Project Notes:

Project Title: Minimizing Fuel-Oxidizer Mixture Inhomogeneities in Rotating Detonation Engines
Name: Kayla Vallecillo
Contents:

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
Why are Rotating Detonation Rocket Engines (RDRE) promising? What are the benefits and what are the drawbacks?	Reading a journal article	Exhamining Structural Inhomogeneities of Detonations in a Rotating Detonation Rocket Engine	08/28/2023
What are aerospike engines, and how are they different or better than normal engines? Why aren't they used in today's rockets?	Reading a factsheet	Linear Aerospike Engine –Propulsion for the X-33 Vehicle	09/03/2023
Can aerospike nozzles be integrated with rotating detonation rocket engines?	Reading a journal article	Design and optimization of aerospike nozzle for rotating detonation engine	09/11/2023
How do different nozzles affect efficiency of an engine? How does fuel efficiency correlate (if at all) to nozzle structures?	Reading a journal article	Study on the performance of a rotating detonation chamber with different aerospike nozzles	09/25/2023
What are the current needs/drawbacks of RDRE systems? What are the benefits?	Watching a video	"What Is A Rotating Detonation Engine - And Why Are They Better Than Regular Engines" by Scott Manley	10/01/2023
How does shape, structure, and material impact aerodynamic	Reading a journal article	Numerical Study of the Propulsive Performance of the Hollow Rotating	10/01/2023

and thermodynamic efficiency in an RDE system?		Detonation Engine with a Laval Nozzle (gives insight on alternative to solve overheating problem)	
How does mesh contribute to efficiency calculations & determinations?	Speaking with an Expert	Project Logbook: Notes taken from meeting with experts from NREL	10/18/23
How does fuel-air mixing impact the efficiency of the greater RDE system?	Reading a Journal Article	Detonation Propagation through Inhomogeneous Fuel-Air Mixtures	10/25/23
How do I simulate mixing processes in the rotating detonation engine?	Speaking with an expert	Project Logbook: Meeting with the Academic Research and Computing Department at WPI	11/13/23

Literature Search Parameters:

These searches were performed between (08/28/23) and XX/XX/2023.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
Advanced Technologies and Aerospace Collection	Rocket Propulsion, Efficiency	Over 9,000 results - many articles about testing and possible applications of different propulsion systems (cold gas, nuclear, liquid chemical, hybrid, etc.) Had difficulty narrowing my search down and choosing an article that was applicable to my research ideas.
ScienceDirect	Rotating Detonation Rocket Engine	Found several articles about nozzle testing, performance, and integration with other propulsive technologies.
Advanced Technologies and Aerospace Collection (ProQuest)	Rotating Detonation Engine AND Nozzles	Found several articles related to similar topics - including RDE engine integration with aerospike and Laval nozzles with a consideration of propulsive efficiency.
Engineering Village (elsevier)	rotating detonation engine AND fuel mixture	Found several articles about gas and air-breathing engine mixtures and their effects on the efficiency of the rotating detonation engine. This was a helpful search in aiding me with nearly 170 articles related to my desired, specific topic.
Comprendex	Rotating detonation engine AND fuel mixture	This search allowed me to get a few specific and applicable works related to my focus on injection configurations in the RDE. Several of these articles are being referenced and used in my grant proposal as well as my project notes.

Tags:

Tag Name	
#rocket propulsion systems	#sustainability
#alternative rocket propulsion systems	#rotating detonation engine
#nuclear propulsion	#RDRE
#aerospike	#nozzle
#optimization	#theoretical nozzles
#hollow rde	#mixing
#homogeneity	#injection

Article #0 Notes: TEMPLATE

Article notes should be on separate sheets

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Source Title	
Source citation (APA Format)	
Original URL	
Source type	
Keywords	
#Tags	
Summary of key points + notes (include methodology)	
Research Question/Problem/ Need	
Important Figures	
VOCAB: (w/definition)	
Cited references to follow up on	
Follow up Questions	

Article #1 Notes: The pollution caused by rocket launches

07.10.23

Source Title: "The pollution caused by rocket launches"

Source Type: General Article

APA Citation:

Piesing, M. (2022, July 15). *The pollution caused by rocket launches*. BBC Future. https://www.bbc.com/future/article/20220713-how-to-make-rocket-launches-less-polluting.

Original Link:
https://www.bbc.com/future/article/20220713-how-to-make-rocket-launches-less-polluting

Keywords: rockets, pollution, climate change, space travel

Tags: #rocket propulsion systems #sustainability

Summary:

The world's first artificial satellite and the first human spaceflight launched from the Baikonur Cosmodrome, located on a vast area of grassland called the Kazakh Steppe. This area has suffered the effect of the highly carcinogenic UDMH fuel, or unsymmetrical dimethylhydrazine. While the fuel was useful and effective, its ecological impacts have left the area poisoned and polluted. As interaction with space through satellite internet services and space tourism increase, the effects of combustion-driven emissions will become more environmentally significant. Research regarding rocket launch emissions has gained momentum, following the trend of increased private and public interest in the industry. The lack of research surrounding rocket emissions is due to the relatively low emission levels when compared to other industries, such as conventional aviation. While statistically the impact of rocket emissions seems small, experts have observed that rockets emit pollutants throughout each atmospheric level, where pollutants in upper layers of the atmosphere last for longer periods of time. Studies have concluded that increased global space travel will cause black carbon emissions to double after just three years, with emitted particles being nearly 500 times more efficient at holding heat, enhancing a climate warming effect and undermining the upper atmosphere's ozone layer recovery. Further research gathered from rocket launch data has concluded that significant carbon emissions as well as the formation of nitrous oxides can be dependent on nozzle design and rocket efficiencies. Research has pointed towards increasingly negative impacts of rocket use, and alternatives to existing fuels as well as the innovation of new rocket engines by various space organizations have centered around the use of methane as fuel, a controversial choice due to methane's nature of possessing significant higher warming qualities when compared to carbon dioxide.

Other space organizations and startups have looked towards employing renewable biofuels, while other options include incorporating new launch methods, such as horizontal launches and powerful slingshots. The impact of rocket launch emissions on Earth's climate will continue to rise, considering a lack of regulation and little incentive within the industry to change existing safe and proven technologies. However, technological innovation is key, the improvement of rocket systems efficiency and the implementation of regulations being essential in reducing the long-term effects of increased space travel.

Research Question/Need: Understanding the effect of rocket propulsion toxin emissions on wildlife, surrounding areas, and atmospheric conditions.

Important Figures:

No figures: This is an image of Orbex's sustainable rocket, which it plans to launch

Vocab w/Definition:

UDMH fuel - unsymmetrical dimethylhydrazine (aerospace fuel)
Baikonur Cosmodrome - a spaceport operated by Russia in Kazakhstan on the Kazakh Steppe.
RP-1 - Highly refined kerosene (Rocket Propellant - 1)
Gigagram - 1,000,000,000 grams
Prometheus Engine - a rocket engine developed by the European Space Agency (ESA) that is run on methane

Cited references to follow up on: N/A

Follow up questions:

- Why is methane considered an alternative, if its effects on the environment are drastic?

- What are inefficiencies in todays' rocket systems?
- How can inefficiencies improve environmental impact?
- Can rockets utilize harmful emissions for propulsion?

Article #2 Notes: NASA, Pentagon developing nuclear-powered rocket for Mars voyage

07.26.23

Source Title: NASA, Pentagon developing nuclear-powered rocket for Mars voyage

Source Type: General Article

APA Citation:
Org, P. (2023, January 24). NASA, *Pentagon developing nuclear-powered rocket for Mars voyage*. Phys.org. https://phys.org/news/2023-01-nasa-pentagon-nuclear-powered-rocket-mars.html

Original Link:
https://phys.org/news/2023-01-nasa-pentagon-nuclear-powered-rocket-mars.html

Keywords: rockets, pollution, climate change, space travel

Tags: #rocket propulsion systems #sustainability #nuclear propulsion

Summary:

This article summarizes a recent collaboration between the Pentagon's Defense Advanced Research Projects Agency (DARPA) and NASA in developing rockets that utilize energy from a nuclear fission reactor. While this particular article does not highlight the drawbacks or constraints of nuclear technology implementation in rocket propulsion, it does draw attention to the enhancements these new proposed developments can make towards humanity's greater interplanetary mission. Nuclear thermal engines work by using intense heat from a fission reactor to convert a liquid propellant into gas, which is then pushed through a nozzle and used to provide thrust. This proposed innovation is estimated to be at least three times more efficient than conventional liquid propellant rockets, with technologies like these seeing possible uses in transportation of materials and passengers to the moon and to Mars through NASA's Artemis missions. Nuclear thermal propulsion systems can decrease fuel usage and increase fuel efficiency. I decided to review this article as it pertains to my greater interest in rocket propulsion systems and provides an overview of current innovations within a new direction of this topic. While I am finding the process of identifying a problem in my topic of interest challenging, nuclear propulsion systems could pose a new topic to explore and research in the hopes of finding new efficiencies and reducing the impact of greater interest in interplanetary exploration on the environment.

Research Question/Need: Develop alternatives to current fuel usage in rockets, due to significant rise in space travel interest and harmful effects of toxic reactant compounds.

Important Figures: N/A (no figures, as it is a general article)

Vocab w/Definition:
Nuclear thermal rockets - a rocket propulsion system in which a small fission reactor produces heat that expands liquid propellants surrounding the reactor and produces thrust.
DARPA - Defense Advanced Research Projects Agency (part of the pentagon)
Fission reactor - a reactor in which atoms are split and release immense thermal and chemical energy.
Chemical propulsion -

Cited references to follow up on: N/A

Follow up questions:

- Is nuclear thermal propulsion safer, or more dangerous than current rocket propulsion methods?
- How is fission contained within a small combustion chamber?
- What are the drawbacks/benefits of nuclear thermal combustion?
- How are inefficiencies in nuclear thermal propulsion being addressed?
- How do nuclear thermal rockets compare on a level of needed funds?
- Is the fuel being used to expand and produce thrust harmful, or is it better/worse environmentally?

Article #3 Notes: Designing high-performance hypergolic propellants based on materials genome

08.09.23

Source Title: Designing high-performance hypergolic propellants based on materials genome

Source Type: Journal Article

APA Citation:
Yuan, W.-L., Zhang, L., Tao, G.-H., Wang, S.-L., Wang, Y., Zhu, Q.-H., Zhang, G.-H., Zhang, Z., Xue, Y., Qin, S., He, L., & Shreeve, J. M. (2020, December 4). Designing high-performance hypergolic propellants based on materials genome- science. Science Advances. https://www.science.org/doi/10.1126/sciadv.abb1899

Original Link:
https://www.science.org/doi/10.1126/sciadv.abb1899

Keywords: rockets, pollution, climate change, space travel

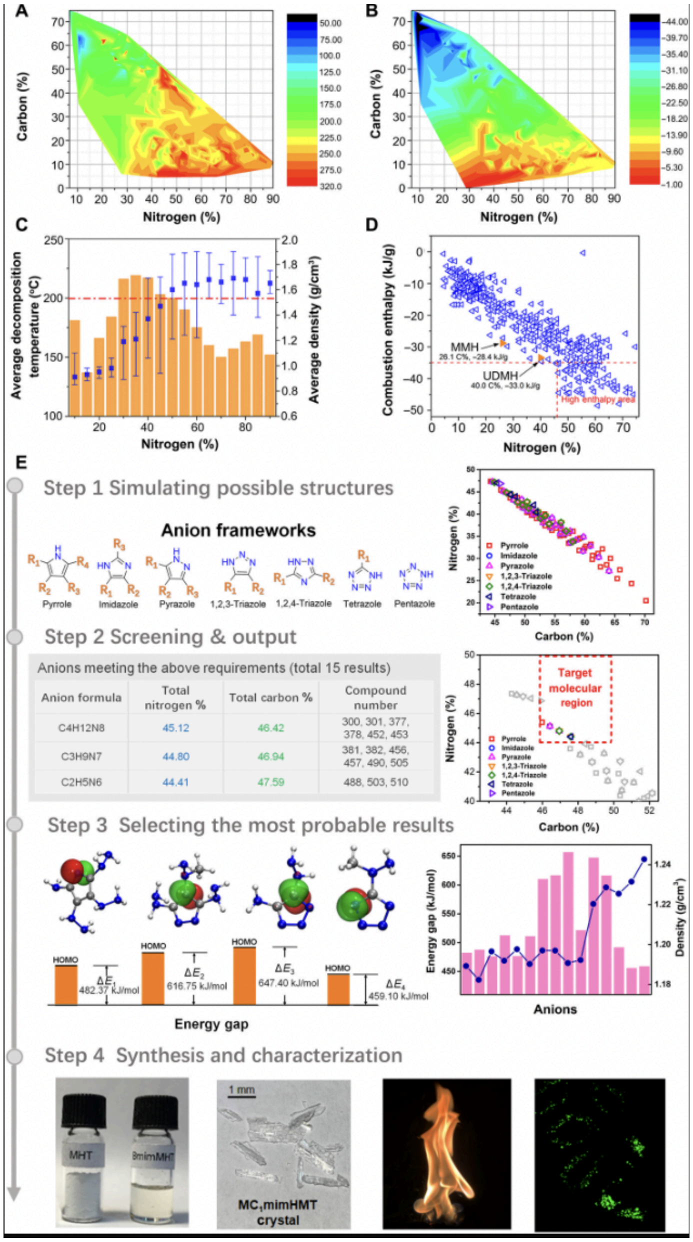
Tags: #rocket propulsion systems #alternative rocket propulsion systems

Summary:
In pursuing alternative energy sources to limit environmental impacts in the long-run rising interest of space exploration, this scientific article highlights a novel method in identifying and analyzing molecular combinations for hypergolic combustion, or spontaneous combustion upon contact with another molecule. While this article highlights this model's specific uses in finding better, more reliable ionic liquid propellants with longer ignition delay times, the model can be used in analyzing the: structure, density, thermal stability, and hypergolic activity of any molecule combination with an estimation of propellant performances and possible applications to solve these issues. This article achieves just that, finding a combination of molecules that can be applied with longer ignition delay times and similar "green", or low toxicity levels. This comprehensive, and incredibly jargon-filled article highlights a new idea that excites me about research, which is the pursuit of molecular combinations that produce low-toxicity hypergolic combustion to be used as fuel. While logistically this interest may be difficult to achieve, I am open to finding alternative methods to improving rocket efficiencies and propulsion systems or strategies. In my brainstorming processes thus far, I have been most excited about alternative rocket propulsion systems with the goal of producing lower pollutive levels before and after launching. This article identifies an additional route I can take in my research, which is mainly chemistry-based studies into how different molecules may reduce environmental impacts and pollutive toxicity levels of rocket propulsion. In consideration of which route to take, one aspect of my research that is definite is that I am most

passionate about pollutive impacts of rocket propulsion, an exciting, rapidly growing industry that must consider and develop around the constraints of a planet already struggling with the impacts of pollutive molecules in its atmosphere.

Research Question/Need: We must work towards finding better, more reliable ionic liquid propellants with longer ignition delay times.

Important Figures:



Anions meeting the above requirements (total 15 results)

Anion formula	Total nitrogen %	Total carbon %	Compound number
C4H12N8	45.12	46.42	300, 301, 377, 378, 452, 453
C3H9N7	44.80	46.94	381, 382, 456, 457, 490, 505
C2H5N6	44.41	47.59	488, 503, 510

Detailed experimental procedure in designing fuel based on materials genome.

Vocab w/Definition:

Hypergolic - a propellant that spontaneously ignites when reacting with another substance.
DCA - dicyanamide, an anion with C2HN3
Enthalpy - total heat content of a system
MMH - monomethylhydrazine - a hypergolic fuel that is extremely toxic and volatile

Cited references to follow up on:

[5] A. Pasini, L. Torre, G. Pace, D. Valentini, L. d'Agostino, Pulsed chemical rocket with green high performance propellants, in 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Jose, CA, 14 to 17 July 2013.

[21] H. H. Koelle, The influence of lunar propellant production on the cost-effectiveness of cislunar transportation systems (Report 19930004795, NASA, 1992).

[28] L. R. Rapp, M. P. Strier, The effect of chemical structure on the hypergolic ignition of amine fuels. J. Jet Prop. 27, 401–404 (1957).

Follow up questions:

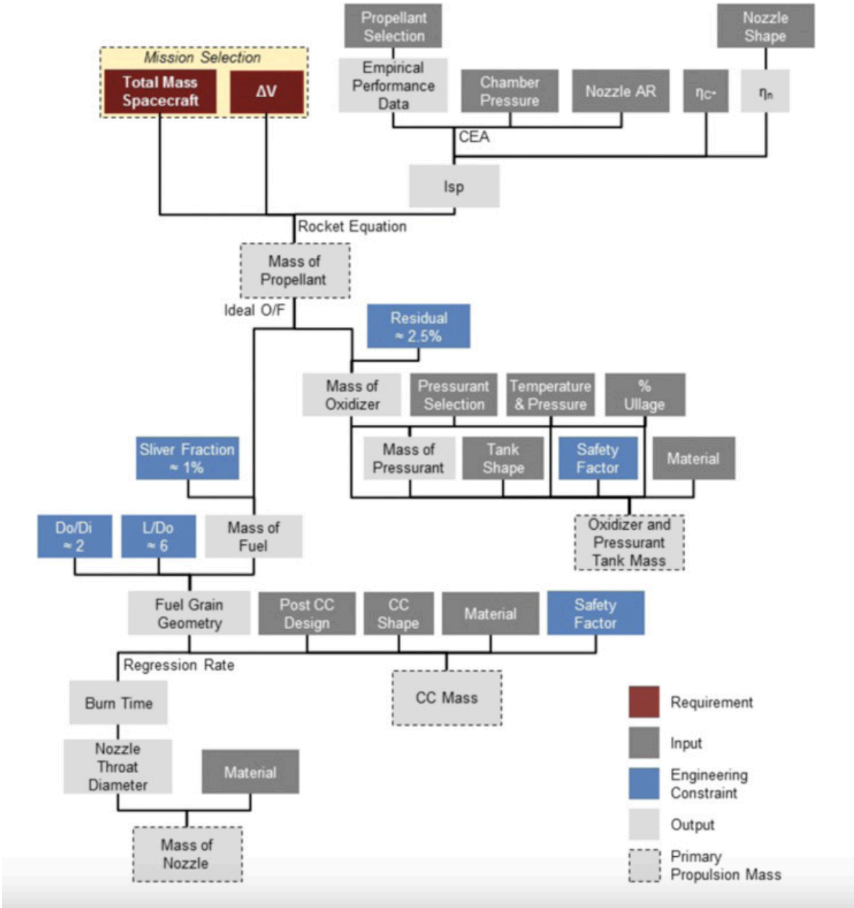
- Can toxins expelled by rockets be condensed, or collected for other purposes?
- Can materials genome be collected for other rocket materials, such as the material used to construct the nozzle, combustion chamber, or nose?
- How does the chemical analysis presented signal an improvement in fuel development?
- Why is ignition delay a goal of combustion?
- Does hypergolic propulsion produce any effects that could result in inconsistent fuel flow, or inefficiencies in thrust performance?

Article #4 Notes: How can hybrid rocket propulsion systems be efficiently configured for interplanetary missions in space?

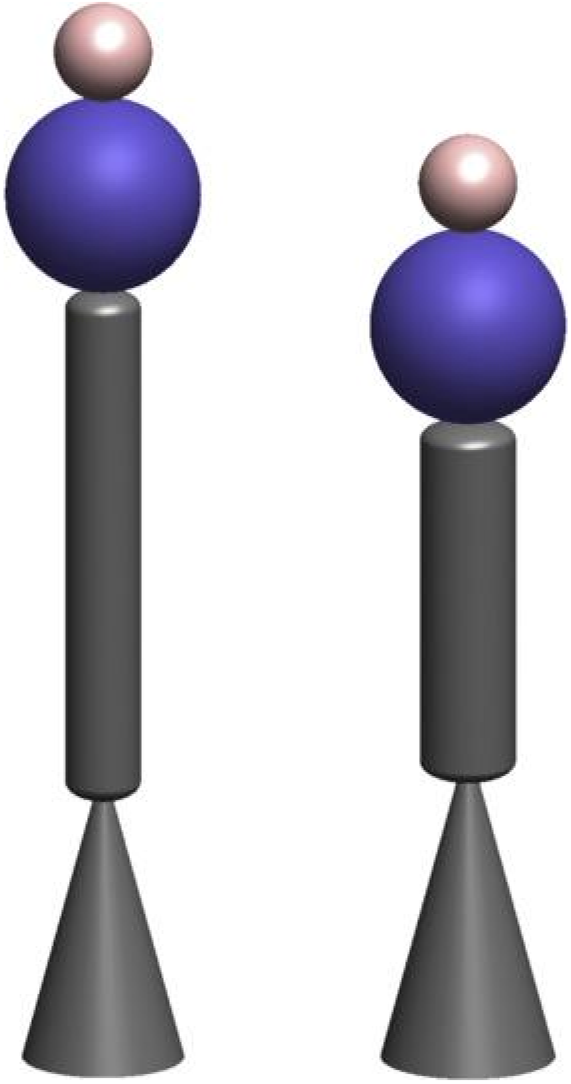
Date: 08.21.2023

Source Title	ScienceDirect
Source citation (APA Format)	Jens, E. T., Cantwell, B. J., & Hubbard, G. S. (2016a). Hybrid rocket propulsion systems for outer planet exploration missions. *Acta Astronautica*, *128*, 119–130. https://www.sciencedirect.com/science/article/pii/S0094576516301941#s0015
Original URL	https://www.sciencedirect.com/science/article/abs/pii/S0094576516301941
Source type	Journal Article
Keywords	“Rockets”, “Rocket propulsion”, “alternative propulsion systems”, “interplanetary missions”
#Tags	#rocket propulsion systems #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	Hybrid rocket propulsion systems, a promising alternative to traditional liquid-propelled or solid-motor propulsion systems, function by chemically activating a thrust response through a reaction between solid fuel and liquid oxidizers. The benefits of adopting hybrid rocket propulsion systems in long-term interplanetary missions include high levels of control in velocity, non-toxic propellants, compact setup, and flexible configuration strategies. This promising propulsion system is under research and design, and this article finds possible configurations and design choices centered around particular missions to Europa and Uranus. Methodology used in creating a 2-3 sentence mini-summary included searching unknown words and referring to google images for reinforcement of concepts.
Research Question/Problem/ Need	How can hybrid rocket propulsion systems be efficiently configured for interplanetary missions in space?

Important Figures



“Simplified overview of the hybrid rocket motor design process adopted in this paper. Details of each step and pertinent equations are provided in the text. AR refers to Area Ratio. η_{c^*} and η_n are the combustion and nozzle efficiency, respectively. CEA refers to Chemical Equilibrium with Applications, see Reference [12]. O/F is the ratio of oxidizer to fuel mass. D_O and D_i refer to the outer and inner fuel grain diameter, respectively. L refers to the fuel grain length. CC refers to Combustion Chamber.”

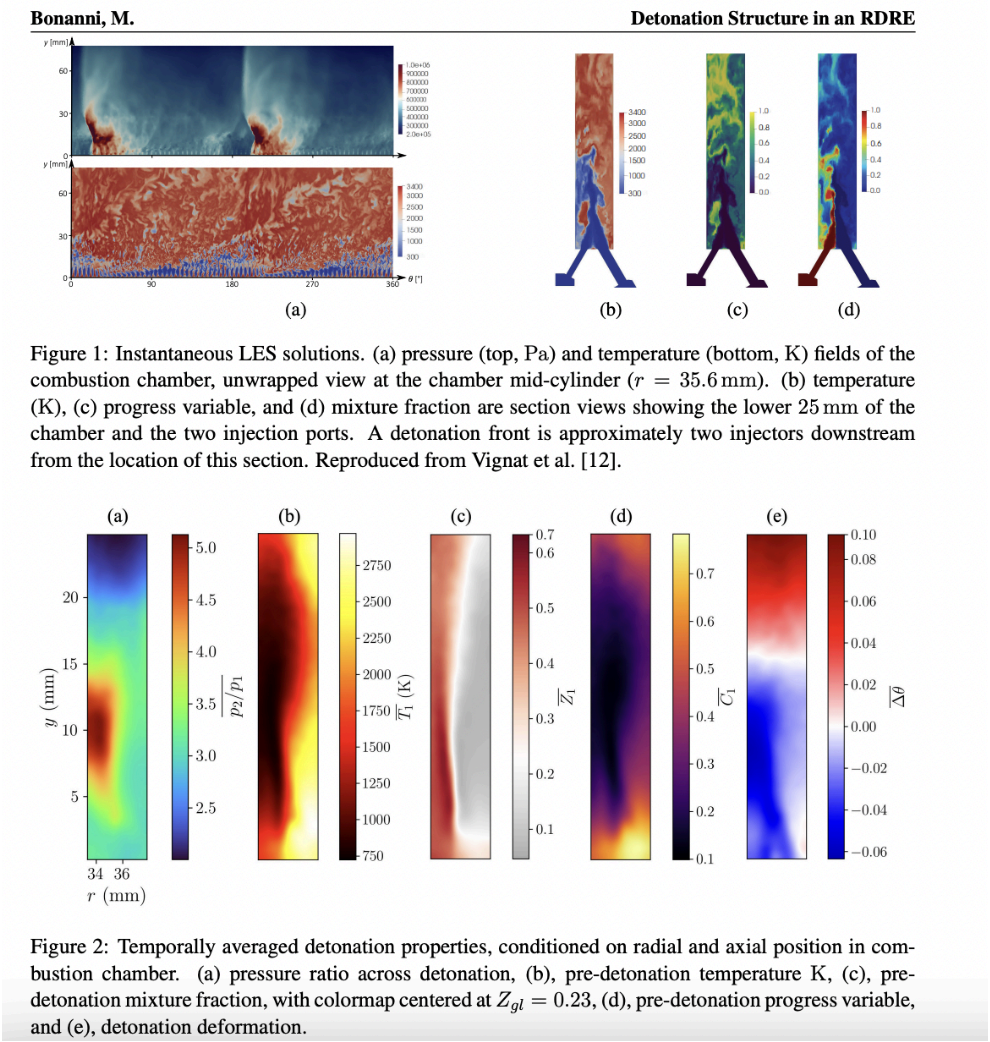
	 “Fig. 9. Example configurations for a long (left) and short (right) hybrid rocket motor for the Europa mission. Oxidizer tanks are shown in blue, pressurant gas tanks in red, and the main motor in gray. Motor geometry is taken from the designs presented in Table 10.”
VOCAB: (w/definition)	Solid fuel grain: hybrid motor fuel (has a cylindrical shape) Oxidizer: a liquid or gaseous substance that contributes to combustion Ports: channels where oxidizer is pumped to fuel. Regression Rate: burning rate as influenced by mass flux. Orbit insertion: inserting, or placing a spacecraft into the desired orbit Baseline Propulsion System: primary propulsion system TVC (Thrust Vector Control): Controlled direction of the engine. ACS - Attitude Control System: System controlling the orientation of the spacecraft Mixture Ratio (MR): the proportions of propellants in a propellant mixture. Reference Mission: a mission used to model concepts in research related to space Single main bipropellant engine: dual-mode engine that uses two propellants

	Monopropellant thrusters: thrusters using one kind of propellant Maximum Expected Operating Pressure (MEOP): Maximum Tank Pressure Composite Overwrapped Pressure Vessels (COPVs): Fuel Tanks with a composite outer layer O/F ratio: Oxidizer to fuel ratio. Gibbs free energy: a way of measuring chemical potential energy. Garolite: fiberglass laminate. Nozzle to Area ratio (NAR): ratio of the nozzle exit area to the nozzle's "throat" area.
Cited references to follow up on	[4] A.A. Chandler, B.J. Cantwell, G.S. Hubbard, Hybrid propulsion for solar system exploration, in: 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, American Institute of Aeronautics and Astronautics, 2011. [7] Space Studies Board Vision and Voyages for Planetary Science in the Decade 2013-2022 National Academies Press (2011) [17] M.J. Chiaverini Hybrid propulsion Encycl. Aerosp. Eng. (2010) [19] G. Zilliac, M.A. Karabeyoglu Hybrid rocket fuel regression rate data and modeling AIAA Paper (2006), p. 4504 [26] A.M. Karabeyoglu Lecture 10 – Hybrid Rocket Propulsion Design Issues Stanford University (2011) AA284a Advanced Rocket Propulsion course
Follow up Questions	1. How do missions to specific locations impact the constraints of hybrid rocket propulsion systems? 2. Can this system be effective in high-thrust propulsion from Earth's surface? 3. How is this system optimizing the listed parameters (including propellant selection, O/F ratio, nozzle area ratio, and chamber pressure)? 4. How does the hybrid rocket propulsion system compare on a level of complexity and cost? 5. How can mixing oxidizers and fuels lead to inefficiencies or inhomogeneities in fuel flow mixtures?

Article #5 Notes: Examining Structural Inhomogeneities of Detonations in a Rotating Detonation Rocket Engine

Date: 08.21.2023

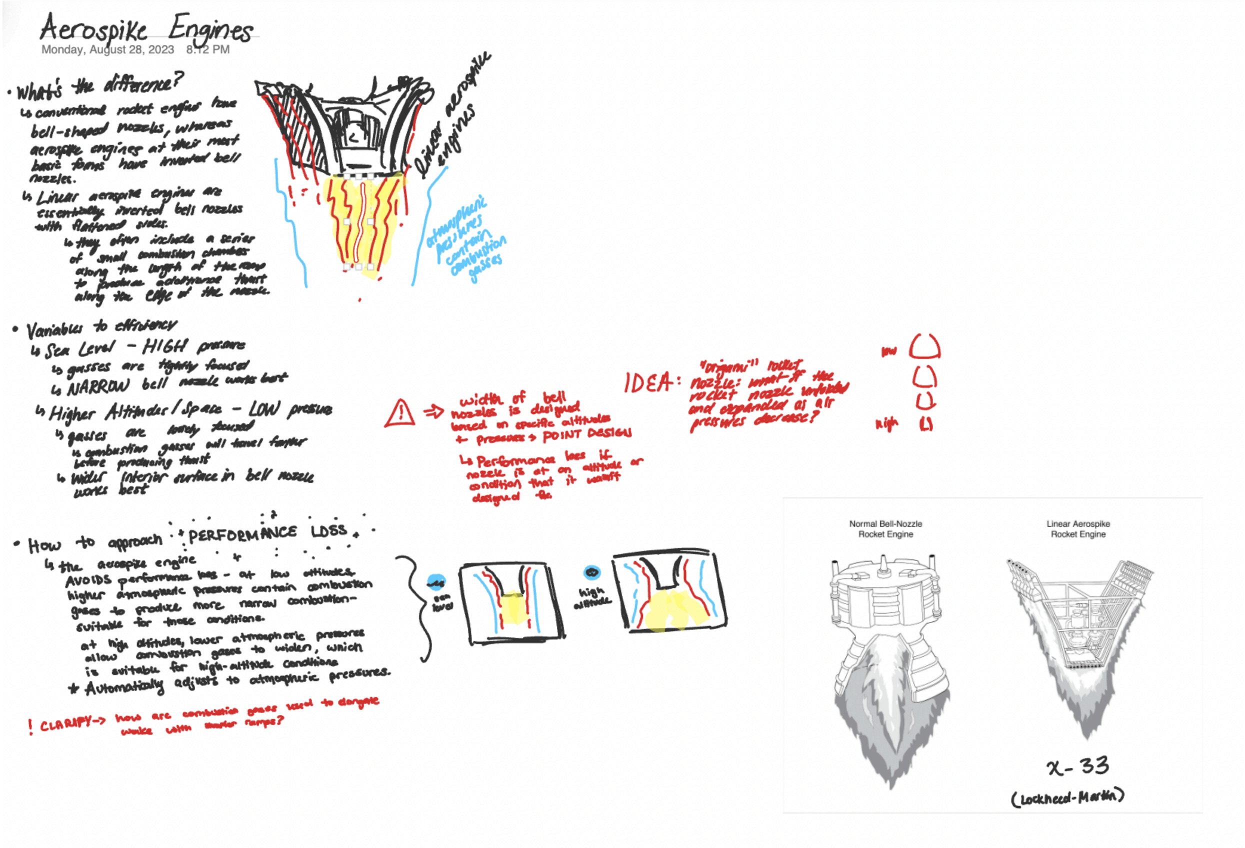
Source Title	Examining Structural Inhomogeneities of Detonations in a Rotating Detonation Rocket Engine
Source citation (APA Format)	Bonanni, M., Brouzet, D., Vignat, G., & Ihme, M. (2023). Examining Structural Inhomogeneities of Detonations in a Rotating Detonation Rocket Engine. *29th ICDERS*, 1–6. http://www.icders.org/ICDERS2023/abstracts/ICDERS2023-160.pdf
Original URL	http://www.icders.org/ICDERS2023/abstracts/ICDERS2023-160.pdf
Source type	Published and Presented Project
Keywords	“Rocket Propulsion”, “Alternative Rocket Propulsion Systems”, “Rocket Engines”
#Tags	#Rotating Detonation Rocket Engine #RDRE #Efficiency #Systems
Summary of key points + notes (include methodology)	Rotating Detonation Rocket Engines, or RDREs, are an alternative rocket propulsion system to traditional liquid or solid combustion rockets, showing signs of improved thermodynamic efficiency and power density. However, RDREs are often activated through non-premixed injection propellants to avoid “flashback”, making an inhomogeneous mixture of propellant and oxidizer and in turn altering detonation patterns. This study examined altered detonation patterns using this system and identified the constraints of non-moving RDREs. Methodology: Google Scholar Search and reading and searching for definition of jargon.
Research Question/Problem/ Need	How do rotating detonation rocket engines (RDREs) with separated propellant injectors mix and how does this affect detonation patterns?

