A Review Towards the Design Optimization of High Performance Additively Manufactured Rotating Detonation Rocket Engine Injectors

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Abstract

Rotating Detonation Rocket Engines (RDRE) have been marketed primarily for their higher specific impulse potential over constant pressure (CP) liquid rocket engines. However, several other performance advantages exist with RDREs over CP engines such as heat transfer advantages for gas expander cycle, increased completeness of combustion at low chamber L*, compact engine design, reduced coolant channel pressure drop potential, and improved injector C* performance. NASA has paved the way for liquid engine system performance enhancement since the Apollo program and continues to do so with metal additive manufacturing (AM), super-alloy materials, and advanced propulsion concepts. A team of propulsion development engineers at NASA are in the process of developing high-performance 7K lbf class RDRE hardware for their potential use in lander, upper stage, and even launch vehicle applications. Clear advantages have been demonstrated with AM including program cost and schedule reductions of up to 50%. It is well known that injector performance is integrally linked to the global performance of a combustion device. This is especially the case for RDREs since detonation stability is heavily dependent on the mixedness of propellants. A major program goal is to rapidly produce ultra-high-performance AM injectors. This paper reviews the available literature on liquid rocket injector design optimization as well as the experimental work conducted to date on injectors tested in RDREs. Major lessons learned are document and suggestions given towards the design of high-performance liquid RDRE injectors. In addition, the integration of metal AM into the design of liquid RDRE injector schemes is discussed. Finally, several candidate AM RDRE injector elements were produced to obtain their diodicity and cold flow characteristics.

I. Nomenclature

AM = Additive Manufacturing
CWN = Channel Wall Nozzle
DED = Directed Energy Deposition
EB = Electron Beam Welding
GH2 = Gaseous hydrogen
GRCop-84 = NASA GRC Copper-alloy (Cu-8 at.% Cr-4 at.% Nb)
H2 = Hydrogen
ID = Internal Diameter
K-lbf = thousand pounds of force (thrust)
LCF = Low Cycle Fatigue
LOX = Liquid Oxygen

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LWDC = Laser Wire Direct Closeout
MCC = Main Combustion Chamber
MIG = Metal Inert Gas Arc-welding
MSFC = Marshall Space Flight Center
MTD = Manufacturing Technology Demonstrator
PBF = Powder-bed Fusion
psi = Pounds Per Square Inch
RDRE = Rotating Detonation Rocket Engine
RDE = Rotating Detonation Engine
RDC = Rotating Detonation Combustor
SLM = Selective Laser Melting
TCA = Thrust Chamber Assembly
TIG = Tungsten Inert Gas
WAAM = Wire Arc Additive Manufacturing

II. Introduction

Detonations have been substantially researched in ducts, area contractions, and various combustor geometries. Their underlying physics are well understood with classical models that have been long since established. The rapid increase in pressure across a detonation front minimizes enthalpy generation causing thermal efficiency to reach a maximum when compared with the Brayton or Atkins cycles for constant pressure combustion. Harnessing this efficiency gain for practical use in modern combustion technology is another challenge altogether. The common solution for maintaining a stable detonation is by making use of an annular combustion chamber with axial or radial injection of propellants. Numerous experimental works have been conducted to date in an effort to understand the effects of geometry, scaling, and operability of this type of detonative combustor configuration. Not to mention the sheer magnitude of modeling efforts conducted to date. Regardless, these works have substantially researched the efficacy of using detonations to increase engine efficiency and are currently at a crossroads in terms of their development.

It is commonly cited that the peak benefit to detonative combustion devices is the promised ~15% boost in specific impulse (Isp) compared to the maximum theoretical Isp in an equivalent constant pressure (CP) combustor. However, other major performance characteristics are advantages with these engines rather than quantities such as Isp and thrust. For one, these engines are often much more compact allowing for reduced hardware mass a geometry. The completion of combustion has been shown to occur much faster than CP combustors and thus drastically reduces L* requirements as well as the potential to maximize characteristic velocity (C*) efficiency. Other works have suggested that these combustion devices could produce lower overall heat fluxes and lower total heat load to active cooling geometries. In addition, lessons learned from the literature indicates that the heat flux curve in a detonative combustor may decrease as the flow gets closer to the chamber exit. This would allow for the design of ultra-low pressure drop integrated coolant channels, which is another major performance advantage for this engine type. Each of these performance criteria make a strong case for investment into detonative combustion device technologies. With that said, no single literature source summarizes the design optimization procedure for a detonative combustor or detonative liquid engine system. It is the goal of this paper to review, discuss, and summarize major findings in the available literature for;

1. The optimization of an annular type rotating detonation rocket engine (RDRE) utilizing cryogenic liquid/gas injectors.
2. Discuss the desirable performance criteria for thermal steady state RDRE liquid injector operation.
3. Characterize the feasibility and advantages of using additive manufacturing techniques for use in a high thrust application RDRE injector.

The term rotating detonation combustor (RDC) or even rotating detonation engine (RDE) are general terms used interchangeably in the literature that refers to any combustion device utilizing a continuous detonation front to achieve combustion. This device could use air or a stored oxidizer while a rotating detonation rocket engine (RDRE) is restricted to utilizing a stored oxidizer that is limited in supply to achieve continuous rotating detonations. The majority of the experimental work conducted to date on

RDC's utilizes short duration heat sink type continuous detonation. Several examples of which are the works of [1]–[8] and many others. In addition, most of these efforts utilize air as the oxidizer including [9]–[12] and many others. The focus of this work is to produce hardware design schemes that successfully demonstrate flight practical hot fire burns while maintaining operable hardware lifecycle performances. The means by which this will be achieved is the incorporation of radially running square coolant channels directly integrated into a laser- powder bed fusion built (L-PBF) GRCop-alloy annular chamber. NASA's Marshall Space Flight Center (MSFC) has pioneered the use of regeneratively cooled metal additive manufactured (AM) thrust chamber hardware for over a decade and has successfully demonstrated this hardware at stoichiometric conditions for cumulatively tens of thousands of seconds and thousands of starts [13], [14]. Several images of these hot fire tests, in most cases using fully AM thrust chamber assemblies (TCA), are shown in the figure below.

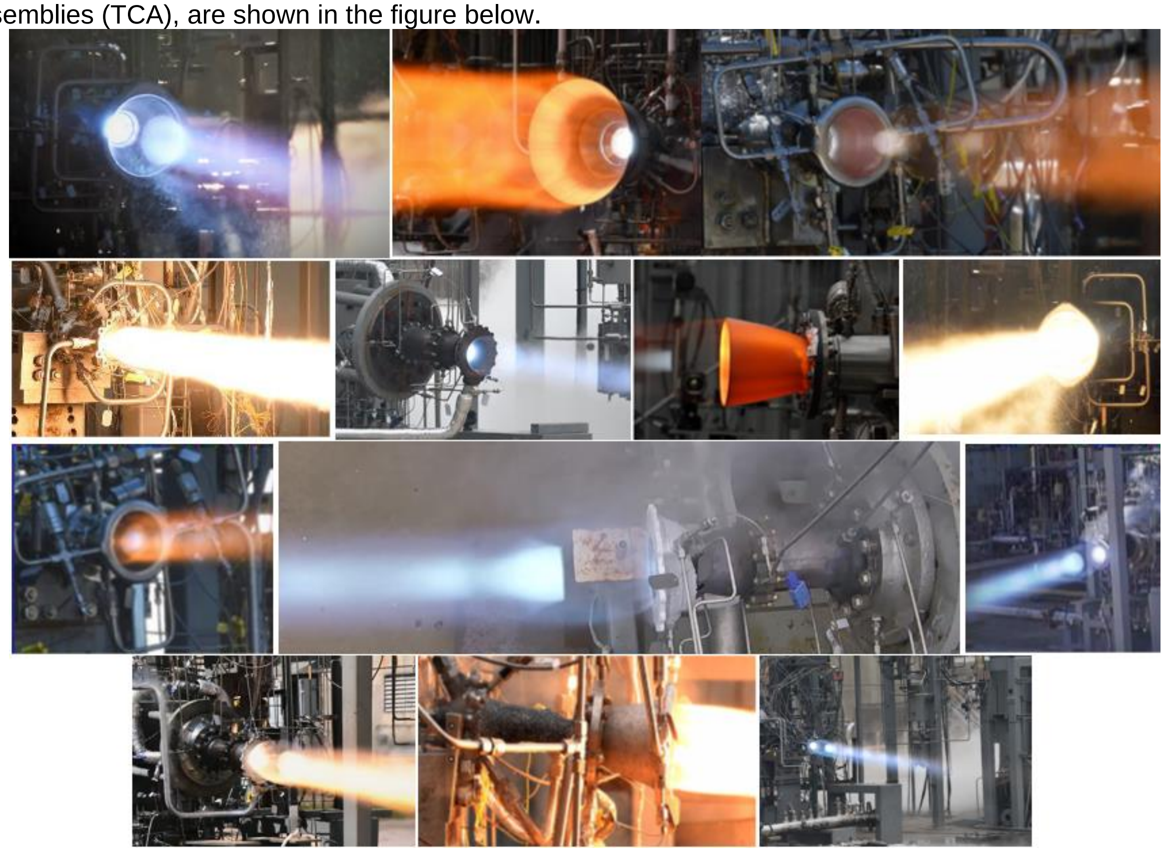

Figure 1. Hot fire testing of metal additively manufactured thrust chamber assemblies including additive injectors, chambers, igniters, and nozzles in various propellant combinations and thrust classes.

Several of these metal AM components are operated in extreme environments often at stoichiometric and even lean combustion for hundreds of seconds at a time. The highly conductive material GRCop-84/42, a NASA invented super-alloy, has been the basis for this success. Other materials that are easily used in additive manufacturing include Inconel 625/718, JBK-75, Monel K500, NASA HR-1, and numerous other refractory and super-alloy materials. A list of metal additive materials commonly used in industry and grouped by their base material are shown in the figure below.

Industry Materials developed for L-PBF, E-PBF, and DED processes *(not fully inclusive)*

Ni-Base
Inconel 625
Inconel 718
Hastelloy-X
Haynes 230
Haynes 282
Haynes 188
Monel K-500
C276
Rene 80
Waspalloy

Cu-Base
GRCop-84
GRCop-42
C-18150
C-18200
Glidcop
CU110

Al-Base
AlSi10mg
A205
F357
6061 / 4047

Fe-Base
SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 420
Tool Steel (4140/4340)
Invar 36
SS347
JBK-75
NASA HR-1

Ti-Base
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

Co-Base
CoCr
Stellite 6, 21, 31

Refractory
W
W-25Re
Mo
Mo-41Re
Mo-47.5Re
C-103
Ta

Bimetallic
GRCop-84/IN625
C-18150/IN625

MMC
Al-base
Fe-base
Ni-base

Figure 2. Metal additive materials commonly used in industry.

