2023

Detonability of a Rotating Detonation Combustor Seeded with Carbon/Hydrocarbon Particles at Fringe Operating Conditions

Matthew Hopwood
University of Central Florida

STARS Citation
Hopwood, Matthew, "Detonability of a Rotating Detonation Combustor Seeded with Carbon/Hydrocarbon Particles at Fringe Operating Conditions" (2023). *Electronic Theses and Dissertations, 2020-*. 1576.
https://stars.library.ucf.edu/etd2020/1576

DETONABILITY OF A ROTATING DETONATION COMBUSTOR SEEDED WITH CARBON/HYDROCARBON PARTICLES AT FRINGE OPERATING CONDITIONS

by

MATTHEW HOPWOOD
B.S. University of Central Florida, 2020

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Mechanical and Aerospace Engineering
in the College of Engineering and Computer Sciences
at the University of Central Florida
Orlando, Florida

Spring Term
2023

ABSTRACT

The Rotating Detonation Combustor (RDC) has, in recent years, been a subject of great interest in the pressure-gain combustion research community. Researchers have been investigating the RDC as a potential improvement over current combustors in today's turbomachinery-based power generation systems. With the theoretical efficiency boost that detonations provide over deflagrating combustors, RDCs have the promise to be a next step in fuel/cost savings in the power generation industry. One mode of research to push an RDCs capabilities is the potential use of combustible carbon/hydrocarbon solid particles in addition to liquid or gaseous fuels. These particles are a source of high energy density and, once added, can reduce the amount of liquid/gaseous fuel needed while operating at the same fuel-to-air ratio. These organic particles are derived from grown sources making them cost-effective and sustainable, in contrast to mined or drilled fossil fuels.

Carbon black, peanut flour, and powdered sugar were seeded into a 6-inch diameter RDC operating on a gaseous hydrogen-air mixture. This was done at the leanest hydrogen-air ratio possible where the combustor, operating on just gaseous fuel, would still experience stable detonation waves. Solid fuel was then seeded in place of the gaseous fuel at varying ratios to study its effects on the ability of the combustor to continue to experience detonations. In general, while stable detonations were achieved when solid fuel began replacing the gaseous fuel, the greater the concentration of solid particles compared to gaseous fuel, the greater the likelihood of irregular detonation modes. These modes were observed using a high-speed camera: taking back-end imaging observations to measure characteristics of present detonation waves, including wave number, speed, stability, and phase angle. CTAPs were also added along the length of the outer body of the RDC to take pressure measurements during operation.

ACKNOWLEDGMENTS

Thank you to Dr. Chiping Li and the Air Force Office of Scientific Research (FA9550-16-1-0403 and FA9550-19-1-0322), as well as the Department of Energy (National Energy Technology Laboratory Award DE-FE0031545) for funding this research. Special thanks to Exolith Labs for their support in processing and characterizing the hydrocarbon particles.

Thank you to Dr. Robert Burke, William Hilal, Gerardo Rodriguez, Santiago Ruales, and the rest of the PERL Lab, as well as my advisor, Dr. Kareem Ahmed, for their support during this process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Detonation combustion is a mode of pressure gain combustion (PGC), where a constant volume combustor experiences a rise in pressure across it, theoretically leading to a combustor with greater efficiency [1]. One such example is the Rotating Detonation Combustor (RDC), which contains and directs propagating detonation waves around its annulus. These rotating detonation waves can propagate continuously in an RDC, given the proper constant introduction of fuel and oxidizer, allowing for consistent energy output.

There are many applications for such a technology, one being in the power generation sector. Recent years have seen research into RDC's as a potential upgrade on current combustors in today's turbomachinery-based power generation systems [2]. One study conducted by the Air Force Research Laboratory (AFRL) demonstrates the efficiency increase noted when integrating an RDC within a gas-turbine. It was observed that the RDC resulted in an increase in turbine factor – the ratio of energy extracted by the turbines relative to the amount of fuel energy input into the system [2]. AFRL is not alone in analyzing the potential for RDC replacements of traditional deflagrating combustors, with some studies finding up to a 22% theoretical or 7-14% experimental boost in efficiency from the constant pressure Brayton cycle describing deflagrative modes vs the constant volume Zeldovich–von Neumann–Döring (ZND) cycle describing detonating modes [3]–[6].

In addition to the power generation sector, engine and aircraft manufacturers are also pushing for yearly reductions in costs and CO_2 emissions. With a direct comparison between a traditional, constant pressure Joule or Brayton cycle and a PGC cycle, it was observed how RDCs showed greater thermal efficiency and specific fuel consumption results compared to a conventional deflagration combustor, both within turbojet engines [6]. The advantages of an RDCs operating cycle can prove useful for cost reductions and carbon emissions, and due to the fast reaction mechanisms with detonations, complex combustor geometries and turbomachinery-based compressor stages are not needed to achieve pressure gain.

To continue to push the RDC's technology readiness level (TRL) in the power generation sector, analysis of efficiency, costs, and power output should be observed from the fuel perspective. This study investigates the idea of incorporating solid carbon/hydrocarbon fuel particles into current gas turbine power generation technology, in addition to the gaseous fuel typically used today. While coal powerplants are already a common mode of power generation, they typically use steam turbine systems, where heat from a coal-fired boiler is used to generate steam, via heat exchanger, in a separate line. In contrast, this study is based on the idea of utilizing an RDC as the combustor in gas turbines systems, with solid particulate fuel is seeded in with the reactants entering the combustor, and where the energetic gaseous products are fed directly through a turbine to generate electricity.

Adding solid particles (such as carbon black) to an RDC provide theoretical benefits to a power generation system. These energy dense particles can allow detonations to occur at leaner gaseous fuel-air conditions when added as a reactant compared to purely gaseous fuel-air reactions. Due to the characteristics of carbon/hydrocarbon particles being highly accessible and cheap, increasing their ratio to more expensive gaseous fuel can provide significant cost savings over time for energy generation. A preliminary cost analysis for performing this partial substitution can be found later on in this paper.

