PERFORMANCE, APPLICATION, AND ANALYSIS OF ROTATING DETONATION ENGINE TECHNOLOGIES (PREPRINT)

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Innovative Scientific Solutions, Inc.

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14. ABSTRACT
Pressure gain combustion (PGC) technologies such as pulsed detonation engines (PDEs) and rotating detonation engines (RDEs) have received significant attention over the past fifteen years. The PGC research is motivated partially by the potential for achieving high thermodynamic efficiencies and compact engine designs for a broad range of power and propulsion applications. Recent accomplishments related to the performance, application, and analysis of RDE technologies are reviewed. Analytical thermodynamic models are shown to capture the principle features of RDEs, to be in good agreement with the results from both high-fidelity simulations and experiments, and to be useful for guiding the design of RDEs with reasonable accuracy. The pioneering development of optically accessible RDEs coupled with the application of established diagnostic techniques is defining a new research direction. In particular, the first OH* chemiluminescence images of detonations propagating through the annular channel of a RDE are reported and appear remarkably similar to computational fluid dynamic results of RDEs published in the literature. Specific impulse measurements of RDEs and PDEs are shown to be quantitatively similar for engines operating on hydrogen/air and ethylene/air mixtures. The encouraging results indicate that RDEs are capable of producing thrust with fuel efficiencies that are similar to those associated with PDEs while operating on gaseous hydrocarbon fuels. An RDE is coupled with a turboshaft engine for the first time. The performance of the RDE gas turbine engine is similar to or better than that of the conventional gas turbine engine across a broad range of operating conditions. Realizing the advantages of pressure gain combustion in rotating detonation engines is enabling new combustion system design opportunities and supporting the development of efficient and sustainable power and propulsion technologies.

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Performance, Application, and Analysis of Rotating Detonation Engine Technologies

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Abstract

Pressure gain combustion (PGC) technologies such as pulsed detonation engines (PDEs) and rotating detonation engines (RDEs) have received significant attention over the past fifteen years. The PGC research is motivated partially by the potential for achieving high thermodynamic efficiencies and compact engine designs for a broad range of power and propulsion applications. Recent accomplishments related to the performance, application, and analysis of RDE technologies are reviewed. Analytical thermodynamic models are shown to capture the principle features of RDEs, to be in good agreement with the results from both high-fidelity simulations and experiments, and to be useful for guiding the design of RDEs with reasonable accuracy. The pioneering development of optically accessible RDEs coupled with the application of established diagnostic techniques is defining a new research direction. In particular, the first OH* chemiluminescence images of detonations propagating through the annular channel of a RDE are reported and appear remarkably similar to computational fluid dynamic results of RDEs published in the literature. Specific impulse measurements of RDEs and PDEs are shown to be quantitatively similar for engines operating on hydrogen/air and ethylene/air mixtures. The encouraging results indicate that RDEs are capable of producing thrust with fuel efficiencies that are similar to those associated with PDEs while operating on gaseous hydrocarbon fuels. An RDE is coupled with a turboshaft engine for the first time. The performance of the RDE gas turbine engine is similar to or better than that of the conventional gas turbine engine across a broad range of operating conditions. Realizing the advantages of pressure gain combustion in rotating detonation engines is enabling new combustion system design opportunities and supporting the development of efficient and sustainable power and propulsion technologies.

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I. Introduction

Power and propulsion systems historically have used the deflagration mode of combustion for the heat addition process. Optimization of the heat addition process can lead to significant thermodynamic advantages because combustion is typically the largest contributor to entropy generation in practical power and propulsion cycles. The combustor results in a net stagnation pressure loss and a corresponding decrease in the available energy (i.e., exergy). Consequently, less energy is available for producing power and thrust in air-breathing propulsion systems such as turbines, ramjets, and scramjets. The detonation mode of combustion results in a net stagnation pressure gain and can be used to minimize entropy generation and maximize exergy.

Pressure gain combustion systems provide novel technologies for satisfying the increasing demand for efficient, clean, and sustainable energy production processes. Increasing efficiencies and reducing exhaust emissions are motivated partially by concerns regarding the availability and sustainability of energy sources and the effects of emissions on the global environment. The topics of energy and global climate trends have been subjects of intense public debate and present global technology, education, and policy challenges. In that sense, pressure gain combustion is a frontier topic of national and global significance that spans broad scientific and engineering interests. Realizing the advantages of pressure gain combustion are enabling new combustion system design opportunities for a broad range of power and propulsion applications.

The objective of this work is to discuss recent progress and accomplishments related to pressure gain combustion technologies with particular emphasis on pulsed detonation engine (PDE) and rotating detonation engine (RDE) research performed at the Air Force Research Laboratory (AFRL). The paper is organized in seven sections starting with a brief review of prior RDE research. Second, analytical thermodynamic modeling of RDEs is discussed. Third, images of detonations propagating through the annular channel of the RDE are presented and analyzed. Detonation cell size measurements at elevated pressures relevant to conditions observed in PDEs and RDEs are presented. Fourth, the performance of RDEs operating on hydrogen/air and ethylene/air mixtures is quantified for a broad range of conditions using a combination of static pressure and thrust measurements. The effects of back pressure, nozzles, and heat transfer on RDE operation and performance are presented. Fifth, experimental results demonstrating the coupling of a RDE with a gas turbine are discussed. The paper concludes with a summary of accomplishments and suggestions for future research directions related to pressure gain combustion technologies.
II. Background

Significant progress has been made in the research and development of RDEs over the past few years [1-3]. Experimental and computational studies have evaluated the effects of fuel and oxidizer compositions [4-6], stagnation and back pressures [7-10], injection geometries [11-13], detonation channel geometries [14-17], curvature [18-20], and exhaust nozzles [21-23] on the flowfield, operation, and performance of RDEs. The experimental studies have focused on acquiring time-dependent and time-averaged static pressures [5, 24], thrust [24], and broadband images [4, 25]. Temperature and water vapor mole fraction measurements recently have been acquired in a converging-diverging nozzle positioned downstream of an RDE using tunable diode laser absorption spectroscopy [23]. The computational studies typically have solved the Euler equations in two- or three-dimensions with reactions modeled using detailed chemistry [26, 27], an induction parameter [7, 28], a single-step reaction [29], or a simple finite rate constant [9, 22, 24]. Thermodynamic models based on Zeldovich von Neumann Döring detonation theory have been used to analyze the flowfield and corresponding performance of RDEs [30-34].

Rotating detonation engines operating on hydrogen/air [24, 25, 35] or oxygen [14, 15] with a range of fuels have received the most attention. Modeling and simulation efforts have shown that RDEs operating on hydrocarbons are feasible and that the flowfield is similar to the one observed for RDEs operating on hydrogen [6]. Two-dimensional simulations have been used to show that the detonation wave height is determined primarily by the stagnation pressure while overall performance is affected predominantly by the pressure ratio [8]. For high pressure ratios, the flow expands to supersonic conditions behind the detonation, isolates the detonation channel, and limits the effect of back pressure on the flowfield [8]. For low pressure ratios, the flow is influenced by a series of secondary shock waves that slow it down and produce significant losses [8]. The flowfield characteristics have been shown to scale with diameter creating minimal effects on performance [16].

The effects of curvature on detonations propagating through channels have been considered in several studies. Three-dimensional simulations have shown that the size of the cellular pattern along the concave wall is smaller than along the convex wall due to curvature [19]. This indicates that the detonation wave near the concave wall (convergent) is stronger than near the convex wall (divergent) [19]. Detonations propagating through curved channels with rectangular cross-sections and varying radii of curvatures have been visualized using high-speed shadowgraphs [18]. The critical condition for detonations to propagate through the rectangular cross-section channel occurred when the radius of curvature of the inside wall was approximately 14 - 40 times the cell width [18].

