findings—the propane-air mixture was able to sustain rotating detonations even after the stoppage of hydrogen [74] However, a detailed chemical kinetics analysis performed at UC on the effects of hydrogen on ethylene-air detonations suggests that chemistry might not be the factor responsible for the sustenance of detonation [75]. Physical effects such as stronger plenum recovery (due to higher pressure from secondary fuel), heat transfer to the mixture from the heated walls of the combustor, etc. might be integral to the observed phenomenon.

The second method to attain rotating detonations is through the use of enriched air. This method is highly effective due to the presence of oxygen, but less practical due to storage and weight considerations for an additional reactant. However, such a study has been used previously to decipher interesting phenomena in RDCs [16], and as such, important elements regarding detonation dynamics could be assessed by using excess oxygen. In this regard, we varied the degree of oxygen enrichment inside the RDC while maintaining the global equivalence ratio nominally constant [76]. The molar ratio (β) of nitrogen to oxygen was varied from 3.76 (atmospheric air) to 1.9 (highly oxygen enriched), at four annulus widths. Rotating detonation wave multiplicity (number of waves existing in the combustor, simultaneously) was found to be dependent on both the width and the molar ratio. Lower molar ratio (higher oxygen content) and lower channel widths promote higher number of detonations waves. This interplay between β and channel width is presented in Fig. 8a. An intriguing scaling relationship exists between these two parameters that predicate the presence of multi-wave detonation behavior—a new wave is spawned every time the ratio of detonation perimeter, P, (assuming the wave to have a rectangular cross-section) and the cell
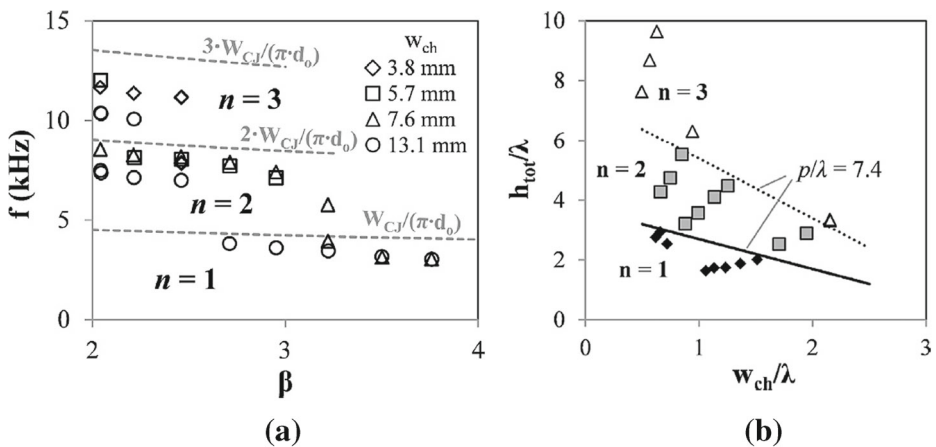

Fig. 8 **a** Multiplicity and frequency of rotating detonation waves and its dependence on β, and **b** detonation regimes demarcated by lines of normalized perimeter of one detonation wave [76]
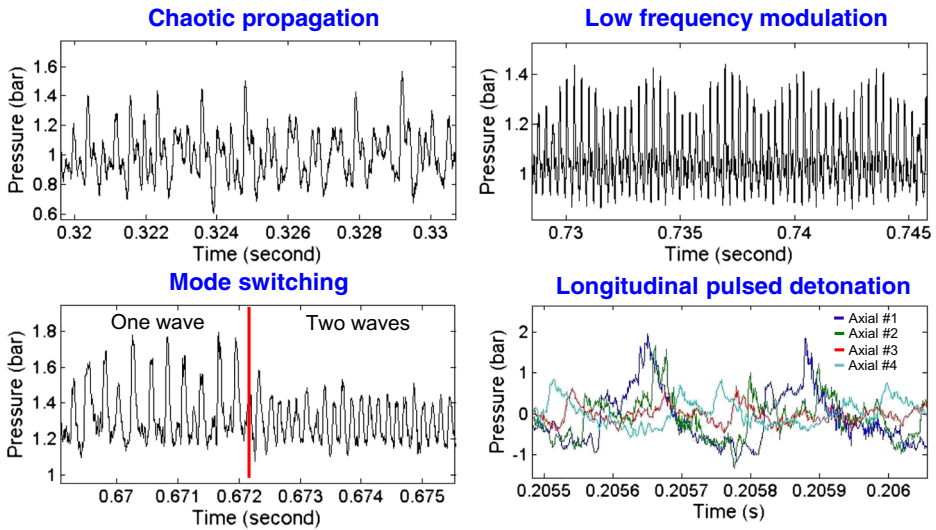
Fig. 9 Pressure traces from RDC annulus showing four diverse modes of annular RDC operation. Note: For longitudinal pulsed detonation (LPD), the pressure traces are acquired from four axially distributed sensors from headwall to the RDC exit end (Axial #1 is near the headwall; Axial #4 is near the RDC choked exit) (UC studies [23, 65])

size, λ, reaches a criticality of 7.4 (see Fig. 8b). This result bodes well to develop a priori models to predict RDC modes, of which there are many and will be discussed next.

5 Modes of Operation

The preferred operating mode of an RDC is to have an eponymous rotating detonation inside the combustor. However, such a mode often never occurs alone. We have identified four different modes of operation that occur in tandem with rotating detonations, or occur separately in annular RDCs [65]. The pressure traces during these four modes, namely chaotic propagation, low frequency modulation, mode switching and longitudinal pulsed detonation, are given in Fig. 9. During chaotic propagation, the subsequent laps of rotating detonations exhibit a highly non-periodic, fluctuation behavior in detonation peak pressure and wave speed, which is attributed to irregular reactants plenum recovery due to the effect of the detonation wave's pressure feedback into the injectors This occurs only for large injector areas or low pressure ratios (hence lean equivalence ratios) across injectors (Fig. 10) On the other hand, almost all the tested operating regimes and geometries in our RDC exhibit low frequency modulation of detonation peak pressures (Fig. 9). This waxing and waning of subsequent detonation peak pressures was theorized to be linked to acoustic coupling between the air plenum and combustor [64, 77], and is not unlike the phenomenon of "chugging"—a well-known low frequency rocket engine instability (LFI) [18]. It is characterized by pulsation of the base pressure of the combustion chamber and exists below 500 Hz [18]. Thus, the similarities between RDC and other deflagrative combustors extend further than just the high frequency instabilities. We have observed that multiple detonation waves form inside an annular RDCs at higher flow rates [43] and lower channel widths [51, 76]. When such a mode switching happens (from a lower wave number to a higher number of waves, or vice
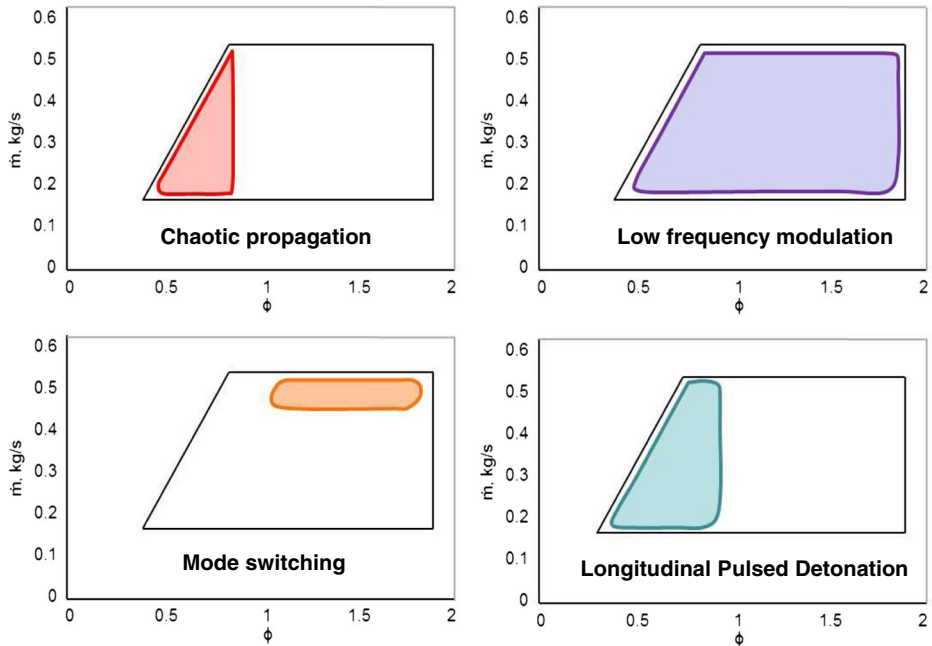
Fig. 10 Four modes of operation in an annular RDC and their corresponding regions of prevalence. Note: Longitudinal pulsed detonation (LPD) is observed only when the RDC exit is choked (i.e. backpressurized) (UC study [65])