When discussing the choice of particles to use being limited to carbon/hydrocarbon fuels, the question arises: why not investigate incorporating other common solid fuel additives like metallic fuels, such as aluminum or beryllium, which are commonly added into solid rocket fuels? The main reason is their applicability to be used in power generation systems. These systems tend to run with lean conditions (as opposed to fuel-rich), where one of the driving factors is to achieve complete combustion of the products entering the combustion chamber. Fuel-rich operating conditions can still contain large concentrations of un-combusted fuel downstream (i.e., soot) which can deposit itself on sensitive downstream electricity-generating turbines and increase maintenance costs. For a similar reason, metallic fuels are not considered in this study due to the way in which they combust: where the particles enter the combustion chamber, melt due to heating from surrounding reacting gaseous fuel, and agglomerate together while combusting in an aluminum oxidation reaction [7], [8]. These agglomerations can damage downstream turbines, and similarly increase maintenance costs. There have been some investigations to incorporate aluminum-water reactions for power generation purposes, however these focus on utilizing an aluminum-water reactor paired with a steam-hydrogen turbine, where aluminum hydroxide particles are not fed through sensitive power generating turbomachinery [9], [10].

The other consideration that needs to be made, in addition to type of particle used, is the size of the particle. Based on the ZND model and given the right conditions to sustain propagation of a detonation wave, there is some length of a detonation front that exits from the base of the combustor (where products are entering) longitudinally outward in the direction of the exhaust, before transitioning into an oblique shock. Building off of previous studies at UCF, it is theorized that when solid particulate fuel is added and combusted directly in a detonation wave's reaction zone, the heat released by this combustion adds energy to the detonation and thus causes the wave's speed to increase [11], [12]. The physics here is important to discuss, as it would make sense that larger, slower burning particles which don't completely combust in a detonation wave's reaction zone would continue burning downstream in a deflagrative manner, where it would no longer contribute energy to the detonation itself. Dunn et al. has proposed a first-order approach to understand the physics behind the burning of particles in a detonation structure based on both the d^2 liquid droplet diffusion-controlled burning methodology and the kinetically controlled burning methodology, where they found that carbon particles on the order of 100-350 nm would theoretically undergo complete combustion within the detonation structure (when utilizing the same experimental facility as this study) [12]. Further analysis on the particle sizes used in this study are done in later sections.

In addition to the first-order particle burning model suggested, Dunn et al. also provided contributions in the area of partial gaseous to solid particulate fuel replacement in an RDC, where up to a 23% increase in operability was attained by seeding carbon black into a hydrogen-air fueled rotating detonation engine [12], [13], when replacing hydrogen with carbon particle fuel. Burke et al. expanded on this idea by seeding hydrocarbon particles into an RDC to observe their effects on the detonation wave speeds based on the amount of particles added but focused on performance based on additions of hydrocarbons as an additive instead of expanding the operability regime and found that, coal and peanut flower increased detonation wave speed while corn starch and sugar decreased it [11], [14]. This investigation pulls motivations from both studies, investigating the operability limit that Dunn et al. did with carbon particles and applying it to the hydrocarbons investigated in the study done by Burke et al.

To continue, this study looks at RDC operation at the leanest conditions that still produce stable detonation waves, hereby known as fringe operating conditions. One thing to consider, however, is the stability of the detonation wave in lean conditions. Xie et al. analyzed 4 different modes of detonation wave stability from a detonating to deflagrating reaction, which was denoted as: fast deflagration, unstable detonation, quasi-stable detonation, and stable detonation [15]. This study focuses on the latter of these, running at the leanest condition that still produces stable detonations. Kindracki et al. [16] and Anand et al. [17] also observed a phenomenon known as chaotic detonations, where a detonation wave breaks up into smaller waves, collide with one another, and eventually drop to deflagrations. This can be observed and characterized as irregular pressure spikes in the combustion chamber, and can therefore aid in determining if a given reacting case is undergoing a stable detonation. Anand et al. also investigated a longitudinal pulsed detonation instability mode, but as this study's experimental setup does not have a converging nozzle downstream of the combustion chamber, and since this instability is dependent on back pressure generated usually because of nozzles at lean operating conditions, this instability mode does not need to be taken into consideration when aiming to maintain stable detonations [17].

MATERIALS AND METHODS

Experimental Setup

The University of Central Florida (UCF) currently tests numerous rotating detonation combustor configurations, of which one standard configuration, utilized in prior studies by UCF [18]–[21], will be examined in this research: the 152.4 mm (6-inch) gaseous hydrogen/air radial slot injection rotating detonation engine (RDE) developed by AFRL Wright-Patterson Air Force Base and utilized by US Department of Energy [22]. While AFRL created and refer to this design as an RDE, the design is referred to as an RDC in the context of this study, as it is used to conduct research in the context of power generation combustors. This configuration is 152.4 mm in diameter with a 7.5 mm annulus channel width for its detonability. The flow system was designed for a nominal total flow rate of 0.7 kg/s and has an injection system consisting of 80 micronozzle fuel injectors flowing axially into the annulus channel, and a 0.559 mm wide air slot flowing radially outwards from the inner body. As the air flows outwards past the gaseous hydrogen from the micronozzles, mixing occurs, and the full mixture flows downstream into the annular combustion chamber.

This RDC is initiated perpendicularly into the annulus by a Shchelkin spiral-design pre-detonator tube of stoichiometric hydrogen and oxygen gas. Capillary tube-attenuated pressure (CTAP) transducers are axially lined at positions 2.2, 3.4, 6.1, and 8.5 cm from the injector face, with a fifth CTAP positioned 90° about the annulus at the first axial position.