III. Thermodynamic Modeling of Rotating Detonation Engines

The vast majority of current pressure gain combustion (PGC) devices can be characterized as following the unsteady Atkinson or Humphrey thermodynamic cycle. The Atkinson/Humphrey cycle differs from the conventional Brayton cycle used in most air breathing propulsion devices in the combustion phase of the cycle. The ideal Brayton cycle is characterized by constant pressure, or isobaric, combustion. In contrast, the ideal Atkinson/Humphrey cycle is characterized by constant volume, or isochoric, combustion. The resulting difference in post-combustion thermodynamic properties is significant as shown in Figure 1. The Atkinson/Humphrey cycle exhibits a significantly higher post-combustion temperature and significantly lower post-combustion entropy due to the constant volume combustion process.
A thermodynamic comparison of the Atkinson/Humphrey cycle and the Brayton cycle, assuming air standard cycles [36], is provided in Figure 2. The ideal Atkinson/Humphrey cycle offers significant efficiency benefits as a result of reduced combustion entropy generation. It is this advantage that modern PGC propulsion devices seek to exploit.

Figure 2: Air standard thermodynamic cycle efficiency for a Brayton cycle and two Atkinson/Humphrey cycles
Recent implementations of PGC for propulsion devices typically incorporate unsteady combustion. Therefore, proper thermodynamic analysis of these devices must consider the unsteady nature of the combustion along with its associated non-uniform exhaust flow. The unsteadiness results in some loss in cycle performance [37]. However, even with proper accounting of unsteady effects the Atkinson/Humphrey cycle maintains a thermodynamic advantage over the Brayton cycle as illustrated in Figure 3.

![Figure 3: Ideal specific impulse for a Brayton cycle and steady and unsteady Atkinson/Humphrey cycles](image)

Over the past decade many numerical codes have been created or modified to analyze the thermodynamic performance of the unsteady Atkinson/Humphrey cycle as implemented in PDEs [38]. Many of these codes have been compared successfully with available PDE performance data. The RDE presents the technical community with unique analytical modeling challenges. Many experimental [4, 25, 35] and computational [6-10, 22, 28] studies have illustrated the complex nature of the detailed flowfield of RDEs [7]. Based on these results, the main features of RDE combustion can be denoted as shown in Figure 4. The fuel and air are injected near the bottom of an annular channel, and the detonation propagates in the azimuthal direction near the inlet. The products expand in the azimuthal direction behind the detonation and in the axial direction towards the channel exit. An oblique shock is established near the downstream region of the detonation. A slip line occurs between the products detonated during the current and previous cycle. The high pressure region immediately behind the detonation prevents inflow of the reactants and can lead to back flow into the fuel and air plenums depending upon the operating conditions. Fresh reactants flow into the bottom of the annular channel further behind the detonation front. Deflagration resulting in decreased performance occurs between the fresh reactants and the products detonated during the previous cycle.
The major processes which affect the flow are the (1) detonation combustion, (2) deflagration combustion, (3) secondary shock, and (4) mixing. To capture these processes, the RDE flow is divided into four discrete elements for thermodynamic analysis: (a) detonation only, (b) detonation plus secondary shock, (c) deflagration, and (d) mixing. This analytical approach is similar to that proposed by Nordeen [39]. A typical T-s diagram with the selected RDE process elements is provided in Figure 5. The fourth element, mixing, occurs somewhere between the detonated and deflagrated flows, depending on the flowfield dynamics. Typically, the amount of flow deflagrated is between 5% and 15% of the total flow.
A thermodynamic analysis routine has been developed and implemented to guide the design of RDEs. The routine performs the thermodynamic analysis of the combustion process and models the air and fuel inlets and nozzle exit. The results from this routine have been compared with high-fidelity CFD simulations and experimental results as shown in Figure 6 and Figure 7, respectively. The thermodynamic analysis routine captures the principle features of the RDE based upon its favorable comparison with the high-fidelity CFD simulations and experimental results. The RDE thermodynamic analysis routine is immature relative to conventional gas turbine engine performance codes. However, the thermodynamic analysis routine is mature enough to be used to guide the design of RDEs with reasonable accuracy.
IV. Detonation Structures

IV.A. Chemiluminescence Images of Optically Accessible Rotating Detonation Engines

The capability to observe the detonation in the RDE channel is critical for improving fundamental understanding and optimizing the operation and performance of RDEs. In particular, the research and development of RDEs can be advanced by the application of well-established diagnostics techniques such as OH* chemiluminescence imaging [35]. This
capability is utilized to acquire instantaneous images of OH* chemiluminescence emitted from detonations propagating through the annular channel of an optically accessible RDE. The OH* chemiluminescence images allow for observation of the size and shape of the detonation structure, trailing edge oblique shock wave, and possible presence of deflagration between the fuel fill region and expansion region containing detonated products. The OH* chemiluminescence images are useful for evaluating the effects of the air mass flow rate, equivalence ratio, air injection area, and fuel injection scheme on the detonation structure and its corresponding impact on RDE operation and performance. The OH* chemiluminescence images are useful for evaluating RDE models and simulations, improving fundamental understanding of the detonation structure in RDEs, and identifying critical design parameters that influence RDE operation and performance.

A schematic and photograph of a representative optically accessible RDE is shown in Figure 8. Air is injected from a plenum through a circumferential slot (123 mm diameter) into an annular detonation channel. The height of the air slot (0.89 – 3.56 mm) is varied to change the air injection area (3.46 – 13.83 cm²). Fuel is injected from a separate plenum through holes evenly spaced on a circle with a circumference (134 mm) located near the inner edge of the annular detonation channel. The diameter (0.71 – 0.89 mm) and number (80 – 120) of the fuel injection holes is varied to change the fuel injection area (0.48 – 0.75 cm²). The inner and outer diameters of the annular detonation channel are 138.7 mm and 153.9 mm, respectively, resulting in a channel width of 7.6 mm. The height of the annular detonation channel is 101.6 mm. Typically, a steel outer-body is used. A quartz tube (2.54 cm thick) is used for some experiments to provide optical access of the annular detonation channel.

The fuel and air mass flow rates are metered upstream of the respective plenums using sonic nozzles. The RDE operation sequence involves establishing the air and fuel flow followed by initiating the detonation. The detonation in the annular channel is initiated using a small tube. Hydrogen and oxygen flow into the small tube (6.35 mm diameter, 63.5 mm long), and the mixture is spark ignited. The deflagration-to-detonation transition occurs in the small tube. The detonation enters and initiates the detonation in the annular channel of the RDE. The pressure in the fuel and air plenums initially increases due to the backpressure associated with the detonation in the channel. Data are reported after steady state conditions have been achieved in the plenums.

![Schematic and photograph of a representative optically accessible RDE](image)

**Figure 8:** Schematic (left) and photograph (right) of a representative optically accessible rotating detonation engine

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Images of the OH* chemiluminescence are acquired using a high speed camera (Photron SA-5 CMOS) and ultra-violet (UV) intensifier (LaVision IRO). The images are acquired using a 45 mm lens (f/1.8) and band-pass filter (320 ± 20 nm). The spatial resolution of the images is approximately 0.31 mm/pixel. The images are collected with an exposure time of 300 ns at a sample frequency of 20 kHz. Images are recorded for 0.5 s resulting in 10,000 images for each operating condition. The spatial and temporal resolutions are sufficient to minimize blurring effects (less than 3 pixels) associated with imaging the high-speed detonation wave. A gamma correction of 0.5 has been applied to all of images. The gamma correction applies to regions of the image that have photon count values less than 25% of the maximum camera detection limit.

The OH* chemiluminescence images are post-processed using a spatial transformation to map the azimuthal direction onto a plane tangent to the detonation channel. The spatial transformation process results in an “unwrapped” two-dimensional OH* distribution that can be compared with two-dimensional simulations of RDEs. The “unwrapped” OH* distributions are reported in this work. The position of the detonation wave is identified in each instantaneous image using the peak intensity. Phase-averaged images are obtained by averaging approximately 30 instantaneous images that contain a detonation wave within ± 0.93 mm (3 pixels) of a particular azimuthal position.

