Effect of Parasitic and Commensal Combustion on Rotating Detonation Combustor Properties

Fabian Chacon, Alex Feleo, and Mirko Gamba
University of Michigan
Ann Arbor, Michigan, United States of America

1 Introduction

Rotating Detonation Combustors (RDCs) use a detonation wave to consume reactants instead of a deflagration as found in traditional gas turbine engines. The benefit offered by the use of detonation over deflagration is a net (stagnation) pressure rise during combustion, an effect that is termed pressure gain combustion and allows for additional work to be extracted, thus increasing the thermal efficiency of the cycle. Typical RDCs are composed of a circular annular channel with a width small compared to the diameter where fresh reactants are continuously fed by a fuel/oxidizer handling system and consumed by a detonation wave traveling azimuthally at the base of the channel; post-detonation gases are then exhausted at the opposite end of the channel where they are processed to extract power or generate thrust.

The flow field of a RDC is highly unsteady and complex [1–3]. The overall operability and performance of an RDC depends on several factors. One of the main factors is rapid and adequate mixing between fuel and oxidizer over a time-scale shorter than the rotational time of the detonation wave, while avoiding stabilization of deflagration fronts that consume the fresh mixture prior to the arrival of the detonation wave [4]. Stabilization of deflagration within the annulus can occur for different reasons, but ultimately limits the fraction of the chemical energy converted through the detonation wave, thus affecting both the stability of the wave itself and the pressure gain achieved in practice.

In general, we can refer to this unwanted deflagration fronts as *secondary combustion*, which is known to occur in RDC flows [5, 6]. In this work, we specifically investigate secondary combustion phenomena, their occurrence and their impact on the detonation wave properties, as well as on some of the parameters used to evaluate the operation of an RDC. Specifically, we investigate the type of secondary combustion and its relation to and impact on the detonation wave. Secondary combustion can occur both before and after the passage of the detonation wave, and might continue as the gases expand past the detonation wave due to incomplete chemical reaction across the detonation wave. We define secondary combustion that occurs before the passage of the wave in the fill region as *parasitic combustion*, while we refer to secondary combustion behind the detonation wave as *commensal combustion*. Differentiation between the two types, which is based on the different relationship that the two forms have to the main detonation wave, is important to understanding the challenges in realizing pressure gain in RDCs, but it is also important for the evaluation and understanding of the reduction in detonation speed and chamber pressure observed in measurements and which are believed to be associated with a reduction in realized performance in practical devices. In addition, we are attempting at quantifying the amount of secondary combustion present in RDC flows through a combination of imaging and emission spectroscopy methods applied to a conventional RDC [7,8] and an optically accessible RDC [9] developed to enable optical diagnostics in RDC flows under realistic geometries and operating conditions.

2 Discussion

For the purpose of this work we conducted a variety of measurements in two RDC systems: our round 15 cm diameter RDC [7,8] and our optical racetrack-shaped RDC [9]. A complete description of these systems and their behavior can be found in our previous work [7–9]. What we present here is based on general observations made over a range of conditions, over multiple realizations of those conditions. The study has identified a number of features not considered in a canonical representation of the RDC flow field [3]. Here we focus on the presence of secondary combustion throughout the flow field on either side of the detonation wave. Additional phenomena and considerations related to secondary combustion in these flow fields have been discussed in our previous work on the topic [5]. A representative OH* chemiluminescence still image of the flow field taken in the racetrack RDC is shown in figure 1. We use OH* chemiluminescence emission as an approximate marker of heat release for air/hydrogen reacting flows. From this still image we can identify the detonation wave as the high intensity region traveling to the left into a partially reacted fill region (PC) and leaving in its wake a region of continuing reaction (CC). Traditionally in the RDC community the term "parasitic combustion" has been used to refer to any non-detonative combustion found in RDCs. Here we will draw a distinction between secondary combustion before and after the passage of the detonation wave because of the different relationship and impact that the two regions have on the detonation wave. Thus, we will reserve the term parasitic combustion to a specific form of non-detonative secondary combustion.

Secondary combustion before the detonation wave is termed parasitic combustion (PC) because it is consuming fresh mixture and thus releasing heat, that might otherwise be used in supporting the propagation of the detonation wave. This has a direct impact on the properties of the detonation wave because it causes a decrease in wave speed as well as peak pressure (i.e., lower C-J state pressure) through a mechanism that is similar to a vitiation effect of the unreacted mixture [5]. In contrast, secondary combustion after the sonic plane of the wave does not contribute to supporting the detonation wave. We refer to this type of secondary combustion as commensal combustion (CC). Here we cannot adequately establish the sonic plane solely with our current measurements, which is required to determine an exact measure of commensal combustion. However, the presence of OH* emission far behind the detonation front, as seen in figure 1 and 2, suggest that chemical reaction (heat release) is undergoing away from the detonation front in what we have termed commensal combustion. Therefore, here we can provide only a qualitative break down between detonation and commensal combustion. Commensal combustion is not a direct form of loss to the wave but a consequence of mixture or heat release leaking through the detonation wave. Similar phenomena have been observed in the computational study of Prakash et al. [10]. In differentiating between parasitic and commensal combustion we adapt terminology used in biology [11], where parasitism is used to identify the relationship between two species when one benefits at the detriment of the other, while commensalism is used when one species benefits without significantly impacting the other.