versa), the peak detonation pressures of the individual waves notably drop. Such an event can be seen in the pressure trace obtained during the bifurcation of one wave to two wave mode (Fig. 9). This was observed to occur at the higher flow rate of 0.5 kg/s at the UC facility (Fig. 10). Note that, as explained earlier, this multi-wave mode can be made to occur at lower flow rates by using enriched air. Of additional interest is the fact that such changes in modes are most often accompanied by similar drastic changes in the acoustic field produced by the RDC, as we have discussed in [78]. For instance, LPD tends to produce azimuthally in-phase far-field acoustic oscillations, as opposed to the rotating detonation mode, which produces out-of-phase azimuthal acoustic vibrations.

At certain geometries and mass flow rates, the RDC transitions from housing rotating detonations to producing azimuthally-pulsed detonation in the kilo-Hertz range inside the combustion chamber. This pulsation first observed in an RDC and named as longitudinal pulsed detonation (LPD) by Bykovskii et al. [79], 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. However, it operates at a frequency that is more than an order of magnitude higher than any known PDC operating frequency [65]. The UC research team determined that, during LPD, shock waves are reflected from the nozzle throat and initiate the next cycle of detonation [23]. This is seen in the pressure traces acquired from four axially distributed pressure sensors (Fig. 9). Interestingly, "high frequency longitudinal instability", which is characterized by axially travelling pressure pulses between the injection head and the nozzle throat at frequencies greater than 1000 Hz are a prominent subset of HFI in rocket engines, and are not comprehensively explained, despite the considerable research into the phenomenon during 1950–80s [17, 18]. Moreover, the instances

of tests producing these instabilities increased progressively when the reactants supply is reduced or when the nozzle throat area is decreased [23]. The above-mentioned sources on rocket engine combustion instability implicitly attribute the phenomenon in rocket thrust chambers to be caused due to periodic detonations. Note that LPD is observed in an RDC only when it is backpressurized (Fig. 10). Hence, an RDC that is oriented towards rocket or gas-turbine applications will have to be analyzed to ascertain the basic physics behind LPD. The results obtained from such a study would complement the findings from deflagrative combustors.

The hollow RDC tested at UC, with ethylene-air mixtures, exhibits a wider range of unstable behavior that was hitherto unseen in an annular RDC, as determined by a set of three circumferentially-distributed pressure sensors and ionization probes. Figure 11
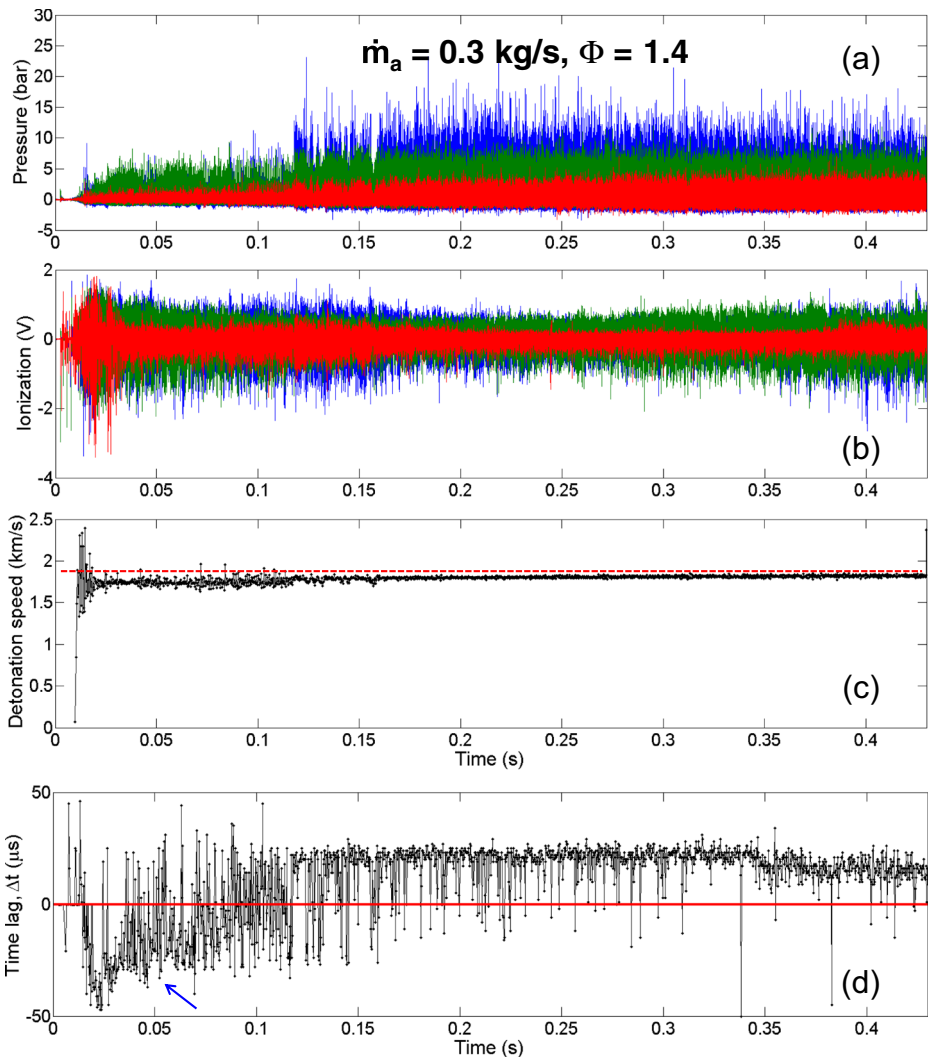