Figure 9 - Figure 11 show instantaneous and phase-averaged images of the OH* chemiluminescence in the optically accessible RDE for varying air mass flow rates and fuel injection schemes. The field of view of each image spans from the fuel injection surface (y = 0) to near the end of the detonation channel (y = 10 cm) in the vertical direction and includes the region between the outer surfaces of the channel (x = ± 7.7 cm) in the horizontal direction. The vertical white lines indicate the inner surfaces of the channel (x = ± 6.9 cm). Regions with low and high OH* chemiluminescence emissions appear in black and white, respectively. The instantaneous images are selected randomly from a set of images in which the detonation is near the image centerline. The phase-averaged images are normalized by the maximum phase-averaged OH* chemiluminescence signal to allow for qualitative comparison of the size and shape of the detonation wave across the range of operating conditions studied in this work. The detonation wave travels from right to left for all of the images shown in this work.

Figure 9 shows instantaneous and phase-averaged images of the OH* chemiluminescence in the optically accessible RDE for four air mass flow rates (0.15, 0.32, 0.61, 0.86 kg/s). The equivalence ratio (1.0), air injection slot (1.78 mm), and fuel injection scheme (0.89 mm diameter – 120 holes) are constant for the images shown in Figure 9. The instantaneous detonation structure is stochastic with significant variation in the size, shape, and intensity of the OH* emissions from cycle to cycle. The height of the detonation, as identified by regions of high OH* chemiluminescence emission, initially increases as the air mass flow rate is increased from low (0.15 kg/s) to intermediate (0.32 kg/s) values. Negligible increase in the detonation height is apparent as the air flow rate is further increased (to 0.61 kg/s). The detonation transitions from one-wave to two-wave operation as the air flow rate is further increased (to 0.86 kg/s) resulting in a reduction in the fuel fill height and corresponding detonation height.
Figure 9: Instantaneous (first, second, and third columns) and phase-averaged (fourth column) images of the OH* chemiluminescence in the optically accessible rotating detonation engine for four air mass flow rates (0.15, 0.32, 0.61, 0.86 kg/s). The equivalence ratio (1.0), air injection slot (1.78 mm), and fuel injection scheme (0.89 mm – 120) are constant for this set of images [35].

Figure 10 shows instantaneous and phase-averaged images of the OH* chemiluminescence for three fuel injection schemes (0.89 mm diameter – 120 holes, 0.71 mm – 120, and 0.89 mm – 80). The air mass flow rate (0.32 kg/s), equivalence ratio (1.0), and air injection slot (0.89 mm) are constant for the images shown in Figure 10. Reducing the diameter of the fuel injection holes (from 0.89 to 0.71 mm) has subtle effects on the height and concavity of the detonation wave front. The mixing between the fuel and oxidizer can be impacted by reducing the number of fuel injection holes (from 120 to 80) while maintaining a constant area for each individual hole. As the air mass flow rate and equivalence ratio are constant for the images in Figure 10, the speed of the fuel exiting the fuel plenum and entering the RDE annular channel is higher for the smaller holes, or for fuel schemes with fewer holes. The reduction in the number of fuel injection holes has a significant effect on the structure of the detonation wave. In particular, the RDE changes from one wave to two-wave operation simply by reducing the number of fuel injection holes. The two-wave operation at this condition can be seen to reduce the detonation wave height shown in the bottom row of Figure 10.
Figure 10: Instantaneous (first, second, and third columns) and phase-averaged (fourth column) images of the OH$^*$ chemiluminescence in the optically-accessible rotating detonation engine for three fuel injection schemes (0.89 mm diameter – 120 holes, 0.71 mm – 120, and 0.89 mm – 80). The air mass flow rate (0.32 kg/s), equivalence ratio (1.0), and air injection slot (0.89 mm) are constant for this set of images [35].

For conditions in which two-waves are established in the RDE, the waves typically co-rotate with the detonations propagating in the same azimuthal direction. A notable exception occurs for stoichiometric conditions with the low air mass flow rate (0.15 kg/s), the small air injection slot (0.89 mm), and the fuel injection scheme with the smaller number of holes (0.89 mm – 80). Figure 11 shows eight temporally uncorrelated instantaneous images of the OH$^*$ chemiluminescence from two counter-rotating detonation waves. The detonations propagate in opposite azimuthal directions causing detonation-detonation interactions that result in structures with unique sizes, shapes, and intensities. The observation of two counter-rotating detonation waves demonstrates one occasional effect of non-ideal mixing between the fuel and air in a RDE. It is interesting to note that immediately after the detonation-detonation interaction, the detonations have no fresh reactants to burn. The detonations continue to propagate and sustain themselves for short distances, resulting in unique wave structures. The fill-zone height is near zero immediately after the detonation-detonation interaction, and then the fill-zone height increases until the next collision. In contrast, the fill-zone height is constant from the perspective of the detonation wave for the single-wave or two-wave co-rotating modes.
Figure 11: Instantaneous images of the OH* chemiluminescence in the optically-accessible rotating detonation engine for an equivalence ratio of 1.0, an air mass flow rate of 0.15 kg/s, a 0.89 mm diameter – 120 holes fuel injection scheme, and a 0.89 mm air injection slot. The figure is intended primarily to illustrate counter-rotating waves [35].

A slightly oblique detonation wave with multiple triple points is apparent in many of the OH* chemiluminescence images. Detonations exhibit instabilities in the form of shock waves that propagate perpendicular to the detonation front. The high intensity localized regions appearing in the images indicate the triple points at the collision of the transverse waves. The density of the transverse waves is related to the properties of the mixture and the initial conditions. The characteristic distance between two transverse waves represents the detonation cell size. The cell size has a highly non-linear dependence upon initial pressure and temperature. The cell size dictates the minimum size of the engine in both PDEs and RDEs. Detonation cell size measurements at relevant pressures and temperatures are needed and are the focus of the subsequent section.

IV.B. Detonation Cell Size Measurements at Elevated Pressures

Significant opportunities exist for acquiring detonation cell size measurements at elevated pressures and temperatures that are relevant to the conditions observed in PDEs and RDEs. Soot foil, schlieren imaging, and focused schlieren imaging techniques have been used to measure cell sizes. This section briefly discusses the three measurement techniques and presents new detonation cell size measures for hydrogen-air and propane-air mixtures at initial pressures ranging from 1 to 10 atm.

The detonation cell size historically has been measured using a foil covered with a layer of soot mounted in a detonation tube. The left side of Figure 12 illustrates the process for measuring detonation cell sizes using a soot foil. The transverse waves and triple points in the detonation inscribe a pattern in the soot which is analyzed to estimate the cell size. Detonation cell sizes are estimated based on a single cell or dominant band of cells. The soot foil technique is susceptible to significant uncertainty due to the subjective nature of the analysis. The uncertainty associated with soot foil cell size measurements is often on the same order as the cell size [40, 41].
Figure 12: Schematic of a detonation wave recorded by a soot foil and schlieren image

Schlieren imaging is an alternative approach for estimating cell sizes in an optically accessible detonation tube. Schlieren imaging utilizes a parallel beam of light to detect density gradients in translucent media. The light source is reduced to a pin hole to approximate a point source. The optical arrangement results in an image that spatially integrates the density gradients along the parallel beam of light. Detonations have an inherently three-dimensional structure, and the schlieren image is a path-integrated image of the cellular structure. The path-integrated distance can be minimized by reducing the thickness of the optically accessible detonation tube. The narrow thickness of the tube forces the detonation into a two-dimensional mode which may not accurately represent the cell size in a three-dimensional wave front.