The presence of parasitic combustion (PC) in the fill region prior to the passage of the detonation wave has practical implications for the performance of the rotating detonation combustor. This non-ideal combustion has two effects on the fill region that will ultimately impact the properties of the detonation wave, such as its speed and pressure ratio. Firstly, it is effectively releasing heat that might otherwise be used to support the propagation of the main detonation wave. Secondly, parasitic combustion changes the composition and temperature of the fresh mixture by producing intermediate and product species of combustion while increasing the temperature of the mixture going through the detonation wave. This is similar to a vitiation effect and leads to a dramatic change in the detonation structure and conditions at the C-J point (within the context of an idealized ZND detonation wave). This effect has been evaluated using a zero-dimensional model in Ref. [5] and found to have a drastic impact on wave speed and peak (C-J) pressure. The practical implication is that this phenomenon results in a reduction of the effective thermodynamic gain that can be achieved in a detonation-based combustor. The cause of parasitic combustion is not currently known but may be caused by entrainment of hot products from the previous cycle, deflagration stabilization in recirculation regions, backflow into the fuel/oxidizer manifolds or hot injector elements, and has been observed to be influenced by secondary waves [5], such as counter propagating waves that exist in RDCs [12, 13].

The presence of commensal combustion (CC) and its associated heat release do not directly impact the properties of the detonation wave because chemical energy is released past the sonic plane of the wave. However, it is evidence of non-ideal behaviors. Ideally, all available chemical energy, such as what remains after parasitic combustion has taken place, would be released at the detonation wave rather than after it. The existence of commensal combustion is evidence of what is referred to as heat release leakage or mixture leakage. Heat release leakage is the hypothesized mechanism by which chemical reactions are not completed across the detonation wave because the wave is a broad (non-compact) region rather than a sharp discontinuity as typically conceptualized [10]. Mixture leakage is another hypothesized mechanism by which some portion of the fill region passes through the detonation wave without reacting, possibly because the detonation wave does not travel as a continuous single wave or is distorted by curvature or mixture stratification across the fill region. Detailed numerical simulations suggest mixture leakage is linked to non-homogeneous mixing and geometric effects [14], but may be influenced by other unknown factors. Regardless of the controlling mechanisms, the effect remains the same: some portion of the reactants do not release their chemical energy at the detonation wave but rather at a later time, resulting in commensal combustion and an additional reduction in the gain that can be achieved in practical devices.

To further evaluate the existence and distribution of parasitic and commensal combustion within the RDC cycle, we have used OH* emission measurements at a single point at a fixed axial location in the detonation channel during steady state operation in our round RDC [15]. Assuming that OH* emission can be used as a qualitative marker of heat release, this provides the temporal evolution of heat release, and thus chemical reaction, taking place during operation. By reducing a time-resolved evolution of the OH* emission to a phase-average distribution of OH* emission over the average detonation cycle, we can identify the regions of parasitic and commensal combustion relative to the detonation wave. An example of a phase-average distribution of OH* emission for a representative case for hydrogen/air operation at 0.3 kg/s and equivalence ratio of 0.6 is shown in figure 2. Details on this diagnostics are reported in our previous work [15].

The cycle phase-averaged OH* emission of figure 2 illustrates non-ideal combustion occurring within the RDC. We can identified several features, that are highlighted and color coded in figure. The average position of the detonation wave in the cycle phase-average distribution is at $t/\overline{\tau}_R \approx 0.5$ by construction. Before the

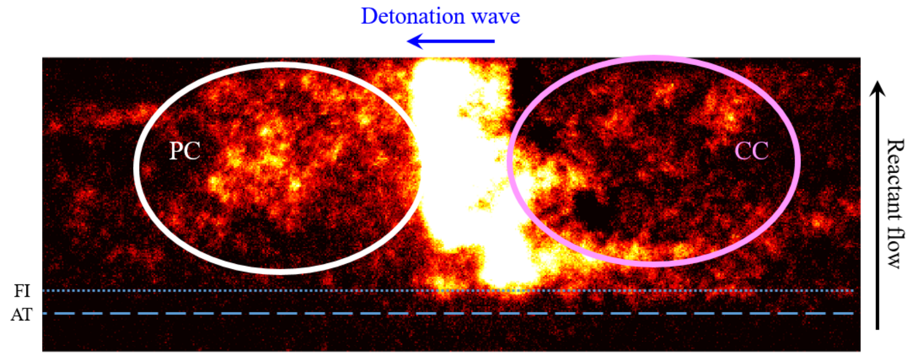

Figure 1: OH* chemiluminescence still image showing regions of secondary combustion both before and after the detonation wave passage. Combustion before the wave is termed parasitic combustion (PC) while the combustion after the detonation's passage is termed commensal combustion (CC). FI denotes line of fuel injectors and AT denotes the air inlet throat of our axial air inlet with transverse fuel injection.