Of particular interest for use in RDRE injector design are the high-temperature nickel alloy material Inconel and iron alloy material NASA HR-1 / JBK-75. These materials have been used in additively manufactured injectors and nozzle hardware under numerous test programs at MSFC including but not limited to PK058, PI051, PJ030, PJ141, PK020, and PJ129. Several super alloy metal additive injectors are shown in the figure below.

Figure 3. Examples of various thrust class and material metal additively manufactured liquid rocket injectors hot fire tested at NASA MSFC.

All tested injectors shown above demonstrated exceptional life cycle performances with cumulatively thousands of starts and tens of thousands of seconds of mainstage duration. For this reason alone, these materials would be an ideal candidate for use in RDRE injectors. The reader is referred to [15] which gives a comprehensive summary of AM injectors hot fire tested at NASA MSFC. Since reasonable life cycle performance is desired during a long duration burn of an RDRE, these materials would stand the best chance for demonstrating hardware survivability. Several images of example nickel-alloy injector designs that have been tested at NASA MSFC and demonstrate exceptional life cycle performances are shown in the figures below.

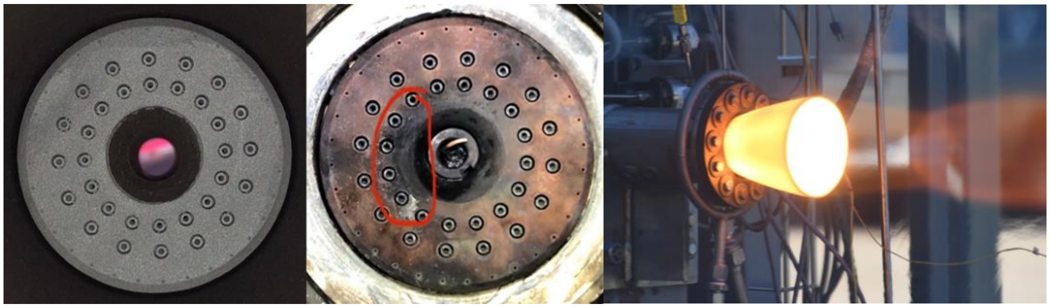

Figure 4. JBK-75 additively manufactured shear coaxial injector. (Left) Prior to testing under PJ141 and PK020. (Middle) Post-testing with More than 3130 seconds of cumulative duration and 21 starts over 2 test series in LOX/GH2 at a nominal Pc of 1000 psi and mixture ratio of close to stoichiometric. Slight face erosion shown in the red circle but not deleterious to injector operation. (Right) Hot fire test demonstration with NASA carbon composite nozzle.

Data from this injector scheme was used to design a co-flow type injector which is discussed later on in this work.

The injector shown above used a JBK-75 additive material produced using L-PBF with a 32-element shear coaxial heritage design. This injector demonstrated great life cycle performance with no element erosion and minimal face erosion circled in red. This injector produced a very high C* performance of nearly 100% theoretical in some test cases. This is however, typical of LOX/GH2 injectors when coupled with high L* chambers. This was also a lower thrust class injector producing thrusts upwards of 2500 lbf. An example of a 7K lbf class lander engine Inconel 625 pentad impingement injector is shown in the figure below.

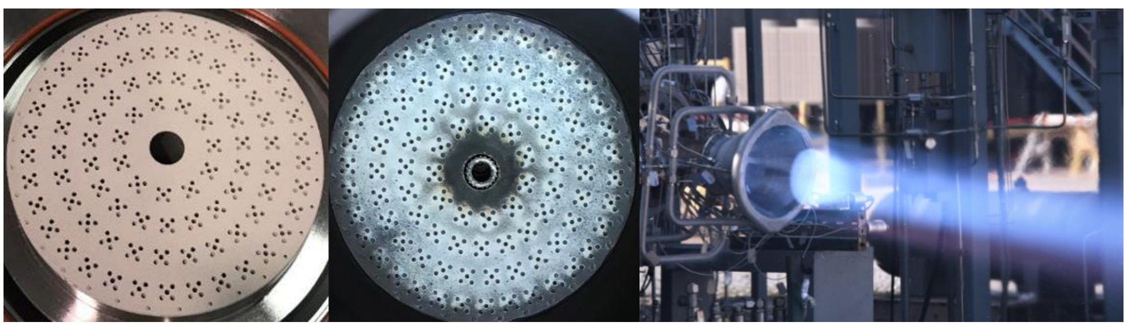

Figure 5. Inconel 625 L-PBF 7K lbf class pentad impinging injector face. (Left) pre-hot fire testing with NiCrAlY thermal barrier. (Middle) More than 720 seconds of cumulative hot fire duration and greater than 32 starts in LOX/GCH4 at a nominal Pc of 750 psi and mixture ratios up to 3.6. (Right) Hot fire test demonstration of AM impinging injector, L-PBF GRCop-42 chamber, and LP-DED NASA HR-1 regenerative nozzle.

This injector design produced high C* performances upwards of 99% theoretical at throttled chamber pressures between 100 psi and 800 psi. Alteration of the hot wall surface finish later showed a C* performance improvement of around 2% at the same operating conditions. Results yet to be published. This in and of itself lays the groundwork for tailor made performance improvement for metal AM components in liquid rocket engines. Experimental data from this injector type was used as a guide towards the design of a similar “close triplet” scheme described later in this work.

These two previously tested injector configurations show reasonably high C* performance and lifecycle performances that can be achieved with additive materials under extreme hot fire conditions. An RDRE variant AM injector will need to have similar mixing, atomization, and life cycle performances to successfully demonstrate flight practical hot fire test durations as well as achieving the ultimate goal of demonstrating equivalent or higher engine specific impulse.

It is not well understood or even completely known if modern combustion device materials and cooling schemes will be able to handle the extreme environments that an RDRE will produce. This is especially the case for flight practical operating durations needed during space missions and launch vehicles. For this reason, a NASA sponsored program denoted the Advanced Rotating Detonation Variant Rocket Combustor (ARDVARC) program was established under the Space Technology Mission Directorate (STMD) announcement for collaborative opportunity (ACO). This effort will characterize the life cycle performances of 7K lbf class AM injectors, chambers, and nozzles to the extreme environment of an RDRE over long duration hot fire tests. There are a substantial number of considerations for hardware development of high thrust regeneratively cooled and additively manufactured hardware as illustrated in the considerations process diagram figure below.

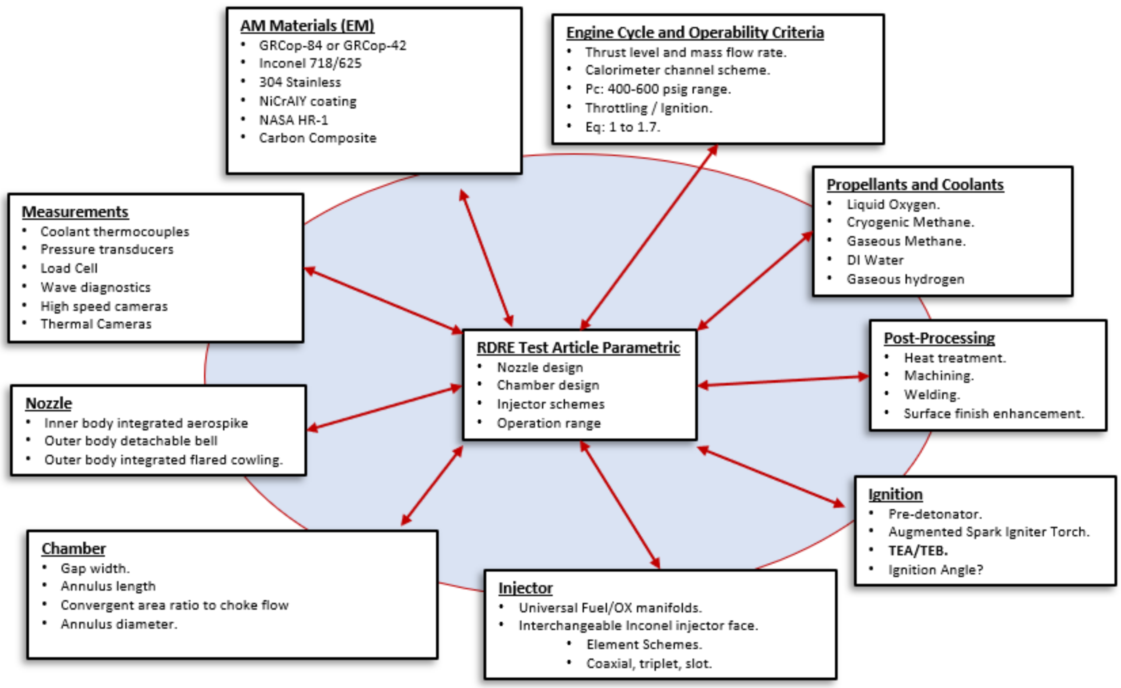

Figure 6. Consideration diagram for development of an optimized performance RDRE.

This work primarily focuses on RDRE injector hardware development in preparation for the experimental program. Several topics and considerations are discussed in reference to optimizing performance for the detonative combustion cycle. Design recommendations are made and incorporated into the design schemes presented.

III. Background and Literature Review

Prior to the design process of an optimized RDRE injector, the available literature was reviewed on annular detonation injectors. Second, an in-depth review on the available constant pressure (CP) combustion device injector performance was also conducted to identify attributes of high C* efficiency injector elements. These reviews are presented below.

A. RDC/RDE/RDRE Injector Research to Date

A limited amount of work has been conducted on detonation combustion device injection. Several articles are in the available literature that describe how injection properties, injector design, and injection mixing effects RDC operation. It was found that air breathing injection schemes dominate the experimental literature in terms of most tests conducted. The typical scheme used is the annular slot injector or annular cross flow orifice injector. It is also very common to see variations in radial and axial injection schemes. Two examples of injection feed systems are shown in the figure below from [1], [16].