Fig. 11 Stable vs. Unstable rotating detonation wave propagation in a hollow RDC [52]
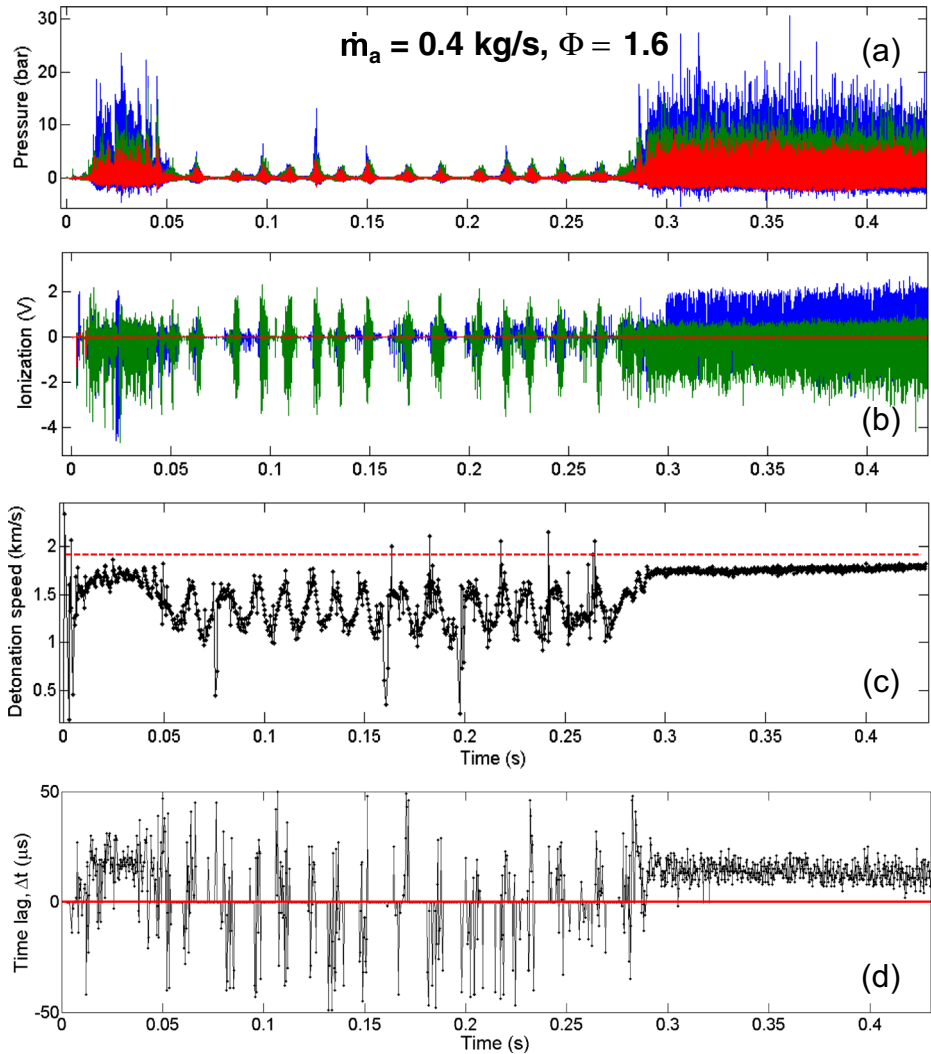
Fig. 11 (continued)

provides: (a) the pressure time-trace for the whole duration of testing (b) the full test-length ionization traces indicating combustion activity (c) lap-to-lap detonation wave speed acquired through peak-tracking, and (d) the time lag between the pressure and combustion wave for two cases—stable (left) and unstable (right). Here, we use the term unstable to denote fluctuations that are deviant from the normally expected steady detonation wave speed and strength. These modes were found to be dependent on the air flow rate and the equivalence ratio of the ethylene-air mixture [52]. During the steady propagation (left), the detonation peak pressures and wave speed were highly steady and repeatable across multiple laps. A similar congruence is observed in combustion through voltage fluctuations in the ion probes, as well as the lap-to-lap detonation wave speed (very close to the C-J speed shown by the dotted red line) acquired from a time-of-flight algorithm As should be expected of

a detonation wave, the shock wave precedes the combustion front, thereby having a positive time lag (above the red line) for most of the laps. During unstable operation, there are significant sinusoidal fluctuations in peak pressures, ionization strength and the wave speed between subsequent laps, as can be seen in the figure. The most interesting feature of this phenomenon is that during this sinusoidal fluctuation phase the combustion wave precedes the pressure wave, which does not exceed 3 bar, implying a mechanism that is not representative of a traditional detonation wave. These very low peak pressure waves seem to gain strength and coalesce into strong rotating detonations with peak pressures greater than 15 bar at a time of about 0.27 s. This suggests a flame acceleration mechanism [80] being responsible for the rotating weak pressure waves. Analysis of the observed phenomena is important to not only understand hollow RDC physics, but also to treat the issue of high frequency combustion instabilities.

6 Combustor-Plenum Coupling and Associated Effects

Increased initial mixture pressure can significantly alter the chemical kinetics within the detonation front and potentially suppress certain reaction paths [75]. Characterization of RDC operation for elevated initial pressures is an expanding area of research, and preliminary results from UC [43, 51] indicate improved initiation, operating range and detonation wave speed for certain conditions. Pressure profiles from low response static pressure sensors acquired from the combustor (red), air plenum (blue) and fuel plenum (green) of an atmospheric vs. backpressurized RDC are given in Fig. 12a and b respectively. Note that the fuel plenum pressure profile is not given for the backpressurized RDC. It can be seen that the static pressure characteristics of a backpressurized RDC are significantly different from an atmospheric exit-RDC. There is an approximately 1 s transient phase during which the mean static pressure inside the combustor experiences a considerable rise due to the detonative environment inside. This appears to be an effect of increase in the stagnation pressure upstream of the choked nozzle due to the detonative process [81]. Note that a similar mean static pressure increase is observed in rocket engine combustors when there is an onset of high frequency instabilities. This is referred to as the "DC shift" [18, 82]; its named after
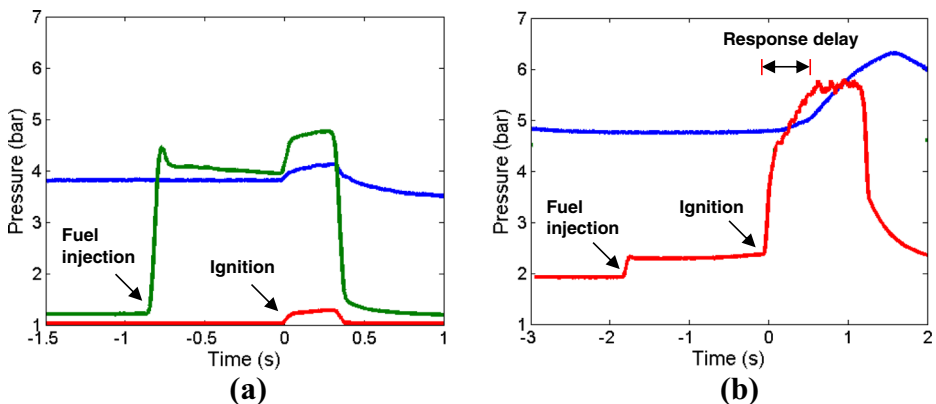

Fig. 12 Pressure-time traces from the combustor (red), air plenum (blue) and fuel plenum (green) at $\dot{m}_a = 0.4$ kg/s, $\Phi = 1.1$, for **a** atmospheric RDC, and **b** back-pressurized RDC

the DC current in electrical systems that have a net non-zero value for the signals. Hence, once again, the observed similarities between RDCs and deflagrative combustors during combustion instabilities indicate a common physical mechanism behind its manifestations.

