OH* Chemiluminescence Investigation of Rotating Detonation Wave Structure

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Abstract

A rotating detonation combustor (RDC) is investigated in order to determine the impact of equivalence ratio, mass flow rate, and channel sizing on a rotating detonation wave. High speed chemiluminescence is used in order to visualize the detonation wave as it propagated through the combustor. Centered images of the detonation wave are aligned and averaged in order to determine the characteristics of the detonation front per test case. Average detonation wave intensities and wave heights are then calculated. The standard deviation is then calculated and divided by the average combustion intensity in order to determine the normalized deviation from the average. It was determined that detonation waves that propagated at a global equivalence ratio of 1 experienced the highest average intensity. Increasing the mass flow rate of the engine also resulted in a reduced normalized deviation; however, this trend is not expected to continue endlessly.

1 Introduction

An RDC is a type of pressure gain combustion (PGC) device that is characterized by a mostly continuous flow of reactants into the combustion chamber. These reactants are then combusted using a tangentially traveling detonation wave that rotates around the combustor annulus in a cyclical pattern. Many visualization studies have characterized rotating detionation waves in a variety of engine configurations.

In order to study the detonation wave itself, an optically accessible conbustor is needed. Several different designs have been used over the years. Bykovskii et al. have found success in adding simply a small longitudinal window into their RDC designs [1]. Using a high speed camera and this small window, they can use a technique called velocity compensation where the video is unwrapped into a rectangular image based upon its velocity [1]. A drawback of this method of visualizing an RDC is that the resulting image is not time-synced, but rather what one area of the combustor looks like through time.

Rankin et al. at the Air Force Research Laboratoy (AFRL) have fully replaced their outerbody of their RDC with a transparent piece of quartz [2, 3]. This method allows the full combustor to be visualized throughout the entire duration of the run. Furthermore, since the outerbody is made of quartz, ultraviolet light is able to freely pass through this material which enables chemiluminescence imaging to be taken of their combustor. The downside to such a design is that the quartz is rather fragile and prone to breaking. If little is done to ensure the longevity of the quartz, it can easily shatter in the high intensity RDC environment.

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Nakagami et al. used a flattened RDC to easily visually study the characteristics of a detonation wave traveling inside of the combustor [4, 5]. This design is advantageous because there are two parallel faces that can be replaced with a transparent material if needed. This allows for shadowgraph and Schlieren videos to be made of the combustion zone inside of the RDC. The strong disadvantage of such a combustor is that such a design has the potential to widely change the characteristics of the detonation front and due to the non-axial design, its practical utility is strongly diminished.

There have been several studies regarding the performance of RDCs under different mass flow rates, equivalence ratios, and geometries [1–3, 6–8]. The behavior of the wave in different studies is described as chaotic or stochastic in some configurations [2, 3]. Rankin et. al. has qualitatively described the stability of the detonation, specifically mentioning that the presence of the wave is inconsistent for fuel lean conditions [2, 3]. An RDC with a quartz outerbody similar to the one used by AFRL will be used in this campaign due to its minimal impact upon the physics of the RDC and the immense viewing area provided by it. The goal of this study is to quantitatively describe the stability of a detonation wave. By determining the effects parameters such as mass flow rate and equivalence ratio have on the consistency of a detonation wave, the reliability of the combustor may be improved when integrating it with an engine.

2 Methodology

During the course of this campaign, the air mass flowrate, equivalence ratio, and combustor geometry were varied while high speed chemiluminescence images were acquired so that a wide operating map could be created of the combustion occurring inside of the engine. The combustor itself is an RDC (detailed specifications available in [9]) whose components can be easily interchanged to facilitate modularity. Specifically, the inner and outer body may be interchanged to edit the dimensions of the combustor, the fuel plate can be replaced if a different injection style is desired, and the air injection scheme can be swapped from a radially inwards injection to a radially outwards scheme.

The engine is run using hydrogen and air as the fuel and oxidizer. It was tested from a mass flow rate of 0.2kg/s up to 0.5kg/s with an equivalence ratio ranging from 0.6 up to 2 (The equivalence ratios achieved vary per mass flow rate). The engine is ignited using an ethylene/oxygen predetonator that is fed through the aft end of the engine. The camera used for this test campaign is a phantom v1610 attached to a LaVision High-Speed IRO Intensifier with an 768x800 resolution at 27,000 fps. The camera setup includes a 320nm band pass filter to capture only the light emissions from OH*. Figure 1 is an image of the engine used for this campaign. The intensifier was set to a gate of 600ns and gain of 60% to avoid excessive blurring of the detonation wave due to motion. The RDC is run for 0.4 seconds for each test case which equates to 10800 images were attained per test.