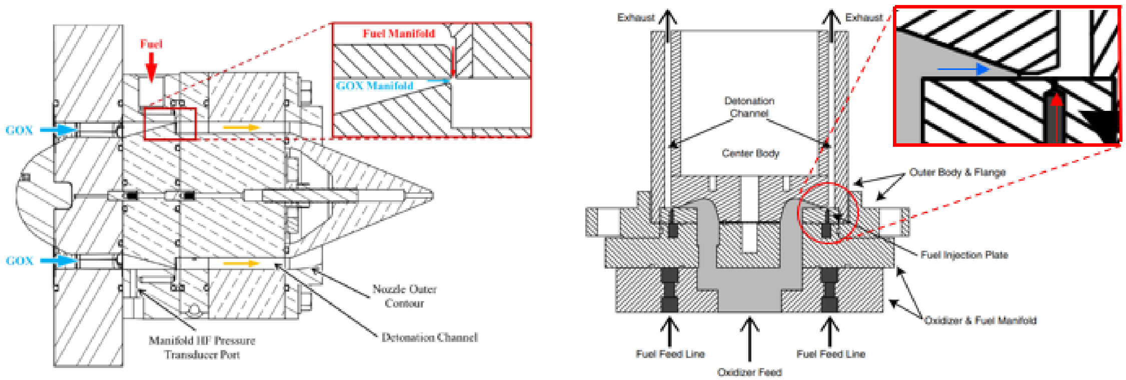

Figure 7. Injection feed systems tested and reported in (left) [17] **and (right)** [1]

The propellant phase commonly employed is the gas/gas bi-propellant combination with hydrogen/air and methane or natural gas (NG) /air is typical. Other works have utilized methane, NG, hydrogen, propane, and even refined petroleum (RP) in conjunction with gaseous oxygen.

Injector scheme aside, several articles were available that looked at variable flow area at constant mass flow rate. Bennewitz et al. 2018 [18], conducted an experimental test series on an uncooled rotating detonation engine at AFRL. The injector flow area and thus pressure drop was varied as well as the mass flow rate across a broad range of mixture ratios using GCH4/GOX as the propellant. Key results noted were a maximum of thrust and specific impulse at or near stoichiometric mixture ratios and a linear increase in thrust with increasing injection mass flow rate. Another interesting feature to note, though not explicitly stated, the number of wave modes present in the combustor for a given test was dependent upon the injection mass flow rate or unburned injected flow velocity.

It was apparent that the number of wave modes present balanced with the propagation velocity of the detonation wave and the annular geometry of the combustor. This lends credibility to the notion that if detonation is achieved in an RDC, sustainability of the wave is not so sensitive to injection properties and channel geometry that the wave will simply be quenched. Instead, the wave will divide or merge the balancing number of wave modes to become anchored in the annulus. Further observations of the experimental data include the following; pressure tap data suggests anchoring of the detonation wave occurred very close to the injector face, specific impulse is maximized when wave speed is the highest and thus when the fewest number of waves are present, a larger injection flow area seems to yield higher wave speeds and higher specific impulse but may be predominantly due to constant mass flow rate error. Finally, the authors note that the engine tended to operate in a specific frequency range which may be caused by a coupling between the RDC natural acoustic modes and the detonation modes.

Anand and Gutmark 2018 [19], summarized the RDC work conducted at the University of Cincinnati. This paper focuses on the experimental results of both an annular RDC and a hollow RDC. It was found that lower injection areas and higher-pressure ratios contribute to an optimal RDC injector design. Both of these variables contribute to a net higher Injector fluidic impedance thus reducing the backflow potential commonly encountered in these combustion devices. Furthermore, a high number of injector ports with small diameters compared to a low number of injector ports with larger flow area, thus holding total injection area constant, was better for sustaining detonation. The cause of this is primarily due to refresh rates and mixing efficiencies. A higher number of ports increases the mixing while simultaneously reducing backflow potential thus improving fresh propellant injection timing. Interestingly, the authors also found that the wave mode operation of detonations to be dependent on the pressure ratio across the injector area. This could be due to a change in mixedness of the propellants which has been previously found to cause wave mode shifts [16].

Full propagation of rotating detonation was observed for pressure ratios that were greater than the chocked criteria pressure ratio. At lower pressure ratios, azimuthal pulsed detonations were observed. It was determined that this was caused by a "chugging" type phenomena where combustion products back flowed through the injector and out again. Finally, this work summarized the wave mode operation space of an RDC. In general, stable wave mode operation occurs at equivalence ratios between 0.8-1.75 and from mass flow rates of approximately 0.2 kg/s and up. These values are likely specific to a certain propellant combination and RDC geometry but nevertheless demonstrates that a minimum mass flow rate and a bounded equivalence ratio band allows for steady and stable detonation to process in an annular RDC.

Since it has been inferred that propellant mixing is of such high importance to wave mode operation, [20] conducted an experimental study on the effects of three different injector configurations in an RDRE. These element configurations from [20] are shown in the figure below.

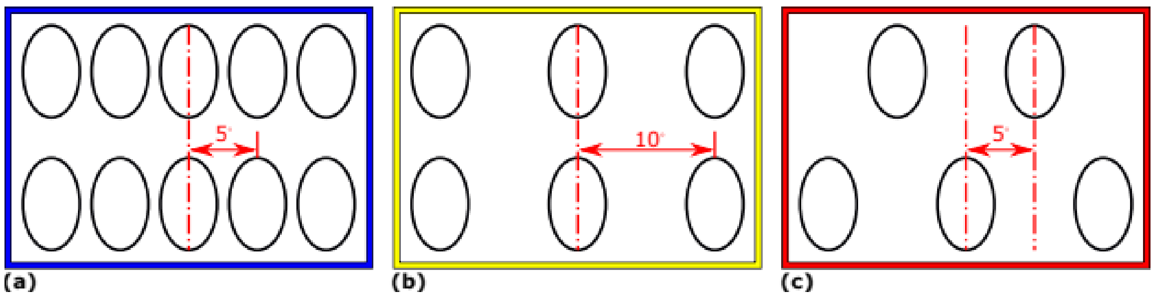

Figure 8. Impinging injector element schemes a) aligned 72 element pairs ~0.131" spacing, b) 36 element pairs ~0.262" spacing, c) misaligned 36 element pairs ~0.131" spacing [20]**.**

The authors found that poor mixing sustained fewer waves in the annulus and causes a breakdown of detonation mode structure, less well-defined waves, and counter propagating waves. In addition, both thrust and wave speed were reduced significantly with lower mixing quality. As the mass flow rate and thus mass flux increased through the annulus, the number of waves present in the annulus increased linearly to seven waves at a mass flow of ~1.3 lbm/s. It is not discussed if the injectors were chocked or not at any given mass flow rate. Some inferences can be made in the data presented in this work to that end. The wave mode operation does increase linearly until about 0.75 lbm/s for the 72-element injector. The wave mode operation appeared to remain constant at five waves until the mass flow rate increases to ~1.3 lbm/s. The tests conducted at this mass flow shows operation at both six waves and seven waves for two different tests. From these observations, it could be that the injector was chocked at and above the 0.75 lbm/s mass flow rate. Since the injection area is not known, this is not certain. The authors did give measured CTAP pressure data for increasing mass flow rates. As expected, the averaged chamber pressure did increase linearly with increasing mass flow rate. Since a single RDRE geometry is presented in this work and as discussed above the wave mode operation ceases to increase linearly at about 0.75 lbm/s, the wave mode operation may plateau and then vary between six and seven waves for the last two cases. At the mass flow rate of 0.75 lbm/s, the measured CTAP pressure is above ~30 psig, which is greater than ~2X atmospheric pressure. This would likely mean that annulus exit was chocked and thus the injector outlet would also be chocked since the injection area is very likely less than the annulus exit area. It is theorized from these results that wave mode operation in an RDC is not as strongly influenced by the chamber pressure as it is by the mixing efficiency, injection velocity, and exit chocked condition.

The last interesting observation made by the authors was that degraded mixing resulted in higher average chamber pressure measurements due to shifting of the reaction zone closer to the measurement location. It can be concluded from this work that injector design for high mixing efficiency is of extreme importance for RDC operation.

Walters et al. 2019 [11], conducted an experimental investigation using natural gas and pre-heated air as well as two different injector configurations. The first was an axial slot injector and the second was an dubbed a sting injector. Both configurations are shown in the image below from [11].

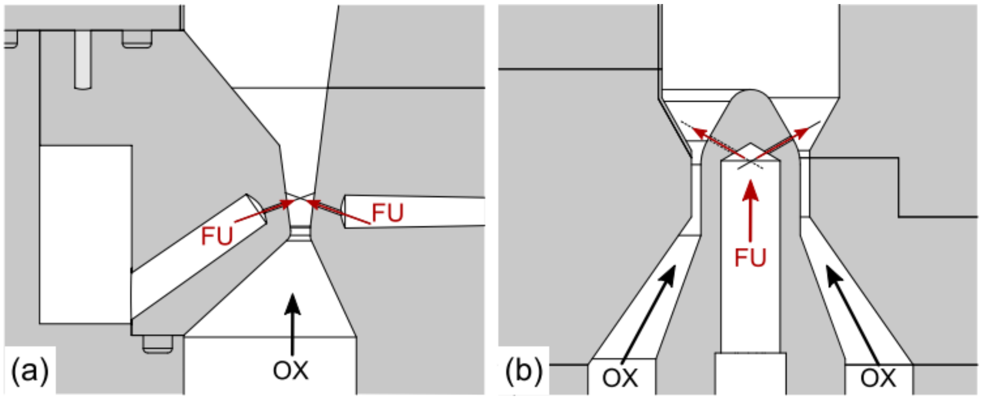

Figure 9. a) Axial slot injector and b) axial sting injector from [11]**.**

It was found that injector configuration (b) produced somewhat higher performance metrics than configuration (a). The thrust efficiency was higher for this configuration and was approximately the same for larger cell sizes. It is unclear to the authors why this was the case. Similarly, injector (b) produced higher C* efficiency band than injector (a).

Fotia et al. 2016 [1], examined the performance gains of axial fed injection versus radially fed injection. Typical injection systems of modern rocket engines employ axial feed systems that inject directly along the fluid flow path through the main combustor. To date, very little work has been done to quantify the effects of axial feed injection in RDREs. This study compared several configurations with JP-8 fuel and hydrogen fuel. It was determined that an increase of ~15% in the corrected thrust was attained with axial fed propellants in similar channel gap configurations when compared to radial feed systems.

Mizener and Lu 2016 [21], built an analytical model of an RDC to determine performance trends with a parametric analysis. The model was designed based on integrated conservation equations and varied several key annular channel designs and operational parameters. It was found that for optimal performance the geometry should have a high injection pressure, low propellant temperature, and positive injection swirl. It was chosen by the authors to model injection swirl likely due to the increased mixing effects. Positive injection swirl likely increased the residence time and thus the mixing efficiency, though it is uncertain if this level of detail was captured in the presented model.