Focused schlieren imaging (Figure 13) modifies the conventional schlieren imaging optical arrangement to remove the need for a narrow test section. Increasing the height of the light source allows a thin, planar region to be brought into focus [42]. The focal plane has a finite depth-of-field (Δz) that is a function of the light source height (b), the focal length of the parabolic mirrors (f₂), and the acceptable circle of confusion (δ): \[ Δz = \frac{δf₂}{b}. \] The focused schlieren technique enables imaging of a focal plane with a finite depth-of-field that bisects the detonation similar to the soot foil while minimizing boundary effects. The focused schlieren image captures the structure of the detonation intersecting the focal plane and leaves the remaining parallel beam of light out of the focus. For the results shown in this work, the focused
The right side of Figure 12 illustrates the process for measuring detonation cell sizes using a focused schlieren image. The schlieren image shows the triple points as cusps in the detonation front and the transverse wave attached to each triple point. Detonation cell sizes are estimated by averaging the distance between the transverse waves or the triple points. The schlieren imaging technique is an efficient approach for measuring cell sizes because it does not require opening of the detonation tube or preparing soot foils between each operating condition. Schlieren imaging is relatively insensitive to the conditions within the detonated volume in contrast to soot foils which are susceptible to reduced clarity especially at high pressures and fuel lean conditions. Schlieren imaging is predisposed to degradation by chemiluminescence especially with hydrocarbon fuels [43].

Existing data on detonation cell sizes for hydrocarbon fuels is limited. Empirical relations for cell size as a function of initial pressure and temperature are required to determine the physical dimensions of detonation-based engines due to the minimum cross-sectional dimensions imposed by the cell size. One effort to expand the available data set is underway in a new high pressure detonation tube (Figure 14). The experimental arrangement is configurable as either a shock tube or a spark ignited detonation tube. Detonations at temperatures above the auto-ignition temperature can be studied by operating the experimental arrangement as a shock tube. The tube is rated for mixtures at pressures up to 260 atm at a temperature of 300 K which limits initial conditions for a detonation to approximately 13 atm. An optically accessible section enables schlieren imaging to be used for measuring cell sizes in the detonation tube.
Two studies have been performed using the high pressure detonation tube and focusing schlieren technique. The first study explored cell size dependence on pressure and equivalence ratio in hydrogen-air mixtures [44]. Figure 15 shows the detonation cell size as a function of the initial pressure for hydrogen-air mixtures at four equivalence ratios. The results indicate a power law relationship between pressure and cell size consistent with previously published data [45-48]. The magnitude of the exponent in the power law relationships is larger for mixtures closer to stoichiometric conditions and represents a new contribution from this work. The empirical correlations provide important insights into the operation and performance of detonation-based combustors. The operational limits will be based on maximum cell size and not minimum heat release in detonation-based engines. Therefore, higher pressure ratio combustors can be designed to be smaller because increasing initial pressure reduces the cell size. The results demonstrate that there is a design tradeoff between combustor size and operating equivalence ratio because fuel lean conditions result in larger detonation cell sizes.
Figure 15: Detonation cell size measurements of hydrogen/air mixtures for a range of initial pressures and equivalence ratios

The second study explored cell sizes in stoichiometric propane-air mixtures at pressures from 1 to 10 atm [49]. Prior work investigated rich propane-air [41] and propane-oxygen mixtures [40]. The results indicate a power law relationship between pressure and cell size. The magnitude of the exponent in the power law relationships is similar to within 10% for the stoichiometric propane-air and propane-oxygen mixtures.
V. Operation and Performance of Rotating Detonation Engines

V.A. Hydrogen/Air Mixtures

Experimental studies have been conducted to improve understanding of the effects of fuel composition, device geometry, and operating conditions on the performance attainable from RDEs. Figure 17 shows a schematic of a representative RDE with an aerospike plug nozzle. The lower section of the device (i.e., oxidizer and fuel manifolds, fuel injection plate, outer-body, and center-body) is common to all of the configurations that will be discussed. The contour of the aerospike plug nozzle is varied or removed all together for some configurations.

Figure 16: Detonation cell size measurements of stoichiometric propane-air and propane-oxygen mixtures for a range of initial pressures.
The RDE typically is instrumented to allow for low and high frequency static pressure measurements in the air plenum, in the fuel plenum, and at select positions along the axial length of the detonation channel. A schematic of the experimental arrangement for the low-frequency and high-frequency static pressure measurements is shown in Figure 18. The high-frequency time-dependent static pressure measurements are acquired using an infinite tube pressure (ITP) arrangement with high temperature, high frequency pressure transducers. The high frequency pressure transducer is offset from the inner surface of the outer-body wall by approximately 76 mm. The semi-infinite tube is 914 mm long with an inner diameter of 1.78 mm. The ITP arrangement minimizes exposure of the transducers to high temperatures and minimizes the effects of pressure-wave reflections on the frequency response of the transducers. The high frequency pressure transducer signals typically are recorded at a sampling frequency of 0.5 – 1 MHz.
Representative high frequency static pressure measurements in the channel, air plenum, and fuel plenum are shown in Figure 19. Time-dependent pressure results are shown for an air mass flow rate of 0.32 kg/s, a stoichiometric hydrogen/air mixture, a fixed fuel injection scheme (0.89 mm – 120), and several air injection slots (0.89, 1.78, and 3.56 mm). The characteristic frequencies and average detonation wave speeds are labeled on the figures for each condition. The time-dependent channel pressure results reveal important features of the detonation structure. The detonation front is evident as a significant increase in the pressure over a short time. The secondary pressure peak that follows the detonation front may result from a reflection from the inlet. It is plausible that the subtle increase in pressure near the end of a particular cycle for some conditions results from a weak shock propagated upstream from the exit.
High frequency static pressure measurements are acquired in the channel (at 2.54 cm downstream of the fuel injection surface), air plenum, and fuel plenum for three air injection areas at a nominal air mass flow rate of 0.32 kg/s.

Low frequency static pressure measurements are acquired using the capillary tube attenuated pressure (CTAP) arrangement (Figure 18). The pressure transducer is positioned at the end of a long (914 mm) tube with a small inner diameter (0.58 mm) designed to attenuate the periodic pressure variations. The low frequency pressure transducer measurements are acquired in the air plenum, in the fuel plenum, and between 6.35 – 70 mm downstream of the fuel injection surface at spatial increments of 6.35 mm. The low frequency pressure transducer signals are recorded at a sampling frequency of 1 kHz. The pressure transducers were calibrated using a high precision pressure calibrator and controller (Druck DPI 510). The RDE is mounted horizontally on a thrust stand. The thrust is measured using a strain-based load cell that is calibrated before and after each set of experiments. The calibration is linear with hysteresis observed to be less than 2.5 N.

Figure 20 shows the static pressure in the detonation channel as a function of axial distance downstream of the fuel injection surface for a range of air mass flow rates, equivalence ratios, air injection slots, and fuel injection schemes. Each panel on the left shows the axial pressure distribution for varying air injection slots and flow rates at stoichiometric conditions. Each panel on the right shows the axial pressure distributions for varying equivalence ratios and flow rates for a fixed air injection slot. The channel pressures are largest near the air and fuel inlets and decrease rapidly with distance downstream of the fuel injection surface. The axial distribution of the detonation channel pressures depend predominantly on the air mass flow rate with small differences observed for varying equivalence ratios, air injection slots, and fuel injection schemes.
Figure 20: Static pressure distribution in the detonation channel as a function of axial distance downstream of the fuel injection surface

Figure 21 shows that an increase in the air mass flow rate through the RDE is matched by an increasing specific thrust. This behavior is due to the increasing initial pressure of the propellants prior to being detonated and the increasing back pressurization of the device due to combustion. The data are shown for combustion of gaseous hydrogen and air, an air injection area ratio \( (A_{\text{Air}}/A_{\text{RDE}}) \) of 0.435, and a nozzle area convergence ratio \( (A_{\text{Noz}}/A_{\text{RDE}}) \) of 0.6. Diminishing returns in performance are apparent for increased air mass flow rate. Heat transfer and friction losses begin to offset the gains created by the combustion of more propellants. A maximum specific thrust is reached at a slightly rich equivalence ratio for a fixed air mass flow rate. This is consistent with mixture conditions that provide the maximum pressure rise across the detonation wave propagating in the annular channel.
Figure 21: Performance of a rotating detonation engine coupled to an aerospike plug nozzle operated on hydrogen/air, shown in terms of specific impulse as a function of specific thrust for a range of air mass flow rates and equivalence ratios [50]