In addition to the low-speed transient coupling between the reactants plenum and the combustor, there is also a significant fast-response coupling between the two, predicated by the high pressure region produced by the detonation waves. We established that every lap of the detonation wave produces considerable shock leakage into both the air inlet and the fuel plenum, which can be seen for two operating points in Fig. 13 [64]. From the pressure profiles obtained using high speed PCB dynamic pressure sensors from the combustor (flush-mounted), air inlet and fuel plenum, it is seen that the pressure feedback inside the air inlet is about 60% of the detonation wave's peak pressure, whereas the fluctuations inside the fuel plenum is only about 20% of the peak detonation pressure. This is attributed to the higher fluidic impedance of the fuel injectors due to their small-holed geometry, in contrast to the large-area of the slotted air injection method. Both amplitude modulated and frequency modulated instabilities are observed in the air inlets (Fig. 13b and e) which were postulated to be responsible for the low frequency instability seen in the actual combustor
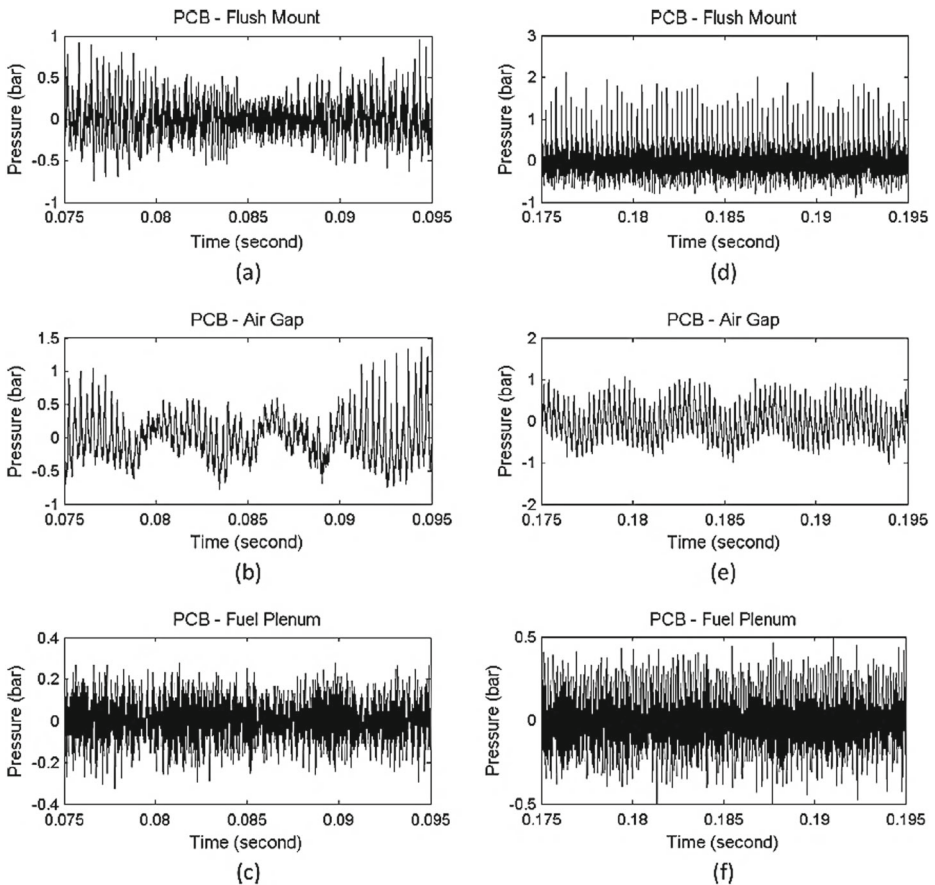

Fig. 13 Pressure–time traces from different RDC components for $\dot{m}_a = 0.2$ kg/s, $\Phi = 1$ (left), and $\dot{m}_a = 0.3$ kg/s, $\Phi = 1$ [64]

(that is not unlike rocket engine chugging) [77]. It is emphasized here that a backpressurized RDC operation also exhibits strong lap-wise coupling between the combustor and the plenums, in addition to the mean pressure shift. It is inferred that, moving forward towards practical application of RDCs, the combustor-plenum coupling will have tremendous impact on the stability and performance of these devices [23].

7 Detonation Enhancements to Improve RDC Performance

Detonability of a given mixture is highly dependent on the internal geometry of the combustor. Below a critical value of channel width, due to heat transfer to the wall, detonation is quenched and failure modes are reached [41, 83]. This problem of geometric constraint, can however, be overcome by artificially increasing the reactivity of the mixtures. One widely-applied (in non-detonative combustors) method of achieving this is through plasma-assisted combustion [84]. The plasmas used for combustion enhancement are non-equilibrium, with an electron temperature that is orders of magnitude higher than the gas temperature. In such a plasma, an applied potential accelerates electrons causing them to collide with nearby chemical species. This collision excites species which then dissociate the oxygen and fuel molecules, while also triggering combustion sustaining chain-branching reactions. Experimental studies have shown that plasma significantly reduce ignition delay time and lower ignition energy requirements. In particular, nanosecond pulsed plasmas produce larger quantities of species relevant to combustion than other excitation methods thereby increasing the fuel-oxidizer mixture reactivity [84]. Beyond kinetic effects, experiments in plasma assisted combustion in supersonic flow have demonstrated fuel-air mixing enhancement due to gas dynamic instability generation [84]. There are several mechanisms responsible for this mixing enhancement including plasma induced vortex generation and fast gas heating. A combined experimental study by the University of Cincinnati and Ohio University (OU) has achieved promising results in a proof-of-concept, plasma-assisted RDC system. To generate the plasma within the RDC, a novel RDC centerbody (which has a conducting electrode ring) was designed (Fig. 14). This was placed in the RDC just like a conventional centerbody (Fig. 14). The rest of the RDC was grounded. The electrode was powered with a nanosecond pulse generator, which produced 10 ns long, 20 kV pulses at a frequency of 1.5 kHz. The electrode was positioned in the path of the detonation wave to maximize the effect of the discharge. The bare metal electrodes and short pulse time produce distributed, high current, streamer discharges, enhancing combustion kinetics and mixing [84]. Uniformly distributed, dim discharges and a few randomly located, bright discharges radiated from the centerbody to the outer wall of the combustion annulus (Fig. 14). The addition of
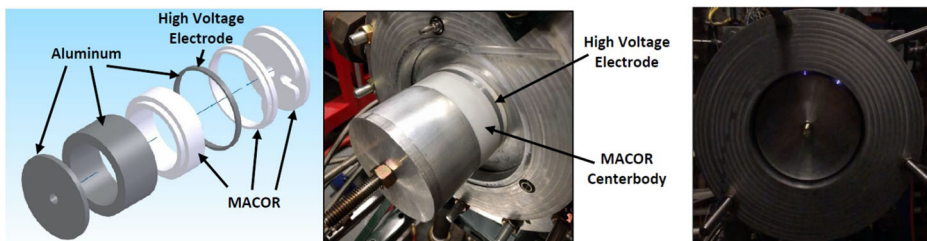

