Rotating Detonation Wave Mechanics through Ethylene-Air Mixtures in Hollow Combustors, and implications to high frequency combustion instabilities

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1 Introduction

Detonation is a supersonic combustion mode that produces a pressure gain [1] across the front due to the shock wave linked to the combustion front behind it. This type of combustion can be activated in suitable mixtures in solid, liquid or gas phase [2]. The phenomenon was first discovered in the 19^{th} century [2], and since then, considerable research has been directed towards understanding this phenomenon. Broadly speaking, detonations can be stable or unstable [1]. Unstable detonations exhibit a highly time-dependent three-dimensional behavior and manifest as different peculiar phenomena. While their actual onset and exact physics are actively studied, there is common consensus that unstable detonations have a decoupled shock wave-reaction zone structure that is brought about due to the quality of reactants (high activation energy), boundary conditions, or both [1]. However, based on the mechanism of a coupled propagation, detonations exist in one of three sub-types: strong detonation, Chapman-Jouguet (C-J) detonation and weak detonation [1, 2]. Of the three, both strong and C-J detonations have been observed rather extensively in experiments. A strong detonation has a subsonic flow of products behind the detonation front, relative to it. As such, a strong detonation ("piston supported") cannot sustain indefinitely, since the detonation wave weakens due to the expansion waves interacting with the reaction zone. C-J detonations ("unsupported"), on the other hand, can be freely propagating (steady state), and most mixtures subscribe to the solutions obtained from the simple Rankine-Hugoniot relation with an additional energy release term. Here, the combusted products are sonic with respect to the detonation front, which means the detonation wave can be continually sustained, provided the upstream and boundary conditions are held constant. The third detonation type — weak detonation — is theoretically possible [2], but requires special conditions to exist. In fact, despite both Zel'dovich and Neumann showing the theoretical possibility of steady-state weak detonations [1], notable apprehensiveness seemed to exist for some time among experimentalists regarding its possibility in the physical world. However, it is the widespread notion today that such weak detonations can indeed exist under certain specific conditions. Weak detonations have a shock wave that is supersonic relative to the expanding products, and as a result have a comparatively (to C-J) higher propagation velocity and lower peak detonation pressure [1, 2]. It is at this juncture that we seek to divert the attention to the work of Adams [3], who tried to experimentally show that weak detonation waves can exist in gaseous mixtures, by varying the boundary conditions of the detonation tube. His work was partly motivated by the results of Voitsekhovskii, who was the first to show the possibility of having sustained and stably propagating rotating detonation waves in an annulus [4]. He observed detonation waves moving at half the C-J velocities of the mixture that was used. While the final conclusion of Adam's investigation into weak detonations were ultimately inconclusive, the questions raised by him regarding the peculiarities observed by Voitsekhovskii in his rotating detonation combustor are of heightened significance, both from a fundamental physical inquiry and from an engineering perspective

Despite the considerable progress made until now on the different facets of the RDC substantial research is still warranted to ascertain the basic physics. An intriguing facet of RDCs is the notably lower wave speed and peak detonation pressures relative to the solutions obtained for the ideal C-J conditions for the given mixture. To the authors' knowledge the rotating detonation wave speed and peak pressure across all the facilities worldwide always exhibit varying levels of deficiencies from the expected ideal performance in an RDC [4–9]. In this regard, rotating detonations differ from weak detonations since they exhibit lower wave speeds from C-J, which is in contrast to the higher wave speeds exhibited by weak detonations. Despite this unanimous RDC behavior, it is interesting to note that most researchers have refrained from addressing this velocity and pressure deficit; a trait in RDCs that was called out by Adams [3]. Such a deficit is also seen in a hollow RDC [10] . A hollow RDC is lighter than an annular combustor of similar dimensions, due to the absence of the RDC center wall. It is emphasized that, interestingly, continuous detonation in a hollow combustor was first demonstrated by Bykovskii et al. [11] using hydrogen, methane, kerosene and diesel with air in 1997. While these results from the literature forecast positive implications to the usage of a hollow rotating detonation combustor, we are left with an extremely 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? That is, 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 make sense to resort to the hollow combustor design due to the 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 [1], logic dictates that we move away from the annular designs that have been the singular signature of rotating detonation combustors until now. In fact, the authors have shown a similar trend— of decreased operating regime, and increased failure to ignite detonation waves— when the annulus of the detonation combustor is reduced for a given hydrogen-air mixture composition [12].