The performance of RDEs with differing detonation channel width shows consistent trends when the appropriate one dimensional analysis based parameters are fixed. Figure 22 shows the specific impulse as a function of equivalence ratio for three detonation channel widths with an air injection area ratio ($A_{\text{Air}}/A_{\text{RDE}}$) of 0.435, a detonation channel mass flux ($\dot{m}_{\text{Air}}/A_{\text{RDE}}$) of 173 kg/sec/m², and a nozzle area contraction ratio ($A_{\text{Noz}}/A_{\text{RDE}}$) of 0.6. Slight vertical shifting of the specific impulse curves between detonation channel widths is observed; however, the slopes of the curves remain the same relative to each other. The difference between the specific impulse curves is attributed to three-dimensional effects such as propellant mixing, flow recirculation losses at the base of the detonation channel, and changes in the radial length scales across the channel.
Specific impulse provides a measure of fuel usage in the production of thrust. The corrected thrust ($F_g/P_o$) is used to describe thrust production from the stagnation pressure supplied to the engine through the air manifold. The difference in the use of the stagnation pressure between channel configurations can be seen in Figure 23. The highest corrected thrust is observed for the 22.86 mm (0.9 inch) channel width, while the 16.25 mm (0.64 inch) channel width configuration shows more effective pressure usage than the 7.62 mm (0.3 inch) channel. If a stoichiometric mixture is considered and the 7.62 mm channel width configuration is used as a basis of comparison, the 16.25 mm channel width provided approximately 9% more specific impulse and 130% more corrected thrust production. The 22.86 mm channel width resulted in 175% improvement in corrected thrust, while providing only a 6% increase in specific impulse. This indicates that the 22.86 mm channel width configuration provided the most efficient use of stagnation pressure and had considerably worse fuel usage.
V.B. Ethylene/Air Mixtures

Figure 24 shows the specific impulse resulting from the detonation of hydrogen/air mixtures in PDEs and RDEs. The hydrogen/air RDE data provide a good match to the performance levels previously measured by Schauer et al. [51] for hydrogen/air mixtures in PDEs. The RDE data provide a good match to the theoretical performance levels calculated by Wintenberger et al. [52]. The measured performance of the detonation of gaseous ethylene and air in similarly configured devices is shown in Figure 24. The measured specific impulses from the ethylene/air RDE compare well to the ethylene/air PDE values reported by Schauer et al. [53] and Cooper et al. [54] and the calculated performance levels of Wintenberger et al. [52]. These results are encouraging and indicate that the RDE is capable of producing thrust with similar levels of fuel efficiency as those associated with a PDE when operated with gaseous hydrocarbon fuels.
Figure 24: Comparison of measured and calculated specific impulses for rotating detonation engines and pulsed detonation engines. The measurements were acquired by Schauer et al. [51, 53] and Cooper et al. [54], and the calculations were performed by Shepard et al. [52].

Figure 25 shows the measured specific impulse and specific thrust as a function of equivalence ratio for a RDE operated on hydrogen/air and ethylene/air mixtures. The results show the expected decrease in specific impulse when considering a change from hydrogen to ethylene fuel. The results show that the usage of air to produce thrust in a hydrocarbon fueled RDE is comparable to that of a hydrogen fueled device. The ethylene/air mixture actually shows slightly higher levels of specific thrust for a given equivalence ratio in comparison to the hydrogen/air mixture. This is the expected relationship and is a good indicator that the RDE is operating in a consistent manner for both the hydrogen and hydrocarbon fueled devices.
Figure 25: Measured specific impulse ($I_{sp}$) and specific thrust ($F_g/\dot{m}_{Air}$) shown as a function of equivalence ratio ($\phi$) for both hydrogen and gaseous ethylene fuel [50]

Figure 26 shows that the measured corrected thrust for the hydrocarbon fueled RDEs matches that of the hydrogen fueled RDEs. This indicates that both hydrogen and ethylene fueled RDEs can attain similar efficiency in the conversion of the supplied stagnation pressure to thrust. Looking forward to future applications and the desired operation of RDEs on heavier hydrocarbon fuels, it is important to know that for a particular geometry it is possible to obtain the same pressure utilization as seen for the canonical hydrogen fueled RDEs. However, it is reasonable to assume that mixing and fuel injection schemes will have a significant influence on realizing a liquid fueled RDE.

Figure 26: Measured corrected thrust ($F_g/P_o$) shown as a function of equivalence ratio ($\phi$) for both hydrogen and gaseous ethylene fuel [50]
A summary of the relative effectiveness of thrust production by the hydrogen and ethylene fueled RDEs is shown in Figure 27. The stagnation pressure utilization is similar for both hydrogen and ethylene as shown by the normalized corrected thrust. The expected difference in attainable specific impulse is shown by the normalized corrected specific impulse.

Figure 27: Measured normalized corrected specific impulse \( \left( \frac{I_{sp}}{P_o} = \frac{F_{g}}{m_{Fuel}/P_o} \right) \) as a function of normalized corrected thrust \( \left( \frac{F_{g}}{P_o} \right) \) for hydrogen/air and ethylene/air mixtures [50]

V.C. Nozzles Effects

Experiments have been conducted on eight different nozzle configurations which included two bluff-body exhausts, three aerospike nozzles, and three converging-diverging nozzles. The experimental configurations are shown schematically in Figure 28. Two different lengths for the RDE outer-body were used, either 21 cm (8.27 inches) or 11.4 cm (4.5 inches). The bluff-body configurations included a case where the exit plane of the center-body and outer-body were set to be even at the same axial position and one where the center-body was recessed by 14.2 mm (0.56 inches) relative to the outer-body exit plane. The two bluff-body configurations were used to assess the influence and sensitivity of the center-body to outer-body alignment on recirculation zone formation at the exit of the RDE and provide reference cases for any performance improvements that may be observed in the aerospike nozzle configurations. The three aerospike nozzle configurations consist of an identical central spike with varying degrees of exhaust area constriction. The three nozzles were designed to provide a 0%, 20%, and 40% area constriction of the detonation channel. The area constriction allows for the extent of the exit choke to be assessed and conclusions to be made regarding the state of the flow at the exit plane of the RDE. The converging-diverging nozzle configuration had the same area constrictions as the aerospike nozzle arrangements.
The different nozzle configurations influence the performance of the RDE. Figure 29 shows a comparison of four different configurations for an air mass flow rate of 1.14 kg/sec and over a range of equivalence ratios. There are incremental improvements in the specific thrust produced by each configuration beginning with the even bluff-body, recessed bluff-body, aerospike nozzle, and choked aerospike nozzle configurations respectively. Greater control of the expansion processes drives the performance increases. The bluff-bodies control the size of the recirculation zones, and the aerospike nozzles add a solid thrust surface to guide the expansion. These levels of specific thrust are encouraging as typical turbofan engines exhibit similar values. Each of the configurations demonstrated the ability to ignite and operate over a throttling range of greater than 25\% of the attainable specific thrust.

The aerospike nozzles show their advantages at higher mass flows and higher back pressures. The choked aerospike indicates that there is additional performance to be realized with additional choking of the flow beyond the thermal choke present in the detonation channel. The area constriction leads to larger local static pressures in the detonation channel which are then multiplied by the detonation process and converted to thrust by the nozzle.
Figure 29: Comparison between an even bluff-body, recessed bluff-body, aerospike, and converging-area aerospike (ANoz/ARDE = 0.8) nozzle for a total mass flow rate of 1.14 kg/sec, shown in terms of specific thrust ($F_g/m_{Air}$) as a function of equivalence ratio ($\phi$) [50].