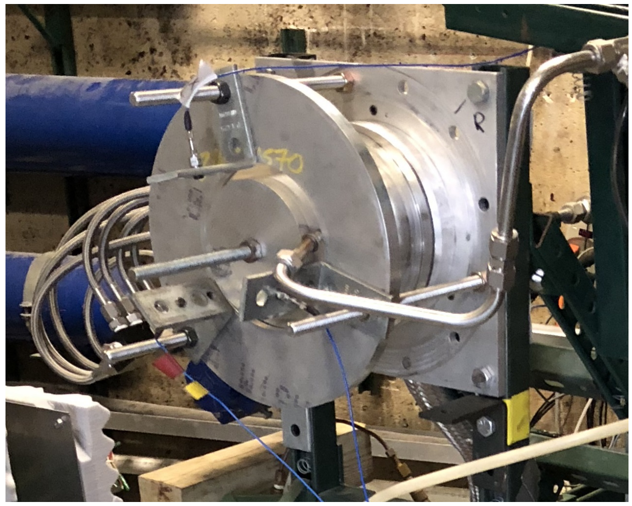


Figure 1: A photograph of the aft end of the RDC

3 Analysis Techniques

3.1 Wave Averaging

In order to quantitatively determine the wave characteristics for each test case, an averaged wave profile is needed. The average of the instantaneous detonation waves are able to provide quantities such as the height of the wave, its intensity, standoff distance, etc. A procedural algorithm was developed to determine which frames from the chemiluminescence video are of sufficient quality for averaging. Firstly, the images from one test case are loaded. For each individual frame, the average intensity of the image is calculated. The average intensity varies over time as the detonation wave rotates around the centerbody. The average intensity will be significantly lower when the detonation wave is located behind the centerbody than when it is in front of it. Next, the intensity was summed for each vertical slice (axial slice relative to the engine) of pixels contained in the image. The summed intensity is then weighted by the x location (or radial location inside of the engine) of that vertical slice and then divided by the summed total intensity of all pixels in order to determine the average x location of the intensities values in the instantaneous image. This x value sinusoidally varies over time and represents the x location of the detonation wave as it travels through the engine. The average value and standard deviation of the x location timeseries is then calculated. Images are considered to be of sufficient quality for averaging if the average intensity of the frame is greater than the average of the intensity timeseries and is within a half standard deviation of the central x location. Using these quality images, a cross correlation is performed to determine the offset between images that results in the most similar overlap and the images are averaged using these offsets to obtain the average wave profiles.

3.2 Wave Height

Wave height was calculated by determining at what height on the image the intensity breaks an arbitrary threshold. The max intensity seen across the entire width of the image was collected as an array and smoothed using a robust locally weighted scatter plot smoothing to reduce noise. This array and the threshold were then used to determine the max height in which the detonation wave was still present. The threshold was set as 70% of the average intensity of the detonation wave. It was set to this value in order to ensure that the background of the image would not cause a false positive detection of the wave. Furthermore, the rise in intensity against the background that the camera sees due to the detonation wave is steep enough that only a relatively small portion of the top of the detonation wave is truncated by such a detection technique.

3 Normalized Deviation

In order to calculate the normalized deviation of the detonation wave, the generated average wave profile was re-compared to the instantaneous waves of sufficient quality. A cross-correlation is once again performed on the instantaneous images that compares it to the averaged to find their point of maximum overlap. Once this point is determined, a pixel by pixel standard deviation of the detonation wave is calculated. This standard deviation is then divided by the average intensity of the detonation wave in order to calculate the normalized deviation. The purpose of this non-dimensionalization is because one may expect that the absolute magnitude of the standard deviation of the wave profile should increase as the wave intensity increases. This new quantity then shows us how much deviation there is in the wave profile in terms of the average intensity. This value can then be used to compare the stability of any arbitrary test cases.

4 Results

Figure 2 depicts three averaged waves for an $\dot{m}$ of 0.35kg/s. The waves are organized in ascending equivalence ratios (0.7, 1, 1.5 respectively). Due to the increase of fuel in the 1 and 1.5 equivalence ratio cases, the detonation front is brighter and larger than the 0.7 equivalence ratio case. Furthermore, the equivalence ratio of 1 resulted in the largest and brightest zone of the three likely due to the proper combination of air and fuel. The 0.7 equivalence ratio test case in particular contains the shortest detonation wave. Furthermore, the detonation wave height appears to grow slightly between the 0.7 and 1 test cases; however, the height is not significantly changed between the 1 and 1.5 test cases.

Figure 3 depicts the average intensity of the detonation waves and their respective heights in that order. The average magnitude of the detonation waves appear to be heavily influenced by the mass flowrate inside of the combustor. For example, at an equivalence ratio near 1-1.1, the average intensity nearly triples between 0.2kg/s and 0.45kg/s. This appears to be correlated to the amount of reactants injected whose change in magnitude is 2.25 in this particular example. Furthermore, the intensity reaches a maximum around an equivalence ratio of 1-1.1. This equivalence ratio corresponds to the little to no excess fuel once burned with air. Any variation from this ratio results in a decrease in average intensity of the detonation front. As the equivalence ratio is lowered, less fuel is available to be burned so a lesser magnitude is expected; however, at higher equivalence ratios, the same amount of fuel should be burned because the air mass flowrate is held constant. It is possible that the excess of fuel is causing the extraneous burning elsewhere in the combustor so that less of the oxidizer is available for the detonation wave, This could potentially cause the observed result of a lower average intensity with a higher than unity equivalence ratio. The detonation wave height appears to only be significantly impacted by low equivalence ratios. Lower equivalence ratios appear to lower the detonation wave height by a maximum of 20%; however, increasing the equivalence ratio above 1 did not appear to correspond to a higher wave height.