Important Figures	 **Bonanni, M.** **Detonation Structure in an RDRE** Figure 1: Instantaneous LES solutions. (a) pressure (top, Pa) and temperature (bottom, K) fields of the combustion chamber, unwrapped view at the chamber mid-cylinder ($r = 35.6\,\mathrm{mm}$). (b) temperature (K), (c) progress variable, and (d) mixture fraction are section views showing the lower 25 mm of the chamber and the two injection ports. A detonation front is approximately two injectors downstream from the location of this section. Reproduced from Vignat et al. [12]. Figure 2: Temporally averaged detonation properties, conditioned on radial and axial position in combustion chamber. (a) pressure ratio across detonation, (b), pre-detonation temperature K, (c), pre-detonation mixture fraction, with colormap centered at $Z_{gl} = 0.23$, (d), pre-detonation progress variable, and (e), detonation deformation.
VOCAB: (w/definition)	Rotating Detonation Rocket Engine (RDRE): a rocket propulsion system that uses pressure-gain combustion and continuous thrust with no moving parts. Aerospike nozzle: high-efficiency thrust nozzle - optimal at all altitudes through automatic adjustment. Pressure-gain combustion: increasing pressure during combustion to enhance propulsive efficiency. Flashback: Not good! Combustion propagation back into fuel injector. Vitiated gasses: gasses lacking combustive components. Lagrangian tracer particles: particles used to track fluid movement within simulations. Choked injector stream: a stream when flow is restricted due to high velocity. Axial co-flow: flowing in the same direction. Flow reversal: when fluid flow direction reverses. Eulerian state data: data used to represent the properties of fluids at fixed points in space.

Cited references to follow up on	[1] F. K. Lu, E. M. Braun, J. Powers, Rotating detonation wave propulsion: Experimental challenges, modeling, and engine concepts, Journal of Propulsion and Power 30 (2014) 1125–1142. [3] R. Yokoo, K. Goto, J. Kim, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, Propulsion performance of cylindrical rotating detonation engine, AIAA Journal 58 (2020) 5107–5116. [10] R. D. Smith, S. B. Stanley, Experimental Investigation of Rotating Detonation Rocket Engines for Space Propulsion, Journal of Propulsion and Power 37 (2021) 463–473. [12] G. Vignat, D. Brouzet, M. Bonanni, M. Ihme, Effect of secondary waves on mixing and injector near-field dynamics in non-premixed rotating detonation engine, Shock Waves (2023, (under review)). [16] T. Poinsot, S. K. Lele, Boundary conditions for direct simulations of compressible viscous flows, Journal of Computational Physics 101 (1992) 104–129.
Follow up Questions	1) How can altered detonation properties impact a mission in its entirety? 2) Are RDREs a viable option for future efforts to travel to space? How can its viability be measured? 3) How may altered detonation patterns from unmixed fuels and oxidizers be mitigated to ensure a constant state of combustion? 4) How can flashback be prevented by timed propulsive settings? (ex. Injection at specific intervals to avoid flashback occurring).

Article #6 Notes: Linear Aerospike Engine —Propulsion for the X-33 Vehicle

Fact Sheet - FS-2000-09-174-MSFC



Aerospike Engines

Monday, August 28, 2023 8:12 PM

- What's the difference?
  - ↳ conventional rocket engines have bell-shaped nozzles, whereas aerospike engines at their most basic forms have inverted bell nozzles.
  - ↳ Linear aerospike engines are essentially inverted bell nozzles with flattened sides.
    - ↳ they often include a series of small combustion chambers along the length of the ramp to produce additional thrust along the edge of the nozzle.
- Variables to efficiency
  - ↳ Sea Level - HIGH pressure
    - ↳ gasses are tightly focused
    - ↳ NARROW bell nozzle works best
  - ↳ Higher Altitudes / Space - LOW pressure
    - ↳ gasses are loosely focused
      - ↳ combustion gasses will travel farther before producing thrust
    - ↳ Wider interior surface in bell nozzle works best

⚠ ⇒ width of bell nozzles is designed based on specific altitudes + pressures → POINT DESIGN
↳ Performance loss if nozzle is at an altitude or condition that it wasn't designed for.

IDEA: "origami" rocket nozzle: what if the rocket nozzle unfolded and expanded as air pressures decrease?

- How to approach PERFORMANCE LOSS
  - ↳ the aerospike engine AVOIDS performance loss - at low altitudes, higher atmospheric pressures contain combustion gases to produce more narrow combustion - suitable for those conditions.
  - at high altitudes, lower atmospheric pressures allow combustion gases to widen, which is suitable for high-altitude conditions.
  - ★ Automatically adjusts to atmospheric pressures.

! CLARIFY -> how are combustion gases used to elongate wake with shorter ramps?

APA Citation:

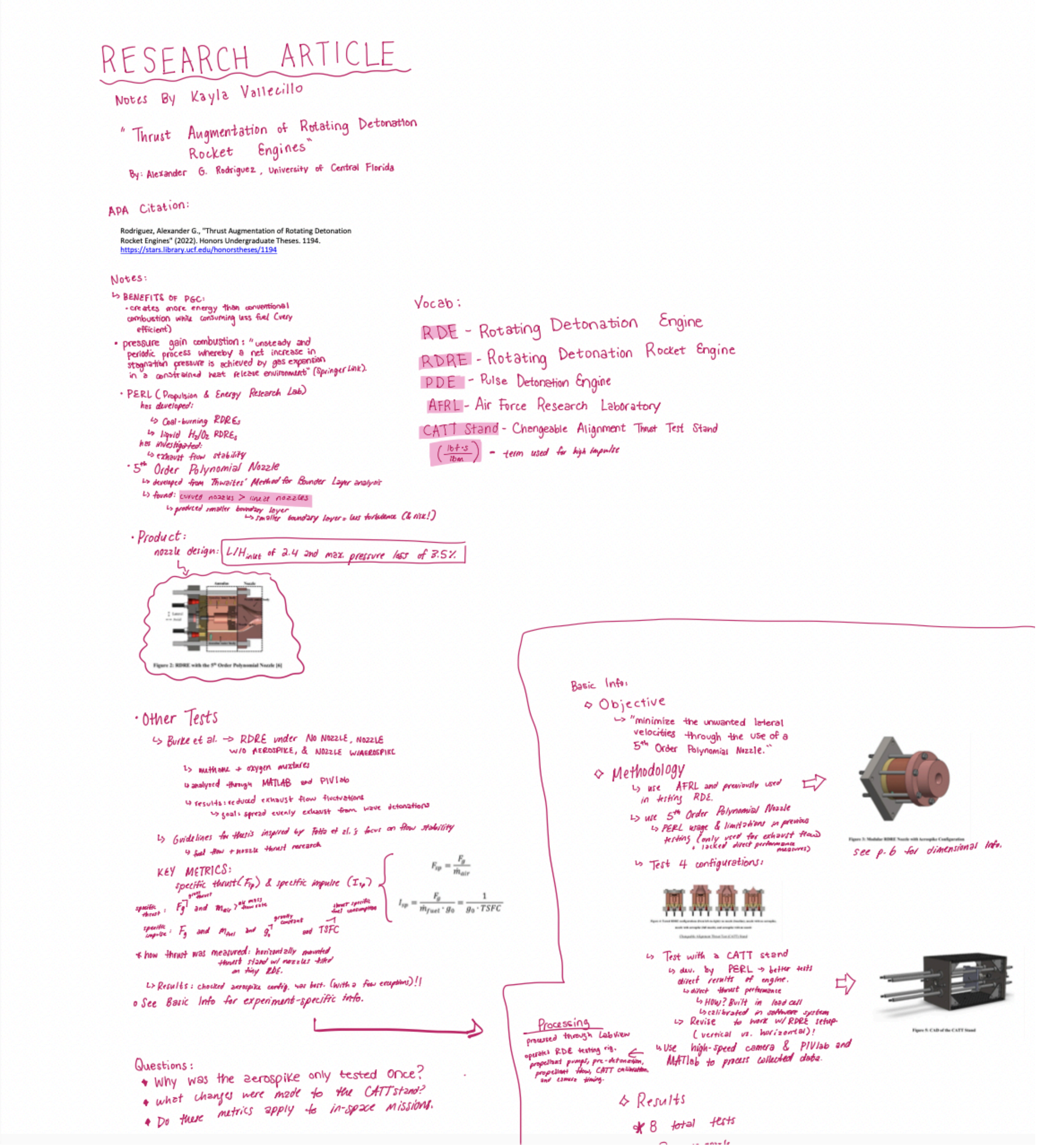
Vinson, J. (1998). The Linear Aerospike Engine. *Aerospace America*, 2–6. https://ntrs.nasa.gov/citations/19990004339

Further Questions:

- Why aren't aerospikes used more if they counteract optimal thrust inefficiencies at varying altitudes?
- Could aerospike engines reduce engine costs by reducing funds spent on multi-stage rocket launches?
- Can aerospike engines be designed with a consideration of engine weight (ex. Hollow chambers, carbon structures, etc.)?
- Are there other engines/nozzles that counteract specific propulsive issues, like the aerospike?

Article #7 Notes: Thrust Augmentation of Rotating Detonation Rocket Engines

Date: 09.19.2023



RESEARCH ARTICLE

Notes By Kayla Vallecillo

"Thrust Augmentation of Rotating Detonation Rocket Engines"

By: Alexander G. Rodriguez, University of Central Florida

APA Citation:

Rodriguez, Alexander G., "Thrust Augmentation of Rotating Detonation Rocket Engines" (2022). Honors Undergraduate Theses. 1194. https://stars.library.ucf.edu/honorstheses/1194

Notes:

↳ BENEFITS OF PGC:
- creates more energy than conventional combustion while consuming less fuel (very efficient)

- pressure gain combustion: "unsteady and periodic process whereby a net increase in stagnation pressure is achieved by gas expansion in a constrained heat release environment" (Springer Link).
- PERL (Propulsion & Energy Research Lab) has developed:
  - ↳ Coal-burning RDREs
  - ↳ liquid H_2/O_2 RDREs

  has investigated:
  - ↳ exhaust flow stability
- 5th Order Polynomial Nozzle
  - ↳ developed from Thwaites' Method for Bounder Layer analysis
  - ↳ found: curved nozzles > linear nozzles
    - ↳ produced smaller boundary layer
      - ↳ smaller boundary layer = less turbulence (& risk!)
- Product:

  nozzle design: L/H$_{inlet}$ of 2.4 and max. pressure loss of 3.5%

Figure 2: RDRE with the 5th Order Polynomial Nozzle [6]

- Other Tests
  - ↳ Burke et al. → RDRE under NO NOZZLE, NOZZLE W/O AEROSPIKE, & NOZZLE W/AEROSPIKE
    - ↳ methane + oxygen mixtures
    - ↳ analyzed through MATLAB and PIVlab
    - ↳ results: reduced exhaust flow fluctuations
      - ↳ goal: spread evenly exhaust from wave detonations
  - ↳ Guidelines for thesis inspired by Fotta et al.'s focus on flow stability
    - ↳ fuel flow + nozzle thrust research

KEY METRICS:

specific thrust (F_{sp}) & specific impulse (I_{sp})

$$F_{sp} = \frac{F_g}{\dot{m}_{air}}$$

$$I_{sp} = \frac{F_g}{\dot{m}_{fuel} \cdot g_0} = \frac{1}{g_0 \cdot TSFC}$$

specific thrust: F_g (gross thrust) and m_{air} (air mass flow rate)

specific impulse: F_g and m_{fuel} and g_0 (gravity constant) and TSFC (thrust specific fuel consumption)

* how thrust was measured: horizontally mounted thrust stand w/ nozzles tilted on tiny RDE.

  ↳ Results: chocked aerospike config. was best. (with a few exceptions)!!

- See Basic Info for experiment-specific info.

Questions:
- Why was the aerospike only tested once?
- what changes were made to the CATT stand?
- Do these metrics apply to in-space missions.

Vocab:

RDE - Rotating Detonation Engine

RDRE - Rotating Detonation Rocket Engine

PDE - Pulse Detonation Engine

AFRL - Air Force Research Laboratory

CATT Stand - Changeable Alignment Thrust Test Stand

$\left(\frac{lbf \cdot s}{lbm}\right)$ - term used for high impulse

Basic Info:

◇ Objective
- ↳ "minimize the unwanted lateral velocities through the use of a 5th Order Polynomial Nozzle."

◇ Methodology
- ↳ use AFRL and previously used in testing RDE.
- ↳ use 5th Order Polynomial Nozzle
  - ↳ PERL usage & limitations in previous testing (only used for exhaust flow + lacked direct performance measures)
- ↳ Test 4 configurations:
- ↳ Test with a CATT stand
  - ↳ dev. by PERL → better tests direct results of engine.
    - ↳ direct thrust performance
      - ↳ How? Built in load cell
        - ↳ calibrated in software system
  - ↳ Revise to work w/ RDRE setup. (vertical vs. horizontal)!
- ↳ Use high-speed camera & PIVlab and MATlab to process collected data.

Figure 3: Modular RDRE Nozzle with Aerospike Configuration

see p. 6 for dimensional info.

Figure 5: CAD of the CATT Stand

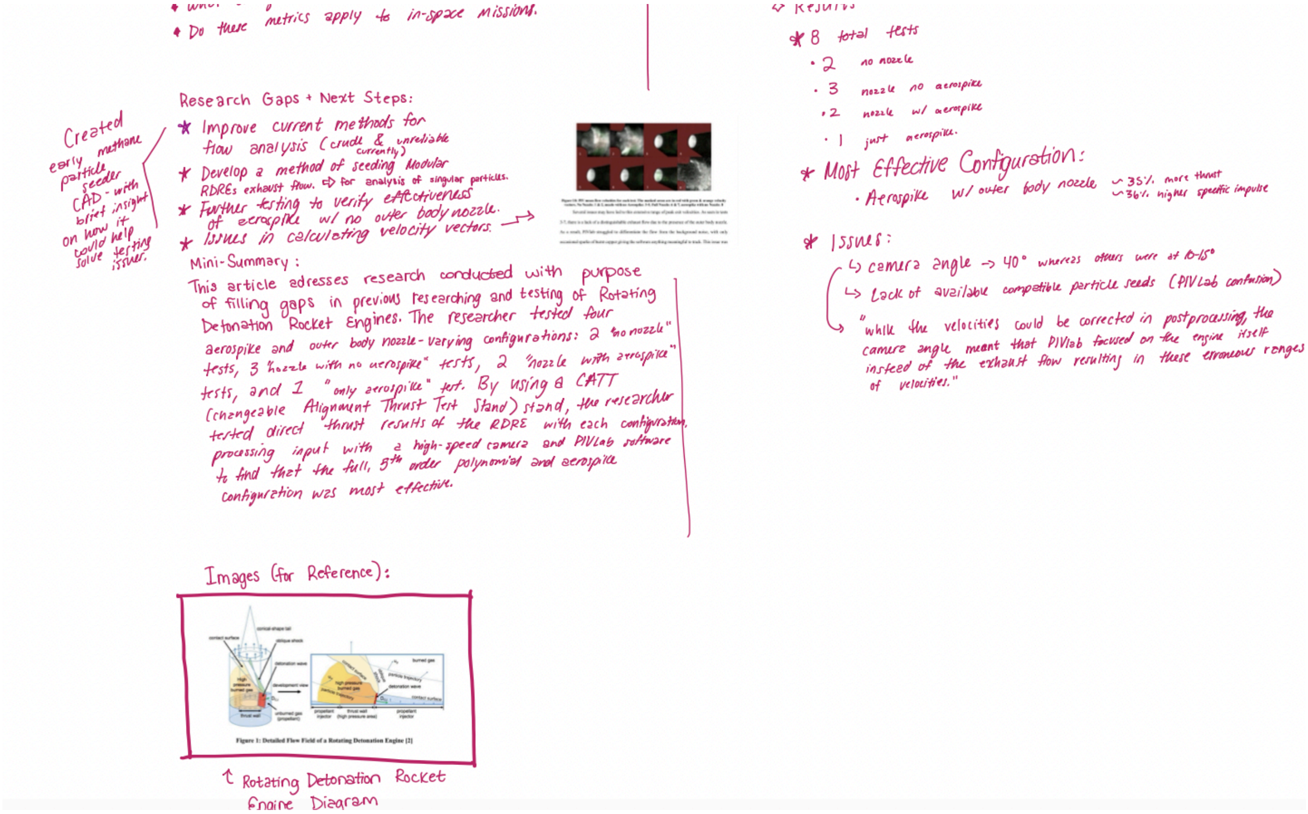
Processing

processed through LabView

operates RDE testing rig. propellant pumps, pre-detonation, propellant flow, CATT calibration, and camera timing.

◇ Results

✱ 8 total tests



- Do these metrics apply to in-space missions.

Research Gaps + Next Steps:

* Improve current methods for flow analysis (crude & unreliable currently)
* Develop a method of seeding Modular RDREs exhaust flow. ⇨ for analysis of singular particles.
* Further testing to verify effectiveness of aerospike w/ no outer body nozzle.
* Issues in calculating velocity vectors. →

Created early methane particle seeder CAD - with brief insight on how it could help solve testing issues.

Mini-Summary:

This article adresses research conducted with purpose of filling gaps in previous researching and testing of Rotating Detonation Rocket Engines. The researcher tested four aerospike and outer body nozzle-varying configurations: 2 "no nozzle" tests, 3 "nozzle with no aerospike" tests, 2 "nozzle with aerospike" tests, and 1 "only aerospike" test. By using a CATT (changeable Alignment Thrust Test Stand) stand, the researcher tested direct thrust results of the RDRE with each configuration, processing input with a high-speed camera and PIVLab software to find that the full, 5th order polynomial and aerospike configuration was most effective.

Images (for Reference):

Figure 1: Detailed Flow Field of a Rotating Detonation Engine [2]

↑ Rotating Detonation Rocket Engine Diagram

Results

* 8 total tests
  - 2 no nozzle
  - 3 nozzle no aerospike
  - 2 nozzle w/ aerospike
  - 1 just aerospike.
* Most Effective Configuration:
  - Aerospike w/ outer body nozzle ~35% more thrust ~36% higher specific impulse
* Issues:
  - ↳ camera angle → 40° whereas others were at 10-15°
  - ↳ Lack of available compatible particle seeds (PIVLab confusion)
  - ↳ "while the velocities could be corrected in postprocessing, the camera angle meant that PIVlab focused on the engine itself instead of the exhaust flow resulting in these erroneous ranges of velocities."

Article #8 Notes: Design and optimization of aerospike nozzle for rotating detonation engine

Date: 09.25.2023

Source Title	Design and optimization of aerospike nozzle for rotating detonation engine
Source citation (APA Format)	Liu, X.-Y., Cheng, M., Zhang, Y.-Z., & Wang, J.-P. (2022). Design and optimization of aerospike nozzle for rotating detonation engine. *Aerospace Science and Technology*, *120*(107300). https://doi.org/https://doi.org/10.1016/j.ast.2021.107300
Original URL	https://www.sciencedirect.com/science/article/pii/S1270963821008105?ref=pdf_download&fr=RR-2&rr=80c5f9566bd64cee
Source type	Journal Article
Keywords	"Rotating detonation engine", "Aerospike nozzle", "Pressure gain", "Propulsion performance"
#Tags	#Rotating Detonation Rocket Engine #Aerospike #Nozzle #Optimization
Summary of key points + notes (include methodology)	Summary: "Design and optimization of aerospike nozzle for rotating detonation engine" by Liu et al. is an investigation of the relationship between isentropic flow and time-averaged parameters in RDE and aerospike integration systems. Through OpenFOAM, an open source software, the thrust performance of aerospike nozzle integration was analyzed, and it was found that parallel flow at the nozzle exit to the chamber axis allows for optimal thrust performance. This study recognized the gap in research, development and experimentation of aerospike-RDE integration that lacked the optimization of the nozzle system, and failed to address thrust efficiency losses in using a flat aerospike ramp rather than an isentropic nozzle geometry. ● RDE integration with aerospike nozzles is primarily difficult due to large pressure fluctuations of rotating detonation waves. ● Current Work: RDE combines with various aerospike nozzles. ● This article: Combine aerospike with an RDE with an annulus combustion chamber. Essentially, how can different RDE combustion chamber configurations optimize RDE/aerospike integration? ● Used OpenFOAM (open source software) to obtain thrust performance of nozzles. ● Flow at nozzle exit was parallel to chamber axis, which allows for optimal thrust.

- Conclusion: “aerospike nozzle is a good match for efficient expansion of rotating detonation products for propulsion”
- Constriction nozzle throat greatly improved stagnation pressure gain in combustor.
- Chamber pressure can be elevated by adding a convergence section in the nozzle throat.
- RDE performance can be maximized by stabilizing rotating detonations.
- Background on previous research:
    - Rankin et al. → studied air injection slots and fuel injection holes with consideration of slot width, hole number, and hole diameter.
    - Sun et al. → studied the propagation characteristics of RD waves under different variables including slot width and mass flow rate. Used simulations of non-premixed RDE.
    - Smirnov et al. → studied perpendicular oxygen injection to main stream in a ramjet type RDE. Used two-dimensional sims.
    - Yan et al. → studied injection slot widths with two-dimensional sims.
    - Xia et al. → studied ignition conditions on initiation characteristics of RD waves in plane-radial RDE.
- Overall, studies show that injection strategies greatly influence RDE detonation and thrust characteristics.
- “...**nozzle design geometries and their impact on thrust generation are necessary to be clarified**.”
- Background on previous nozzle geometry research:
    - Fotia et al. → measured total thrust and nozzle efficiency in RDE combined with different aerospike nozzles
        - thrust was sensitive to the nozzle internal expansion ratio.
    - Jourdaine et al. → numerically investigated effect of open vs chocked nozzle on thrust performance.
        - Chocked nozzle improved specific impulse by 4% ~7%
    - Goto et al. → experimented with throat geometries
        - RDE is similar to constant pressure combustion rockets.
    - Haroun et al. → experimented with aerospike nozzle geometries:
        - internal-external aerospike and a flared aerospike.
        - Cowl design greatly influences thrust and plume field.
    - Betelin et al. → studied RDE performance with different nozzle center body lengths.
- OVERALL: “These studies suggested that the thrust performance of RDE was indeed improved with aerospike nozzles compared to nozzle-less conditions and was closely related to nozzle configurations.”
    - GAP: aerospike was not optimally designed.
    - This research hopes to identify optimal geometric designs of aerospike nozzles to optimize thrust generation.
- “Traditionally, the aerospike nozzle design method has been fully developed based on the theory of one-dimensional isentropic steady flow.”
- RDE propulsion is a time varying phenomenon:
    - Kawasaki et al. → captured self-luminescence of exhaust plumes

with a high speed camera
        - Many studies on instantaneous plume fields.
    - Jourdaine et al. → found that time-averaged exhaust plumes were similar to axis-symmetric supersonic jets.
    - Zhu et al. → took previous research concepts (time-averaged exhaust plumes and isentropic relationships) for aerospike integration research.
- This study numerically simulated RDE and aerospike integration by understanding the one-dimensional isentropic relationships present.
- This study used time-averaged parameters to develop an aerospike-RDE integration system, with a consideration while simulating regarding the flow-field structure and thrust performance of the engine.
    - Study discovers relationship between isentropic relationships and time-averaged parameters.

SIMULATIONS

- Detonation is composed of multiple chemical reactions, expressed by the Navier-Stokes equations.
    - “Three-dimensional compressible Navier-Stokes equations with the mass conservation equations for each species are used as governing equations…” → **consider going back here when breaking research down mathematically!**
    - **Governing EQs: page 3**
- Equations implemented with OpenFOAM → Reynolds Averaged Navier-Stokes (RANS) combined with the partially stirred reactor (PaSR). Convective terms integrated Godunov type scheme Harten-Lax-van-Leer-Contact (HLLC).
    - Time integration → 2nd order Crank-Nicholson scheme
    - Solver has been proven to work in detonation sims.
- Uses Kerosene type fuel Jet-A for sims
- Chemical sims mechanism includes 21 species and 37 irreversible reactions
- Sims proven to be accurate - error less than 1% w/chemical eqs

PHYSICAL MODELS (still sim but w/structural info)

- In previous studies w/ RDRE and aerospike integration, the flat ramp surface on the nozzle caused a significant loss in thrust.
- Traditional rocket engines with aerospike integration include a cowl-lip, which allow exhaust plumes to be directed at a parallel to the chamber axis and the lip serves as an adjusting invisible outer wall that optimizes at various altitudes.
    - Personal note - the traditional integration is clever and simple, and I wonder how unstable detonation in RDREs affects how it's integrated.

AEROSPIKE NOZZLE GEOMETRIES :)

- Flow-field is very unstable in the RDE
- **Traditional aerospike nozzle design methods integrated with time-averaged parameters were used to configure the aerospike with RDE.**
- Simulated FOUR kinds of nozzles with RDE (w/annular combustion

chamber)
    - Case A - open nozzle, flat ramp
    - Case B - choked nozzle, flat ramp
    - Case C- aerospike nozzle, cowl lip, isentropic ramp
    - Case D - truncated aerospike nozzle
- B, C, D constriction ratios are the same

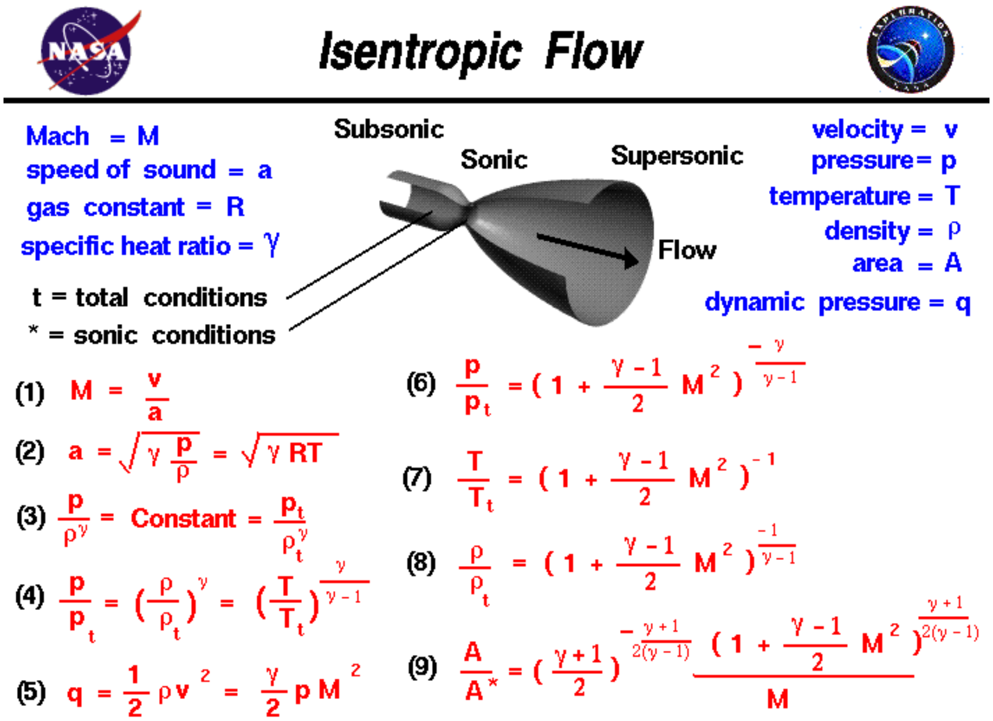
MESH
- Unstructured Cartesian trimmed mesh used in simulations.
    - Used Error Estimation method proposed by Smirnov et al.
- The grid system is used to analyze the flow field structure and propulsion performance of RDE.

Inlet Conditions
- Used sims to model flow fields with standard injection ratios (from previous work)

Results & Discussion
- Case A (flat aerospike)
    - Mach disk developed in the plume field.
    - Oscillatory nature of nozzle flow caused the exhaust plume to vary in time and lack parallelism with the chamber axis.
- RDE Waves
    - Structures of RDE waves include wedge shape gas layer, slip line, and oblique shock wave.
- Case B (flat aerospike)
    - Reflected shock is less than case A and does not disturb stable propagation of the detonation wave.
    - Complex wave structure.
    - Exhaust flow velocity was under-expanded (pressure was greater than ambient) and exhaust flow was congested at the nozzle throat.
- Case C (isentropic w/cowl lip and full length)
    - Lateral expansion of gasses was restricted by cowl lip
    - No mach disks
    - Influence on thrust performance:
    - Supersonic flow expands through a series of Prandtl-Meyer expansion waves
    - Pressure matched ambient pressure!
    - Mach number didn’t match designed mach point - likely caused by inhomogeneities in flow mixture at the nozzle throat or non-exact expansion.
    - Includes expansion fan - **inquire on this.**
- Case D (isentropic, but truncated)
    - Truncated spikes produced lip shocks and trailing shocks.
    - Flow separation at the nozzle base generates an enclosed recirculation zone.
    - No mach disks (isentropic flow)
    - Enclosed recirculation zone at nozzle base because of truncated nozzle
    - Thrust performance is “basically parallel” to the nozzle axis despite

	○ the recirculation zone. ○ Small thrust loss due to the effect of truncation on reaching design point. Overall ● Aerospike nozzles of RDE designed with the one-dimensional isentropic relations based on time-averaged parameters can ensure expansion of exhaust gasses. Streamline of exhaust flow is parallel to the exhaust axis. Pressure Gain ● Higher in isentropic aerospike nozzle config. (truncation has no effect) Thrust Performance ● Total thrust is the sum of thrust at exit, thrust on the ramp, thrust at the base, and frictional resistance on the ramp surface. ● Anywhere where pressure is lower than ambient pressure on the ramp surface will produce drag. ● Frictional resistance on the ramp is essential for thrust. ● The truncated nozzle is preferable for reduction in engine size and weight without significant thrust loss. ● Oblique shock waves extending outside the combustor will reduce nozzle efficiency - but this cannot be cleaned due to the nature of RDE waves. ● “In summary, the aerospike nozzle designed based on the one-dimensional isentropic theory can still improve the propulsion performance and nozzle efficiency of RDE and should be applied in further studies” Conclusions ● Isentropic ramp surface is designed for optimum thrust generation baked on one-dimensional isentropic theory ● Plume field streamline at the nozzle outlet is parallel to the combustion chamber axis, which is beneficial for thrust efficiency. ● The inward cowl lip lining the edge of the isentropic aerospike nozzle was found to be incredibly effective in increasing thrust generation. ● RDE waves cause pressure-gain combustion to occur, which is maximized through a constriction nozzle. ● This article applies one dimension isentropic relationships with time-averaged parameters in RDE and aerospike integration optimization.
Research Question/Problem/ Need	“...**nozzle design geometries and their impact on thrust generation are necessary to be clarified**.”

Important Figures



Isentropic Flow

Mach = M
speed of sound = a
gas constant = R
specific heat ratio = γ

t = total conditions
* = sonic conditions

velocity = v
pressure = p
temperature = T
density = ρ
area = A
dynamic pressure = q

(1) $M = \frac{v}{a}$

(2) $a = \sqrt{\gamma \frac{p}{\rho}} = \sqrt{\gamma R T}$

(3) $\frac{p}{\rho^{\gamma}} = \text{Constant} = \frac{p_t}{\rho_t^{\gamma}}$

(4) $\frac{p}{p_t} = \left(\frac{\rho}{\rho_t}\right)^{\gamma} = \left(\frac{T}{T_t}\right)^{\frac{\gamma}{\gamma - 1}}$

(5) $q = \frac{1}{2} \rho v^2 = \frac{\gamma}{2} p M^2$

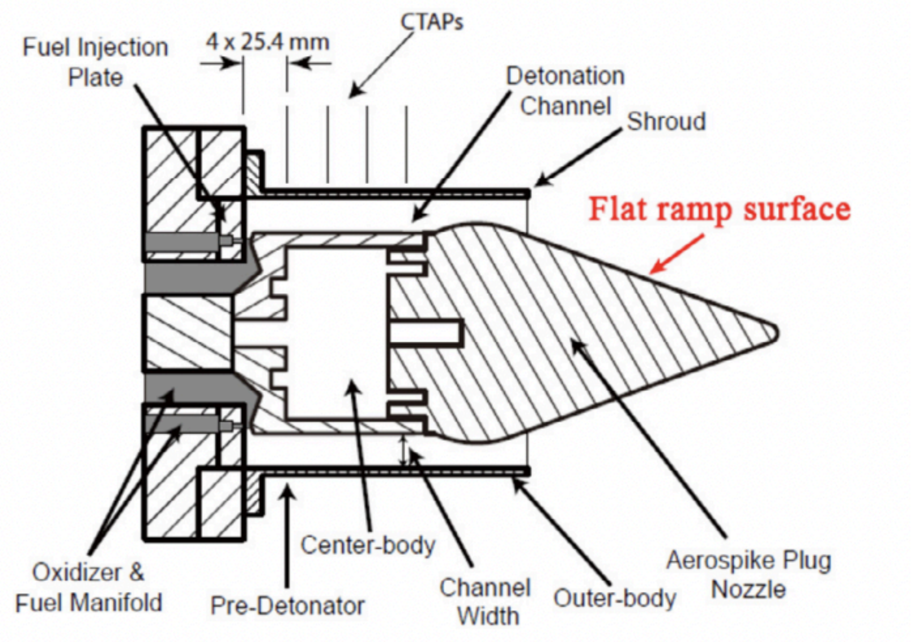
(6) $\frac{p}{p_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}}$

(7) $\frac{T}{T_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1}$

(8) $\frac{\rho}{\rho_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-1}{\gamma - 1}}$

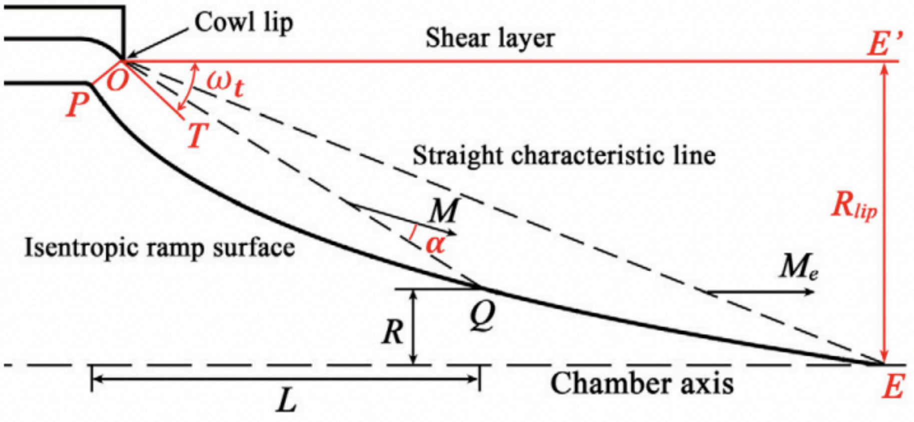
(9) $\frac{A}{A^*} = \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma + 1}{2(\gamma - 1)}} \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}}{M}$

THIS IS NOT FROM THE ARTICLE Source: https://www.grc.nasa.gov/www/k-12/rocket/isentrop.html
This is a supplement to confusion over isentropic relationships.