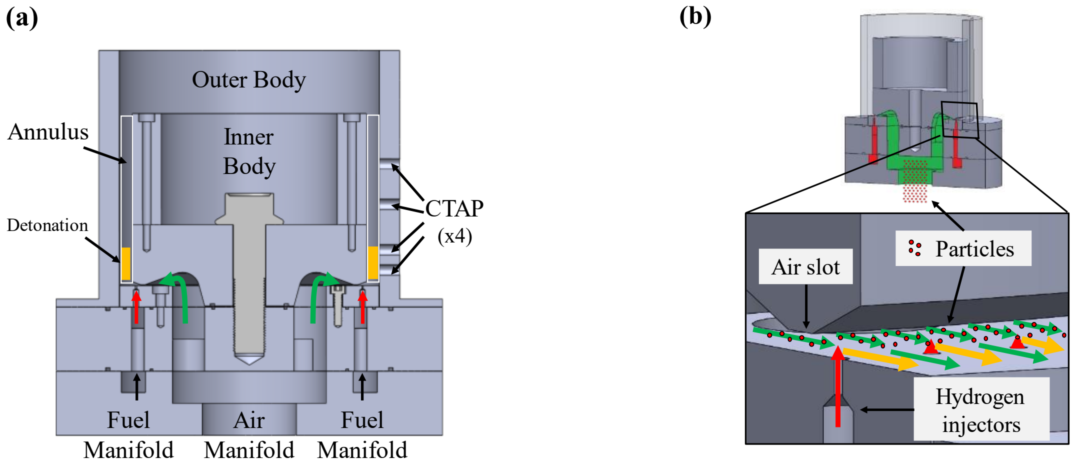

Figure 1: Cross section of the RDC, (a) showing ports and (b) showing air (green) and fuel (red) paths with particle seeding in air.

The air and fuel are supplied by a 31 MPa (4500 psi) tank farm and a 19.3 MPa (2800 psi) ultra-high purity hydrogen cylinder manifold, respectively. The air feed line is flow-metered by a 0.5 in. USA Industries restriction orifice union (ROU) with a 0.887 discharge coefficient, and the fuel feed line is flow-metered by a 0.175 in. ROU with a 0.668 discharge coefficient.

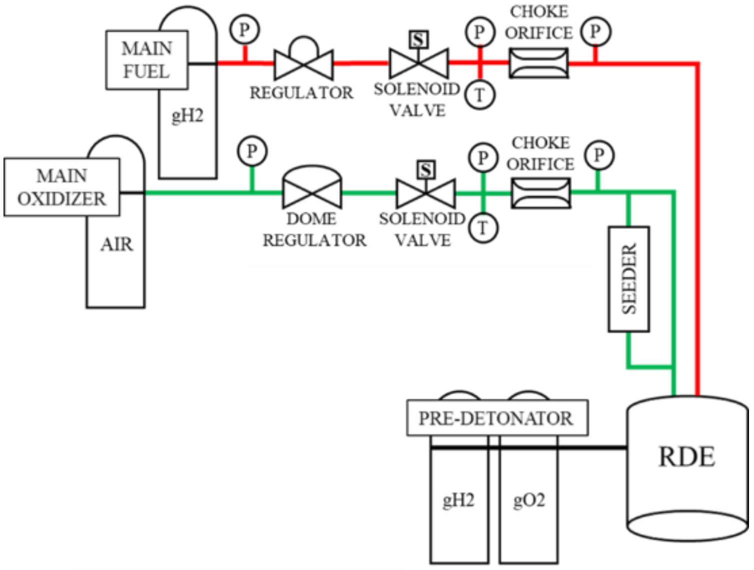

Figure 2: Piping and instrumentation diagram (PI&D) of RDE system.

A high-speed camera setup was also utilized in the experimental setup of this study, for both seeder calibration via Mie scattering as well as to observe the rotating detonation waves propagating around the annulus of the RDC via chemiluminescence imaging. A Photron SA-1 high-speed camera was used, set up to point at the annulus via mirror setup to protect the camera from the harsh reaction products exiting the RDC.

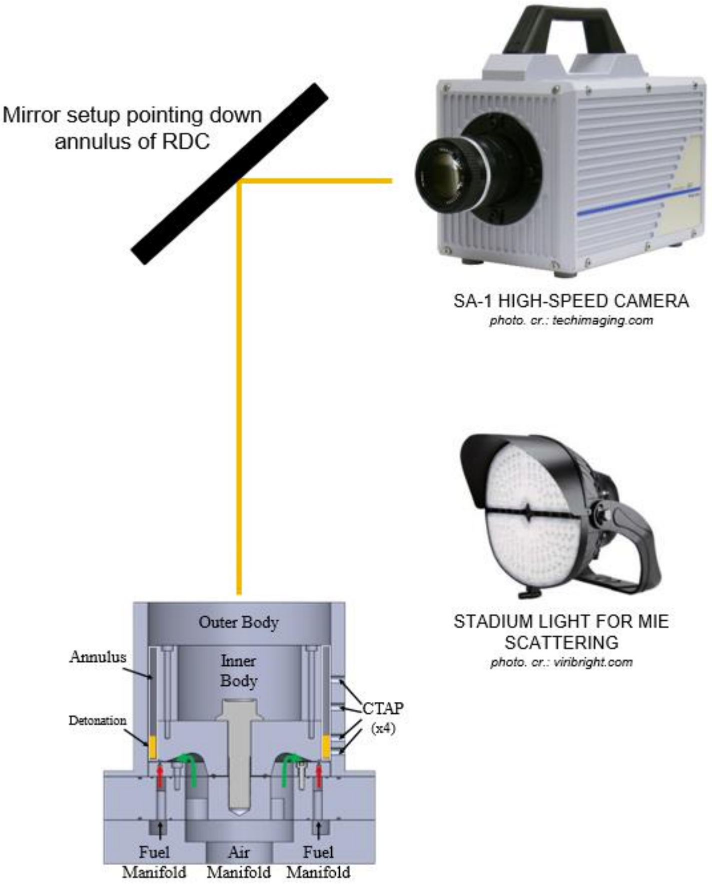

Figure 3: High-speed imaging setup

The camera was run at 67,500 frames per second (fps) for the reacting control and substantive cases and at 1,000 fps for the non-reacting, Mie scattering seeder calibration tests. A stadium light was setup under the RDE to illuminate the seeded particles during non-reacting tests to perform this Mie scattering.

Particle Tests

A solid particle seeder is placed in parallel with the air feed line. The seeder consists of a large cylindrical holding volume of diameter 7.62 cm, containing a tube fitted with an array of sonic orifice holes. Upstream air is injected into the seeder and mixes with the deposited particles as the air recirculates within. The air passing through the seeder is a regulated partial portion of the total air flow, with the rest of the air passing through a bypass line, which recombines with the seeded air downstream. This is to encourage better flow quality into the RDE manifold and RDE. A valve was place above and below the seeder to both allow for the loading of the particles before each test, and to introduce water to purge the seeder in between tests utilizing different particles.