Fig. 14 Exploded view of the centerbody electrode (left) and assembled RDC with plasma induction (right) [85]

the plasma positively impacted RDC operation at conditions that did not previously support rotating detonations, in addition to causing a minor increase in the wave speed at conditions that did support detonations without plasma [85].

Another method to attain detonations in otherwise unfavorable situations in an RDC is to use blended-reactants, as we noted before. However, such a practice has to be employed with caution, since the chemical pathways of different reactants alter markedly based on a variety of factors. For instance, hydrogen-ethylene-air blends of the kind that we used experimentally are prone to aid detonation formation only at suitable conditions of initial pressure and equivalence ratio [75]. This is seen in Fig. 15, where the detonation cell size, λ, is seen to decrease with increasing hydrogen content (and hence, a lower cell size), up to a critical value of pressure (dependent on the overall equivalence ratio). Above this pressure, hydrogen addition actually works against detonation enhancement due to the pressure-dependent recombination reactions occurring for hydrogen at higher pressures. Hence, a proper application of this technique necessitates the knowledge of the kinetics of the blends used.
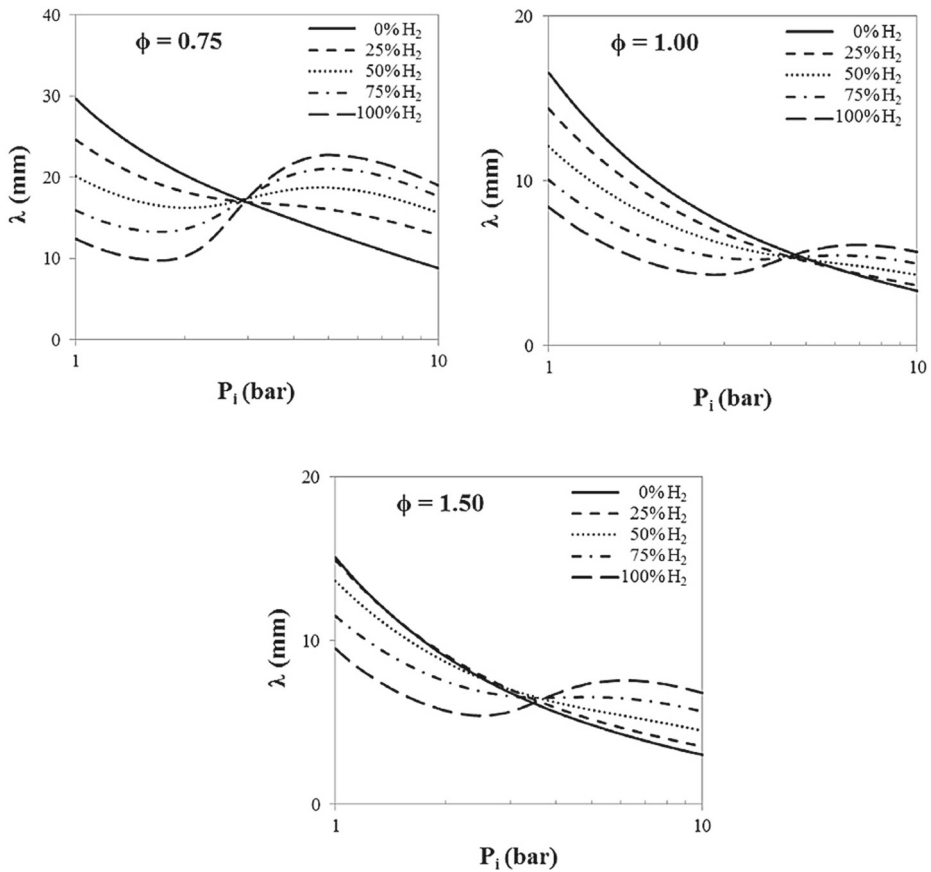

Fig. 15 Cell width variation of $C_2H_4-H_2$–air mixtures with initial pressure for three equivalence ratios, obtained using chemical kinetics modeling [75]
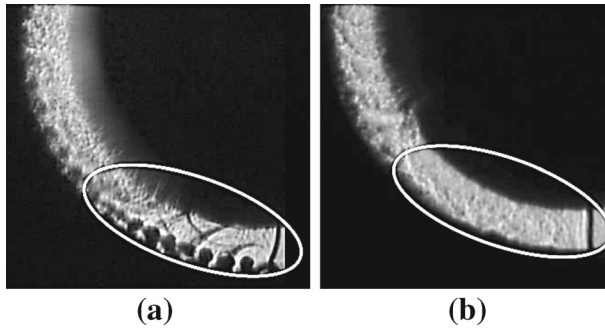
Fig. 16 Shadowgraphy of a detonation wave propagating through an RDC annulus with **a** a corrugated outerbody showing strong vortices and reflected shocks, and **b** a smooth outerbody with no visible structures [86]

Fundamental studies on detonation propagation behavior in tubular geometries have produced a vast collection of data that deals with detonation failure regimes, modes and causes. In particular, the use of obstacles to sustain the ignited detonation wave, either through shock reflection, or turbulence generation, or the combination of both, is well known to purists [41]. In theory, it is possible to obtain similar effects in an RDC-type annular geometry as well, in order to sustain detonations in what are otherwise the failure regimes in the operating map. We have performed one such preliminary study with an unoptimized obstacle configuration [86]. The outer wall of the combustor was machined to have an array of small, right isosceles triangle obstacles throughout the circumference. This geometry was preferred over the saw-tooth one sided geometry to deal with the well-known stochasticity of rotating detonation wave's directionality [65, 77, 87], hence an isosceles triangle would provide a similar effect on the wave irrespective of the direction of its propagation—clockwise vs. counterclockwise. Multiple flow rates, equivalence ratios and annulus widths were tested to compare the corrugated walled RDC operation with the conventional smooth walled RDC. The annulus width in a corrugated RDC is defined as the distance between the highest point on the obstacle (the apex of the triangle) and the inner annulus wall, i.e. the unobstructed passage width, which Teodorczyk contended to be the analogous term to width in a smooth passage [88]. We found that, despite the corrugations slowing the detonation wave speed to a minor extent, it produced sustained detonation propagation at very small annulus widths (3.2 mm), which provided minimal anchored detonation events with the smooth combustor wall. This was attributed to the strong reflected shock waves and associated turbulence produced by every obstacle in the path of the detonation wave, as it moves along the circumference, thereby sustaining the wave until fuel supply is stopped. Figure 16 shows these structural differences in detonation propagation through images acquired from the Shadowgraphy technique.