A comparison of the performance attained from two identical choked aerospike nozzles with different detonation channel heights (21 cm and 11.4 cm) is shown in Figure 30. The results from a converging-diverging nozzle configuration with a 21 cm channel height are shown for comparison. The arrangements have the same nozzle area contraction ratio (ANoz/ARDE) of 0.6. The specific thrust attained by each of the configurations is comparable over the range of equivalence ratios examined in this work. The nozzle area contraction ratio is an important parameter in the efficiency of air handling for any combustor and nozzle arrangements. The result suggests that the unsteady exhaust from the RDE does not create unforeseen issues with respect to nozzling of the exhaust flow.
Figure 30: Experimental specific thrust ($F_{\text{th}}/m_{\text{Air}}$), shown as a function of equivalence ratio ($\phi$) for three different nozzle configurations with a nozzle contraction ratio ($A_{\text{Noz}}/A_{\text{RD}}$) of 0.6 [55].

Figure 31 shows the normalized corrected thrust as a function of equivalence ratio for the same three nozzle configurations as shown in the previous figure. The aerospike nozzle with the shorter detonation channel height shows a substantially increased effectiveness in the utilization of the air manifold pressure in the production of thrust. Both the aerospike and converging-diverging nozzle configurations with longer channel heights can be seen to have greater apparent pressure losses, leading to a reduction in their effectiveness. This is a curious result because it is difficult to identify a single mechanism that would create similar levels of loss in both tall configurations. The total confined flow height of the converging-diverging nozzle is much larger than that of the aerospike nozzle while the detonation channel height of both under-performing arrangements is the same. Many potential loss mechanisms (e.g., shock, viscosity, or heat transfer) which might create the difference between the short and tall channel configurations should be expected to create a larger difference when considering the converging-diverging nozzle. Additional experiments are required to determine if the two taller arrangements achieve similar performance due to similar channel heights or if the various losses mechanisms add up to provide comparable results.
Figure 31: Experimental corrected thrust ($F_g/P_o$) shown as a function of equivalence ratio ($\phi$) for three different nozzle configurations with a nozzle contraction ratio ($A_{Noz}/A_{RDE}$) of 0.6 [55]

In addition to detonation channel height, the width of the annular detonation channel can have a substantial impact on the pressure utility of the device. Figure 32 shows the measured normalized corrected thrust for three different detonation channel widths. The results indicate that there is an optimum channel width that maximizes the production of thrust from the available air manifold pressure. The 16.25 mm (0.64 inches) channel provides a larger corrected thrust than both the 7.62 mm (0.3 inches) and 22.86 mm (0.9 inches) channel configurations. The optimum channel width will be unique to the device geometry and operating conditions demonstrating that RDEs have the potential to be tailored to particular applications.
Figure 32: Measured corrected thrust \( (F_g/P_o) \) shown as a function of equivalence ratio \( (\phi) \) for various detonation channel widths and a nozzle contraction ratio \( (\text{ANoz}/\text{ARDE}) \) of 0.6 [55]

V.D. Heat Transfer Effects

Understanding the thermal environment in RDEs and quantifying the heat transfer to the containing walls is critical to develop an engine capable of sustained operation. The schematic on the left side of Figure 33 shows a representative RDE that has water-cooled inner and outer walls for the detonation channel. The photograph on the right side of Figure 33 shows the RDE at thermal equilibrium with a water-cooled inner wall and un-cooled outer wall. The water-cooled RDE is used in conjunction with calorimetry to estimate the heat transfer rates to the inner and outer walls of the detonation channel for a range of operating conditions.
Figure 33: Schematic (left) of the water-cooled rotating detonation engine. Photograph (right) of the rotating detonation engine at thermal equilibrium with a water-cooled inner wall and uncooled outer wall.

Figure 34 shows the heat transfer rate to the walls of the water-cooled RDE for a range of air mass flow rate and equivalence ratios. The panels on the left and right are for the outer and inner walls of the RDE detonation channel, respectively. The panels on the top and bottom show the heat transfer rate and the heat transfer rate as a percentage of the fuel lower heating value (LHV), respectively. The heat transfer rates were measured using calorimetry based on the inlet and outlet water temperatures and flow rates. The heat transfer to the walls increases with increasing mass flow and equivalence ratio. A larger fraction of the available energy in the flow is transferred to the walls during detonation-based combustion in comparison to the unsteady operation conditions. The detonation-based combustion conditions were characterized by a detonation wave which rarely reversed direction and are indicated by the white bands in Figure 34. The unsteady conditions were characterized by intermittent detonation waves which frequently reversed direction or deflagration in the channel and are indicated by gray bands in Figure 34.
Figure 34: Heat transfer to the outer (left) and inner (right) walls of the water-cooled rotating detonation engine for a range of air mass flow rates and equivalence ratios. Both the inner and outer walls of rotating detonation engine channel are water-cooled for the data shown in this figure.

Additional experiments investigated the feasibility of cooling the RDE containing walls with air rather than water. Figure 35 shows measured heat fluxes for a RDE with a water-cooled inner wall and an air-cooled outer wall. The temperatures of the cooling medium at the inlet and outlet and the mass flow rates of each were measured. The heat transfer rate was averaged over the flame-wetted surface area of each wall to estimate the heat flux into each cooling medium. The RDE was operated on hydrogen/air at stoichiometric conditions with an air mass flow rate of 0.42 kg/s. The RDE was operated for two minutes with a cooling air mass flow rate of 0.42 kg/s followed by discrete step reductions in cooling air rates to quantify the minimum cooling requirements. Several non-physical artifacts are evident in Figure 35 because the heat fluxes are estimated from mass flow rates and temperatures. For example, the thermocouple used at the cooling air exit responded more slowly than the pressure transducers used in the mass flow rate measurements, resulting in sharp decreases in measured heat flux after each decrease in mass flow rate. The air-cooled wall should absorb less heat as the cooling flow rate decreases, so there was likely a significant amount of heat transferred directly from the hot wall to the thermocouple, increasing the measured temperature above the mean exit temperature of the cooling air. Even with these issues, the experiment successfully demonstrated that an air-cooled wall could survive thermal equilibrium and would absorb a similar heat flux as a water-cooled wall. Moreover, the experiment demonstrated that only a small fraction of the total airflow is required to cool an RDE wall making air-cooling schemes feasible.
Figure 35: Time-dependent heat flux through the inner water-cooled (blue) and outer air-cooled (red) walls of the RDE. The inner wall of the rotating detonation engine channel is water-cooled, and the outer wall of the rotating detonation engine channel is air-cooled for the data shown in this figure.

Although steady-state heat flux is sufficient information to design a RDE to survive the thermal environment, it is difficult to extrapolate outside the observed operating conditions or to other engine configurations. A more fundamental understanding of the heat transfer mechanisms from the flowfield is required to accurately predict heat transfer at conditions that have yet to be observed. This level of detail requires high frequency heat flux sensor measurements capable of characterizing the periodic heat transfer waveform. Thin-film, two-sided platinum resistance temperature detectors (RTDs) have been used in RDEs and PDEs to measure high frequency heat flux from detonation waves. Although the fragility of the RTDs limits operation times to approximately 100 ms, this approach reduces cost and improves reliability since the RTDs are based on high frequency sensors historically used in hypersonic and turbine research [56-58] and are currently produced at relatively low cost [59]. These RTDs can be combined into an array along a surface without affecting the boundary layer, enabling a detailed examination of the heat transfer into the surface.

Resistance temperature detectors operate based on the principal that the resistance varies linearly with the temperature of the sensor. Transient solution techniques have been devised to estimate heat fluxes from time-resolved temperature signals [60]. The two-sided technique used in this paper was developed by Oldfield [61] and has been utilized on RTD arrays to describe heat flux perturbations in turbulent unsteady flowfields applicable to turbomachinery [62, 63]. The calculation of heat flux from high bandwidth temperature measurements is highly sensitive to high-frequency noise, and this has presented a challenge to obtaining a clear heat flux waveform using other conventional techniques in the past.
Figure 36 shows an array of eight two-sided RTDs along the flame-wetted surface of the outer wall of the RDE. Each RTD consists of a platinum element with a copper/gold alloy serving as the leads. The substrate is a polyimide sheet which enables the array to conform to the shape of the wall. Each element is excited individually via quarter-bridge circuits and the resulting signal is amplified and processed by a 100 kHz low-pass filter to maximize resolution and minimize noise. Imperfections in the fabrication process led three sensor positions to fail. Figure 37 shows representative time-dependent temperatures measured by the working sensors.