Li et al. 2018 [22], investigated injection strategies for liquid-fuel RDEs. A premixed and non-premixed combination of liquid jet A-1 fuel and air was injected into the chamber via a radial slot inlet scheme. It was found that a rotating mode detonation formed in the startup and transitioned to an axial pulsating mode using premixed propellants. In the non-premixed cases, similar results were observed. In all cases, the detonation front was fairly weak with a low wave pressure gradient.

Stechmann et al. 2017 [16], conducted a high-pressure experimental investigation of an RDRE using O2/methane, O2/NG, and O2/H2. The facility and test article utilized an oxygen pre-burner setup and annular slot with various upstream and downstream fuel orifices in a crossflow arrangement to the oxidizer slot. An image of the injection element arrangement is shown in the figure below from [16].

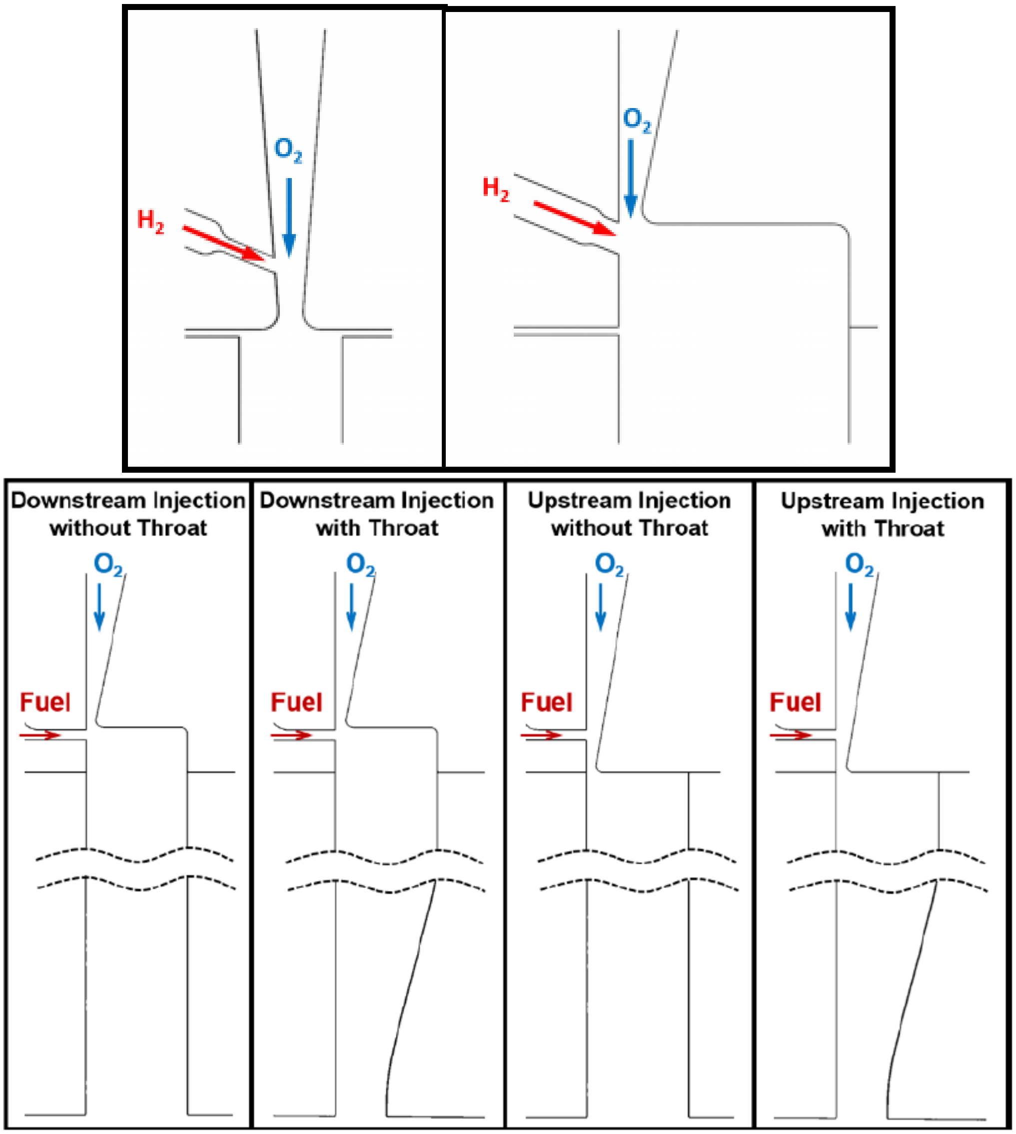

Figure 10. Arrangement of injector and channel schemes experimentally investigated in (Stechmann, et al., 2017). On top left is V1.0 configuration, top right is the V1.1 configuration, and on the bottom are various V1.2 configurations [16]**.**

This work is the most applicable to the injector operating conditions expected during this program. The injector orifice and slot sizing was altered as shown in the figure above to gauge the detonation stability and engine performances. The element scheme shown on the top left (V1.0) is more similar to CP liquid rocket engine elements. Detonation in the V1.0 and V1.1 configurations only occurred near shutdown when the injector plenum pressures were low. It must be noted that a significant analysis was given on flame holding and parasitic deflagration through short ignition delay. This was likely a problem experienced due to the hot oxygen from the pre-burner greatly increasing the chance for parasitic deflagration. Other works such as [23], were able to achieve rotating detonation in O2/H2 using much lower injection temperature thus increasing the ignition delay. The V1.2 injector did successfully yield rotating detonation in all configurations. It was concluded that the detonation behavior was highly sensitive to the injector and throat configuration. The work of [16] and other works by this author are further reviewed in a later section.

Sosa et al. 2020 [23], conducted an experimental investigation with gaseous O2/H2 in an uncooled annular RDRE. The injector configuration incorporated 72 aligned impingement ox and fuel jets with orifice sizes of 0.9 mm and 1.1 mm in diameter. Consequently, this element scheme is identical to a configuration described in [24]. An image of the test article and injection scheme is shown in the figure below.

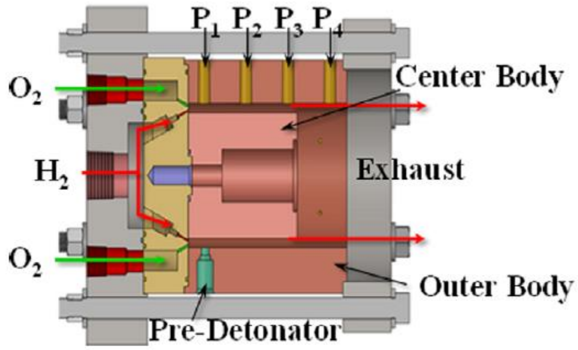

Figure 11. RDRE test article hot fire tested in [23]**.**

This injector configuration was tested up to just under a total mass flow rate of 1.2 lbm/s and produced 5 rotating detonation waves in all cases shown. CTAP pressures measured reached up to 153 psia. All cases tested utilized some percentage of methane as a tracer to visualize the rotating detonation wave front.

As mentioned above, a similar experimental investigation by Hargus et al. 2018 [24], was conducted at the Air Force Research Laboratory (AFRL) using an uncooled annular combustor with typical hot fire tests lasting 1.25 seconds. In addition to the injector geometry presented in Sosa et al. 2020, another misaligned geometry was considered with a 2.5 degree spacing which translates to roughly 0.065 inches. These two element schemes are shown in the figure below from [24].

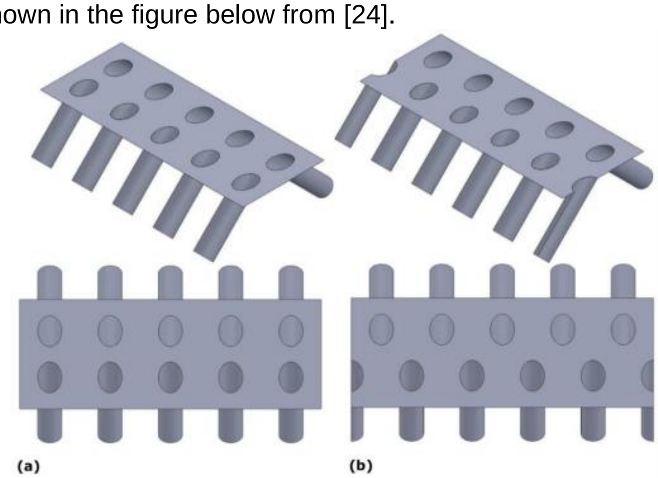

Figure 12. a) Aligned impingement injector element scheme, b) non-impinging and misaligned injector element scheme [24]**.**

The misaligned element scheme solely relies either on wall impingement and/or secondary detonation front mixing while the aligned injector scheme relied on jet impingement in addition to secondary mixing processes. This investigation was also capable of altering the element flow areas from 1, 1.5, 2, and 2.5 times the smallest area. A suite of tests were conducted across equivalence ratios and mass flow rates. The authors note that the performance of the engine varied only slightly with altered orifice area and equivalence ratio. It was also noted that substantial drops in plenum pressure did not appear to be detrimental to engine performance. A closer look at the data suggests that the 2X area elements performed the highest in the range of typical liquid rocket engine equivalence ratios but this may not be statistically significant. This may be due to some optimization between element spacing causing increased mixedness as the elements encompassed a large amount of the injector faces “dead space”. Once the orifice area became large enough, atomization may have been adversely affected. As for the injector element type, impingement or misaligned, there is a notable drop in engine performances with the misaligned elements. As tests moved away from stoichiometric conditions, the performance of both element schemes showed similar performances. The performance metrics mainly assessed included thrust and specific impulse. The authors also note that mixedness may compete with equivalence ratio for direct impacts on the detonation cell width. An image during hot fire test of this RDRE configuration is shown in the figure below from [24].

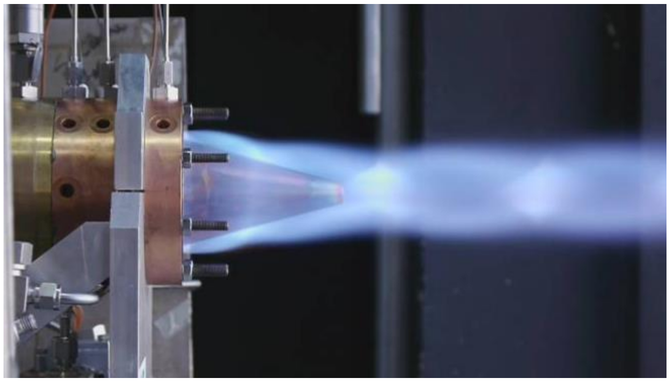

Figure 13. AFRL GHKN RDRE during hot fire test [24]**.**

Goto et al. 2019 [25], conducted an experimental investigation of an RDE with different nozzle and injector configuration to asses performance. Two injector types were used including a triplet and doublet element scheme. These schemes from [25] are shown in the figure below.