A hollow RDC is, in essence, a basic cylindrical combustor that is widely prevalent in both gas-turbine and rocket engine combustors, and naturally, analyzing detonation propagation inside it has heightened significance for both the engines. While the previously discussed demonstration of continuous rotating detonation in a hollow combustor is voluntary, multiple researchers [13–17] studying rocket engines (both liquid propellant engines and solid motors) have observed "detonation-like" (probably because of the inability to explain large deviations in wave speed and pressure from the ideal C-J conditions, which has now been accepted as the standard operation in an RDC) waves spinning around the rocket combustion chamber at thousands of Hertz. This "high-frequency tangential instability" in rocket engines has 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 had traditionally lead to the 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 of altering the rocket geometry and mixing scheme, among other things, rather than addressing the nuclei of the issue [18]. For instance, 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, as it appeared to be highly sensitive to the injection scheme and flow rates used [19]. Of notable loss is the Ariane 4 rocket, which experienced a catastrophic explosion minutes after takeoff, due to one such high-frequency tangential instability event in its Viking engines [18]. The high-frequency instabilities in rocket engines have been attributed to a variety of factors, some making more sense than others depending on the research facility [20]. A combustion-acoustic coupling in the form of an "acoustic wave", conforming to the Rayleigh heat addition criterion [21–23], velocity fluctuations, entropy waves, "detonation-like" waves, liquid stream shattering and supercritical droplets explosion are some of the proposed theories [20]. It is to be emphasized that significant contention still exists among the researchers of rocket engine instabilities on the fundamental nature of the high-frequency tangential instability. Most studies still prescribe to the Rayleigh heat addition process through in-phase pressure and heat addition and explain the "steep-fronted, detonation-like" waves to be a kind of acoustic wave or a "heat wave" [24]. However, some other studies [13, 17, 25] have rightly pointed out the debilitating shortcomings, both logical and observational, of this theory. Flandro et al. [25], who are responsible for one of the most accurate analytical model on these high-frequency instabilities, go so far as to say that the theories that are purely based on the acoustic wave point of view have spent "much time and energy on attempts to correct deficiencies in the linear model by introduction of *ad hoc* fixes that are often based on guesswork, and misinterpretation and/or distortion of experimental evidence". However, the physical mechanisms responsible for these instabilities have not yet been pinpointed, and as a result multiple unanswered questions remain.

From the above information it can be ascertained that there seem to be two scientific communities operating rather independently of each other. The motivation for the current work is to ascertain if the physics dictating the combustion dynamics in an RDC is the same as the one causing high frequency combustion instabilities in varied combustors. To investigate this, we resort to using a hollow atmospheric combustor, without backpressure, and 'force' it to sustain rotating detonations.

2 Experimental methodology

As explained earlier in the introduction, we are concerned about inducing rotating detonations in a hollow combustor. To effect this, two different geometric variations/ schemes are utilized to change the degree of mixing inside the combustor, since global equivalence ratio (Φ) should be markedly different from the local equivalence ratio in a hollow combustor, unlike the conventional annular RDC geometries. Three air flow rates ($\dot{m}_a$) are tested. The current study utilizes a single air injection area for all the tested points. Three piezoelectric pressure sensors placed near the combustor headwall capture if the oscillation is in-phase or out-of-phase (i.e. rotating).

3 Results and discussion

In this section, we demarcate the fundamental differences in operation produced by the two schemes (Figure 1). For Scheme I, rotating detonations are not observed in the regimes of $\dot{m}_a$ and Φ tested. Operating points that are prone to an anchored deflagration flame throughout the test duration or those points that did not exhibit any combustion initiation at all are defined as failure points and are presented as blue markers. When 'rough' combustion (notable activity in the piezoelectric pressure sensors) is observed, the operating points are differentiated between rotating oscillations (red markers) and transverse oscillations (orange markers). For Scheme I, high frequency transverse combustion instability is observed for all three air flow rates, only at $\Phi = 1.4$. When two of the three azimuthally distributed pressure sensors exhibit in-phase pressure oscillations it is inferred that transverse instabilities (radial oscillations) are set up inside the combustor. The pressure oscillation never exceeds ± 0.2 bar. The frequency of the instability decreases from 2939 Hz to 2848 Hz as $\dot{m}_a$ increases from 0.2 kg/s to 0.4 kg/s. Assuming crude hot flow conditions having a heat capacity ratio of 1.2, "average" gas temperature inside the combustor of 3000 K, and specific gas constant of 287 J/(kg-K), we get a sound speed of 1016 m/s. This, in turn generates a half-wave frequency for the transverse instability to be 3300 Hz, which is close to the recorded values. Since the first transverse mode between two walls is a half-wave eigenmode [26], one could contend that the transverse HFI produced with Scheme I at $\Phi = 1.4$ is due to an acoustic standing wave that is set up inside the hollow combustor. This equal strength in compression and expansion further strengthens the claim that the transverse HFI is caused due to standing acoustic waves that are intertwined with combustion, similar to the process seen in other hollow combustors [26–28].