The solid particle seeder was calibrated by exhausting particles at varying additions and determining the concentration of particles in the exhaust through Mie scattering, where the flow rate of particles was found to be directly proportional to the amount deposited into the seeder.

Figure 4: Particle seeding calibration using the Mie scattering technique.

A high-speed camera and stadium light were set up perpendicular to the combustor's exhaust to capture the particle concentration. The resulting high-resolution images were then run through a script to calculate pixel intensity with respect to time (Figure 3).

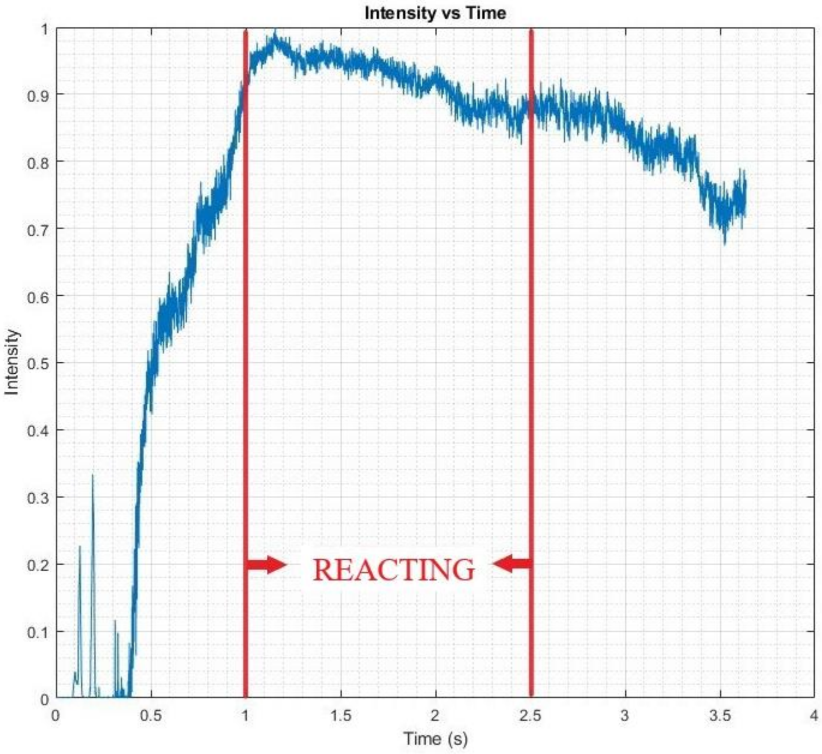

Figure 5: Solid particle concentration in flow.

The flow takes roughly 1 second to stabilize, after which the concentration in the flow does not differ more than 10% for the 1.5 seconds during a reacting test. It is important to note that while the varying concentration of particles does affect the overall fuel to air ratio in the combustor, given the decreasing nature of the trend (meaning increasingly lean operating conditions) and the scope of the study investigating detonability in lean conditions, this variation was deemed acceptable.

Three different carbon/hydrocarbon particles were used in this study: carbon black, peanut flower, and powdered sugar. Table 1 lists the particles and their properties, including density, mean diameter, molecular weight (MW), and chemical composition. Note that the particles used in the study were assumed to be 100% pure when loaded into the airline seeder for testing. Also, the particles in this study were not packed down while measuring density, which may explain any discrepancies between densities listed here versus those found in other literature.

Table 1: Physical specifications of particles.

Particle Name	Density (g/mL)	Sauter Mean Diam. (d_{32})	Mean Diameter (d_{10})	Mean Diam. Uncert. @ 95%
Carbon Black	0.304 g/mL	nanoscale	29.00 nm	± 10 nm
Peanut Flower	0.396 g/mL	60.7 µm	19.19 µm	± 60 µm
Powdered Sugar	0.401 g/mL	42.6 µm	14.96 µm	± 15 µm

The carbon black particles were sourced pre-processed, having a mean particle size of 29 nm (±10 nm at 95%). With regards to the hydrocarbons, the particles had to first be processed from their source to a desired mean particle diameter, via shaking a series of mesh screens with reducing gap sizes. The mean diameter was then verified by method of ultrasonic spectroscopy, performed by Exolith Labs. The mean diameter and uncertainty at 95% of particles measured are listed in Table 1, along with their average calculated density. The desired size of the particles was determined to be the smallest diameter achievable by Exolith to try and reach the roughly 350 nm limit for complete combustion in the detonation wave's reaction zone as proposed by Dunn et. al., however the lab was only able to sift and characterize particles down to the microscale in which the hydrocarbons were acquired [12]. After the processing, a phase Doppler interferometer was used on the hydrocarbons to estimate their Sauter mean diameter, or d_{32}.

The Sauter mean diameter was characterized for the particles as the value itself plays an important role in understanding how particles will burn when introduced into a combusting flow. The metric is found via a sum of the ratios of a particle's cube of its volume mean diameter to the square of its surface mean diameter, and is used to generalize a particle or droplet as having the same volume/surface area ratio as the entire batch used. This is important for this study, as the single averaged d_{32} value summarizes the fuel/oxidizer interface and thus simplifies the analysis done on the combusting particles by enabling a general conclusion to be made on wave speed in the results/discussion section.

Table 2 lists the chemical information of each of the fuels used in this study, including their chemical formula and respective molecular weights for reference, as well as the heat of combustion.

Table 2: Chemical specifications of the fuels.