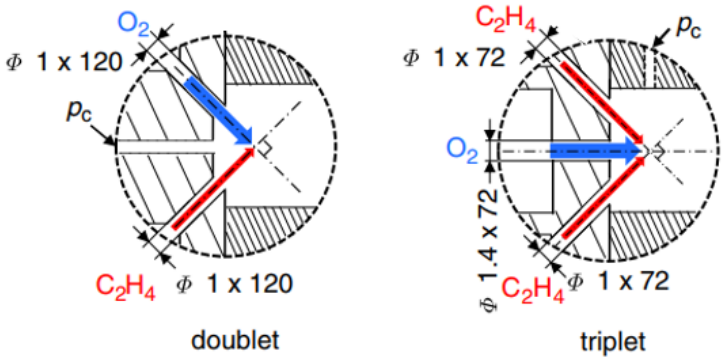

Figure 14. Injector element configurations tested under the experimental investigation in [25]**.**

The doublet scheme used 120 sets of 1mm diameter fuel and oxidizer orifices. The triplet scheme used 72 sets of 1mm fuel orifices and 1.4mm oxidizer orifices. A slot injector configuration was also included in the study, likely as a control. Both the triplet and doublet injector schemes showed clear performance advantages over the slot injector. Both schemes trended closely with the optimally calculated specific impulse. As the pressure ratio increased, the specific impulse increased as expected but with the injector and chamber configuration producing nearly 100% theoretical specific impulse in some cases. Not surprisingly, cases that employed a throat constriction performed very well. It was interesting to note that a single case of the triplet injector with open throat produced higher specific impulse than the highly constricted throat configuration at nearly the same operating conditions. These results were, however, within measurement error. The authors go on to note that characteristic velocity was nearly identical for all cases of the triplet and doublet schemes at elevated conditions. The slot injector on the other hand was consistently in the range of 15-40% lower in normalized chamber pressure at the same conditions. Finally, the authors note that the doublet configuration cause damage to the combustor wall likely due oxidizer rich environment near the chamber wall causing substantial erosion. The authors thus recommend a triplet scheme due to improved wall compatibility.

The study above as well as the work of Ishihara et al. 2017 [26] utilized the same triplet injector configuration in addition to a slot injector shown in the figure below from [26].

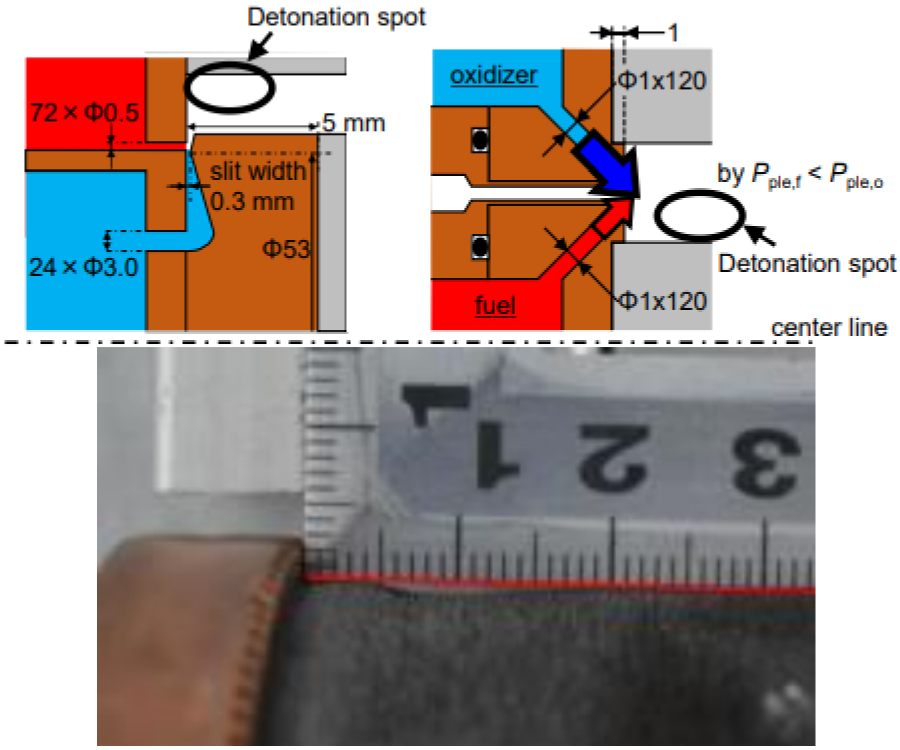

Figure 15. Injector element schemes tested under [26] **(top) and region of anchored detonation causing damage to the chamber carbon composite wall using the triplet configuration.**

Consequently, the figure below also reveals the location of where the detonation was anchored confirmed by an indentation from where the detonation resided causing damage to the combustor wall. This piece of information is invaluable as it suggests that the detonation can be stood off from the injector face by means of moving the impingement location similarly to altering the location of the anchored flame in a CP combustion device. This work also reveals the length of the detonation front which is not typically reported in the experimental literature. In this case, the detonation "groove" in the chamber wall appears to be about 0.4 inches in length. Of course, this must be confirmed prior to making significant assumptions.

Lim 2019 [27], conducted an exhaustive study (as is typical with a PhD dissertation) on the responds of liquid injector orifices to transverse detonation waves at elevated pressures and hot fire tested an RP-2/gaseous oxygen RDE. Several performance parameters of the RDE were quantified including heat flux, multiple injector element schemes, thrust and Isp, and visual confirmation of detonation stability. Tests were conducted up to 7.7 lbm/s with static chamber pressures up to 258 psia. A significant study on liquid injector response to a passing transverse detonation wave was given. Summarizing the findings, the author found a correlation of backflow potential and orifice geometry. Several different injectors were hot fire tested and their performances compared. The thrust was found to be consistently between 85% and 95% that of a CP equivalent engine operating at 100% efficiency.

Several articles have been reviewed in an attempt to understand how to optimally design an injector for operation in an RDRE. Several lessons learned were noted and design schemes that appeared to yield higher overall performances. These lessons learned are documented below.

- Higher thrust and stronger wave fronts are observed for well mixed propellants.
- High element density with a large number of elements in a close spacing produced higher overall engine performance and detonation stability.
- Small inlet orifices yield higher fluidic impedances reducing the likelihood of back flow and increasing the refresh rate for identical back pressures.
- Axial fed propellants produce higher overall engine performances than radial fed propellants.
- Low feed pressures don't appear to be detrimental to engine performance.

- A chocked annulus exit and chocked flow at the injection orifices may isolate the detonation fronts and increase detonation stability.
- High mixedness tends to yield fewer but stronger detonation waves.

The literature presented above appears to suggest that RDRE injectors are not so dissimilar from CP combustion devices. They do also rely on highly mixed and well atomized propellants to improve overall combustion performance as well as sustain the detonation.

B. Review of Constant Pressure Combustion Device Injector Design

In an effort to better understand how to optimize the performance of an RDRE injector, and since RDREs are not so dissimilar from CP combustion devices, the available literature was reviewed on the design optimization of traditional liquid rocket injector elements. Several of these traditional element schemes are shown in the figure below.

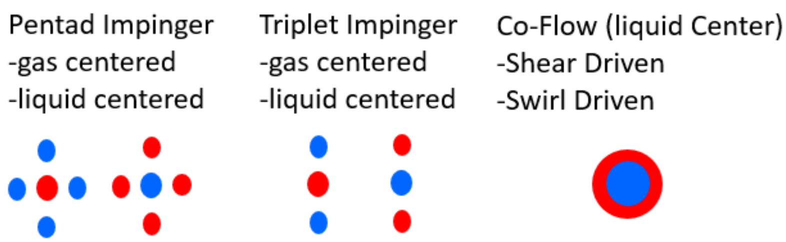

Figure 16. Traditionally manufactured and most common liquid bi-propellant injector elements schemes. Blue represents liquid phase propellants and red represents gas phase propellants.

A particular focus was placed on the review of co-flow or co-axial elements as they were the most prevalent in the literature and in many articles, the highest performing. Impingement type elements were also reviewed from the available literature but to a lesser extent.

Coaxial Type Injector Elements

The coaxial injector configuration is a common type of non-impinging injector element, well known for its use on the Space Shuttle Main Engine. It is noted for excellent mixing and atomization, low pressure drop, and proven dependability [28]. The element typically consists of a central low velocity liquid oxidizer surrounded by a high velocity gaseous fuel. Mixing, atomization, and mass distribution rely upon shearing or swirled cross-flow of the liquid with the gaseous exterior. Maintaining a high velocity gradient between the gaseous fuel and liquid oxidizer is crucial to ensuring that proper breakup and atomization occurs [29]. Mixing plays a significant role in determining the performance and wave propagation characteristics of RDREs [20]. While research on RDRE coaxial injectors is sparse, coaxial injectors for constant pressure combustors have been studied in great depths. An image representation of a typical coaxial injector element is shown in the figure below from [30].

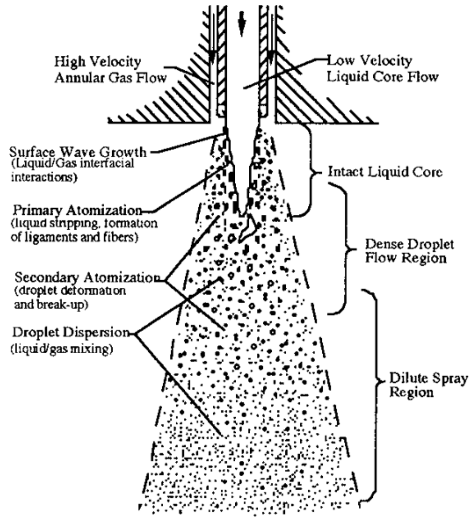

Figure 17 Coaxial injector element and atomization spray field [30].