arrival of the wave we observe an ignition event at $t/\overline{\tau}_R \approx 0.2$ and this corresponds to the onset of parasitic combustion. At the arrival of the primary detonation wave we observe a rapid increase in the OH* emission, which is associated with the intense heat release across the detonation wave that supports it. Trailing the detonation wave is a region of significant OH* emission, indicating that the heat release continues past the detonation wave until OH* emission disappears, possibly because of the arrival of the fresh mixture. The presence of the long OH* emission tail is indicative of mixture or heat release leakage through the wave associated with commensal combustion. It is important to point out that at this stage the separation between the three combustion modes (parasitic, detonation and commensal) was arbitrarily based on the keens of the cycle phase-average distribution of OH* emission. Though in a rigorous sense the distinction between the parasitic combustion region and the detonation wave would be the arrival of the shock wave associated with the detonation wave. In the case of commensal combustion the proper delineation is the point at which the flow becomes sonic. However, diagnostic limitations do not allow these demarcations to be identified and we are only able to provide a qualitative breakdown into the different regions.

If it is assumed that there is a fixed total amount of chemical energy Q_T available, and that Q_T is proportional to the area under the phase-averaged OH* emission curve, then we can assess the fraction of heat release associated with each region of combustion. The green area corresponds to parasitic combustion, red with the detonation wave, and blue with commensal combustion. After taking the area under the curve of each of the three combustion regions and normalizing with respect to Q_T, it was found that $Q_P/Q_T \approx 0.25$, $Q_D/Q_T \approx 0.5$, and $Q_C/Q_T \approx 0.25$. This means that based on this metric, it appears that only half of the total heat release in the system is directly supporting the detonation wave. If we normalize the wave speed from this run by the ideal CJ speed for an equivalence ratio of 0.6 we get 0.78 D_{CJ}. If however we normalize by the wave speed predicted from equations accounting for parasitic combustion and mixture leakage effects we get 0.94 D_{CJ}. A similar comparison can be made with pressure; an ideal hydrogen/air detonation should result in a pressure ratio across the wave of approximately 12.6, taking into account parasitic combustion and mixture leakage reduces this ratio to 3.8, which is more in line with the measured value of approximately 3.2. There is still some discrepancy between predictions and observation, part of this is likely due to the rough estimate of the three regions proportions, more detailed work is necessary to get better estimates for the proportions of parasitic and commensal combustion. Understanding the relationship

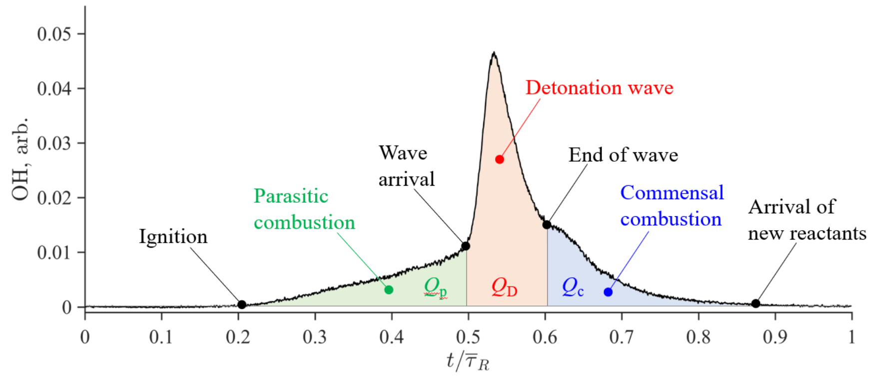

Figure 2: Representative phase-averaged OH* emission profile (marker of heat release) over a cycle. $\overline{\tau}_R$ is the average rotational time of the detonation wave in the RDC.

between all three regions, their exact impact on the detonation wave, and the ultimate performance of the combustor in the presence of these undesired phenomena are the focus of current work.

3 Conclusion

Secondary combustion has been observed to occur in RDCs, both before and after the passage of the detonation wave. This results in what we term parasitic and commensal combustion. These two forms of secondary combustion have different impacts on detonation wave properties. These forms of secondary combustion have been observed experimentally in our optically accessible racetrack-shaped RDC and round RDC, as well as in detailed computational work [10, 14]. By using OH* emission as an approximate marker of heat release we have begun to quantify the fraction of heat release associated with the main detonation wave as well as with each of the two secondary combustion modes. Current estimates suggest that as much as 50% of all heat release in the RDC may be consumed by secondary combustion rather than by the main detonation wave. This large heat release deficit is likely to impact both the detonation wave properties as well as the ultimate benefits that may be expected from an RDC.

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