Figure 3 is a map of how the normalized deviation values change with mass flow rate and equivalence ratio. The most notable trend that can be seen from this figure is that as the mass flow rate is increased, the wave appears to become more consistent as well up to a certain point. Once the mass flowrate is above 0.35kg/s, the stability of the detonation wave does not appear to be significantly impacted by mass flowrate. One possible explanation is that each geometry may have an air flowrate dependent stability limit. We postulate that this trend of increasing mass flow resulting in an increased stability will not continue endlessly. If the mass flowrate were to be increased further, it is likely that the wave would become less steady until it experienced some sort of blowout that prevents it from operating. Furthermore, each geometry (specifically channel width will be tested in the full campaign) will likely experience a varied stability change with a change in mass flow rate.

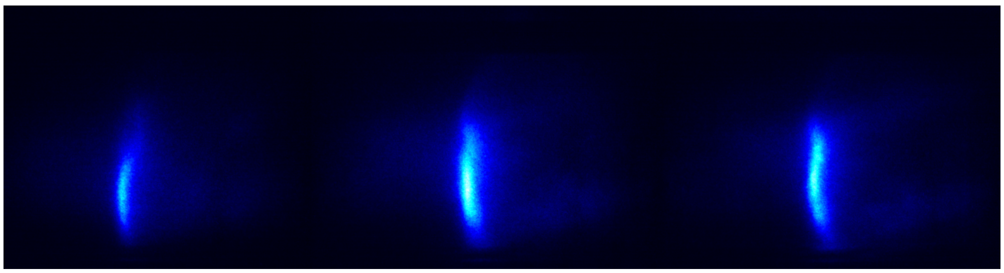
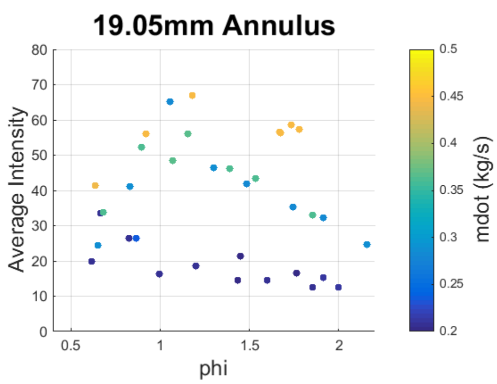
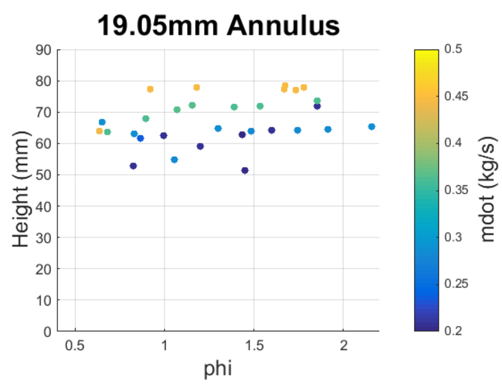


Figure 2: The average of all centered frames of test cases $\dot{m}$=0.4kg/s, $\Phi = 0.7, 1, 1.5$ respectively



(a) The Average wave intensity of the detonation wave



(b) The height of the detonation waves

Figure 3: Detonation wave intensity and height

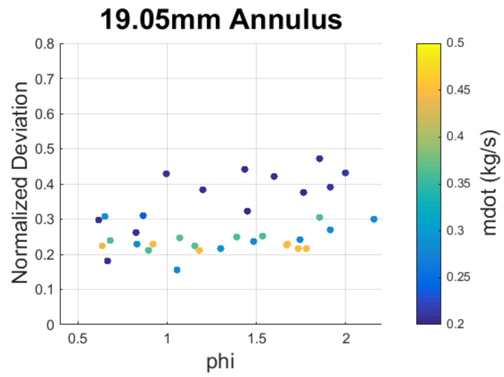


Figure 4: The normalized deviation of the detonation waves

4 Future Work

For the full presentation, several components will be included. The following components will be added; however, the final additions are not limited to the following. Firstly, several different geometries will be tested to determine the impact of channel width on the detonation itself. Specifically, the channel width will vary from 6.35-19.05 mm. Channel sizing can significantly alter the operational map of the RDC [8]; therefore, it likely will have a visual effect upon the detonation front as well. The intensities, wave heights, and normalized deviations will be examined to determine the effects of the various tested parameters on RDC operation. Finally, any oddities in the structure of the detonation front will be described in order to further the understanding of their formation and behavior.

Acknowledgments

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