The state of available co-flow injector literature was reviewed for ways to optimize performance, specifically C* efficiency which is a the confluence of atomization and mixing efficiency [31]. Several articles reviewed provided a fundamental background for coaxial injectors [28], [29], [32]–[36], with articles [20], [36], [37] specifically detailing the state of injectors in RDRE's. Additive manufacturing methods and applications were reviewed in articles [15], [37]–[42]. Aspects of atomization were investigated in articles [20], [30], [31], [43]–[58], while flame dynamics were reviewed in [59]–[68] . Ignition dynamics literature was found to be less prevalent but reported in [69], [70] as well as injector face heat flux in [71]. Finally, supercritical propellant conditions are examined in [35], [48], [51], [65], [66], [72]–[75].

Atomization describes the ability of the injector to break down the propellants into small droplets, where the droplets mix in the spray field, vaporize, and begin to combust. The atomization process strongly depends upon injection conditions, propellant properties, and the local flow of the spray field. The ability for a coaxial injector to atomize liquid propellants is essential to high-performance. The complexity of the atomization process means that coaxial injector design must be based on both basic principles and empirical rules, leading to numerous experimental and theoretical investigations.

Maintaining a high velocity ratio between the gaseous fuel and liquid oxidizer is critical for overall performance by helping to properly atomize the propellants [28]. LOX and fuel velocities can be influenced by several factors. These include injector geometry such as the LOX or fuel post diameters, or system parameters such as propellant density and mass flow rate. Adding a tapered angle to the inside of the LOX post has consistently been found to increase the mixing quality. Mixing can be further improved by recessing the distance of the exit of the LOX post from the exit of the fuel post. Ideal performance occurs when the recess length is approximately the same distance as the LOX post diameter [52]. Other studies have been conducted to determine a specific model for predicting the diameter of atomized droplets. It was found that droplet diameters of 1000 microns or less should be required, with an ideal injector creating droplets smaller than 10 microns [46]. A test campaign completed by R.J. Burick of the Rocketdyne Corporation found, for example, that a reduction in droplet diameter by a factor of 2 would increase efficiency enough to allow a reduction of L* by a factor of 4 [31]. It should be noted that there are many other non-dimensional numbers or ratios besides the velocity ratio that are commonly used to evaluate injector performance in coaxial injector studies. The momentum flux ratio and Weber number can play an important part in characterizing an injector [55].

Investigations of reactive sprays have shown a notable interaction of combustion and atomization. This means that aerodynamic forces between the propellants are not the only thing controlling atomization. The release of heat and combustion reaction products change the conditions for atomization and droplet vaporization [61]. Flame dynamics and the type of fuel can have a further effect on atomization. Different atomization regimes can occur depending on whether the flame is attached or detached from the LOX post. Flame blowout and liftoff can initiate by a high velocity ratio and small LOX post diameter. A tapered LOX post has been shown to improve atomization by inducing an oscillation in the liquid jet core [31]. Consequently, this also reduces the vorticity region in the gap between the LOX and fuel annulus where a flame would typically anchor [59]. Another study found that the high-pressure flame emission spectra of LOX/CH4 is similar to that of LOX/H2. They found that as soon as the oxidizer was supplied, the flame anchored in the wake of the LOX post at all observable operating conditions. The flame shape itself was found to be influenced by the injection velocity ratio and momentum flux. Sonic injection of both Ch4 and H2, can result in low velocity ratios and produce stretched flames, while a larger momentum flux can cause a more confined spreading angle and constricted flame [60]. Another experiment comparing the flames of H2 to CH4, found that under the same chamber pressure, the liquid intact core length was shorter for CH4 than H2. This is attributed to the higher density of CH4. Higher momentum flux ratio tends to promote jet instability and result in an earlier onset of jet disintegration. Key findings in this work showed that as the weber number decreased, the flame lift off distance and the intact core length decreased [61]. Flame-acoustic interaction was found to be most sensitive to changes in fuel-oxidizer density ratio [63]. In a test of supercritical hydrogen-oxygen with a chamber pressure of 80-bar, dynamic mode decomposition results showed that the flame dynamics were strongly influenced by the LOX injector acoustics, whereas no flame response to injector acoustics was observed for a 50-bar chamber pressure [66].

As for the optimized design of a coaxial element, a few articles stand out. The work of Oschwald et al. 2008 [61], describes a number of advantageous design characteristics for coaxial injectors. First, the atomization process is highly complex and can be described by the momentum flux ratio. For large values, the liquid jet tends to result in earlier onset of disintegration due to imparted instability at the surface of the jet. Similarly, the Weber number represents the relative disturbance of the gaseous co-flow to the liquid jet surface. It has been observed that as Weber number increases, ligament and droplet dimensions become smaller and secondary atomization is encouraged. Droplets have also been observed being transported to a larger radial distance. Key findings in this work showed that as the weber number decreased, the flame lift off distance decreased and the intact core length also decreased. Finally, it was found that the intact LOX core length decreased when the LOX post thickness was decreased. This also resulted in a thinner anchored flame at the post and in the stagnation region downstream.

Next, the work of Burick 1972 [31], gave a comprehensive experimental review of co-flow type injector design optimization. Several key takeaways can be gathered from this work. First, as the gas density increased, so did the mixing efficiency and overall C* performance. A LOX post recess of approximately one LOX post diameter resulted in higher overall efficiencies as described previously. Element spacing plays a key role in the mixing process and generally speaking, a well distributed field of elements produces higher efficiencies. Smaller LOX jet diameters produce smaller droplet diameters. As the liquid jet velocity increases, the average droplet diameter decreases. High gas injection velocity allows for improved mixing and secondary atomization of the liquid jet. Finally, small droplet diameters are essential for high efficiency combustion.

Finally, several secondary observations have been made from the available literature. Mixing quality increased with an increase in LOX post inner taper and injection gas density [52]. Nondimensional numbers characterizing fluid-dynamic interactions are not sufficient to scale coaxial injector performance in hot fire tests from one fuel to another [55]. If the liquid jet has a much higher velocity than the flame speed, flame holding can only occur when the post thickness is greater than or on the order of the flame thickness [59]. Under the same chamber pressure, the liquid intact core length was shorter for CH_4 than H_2 which is attributed to the higher density of CH_4 [61]. The combustion efficiency of the subcritical oxygen case had the highest performance with a slightly increasing efficiency as the injection velocity ratio increased [72]. Higher chamber pressures correlate to higher efficiencies at the same droplet sizes [52].

In summary, there are two types of control that can be used to alter the performance of coaxial injectors; geometry and flow parameters. These parameters are listed below.

1. A beveled internal LOX post seems to allow the liquid jet to disperse and impinge on the high velocity gas sooner, thus reducing the in-tact core length.
2. A recessed LOX post of 1X post diameter seems to be optimal in imparting an oscillation in the jet which allows for the jet to fan out and break up sooner.

3. High velocity gas and low relative velocity liquid allows for quicker breakup of the liquid core.
4. A higher velocity liquid core produces better atomization but reduces the mixedness between injector elements.
5. Swirling of the liquid core increases the mixedness and atomization and thus drastically improves combustion performance.

In the case of the swirl coaxial element, put simply, swirling allows for the effective dispersion or "thinning" of the liquid core into an annular sheet which is then effectively atomized in the crossflow of the high velocity gaseous annulus. Consequently, this swirling also rapidly disperses the propellants so that mixedness between elements is maximized. An image of the swirl coaxial AMDE injector from [15] demonstrating this high degree of atomization and mixedness in cold flow testing is shown in the bottom right image of Figure 20.

Impingement Type Injector Elements

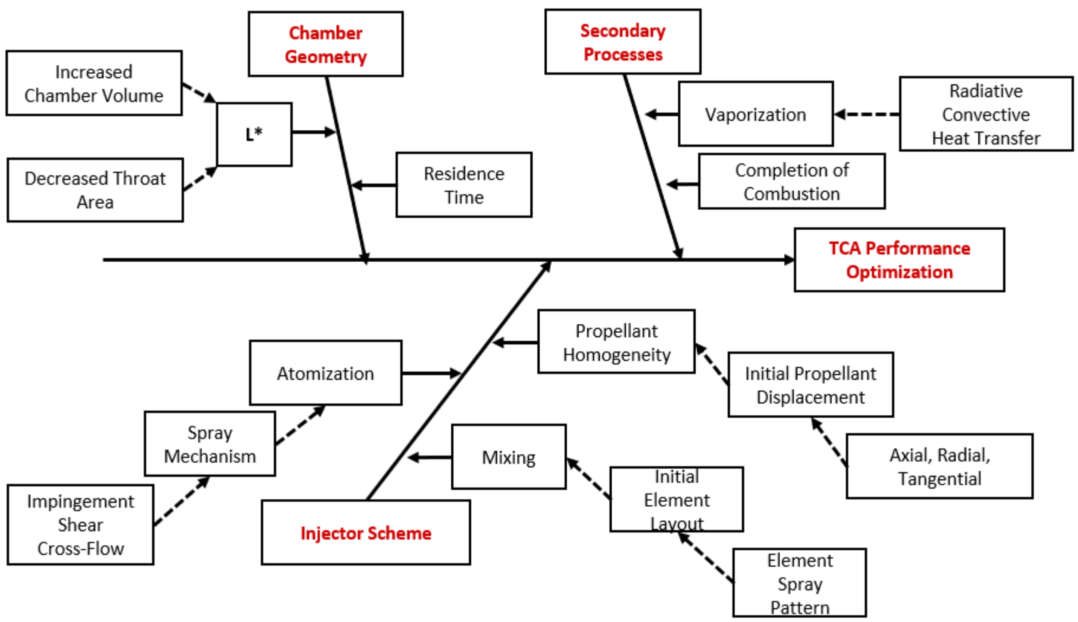

Figure 18. Process flow diagram for considerations in combustion performance of an injector assembly.

C. Integration of Additive Manufacturing into Injector Design

Several different coaxial type injectors have been tested at NASA MSFC outlined in [15]. Several different thrust class, bi-propellant, and material AM co-flow injectors from [15] are shown in the figure below.