8 Conclusions

The preceding sections dealt with the specific areas of RDCs that have been investigated at the University of Cincinnati, namely: geometry, injection and mixing, reactants, modes of operation, coupling with plenum, and some methods to enhance the formation and sustenance of detonations. Fundamental detonation physics explains most of the observed RDC

behavior. The dynamics of detonation propagation in annular and hollow RDC configurations are discussed. Evidence is presented that supports the notion that a hollow combustor is more conducive to produce stronger and faster rotating detonation waves. The importance of injection elements and pressure ratios in determining stable detonation wave operation is discussed. Four fundamentally different modes of operation are recognized, namely: chaotic propagation, low frequency modulation, detonation wave multiplicity and longitudinal pulsed detonations. Generally, higher fluidic impedance counteracts the instantaneously high backpressure produced by the detonation wave thereby allowing for proper recovery of the reactants plenum before the next lap of the wave. Subcritical pressure ratios, especially between 1.4 and 1.85, tend to produce the azimuthally simultaneous, axially moving phenomenon of longitudinal pulsed detonations, when the RDC is backpressurized. The importance of analyzing the difference between the global and local equivalence ratio is presented using numerical simulations and experimental emissions measurement at different locations in the combustor plane. For the flow-through hollow configuration, almost no NOx is measured at the central axis region whereas about 35 ppmv of NOx, on an average, is recorded near the combustor wall. Hydrogen and oxygen blending are proven to be viable concepts in enhancing the detonative behavior of RDCs. The strong dependence of the number of simultaneously existing rotating detonation waves on the reactivity of the supplied mixture is studied. The ratio of the nominal perimeter of the detonation wave front to the cell size of the reactive mixture is discovered to be a critical parameter that dictates detonation wave multiplicity. A new wave is spawned every time this ratio exceeds 7.4. For backpressurized RDCs, there is an additional complexity signified by a transient rise in mean combustor static pressure, not unlike the "DC shift" phenomenon seen in rocket engines during the presence of nonlinear combustion instabilities. Finally, plasma induction and obstacle-integrated combustor wall are shown to be methods of enhancing/producing rotating detonations at otherwise failure points of operation. The pervasive issues of chugging, tangential and longitudinal high frequency instabilities, and mean pressure shifts seen in other combustors appear to be a part of normal RDC operation, and as such, predicate significant challenges before practical applications of RDC. It is our contention that the two seemingly disparate fields require knowledge exchange, and can consequently benefit from each other, due to the overlap in the observed physics.

References

1. Turns, S.: An introduction to combustion. McGraw-Hill International, Singapore (2006)
2. Wolański, P.: Detonative propulsion. Proc. Combust. Inst. **34**, 125–158 (2013)
3. Yi, T.-H., Lou, J., Turangan, C., Choi, J.-Y., Wolanski, P.: Propulsive performance of a continuously rotating detonation engine. J. Propuls. Power. **27**, 171–181 (2011)
4. Wintenberger, E., Sheperd, J.E.: Thermodynamic cycle analysis for propagating detonations. J. Propuls. Power. **22**, 694–697 (2006)
5. Jones, S., Paxson, D.: Potential benefits to commercial propulsion systems from pressure gain combustion. In: Joint propulsion conference, San Jose (2013)

6. Frolov Dubrovskii, A.V., Ivanov, V.S.: Three-dimensional numerical simulation of operation process in rotating detonation engine. Prog. Propuls. Phys. **4**, 467–488 (2013)
7. Sousa, J., Paniagua, G., Collado Morata, E.: Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor. Appl. Energy. **195**, 247–256 (2017)
8. Strakey, P., Ferguson, D., Sisler, A., Nix, A.: Computationally quantifying loss mechanisms in a rotating detonation engine. In: 54th AIAA Aerosp. Sci. Meet., pp. 1–14 (2016)
9. Sonwane, C., Clafli, S., Lynch, E.D., Stout, J.: Recent advances in power cycles using rotating detonation engines with subcritical and supercritical CO2. In: The 4Th international symposium - supercritical CO2 power cycles, Pittsburgh (2014)
10. Frolov, S.M., Aksenov, V.S., Ivanov, V.S.: Experimental proof of Zel'dovich cycle efficiency gain over cycle with constant pressure combustion for hydrogen-oxygen fuel mixture. Int. J. Hydrogen Energy. **40**, 6970–6975 (2015)
11. Wolański, P.: Application of the continuous rotating detonation to gas turbine. Appl. Mech. Mater. **782**, 3–12 (2015)
12. Naples, A., Hoke, J., Battelle, R., Wagner, M., Schauer, F.: Rotating detonation engine implementation into an open- loop T63 gas turbine engine. In: 55th AIAA aerospace sciences meeting, Grapevine (2017)
13. Clayton, R.M., Rogero, R.S.: Experimental measurements on a rotating detonation-like wave observed during liquid rocket resonant combustion (1965)
14. Levine, R.S.: Experimental status of high frequency liquid rocket combustion instability. Symp. Combust. **10**, 1083–1099 (1965)
15. Ar'kov, O.F., Voitsekhovskii, B.V., Mitrofanov, V.V., Topchiyan, M.E.: On the Spinning-Detonation-Like properties of high frequency tangential oscillations in combustion chambers of liquid fuel rocket engines. J. Appl. Mech. Tech. Phys. **11**, 159–161 (1970)
16. Edwards, B.D.: Maintained detonation waves in an annular channel: a hypothesis which provides the link between classical acoustic combustion instability and detonation waves. Symp. Combust. **16**, 1611–1618 (1977)
17. Male, T., Kerslake, R., Tischler, A.O.: Photographic study of rotary screaming and other oscillations in a rocket engine, Cleveland (1954)
18. Harrje, D.T., Reardon, F.H.: Liquid propellant rocket combustion instability. Washington (1972)
19. Oefelin, J.C., Yang, V.: Comprehensive review of liquid-propellant combustion instabilities in f-1 engines. J. Propuls. Power. **9**, 657–677 (1993)
20. Culick, F.E.C.: Combustion instabilities in liquid-fueled propulsion systems - an overview. AGARD Conf. Combust. Instab. Liq. Propuls. Syst. **450**, 1–37 (1988)
21. Culick, F.E.C.: Combustion instabilities in solid propellant rocket motors. pp. 27–31 (2002)
22. Clayton, R., Rogero, R., Sotter, J.: An experimental description of destructive liquid rocket resonant combustion. AIAA J. **6**, 1252–1259 (1968)
23. Anand, V., St. George, A., Driscoll, R., Gutmark, E.: Longitudinal pulsed detonation instability in a rotating detonation combustor. Exp. Therm. Fluid Sci. **77**, 212–225 (2016)
24. Chenglong, Y., Xiaosong, W., Hu, M., Lei, P., Jian, G.: Experimental research on initiation characteristics of a rotating detonation engine. Exp. Therm. Fluid Sci. **71**, 154–163 (2016)
25. Frolov, S.M., Aksenov, V.S., Ivanov, V.S., Shamshin, I.O.: Large-scale hydrogen-air continuous detonation combustor. Int. J. Hydrogen Energy. **40**, 1616–1623 (2015)
26. Kindracki, J., Wolański, P., Gut, Z.: Experimental research on the rotating detonation in gaseous fuels-oxygen mixtures. Shock Waves. **21**, 75–84 (2011)
27. Dyer, R., Naples, A., Kaemming, T., Hoke, J., Schauer, F.: Parametric testing of a unique rotating detonation engine design. In: 50Th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition, Nashville (2012)
28. Gawahara, K., Nakayama, H., Kasahara, J., Matsuoka, K., Tomioka, S., Hiraiwa, T., Science, A., Matsuo, A., Funaki, I., Science, A., Science, A., Science, A., Science, A.: Detonation engine development for reaction control systems of a spacecraft. In: AIAA Joint Propulsion Conference, San Jose (2013)
29. Bellman, D.R., Humphrey, J.C., Male, T.: Photographic investigation of combustion in a two-dimensional transparent rocket engine, Cleveland (1953)
30. Krieg, H.C. Jr.: Tangential mode of combustion instability. Detonation and two-phase flow, pp. 339–366 (1962)
31. Anderson, W.E., Yang, V. (eds.): Liquid rocket engine combustion instability. American Institute of Aeronautics and Astronautics, Washington (1995)
32. Lubarsky, E., Hadjipanayis, M., Shcherbik, D., Bibik, O., Zinn, B.T.: Control of tangential instability by asymmetric baffle. In: 46Th AIAA aerospace sciences meeting and exhibit, Reno (2008)
33. Bennewitz, J.W., Frederick, R.A.: Overview of combustion instabilities in liquid rocket engines - coupling mechanisms & control techniques. In: 49Th AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit, San Jose (2013)