FUELS	Chemical Formula	Heat of Combustion (Δh_c)		C mol. weight %	H mol. weight %	O mol. weight %
Hydrogen	H_2	286 kJ/mol	141.8 kJ/g	0%	100%	0%
Peanut Flower	$C_{57}H_{104}O_6$	35099.6 kJ/mol	39.6 kJ/g	77%	12%	11%
Carbon Black	C	393.5 kJ/mol	32.8 kJ/g	100%	0%	0%
Powdered Sugar	$C_{12}H_{22}O_{11}$	5643.4 kJ/mol	16.5 kJ/g	42%	7%	51%

Test Campaign

In this research, a few parameters were varied and defined: (1) the local fuel-air equivalence ratio, which consists of the ratio between the hydrogen fuel and the air oxidizer, based on the stoichiometric fuel-air ratio of gaseous hydrogen and air, (2) the global fuel-air equivalence ratio, which consists of the ratio between the both the hydrogen fuel and solid particle fuel with the air oxidizer, based on the stoichiometric fuel-air ratio of the combined hydrogen and solid particle fuel with the air, and (3) the mass percentage of the amount of solid particulate fuel to hydrogen fuel. Altogether, these parameters can be used to determine how solid particle addition can enhance the detonability and operation of the RDC at the edges of its performance regime. The goal of the study is to find the specific range in hydrogen-air fuel-air equivalence ratio at total flow rate into the RDC such that the RDC operates with some stable detonation wave mode. Then, by replacing some amount of the gaseous hydrogen with solid particles to a flow condition that is already on the fringe, or edge, of the hydrogen's detonability regime, stable RDC operation can be extended past the solely hydrogen and air lean barrier. With the parameters defined previously, the amount of solid particles and how it affects the global chemistry of the reactants can be characterized to determine the mechanism to extend RDC operation with the addition of the solid fuel particles.

The RDC was further characterized by the detonation waves inside of the annulus, which are analyzed through back-end imaging. This diagnostic consists of a high-speed camera imaging the detonation annulus through the exhaust, recording the broadband chemiluminescence of the combustion. Using a back-end image processing method based on work by Bennewitz *et al*., the number of detonation waves, their propagation frequency, and their propagation speed can be determined throughout the reacting portion of a test [23]. The discussion of how stable detonation modes were determined will be discussed in the next section.

RESULTS AND DISCUSSION

The testing began with solely hydrogen-air tests, without particles added via the seeder. The control group tests were conducted starting with a fuel-air equivalence ratio of 1 and walked down until the combustor no longer had stable detonation waves, measured with the high-speed camera (Figure 4). The lowest equivalence ratio where two stable detonation waves were observed in the combustor was found to be at 0.55. Compared to previous studies done at the University of Central Florida utilizing this specific RDC design, this value initially seems low, as the detonability limit found earlier ranged from 0.8 down to only 0.65, instead of the 0.55 found here [11], [13]. However, it has been found that a higher mass flow of reactants enables stable detonation waves to propagate at a leaner equivalence ratio [14], [24], [25]. With this baseline set, the particle addition tests began.

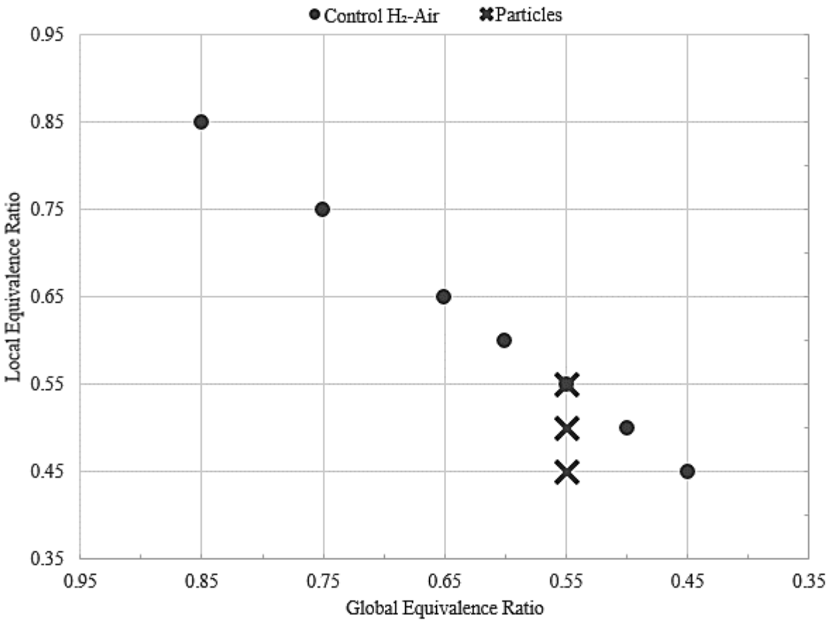

Figure 6: Local vs global equivalence ratio test campaign

The tests with the particles used a constant global equivalence ratio equal to that which was found during the baseline found in the control hydrogen tests: 0.55. The local (hydrogen-air) ratio was then lowered below this threshold to 0.45 via 0.05 increments (Figure 4), and solid fuel particles were added to keep the global ratio constant at the 0.55. It was observed that the RDC maintained two stable detonation waves while operating with particles down to the 0.45 local ratio, (that is, a lower local H_2-Air ratio than able to be stably sustained without particles) before the waves fell into unstable modes when the condition was pushed leaner.

Figure 7: Back-end imaging of H_2-Air detonating case (left), H_2+Carbon Black-Air detonating case (mid), and H_2+Peanut Flour-Air deflagrating case (right).

Table 3 tabulates the mass ratio of solid particles to gaseous hydrogen fuel out the total mass of fuel reactants, showing the amount of hydrogen that can be substituted with the solid fuel at a global and local fuel equivalence ratio of 0.55 and 0.45, respectively. The molecules' weight percentage broken up by chemical composition is included as well.

The powdered sugar can greatly replace the amount of gaseous hydrogen used in the combustor, up to 85% by weight. This continues with peanut flower and the carbon black particles at 70% and 65% respectively. The weight percentage trend over the three particles shown in Table 3 make sense, as the particles with more combustible material in their molecule (C & H in this case) do not need to be as densely seeded into the flow to maintain the same fuel-to-oxidizer conditions in the combustor.