Figure 36: Position of the heat flux gage array on the outer wall of the rotating detonation engine

Figure 37: Time-dependent temperature measurements in the RDE recorded by the top (left) and bottom (right) RTD sensors. The inner and outer walls of RDE channel are neither water-cooled nor air-cooled for the data shown in this figure.
Figure 38 shows a comparison between measured and simulated phase-averaged heat flux in the RDE at an air mass flow rate of 0.3 kg/s and a stoichiometric mixture of hydrogen and air. The measured heat flux distributions are obtained by phase-averaging 10 consecutive detonations waves. Both the measurements and simulations have been processed using a 100 kHz low-pass filter. The phase-averaged heat fluxes from the detonations wave are shown twice in Figure 38 to better illustrate the cycle. An important difference is that the measured and simulated detonation wave speeds are approximately 1750 m/s and 1600 m/s, respectively. A broader region of lower heat flux behind the detonation is observed in the simulations whereas a relatively uniform heat flux after each wave is observed in the measurements. This suggests that the refill may have a relatively small cooling effect. Although this data is useful for understanding the instantaneous heat transfer, more data at other operating conditions and at other positions along both walls will be necessary to understand the thermal environment in RDEs.

![Phase-Averaged Heat Flux](image)

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**VI. Rotating Detonation Engine Gas Turbine Combustor Application**

One potential application for RDEs is gas turbine combustors. Detonation combustion can improve gas turbine efficiency, and RDEs have some benefits over other detonation concepts such as PDEs. The RDE has high power density which reduces engine size and surface area for heat transfer losses. The inlet flow to the RDE does not require a mechanical valve, which could be beneficial when interfacing with a compressor. The exit flow from the RDE is already annular which allows for more convenient interfacing with a turbine. The RDE has lower unsteady pressure magnitudes than a PDE.

The significant advantages of RDEs are balanced by corresponding technical challenges that need to be addressed through further research and development. The high power density yields high heat transfer to engine hardware, requiring advanced cooling strategies and materials. Reactant injection needs to minimize pressures losses and simultaneously isolate the compressor from the RDE pressure waves. Detonation results in high exhaust temperatures; therefore, efficient dilution of the exhaust must be achieved before the flow enters the high pressure turbine. Periodic pressure oscillations will be present even after dilution, and effective turbine energy conversion from this unsteady flow needs to be optimized.

The present study investigates the response of a turbine, designed for steady inlet flow, to the unsteady pressures of a diluted RDE exhaust. The Allison T-63 gas turbine was selected for the

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experiment. The T-63 is a reverse-flow turboshaft engine. The reverse flow design allowed for removal and replacement of the combustor, without modification to the turbomachinery. The T-63 is a 1960’s gas turbine; thus, the turbine blades operate at lower temperatures and do not have film cooling. Therefore, there is no concern that the unsteady pressure and flow of the RDE could disrupt blade cooling dynamics.

To simplify RDE development, the turboshaft engine was operated in an open loop configuration as shown in Figure 39. The open loop configuration involves measuring and dumping the compressor inflow and supplying fresh air and fuel to the RDE via external high pressure tanks. This process allowed the engine to use large pressure losses across the reactant injection streams. It allowed pressure waves to propagate into the injection system and not affect the compressor operation.

![Figure 39: Flow diagram of open-loop T-63 engine](image)

The RDE exhaust flow was diluted using an ejector scheme. The dilution scheme was designed to result in acceptable turbine inlet temperatures, while retaining unsteady pressure oscillations with a magnitude of approximately 20%. The dilution air was used to cool the detonation channel walls of the RDE. The air cooling scheme simplified hardware manufacturing in comparison to a water-cooled design. The air cooling scheme simplified the analysis because energy transferred to the walls and into the cooling flow remained within the engine. A schematic and photograph of the RDE gas turbine combustor is shown in Figure 40.
Table I lists the mass flow rates and compressor speeds for the operating conditions of interest. Flow rates to the engine were controlled via sonic nozzles. The flow rates match the air flow and energy release of the stock T-63 engine. The engine was started by flowing air only through the turbine stages. After a predetermined turbine speed was reached, fuel injection began and the device was ignited. The experimental sequence was to ramp and hold at each of the operating conditions with the entire sequence lasting for approximately 5 - 10 minutes per test. Multiple sensors monitored engine operation temperatures, pressures, and shaft speeds throughout the experimental sequence. High speed pressure data was acquired at each power setting, after sufficient time to allow the engine to reach steady state conditions.

<table>
<thead>
<tr>
<th>Power Setting</th>
<th>Air Mass Flow Rate (kg/s)</th>
<th>Hydrogen Mass Flow Rate (g/s)</th>
<th>Equivalence Ratio</th>
<th>Compressor Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>0.65</td>
<td>3.23</td>
<td>0.17</td>
<td>30,700</td>
</tr>
<tr>
<td>70% Maximum</td>
<td>0.81</td>
<td>4.69</td>
<td>0.20</td>
<td>35,800</td>
</tr>
<tr>
<td>80% Maximum</td>
<td>0.97</td>
<td>6.56</td>
<td>0.23</td>
<td>40,900</td>
</tr>
<tr>
<td>Rated</td>
<td>1.12</td>
<td>9.41</td>
<td>0.29</td>
<td>46,000</td>
</tr>
</tbody>
</table>

Two, diametrically opposed, instrumentation ports were available upstream of the high pressure turbine. Four, circumferentially evenly spaced, instrumentation ports were available between the high pressure and low pressure turbine. One port at each location was used for a high frequency (MHz response rate) absolute pressure transducer (Kulite) offset from the engine wall. The remaining ports at each location were used for thermocouples. Figure 41 shows the high frequency pressure measurements at the rated engine power condition. The curves labeled with station 4 represent pressures at the inlet to the high pressure turbine, and curves labeled with station 5 represent pressures between the high and low pressure turbines. The results show that...
there is a 15-20% unsteady pressure for the RDE, while there is minimal unsteady pressure for the original engine manufacturer combustor (OEMC). The results indicate that the unsteady pressure is effectively eliminated in the high pressure turbine. These results are qualitatively representative of pressures at each of the power settings examined in this work.

Figure 41: T-63 high pressure turbine upstream (P4) and downstream (P5) pressure measurements, for engine operation at the rated power test point

Multiple techniques were employed to estimate the turbine component efficiency. First, the isentropic efficiency was calculated using the average temperatures before and after each of the turbine stages, as well as average pressure ratio. This method is questionable in practice because the pressure ratio is varying by up to 20%. Unfortunately, there was significant circumferential variation in the temperature at each axial measurement location, for both the OEMC and the RDE. Using the average of the temperature measurements at each axial position resulted in non-physical component efficiencies (e.g., greater than 100% or less than 0%). It is plausible that the circumferential variation in the temperature is caused by buoyancy effects. The low molecular weight of the hydrogen and water vapor (combustion products) affects the flow, as the engine is mounted in a horizontal orientation. The RDE was operated in a vertical orientation in preliminary experiments, and minimal circumferential variation of the exhaust temperature was observed.