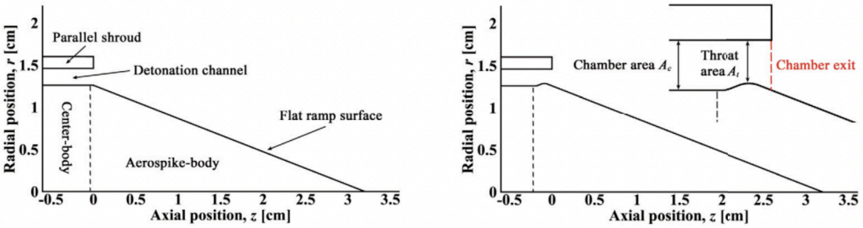
(a) Nozzle with flat ramp surface in RDE experiments [25].

Previous Research RDE-Aerospike integration (lost thrust due to flat ramp surface)



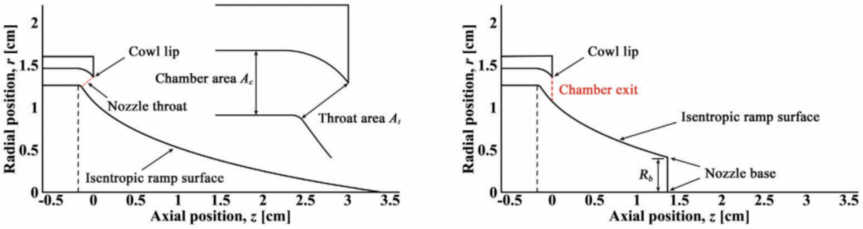
(b) Aerospike nozzle with isentropic ramp surface in rocket engines.

Traditional engine w/ aerospike - cowl lip with curved (isentropic) ramp surface.



(a) Case A, flat aerospike with $\varepsilon = 100\%$

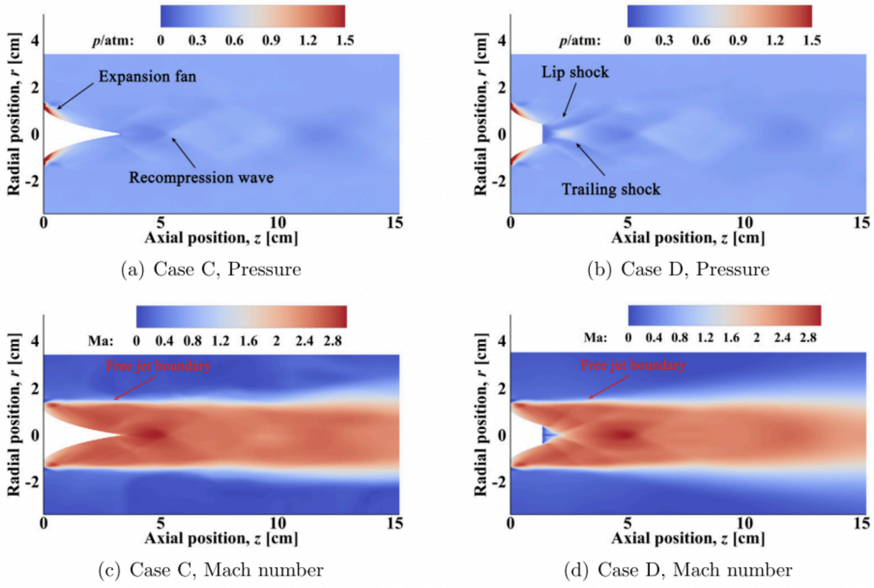
(b) Case B, flat aerospike with $\varepsilon = 87.3\%$



(c) Case C, Isentropic aerospike.

(d) Case D, 40% truncated isentropic aerospike.

Engine Nozzle Design Configurations Tested in Sim



(a) Case C, Pressure (b) Case D, Pressure

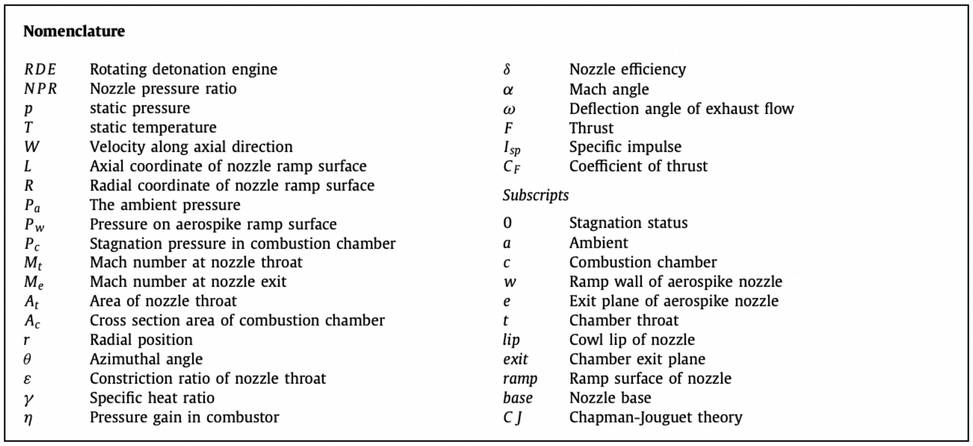
(c) Case C, Mach number (d) Case D, Mach number

2. Time-averaged plume field with isentropic aerospike nozzle. Case C with full-length aerospike and Case D with 40% truncated aerospike.

Fig. 12 - pressure and mach number observations in Case C and D (isentropic)

VOCAB: (w/definition)

Provided Nomenclature:

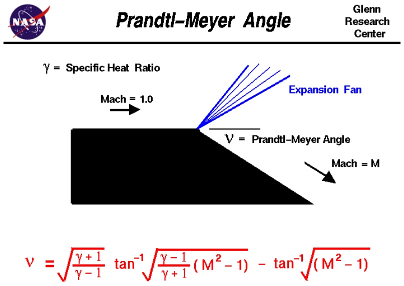


Nomenclature

RDE	Rotating detonation engine	δ	Nozzle efficiency
NPR	Nozzle pressure ratio	α	Mach angle
p	static pressure	ω	Deflection angle of exhaust flow
T	static temperature	F	Thrust
W	Velocity along axial direction	I_{sp}	Specific impulse
L	Axial coordinate of nozzle ramp surface	C_F	Coefficient of thrust
R	Radial coordinate of nozzle ramp surface	*Subscripts*	
P_a	The ambient pressure		
P_w	Pressure on aerospike ramp surface	0	Stagnation status
P_c	Stagnation pressure in combustion chamber	a	Ambient
M_t	Mach number at nozzle throat	c	Combustion chamber
M_e	Mach number at nozzle exit	w	Ramp wall of aerospike nozzle
A_t	Area of nozzle throat	e	Exit plane of aerospike nozzle
A_c	Cross section area of combustion chamber	t	Chamber throat
r	Radial position	lip	Cowl lip of nozzle
θ	Azimuthal angle	$exit$	Chamber exit plane
ε	Constriction ratio of nozzle throat	$ramp$	Ramp surface of nozzle
γ	Specific heat ratio	$base$	Nozzle base
η	Pressure gain in combustor	CJ	Chapman-Jouguet theory

Recorded Vocabulary:

- Annulus Combustion Chamber - ring-shaped chamber located between inner and outer casings of an engine’s combustion chamber.
- Flow-field structure - movement of forces (drag, shear, pressure, etc.) in a structure
- Plume field - concentration of exhaust gasses
- Under-expanded - When the pressure of the exhaust leaving the nozzle is above ambient pressure.
- Ambient Pressure - pressure of surrounding medium
- Isentropic Expansion - isentropic: constant entropy. The gas is in

	thermodynamic equilibrium (no spontaneous changes) ● Axisymmetric - symmetrical about an axis (Oxford Languages) ● Stagnation pressure - pressure of a fluid when brought to rest with no loss in mechanical energy. ● Constriction nozzle throat - fluids moving through a constricted nozzle throat may increase in velocity when moving to lower-pressure environments. ● Isobaric - Thermodynamic reaction taking place at constant pressure. ● Ramjet - an airbreathing jet engine that uses forward motion to collect air for combustion. ● Plane-radial RDE - engine that radiates outward ● Isentropic Relationship: An isentropic flow is when a fluid flow is both adiabatic and reversible. ● Adiabatic - heat does not leave or enter ● Constriction ratio - couldn't find anything on constriction ratio, but contraction ratio regards the ratio of chamber cross-sectional area to throat area ● Mach - quantity representing ratio of flow velocity past a boundary to the speed of sound ● Prandtl-Meyer expansion fan - a continuous sequence of infinitesimal Mach expansion waves  https://www.grc.nasa.gov/www/k-12/airplane/pranmyer.html ● Time-averaged parameters - time-weighted efficiency markers (perhaps continuity and frequency of detonation waves?)
Cited references to follow up on	[11] S. Prakash, R. Fiévet, V. Raman, J. Burr, K.H. Yu, Analysis of the detonation wave structure in a linearized rotating detonation engine, AIAA J. 58 (12) (2020) 5063–5077. [34] N. Kurita, N.H. Jourdaine, N. Tsuboi, K. Ozawa, K.A. Hayashi, T. Kojima, Three Dimensional numerical simulation on hydrogen/air rotating detonation engine with aerospike nozzle: effects of nozzle geometries, in: AIAA SciTech 2020 Forum, 2020, p. 0688. [39] Y. Zhu, K. Wang, Z. Wang, M. Zhao, Z. Jiao, Y. Wang, W. Fan, Study on the performance of a rotating detonation chamber with different aerospike nozzles, Aerosp. Sci. Technol. 107 (2020) 106338.

Follow up Questions	Next Steps: “The future research will focus on RDE experiments with the isentropic aerospike nozzles. Based on the experimental results, the nozzle structures will be further optimized and verified in RDE flight tests.” Questions: ● How do unstable detonation waves impact thrust efficiency? ● Is there a way to automate pressure equilibrium for maximized propulsive efficiency? ● How can RDE’s be modeled and tested without use of detonative materials? ● How can isentropic nozzle shaping be shifted to organic shapes? Is there a way to promote axial parallelism through shaped structural components?

Article #9 Notes: Study on the performance of a rotating detonation chamber with different aerospike nozzles

Date: 10.01.2023

Source Title	Study on the performance of a rotating detonation chamber with different aerospike nozzles
Source citation (APA Format)	Zhu, Y., Wang, K., Wang, Z., Zhao, M., Jiao, Z., Wang, Y., & Fan, W. (2020). Study on the performance of a rotating detonation chamber with different aerospike nozzles. *Aerospace Science and Technology*, 107, 106338.
Original URL	https://doi.org/10.1016/j.ast.2020.106338
Source type	Journal Article
Keywords	*Referenced in a previous article* Keywords: “Rotating Detonation Rocket Engine”, “Nozzle”, “Detonation”
#Tags	#Rotating Detonation Rocket Engine #Nozzle Geometries #Aerospike Integration
Summary of key points + notes (include methodology)	**Mini-Summary:** “Study on the performance of a rotating detonation chamber with different aerospike nozzles” by Zhu et al. is an experimental investigation into the behavior in chamber pressure and propulsive thrust efficiency when a rotating detonation engine chamber is introduced to conical and flat nozzles. This study found that conical, aerospike nozzles had greater propulsive performance than flat or nozzle-less engine configurations, while the trade-off was that the detonation waves produced within the chamber greatly impacted the oxidizer-fuel injection process. **Notes:** INTRODUCTION: ● Detonation chamber pressure significantly increases due to rapid energy release rate consuming fuel and oxidizer mixture zone. ● Believed that detonation waves produce higher thermal efficiency, compared to other deflagration systems. ● RDEs can produce a steady thrust as detonation waves are propagated inside of the combustion chamber ● Previous research primarily consists of initiation, propagation, and stabilization. ● NEED - more research on propulsive performance AND nozzle design and resulting propagation characteristics.

- Flow is unsteady in the combustion chamber due to RD waves.
- Spontaneous distributions of detonation waves have visually led to an unsteady exhaust plane at combustor exit.
- CAN NOZZLE DESIGN MINIMIZE UNSTEADY EXHAUST FLOW?
- testing/iteration: Combustion chambers lead to different exhaust nozzles
- Hollow chamber may lead to a Laval nozzle. Annular chamber leads to efficiency with aerospike geometry.
- Chamber exit blockage has been proven to increase the number of detonation waves.
- Convergent sections = more reflected shock waves
- Chocked aerospike nozzle = improved static pressure gain and specific impulse
- Best propulsive behavior occurs when flow is fully expanded to the atmospheric pressure.

NOZZLE DESIGN:

- Lack of uniformity of pressure and temperature within the detonation chamber make it necessary to design a nozzle capable of adjusting unevenness for more even flow outside of the nozzle.
- Ideal expansion is very hard to reach with unsteady flow.
- Time-averaged parameters have been adopted for RDE nozzle design input.
- PARAMETERS:
    - Stagnation parameters of exhaust flow from combustion chamber
    - Total mass flow rate
        - No shock wave exists before nozzle throat (SEE EQs)
    - Ambient pressure
- Before Nozzle
    - No shock waves
- Divergent Section
    - Isentropic supersonic flow
    - Area ratio is governed by Mach numbers based on gas dynamic theory
    - Mach # calculated by the design pressure ratio
    - Nozzle divergence - look at Fig. 1
        - Divergence and nozzle throat geometry determine “imaginary” exhaust flow constraints
- Expansion area
    - Expansion area ratio → base area radius, exit radius, geometric angle between characteristic line and reference axis all considered in geometry design

EXPERIMENTAL SETUP

- See 3.1 for specific design info and measurements
- See figure 2 for experimental setup diagram
- WHAT'S BEING TESTED?
    - Conical configuration nozzle (Aerospike)
        - has transition section connecting annular combustion

chamber and exhaust nozzle

- Flat configuration nozzle (aerospike)
  - Larger base area and greater nozzle radius
- Platform:
  - Consists of…
    - supply system
      - One for RD chamber (oxidizer, ethylene, nitrogen)
        - Nitrogen supply is independent
      - One for pre-detonator tube (oxidizer, ethylene)
    - measurement system
      - Mass flowmeters
        - Measure mass flow rates of ethylene and oxidizer
      - Pressure transducers
      - Load cell - measured thrust
      - All sent to a data acquisition system ?
    - control unit
      - Data acquisition
      - Supplies of fuel, oxidizer, and purge gas (essentially controls what goes where)
    - rotating detonation chamber
      - Dynamic piezoelectric transducers arranged on circumference of chamber head
        - Cooled with water (may not hold applications in my project)
  - Nozzle had piezoelectric transducer to measure static pressure

ERROR ANALYSIS

- Measurement accuracy of +-1% for mass flowmeters and measurement precision, and +-3% for piezoelectric transducer
- Mean values gathered from:
  - Mass flowmeters
  - Pressure transducers
  - Load cell

RESULTS

- CONTROL: RD CHAMBER W/O NOZZLES
  - Used to study influence of nozzle addition on mass flow rate
- Convergent nozzles impact fuel and oxidizer supply
- Wave operation modes observed:
  - Single-wave mode
  - Dual-wave mode
  - Hybrid mode
- Wave intensity was reduced by the expansion waves bc of lateral expansion effect
- As wave #s increase, mixing conditions are strained
- See Important Figures Fig.12 for mass flow rate results by nozzle type

- See Important Figured Fig. 13 for pressure distribution by nozzle type
- WAVE PATTERNS:
- Nozzle-less test cases could only produce single-wave modes, while nozzles were essential in multi-wave modern with higher mass flow rates.
    - Existence of nozzle facilitates wave mode transitions
- CHAMBER PRESSURE:
- Detonation process naturally gains pressure in combustion chamber
- Peak pressure was higher w/nozzle rather than without
- Wave intensities could easily be affected by lateral expansion.
- In the nozzle-less cases, the standard deviation in wave pressure was lower than the nozzle cases, showing that the NOZZLE-LESS case is more stable!
- Nozzle C fluctuated less than Nozzle A and B.
    - WHY? Nozzle geometry was different and so were parameters.
    - Longer curved transition part could have made the converging process easier, which would cause chamber pressure to rise, resistance to fuel and oxidizer injection,
    - Oblique shock waves would propagate in nozzle C, but the intensity would decrease due to elongated passage and less effect on fuel and oxidizer mixture (and its homogeneities)
- Improving Propulsive Performance
    - Detonation waves are essential in improving propulsive performance
    - Nozzle throat produces a throttle effect that increases pressure in the chamber
- No nozzle - no pressure gain
- Mass Flow Rate increase = static pressure increase = reaction rate increase
- “different nozzle geometries would induce different pressure increase in the combustion chamber.”
- Throat area calculated by DPR (Design pressure ratio) was larger than required, although it increased chamber pressure.
- PROPULSIVE PERFORMANCE
    - Before Ignition - 1st stage
        - fuel + oxidizer
        - cold flow state → a bit of thrust
    - Rotating Detonation Operations - 2nd Stage
        - Ignition process
    - Detonation Quenching Process
        - fuel + oxidizer flow closed
- “It is believed that the pressure gains in the combustion chamber and the nozzles accelerate the exhaust flow and, therefore, a higher propulsive performance is generated”
- Loss of total temp. resulted in decrease of specific impulse in nozzle versions
    - Found that specific impulse would increase then decrease when increasing the mass flow rate
- Nozzle-less had no pressure gain - less propulsive performance

	● Design Pressure Ratio (DPR) determines optimal throat area - and it's very important that the design is as close as possible.
	  ○ Below DPR - overexpansion
	  ○ Over DPR - underexpansion
	CONCLUSIONS
	● Study researches and discusses the effect of nozzles, and aerospike nozzles on RC CHAMBER propulsive performance.
	● They studied:
	  ○ Three modes during nozzle adoption: single-wave, dual-wave, and hybrid mode
	  ○ Propulsive performance
	● Results
	  ○ nozzle -less case: single-wave
	  ○ Nozzle cases: multi- and hybrid waves
	    ■ Wave propagating velocity decreased because waves deteriorated the fuel and oxidizer mixing process.
	    ■ Waves were more intense and repeated in nozzle cases
	    ■ Peak pressures were higher
	    ■ Standard deviations increased
	    ■ Nozzles = pressure gain, but impacts injection process
	  ○ Overall, propulsive performance was enhanced with nozzles.
	    ■ B was better than A, but also had greater losses because of overexpansion
	    ■ Conical was better than flat, as flat had less pressure gain and recirculation was weak, causing thrust loss.

Research Question/Problem/ Need	**Need:** Clarification on the effect of exhaust nozzles on propagation characteristics of rotating detonations, and the connection between propulsive performance and wave operation modes. Evidence from the text: “However, how to improve the propulsive performance is an important topic for the practical application as well. Therefore, proper design of the exhaust nozzle and its impact on the propagation characteristics of rotating detonations are necessary to be clarified.” “...few of them have analyzed the correlation between the operation modes and the propulsive performance.” “...there are few attempts on the design method of a proper nozzle for the rotating detonation chamber.”

Important Figures

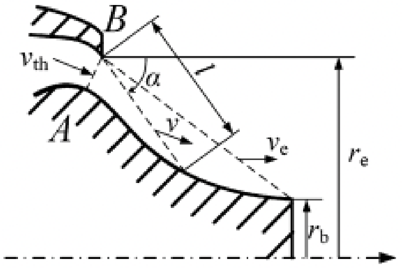


Fig. 1. Schematic of the divergent profile of the aerospike nozzle [32].

Refer to this figure for nozzle throat divergence geometries.

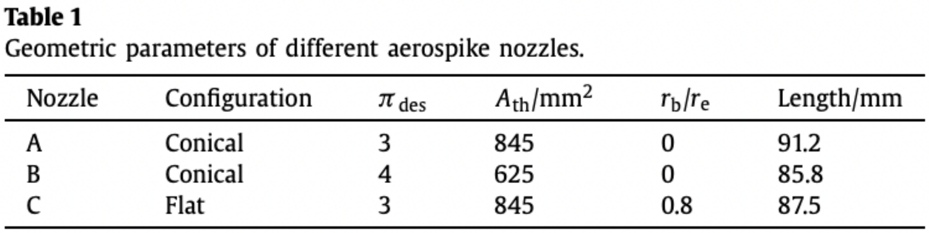
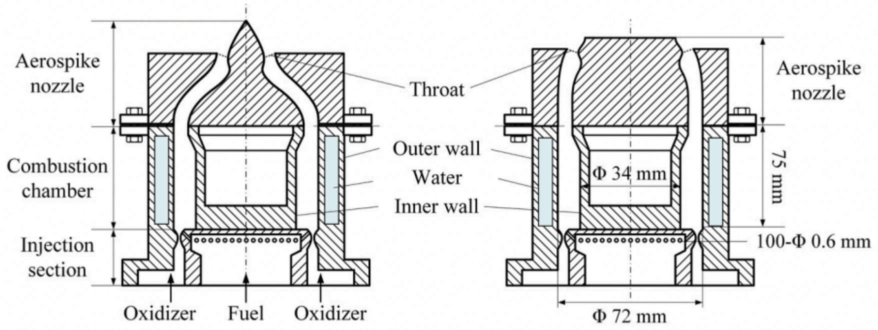


Table 1
Geometric parameters of different aerospike nozzles.

Nozzle	Configuration	π_{des}	A_{th}/mm^2	r_b/r_e	Length/mm
A	Conical	3	845	0	91.2
B	Conical	4	625	0	85.8
C	Flat	3	845	0.8	87.5

Experimental setup for aerospike nozzles - geometric parameters



(a) Rotating detonation chamber with a conical configuration nozzle.

(b) Rotating detonation chamber with a flat configuration nozzle.

Fig. 2. Schematic of the rotating detonation chamber with different aerospike nozzles.

Aerospike nozzles being tested (mentioned 3 but only showed 2)

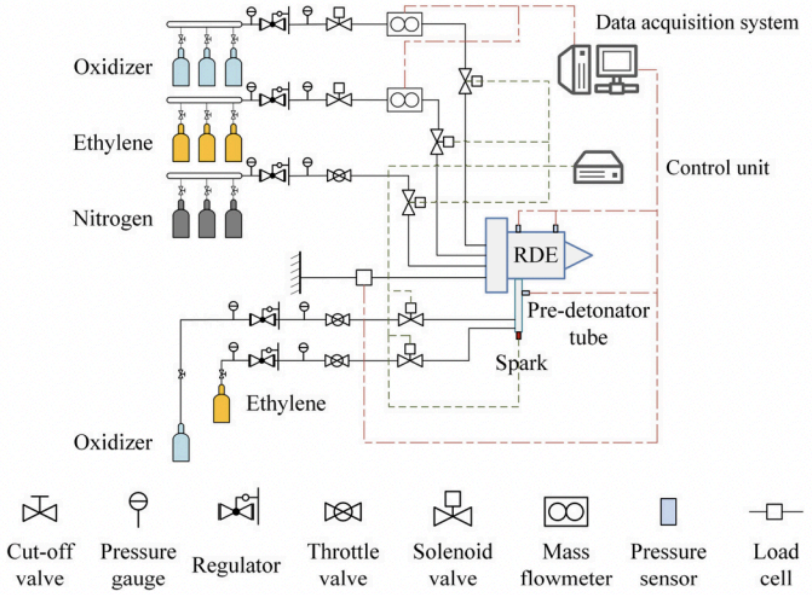


Fig. 3. Schematic of the experimental platform.

Experimental Setup Schematic

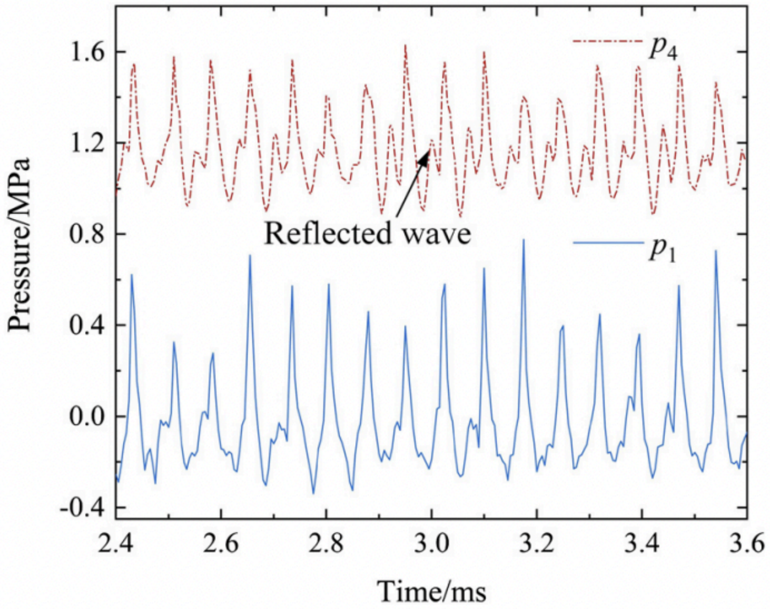


Fig. 8. Pressure profiles of the dual-wave mode with nozzle A at 0.221 kg/s.

Dual-wave mode created with nozzle A

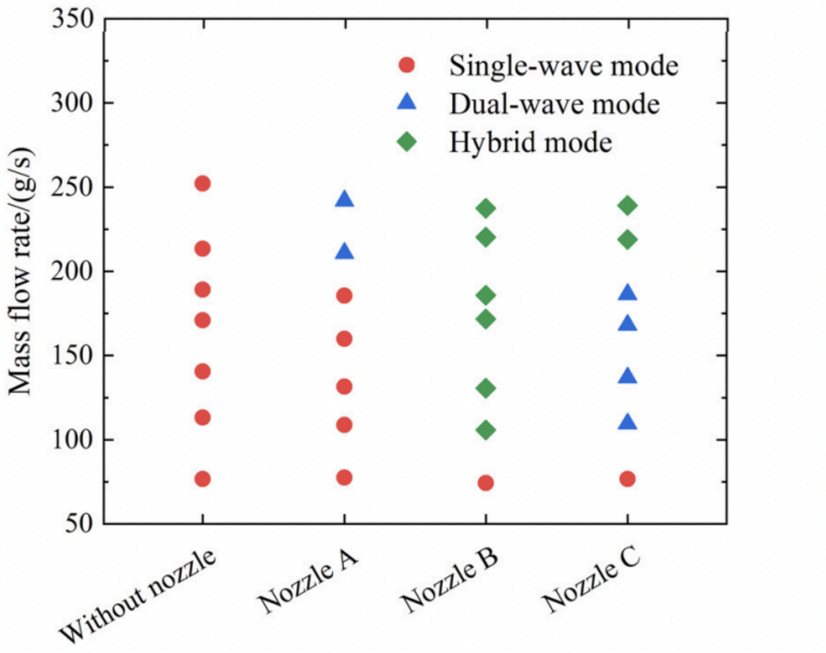


Fig. 12. Operation modes with and without nozzles at different mass flow rates.

Results of Nozzle Testing on Mass flow rates

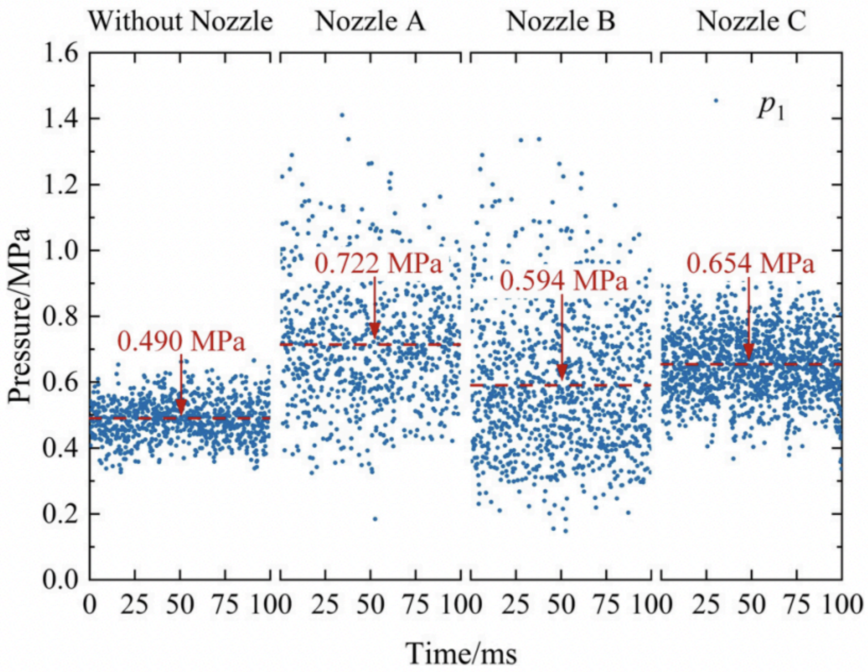
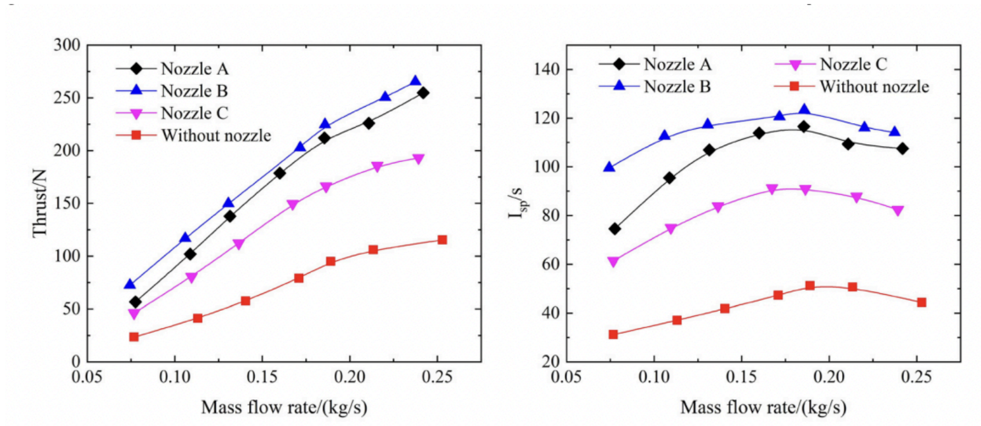
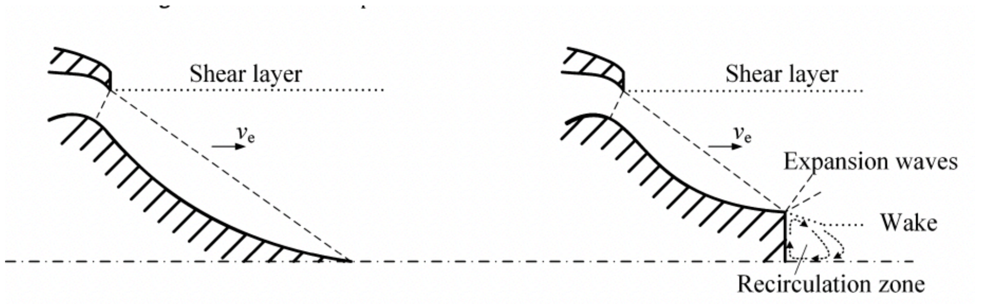


Fig. 13. Peak pressure distribution at a flow rate of 0.190 kg/s.

Pressure distribution by tested nozzle

	 (a) Thrust comparison. (b) Specific impulse comparison. Thrust comparison and specific impulse comparison among all tested nozzles.  (a) Nozzle with a conical centerbody (b) Nozzle with a flat centerbody **Fig. 18.** Flows caused by different nozzle centerbodies [15]. Visual representation of exhaust flows and changes and recirculations based on nozzle structure.
VOCAB: (w/definition)	- Deflagration - combustion that propagates at a supersonic speed - Propagate - transmit through a medium - Laval nozzle - hourglass shaped nozzle, used to accelerate hot, pressurized gas to supersonic speeds. - Lateral Expansion Effect - expansion of gasses within combustion chamber (along sides) - Throttle Effect - closing the valve slightly to convert high pressure to low pressure - Specific Impulse - how fast the propellant is ejected (impulse per propellant)
Cited references to follow up on	[15] G. Hagemann, H. Immich, T.V. Nguyen, G.E. Dumnov, Advanced rocket nozzles, J. Propuls. Power 14 (5) (1998) 620–634. [19] Y. Wang, J. Le, A hollow combustor that intensifies rotating detonation, Aerosp. Sci. Technol. 85 (2019) 113–124.