Table 3: Particle weight percentage of total fuel reactants at a global, local phi of 0.55, 0.45

Particle	Particle Weight %	C weight %	H weight %	O weight %
Carbon Black	65%	100%	0%	0%
Peanut Flower	70%	77%	12%	11%
Powdered Sugar	85%	42%	7%	51%

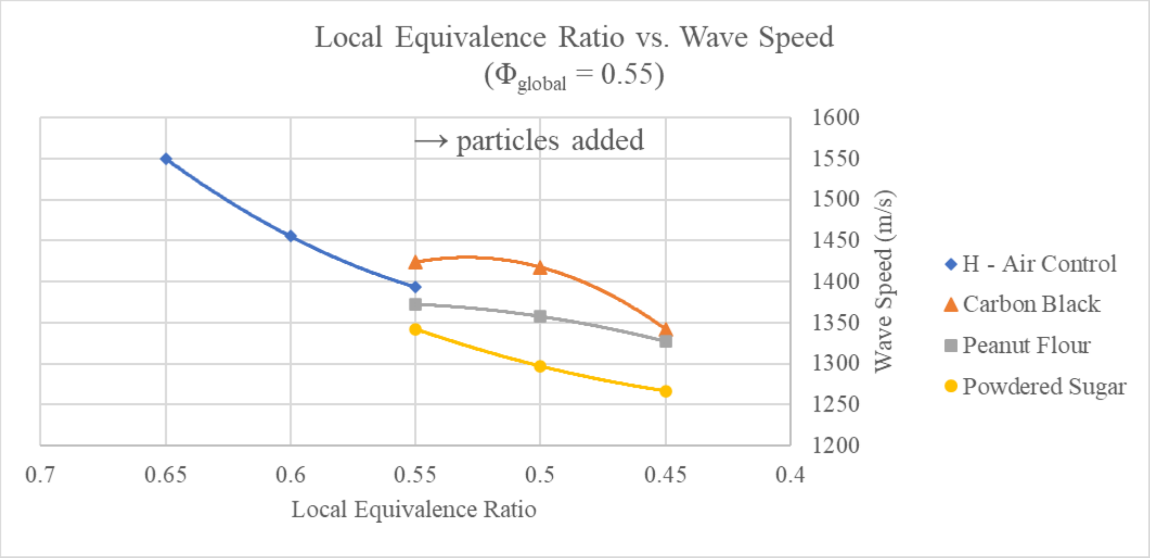

Figure 8: Local Equivalence Ratio vs Wave Speed

Recalling the order of the particles' heat of combustion from most to least, as listed in Table 2, as well as the particles' Sauter mean diameters as listed in Table 1, a pattern begins to emerge. Carbon, with a d_{32} on the nanoscale, is able to release its Δh_c much faster than the microscale hydrocarbons. Similarly, peanut flour, with a higher Δh_c than powdered sugar, is able to supply greater energy to the detonation wave during its burn time in the reaction zone than the latter.

A critical point to make, however, is that both of the hydrocarbons are three orders of magnitude larger than the carbon black particles, and well outside the theoretical 350 nm max particle diameter for complete combustion within the reaction zone of the passing detonation wave. In other words, there is still potential energy able to be supplied to increase wave speed that is otherwise being released during deflagrative combustion. An interesting correlation arises along this line, where even though peanut flour has a similar, yet higher, Δh_c than that of carbon black, the complete combustion of the carbon is a more prominent factor, as seen with carbon's higher observed wave speed. What can be concluded for certain, however, is the fact that regardless of complete combustion behind a detonation, all particulate fuels were able to provide sufficient energy to the detonation wave to supplement hydrogen as fuel and decrease the overall H_2-air fuel to air operating limit from 0.55 to 0.45.

Detonation Wave Stability Analysis

The back-end imaging data was used to not only determine the effects that increasing the solid to gaseous fuel ratio had on the speed of the detonation waves, but also as a metric to ensure that the detonation waves themselves were propagating stably. When analyzing the speed of the waves, 10 samples of 2,000 frames were taken at different times out of the total run, and after the waves initially stabilized post unstable start-up condition, there was less than 2% variation in wave speed over the duration of any given test. This, combined with visual inspection of clear propagating wave, and finally the analysis of CTAP pressure data discussed in the following section, allowed for the cases to be deemed undergoing stable detonations.

In terms of the CTAP pressure data collected, visual inspection of the plots allows for stability determinations to be made.

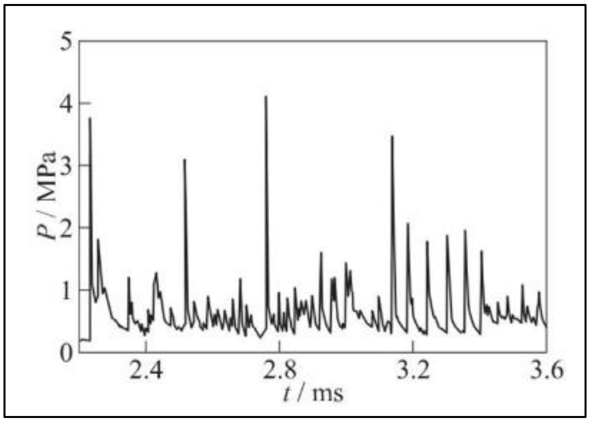

Figure 9: Pressure vs time of Chaotic detonation modes as observed by Kindracki et al. [16]

The CTAP data collected on this investigation's setup in Figure 10 shows stable, regular oscillations in pressure data collected, signifying stable detonation wave propagation [4], [16]. It is important to comment, however, on the differing time scales between the two figures, as the time axis used in Figure 9 is on the scale of milliseconds while Figure 10 is on the scale an order of magnitude higher.