34. Popov, P.P., Sideris, A., Sirignano, W.A.: Stochastic modelling of transverse wave instability in a liquid-propellant rocket engine. J. Fluid Mech. **745**, 62–91 (2014)
35. Bennewitz, J., Lubarsky, E., Shcherbik, D., Bibik, O., Zinn, B.: Asymmetric injector distribution for passive control of liquid rocket engine combustion instabilities. In: 48Th AIAA aerospace sciences meeting, Orlando (2010)
36. Brownlee, W.G., Marble, F.E.: An experimental investigation of unstable combustion in solid propellant rocket motors. AIAA Prog. Astronaut. Rocket. Solid Propellant Rocket Res. **1**, 455–494 (1960)
37. Freeman, R.H.: Understanding space launch vehicle complexity?: a case study in combustion instabilities. In: AIAA SPACE conferences and exposition, Pasadena (2015)
38. Flandro, G.A., Majdalani, J., Sims, J.D.: On nonlinear combustion instability in liquid propellant rocket motors. In: 40th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf. (2004)
39. Campbell, C., Woodhead, D.W.: The ignition of gases by an explosion-wave. Part I. Carbon monoxide and hydrogen mixtures. J. Chem. Soc. **129**, 3010–3021 (1926)
40. Vasil'ev, A.A.: Some aspects of recording and interpretation of rotating detonation waves. Combust. Explos. Shock Waves. **51**, 710–716 (2015)
41. Lee, J.H.S.: The detonation phenomenon. Cambridge University Press, Cambridge (2008)
42. Voitsekhovskii, B.V., Mitrofanov, V.V., Topchiyan, M.E.: Structure of the detonation front in gases. Izd Sib Branch Acad Sci USSR (1963)
43. Anand, V., St. George, A., Driscoll, R., Gutmark, E.: Investigation of rotating detonation combustor operation with H2-Air mixtures. Int. J. Hydrogen Energy. **41**, 1281–1292 (2016)
44. Anand, V., St. George, A., Gutmark, E.: Hollow rotating detonation combustor. In: 54Th AIAA aerospace sciences meeting, San Diego (2016)
45. St. George, A., Randall, S., Anand, V., Driscoll, R., Gutmark, E.: Characterization of initiator dynamics in a rotating detonation combustor. Exp. Therm. Fluid Sci. **72**, 171–181 (2016)
46. Yang, C., Wu, X., Ma, H., Peng, L., Gao, J.: Experimental research on initiation characteristics of a rotating detonation engine. Exp. Therm. Fluid Sci. **71**, 154–163 (2016)
47. Bykovskii, F.A., Vedernikov, E.F., Polozov, S., Golubev, Y.: Initiation of detonation in flows of fuel – air mixtures. Combust. Explos. Shock Waves. **43**, 345–354 (2007)
48. St. George, A.C., Anand, V., Driscoll, R.B., Gutmark, E.J.: A correlation-based method to quantify the operating state in a rotating detonation combustor. In: 54Th AIAA aerospace sciences meeting. American institute of aeronautics and astronautics, San Diego (2016)
49. St. George, A.C., Driscoll, R.B., Anand, V., Gutmark, E.J.: Starting transients and detonation onset behavior in a rotating detonation combustor. In: 54Th AIAA aerospace sciences meeting. American institute of aeronautics and astronautics, San Diego (2016)
50. Tang, X.M., Wang, J.P., Shao, Y.T.: Three-dimensional numerical investigations of the rotating detonation engine with a hollow combustor. Combust. Flame. **162**, 997–1008 (2015)
51. Driscoll, R.B., Anand, V., St. George, A.C., Gutmark, E.J.: Investigation on RDE operation by geometric variation of the combustor annulus and nozzle exit area. In: 9Th U.S. national combustion meeting, Cincinnati (2015)
52. Anand, V., George, A.S., Farbos De Luzan, C., Gutmark, E.: Rotating detonation wave mechanics through ethylene-air mixtures in hollow combustors, and implications to high frequency combustion instabilities. Exp. Therm. Fluid Sci. **92**, 314–325 (2018)
53. Hansmetzger, S., Zitoun, R., Vidal, P.: Detonation regimes in a small-scale RDE. In: 26Th ICDERS, Boston (2017)
54. Wilhite, J., Driscoll, R.B., St. George, A.C., Anand, V., Gutmark, E.J.: Investigation of a rotating detonation engine using ethylene-air mixture. In: 54Th AIAA aerospace sciences meeting, San Diego (2016)
55. Andrus, I.Q., King, P.I., Polanka, M.D., Schauer, F.R., Hoke, J.L.: Design of a premixed Fuel–Oxidizer system to arrest flashback in a rotating detonation engine. J. Propuls. Power. **33**, 1063–1073 (2017)
56. Yao, S., Tang, X., Luan, M., Wang, J.: Numerical study of hollow rotating detonation engine with different fuel injection area ratios. Proc. Combust. Inst. **0**, 1–7 (2016)
57. Randall, S., Anand, V., St. George, A.C., Gutmark, E.J.: Numerical and experimental study of heat transfer in a rotating detonation engine. In: 53Rd AIAA aerospace sciences meeting. American institute of aeronautics and astronautics, Kissimmee (2015)
58. Stoddard, W.A., St. George, A., Driscoll, R., Anand, V., Gutmark, E.J.: Experimental validation of expanded centerbodiless RDE design. In: 54Th AIAA aerospace sciences meeting, San Diego (2016)
59. Stoddard, W., Gutmark, E.J.: Numerical investigation of expanded and stepped centerbodiless RDE designs. In: 51St AIAA/SAE/ASEE joint propulsion conference, Orlando (2015)
60. Schwer, D., Kailasanath, K.: Fluid dynamics of rotating detonation engines with hydrogen and hydrocarbon fuels. Proc. Combust. Inst. **34**, 1991–1998 (2013)