	[25] H. Peng, W. Liu, S. Liu, H. Zhang, Experimental investigations on ethylene-air continuous rotating detonation wave in the hollow chamber with Laval nozzle, Acta Astronaut. 151 (2018) 137–145. [30] A. Harroun, S.D. Heister, S.V. Sardeshmukh, J.H. Ruf, Effect of Aerospike Plug Nozzle Design on Rotating Detonation Engine Performance for Rocket Applications, AIAA 2019-0197. [1] J.H. Lee, The Detonation Phenomenon, 2008. [2] K.K. Kuo, Principles of Combustion, John Wiley and Sons, New York, 2005. [3] P. Wolanski, ´ Detonative propulsion, Proc. Combust. Inst. 34 (1) (2013) 125–158. [5] F.K. Lu, E.M. Braun, Rotating detonation wave propulsion: experimental challenges, modeling, and engine concepts, J. Propuls. Power 30 (5) (2014) 1125–1142.
Follow up Questions	1. Why do waves intensify with nozzles? Where are they propagating in the nozzle structure? 2. Why are waves impacting oxidizer and fuel injection processes? 3. Can injection patterns be altered to adhere to wave detonation patterns? 4. How does pressure distribution and specific impulse improve thrust? 5. Are there other nozzle geometries that could be texted and weren't?

Article #10 Notes: Numerical Study of the Propulsive Performance of the Hollow Rotating Detonation Engine with a Laval Nozzle

Date: 10.06.2023

Source Title	Numerical Study of the Propulsive Performance of the Hollow Rotating Detonation Engine with a Laval Nozzle
Source citation (APA Format)	Yao, S., Tang, X., & Wang, J. (2017). Numerical Study of the propulsive performance of the hollow rotating detonation engine with a Laval nozzle. *International Journal of Turbo & Jet-Engines*, *34*(1). https://doi.org/10.1515/tjj-2015-0052
Original URL	https://www.proquest.com/advancedtechaerospace/docview/1876570942/E6384CAAA55A47CCPQ/10?accountid=29120
Source type	Journal Article
Keywords	Rotating detonation rocket engine, rocket propulsion, theoretical nozzles
#Tags	#rotating detonation rocket engine #theoretical nozzles #hollow rde
Summary of key points + notes (include methodology)	SUMMARY: In the article, “Numerical Study of the Propulsive Performance of the Hollow Rotating Detonation Engine with a Laval Nozzle,” the propulsive performance of a hollow rotating detonation engine is evaluated with a Laval nozzle. In addition to propulsive performance, improvement in efficiency will be determined by the thermal efficiency, thrust, specific impulse, and mass flow rate, all parameters being compared to a hollow RDE with no nozzle setup. The results of this experimental process prove that the Laval nozzle significantly improved the propulsive performance of the hollow RDE, while propulsive efficiency was likely less than the RDE due to its hollow structure, despite its reduction of the issue with overheating in traditional RDE configurations. The hollow RDE experienced a 5.5% decrease in propulsive efficiency when compared to the annular RDE, although the hollow configuration still performed well. INTRODUCTION: ● Why is detonation promising? ○ Detonation is a shock-induced combustion wave propagated at supersonic speeds, the energy released by detonative products being similar to an isochoric process’ thermal efficiency. ○ In being thermodynamically more efficient, detonation has been a

promising way to generate propulsion.

- Three types of detonation engines:
    - Standing detonation engine (SDE)
    - Pulse detonation engine (PDE)
    - Rotating detonation engine (RDE) - most advantageous
- RDE's
    - Can provide thrust with smaller detonation chambers
    - Initiation happens once, and it keeps going continuously.
    - Studies include numerical studies about flow-field and mechanism, and experimental/numerical studies recently have been about co-axial annular combustor models.
- Challenges with co-axial annular combustor models
    - Overheating → complicated cooling system!
    - To fix this, Tang et al. developed a hollow RDE model.
- Hollow RDE Model
    - goal : improve propulsive parameters
    - propulsive parameters: thrust, specific impulse, and mass flow rate.

GOVERNING EQUATIONS:

- 3D Euler Equations used → IGNORING viscosity, thermal conduction and mass diffusion.
- Ma et al. informed governing equations, which find:
    - Mass production rate of reactants
    - Gas constant
    - Pressure
    - Temperature
    - Convective flux
    - Conservative variable vector
    - Source vector

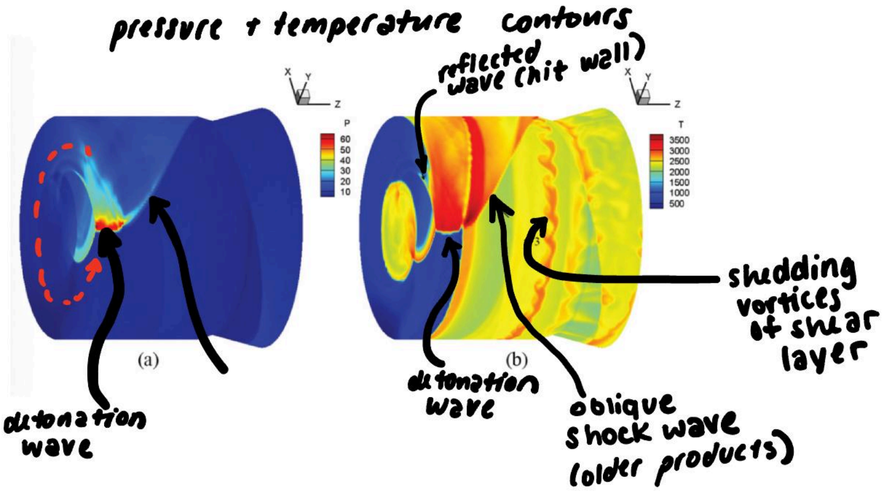
CONDITIONS:

- See "important figures" for the Hollow RDE schematic.
- Subsonic and supersonic exhaustion, relaxation rate coefficient, and ambient pressure and fluid parameters were calculated.
- Used in-house code to test RDE simulations:
    - Is this good practice? Should in-house code be used to simulate RDEs? Do other people use the same code, and could results differ?
- Observed grid convergence by finding that in 1D detonation simulations, pressure distributions with different grid sizes were the same.
    - ASK ABOUT READING / UNDERSTANDING COMP FLUID DYNAMICS REFERENCES.

RESULTS & DISCUSSION

- Specific Impulse is split into fuel-based and fuel-oxidizer mixture-based.
- They chose to test with the convergent divergent nozzle (Laval nozzle).
- Convergent part - used for flow acceleration (smooth curve)

- Researchers also performed tests with an annular RDE and the same Laval nozzle.
- Detonation waves successfully propagated and resembled typical rotating detonation waves.
- See annotated figure:



Improvements:

- Laval nozzle significantly improved propulsive performance of hollow RDE.
- Thrust increased by 95%
- Fuel-based specific impulse increased by 11.4%
- Engine displacement increased by 84%
    - Laval nozzle changes the entire rotating detonation flow field
    - Has effect on fuel intake and burnt product
- Conclusion: propulsive performance is affected by injection conditions.
    - Compared to propulsive performance of annular RDE model with same nozzle shape.
    - It lost propulsive performance compared to the annular RDE model, but overall the hollow RDE worked well.

CONCLUSION:

- Fuel-based specific impulse, thrust, and mass flow rate all increased with the addition of the Laval nozzle.
- Compared with RDE, the removal of an inner wall led to propulsive performance decreases, but still solved the overheating problem and is considered a promising technology by the researchers.

Research Question/Problem/ Need	An understanding of how the hollow RDE model, a model developed with the goal of improving thermal conditions in a standard RDE, gains or loses propulsive performance with the implementation of a Laval nozzle.

Important Figures

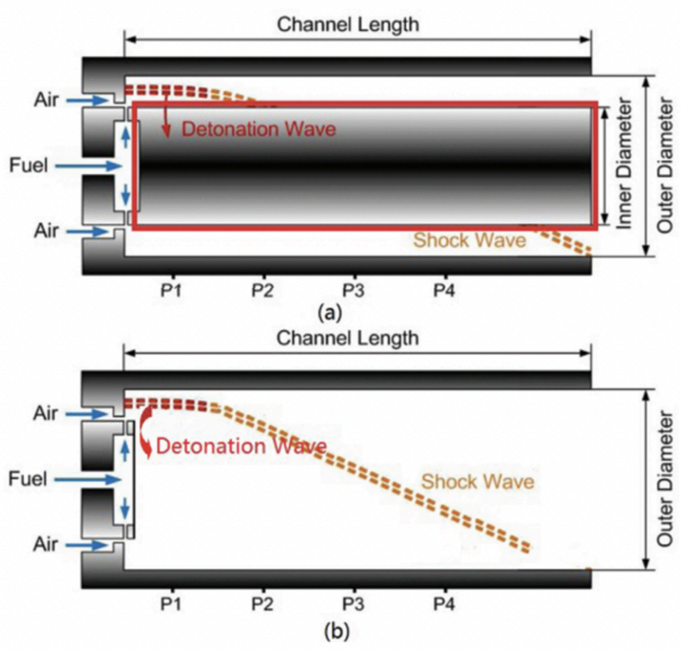


Figure 1: Schematic of RDE models. (a) Annular model [19] and (b) hollow model.

RDE vs Hollow RDE Schematic.

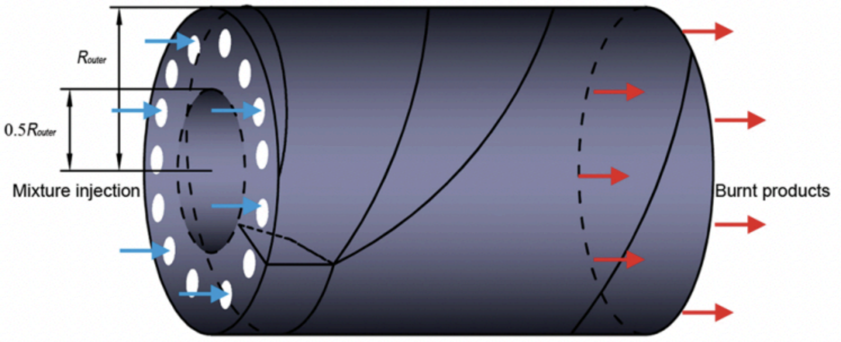
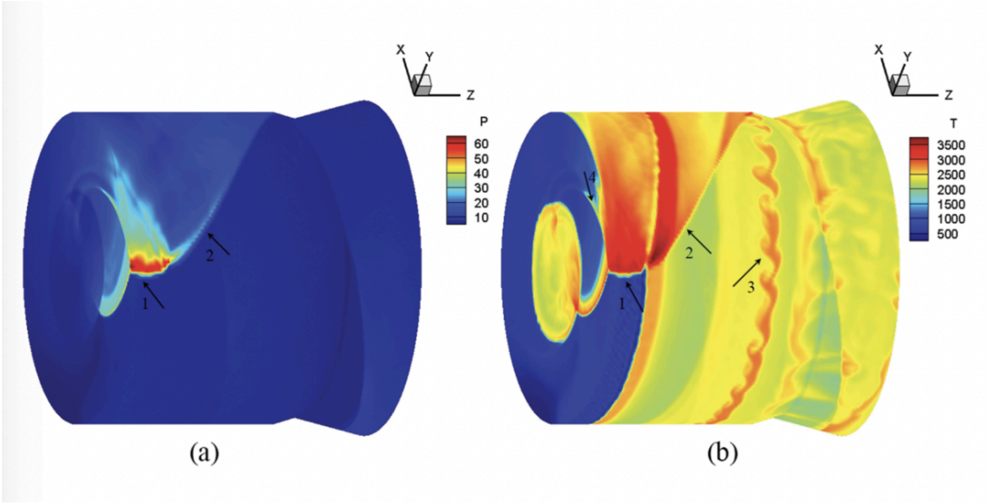


Figure 2: Schematic of the geometric shape of the hollow RDE model.

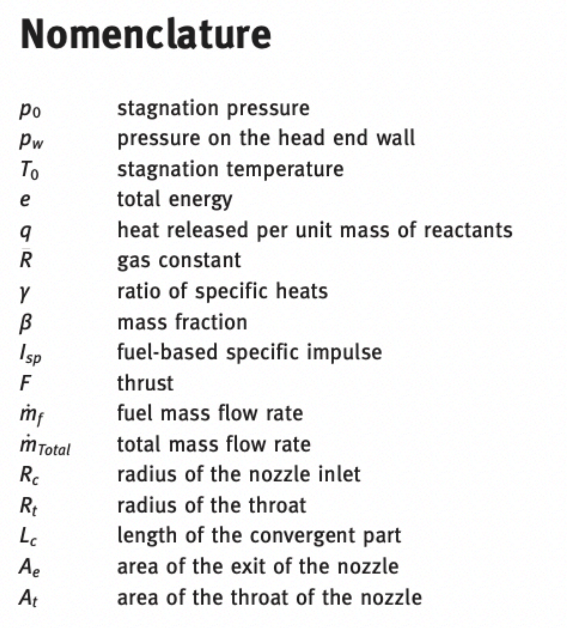
Hollow RDE: schematic - see page 2 for shape and dimensional specifics.



(a) (b)

Figure 6: pressure vs temperature patterns w/wave movement.

VOCAB: (w/definition)



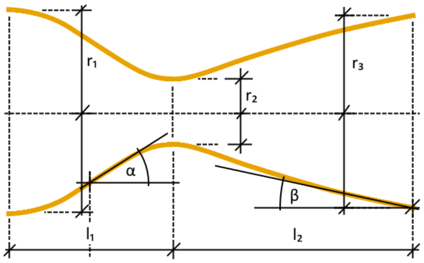
Nomenclature

p_0	stagnation pressure
p_w	pressure on the head end wall
T_0	stagnation temperature
e	total energy
q	heat released per unit mass of reactants
$\bar{R}$	gas constant
γ	ratio of specific heats
β	mass fraction
I_{sp}	fuel-based specific impulse
F	thrust
$\dot{m}_f$	fuel mass flow rate
$\dot{m}_{Total}$	total mass flow rate
R_c	radius of the nozzle inlet
R_t	radius of the throat
L_c	length of the convergent part
A_e	area of the exit of the nozzle
A_t	area of the throat of the nozzle

Provided Nomenclature.

Vocab List:

- Co-Axial Annular Combustor - a combustion system unified on one access (injection and propulsion are all directed along the same axis).
- Grid convergence - a study carried out demonstrates grid independence of the parallel computation solver.
- De Laval nozzle - a De Laval nozzle is an hourglass-shaped nozzle that takes a subsonic interior flow and transforms it into a supersonic flow by compressing it through a small diameter.

	 ● Subsonic - moving at a speed lower than the speed of sound. ● Supersonic - moving at a speed that is faster than the speed of sound. ● a fifth-order WENO scheme - a spatial discretization method for hyperbolic partial differential equations. ● Third-order Runge-Kutta scheme - a formula for solving differential equations in “fuzzy” environments
Cited references to follow up on	[1] Nicholls JA, Wilkinson HR, Morrison RB. Intermittent detonation as a thrust-producing mechanism. J Jet Propul 1957;27:534–41. [5] Naour BJ, Falempin F, Miquel F. Recent experimental results obtained on continuous detonation wave engines. 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2011. [19] Yi TH, Turangan C, Lou J, Wolanski P, Kindracki J. A three dimensional numerical study of rotational detonation in an annular chamber. 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 2009. [15] Nordeen CA, Schwer D, Schauer F, Hoke J, Cetegen B, Barber T. Thermodynamic modeling of a rotating detonation engine. 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2011.
Follow up Questions	● What other RDE-based alternatives aim to solve issues in propulsive efficiency? ● How can chamber shape be altered to best guide and direct wave and exhaust flow patterns? ● Are shedding vortices impacting the maximization of the rocket’s propulsive efficiency? ● How does fuel-oxidizer mixture-based specific impulse impact the determination of a rocket’s propulsive performance?

Article #11 Notes: Detonation Propagation through Inhomogeneous Fuel-Air Mixtures

Date: 10.25.23

Source Title	Detonation Propagation through Inhomogeneous Fuel-Air Mixtures
Source citation (APA Format)	Prakash, S., & Raman, V. (2019, July 28). Detonation Propagation through Inhomogeneous Fuel-air Mixtures,.*29th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS).* https://www.osti.gov/servlets/purl/1808477#:~:text=The%20mixture%20inhomogeneity%20results%20in
Original URL	https://www.osti.gov/servlets/purl/1808477#:~:text=The%20mixture%20inhomogeneity%20results%20in,and%20diminished%20wave%20propagation%20velocities.
Source type	Conference Article
Keywords	Rotating detonation rocket engine, rocket propulsion, mixing
#Tags	#Mixing #Rotating Detonation Engine #rocket propulsion systems

Summary of key points + notes (include methodology)	Summary:
	This article tests the effect of varying stratification lengths in inhomogeneous fuel mixture concentration gradients on the propagation characteristics of rotating detonation engines. The researchers used a 2D "rolled out" model to express this effect. They measured detonation stability, pressure, wave velocity, and overall wave properties (such as location and size of eddy currents) to determine the relationship between equivalence ratios and stratification lengths (determining level of homogeneity) and detonation wave performance in rotating detonation engines. Case 1, which had the most homogenous mixture concentration gradient, had the most complete and homogenous consumption of fuel. This allowed the wave performance to be optimized.
	
	BACKGROUND INFORMATION -
	+ Practical RDE's fuel and air injection is not premixed to avoid back-propagation of detonation waves into the injection feed plenums.
	+ This:
	    + Decreases thrust efficiency
	    + Skews and diminishes wave properties
	    + Reduces peak pressure
	    + Detonation stability is affected by the fuel concentration gradient
	
	RESEARCH QUESTION/GOAL -

- What are the specific impacts of mixture inhomogeneity on detonation propagation from the other complexities associated with a practical RDE?
    - isolate inhomogeneity impact on waves!
- This approach introduces the following aspects:
    - left side is the inflow (this is where the detonation wave comes from, which travels across the screen).

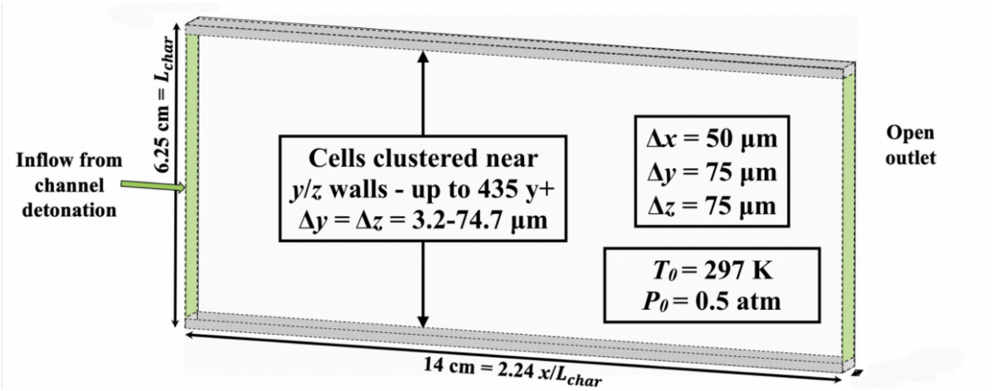
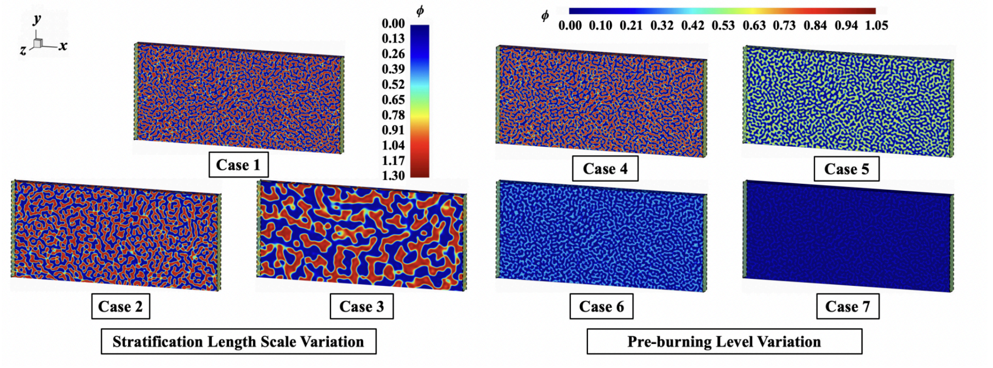
      The right side is an open outlet, meaning that cyclical wave propagation does not occur. This model analytically tracks stoichiometric hydrogen-air detonations.
- "...discreetly-placed fuel sources act as concentrated pockets of energy release and enforce a nonequilibrium state for the detonation wave."

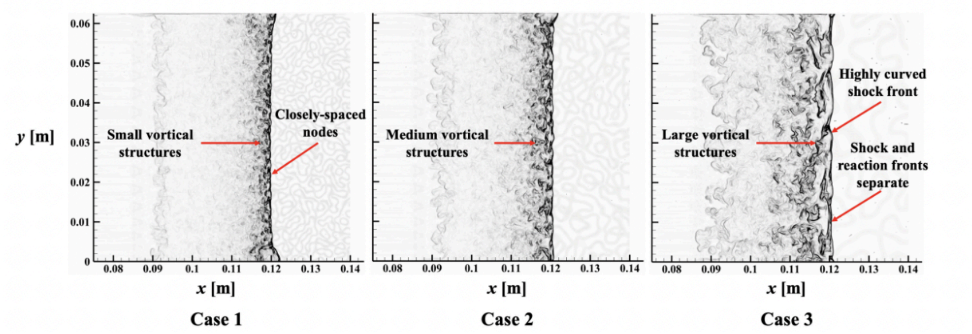
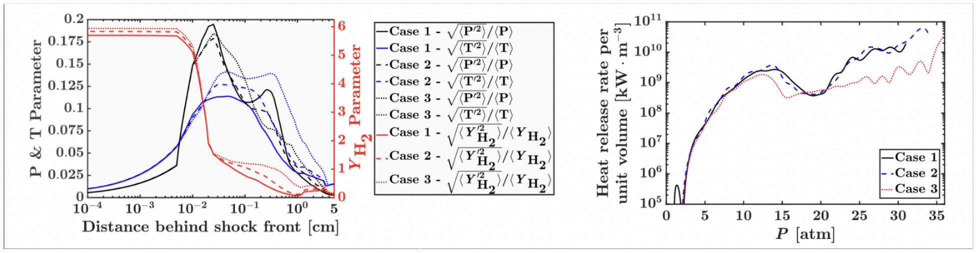
Approach, Continued:

- canonical chamber geometry is used to examine the detonation wave structure within the chamber.
- DNS - Direct Numerical Simulation
    - 5th order weighted essentially non-oscillatory (WENO) scheme - used for NON LINEAR CONVECTIVE FLUXES
    - quadratic upstream interpolation for convective kinematics (QUICK) scheme - NONLINEAR SCALAR TERMS
    - 4th order central scheme - DIFFUSIVE TERMS +4th order Runge-Kutta scheme - TEMPORAL DISCRETIZATION (for flow problems
- The researchers use a variety of physics-based solvers in their numerical simulation, all proven to work in previous, referenced sources.
    - These solvers and equations are outside of my area of knowledge, and I hope to receive expert advice on tackling this component.
- 7 cases are tested:
    - The first three differ in integral length scales, meaning that concentration gradients differ in fineness.
    - The last four differ in levels of pre-burning by a percentage of the equilibrium.

Results:

- Waves behave very differently among all three cases.
- Findings show that altering stratification lengths changed the detonation cell size.
- This means that altering the length of fuel concentration pockets altered the detonation cycle.
    - "...causing it to vary vastly from the homogeneous condition typically used for annulus sizing. "
    - This means that changing conditions make it more difficult to determine chamber design.
- They found…
    - Case 1 had lowest variability in T and P, lowest standard deviation
    - MOST HOMOGENOUS and COMPLETE CONSUMPTION OF FUEL.
- What are eddy currents?

	+ a reverse current structure that is created when flow is turbulent. Conclusions + Smaller stratification length scales create small eddy structures that are more efficient in mixing post-detonation gasses in the reaction zone. + initial detonation wave strength is greater with larger stratification lengths + reaction proceeds to equilibrium closer to the shock front + case 1 eddy structures aid in deflagración, with more combustible efficiency and a more homogenous post-detonation mixture. + stratification level changes cell size
Research Question/Problem/ Need	The research question asked was regarding the impact of stratification lengths, or inhomogeneity levels, in fuel-air mixtures on detonation wave characteristics within the Rotating Detonation Engine.
Important Figures	 Experimental Configuration: inflow channel and open outlet, where a rotating detonation wave enters from the inflow channel and mixtures within the chamber impact propagation characteristics.  Preset stratification lengths in the experimental configuration. gradient represents an equivalence ratio. If the equivalence ratio = 1 --> combustion is stoichiometric.

	If it is < 1 --> the combustion is lean with excess air if it is >1 --> the combustion is rich with incomplete combustion.  This graph shows the detonation wave's structure prior to reaching the output point. Highlighted are the effects of turbulent mixing and eddy structures.  On the left: normalized standard deviation of pressure, temperature, and fuel mass fraction behind the detonation wave front for cases 1, 2, and 3. On the right: Low pressure - deflagration, high pressure - detonation. The increased intensity of heat release at lower pressures for case 1 corresponds to increased deflagration in this configuration.
VOCAB: (w/definition)	**Canonical** - relating to a standard formula **Feed Plenums** - a space designated for air flow (or other fluid) **Stratification** - the act of sorting data/objects into distinct groups or layers. **Interpolation** - the insertion of something of a different nature into something else **CHEMKIN** - (Ansys Chemkin-Pro) a chemical kinetics simulator that models idealized reacting flows and provides insight into results before production testing. **Vortical** - like that of a vortex; whirling. **Nodes** - a point at which lines or pathways intersect or branch; a central or connecting point.
Cited references to follow up on	S. Prakash, R. Fievet, V. Raman, J. Burr, and K. H. Yu, "Analysis of the detonation wave structure in a linearized rotating detonation engine," 2018. Accepted to the AIAA Journal special issue on Continuous Detonation and its Applications. R. K. Azadboni, A. Heidari, L. R. Boeck, and J. X. Wen, "The effect of

	concentration gradients on deflagration-to-detonation transition in a rectangular channel with and without obstructions a numerical study," International Journal of Hydrogen Energy, vol. 44, no. 13, pp. 7032 – 7040, 2019. D. Santavicca, R. Yetter, and S. Peluso, "Effect of mixture concentration inhomogeneity on detonation properties in pressure gain combustors." University Turbine Systems Research (UTSR) 2015 Kick-off Meeting (Presentation), October 2015. D. Santavicca, R. Yetter, and S. Peluso, "Effect of mixture concentration inhomogeneity on detonation properties in pressure gain combustors." University Turbine Systems Research (UTSR) 2015 Kick-off Meeting (Presentation), October 2015.
Follow up Questions	1. How can injection be modeled and used to construct the concentration gradients that were tested in this research paper? 2. Are the remains of fuel air mixtures after the detonation wave passes godo or bad? Do these fragments of left-over fuel and air impact the next wave's propagation characteristics? 3. Why do vortical velocities and eddy structures introduce information regarding the success of a wave? Why are these factors important in determining the success/efficiency of a rotating detonation wave? 4. How do mathematical solvers contribute to simulation development? What are these mathematical solvers doing?

Article #12 Notes: Design and Analysis of Rotating Detonation Wave Engine

Date: 11/3/23

Source Title	Design and Analysis of Rotating Detonation Wave Engine
Source citation (APA Format)	Ramanujachari, V., Roy, R. D., & Amrutha Preethi, P. (2022). Design and Analysis of Rotating Detonation Wave Engine. Proceedings of the National Aerospace Propulsion Conference, 2022, 415–430. https://doi.org/10.1007/978-981-19-2378-4_24
Original URL	https://link.springer.com/chapter/10.1007/978-981-19-2378-4_24
Source type	Conference Article (CA)
Keywords	rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary** This article addressed the development of a rotating detonation system using computational and numerical analyses of engine performance. Using a 2D model, the researchers were able to model detonation wave properties and obtain parameters based on the Chapman-Jouguet detonation model. Before obtaining these detonative values, a simple mixing analysis was performed (done with injecting hydrogen and air) in order to obtain conditions prior to the arrival of the detonation wave. It was stated that this process was helpful in obtaining reasonable results. The results, related to specific impulse and parameters based on a pressure history model, were comparable to other studies. In the future, high-fidelity models could be pursued to identify the strengths and weaknesses of this model. **Key Points + Notes** (1) Introduction: ● Cell size in detonation waves are strongly dependent on: ○ Choice of fuel and oxidizer ■ This study uses a hydrogen and air mixture ○ Equivalence ratio ○ Initial temperature ○ Initial Pressure ● Hydrogen fuel and air are entering as two different streams perpendicular to each other ○ Simple mixing analysis was conducted to evaluate the mixture properties prior to the arrival of the detonation wave

- Detonation waves are simulated using Chapman-Jouget (CJ) detonation computations
- Results (SI and EQ ratio) are comparable to other literature, validating this study's results.

(2) Concept of RDE:

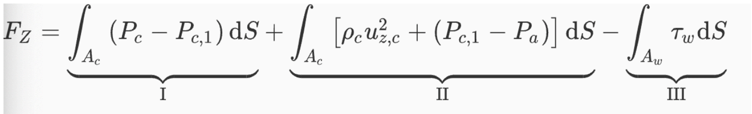
- Annular nozzle expands compressed gasses to produce sufficient thrust
- Combustion is initiated on one end of the chamber, and detonation wave travels circumferentially around the chamber to consume premixed and annularly injected hydrogen (fuel) and air
- RDE provides steady thrust, and needs only one initiation.
- Challenges to consider with RDEs:
    - Axial injection makes the flow field complex → makes design more difficult
    - Heat transfer to the wall caused by the continuous rotation of the wave
- See figure one for a helpful diagram of the elements within an RDE.
- Variation of flow properties are negligible in the radial direction.
    - Flow field behind the detonation wave is incredibly complex.
    - Consider this when creating a simulation of the RDE's injection and flow properties within the detonation chamber.
- Pursued 2D ("unrolled") RDE configuration (very common due to high flow complexity).

(3) Pressure History Model of RDE:

- Assumptions: **fuel and oxidizer are well mixed and injected at a constant mass flow rate**
- More assumptions to consider: flow properties are periodic with a period of T and the detonation wave propagates at a constant speed equal to the Chapman-Jouguet detonation speed.
- The 2D model is adequate, even for detonation calculations.
- Azimuthal flow and time dependence of the flow can be eliminated for computing propulsion parameters.
- Control volume can be expressed through the diagram in Figure 3.
- A pressure history model is pursued to enclose the engine and consider pressure in calculations.

IMPORTANT EQUATIONS:

Forces in the axial direction for the given control volume:



$$F_Z = \underbrace{\int_{A_c} (P_c - P_{c,1})\,\mathrm{d}S}_{\mathrm{I}} + \underbrace{\int_{A_c} \left[\rho_c u_{z,c}^2 + (P_{c,1} - P_a)\right]\mathrm{d}S}_{\mathrm{II}} - \underbrace{\int_{A_w} \tau_w \mathrm{d}S}_{\mathrm{III}}$$

Generated pressure force on the injector surface at the upstream end:

$$F_{\mathrm{I}} = A_c\left(\overline{P}_c - P_{c,1}\right)$$

Need averaged pressure! ^^

Force associated with the momentum flux of the gas at the inlet to the combustion chamber:

$$F_{\mathrm{II}} \approx A_c\left(P_{c,1} - P_{\mathrm{a}}\right) + \overline{u}_c\dot{m}$$

- These equations can provide a glimpse into the parameters marking the performance of an RDE, and provide comparable results to existing detonation engine results.

(4) Modeling of Injection Process: (this part is most applicable to my project)

- An injection model is essential for the subsequent modeling of detonation based on the pressure history model
- Equations used:
    - One dimensional steady flow equations of continuity, momentum, and energy
    - Solved to obtain the mixture properties of fuel and oxidizer ahead of the detonation waves
    - Three states:
        - State 1: air flow
            - Flow rate: 3.852 kg/s
        - State 2: fuel flow
            - Varied depending on fuel-based equivalence ratio
        - State 3: mixture conditions
    - Total pressure is at 4.5 bar(abs)
    - See Fig. 4 for a detailed diagram of injection modeling process

- CONTINUITY EQ

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \tag{4}$$

$$\dot{m}_3 = \rho_3 A_3 V_3 \tag{5}$$

- ENERGY EQ

$$\frac{\dot{m}_1}{\dot{m}_3}\left(h_1 + \frac{V_1^2}{2}\right) + \frac{\dot{m}_2}{\dot{m}_3}\left(h_2 + \frac{V_2^2}{2}\right) = c_{p,3}T_3 + \frac{V_3^2}{2}$$

- AXIAL MOMENTUM EQ

$$\dot{m}_2 V_2 + p_2 A_2 + p_1 \left(A_3 - A_2\right) = \dot{m}_3 V_3 + p_3 A_3$$

- Axial momentum of air flow is not considered
    - This is because of the perpendicular injection scheme
- Three Equations
    - Solved using Newton-Raphson method
- Three Unknowns (P_3, T_3, V_3)
- During the mixture state:
    - Stagnation pressure, stagnation temperature, and mach number at mixture state can be obtained by solving isentropic equations
- Fuel flow rate increased with each increase in equivalence ratio (see figure 5)
- Equivalence ratio also impacts mach #, pressure, and temperature (see graphs in the article for a more detailed view of how equiv. ratio changes those values.