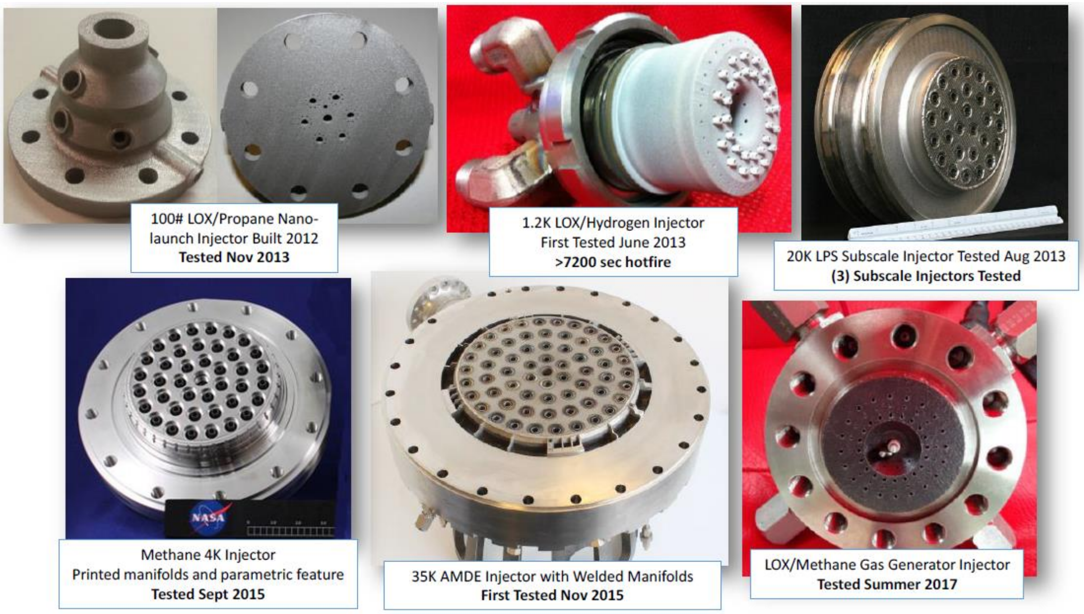

Figure 19. Various L-PBF Injectors manufactured and tested at NASA MSFC.

Several works have found clear advantages with using AM to produce injector hardware including reduced number of parts, rapid manufacturing, equivalent performance to traditionally manufactured injectors, and reduced overall costs of manufacturing [15], [76]. In addition, AM allows for the production of components with complex internal structures not previously possible with single piece traditional manufacturing [76]. Even large scale AM injectors can be produced where the work of [77] designed and hot fire tested a 35K lbf class upper stage AM injector.

Water flow testing to characterize the mixing and atomization has been a benchmark for injector design. This is particularly the case for AM produced injectors since validation of free and clear channels is vital to their operation. Often powder can remain in the elements, thus water flow testing can be used to confirm their flow uniformity. Several images of AM injector water flow testing is shown below.

Figure 20. Water flow testing of various thrust class AM injectors.

Water flow testing can also give an engine designer a qualitative idea of its effective atomization and mixing since a high degree of which would translate to high performance. The common notion for injector design would be to simply print thousands of extremely small orifices that effectively atomize and disperse propellants into the chamber to optimize combustion performance. However, there are still limitations with metal AM that the design must be aware of. First, there is a lower limit of orifice size that can be effectively printed. Laser powder bed fusion (L-PBF) would yield the lowest orifice size possible of all AM build methodologies. This limit is further compounded by the requirement of the orifice being cleared of powder in post processing. All powder must be cleared from the orifice prior to heat treatments. In the case of materials that require stress relieving and solutioning heat treatments, the designer must also consider the build orientation. For Inconel components, residual stresses must be relieved prior to removal from the build plate. Thus the engineer must be able to remove powder from all orifices while the part remains on the build plate. An example image of an Inconel 718 L-PBF produced NASA impingement pentad injector on the build plate and off the build plate is shown below.

Figure 21. NASA 7K lbf LOX/methane pentad impingement Inconel 718 injector.

Both NASA and industry have been developing AM injector elements for the last several years. Several works are available that describe AM injector performances under cold flow and hot fire conditions, their development process, and empirical models for design iteration.

Sims and Hulka 2019 [78], developed AM liquid propellant swirl injector flow elements. This work documented their design, modeling, cold flow testing, hot fire testing, and lessons learned. It was found that wall powder buildup after the L-PBF process caused non-uniformities in the spray cone when the slot was very small. It was also found that traditional models could not accurately predict the spray cone evolution to full flow but a Reynolds number like nondimensional value may exist to predict such evolution. This information was then used to develop a multi-element injector which yielded high performances at 50% power level.

D. Traditional and Potential Injector Element Flow Properties

From the start, it was apparent that the element design trade space could be significantly broadened by integrating metal AM technology with the design of an injector. First, traditionally manufactured injectors typically rely on circular ports to transport propellants into the combustion chamber. The flow vector of traditional element schemes often incorporates axial injection with the exception of the like or unlike doublet element scheme. A representation of element orifice flow vectors relative to the axial chamber geometry are shown below.

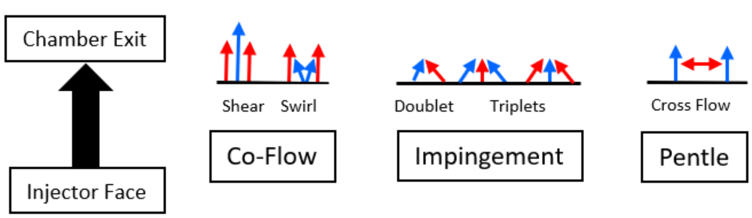

Figure 22. Traditionally manufactured injector element orifice flow vector relative to the axial chamber coordinate system.

These element schemes often rely on high gaseous fuel velocity or rapid chemical kinetic rates to effectively breakup the axially injected liquid oxidizer jets. It has been observed during hot fire testing at NASA MSFC that low injector pressure drop conditions on the gas fuel side can produce low relative C* performance due to ineffective breakup of the liquid jet. This has generally been observed to be the case for all element types that employ axial liquid injection. With slower chemical kinetic propellants, these performance detriments are only further amplified. The performance of axial injected gas elements is affected to a lesser extent and typically produce slightly higher on average performances with similar peak performances. Some, if not all, traditional injector types can produce higher performances with low engine throttling. This has been observed to be caused by slower axial injection of liquid propellants which increases their residence time in the chamber and decreases the jet stiffness allowing for more effective breakup by secondary mechanisms such as attached flame breakup. A plot that depicts these observations is shown in the figure below.

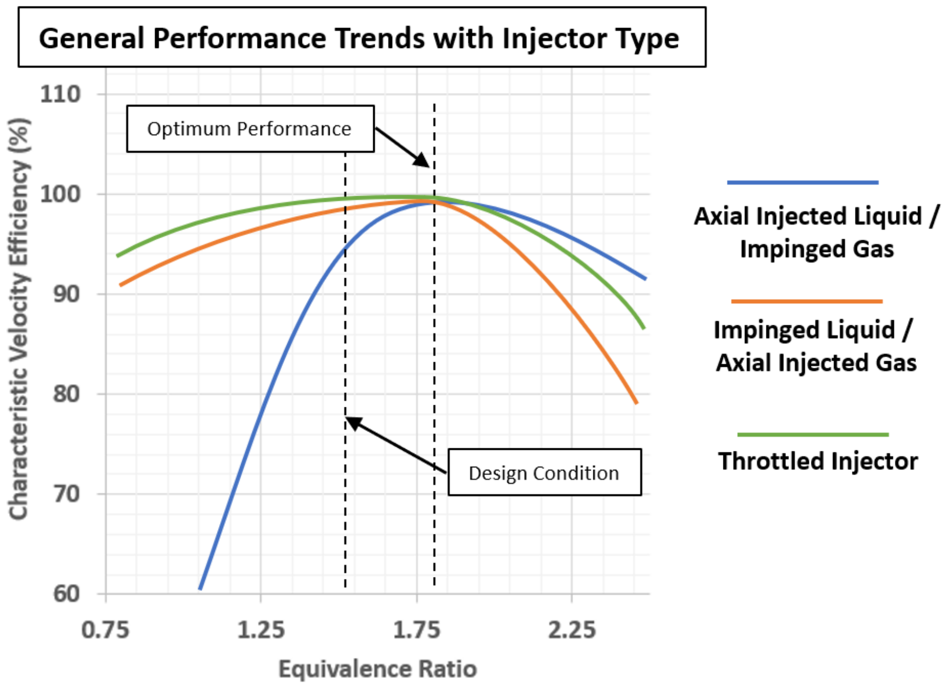

Figure 23. General performance trends of traditionally manufactured injector elements.

These trends do not describe all injector types but rather are a representation of those observed during hot fire testing at NASA MSFC. Another important observation is that these the optimum injector performance may not align with the design performance of the engine. This is due to a number of challenges including but not limited to off nominal injector flow area and reduced effectiveness of secondary mixing processes.

AM has the unique capability of producing new element schemes that were not previously possible with traditional manufacturing techniques. This includes slots, ovals, mesh screens, and micro-elements. These geometries have the potential to produce better atomization and mixing, increased residence time, and improved rate of vaporization all with equivalent injector pressure drop performances to traditionally manufacture element schemes.

The desirable attributes for AM detonative injectors are further highlighted in the following section.

IV. Desirable Attributes for an Additively Manufactured RDRE Injector

Several attributes that may solve significant challenges present in RDREs are discussed in this section with realizations from the available literature. Backflow, mixedness, fill height, system losses, and hardware robustness are all discussed.

E. Element Diodicity

Diodicity is typically utilized as a measure of performance for fluid diodes such as tesla valves. This is formulated as the ratio of the pressure drop in the reverse direction of flow to the pressure drop in the forward direction of flow.

$$D_i = \Delta P_r / \Delta P_f$$

Several articles were reviewed for information on the design and integration of a simple fluidic diode structures [79]–[86]. Experimental values of D_i for optimized fluid diodes can be as high as 10 for low Reynolds numbers (~100) [79]. It is theoretically possible to achieve D_i values significantly higher for systems where the Reynolds number is significantly higher. Similarly, the impulsive diodicity may be substantially higher still. The impulsive diodicity is a transient measure of the diodicity where the reverse flow is achieved from transient pressure gradient rather than steady state pressure. An example of a fluid diode is shown in the figure below.

Figure 24. Tesla type fluid diode with high resistance in the reverse direction and low resistance in the forward direction. Individual junctions or cavities also shown.

It may be more applicable to incorporate the impulsive diodicity rather than the steady state diodicity for applications in RDEs. For an RDRE injector element, the Diodicity of a element may not fully characterize the elements performance potential to negate back flow when a detonation front passes. In this case, the impulsive diodicity is more a function of the fluids inertia, duration of the transient event, and the original back pressure of the element. Modeling of this transient system can really only be fully realized through computational fluid dynamic modeling or experimental testing. So for the purposes of this effort, a general fluid diode design, informed by the literature and limitations on AM build processes, will be incorporated into the AM injector elements to reduce the potential to back flow. Several AM informed fluidic diode schemes under consideration are shown in the figure below.