61. Stoddard, W., Anand, V., Driscoll, R., Dolan, B., St. George, A., Villalva, R., Jodele, J., Wilhite, J., Gutmark, E.: Experimental characterization of centerbodiless RDE emissions. In: 55Th AIAA aerospace sciences meeting, Grapevine (2017)
62. George, A.S., Driscoll, R., Anand, V., Munday, D., Gutmark, E.J.: Fuel blending as a means to achieve initiation in a rotating detonation engine. In: 53Rd AIAA aerospace sciences meeting, Kissimmee (2015)
63. Driscoll, R., Aghasi, P., St. George, A., Gutmark, E.J.: Three-dimensional, numerical investigation of reactant injection variation in a H2/air rotating detonation engine. Int. J. Hydrogen Energy. **41**, 5162–5175 (2016)
64. Anand, V., St. George, A., Driscoll, R., Gutmark, E.: Analysis of air inlet and fuel plenum behavior in a rotating detonation combustor. Exp. Therm. Fluid Sci. **70**, 408–416 (2016)
65. Anand, V., St. George, A., Driscoll, R., Gutmark, E.: Characterization of instabilities in a rotating detonation combustor. Int. J. Hydrogen Energy. **40**, 16649–16659 (2015)
66. Rankin, B.A., Richardson, D.R., Caswell, A.W., Naples, A.G., Hoke, J.L., Schauer, F.R.: Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. Combust. Flame. **176**, 12–22 (2016)
67. Driscoll, R., St. George, A., Gutmark, E.J.: Numerical investigation of injection within an axisymmetric rotating detonation engine. Int. J. Hydrogen Energy. **41**, 1–12 (2015)
68. Stoddard, W.A., George, A.S., Driscoll, R., Gutmark, E.J.: Computational analysis of existing and altered rotating detonation engine inlet designs. In: 50th AIAA/ASME/SAE/ASEE Jt Propuls. Conf., pp. 1–8 (2014)
69. Stoddard, W., Gutmark, E.: Numerical study of obstacles in rotating detonation engines. In: 51St AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. American Institute of Aeronautics and Astronautics, Grapevine, Texas (2013)
70. Stoddard, W., Gutmark, E.J.: Comparative numerical study of RDE injection designs. In: 52Nd aerospace sciences meeting. American institute of aeronautics and astronautics, National Harbor, Maryland (2014)
71. Gaillard, T., Davidenko, D., Dupoirieux, F.: Numerical simulation of a rotating detonation with a realistic injector designed for separate supply of gaseous hydrogen and oxygen. Acta Astronaut. **141**, 64–78 (2017)
72. Gaillard, T., Davidenko, D., Dupoirieux, F.: Numerical optimisation in non reacting conditions of the injector geometry for a continuous detonation wave rocket engine. Acta Astronaut. **111**, 334–344 (2015)
73. Lu, F.K., Braun, E.M.: Rotating detonation wave propulsion: experimental challenges, modeling, and engine concepts (invited). J. Propuls. Power. **30**, 1125–1142 (2014)
74. Frolov, S.M., Aksenov, V.S., Ivanov, V.S., Shamshin, I.O.: Continuous detonation combustion of ternary hydrogen-liquid propane-air mixture in annular combustor. Int. J. Hydrogen Energy **42**(26), 6808–16820 (2017)
75. George, A., Driscoll, R., Anand, V., Gutmark, E.: Chemical kinetic analysis of detonability-enhancing strategies for ethylene–oxidizer mixtures. Acta Astronaut. **128**, 194–202 (2016)
76. St. George, A., Driscoll, R., Anand, V., Gutmark, E.: On the existence and multiplicity of rotating detonations. Proc. Combust. Inst. **36**, 2691–2698 (2017)
77. Anand, V., St. George, A., Gutmark, E.: Amplitude modulated instability in reactants plenum of a rotating detonation combustor. Int. J. Hydrogen Energy. **42**, 12629–12644 (2017)
78. Pandiya, N., St. George, A.C., Driscoll, R.B., Anand, V., Malla, B., Gutmark, E.J. In: 54Th AIAA aerospace sciences meeting, San Diego (2016), Efficacy of acoustics in determining the operating mode of a rotating detonation engine
79. Bykovskii, F.A., Vedernikov, E.F.: Continuous detonation of a subsonic flow of a propellant. Combust. Explos. Shock Waves. **39**, 323–334 (2003)
80. Ciccarelli, G., Dorofeev, S.: Flame acceleration and transition to detonation in ducts. Prog. Energy Combust. Sci. **34**, 499–550 (2008)
81. Fotia, M.L., Schauer, F., Kaemming, T., Hoke, J.: Experimental study of the performance of a rotating detonation engine with nozzle. J. Propuls. Power. **32**, 674–681 (2016)
82. Flandro, G., Fischbach, S., Majdalani, J.: Nonlinear rocket motor stability prediction: limit amplitude, triggering, and mean pressure shift. Phys. Fluids. **19**(9), 094101–094116 (2007). https://doi.org/10.1063/1.2746042
83. Bykovskii, F.A., Zhdan, S.A., Vedernikov, E.F.: Continuous spin detonations. J. Propuls. Power. **22**, 1204–1216 (2006)
84. Ju, Y., Sun, W.: Plasma assisted combustion: dynamics and chemistry. Prog. Energy Combust. Sci. **48**, 21–83 (2015)
85. Zhu, Y., Anand, V., Jodele, J., Knight, E., Gutmark, E., Burnette, D.: Plasma-assisted combustion in a rotating detonation combustor. In: Joint propulsion conference (2017)

86. Knight, E., Anand, V., Jodele, J., Malla, B., Zahn, A., St. George, A., Gutmark, E.: Effect of corrugated outer wall on operating regimes of rotating detonation combustors. In: Int. Conf. on jets, wakes and separated flows, Cincinnati (2017)
87. Anand, V., George, A.S., Driscoll, R., Randall, S., Gutmark, E.J.: Statistical treatment of wave instability in rotating detonation combustors. In: 53Rd AIAA aerospace sciences meeting, Kissimmee (2015)
88. Teodorczyk, A.: Fast deflagrations and detonations in obstacle-filled channels. Bull. Inst. Heat. Eng., Warsaw Tech. Univ. **79**, 145–178 (1995)