A drastic variation in the hollow combustor operation is produced when Scheme II is used. First, rough combustion is observed for all but one operating point tested ($\dot{m}_a$ = 0.4 kg/s and $\Phi = 0.8$ only supports anchored deflagration). All points tested at the lowest $\dot{m}_a$ of 0.2 kg/s had two of the three row 1 pressure sensors exhibiting in-phase pressure oscillations that are illustrative of transverse HFI. Here however, two distinct bands of transverse HFI are observed — one in the same range as before at about 3000 Hz, and the other at a notably higher range at about 5000 Hz. The transverse HFI high frequency band occurs at $\Phi < 1.3$, whereas the low frequency band occurs at $\Phi > 1.3$. Sinusoidal pressure oscillations, not exceeding 0.6 bar is observed at the high frequency band. These observations suggest that, once again, standing transverse acoustic modes are responsible for the rough combustion produced when $\Phi < 1.3$. However, unlike the prior cases with Scheme I, higher modes at around 5000 Hz seem to be excited when Scheme II is used, which might be due to the higher modes and orientations of the standing wave transverse instability, a phenomenon observed in hollow combustors [26, 27]. For the low frequency band, peak pressure is always around 1 bar or greater, whereas the negative pressure does not fall below 0.5 bar, for all the operating cases investigated. Additionally, the pressure signals are no longer sinusoidal, but are now characterized by very sharp rise-times characteristic of shock waves inside the combustor. It is this type of sharp rising pressure signals that have been attributed to the "shock-fronted" behavior of high frequency combustion instabilities seen in rocket engines (as detailed in the introduction). For $\dot{m}_a$ of 0.3 kg/s and 0.4 kg/s, and $\Phi > 0.9$, we no longer observe any in-phase pressure oscillations. For these operating points with Scheme II, continual rotating detonations (red markers) are observed. This is verified by a time-of-flight algorithm that captures the subsequent (temporally) peak pressures across all the three pressure sensors in the first row, and using the obtained time interval to divide the sectoral distance between the stations the sensors are instrumented in. To further expand, we confirm that what we observe is indeed rotating by ensuring that: 1) the three sensors are phase-lagged, and 2) the speed of occurrence of the phenomenon is uniform and relatively constant across the three sensors distributed azimuthally. Both stable and unstable rotating detonation propagations are observed. We define stability based on the scatter in wave speed and peak pressure of subsequent laps of the rotating pressure wave. If the wave speeds are highly repeatable and without much scatter (in a manner similar to Lee's definition of detonation wave stability [1]) the operating points are deemed to be stable.

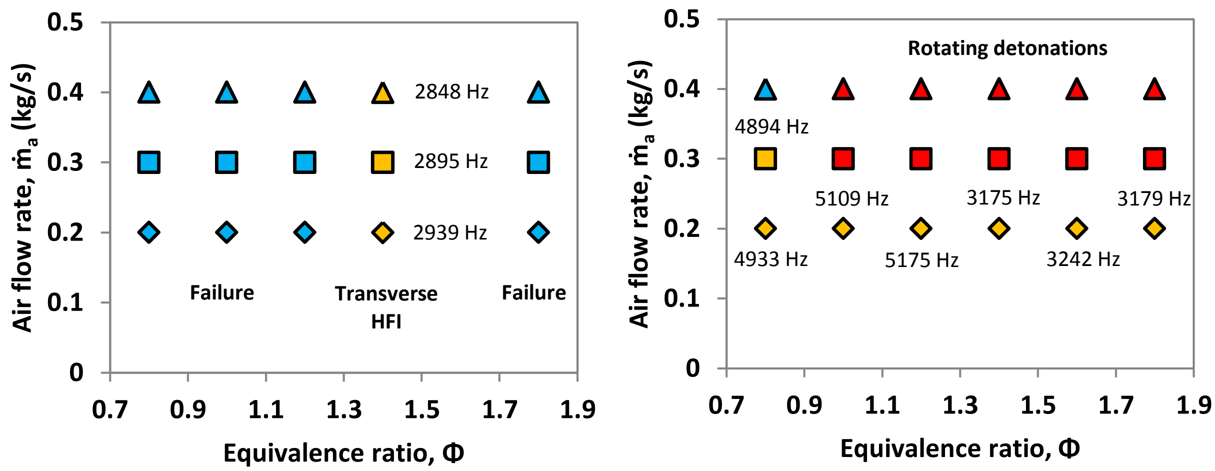

Figure 1. Operating regime for (a) Scheme I, and (b) Scheme II

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