(5) Computation of Detonation Properties:

- Used Cantera software (assuming chemical equilibrium)
- CJ detonation computations
    - Consider detonation velocity, pressure, temperature, and density
    - All of these quantities of interest are dependent on equivalence ratio

(6) Determination of Averaged Pressure on the Thrust Wall:

- Modeling the gas dynamics of the flow field is a simple way to evaluate the averaged pressure on the detonation chamber solid surface
- Flow field downstream is incredibly complex to model (mostly due to an oblique shock wave), so simplifications are made to model the above using a self-similar rarefaction wave pressure profile
    - What does this mean?
- Used several equations:
    - One which expressed pressure along the ground behind the wave front
    - Average pressure along the thrust surface
    - Function for an x/H curve using a fourth order polynomial

(7) Propulsion Parameters Under Pressure History Model:

- Used several parameters to measure engine performance under the pressure history model.
    - Average thrust
    - Specific thrust → thrust/total mass flow rate
    - Specific impulse → thrust / (fuel flow rate * g)
- All are dependent upon the equivalence ratio.
  (see graphs in the article if needed, but this part isn't very applicable to my

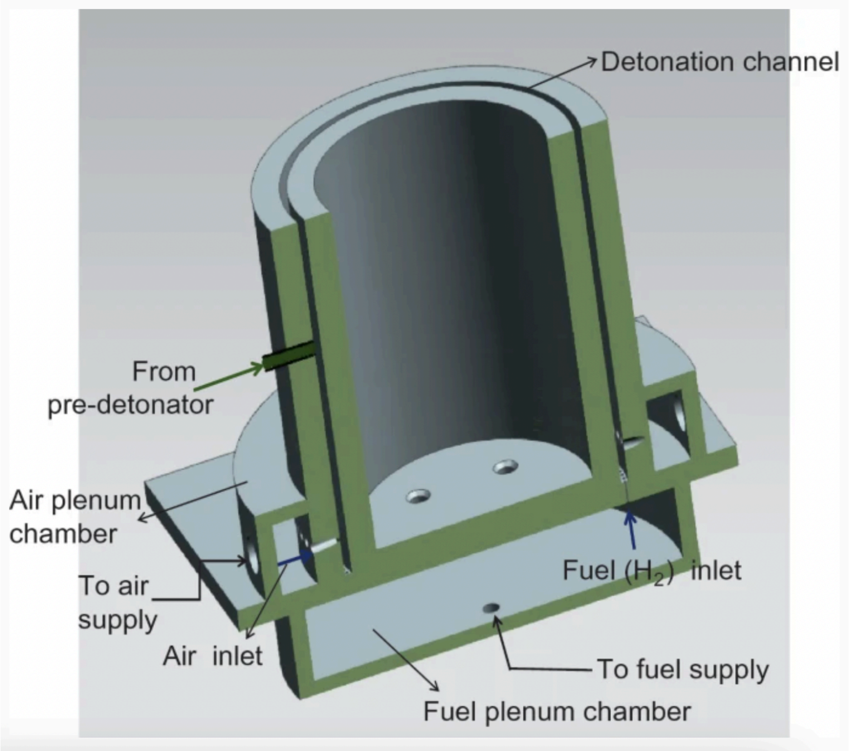
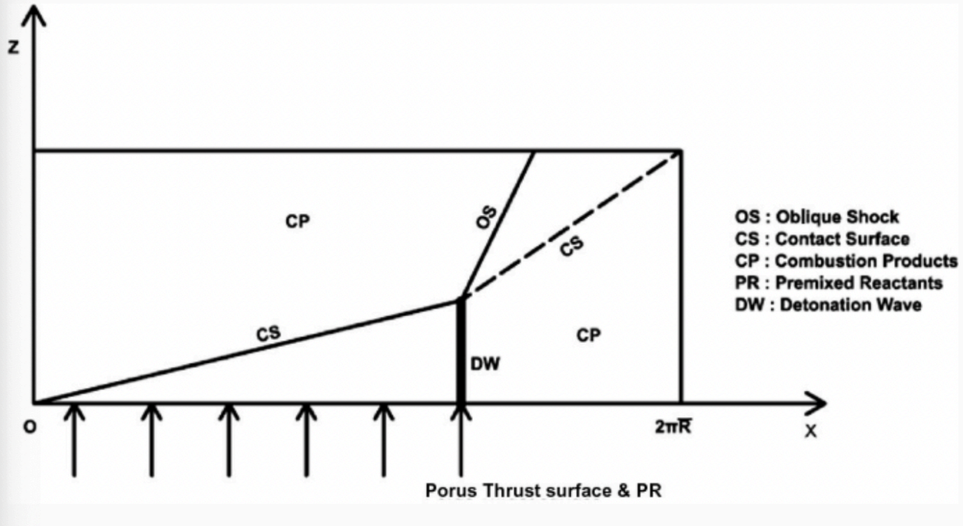
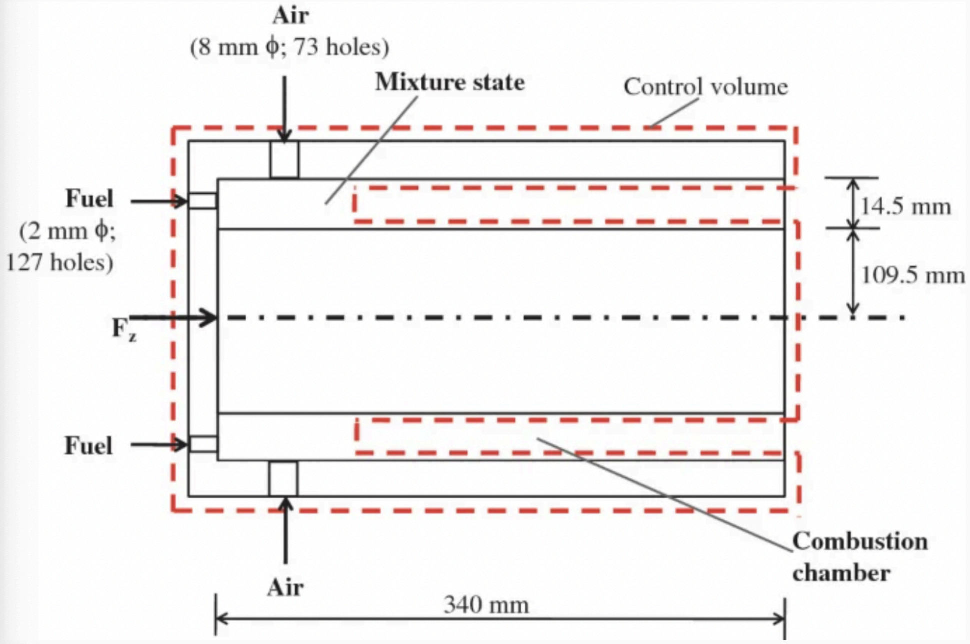
	project). (8) Conclusions: ● Obtaining conditions was successful ○ Hydrogen fuel and air injection were modeled, with varying equivalence ratios which laid dependence upon available flow rates. ● A simple mixing analysis was performed to obtain conditions ahead of the detonation wave. ○ It was stated that this was helpful in getting reasonable propulsive performance. ● Flow properties were obtained using a well-tested tool box (CJ detonations) ● A pressure history model was used to compute thrust and specific impulse ● The results (SI) were comparable to other literature/research works ● The mixing model was stated as an improvement in this study when compared to other studies ● Next steps: identify shortcomings or strengths using high-fidelity models based on CFD.
Research Question/Problem/ Need	How do the results of this designed and tested RDE configuration (using both Hydrogen and Methane as fuel sources) compare to previous impulse and fuel-based equivalence results as reported in 1975 literature?
Important Figures	**Fig. 1**  Diagram expressing the elements within a rotating detonation engine (RDE).

Fig. 2

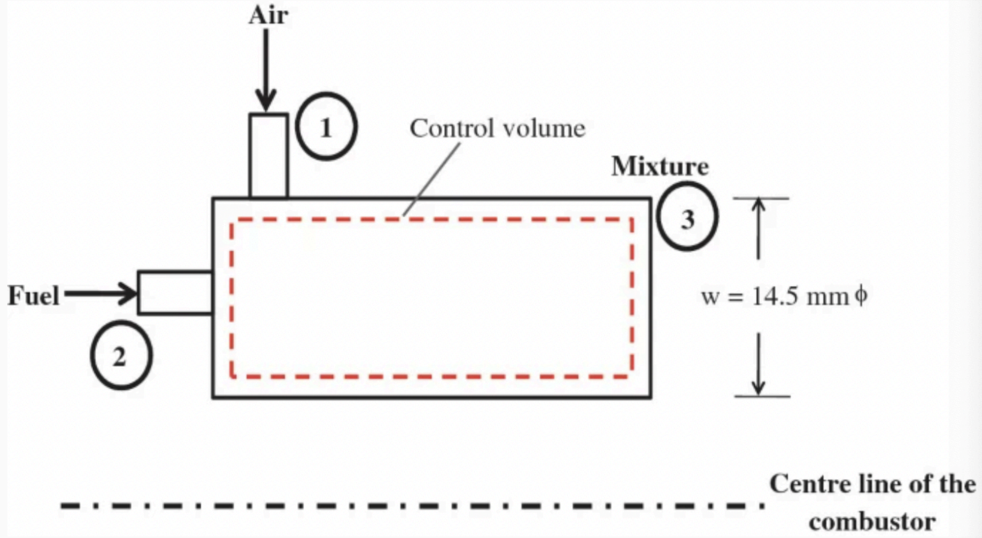
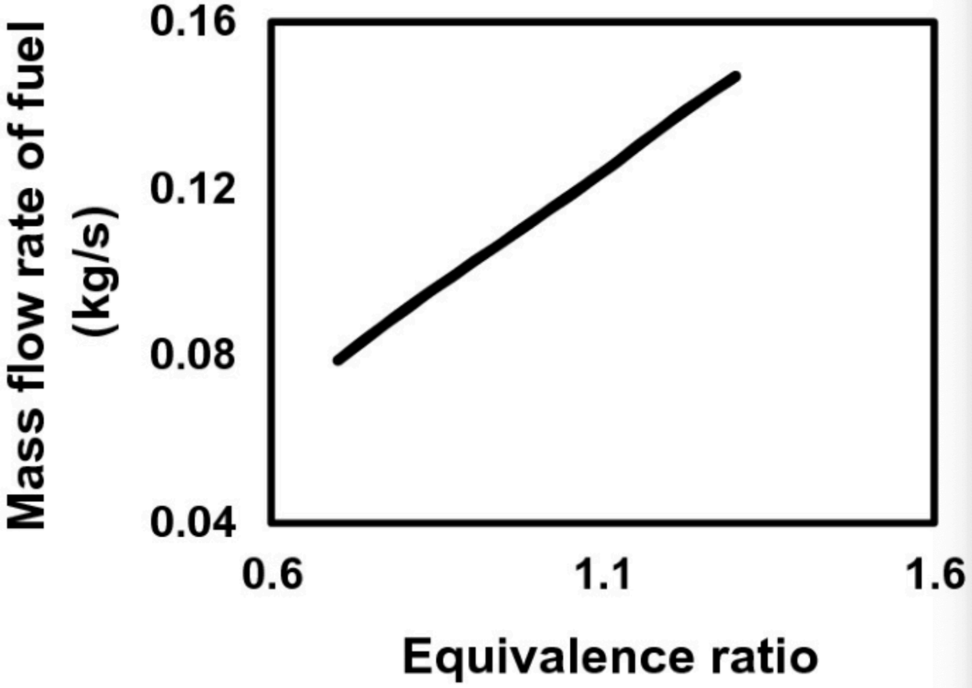


2D “unrolled” diagram of simulated RDE flow field.

Fig. 3



The control volume used for the pressure history model. Postulated by Shepherd and Kasahara. This helps in identifying how pressure is increased and mixture state can be analyzed in the given location within the pressure history model.

	Fig. 4  This diagram expresses the pre-detonation mixture injection scheme. There are three states. Air is injected at a fixed mass flow rate while fuel is injected at a proportional pressure depending on the fuel-based equivalence ratio. Fig. 5  This graph shows the relationship between equivalence ratio and mass flow rate of the fuel. Depending on this equivalence ratio value, the amount and rate of injection will change proportionally.
VOCAB: (w/definition)	**Pressure history model:** (this could be different from what the article is referring

	to) a pressure history model is a strategy used to compare data to existing data points (historically, what have the results been, and how do my results compare?) **Quasi:** partly/almost **Cantera**: Open-source toolkit used for solving problems that involve chemical kinetics, thermodynamics, and transport processes. **NCCRD**: National Centre for Combustion Research & Development **IIT:** Illinois Institute of Technology OR Indian Institute of Technology **Madras:** Madras Engineering Industries **Fuel regime:** a way of doing things, in this case, strategy for injecting fuel and air into an engine Other abbreviated terms that were used in the equations have been defined in the article.
Cited references to follow up on	Yi TH, Lou J, Turangan C, Choi JY, Wolanski P (2011) Propulsive performance of a continuously rotating detonation engine. J Propul Power 27(1):171–181 Roy RD, Amrutha P, Ramanujachari V (2019) Design of rotating detonation wave combustor based on detonation cell width correlations. In: Proceedings, 26th national conference on internal combustion engines and combustion, NIT Kurukshetra, India Davidenko DM, Eude Y, Gokalp I, Falempin F (2011) Theoretical and numerical studies on continuous detonation wave engines. In: AIAA 2011–2334
Follow up Questions	1. Did their simple mixing analysis incorporate turbulent flow equations, or any modeling of the interaction of fuel flows? 2. How does this article address the detonation products left behind from a detonation wave? 3. Where are injectors positioned? How does this work in a 3-dimensional model, and does this follow the traditionally used modular injection configuration strategy? 4. How do axial injection configurations change in their calculations when they are not placed perpendicularly, but rather in a radial injection scheme? 5. Is there a relationship between homogeneity levels of a fuel mixture post-injection and the quality of detonations produced?

Article #13 Notes: Novel approach for computational modeling of a non-premixed rotating detonation engine

Date: 11/24/23

Source Title	Novel approach for computational modeling of a non-premixed rotating detonation engine
Source citation (APA Format)	Subramanian, S. (2019). Novel approach for computational modeling of a non-premixed rotating detonation engine. *Journal of Propulsion and Power*, *36*(4), 617–631. Comprendex. https://doi.org/10.2514/1.B37719
Original URL	https://www-engineeringvillage-com.ezpv7-web-p-u01.wpi.edu/app/doc/?docid=cpx_48105b261734dca8265M667910178163190&pageSize=25&index=18&searchId=8ea6a706f9134801a9227d3e946b2271&resultsCount=169&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick PDF: https://vtechworks.lib.vt.edu/bitstream/handle/10919/101777/Subramanian_S_T_2019.pdf?sequence=1&isAllowed=y
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#RDE #mixing #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	Summary: The present work introduces a novel method of evaluating engine performance by comparing premixed vs non-premixed axial injection and their respective effects on overall engine performance using a two-dimensional CFD analysis to replicate three-dimensional numerical functions and configurations. **NOTE** Since this journal article is part of a broader work of nearly 70 pages, I have decided to focus my attention towards the Introduction and Computational Method sections due to a lack of need for detonation computation information. General Abstract: ● The Brayton cycle which is used in power and propulsion applications is highly optimized ○ Has higher thermodynamic efficiency ○ Detonations deemed as an efficient alternative ● Detonations compress gasses → high compression ratios reduces # of

compression phases

- Fuel and oxidizer are injected axially into combustion chamber
- Ignition happens, detonation occurs, detonation wave spins continuously through the chamber consuming fresh fuel mixture
    - Thrust is produced!
- This work introduces the use of three-dimensional numerical analysis due to extensive computation ability.
- Traditionally, RDE’s are supplied with fuel by separated injection plenums
    - This separated injection leads to inhomogeneity of the fuel-air mixture within the RDE → Adversely affects engine performance
- This study uses a novel method to compare perfectly premixed injection and non-premixed injection and their respective impacts on engine performance.

Intro + Background:

- PGC - very promising, increases thermodynamic efficiency
- Probability density function - non-reacting simulation used as an inlet boundary condition in 2D sim.
- Fuel: H2 Oxidizer: air
- Results are validated against other experimental results (compare non-premixed with existing premixed results)
- RDE’s produce continuous quasi-steady output with only one ignition
- Can provide thrust or can provide mechanical energy when coupled to a turbine
- Overviews flashback -> perfect premixed mixture produces uniform and complete combustion, high pressure regions push product backflow into the injection show
    - Produces chocked orifices
    - Recommended manifold pressure: 2-3 times higher than chamber pressure

Injection Part:

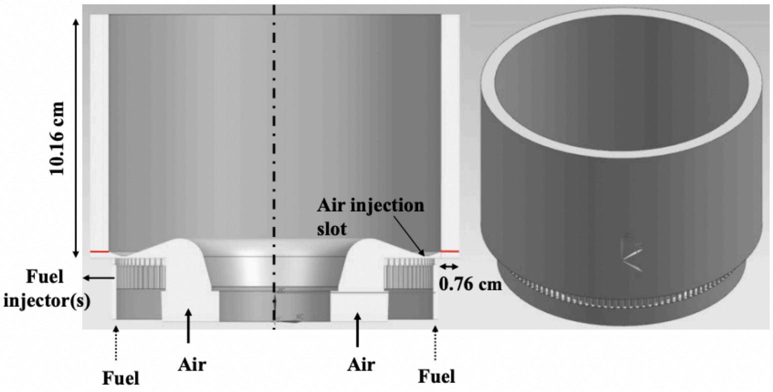
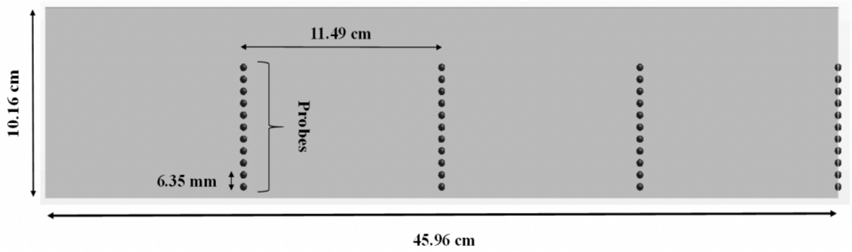
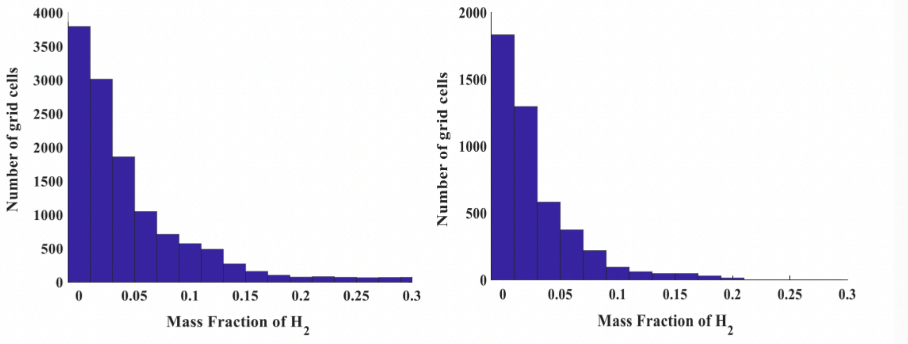
- Poorly mixed fuel-oxidizers have shown similar effects to inert diluents
- Effects of mixing based on different injector configurations was deemed as not very significant by previous research
- Imperfect mixing did drop instantaneous peak static pressures and lead to detonation wave instabilities
- Fuel-oxidizer stratification from mixing evidently affects the detonation waves structure, velocity, and pressure profiles
- Challenge in using CFD is large differences in time-scale resolving the flow field and chemical reactions involved in the combustion process
- 2-D high res euler codes were used to predict wave speeds in premixed RDE, changing pressure and inlet area parameters.
- Previous studies (Prakash et al.) found that fuel stratification affects wave dynamics. ← this one has been read!
- **Objective:** numerically model inhomogeneity arising from discrete fuel-oxidizer injection
    - How: extracting a probability density function (PDF) of the fuel

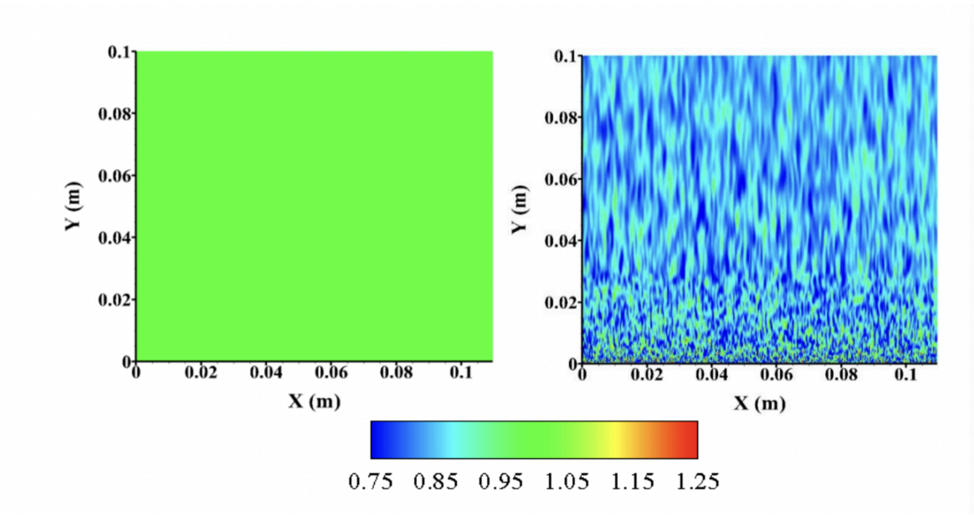
mass fraction from a 3-D non-reacing sim to map onto inexpensive 2D simulations.
- Validated?: validated against existing literature

Computational Method
- Air injector: 0.89 mm
- 120 injectors of 0.71 mm along circumference
- Outer diameter of engine: 153.9 mm
- Inner diameter of engine: 138.7 mm
- Height of detonation channel: 101.6 mm
- **Cold-flow analysis from which PDF of fuel mass fraction is extracted to be simulated in a 2D setting.**
- 2D: length of domain is equal to mean circumference of 3D geometry (45.96 cm)
  - No air and fuel manifolds in 2D geometry
  - Used inlet boundaries instead.
  - Used probes to measure time-averaged static and instantaneous peak pressures.

Solver notes:
- RANS equations
  - Conserve mass, momentum, energy, and species
  - Used to predict flow field in 3D cold-flow simulations from which PDF is extracted
- Menter model was used to resolve turbulent flow
- MUSCL used for spatial discretization of fluxes
- uRANS used for reacting flow field → this is about detonation, however.

2D injection:
- Air injected at 0.32 kg/s
- Fuel injected at 0.0093 kg/s
- Constant values to maintain stoichiometric mixture inlet
- Hydrogen-air injection at inlet is governed by downstream pressure
- Injected at sonic conditions
- Important equations for injection:
  - Critical pressure
  - Total pressure
  - Mach Number
  - Mass flux source term (for 2D domain)
  - Total Energy
  - Cell Static temperature
- Consider downstream pressure! (governs the flow of the mixture into the domain)
- **PDF of fuel mass fraction is extracted to model inhomogeneity**
- Use java to generate random values that follow the distribution of the fuel-mass fraction.
- The assigned random numbers (H2 mass fractions) are updated every three

	steps, and local equivalence can be modeled for a specific 2D domain.
Research Question/Problem/ Need	Develop an effective strategy for predicting flow characteristics and overall engine performance in a Rotating Detonation Engine based on injection strategy (premixed vs. non-premixed).
Important Figures	 Cross-sectional and isometric view of the 3D RDE geometry.  2D simulation domain, modeling 3D RDE geometry. Notice that there are no fuel or air manifolds, but rather selected inlet boundary conditions.  Distribution of fuel mass fraction from non-reacting 3D sim. A PDF was produced by using a Java code to generate random numbers that follow this distribution.

	 Equivalence ratio contours in a part of the 2D domain, obtained using the java-developed PDF method. (left = premixed, right non-premixed).
VOCAB: (w/definition)	**Brayton Cycle:** a thermodynamic cycle that describes how gas turbines operate. Based on extracting energy from the flowing air and fuel to generate usable work. This can be used to evaluate how much power could be supplied, by evaluating relevance to thrust. **PDF (Probability Density Function):** a statistical measure that estimates the likelihood of an event occurring based on the event returning a range of specific values. **Temporally:** relating to or involving time. **Mass flux:** amount of mass transported per unit time across a unit area that is perpendicular to the direction of mass transport **Manifold:** a collection of points forming a certain kind of set **Diluent**: a substance used to dilute something **Probe:** a probe extracts the values and conditions from a specific cell coordinate. **Discretization:** process of transferring continuous functions, models variables and equations into discrete counterparts. **Laminar:** taking place along constant streamlines (not turbulent) **Adiabatic:** a process or condition in which heat does not enter or leave the system
Cited references to follow up on	Zhdan, S. A., Bykovskii, F. A., and Vedernikov, E. F. "Mathematical Modeling of a Rotating Detonation Wave in a Hydrogen-Oxygen Mixture," Combustion, Explosion, and Shock Waves Vol. 43, No. 4, 2007, pp. 449-459. doi:10.1007/s10573-007-0061-y Prakash, S., Fiévet, R., and Raman, V. "The Effect of Fuel Stratification on the Detonation Wave Structure," AIAA Scitech 2019 Forum. 2019, AIAA 2019-1511. doi:10.2514/6.2019-1511 Nordeen, C., Schwer, D., Schauer, F., Hoke, J., Barber, T., and Cetegen, B. "Divergence and Mixing in a

	Rotating Detonation Engine," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. 2013, AIAA 2013-1175. doi:10.2514/6.2013-1175 Ishii, K., and Kojima, M. "Behavior of Detonation Propagation in Mixtures with Concentration Gradients," Shock Waves Vol. 17, No. 1-2, 2007, pp. 95-102. doi:10.1007/s00193-007-0093-y Calhoon, W., and Sinha, N. "Detonation Wave Propagation in Concentration Gradients," 43rd AIAA Aerospace Sciences Meeting and Exhibit. 2005, AIAA 2005-1167. doi:10.2514/6.2005-1167 Schwer, D., and Kailasanath, K. "Effect of Inlet on Fill Region and Performance of Rotating Detonation Engines," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2011, 6044. doi:10.2514/6.2011-6044
Follow up Questions	1. Has using the described java-based PDF process been done before? 2. Could this new method produce different or varying results from what has been comparable in the past? 3. Why are the inlet geometries not included in the 2D model extracted from the 3D model? 4. Is there a direct relationship between the tested injection configuration and thrust production? 5. How can I use, in my project, the concept of produced power from fuel stratification to create a comparative prediction in effectiveness of injector configurations on engine efficiency?

Article #14 Notes: Performance of rotating detonation engine with stratified injection

Date: 11/24/23

Source Title	Performance of rotating detonation engine with stratified injection
Source citation (APA Format)	Lei, Z., Yang, X., Ding, J., Weng, P., & Wang, X. (2020). Performance of rotating detonation engine with stratified injection. *Journal of Zhejiang University: Science A*, *21*(9), 734–744. Compendex. https://doi.org/10.1631/jzus.A1900383
Original URL	https://www-engineeringvillage-com.ezpv7-web-p-u01.wpi.edu/app/doc/?docid=cpx_2a8afd2d175652258aaM7b7110178163190&pageSize=25&index=19&searchId=8ea6a706f9134801a9227d3e946b2271&resultsCount=169&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick With PDF: https://link.springer.com/article/10.1631/jzus.A1900383
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#Alternative Rocket Propulsion Systems #RDE #mixing #injection
Summary of key points + notes (include methodology)	**Summary:** **Background Information:** ● **There exists deflagration combustion on the contact surface between fuel and detonation products.** ○ fuel mixture is injected, and produces deflagration combustions when interacting with remaining fuel after the wave. ○ this deflagration process has lower thermal efficiency and may cause detonation instability ● **Stratified injection is a new injection pattern aiming to decrease deflagration with detonation wave products.** ○ propulsion performance is tested with stratified injection (new) vs interval injection

Approach:

- A 3D RDE is “rolled out” into a 2D model to be used in calculations.
- **Traditional Interval Injection**
  - fuel is injected, surrounded by walls
- **New Stratified Injection**
  - surround fuel injector with inert gas injector
- **Article-Specific**
  - premixed fuel mixture (hydrogen, oxygen, nitrogen)
  - inert gas (non-reacting) is pure argon
- **Ignition**
  - a small square area is set with higher temperature and pressure to initiate detonation.

[see important figures for visual configuration]

Data:

Data Analysis 1 - Verifying Detonation Wave

Velocity values at the Chapman-Jouguet (CJ) point: the chemical equilibrium of the products at the end of the reaction zone

- (stoichiometric change due to chemical reaction has occurred)

This table [Table 1] is:

- Comparing DW velocities to previous works:
  - theoretical solution
  - experimental data

Data pt. 2:

Data Analysis 2 - [see figure 3]

3a + 3b - hydrogen mass fraction contours

- hydrogen content is stratified (reduced) due to inert gas reducing its available expansion area.

3c + 3d - typical RD flow fields

- In interval injection, the mixture is injected directly at the hot detonation products.
- thermal efficiency is visible in stratified injection / reduced direct injection at products.

	3e + 3f - heat release energy ● contact surface reaction with detonation products is weakened with stratified injection. **Data pt. 3:** ***Data Analysis 3 - Temperature Differences [Figure 4]*** temperature-time profile for stratified vs interval injection at the combustor and at the outlet of the RDE configuration. ● Overall, stratified injection reduces the distribution of temperature, thus making the stratification method more thermally efficient. **Conclusions:** ● **Stratified injection can be achieved.** ○ Can be done by injecting inert gas surrounding each fuel injector. ● **Contact-surface combustion with detonation products was weakened with stratified injection.** ○ Fuel consumption of remaining detonation products decreased from 33% to 5%. ● **Engine performance is better with stratified injection.** ○ Specific impulse increased, meaning that this configuration was more fuel efficient Measures of changes in pressure, thrust, temperature, and specific impulse imply that the SI engine configuration is more stable. ● **Stratified injection increases thermal efficiency.** ○ output temperatures were decreased by 19.1% with stratified injection, making this system more efficient and applicable to energy generation/turbine applications. **Applications to my project:** ● Mixture Distribution ○ DW Velocity was lower for stratified injection due to discontinuous mixture distribution. ● Stratified Injection ○ A simple mixing analysis will be conducted on a pre-existing injection configuration. This configuration is promising, and could be used as an injection configuration to be improved through this project.
Research Question/Problem/ Need	There exists deflagration combustion on the contact surface between fuel and detonation products. To address this, the effect of a novel injection strategy, stratified injection, must be addressed to determine its effectiveness.

Important Figures

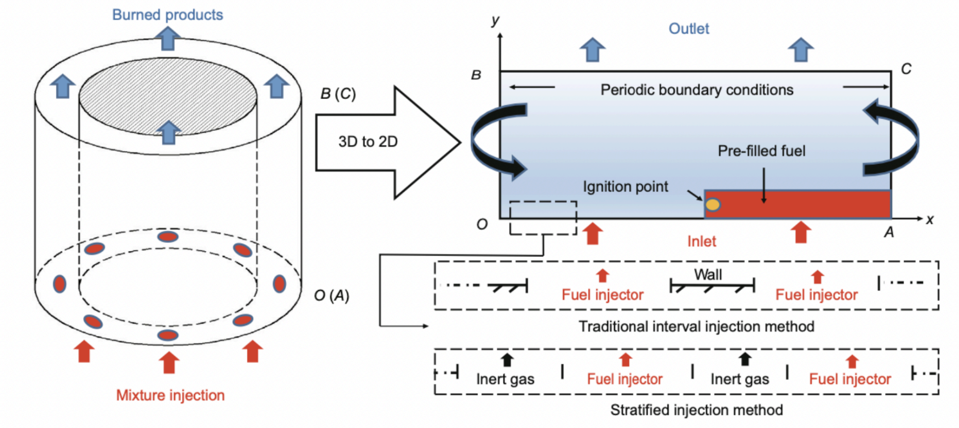


Fig. 1 Combustion chamber and computational domain

Experimental Configuration

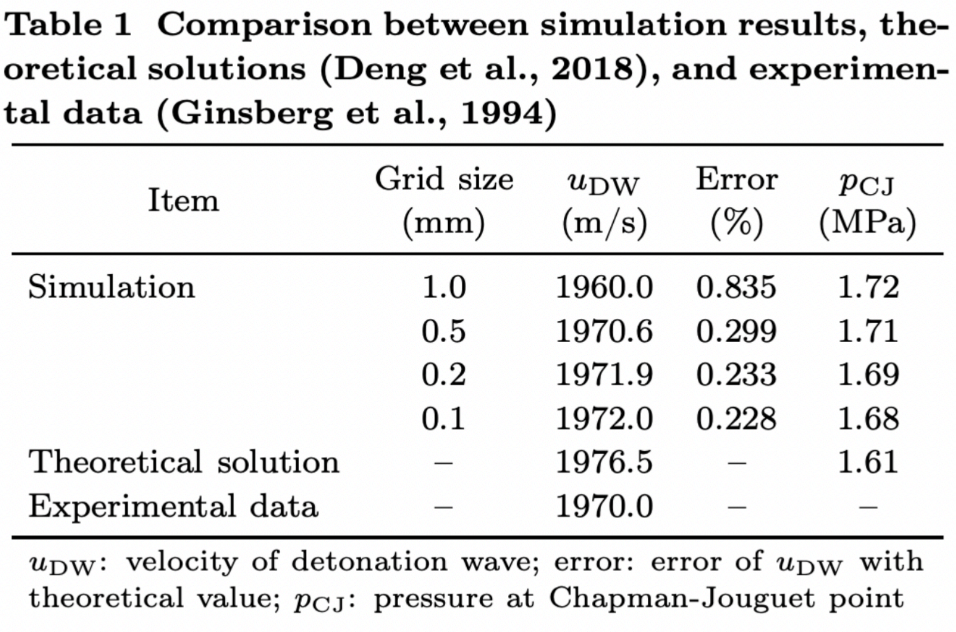


Table 1 Comparison between simulation results, theoretical solutions (Deng et al., 2018), and experimental data (Ginsberg et al., 1994)

Item	Grid size (mm)	u_{DW} (m/s)	Error (%)	p_{CJ} (MPa)
Simulation	1.0	1960.0	0.835	1.72
	0.5	1970.6	0.299	1.71
	0.2	1971.9	0.233	1.69
	0.1	1972.0	0.228	1.68
Theoretical solution	–	1976.5	–	1.61
Experimental data	–	1970.0	–	–

u_{DW}: velocity of detonation wave; error: error of u_{DW} with theoretical value; p_{CJ}: pressure at Chapman-Jouguet point

Comparison between simulation results achieved in this study with existing theoretical and experimental values.