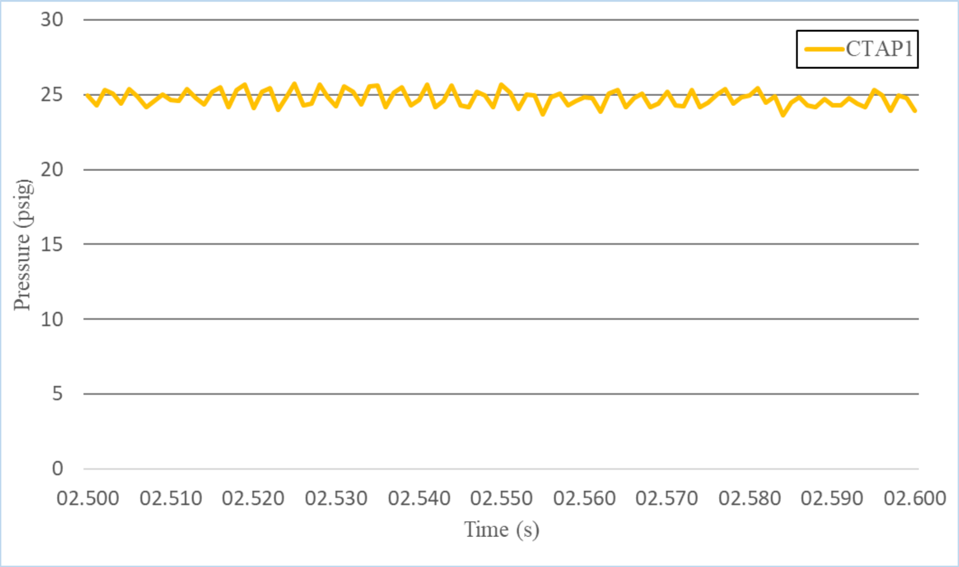

Figure 10: CTAP data collected of a stable detonation case, at CTAP location 1

This is due to the resolution of the CTAP data collected, as the sampling rate of the transducers was not high enough for accurate readings on the order of a tenth of a millisecond. That being said, chaotic instabilities by nature happen irregularly, so due to the significant lack of any instabilities in Figure 10, the data is deemed to have high enough resolution for the means of ruling out chaotic detonation modes. This, in addition to the stability analysis techniques previously mentioned, allowed wave stability conclusions to be drawn.

Preliminary Cost Analysis

A preliminary cost analysis was also performed to continue to analyze the idea of applying this knowledge to potential power generation applications. Taking the average costs per kilogram of the four fuels that were considered in this study, the most cost-effective method would be to replace 65% of the hydrogen with carbon black particles, as this solid fuel has the highest heat of combustion per dollar spent on fuel. Note that these calculations are solely to introduce the idea of beginning to analyze the viability of fuel particulate replacement of gaseous fuels, and thus ideally assumes 100% efficiency of heat generated to power out and takes averages of fuel prices.

Table 4: Average heat of combustion per dollar spent on fuel.

Fuel	Cost per kg	Δh_c	ΔH_c per \$
Hydrogen Gas	\$13 per kg	141.6 MJ/kg	10.9 MJ/\$
Carbon Black	\$0.14 per kg	32.8 MJ/kg	228.6 MJ/\$
Peanut Flower	\$12 per kg	39.6 MJ/kg	3.3 MJ/\$
Powdered Sugar	\$3 per kg	16.5 MJ/kg	5.5 MJ/\$

Future Potential Research

The scope of this study could be expanded upon by sourcing the hydrocarbon particles used in this study with diameters on the nanoscale and ensure complete combustion within the reaction zone of the detonation wave, allowing a more direct comparison when analyzing the wave speeds (and subsequent performance) of all of the particulate fuels used. Also, continuing to vary the local equivalence ratio and particle weight percentages while testing over a spread of global equivalence ratios, instead of the minimum detonatable ratio found when running solely hydrogen and air can also be investigated, to increase the spread of data to draw correlations from.

The humidity level of the air introduced into the seeder and engine is also a metric that can be studied, as high levels of humidity may cause the particles to agglomerate, slowing down the process of combusting the particles which may affect the detonation wave characteristics. In addition to carrying the humidity levels, potential "wet" particle seeding methods (i.e. suspending particles in some form of suspending solvent for atomization) could be attempted to study their effects on the detonation wave characteristics and stability, as discussed in [26].

Also, if operating on the lean fringe of detonations become an attractive option for power generation systems, highly fidelity particle seeders will need to be characterized. Approaching this condition will require more accurate knowledge of particle mass flow values instead of averages obtained from concentration duration and Mie scattering, as was done in this study. Some work in this has already been done by Howison et al., however the application was focused on seeding particles into supersonic flows for use in a scramjet combustor instead of a focus on the power generation sector [27].

CONCLUSION

Carbon and hydrocarbon particles were seeded into the flow of a hydrogen-air operating rotating detonation combustor, as a supplementary fuel to extend the stable detonation regime into leaner hydrogen-air equivalence ratios. It was found that, when operating with just hydrogen and air at 0.7 kg/s, the RDC could sustain detonations at an equivalence ratio of 0.55. When supplementing up to 65%, 70%, and 85% (by mass) of the hydrogen fuel with carbon black, peanut flour, and powdered sugar solid fuel particles respectively, the hydrogen-air equivalence ratio was able to be decreased to 0.45 while still maintaining stable detonation waves.

REFERENCES

[1] K. Kailasanath, “Review of Propulsion Applications of Detonation Waves,” *AIAA Journal*, vol. 38, no. 9, pp. 1698–1708, Sep. 2000, doi: 10.2514/2.1156.

[2] A. Naples, J. Hoke, R. T. Battelle, M. Wagner, and F. R. Schauer, “RDE Implementation into an Open-Loop T63 Gas Turbine Engine,” in *55th AIAA Aerospace Sciences Meeting*, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jan. 2017. doi: 10.2514/6.2017-1747.

[3] S. M. Frolov, V. S. Aksenov, and V. S. Ivanov, “Experimental proof of Zel’dovich cycle efficiency gain over cycle with constant pressure combustion for hydrogen–oxygen fuel mixture,” *Int J Hydrogen Energy*, vol. 40, no. 21, pp. 6970–6975, Jun. 2015, doi: 10.1016/J.IJHYDENE.2015.03.128.

[4] V. Anand, A. St. George, R. Driscoll, and E. Gutmark, “Characterization of instabilities in a Rotating Detonation Combustor,” *Int J Hydrogen Energy*, vol. 40, no. 46, pp. 16649–16659, Dec. 2015, doi: 10.1016/j.ijhydene.2015.09.046.

[5] M. Zhao, L. Zhang, W. Huo, H. Yang, and Y. Yuan, “Performance analysis of a rotating detonation model for future thermal power system using hydrogen as fuel,” *Energy Reports*, vol. 8, pp. 66–74, May 2022, doi: 10.1016/J.EGYR.2021.11.036.

[6] J. Sousa, G. Paniagua, and E. Collado Morata, “Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor,” *Appl Energy*, vol. 195, pp. 247–256, Jun. 2017, doi: 10.1016/J.APENERGY.2017.03.045.