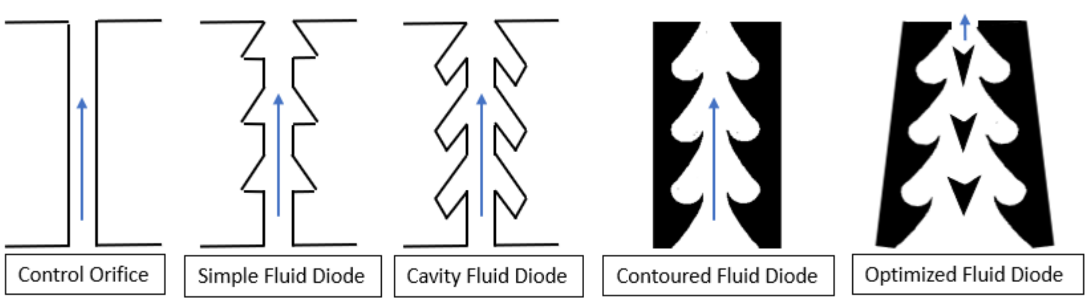

Figure 25. Potential fluidic diode structures integrated into an injector orifice and control case for comparison.

Not surprisingly, to achieve the mixedness and atomization desired in an RDRE for stable detonation propagation small element orifices are practically a must for a uniform and homogeneous mixture. As a general rule of thumb for maximizing mixedness the smaller the element size and more uniformly distribute the elements the better [31], [52]. This design practice for injector elements has also yielded higher on average C* efficiency for constant pressure thrust chamber assemblies. It stands to reason that this would similarly hold true for detonative combustors. This is however, only one side of the coin for consideration with injector design. The other consideration is high atomization of the mixture which can be achieved by optimizing the injector elements geometry and comparable pressure drop across both the fuel and oxidizer orifices [31]. Pressure drop is really a stand in for injection velocity and injection momentum of the working fluid.

The phase state of the propellant, typically gas or liquid, is also an important consideration for negating the potential of the fluid to backflow. Liquids can theoretical reduce the bulk back flow potential due to their inherent incompressibility but with the drawback of reducing their effective fill height due to low injection velocity compared to gaseous phase propellants. Gasses, on the other hand, can recover much quicker but at the detriment being forced further back into the plenum than liquids. Implementation of fluidic diodes could theoretically accentuate the positive attributes of propellant injection and hinder the negative attributes. For example, an incompressible liquid would naturally act as a rigid column when experiencing a sharp pressure gradient. In a fluid diode structured element, the entire column would resist backflow and allow for quicker refresh once the detonation front passes. Gaseous propellants will not behave this way due to their natural compressibility. In this case, the gases would likely compress with the sharp pressure gradient like a spring would if encountering a sudden force. Regardless, a fluid diode could in theory hinder back flow but would need to act on time scales similar to that of the rate of detonation passage. In the image of a fluid diodes presented in Figure 25, the first fluid junction would play the most important role in hindering back flow since it would experience the sharp pressure gradient the earliest. These short time scales would also require very short junctions that can delay, purge, and refresh the unburned propellants into the chamber. With the advent of additive manufacturing, these geometries could be feasibly printed directly into injector elements. Their lifecycle performance, however, would be unknown until after hot fire testing.

F. Considerations for Flame Holding Mechanics and Combustion Delay

Parasitic deflagration is a major concern for RDCs in general, but it is not clear that it would be a concern for a liquid/liquid or even a gas/liquid RDRE. The vaporization time, ignition delay, and on average droplet size would need to be considered [87]. The vaporization time alone would be on the order of magnitude of milli-seconds which puts the droplets complete vaporization on the same order as typical rotating detonation cycle time [87], [88]. If the on average droplet size was approaching that of the lower limit of what is capable of being generated for droplet spray fields in combustion devices this would place the droplet size around 50 micro-meters in diameter. At this diameter of droplet size, the vaporization efficiency and subsequent C* efficiency of a typical combustion device would be close to 100% [52]. Also if this were the case, the droplets lifetime would be very short relative to the detonation cycle time. Some simple mathematics for droplet lifetime are laid out by [89]–[91]. If a simple example of a 50 micron diameter on average droplet is assumed with the theoretical combustion environment for a liquid/gas RDRE then the chamber length required for complete vaporization of the droplet would be in the range of 30 to 50 inches. This of course neglects secondary mixing from the detonation front. It is assumed that the detonation would likely cause the remaining mixing of the droplet and subsequent rapid combustion at super-critical conditions just behind the wave front.

As stated previously, parasitic deflagration and resultant flame holding is a major concern with RDC's particularly when considering realistic thrust chamber operating pressures. A study conducted by [87], discussed the role of ignition delay on RDE performance and operability. Several important factors are discussed in detail including the challenge of overcoming back-flow through the injector. The injector type effectively modeled and discussed in this article was of an annular slot type. It was determined that if the manifold to annulus pressure ratio was large enough, 1.5-2 times the annulus pressure, meeting the critical pressure criteria and choking the injector orifices then back-flow is unlikely to happen. This is in part due to the large pressure pulse meeting the momentum of the injection flow. While this is the case for compressible gas/gas detonations, it is likely that the dynamics of liquid/gas and liquid/liquid detonations would respond differently. The authors then utilize chemical kinetics along with other modeling methodologies to determine that flame holding for methane oxygen environments would be unlikely to dominate chamber behavior unless the chamber pressure was at or a much greater than 100 atm. The authors then go on to give two possible means of flame holding or parasitic deflagration. The first is auto ignition phenomena causing multiple waves to form until a limit cycle donation process is reached and standard deflagration holds. The second is the wave mode operation dependency on vortical recirculation time scales. If this were the case then the number of waves at any given operation condition would not change significantly as the pressure increased. However the amount of combustion or preignition of propellants would increase. It is then noted that the above two possibilities are for gas/gas propellants. If liquids were to be used, the delay due to vaporization time would significantly change RDC operability. This is supported by fundamental detonation work in spray-fields such as the work of [92].

G. Detonation Propagation in Liquid Droplet Spray Fields

To further expand on the concept of using liquid propellants, Borman and Raglands Combustion Engineering 2011 [93] text gives two sections on detonations. One in purely gaseous mixtures and one in liquid-gaseous mixtures. Of particular interest is the detonation of liquid fuel sprays as well as spray detonations. A clear correlation is laid out for the required on-average droplet size in a spray field for a detonation wave to achieve its full CJ-velocity. The text references the work of [92] that conducted detonation tube experiments of liquid fuel spray fields dispersed in gaseous oxygen. It was found that the detonation structure was similar to that of a gaseous mixture detonations but with a much thicker reaction zone behind the detonation front. The authors point out that this is due to deformation, stripping, vaporization, and diffusion of the liquid fuel by the detonation. The breakup-combustion process for the droplets is further described as being synergistic for the wave front sustainability. Primary and secondary explosions were observed and described as a powerful means of accelerating the detonation front.

Furthermore, this section for which the work of Ragland et al. 1968 [92] is referenced, also discusses the effects of detonations in spray fields of various droplet sizes. To summarize, it was found that detonations occurred in a fuel-oxygen combination, controlled for minimizing initial fuel vapor in the system, in a wide range of on average droplet size spray fields of 2 μm – 2600 μm in diameter. It was found that the propagation velocity was significantly less than the theoretical CJ-velocity in a gaseous equivalent in larger droplets size spray fields but only above ~1000 μm in diameter. It was also found through modeling efforts that for droplets below 10 μm, the mechanism of vaporization was enough to sustain detonation. Droplets from 10 μm to 1000 μm would need an additional mechanism for creating micro sprays from the detonation front breaking up the droplets first and then vaporizations. Regardless, as long as the average droplet size is below 1000 μm on average, the detonation wave propagates with approximately a 2% detriment to the theoretical CJ-velocity of the gaseous equivalent mixture. It must also be pointed out that this work was conducted at ambient initial temperatures and pressures. It is not certain how these trends would change, if at all, to the spray field of cryogenic propellants or even a spray field of oxidizer rather than fuel. Since the droplet lifetime of cryogenic propellants is significantly shorter than ambient propellants, it is feasible to imagine that the detonation limits for propagation would shift to higher on average initial droplet sizes.

The implications of the works presented above is multi-faceted when it comes to the application of RDC technology. First, high-pressure detonations can be achieved without the need to account for parasitic deflagration. An injector can be designed so that it accounts for ignition and vaporization delays alone. Furthermore, lower operating injection temperatures can be utilized with cryogenics to enhance detonation properties. All experimental RDC literature reviewed to date has utilized gaseous propellant combinations. An RDC that operates with a liquid fuel or oxidizer is a next step for design advancement in the technology. This is currently being pursued by several academic sources such as the University of Alabama at Huntsville [94].

According to the review of the available literature above, liquid propellant injection may hold the key to rotating detonation combustor performance at realistic rocket chamber pressures. Further results suggest that more delays in parasitic deflagration and flame holding can be achieved by use of cryogenics by means of the latent heat of vaporization. Ultimately, a major conclusion of this work was that flame holding operating modes of these combustors will be pushed out to higher pressures if the correct propellant combinations are chosen. Injector design is also highly important for prioritizing mixing and to optimize total propellant Injection height. It has been successfully demonstrated that rotating detonation modes are possible with liquid/gas injection with recent works [27]. There is a single inherent concern for liquid injection, that is the limitation on fill height. This was covered somewhat in the previous section by assisting the liquid oxidizers injection velocity with a gaseous fuel. It is not yet known if this would work in practical applications.

V. Lessons Learned

Lessons learned from the available literature have been summarized and discussed towards their integration into high performance AM RDRE injectors. This section combines all topics discussed in previous sections as well as the hot fire test experience from the authors and experimental investigation of AM injectors. Numerous desirable attributes for a high-performance detonative injector have been outlined. Several of these design features are only possible with the use of additive manufacturing. Otherwise, they would require labor intensive machining, EDM, and post-processing capabilities that do not currently exist using traditional manufacturing techniques. In addition, the use of AM would allow for the rapid production of these hardware and minimal post-processing to optimize the components material, flow area, and heat load performance.

VI. Summary and Conclusions

Provide a concise summary of the work, as well as conclusions and recommendations drawn from the effort. Do not introduce any new material

Appendix

An appendix, if needed, should appear before the acknowledgments.

Acknowledgments

An Acknowledgments section, if used, **immediately precedes** the References. Sponsorship information and funding data are included here. The preferred spelling of the word "acknowledgment" in American English is without the "e" after the "g." Avoid expressions such as "One of us (S.B.A.) would like to thank…" Instead, write "F. A. Author thanks…"

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