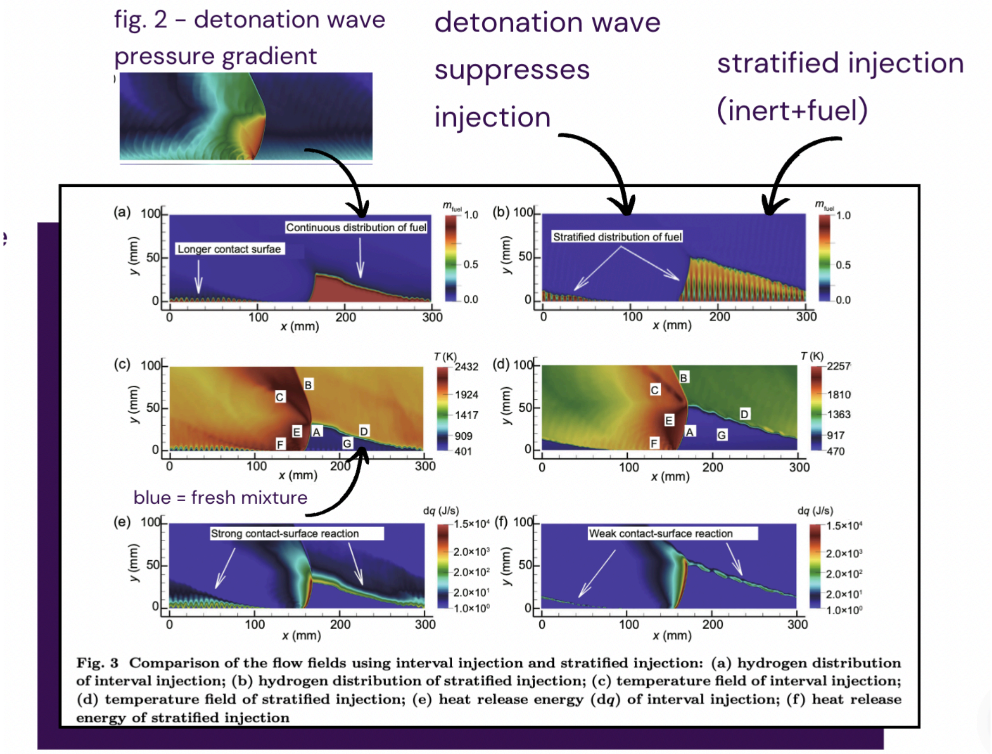


Fig. 3 Comparison of the flow fields using interval injection and stratified injection: (a) hydrogen distribution of interval injection; (b) hydrogen distribution of stratified injection; (c) temperature field of interval injection; (d) temperature field of stratified injection; (e) heat release energy (dq) of interval injection; (f) heat release energy of stratified injection

See data analysis section for a description. This is a comparison in the flow fields during the passing of detonation waves, expressing a pressure gradient.

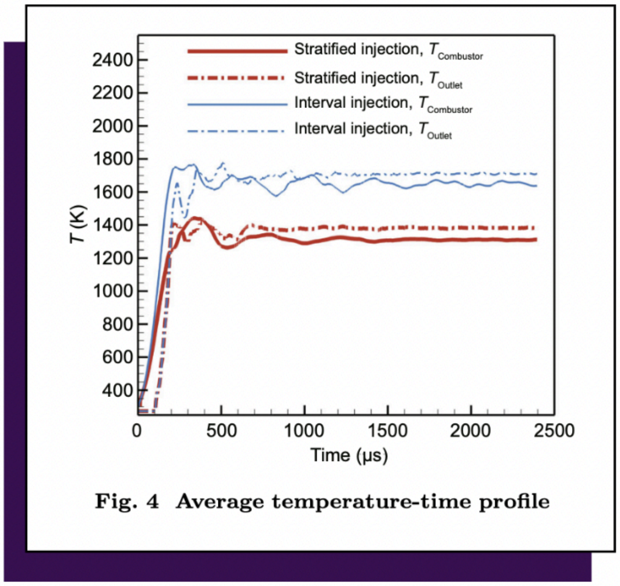


Fig. 4 Average temperature-time profile

Temperature differences between each tested injection strategy.

VOCAB: (w/definition)	**Stratified Injection:** stratified injection is a kind of injection strategy in which fuel

	is injected into the combustion chamber, surrounded by inert gas injectors on either side. **Micro-convergent:** a small convergence or approaching of a limit **Orifices:** An opening or hole **Fractional step method:** an approach to solving complex partial differential equation (PDE) problems in which various coupled physical processes are treated uncoupled and sequentially **Inert gas:** a gas with low reactivity with other substances
Cited references to follow up on	Zhang S, Yao S, Luan M, et al., 2018. Effects of injection conditions on the stability of rotating detonation waves. Shock Waves, 28(5):1079-1087. https://doi.org/10.1007/s00193-018-0854-9 Gaillard T, Davidenko D, Dupoirieux F, 2017. Numerical simulation of a rotating detonation with a realistic injector designed for separate supply of gaseous hydrogen and oxygen. Acta Astronautica, 141:64-78. https://doi.org/10.1016/j.actaastro.2017.09.011 Wang YH, Wang JP, 2015. Rotating detonation instabilities in hydrogen-oxygen mixture. Applied Mechanics and Materials, 709:56-62. Yao SB, Han X, Liu Y, et al., 2017. Numerical study of rotating detonation engine with an array of injection holes. Shock Waves, 27(3):467-476. https://doi.org/10.1007/s00193-016-0692-6 Zhang S, Yao S, Luan M, et al., 2018. Effects of injection conditions on the stability of rotating detonation waves. Shock Waves, 28(5):1079-1087. https://doi.org/10.1007/s00193-018-0854-9
Follow up Questions	1. How does stratified injection compare to other injection configurations (so, not limited to interval injection, but broader) such as radial, axial, etc.? 2. Is there a reason why injection schemes are evaluated by their ability to effectively aid in the propagation of detonation waves? 3. Are all detonation wave simulations following the same parameters/following the same characteristics? 4. How could varying results and obtaining strategies reduce the validity of comparison of injection configurations and quantitative dependence on wave performance? 5. How can deflagration/detonation products be factored into a simple mixing model mimicking the process of injection?

Article #15 Notes: Numerical simulation of a methane-oxygen rotating detonation rocket engine

Date: 11/25/23

Source Title	Numerical simulation of a methane-oxygen rotating detonation rocket engine
Source citation (APA Format)	Prakash, S., Raman, V., Lietz, C. F., Hargus, Jr., W. A., & Schumaker, S. A. (2020). Numerical simulation of a methane-oxygen rotating detonation rocket engine. *Proceedings of the Combustion Institute*, *38*(3), 3777–3786. Elsevier. https://doi.org/10.1016/j.proci.2020.06.288
Original URL	https://www-engineeringvillage-com.ezpv7-web-p-u01.wpi.edu/app/doc/?docid=cpx_552bf90e176862d5c93M7f6610178163190&pageSize=25&index=17&searchId=8ea6a706f9134801a9227d3e946b2271&resultsCount=169&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick With PDF: https://www.sciencedirect.com/science/article/abs/pii/S1540748920303801
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	Summary: This article aimed at identifying the relationship between methane-oxygen injection in a discretely spaced reactant jet injector configuration and detonation wave characteristics and strengths. The detonation wave structure and the mixing process was modeled using numerical and computational approaches, which regarded both chemical-reacting and non-reacting flows. It was found that while separated injectors does minimize the flashback effect, or the effect of detonation waves on injector functions due to its high pressure output, the separated injection configuration weakened and unstabilized the detonation wave due to an asymmetrical configuration which caused an uneven fuel-oxidizer mixture. However, mixture conditions resembled premixed conditions at the walls, which should be considered during the iteration phase of this project. Introduction:

- Dual-benefits of detonation-based combustion for rockets:
    - Thermodynamic efficiency increase
        - Smaller size; less turbomachinery
    - Continuous thrust output
- Theoretically, rotating detonation rocket engines (RDRE) can increase specific impulse by 6-8%.
- Promising advantages are entirely dependent upon design, and significant losses can be caused by incomplete or non-ideal detonation.
    - Separated, non-premixed injection of fuel and oxidizer make it essential that the reactants are sufficiently mixed.
- Shock waves and high mach numbers from incoming flow can inhibit or reduce reactant flow.
- **Incomplete mixing can lead to incomplete mixing, weaker detonations, and slower heat release.**
- **Detonation wave speed may not be stable. Variations in RD waves are due to turbulent mixing-induced stratification.**
    - This likely means that turbulence caused by incomplete mixing causes unstable wave speeds.
    - However, I don't think that this directly relates to a turbulent mixing model used to quantify homogeneity.
- Complex pressure waves created by a distributed reaction zone leads to mixture homogenization behind the shock wave.
    - The RD wave itself homogenizes trailing mixtures!
        - Homogeneous mixture => complete wave => homogeneous residuals
- Discrete injection brings wave velocity from 90% of theoretical CJ velocity to 81%.
- Important to understand the relationship between mixing and compressible conditions with RD wave behavior.
- This study focuses on the interaction between mixing and detonations.
    - Used methane and oxygen to test in a simulatory setting.

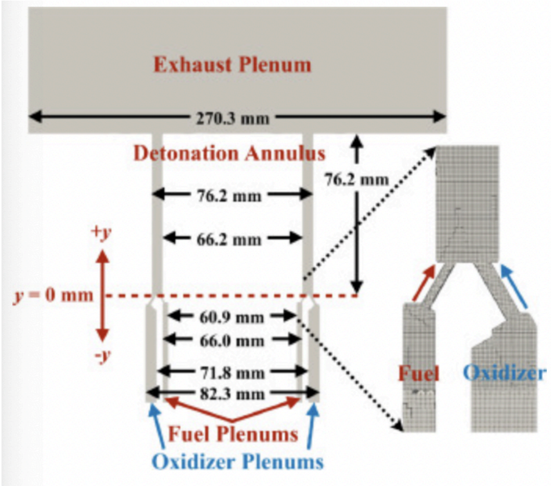
Simulation Configuration and Numerical Approach:

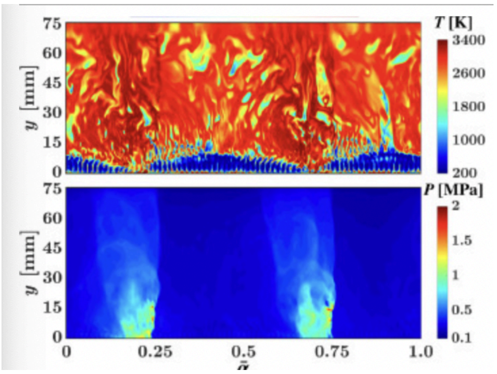
- Configuration information:
    - 72 impinging injectors (uniformly spread around circumference of annular chamber)
    - 5mm detonation channel
    - Mass flow rates
        - Fuel: 0.0597 kg/s
        - Oxidizer: 0.207 kg/s
    - EQ ratio: 1.15
    - Pressurized Plenums
        - Fuel - 1.21 MPa
        - Oxidizer - 1.10 MPa
- Numerical approach
    - High fidelity numerical simulation
    - Governing Equations

        - Conserve mass, momentum, energy, and species conservation equations
    - Numerical simulations equations
        - Navier-Stokes for reacting fluid flow
        - MUSCL and 2nd order runge-kutta for spatial and temporal discretization
        - KNP method for chemical diffusion
        - Solver and mach # adaptation validated against previous ranges of turbulent and reacting flows
        - 5000 cores - MPI domain decomposition executed
        - FFCMy-12
    - Mesh - 200 (mu)m at injector and chamber → 400 upstream
    - **3D detonation with non-premixed injection causes a highly non-ideal detonation process**
    - 29.2 million computational control volumes!!
    - Runs for 1.0ms at unsteady state
        - Additional 1.0 ms at steady state

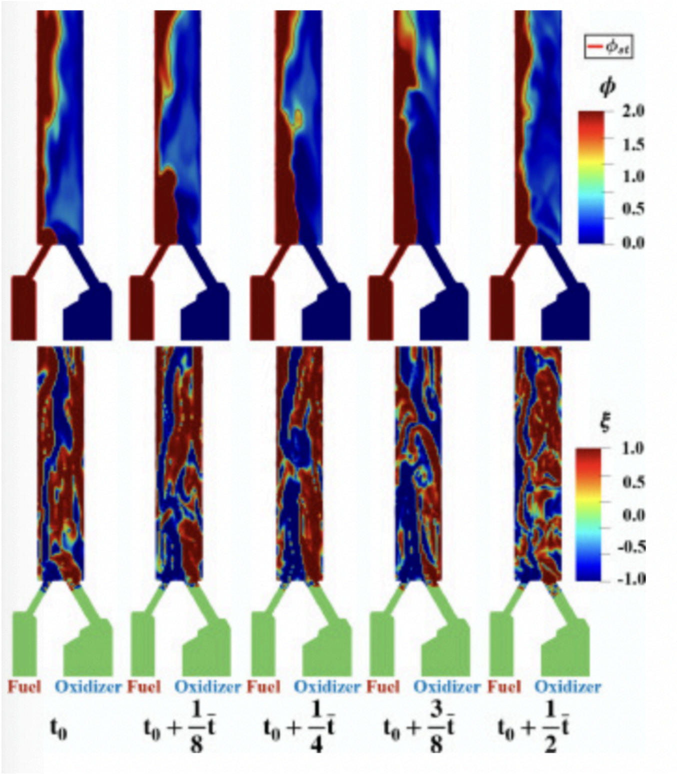
Results and Discussion:

- Jet impingement prevents much of the post-reaction gasses from entering injector plenums
- High plenum pressures prevent complete blockage of reactant flow
- Jet impingement worked very well! Prevented backflow, premature deflagration, and loss of efficiency.
- No significant deflagration close to injection plane
    - **However, pressure contour shows significant deflagration and “thicker” detonation wave due to variations in mixture properties between the injectors.**
    - Weakened detonation structure, parasitic combustion in premature ignition
    - Significant shock-weakening caused by discrete injection
- Why did this happen? → mixture inhomogeneities!
    - High concentration of fuel in inner wall causes reduced detonation strength
    - Closer to the walls, mixture is more complete
    - In the center, however, mixture is visibly unevenly mixed
    - See figure 3.
- Compared with AFRL results
- Peak pressures vary significantly → unsteady and variable detonation front
- Time-averages gathered for injector velocity, injector pressure, injector temperature, and a second injector and plenum pressure data collection
- Pressure waves did enter injection plenums but were quickly dissipated by viscous forces.
- **Higher plenum pressure = quicker recovery**
- Higher mass flow rate biases the stoichiometric line towards the fuel injectors (aka, wave propagation happens at well-mixed mixtures (because that’s what detonations like))

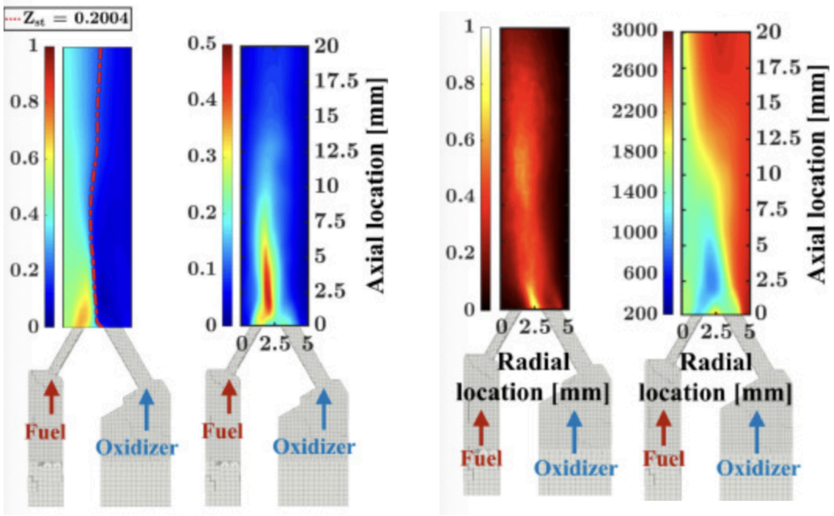
	● Unmixed flow downstream means that mixing is not high in this config. ● 95.7 of the fuel is converted (and consumed) and left behind as products. ● Conditional temp rises on rich side → due to complete combustion ● Heat release rate further supports finding of deflagration downstream Conclusions: ● Stronger detonation waves and heat release peaks towards inner wall due to asymmetrical injection ● Results are between 30-50% of CJ conditions (this means that ths engine failed to perform at a significant fraction of theoretical optimal conditions) ● 95.7% of fuel was consumed at exit plane ● How the injector configuration performed: ○ This injection configuration successfully minimized impact of detonation waves on injector functions ○ However, asymmetrical configuration produced an uneven mixture responsible for diminishing the strength, speed, flow compression, and energy of the wave. ○ **Regions closer to the wall were more similar to premixed-like behavior. → cool innovation idea: maybe use injectors facing/directed at the walls for mixing?**
Research Question/Problem/ Need	The focus of this study was to understand the interaction between mixing and detonations in an RDRE.
Important Figures	 Cross-sectional view of computational configuration as well as computational mesh representation.



Results expressed in an “unrolled” contour. Above is temperature in K, below is pressure in MPa. Two waves running → visibly reduced deflagration and blue bottom in P contour are visibly recovered from passing detonation waves (lower pressures, with injectors being unaffected by jet impingement.



Top row - EQ ratio. Bottom row- Takeno flame index
Contour with consideration of time history during passage of the detonation wave.
Wave passed in the initial time, wave swept in the last time history.

	 Mixture Fraction → Unmixedness factor → Normalized heat release rate → temperature in lower detonation channel (averaged)
VOCAB: (w/definition)	**Discrete Injection:** a seperated or divided injection **Vortical flow:** a region in a fluid in which the flow revolves around an axis line (axis line can be straight or can be curved) **Coking propensity:** frequency/tendency of buildup of unwanted deposits in an engine **UMdetFOAM:** computational detonation simulation based on OpenFOAM (open-source field operation and manipulation) **Jet impingement:** a flow phenomenon in which a fluid is sprayed as a jet onto a surface **Pressure perturbations:** regions of low or high pressure **Attenuated:** reduced in force, effect, or value **Continuous tube attenuated pressure (CTAP):** a function of the magnitude of nonlinear pressure fluctuations **Heat release rate:** the amount of (thermal) energy released per unit time from the combustion of a fuel **Unmixedness Factor:** a parameter of molecular segregation (not very many definitions available)
Cited references to follow up on	J.R. Burr, K. Yu, Detonation wave propagation in cross-flow of discretely spaced reactant jets, Detonation wave propagation in cross-flow of discretely spaced reactant jets, AIAA Paper 2017–4908, 2017, doi:10.2514/6.2017-4908 P.A. Cocks, A.T. Holley, B.A. Rankin, High fidelity simulations of a non-premixed rotating detonation engine, High Fidelity Simulations of a Non-premixed Rotating Detonation Engine, AIAA Paper 2016-0125, 2016, doi:10.2514/6.2016-0125 D. Schwer, K. Kailasanath, Feedback into mixture plenums in rotating detonation

	engines, Feedback into mixture plenums in rotating detonation engines, AIAA Paper 2012-617, 2012, doi:10.2514/6.2012-617
Follow up Questions	1. Is this work based upon the previous understanding of the negative effects of fuel-oxidizer mixture inhomogeneities on rotating detonation engine performance? 2. Is there a drawback to comparing injection configurations by mixture homogeneity (equiv. ratio, fuel stratification, Takeno scheme?) rather than comparison with detonation wave quality? 3. Why are the theoretical CJ detonation characteristics so difficult to achieve? What does this say about the actual abilities of the RDE? How do their experimental results skew their perception as a promising, competing technology with current systems? 4. What defines a high-fidelity model? Are 3-D models incorporated into this model, and if so, how are 3-D models converted into 2-D representations of detonation conditions? 5. What does the “unmixedness factor” tell you about injector ability? Is this a valid, or widely used way to measure mixture homogeneity?

Article #16 Notes: Mixing and Detonation Structure in a Rotating Detonation Engine with an Axial Air Inlet

Date: 12/01/23

Source Title	Mixing and Detonation Structure in a Rotating Detonation Engine with an Axial Air Inlet
Source citation (APA Format)	Sato, T., Chacon, F., White, L., Raman, V., & Gamba, M. (2020). Mixing and Detonation Structure in a Rotating Detonation Engine with an Axial Air Inlet. *Proceedings of the Combustion Institute*, *38*(3), 3769–3776. Elsevier. https://doi.org/10.1016/j.proci.2020.06.283
Original URL	https://www.sciencedirect.com/science/article/pii/S1540748920303758?via%3Dihub
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** This study aimed at understanding the effectiveness of an axial injector configuration and its effects on rotating detonation wave characteristics. The researchers pursued a high-fidelity model that incorporated several chemical kinetic-based solvers with the hopes of modeling an experimental or theoretical rotating detonation engine. It was found that significant parasitic combustion, or unwanted combustion occurring in places that do not include the detonation wave front, occurred significantly in this model. Significant parasitic combustion and large deflagration zones decreased the engine's overall efficiency and wave speed and control. This is largely due to the injectors' inability to recover quickly enough due to a high-pressure post-detonation region which prevented continued injection. It was determined that optimizing the injector recovery process is essential in creating an efficient RDE that is capable of pursuing complete consumption of fuel and high thrust output. **Notes:** Introduction: ● Mixing plays an important role in determining the detonation wave

structure

- Detonation wave front is marked by strong fluctuations, which are largely dependent upon the fuel-air mixture and injection process turbulence.
- Fuel-air mixing needs to be fast to avoid pre-burning, but high levels of turbulence may lead to efficiency losses
- Existing injection configs.
    - Radial
    - impinging
    - Axial
- Injection structure should promote complete mixing to ensure that efficient and stable detonation can occur
- Detonations are generally stable even when geometries are dramatically changed in size.
- Canonical configuration simulations have shown that stratification of fuel and air causes the detonation wave to thicken and exhibit a complex internal structure.
- Goal of study: numerically simulate the axial air injector based RDE to understand its effect on detonation structure details.
- What is pursued:
    - Configuration based on experimental studies aiming to characterize OH chemiluminescence, OH-PLIF + pressure traces
    - Simulation approach based on previous work
    - Multi-step chemical kinetics for combustion problems

RDE configuration and numerical data:

- Pursued axial air injection system
- Fuel injected using discrete ports → positioned at an angle to oxidizer stream
- Fuel injection specifics:
    - Mass flow rate for air: 404.2 g/s + Global EQ: 1.01
    - Plenum conditions → atmospheric conditions
    - Subsonic flow
- Simulation + Solvers
    - Chemical Kinetics
        - UMdetFOAM solver → for complex geometries + chemical kinetics
        - Navier-Stokes → continuity, energy, and species transport
        - OpenFOAM framework with CANTERA
        - MUSCL-based HLLC scheme → discretization
        - 2nd Order Range-Kutta → time advancement
        - KNP → diffusion discretization
    - This has all been validated by experiments in the past. MPI domain tested on 4000 cores.
- Mesh size found to not change results significantly (see figure in important figures section).
- Linear model → reaction zone is distributed along the circumference
- Wave front is defined by maximum pressure gradient (asks, where is the

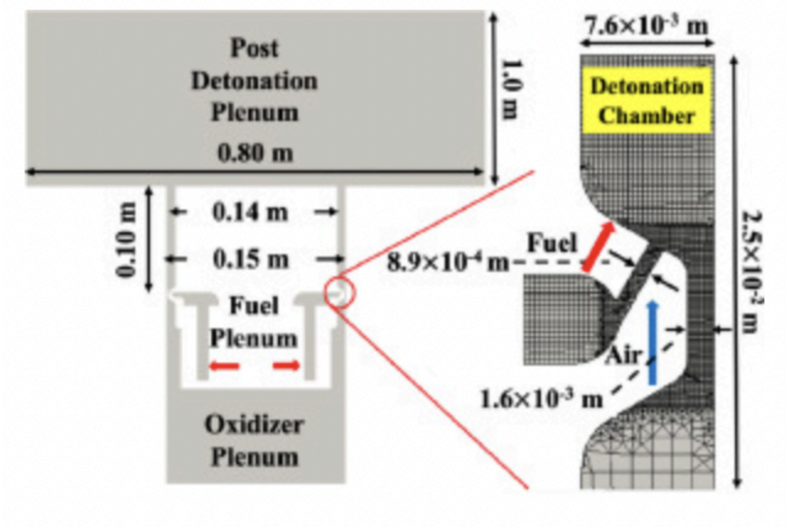
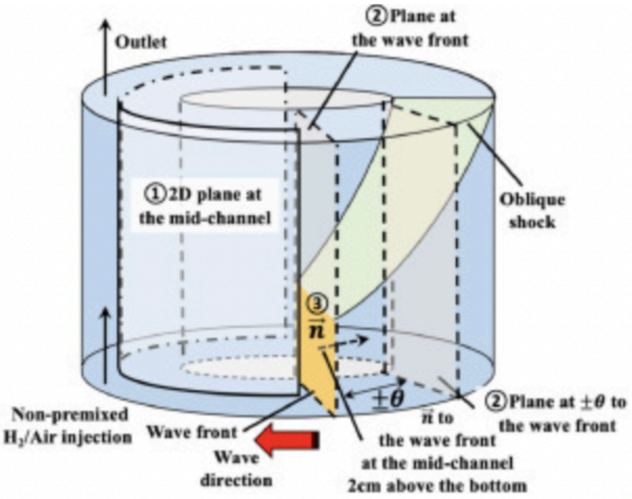
highest pressure build-up?)
    - Run for 15 cycles → make sure its working! Collect data for +10

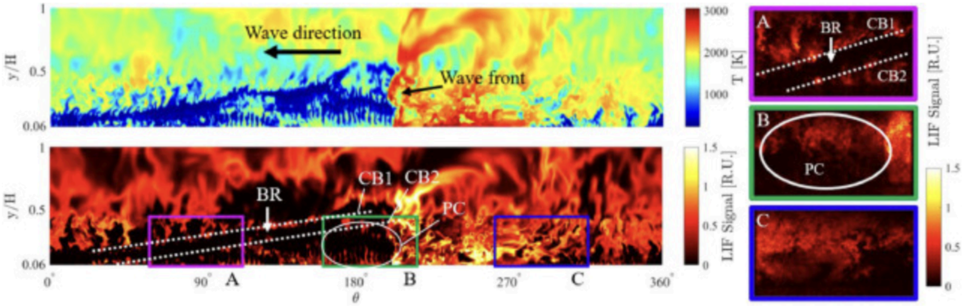
Results & Discussion:

- 3D discrete injection results show richer flow structure - characterized by multiple regions where combustion occurs (better, compared with 2D)
- Computational predictions are similar to experimental observations
- Parasitic Combustion:
    - CB (contant burning) region 1
        - Parasitic combustion between unburnt and burnt gases from previous cycle
    - CB2:
        - Parasitic combustion near injection zone
        - Injection into burnt gases creates a rich mixture → perfect for detonation! But causes parasitic combustion :(
    - Buffer region separating regions depends on injector response time
    - Buffer region is where parasitic combustion starts, which means that injection is very important in reducing the weakening of detonation waves?
- **Recovery time in injectors**
    - The flashback effect causes there to be a lengthy recovery time in fuel and oxidizer injectors after the passing of the detonation wave due to a high-pressure post-detonation region.
    - This recovery time takes a long time → recovery of oxidizer inlet velocity causes the next cycle to be 93% of the one before it.
- Pockets of rich mixture cause parasitic combustion
- Significant losses in peak pressure are caused due to parasitic combustion.
- Wave speeds:
    - 1804 m/s for sims
    - 1566 m/s for experiments
- PC - causes peak exothermicity and high pressure change
- Higher peak temp. at richer mixture fraction values
- Richer mixtures → more complete consumption of fuel and oxidizer
- Found that there is significant variation at rich conditions in heat release rates.

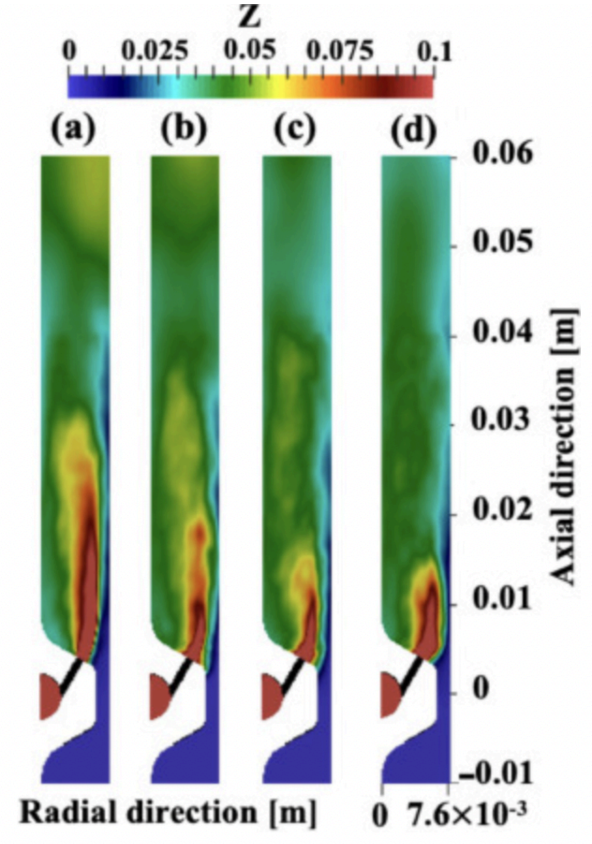
Conclusion:

- Showed significant differences compared with 2D premixed detonation results.
    - Most significantly, there was a high deflagration region due to recirculation caused by the inlet design.
    - Unsteady response of injectors to passing RD wave
    - Unsteady mixing caused large fluctuations and intermittent and stratified fuel-air distribution
- The study shows that stable detonaions are achievable with the axial configuration, however to reduce the losses of pressure and efficiency, **the injector recovery process must be optimized.**

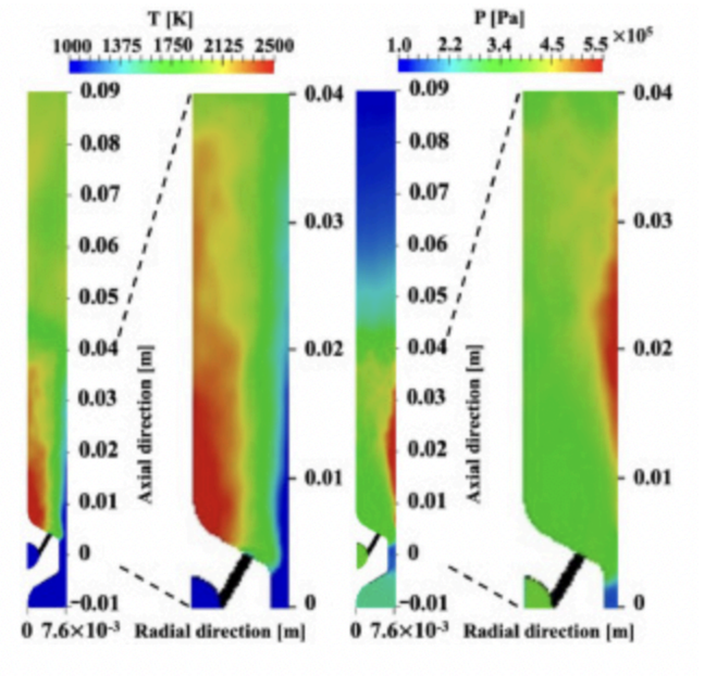
Research Question/Problem/ Need	The goal of this study is to numerically simulate the axial air injector based RDE to understand its effect on detonation structure details.
Important Figures	 Computational geometry as well as injection config. meshing expressed in the diagram above.  Diagram showing how planes were averaged and generalized 3D configuration/analysis set-up.