[7] Y. Chen *et al.*, “Study of aluminum particle combustion in solid propellant plumes using digital in-line holography and imaging pyrometry,” *Combust Flame*, vol. 182, pp. 225–237, Aug. 2017, doi: 10.1016/J.COMBUSTFLAME.2017.04.016.

[8] J. C. Melcher, H. Krier, and R. L. Burton, “Burning Aluminum Particles Inside a Laboratory-Scale Solid Rocket Motor,” *J Propuls Power*, vol. 18, no. 3, pp. 631–640, May 2002, doi: 10.2514/2.5977.

[9] M. S. Vlaskin, M. V Gaykovich, and A. O. Dudoladov, “Modelling of Aluminium-fuelled Power Plant with Gas Turbine,” *IOP Conf Ser Earth Environ Sci*, vol. 159, p. 012039, Jun. 2018, doi: 10.1088/1755-1315/159/1/012039.

[10] M. S. Vlaskin *et al.*, “An experimental aluminum-fueled power plant,” *J Power Sources*, vol. 196, no. 20, pp. 8828–8835, Oct. 2011, doi: 10.1016/J.JPOWSOUR.2011.06.013.

[11] R. F. Burke, T. Rezzag, and K. Ahmed, “Carbon and Hydrocarbon Particle Seeding in Air-Breathing Rotating Detonation Engine,” *J Eng Gas Turbine Power*, vol. 144, no. 1, Jan. 2022, doi: 10.1115/1.4051987.

[12] I. B. Dunn, V. Malik, W. Flores, A. Morales, and K. A. Ahmed, “Experimental and theoretical analysis of carbon driven detonation waves in a heterogeneously premixed Rotating Detonation Engine,” *Fuel*, vol. 302, p. 121128, Oct. 2021, doi: 10.1016/j.fuel.2021.121128.

[13] I. Dunn, W. Flores, A. Morales, V. Malik, and K. Ahmed, “Carbon-based multi-phase rotating detonation engine,” *Journal of Energy Resources Technology, Transactions of the ASME*, vol. 144, no. 4, Apr. 2022, doi: 10.1115/1.4051540/1111556.

[14] R. F. Burke, T. Rezzag, and K. A. Ahmed, “Sustainable Particles Seeding in Air-Breathing Rotating Detonation Engine,” in *AIAA Scitech 2021 Forum*, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jan. 2021. doi: 10.2514/6.2021-0556.

[15] Q. Xie, H. Wen, W. Li, Z. Ji, B. Wang, and P. Wolanski, “Analysis of operating diagram for H2/Air rotating detonation combustors under lean fuel condition,” *Energy*, vol. 151, pp. 408–419, May 2018, doi: 10.1016/j.energy.2018.03.062.

[16] J. Kindracki, A. Kobiera, P. Wolański, Z. Gut, M. Folusiak, and K. Swiderski, “Experimental and numerical study of the rotating detonation engine in hydrogen-air mixtures,” vol. 2, pp. 555–582, 2011, doi: 10.1051/EUCASS/201102555.

[17] V. Anand, A. St. George, R. Driscoll, and E. Gutmark, “Longitudinal pulsed detonation instability in a rotating detonation combustor,” *Exp Therm Fluid Sci*, vol. 77, pp. 212–225, Oct. 2016, doi: 10.1016/J.EXPTHERMFLUSCI.2016.04.025.

[18] R. F. Burke, T. Rezzag, and K. Ahmed, “Carbon and Hydrocarbon Particle Seeding in Air-Breathing Rotating Detonation Engine,” *J Eng Gas Turbine Power*, vol. 144, no. 1, Jan. 2022, doi: 10.1115/1.4051987.

[19] R. Burke, T. Rezzag, I. Dunn, W. Flores, and K. Ahmed, “The effect of premixed stratification on the wave dynamics of a rotating detonation combustor,” *Int J Hydrogen Energy*, Jun. 2021, doi: 10.1016/j.ijhydene.2021.06.003.

[20] I. B. Dunn, J. Sosa, M. Salvadori, K. A. Ahmed, and S. Menon, “Flowfield Velocity Measurements of a Rotating Detonation Engine,” in *AIAA Scitech 2020 Forum*, 2020, p. 1176.

[21] I. B. Dunn, K. Thurmond, K. A. Ahmed, and S. Vasu, “Exploration of Measuring Pressure Gain Combustion within a Rotating Detonation Engine,” in *2018 Joint Propulsion Conference*, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jul. 2018, p. 4566. doi: 10.2514/6.2018-4566.

[22] W. A. Hargus, S. A. Schumaker, and E. J. Paulson, “Air Force Research Laboratory Rotating Detonation Rocket Engine Development,” in *2018 Joint Propulsion Conference*, 2018, p. 4876.

[23] J. W. Bennewitz, B. R. Bigler, S. A. Schumaker, and W. A. Hargus, “Automated image processing method to quantify rotating detonation wave behavior,” *Review of Scientific Instruments*, vol. 90, no. 6, p. 065106, Jun. 2019, doi: 10.1063/1.5067256.

[24] Y. Zhong, Y. Wu, D. Jin, X. Chen, X. Yang, and S. Wang, “Investigation of rotating detonation fueled by the pre-combustion cracked kerosene,” *Aerosp Sci Technol*, vol. 95, p. 105480, Dec. 2019, doi: 10.1016/j.ast.2019.105480.

[25] F. Song, Y. Wu, S. Xu, D. Jin, and X. Chen, “Pre-combustion cracking characteristics of kerosene,” *Chem Phys Lett*, vol. 737, p. 136812, Dec. 2019, doi: 10.1016/j.cplett.2019.136812.

[26] A. Melling, “Tracer particles and seeding for particle image velocimetry,” *Meas Sci Technol*, vol. 8, no. 12, pp. 1406–1416, Dec. 1997, doi: 10.1088/0957-0233/8/12/005.

[27] J. C. Howison and C. P. Goyne, “Assessment of Seeder Performance for Particle Velocimetry in a Scramjet Combustor,” *J Propuls Power*, vol. 26, no. 3, pp. 514–523, May 2010, doi: 10.2514/1.44469.