Due to the issues with isentropic efficiency calculations, total turbine efficiency was calculated using an alternative approach. The alternative approach involves comparing total fuel energy input to the system to energy extracted by the turbines and is referred to as the “turbine factor” in this work. Accurate measurement of the fuel flow rate into the engine was achieved using a sonic nozzle. The power input was estimated using the measured fuel flow rate and assumption of complete combustion. The high pressure turbine is directly connected to the
compressor. Power transmitted to this shaft was calculated using the compressor air flow rate, inlet temperature, and outlet temperature. The low pressure turbine drives an engine output shaft that was attached to a dynamometer. This yields a direct measurement of output shaft speed and torque, which can be converted to power output. This turbine factor was calculated for the OEMC and RDE experiments. The compressor input power, shaft output power, and turbine factor were calculated using the following equations:

\[
W_{\text{Compressor}} = \dot{m}_{\text{Air}} \int_{T_2}^{T_3} C_p(T) dT
\]

\[
\dot{W}_{\text{Output Shaft}} = \omega_{\text{Dyna}} \cdot T_{\text{Dyna}}
\]

\[
\text{Turbine Factor} = \frac{W_{\text{Compressor}} + W_{\text{Output Shaft}}}{\dot{m}_{H_2} \cdot LHV_{H_2}}
\]

Figure 42 shows the turbine factor as a function of the engine energy input for the OEMC test and three RDE tests. The results demonstrate the promise and potential of coupling a RDE with a turbine. The engine survived the experiment and showed no damage after more than 20 minutes of total RDE operation. The RDE gas turbine engine generated power levels similar to those observed with the OEMC. The turbine factor shows promising results, in that the RDE efficiency is similar to or better than the standard combustor across the range conditions explored in this work, and results are repeatable for multiple RDE tests. The turbine factor suggests that turbine efficiency is better with the unsteady RDE flow than with the OEMC; however, there are a few challenges that make quantitative conclusions difficult to achieve. First, the analysis assumed that the combustor and RDE both have 100% fuel conversion efficiency. A sensitivity analysis indicates that if the OEMC combustion efficiency was 15% higher than the RDE, then the measured OEMC turbine factor would be higher than the measured RDE turbine factor. Combustion efficiency was not measured, but with the high reactivity of hydrogen, it is not expected to be very different between tests. Second, the bleed valve that prevents compressor surge during startup is designed to close at higher shaft speeds. In the RDE experiments, the bleed valve closed properly at high shaft speeds, while the bleed valve stayed open to an undetermined degree during the OEMC experiments. The dumped mass was not measured and represents additional energy extracted by the high pressure turbine that is not accounted for in the turbine factor calculation. This could explain the divergence between the combustor and RDE at the high energy input conditions. The unbalanced vertical error bars are a result of this bleed valve issue, and are calculated based on a worst case scenario (i.e., bleed valve completely open). Last, heat loss through radiation and convection from the surface of the engine was not accounted for in these calculations. This is expected to be a minimal effect, as both the RDE and OEMC operated with engine surface temperatures near ambient conditions.
VII. Conclusions and Future Directions

Specific topics discussed in this work include the thermodynamic modeling of RDEs; the pioneering design and development of optically accessible RDEs; the first high-repetition-rate chemiluminescence images of RDEs; the acquisition of detonation cell size measurements at elevated pressures using focused schlieren imaging; the performance of RDEs operating on hydrogen/air and ethylene/air mixtures; the innovative acquisition of heat transfer measurements in water and air cooled RDEs; and the first application of RDEs to gas turbines. The primary conclusions from this work are discussed here.

- The results from analytical thermodynamic models of RDEs compare favorably with the results from both high-fidelity simulations and experiments. RDE thermodynamic models are immature relative to conventional gas turbine engine performance analyses. However, the thermodynamic models appear to capture the principle features of the RDE based on comparisons with the high-fidelity simulations and experiment. As a result, the RDE thermodynamic models are mature enough to be useful for guiding the design and development of RDEs with reasonable accuracy.

- The capability to observe the detonation process in the channel is critical to supporting future progress in the development of RDEs. The application of well-established diagnostic techniques such as OH* chemiluminescence imaging to emerging propulsion devices such as RDEs is defining a new research direction and represents one of the novel contributions of this work. The OH* chemiluminescence images appear remarkably similar to CFD results of RDEs published in the literature.

- Empirical correlations of detonation cell sizes provide important insights into the operation and performance of detonation-based combustors. Detonation cell size measurements of hydrogen/air and propane/air mixtures at initial pressures ranging from 1 – 10 atm are reported in this work. The results demonstrate that higher pressure ratio detonation-based combustors can be designed to be smaller because increasing initial pressure reduces the detonation cell sizes. The results indicate that there is a design tradeoff between combustor...
size and operating equivalence ratio because fuel lean conditions result in larger detonation cell sizes.

- A large fraction of RDE research has focused on achieving detonation and quantifying the operation and performance for a range of geometrical configurations. The specific thrust, specific impulse, and static pressure distribution have been measured for a range of fuel injection schemes, air injection areas, detonation channel areas, aerospike plug nozzles, and converging-diverging nozzles.

- Measured specific impulses of RDEs operating on hydrogen/air and ethylene/air mixtures compare well to measured specific impulses of PDEs and theoretical calculations reported in the literature. The results are encouraging and indicate that RDEs are capable of producing thrust with similar levels of fuel efficiency as those associated with PDEs while operating on gaseous hydrocarbon fuels.

- Rotating detonation engines operating on hydrogen/air and ethylene/air attain similar efficiencies in the conversion of the supplied stagnation pressure to thrust. The measured corrected thrust for the hydrocarbon fueled RDEs matches that of the hydrogen fueled RDEs. The result indicates that it is possible to obtain similar stagnation pressure to thrust conversion efficiencies for hydrogen and ethylene fueled RDEs which is important for future application and desired operation of RDEs on heavier hydrocarbon fuels.

- Performance measurements show that there are incremental improvements in the specific thrust produced as the RDE exit geometry is changed from a bluff-body to an aerospike. The choked aerospike design indicates that there is additional performance to be realized with additional choking of the flow beyond the thermal choke present in the detonation channel. The area constriction leads to larger local static pressures in the detonation channel which are then multiplied by the detonation process and converted to pressure thrust by the nozzle.

- The operation of RDEs for extended periods of time has been demonstrated using water and air cooled geometries. Heat transfer to the RDE channel walls has been measured using calorimetry and resistance temperature detectors. The heat transfer experiments successfully demonstrated that an air-cooled RDE could survive thermal equilibrium and that only a small fraction of the total airflow is required to cool an RDE making air-cooling schemes feasible.

- The coupling of a RDE with a turboshaft engine demonstrated encouraging results. The engine showed no damage after more than 20 minutes of RDE operation. The RDE gas turbine engine generated power levels similar to those observed with the conventional gas turbine engine. The turbine performance of the RDE gas turbine engine is similar to or better than that of the conventional gas turbine engine across the range of operating conditions examined in this work.

Significant opportunities exist for improving the fundamental understanding and the operation and performance of RDEs building on the past progress. Specific areas for future work are briefly discussed here.

- Further attention is needed to quantify the effects of partial premixing, lateral relief, curvature, and turbulence on the behavior of detonations which continuously propagate through non-homogenous mixtures in partially confined annular channels. The effects of partially premixed fuel and air, resulting in non-homogenous or stratified mixtures, on the detonation structure and behavior are largely unknown. The effects of lateral relief result in
partially confined detonations and have received minimal attention. Turbulence-detonation interactions and their quantifiable relative importance represent a potentially important topic.

- From an operation and performance perspective, one of the most important issues involves identifying fuel and air injection schemes that optimize mixing, minimize acoustic interactions between the plenums and channel, and reduce pressure losses across the inlet so that the pressure gain associated with detonations can be optimized. Reducing the pressure losses across the inlet typically results in large oscillations in the air and fuel plenums upstream of the detonation channel.
- Developing fuel and air injection schemes that allow RDEs to operate on liquid hydrocarbon fuels and air is critical to realizing the long-term potential of pressure gain combustion for a range of power and propulsion applications.
- Measurements and calculations of pollutant emissions and acoustic radiation require further attention.

Significant progress has been made in the research and development of RDEs over the past 15 years particularly in the areas of thermodynamic modeling, operation and performance measurements, heat transfer measurements, imaging of optically accessible engines, and application to gas turbine engines as discussed throughout this paper. Significant challenges and opportunities for future research and development of RDEs exist as well. Realizing the advantages of pressure gain combustion in rotating detonation engines is enabling new combustion system design opportunities and supporting the development of efficient and sustainable power and propulsion technologies.

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