LEFT: “Unwrapped” 2D temperature field → RIGHT: OH-PLIF images
This is an idealized simulation → with boundaries of parasitic combustion being unclear due to a highly chaotic flowfield.



Mixture fraction at several stages:
(a) 15 deg. ahead of wave front (b) the wave front
(c) 15 deg. behind wave front (d) 30 deg. behind wave front

	 TEMP → PRESSURE at detonation front
VOCAB: (w/definition)	**OH-PLIF:** OH (oxygen-hydrogen) planar laser induced fluorescence. This is a technique that targets minor combustion species by exciting electrons. **KNP:** a combustion kinetics analysis tool (stands for Kurganov, Noelle, and Petrova). Used for discretization of diffusion terms. **Mixture fraction:** a measure of the mass fraction of one stream in a mixture **Parasitic combustion (PC):** partially-burnt gas combustion, occurring in rich mixture locations as well as near the injector zone. This reduces wave stability and causes pressure and temperature to rise in unevenly distributed locations.
Cited references to follow up on	Numerical simulation of a rotating detonation with a realistic injector designed for separate supply of gaseous hydrogen and oxygen Acta Astronautica, 141 (2017), pp. 64-78 S. Prakash, R. Fiévet, V. Raman, The effect of fuel stratification on the detonation wave structure, AIAA Paper 2019-1511, AIAA SciTech Forum, 2019, San Diego, California.
Follow up Questions	1. Considering the varied results achieved, is there any consideration of the quantitative analysis of axial injection performance? 2. Why was an axial injection deemed as being effective despite high levels of inefficiency? 3. How can injection recovery be simulated without the use of extensive, high-fidelity computational models? 4. At what pressure and mass flow rate should injectors be at to avoid lengthened recovery times?

	5. How can post-detonation gases be simulated without chemical kinetics simulations? Can they be easily incorporated through an adjustment of pressure beyond the injector region to simulate a high-pressure post-reaction zone?

Article #17 Notes: A Theoretical Review of Rotating Detonation Engines

Date: 12/05/23

Source Title	A Theoretical Review of Rotating Detonation Engines
Source citation (APA Format)	Shaw, I. J., Kildare, J. A. C., Evans, M. J., Chinnici, A., Sparks, C. A. M., Rubaiyat, S. N. H., Chin, R. C., & Medwell, P. R. (2019). A Theoretical Review of Rotating Detonation Engines. In *www.intechopen.com*. IntechOpen. https://www.intechopen.com/chapters/70511
Original URL	https://www.intechopen.com/chapters/70511
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** ● This article aims to clarify and review the fundamental operating principles of rotating detonation engines by producing a through literature review, which covers computational and experimental studies as well as the main focuses, drawbacks, and efficiencies present in the current state of RDE research. The goal of this article is to aid in the identification of future work (what work need to do) for RDE research. In its applications to my project, this article provides a glimpse into the injection process as well as the progression and development of solutions and issues in efficiency. **Notes:** Introduction ● Detonative propulsion ○ Promising → high efficiency, low mechanical complexity ○ Deflagration is easier to control ○ Limited research so far ○ Compact configuration ○ Highly efficient thrust generation ○ Thermodynamically efficient cycle

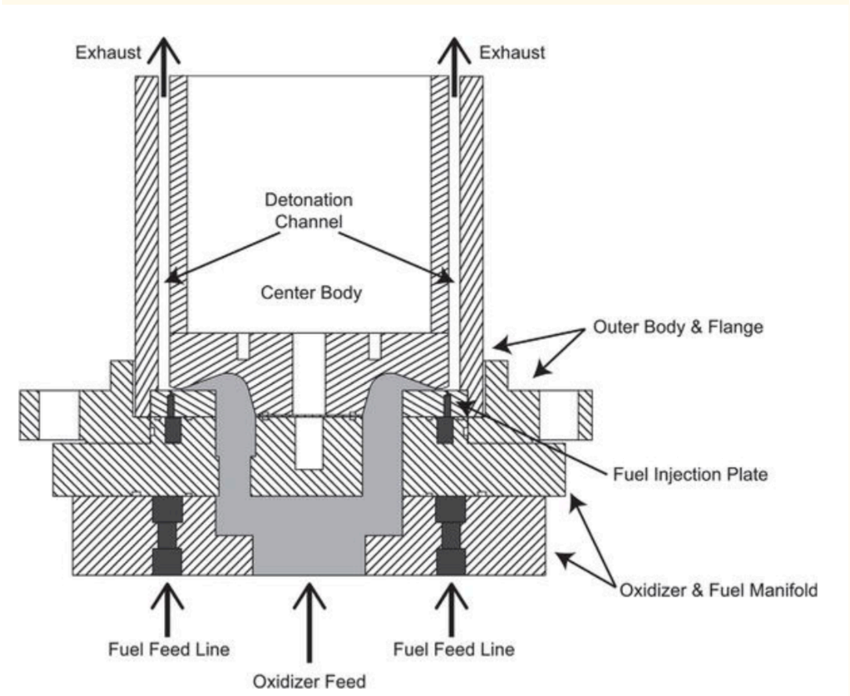
- RDE can be used as a rocket engine or as a part of a gas turbine
- Deflagration → sonic, detonation → supersonic
- Detonation wave uses heat from combustion to generate a rapid shock wave
- Much of previous work has been theoretical → modern RDE research is computational and experimental
- Injection:
  - Fuel and oxidizier are injected
  - DW consumes reactants azimuthally
- Detonation Info:
  - 2D “unwrapped” computational model is often used in expressing shock wave behavior or fuel/air injection.
  - Figure 5 (DW pressure contour) expresses the flashback effect, figure 5b showcasing the formation of detonation cells which are incorporated into the design and development of the engine to ensure the wave can continuously propagate.
  - Triple-pointed structure - likely a result of detonation cell width and chemical characteristics
  - High pressure zone expands in a Prandtl-Meyer fan
  - Deflagration caused by interaction of reactants and detonation products
    - Deflagration → varying propagation velocities, pressure increase.
    - Back-flow of injector reactants could lead to the engine’s catastrophic failure

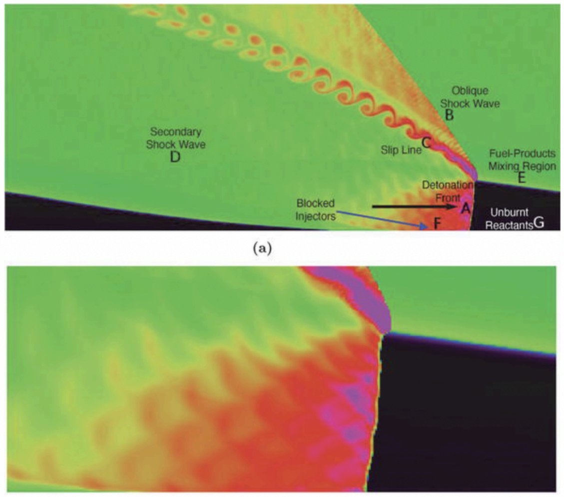
Injection

- Generally (in modern research), axial injection is used on a circumferential orifice plate for testing/modelling/analysis.
- Premixed injection has generally been avoided to due to concerns with flashback.
- Shock wave propagation into injector plenum can be avoided by sufficient pressure (2.3-3 times the chamber pressure for injector pressure).
- Fuel flowrate often influence RDE engine reliability. This is due to “hot-spots”, or places where the RDE favors certain kinds of combustion or deflagration.
- Previous have identified the following relationships in injection:
  - Increasing the fuel injection area results in more efficient pressure gain and generates higher levels of thrust.
  - Lower fuel injection velocities increases risk of flashback.
  - The pressure ratios between the inlets and the engine of less than 10 show notable reductions in specific impulse.
- Work is needed to optimize fuel injection area, configuration, and flow/plenum boundary properties to ensure that the mixture is most homogeneous.
  - Conflicting requirements make injection design complex.
  - Must be optimized to improve fuel consumption and thrust output.

Computation
- Analyzed using CFD analysis
- high -fidelity models are complex, large-scale, and require millions of cells for DNS and LES analysis
- 3D models require more complex compuattional geometries (yet introduce several features, similarly to 2D, at a refined analysis viewpoint)
- Boundary Conditions:
  - Fuel and oxidizer inlets can be modelled as simple geometries (points, lines, surfaces, discrete injectors)
- Mixing based on Euler equations (may affect model fidelity)
- Run on a simplified induction parameter model
- Dimensions are based on nozzle-to-throat ratios
- Turbulence Modeling:
  - Euler equations conserve momentum, mass, and energy
    - However, they do not account for viscosity
    - This is only a 7% effect on predicted specific impulse
  - Viscous properties can be incorporated by using Reynold-Averaged Navier Stokes (RANS) → improve model fidelity
- Previous Geometries:
  - Meshing: 200 (mu)m
  - Mid-channel diameter: 90 mm
  - Inner diameter: 140 mm
- Consider linearized model for simulation/physical modeling (easy to see and understand mixing, pressure, and wave behavior properties and relationships

Future Outlook:
- RDE could have applications in space due to their comparable thrust-to-weight ratios to existing/currently used technologies
- The following research gaps have been identified in this article:
  - Varying wall angles may benefit thrust production by directing pressure to the nozzles → still needs more support
  - Performance in microgravity?
  - Find a way to lower maximum equivalence ratio limit
  - Triple-points effect of those stable and consistent points on pressure and propagation
  - Relationship between detonation cell width and geometry requirements
  - Channel width and stability relationship
  - Effect of chamber length on design parameters and specific impulse
  - Hollow RDEs? → “centribodiless” design performance
  - RDE and turbine combination
  - Effect of euler equations on fidelity level of model
  - Viscous and thermal-wall effects → accuracy is essential in experimental values return
  - Why is there a significant difference between experimental and

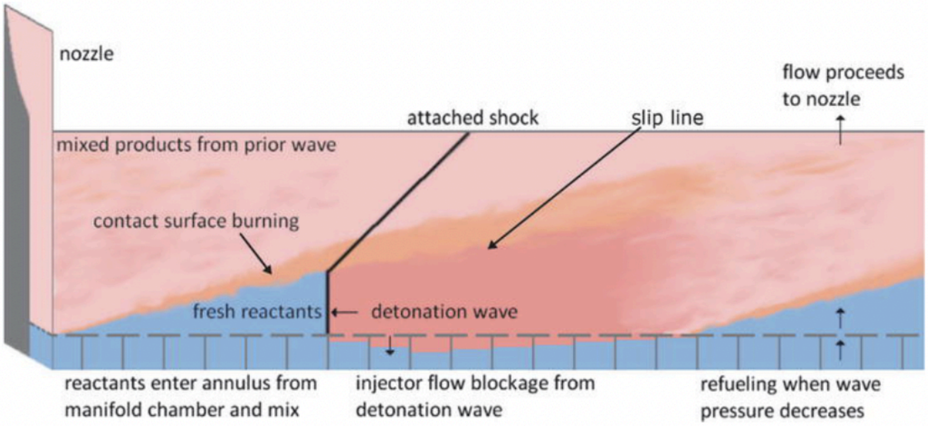
	computational wave-speeds and plenum pressures?
Research Question/Problem/ Need	The need that this article is addressing is increased research (both experimental and computational) with rotating detonation engine technologies. It can often be difficult to identify issues in an industry or system, with the RDE being no exception. This article hopes to fill that gap by providing a thorough review of literature regarding the primary components and functions of an RDE to aid research and guidance of key, unsolved issues.
Important Figures	 Cross-sectional view of RDE configuration. Labeled to express components and modular design. My project aims at optimizing reactants injection into the detonational channel.



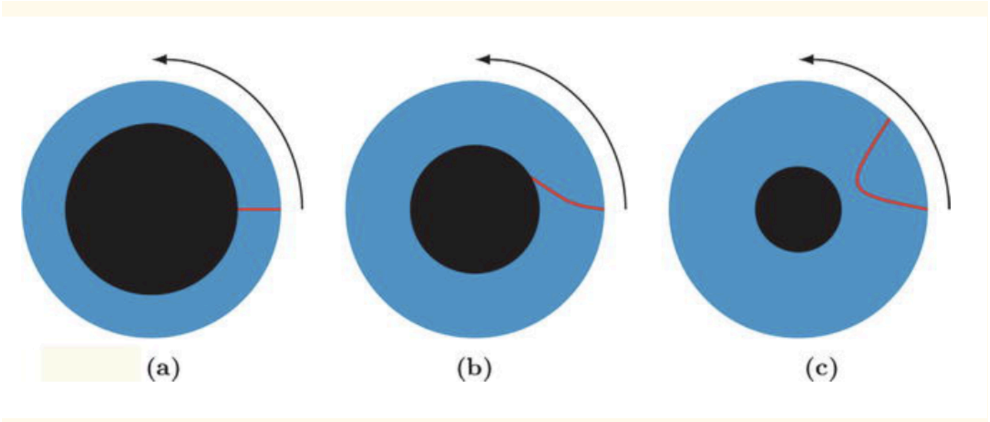
(a)

(b)

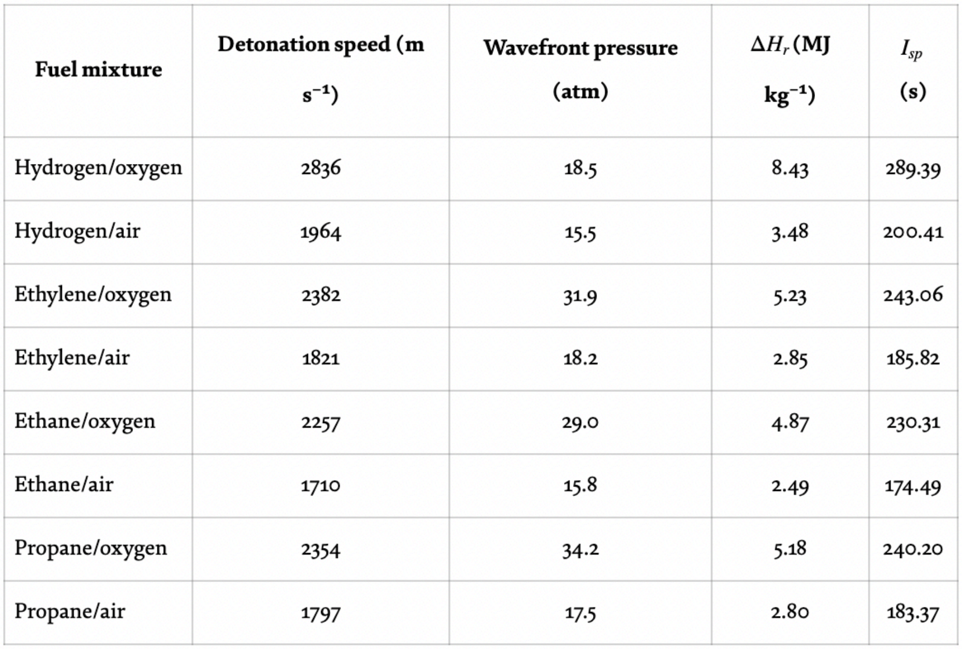
5a - flashback effect (injector blockage caused by high-pressure post-detonation gases
5b - detonation cell structure in an RD wave → length is used to determine engine proportion



6 - “unwrapped” RDE detonation cycle → notice that flashback occurs at the detonation wave due to very high pressure, but quick recovery allows wave to continue propagating + consuming fuel+air.



Effect of varying channel width on direction of wave motion → how large channel widths can least to engine instabilities



Fuel mixture	Detonation speed (m s^{-1})	Wavefront pressure (atm)	ΔH_r (MJ kg^{-1})	I_{sp} (s)
Hydrogen/oxygen	2836	18.5	8.43	289.39
Hydrogen/air	1964	15.5	3.48	200.41
Ethylene/oxygen	2382	31.9	5.23	243.06
Ethylene/air	1821	18.2	2.85	185.82
Ethane/oxygen	2257	29.0	4.87	230.31
Ethane/air	1710	15.8	2.49	174.49
Propane/oxygen	2354	34.2	5.18	240.20
Propane/air	1797	17.5	2.80	183.37

How fuel selection can alter detonation wave performance, with a consideration of detonation speed, pressure at the wavefront, height, and specific impulse.

VOCAB: (w/definition)

Oblique shock wave: shock wave that is directed at an incline with respect to incident upstream flow direction

Slip line: a line that appears between two flow regions that have the same flow direction (split between similarly directional flow)

Premixture: the mixture produced and occupying detonation channel from premixed fuel and oxidizer

Kelvin-Helmholx instabilities: a fluid instability → occurs when there is a velocity difference across the interface between two fluids

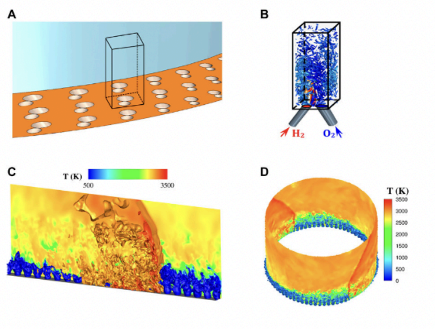
Cryogenic fuels: fuels that are stored at very low temperatures (in a liquid state)

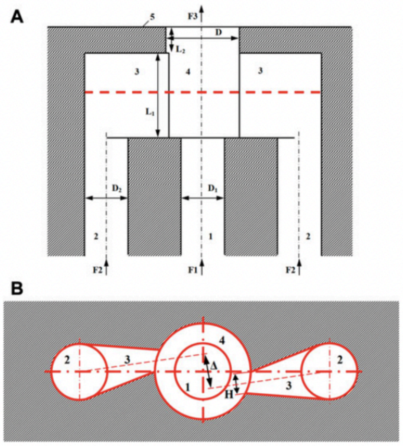
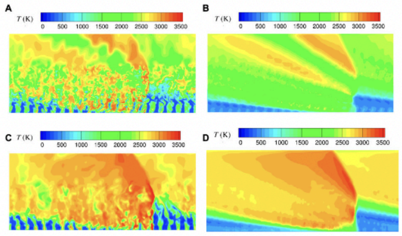
	Flash vapourization: passing a heated liquid mixture through a valve to vaporize it (increase pressure → vaporize mixture) **LES (Large-eddy simulations):** mathematical model for turbulence in CFD
Cited references to follow up on	Rotaru C, Mihăilă-Andres M, Renard P. New constructive solutions for aircraft turbojet engine combustion chamber. Journal of Military Technology—MTA Review. 2013;23(4):219-230 Kindracki J, Wolański P, Gut Z. Experimental research on the rotating detonation in gaseous fuels–oxygen mixtures. Shock Waves. 2011;21(2):75-84 Bykovskii FA, Zhdan SA, Vedernikov EF. Continuous spin detonation of fuel-air mixtures. Combustion, Explosion, and Shock Waves. 2006;42(4):463-471 Kindracki J, Kobiera A, Wolański P, Gut Z, Folusiak M, Swiderski K. Experimental and numerical study of the rotating detonation engine in hydrogen-air mixtures. Progress in Propulsion Physics. 2011;2:555-582
Follow up Questions	1. What current work, or research initiatives are being taken to address these identified gaps? 2. Why is the effect of fuel inhomogeneities on rotating detonation waves mentioned slightly? Is there a greater problem with injection to address? 3. What is the “bigger picture” → are RDE’s going to be implemented, and what are the extents of its impact on aerospace or energy generation? 4. Are Reyonds-Averaged Navier Stokes (RANS) equations necessary for non-chemically kinetic reactions/mixing problems? 5. What are the limits and drawbacks of pursuing computational research? Is experimental research more valid? Are computational results valid, or actually possible?

Article #18 Notes: Rotating detonation combustors for propulsion: Some fundamental, numerical and experimental aspects

Date: 12/10/23

Source Title	Rotating detonation combustors for propulsion: Some fundamental, numerical and experimental aspects
Source citation (APA Format)	Naour, B. L., Davidenko, D., Gaillard, T., & Vidal, P. (2023). Rotating detonation combustors for propulsion: Some fundamental, numerical and experimental aspects. *Frontiers in Aerospace Engineering*, *2*. https://doi.org/10.3389/fpace.2023.1152429
Original URL	https://www.frontiersin.org/articles/10.3389/fpace.2023.1152429/full
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** This article aims at breaking down the rotating detonation engine through a thorough technical breakdown of experimental and computational results regarding the rotating detonation engine. It breaks down wave behavior, chamber geometry, and impacts of several parameters on RDE performance. To note, this article was read partially (injection-specific sections) due to lack of an emphasis on my project regarding the other included sections. **Notes:** ● Detonation waves are supersonic combustion waves with complex cellular structures. ○ RDEs utilize rotating detonation waves for high-pressure combustion. ○ Non-ideal RDE performance (e.g., lower velocity) is caused by factors like: ■ Mixing imperfections: ● Fresh gases don't mix perfectly before detonation ■ Chamber geometry:

	● curvature and size of engine geometrical configuration affect detonation stability and performance ○ Injection technology: ■ Risky premixed injection (FLASHBACK, FLASHBACK, FLASHBACK) ● separate injection => efficient mixing ○ RDEs can have single or multicellular detonation fronts depending on chamber dimensions and mixture ● Unstable RDE operation **(quenching and re-ignition)** can occur with narrow chambers or poor mixing. ● Larger chambers and better mixing generally lead to higher RDE performance ○ Velocity and pressure optimization ● Premixed injection is ideal for performance ○ However it’s very RISKY for detonation transmission through injector ● Separate injection needs careful design to ensure rapid and efficient mixing of fresh gases. ○ Partially premixed injection might be a promising **compromise between performance and safety.**
Research Question/Problem/ Need	This research aims to break down the overall fundamental concepts regarding RDEs, including computation and performance-based information with both experimental and computational engine domains.
Important Figures	 **FIGURE 4**. General approach for injection studies. **(A)** Definition of the injection elements composing the RDC injector, **(B)** precise computation on a fine mesh of the mixing interactions for an injection element, **(C)** simulation of the RD propagation on a linear series of injection elements, **(D)** simulation of the RD propagation in an annular RDC.

	 **FIGURE 7**. Design of the ITEM injection element with three feeding tubes (1, 2). **(A)** Section passing through the axes of the feeding tubes and normal to the injection wall (5), **(B)** section parallel to the injection wall in the middle of the pre-chamber (4).  **FIGURE 9**. Instantaneous **(A,C)** and averaged **(B,D)** temperature fields for RD propagation on a series of SI **(A,B)** and ITEM **(C,D)** elements.
VOCAB: (w/definition)	**Cellular structure:** diamond-shaped regions observed in detonation waves, resulting from interactions between shock waves and the reactive flow. **Mixing imperfections:** Incomplete or uneven mixing of fresh gases before detonation **ONERA:** French aeronautical research lab **Gaseous flow:** gaseous flow is the flow of gases (post-detonation and reactive mixtures). This interaction often impacts parasitic combustion!
Cited references to follow up on	Kindracki, J., Wolański, P., and Gut, Z. (2011). Experimental research on the rotating detonation in gaseous fuels–oxygen mixtures. Shock waves 21, 75–84. doi:10.1007/s00193-011-0298-y Nicholls, J., Cullen, R., and Ragland, K. (1966). Feasibility studies of a rotating detonation wave rocket motor. J. Spacecr. Rockets 3, 893–898. doi:10.2514/3.28557
Follow up Questions	1. How can the trade-off between performance and safety be further optimized in RDE design? 2. Can computational simulations accurately predict behaviors of detonation waves within RDEs? 3. How can the scalability of RDE technology be addressed for real-world applications, such as propulsion systems or industry? 4. What environmental impacts might RDE technology have, specifically,

	reduced emissions and energy consumption compared to traditional engines? 5. What are the potential future directions for RDE research and development (combustion and control systems!!)?

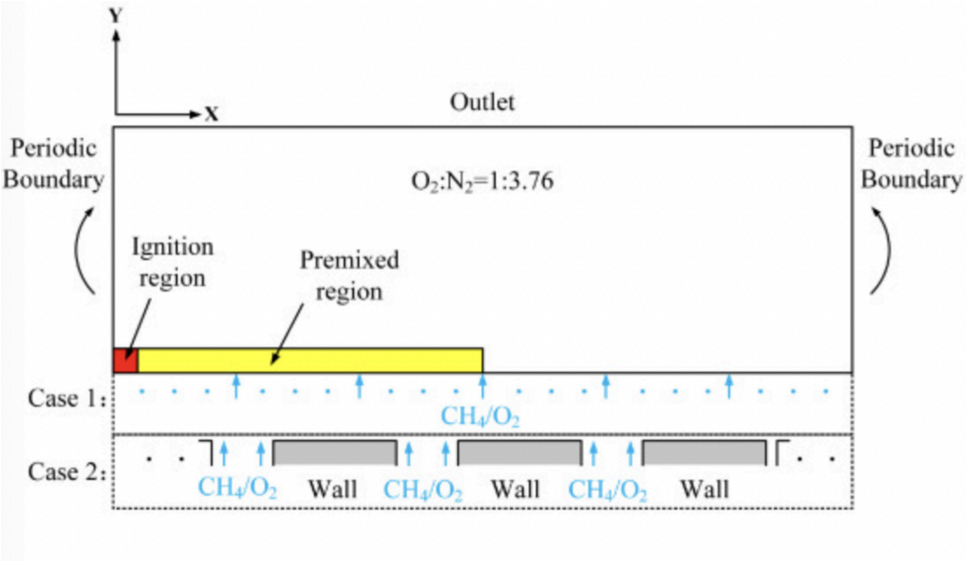
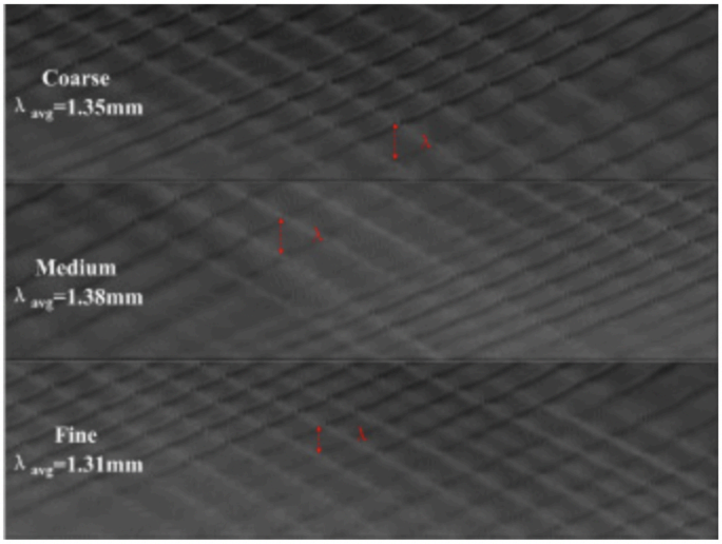
Article #19 Notes: Formation of multiple detonation waves in rotating detonation engines with inhomogeneous methane/oxygen mixtures under different equivalence ratios

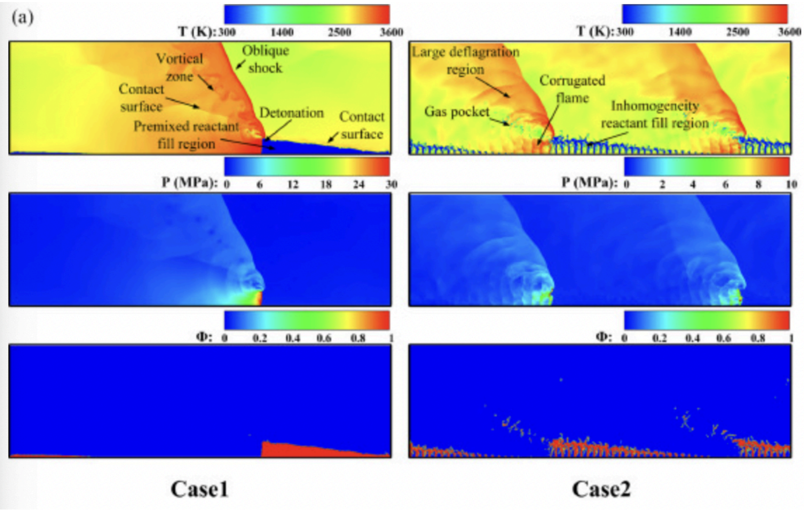
Date: 12/11/23

Source Title	Formation of multiple detonation waves in rotating detonation engines with inhomogeneous methane/oxygen mixtures under different equivalence ratios
Source citation (APA Format)	Luan, Z., Huang, Y., Gao, S., & You, Y. (2022). Formation of multiple detonation waves in rotating detonation engines with inhomogeneous methane/oxygen mixtures under different equivalence ratios. *Combustion and Flame*, *241*(112091). Elsevier. https://doi.org/10.1016/j.combustflame.2022.112091
Original URL	https://www.sciencedirect.com/science/article/pii/S0010218022001109
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** This paper aims to investigate the effects of equivalence ratios on the number of detonation waves propagated in a rotating detonation engine. A numerical analysis of chamber conditions, wave behavior, and wave propagation characteristics (cell width, varied with mesh scale, homogeneity, in T and P) is conducted to better understand this relationship for applications in rocketry and energy generation. It was found that the number of detonation waves increased as the equivalence ratio rose in an inhomogenous environment. When the equivalence ratio is close to 1.0, the heat release, intensity, and wave velocity rises. With the consideration of its applications to my project, this article identifies a relationship that could be incorporated in mass flow rates of fuel-oxidizer injectors in an RDE configuration. An equivalence ratio calculation could be conducted to optimize the detonation wave propagation, increase waves, or it could be adjusted to account for the needs

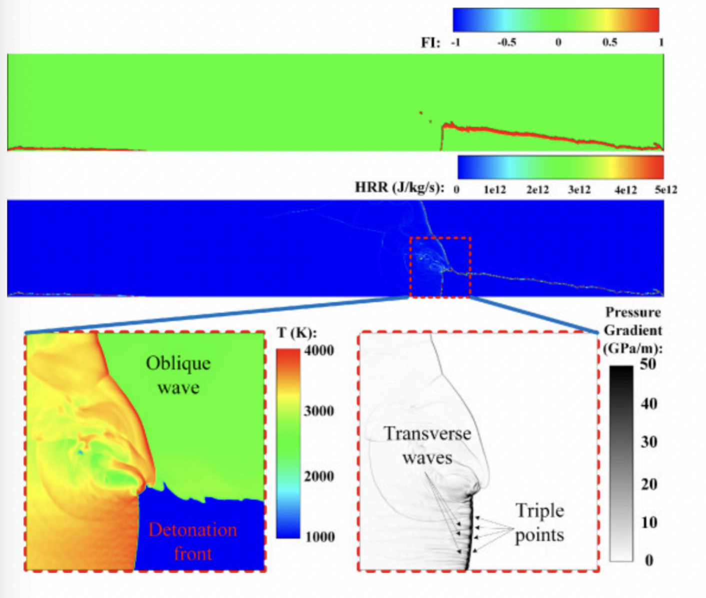
	of its use (rocketry, energy generation).
	Notes:
	● Independent variable: equivalence ratio level
	● The effect of inhomogeneous mixtures holds the following impacts on detonation wave propagation, as well as pressure, temperature, and visible front/stucture profile:
	  ○ Corrugated flow field is formed after the detonation
	  ○ Number of gas pockets and unburned regions increases (less homogenous post–reaction gases)
	  ○ Successive coupling-decoupling-coupling modes occur
	    ■ Reduces energy output due to increased energy direction towards phase completion
	  ○ Post-detonation flow field is enhanced by incorporation of higher equivalence ratio incorporation, as post-detonation gases and reactants are injected and left at a more homogenous state due to varying pressure increases
	  ○ Assimilation of fuel in local hot spots causes parasitic combustion
	    ■ It is apparent that parasitic combustion, or unwanted combustion which alters the detonation mode based on location and mixing configuration occurs as richer mixtures are introduced and less homogeneity between fuel and oxidizer is pursued.
	  ○ The ingomogenous mixture introduction reduces overall mixing efficiency and transforms an effective wave stricture into multiple weak detonation waves.
	● It was found that as you increase the equivalence ratio in an inhomogenous (and therefore more realistic) environment, the number of RD waves increases
	  ○ This also causes there to be a greater reactnat height
	  ○ Higher heat release
	● In the homogenous case, increased height and increased detonation cell width causes the detonation wave number to rise.
	  ○ The inhomogeneous environment (when the spacing and velocity of the jets are constant):
	    ■ width of the detonation decoupled zone W depends on reactant reactivity.
	    ■ Higher reactivity reactants → lower W values
	    ■ the number of transverse waves depends on the height of the reactants.
	      ● transverse waves + detonation surfaces cross to form the parallelogram structure.
	● **Overall, the equivalence ratio has little effect on the average thrust**
	  ○ multiple detonation waves can be used to stabilize the thrust in the combustion chamber. (if approached in the right way).

Research Question/Problem/	The research question of this study is to identify the relationship between

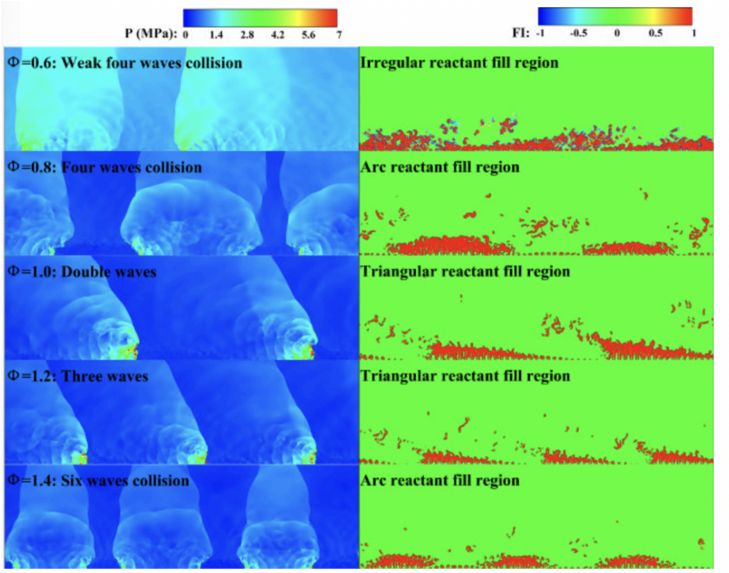
Need	equivalence ratio and number of detonation waves produced in a rotating detonation engine. This relationship was found by conducting a numerical and computational model, which examines wave propagation characteristics and classic dynamics comparisons.
Important Figures	 Computational domain schematic. If you take a closer look at the boundary conditions, case 2 exhibits methane and oxidizer injection with a wall separation separating fuel and oxidizer combined injector plenum. In case 1, boundary conditions in the form of points, or lines can be pursued to mimic the injection process similarly.  Analysis of detonation cell width on the basis of changing mesh scales.



Temperature, Pressure, and Equivalence Ratio contour gradients based on cases 1 and 2. The effect of injection can be visibly conveyed; case 1 exhibits a strong singular wave while case 2 demonstrates double-wave propagation, with lower tepertaure and more stratified equivalence ratios at the inlet zone.



Imaging annotation on a pressure gradient for case 1. Visibly, there exists a strong difference in flow dynamics for the oblique shock wave and the detonation front.

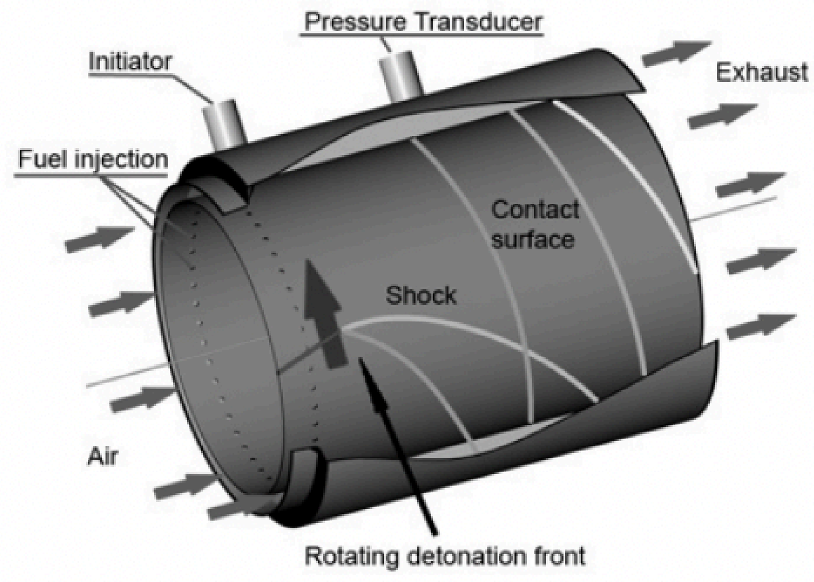
	 Pressure and fill irregularity based on equivalence ratio independence. The effect can be shown that more waves are produces as a higher equivalence ratio is introduced, likely due to a richer, more easily combustible mixture.
VOCAB: (w/definition)	**Vocabulary:** **Equivalence Ratio:** the ratio of the oxygen content in the oxidizer mixture to the amount required for complete stoichiometric combustion. In other cases, it can also be the fuel to air ratio in multiphase physical models **Timescale relations:** parameter-based relation to time **ZND Model:** reaction zone - induction zone - detonation zone structure of rotating detonation wave and respective residual materials **AMROC:** the American Rocket Company
Cited references to follow up on	F.A. Bykovskii, S.A. Zhdan Continuous spin detonation of poorly detonable fuel-air mixtures in annular combustors J. Phys.: Conf. Ser., 899 (2017), Article 042002, 10.1088/1742-6596/899/4/042002 F.A. Bykovskii, S.A. Zhdan, E.F. Vedernikov Continuous detonation in the regime of self-oscillatory ejection of the oxidizer. 2. Air as an oxidizer Combust. Explos. Shock Waves, 47 (2) (2011), pp. 217-225, 10.1134/S0010508211020110 V. Anand, A. St. George, R. Driscoll, E. Gutmark Investigation of rotating detonation combustor operation with H2-Air mixtures Int. J. Hydrog. Energy, 41 (2) (2016), pp. 1281-1292, 10.1016/j.ijhydene.2015.11.041
Follow up Questions	1. How can an equivalence ratio be directly changed in a simulation setting? 2. In terms of injection configuration and computational domain, could a

	specified mass flow rate alter the equivalence ratio post-injection and into the mixture prior to the arrival of the detonation wave? 3. Aside from its negative impacts on detonation engine stability and controlled combustion, are there any benefits to having more detonation waves? 4. Are reduced inhomogeneities in the fuel-oxidizer mixture positive for reducing the unbalancing impacts on RDEs? 5. How can cell structure and size be incorporated into mixing problems? Considering the relationship between detonation cell size and RDE config. Geometry, is there any effect on injection configuration as well?

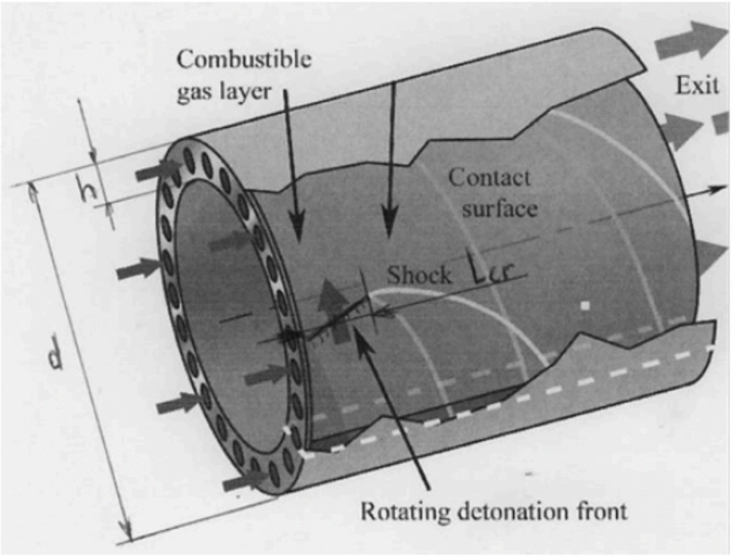
Article #20 Notes: Rotating Detonation Wave Stability

Date: 12/12/23

Source Title	Rotating Detonation Wave Stability
Source citation (APA Format)	Wolański, P. (2011). Rotating Detonation Wave Stability. *23rd International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS)*. http://www.icders.org/ICDERS2011/abstracts/ICDERS2011-0211.pdf
Original URL	http://www.icders.org/ICDERS2011/abstracts/ICDERS2011-0211.pdf
Source type	Journal Article (JA)
Keywords	Rotating detonation engine AND fuel mixture
#Tags	#rotating detonation engine #mixing #injection #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** This article aims at investigating the stability quantities of rotating detonation waves when tested in a cylindrical chamber. It analyzes W (wave quantity) I_{CR} (critical zone length) and critical zone length uncertainties to analyze the effect of geometrical configuration on detonation wave stability. **Key Points Notes:** ● Dependency on mixture supply for stability ○ -> a fresh, homogeneously injected mixture is essential for improving detonation wave continuous propagation ○ Parameters used to quantify stability: ■ W - detonation wave number ● This parameter was introduced by the author as a new parameter for measuring the number of waves propagating in a chamber. Compares revolution time to mixture creation time to quantify detonation waves based on revolution quantity within a given mixture injection ■ What W values mean: ○ W=1: 1 head, W>1: multiple heads, W<1: unstable or failure. ■ Icr - critical zone length ● Minimum fresh mixture volume for stable propagation.

	■ Change/uncertainties in Icr ● Dependent upon: ○ Mixture homogeneity ○ Pressure ○ Temperature ○ Geometry ○ Injector geometry ● This engine can be applied in various settings: particularly an incorporation with rockets and turbojets is identified and considered in analysis of this engine configuration. ● Author discusses challenges ○ Primary challenge is detonation stability ■ Instabilites in RD can cause galloping behavior ● This means that velocity, pressure, and temperature fluctuate both by wave and by individual wave characteristics ○ Secondary challenges include finding the critical zone length, ■ Incorrectly/not fully determining Icr could be crucial for propulsion system applications and overall wave behavior ■ The goal for RDWs are to pursue stable, continuous, and repetitive waves so that applications in other industries is possible. ○ Focus on getting Icr in the future!
Research Question/Problem/ Need	This article aims at investigating the stability quantities of rotating detonation waves when tested in a cylindrical chamber.
Important Figures	 Image showcasing 3D portrayal of RD engine, including detonation wave behavior

and injection/initiation/transducrtion mechanisms.



Cylindrical detonation chamber configuration → described injection and output strategy. Wave detonation characteristics can be modeled by annotated shock wave line markers.

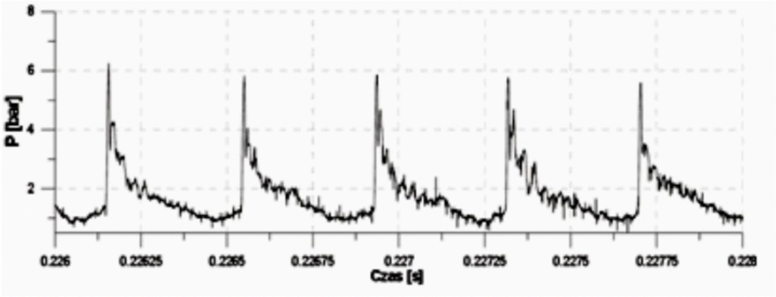
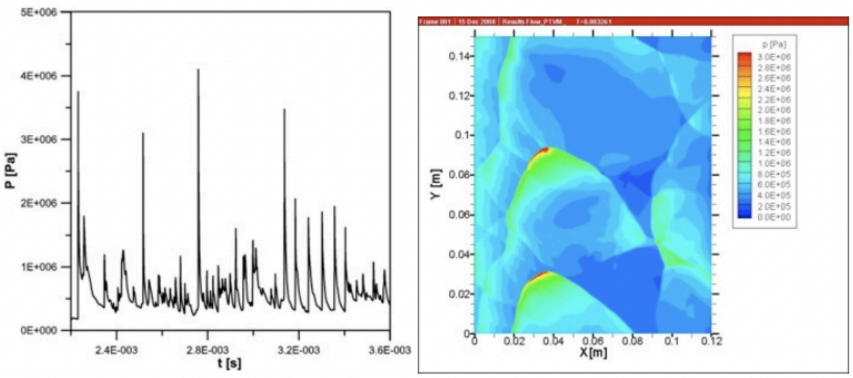


Fig. 3 Stable rotating detonation (experiment)

Stable rotating detonation wave. Compared pressure [bar] with time passage.

	 Fig. 5. Unstable (galloping) rotating detonation (calculations)
VOCAB: (w/definition)	**Critical Zone Length:** Minimum fresh mixture volume for stable propagation. **Transducer:** an electronic device that converts energy from one form to another **W: wave number:** Compares revolution time to mixture creation time to quantify detonation waves based on revolution quantity within a given mixture injection **Galloping:** instability/unevenness/non-repetition **RDW** - rotating detonation wave
Cited references to follow up on	Bykovskii F.A., Zhdan S.A. and Vedernikov E.F., Continuous Spin Detonation of Hydrogen–Oxygen Mixtures. 1. Annular Cylindrical Combustors Combustion, Explosion, and Shock Waves, Vol. 44, No. 2, pp. 150–162, 2008 .Davidenko DM, Gökalp I, Kudryavtsev AN. (2008). Numerical study of the continuous detonation wave rocket engine. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference.
Follow up Questions	1. How does this new parameter (W) compare with previously collected data and experimental results? Is there any comparable, existing stability criteria? Is stability in repetition necessary for RD wave effectiveness? 2. What are the limitations of measuring critical zone length? Why is critical zone length difficult to find/quantify? 3. How can this paper and parameter development apply to other geometries? Is there any clear difference? 4. How can detonation reactant products (post-detonation) be incorporated into this model? 5. What other factors must be addressed, other than stabilities? Are there any significant technological concerns?

Patent #1 Notes: Homogeneous mixture formation by swirled injection of the fuel

Date: 12/12/23

Source Title	Homogeneous mixture formation by swirled injection of the fuel
Source citation (APA Format)	Dörr, T. Dr., & Rackwitz, L. (2009). *Homogeneous mixture formation by swirled injection of the fuel* (European Patent Office Patent). https://patents.google.com/patent/EP1512912A3/en
Original URL	https://patents.google.com/patent/EP1512912A3/en
Source type	Patent
Keywords	Homogenous AND gaseous fuel and oxidizer AND injection
#Tags	#mixing #injection #homogeneity
Summary of key points + notes (include methodology)	Summary: The objective for this patent was to develop an effective strategy for injecting gaseous fuel into a combustion engine with an existing air flow. The design utilizes circumferentially inclined fuel injectors, in order to produce a "swirled" mixture effect. In pursuing this injection scheme, a more homogenous fuel-air mixture can be produced by incorporating a vortex-like injection scheme. Notes: ● This invention aims at injecting fuel into a combustion engine's air flow using circumferentially angled placement of fuel injector plenums. ● This process is called "swirled" injection due to its effect on fluid flow characteristics within the mixture. ● The fuel openings are positioned at a slight angle, at least in the circumferential direction in order to produce a vortex-like fuel mixing effect. ● In pursuing this injection configuration, the inventors of this configuration strove to inject the fuel into an existing air flow, in order to create a homogenous mixture of fuel and oxidizer to be ignited for powerful combustion, either from thrust or chemical combustion. ● This patent is applicable to my project as my project aims to take existing and popular injection schemes in the Rotating Detonation Engine work day,
Research Question/Problem/ Need	Develop an effective strategy for injecting gaseous fuel into an air flow within a combustion engine to produce a highly homogenized mixture.

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<tr>
<td>Important Figures</td>
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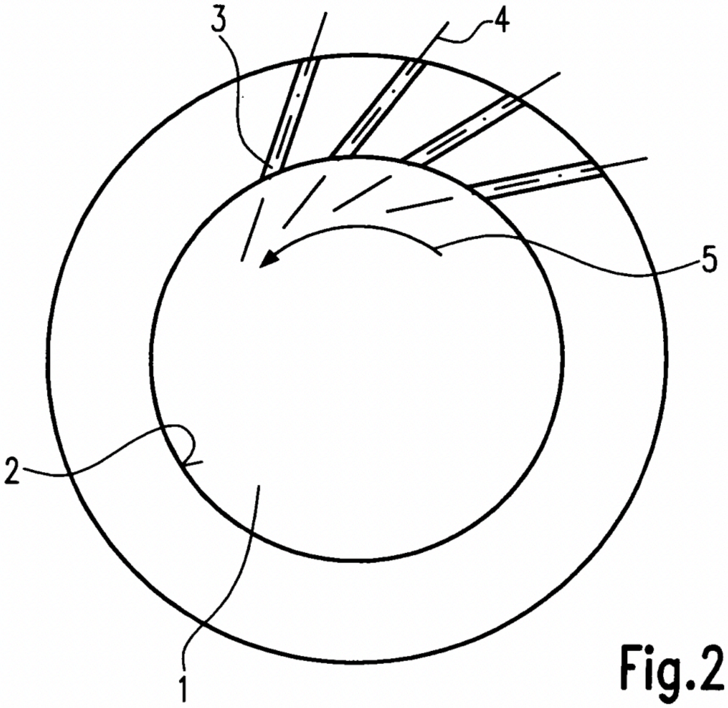

Fig.2

Top-view of fuel injectors into airstream (circumferential performance).

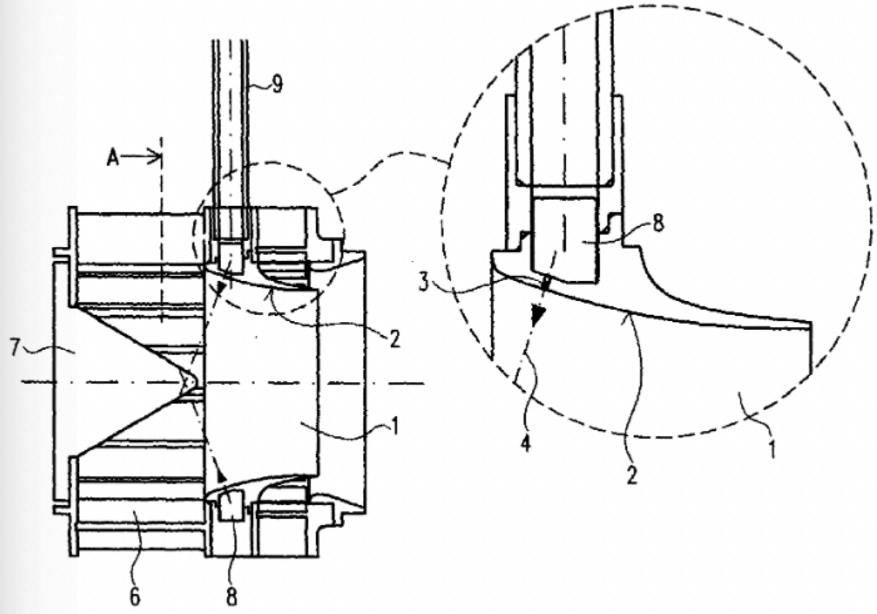

Fig.1

Placement and configuration of inclined and “swirled” injectors in the fuel pipe.
</td>
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<tr>
<td>VOCAB: (w/definition)</td>
<td>Circumferential: relating to the circumference of a curved geometric figure.</td>
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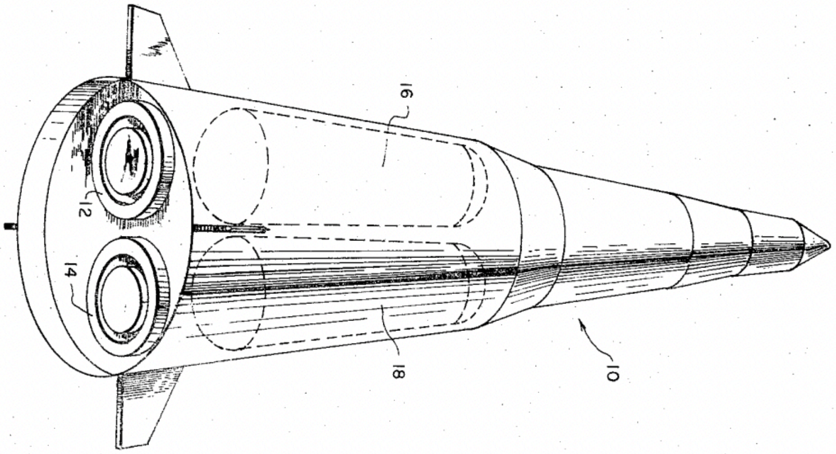
</table>

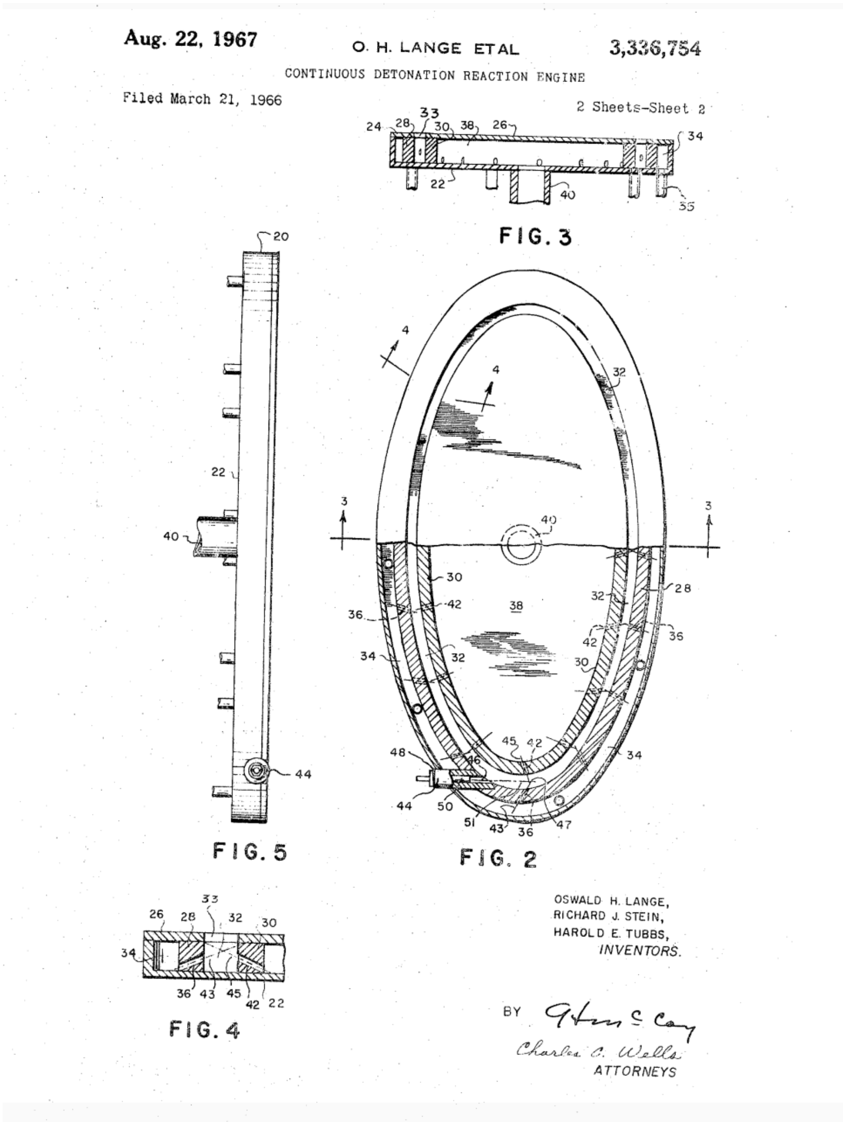
	Gas Turbine: a combustion engine that converts natural gas or liquid fuel into mechanical energy. The energy is then used to drive a generator to produce electrical energy.
Cited references to follow up on	No References Included.
Follow up Questions	1. Is this configuration effective in producing a homogeneous mixture? If so, by what degree? 2. What are the benefits and drawbacks of adopting a swirled injection scheme? 3. What are the specific dimensions, or relationships in size and location within this patented invention? 4. How often and in what applications has this injection method been used? 5. How many fuel injectors should be used in this configuration? 6. Does a swirled configuration reduce the turbulent kinetic energy produced outside of the injector gate?

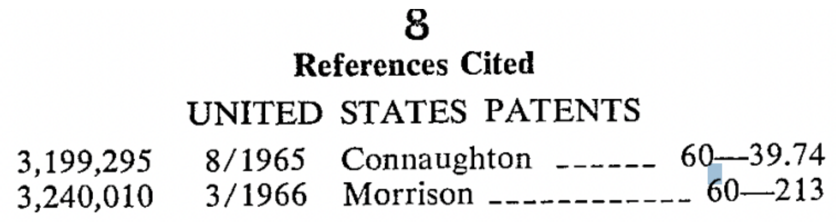
Patent #2 Notes: Continuous detonation reaction engine

Date: 12/13/23

Source Title	Continuous detonation reaction engine
Source citation (APA Format)	Lange, O. H., Stein, R. J., & Tubbs, H. E. (1967). *Continuous detonation reaction engine* (United States Patent Office Patent). https://patents.google.com/patent/US3336754
Original URL	https://patents.google.com/patent/US3336754
Source type	Patent
Keywords	Homogenous AND gaseous fuel and oxidizer AND injection
#Tags	#rotating detonation engine #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	Summary: This invention details the continuous detonation reaction engine, a revolutionary engine dedicated to improving engine functions through controlled re-activation of continuous detonation waves. Detonation can be utilized to circulate and push residual flow gasses out and produce effective and efficient thrust. Despite its high potential, several issues such as detonation control and unbalanced/torque inducing effects must be minimized before its development and use in modern energy/thrust applications. This patent is a great glimpse into the origins and beliefs of RDEs before an era of computational and numerical analysis with the use of high-fidelity simulation. Notes: ● The introduced continuous detonation engine system uses detonation to produce promising levels of thrust ● Includes a “closed loop channel” → this means that fuel and oxidizer are injected at specific points in order to create detonation waves that travel arround a circumferential chamber ● Highly efficient detonations ○ Produce more thrust and greater velocity of exhaust flow ○ Avoids torque issues commonly seen in existing engine configurations ● Configuration ○ Engine structure includes an “outer housing” encasing inner walls which create a thin detonation channel for rotating propagation of detonation waves. ○ Fuel and oxidizer are injected into the chamber

	■ At an angle ■ Injected at spaced intervals ● This creates impingement points (see vocab) ○ Initialization occurs → increase temperature and pressure in one part of the mixture to produce a strong detonation reaction ■ A generator is included in the design to initiate the reaction. ○ The detonations produced by the initiation are self-sustaining → propagation as detonation wave passes where it began. ■ This allows you to have continuous thrust production and detonation re-propagation without the use of additional initiations → keeps going by itself ■ Due to high temperatures and pressures. (conditions perfect for restarting a detonation) ○ Detonation products are pushed out of the thruster → thrust production occurs! ● Functionality ○ Very promising, high thrust and energy output ○ Uncontrolled detonation reaction and unwanted torque are main challenges. ○ Lower emission output → better for the environment due to wave consumption? ○ Complex → hard to manufacture or standardize for broader applications
Research Question/Problem/ Need	The need addressed through this invention is the need for greater efficiency and thrust production in conventional engines. In addition, it avoids key torque issues that are often seen in traditionally used engines (for power supply, large vehicles, and some rocketry applications).
Important Figures	FIG. 1  (rotated to reduce large doc size) → This schematic represents the engine configuration (outside/view from thrust nozzle)

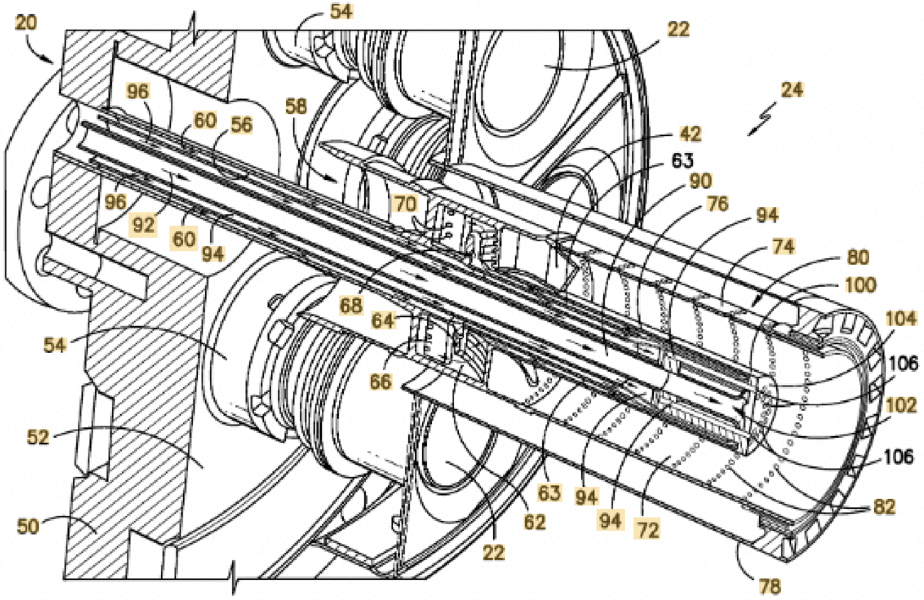
	 Aug. 22, 1967 O. H. LANGE ETAL 3,336,754 CONTINUOUS DETONATION REACTION ENGINE Filed March 21, 1966 2 Sheets-Sheet 2 OSWALD H. LANGE, RICHARD J. STEIN, HAROLD E. TUBBS, INVENTORS. BY Charles C. Wells ATTORNEYS Schematic of continuous detonation engine configuration. Inner wall, outer wall, detonation channel, and injection configuration all included in the above patent schematic.
VOCAB: (w/definition)	**Closed loop channel:** a closed circular channel in which a detonation is ignited, and it circulates around the chamber in a closed loop. **Impingement points:** point of contact **Continuous detonation:** a form of combustion in which a detonation is introduced to a closed loop style chamber, and produces continuous detonation energy and thrust. **Detonation**: a detonation is a chemical reaction that produces a significant, immediate rise in thermal energy and pressure.

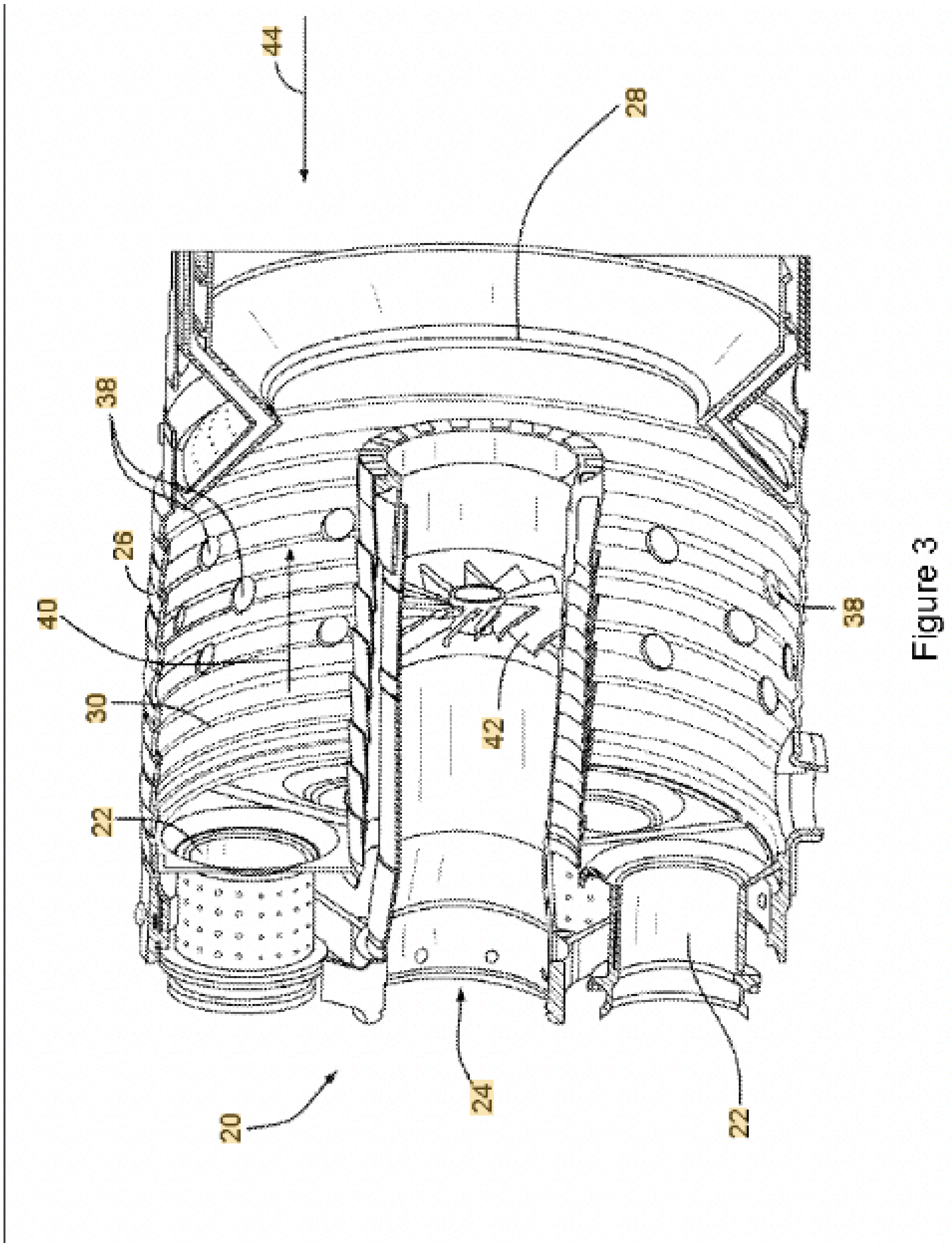
Cited references to follow up on	 8 **References Cited** UNITED STATES PATENTS 3,199,295 8/1965 Connaughton ------ 60—39.74 3,240,010 3/1966 Morrison ------------ 60—213 No other details/references cited.
Follow up Questions	1. How did this patent influence the development of RDE development over the next couple of years? Were people able to study or research this technology with the patent being incorporated? 2. How does the design of the injector ports contribute to detonation? Why are they positioned in this way, and was there any logical progression to getting there? 3. What other challenges could uncontrolled detonation and torque issues bring? 4. What are the limitations of this concept? What fuel-oxidizer mixture, EQ ratio, fuel flow rate, or any specific technical parameters are used? 5. How was the design tested? What are the parameters for betterment of the engine?

Patent #3 Notes: Fuel nozzle for combustor

Date: 12/13/23

Source Title	Fuel nozzle for combustor
Source citation (APA Format)	Khan, A. Rafey, Ziminsky, W. S., & Stevenson, C. (2013). Fuel nozzle for combustor (United States Patent Office Patent). https://patents.google.com/patent/US8464537B2/en?q=(F23R3%2f286)
Original URL	https://patents.google.com/patent/US8464537B2/en?q=(F23R3%2f286)
Source type	Patent
Keywords	Homogenous AND gaseous fuel and oxidizer AND injection
#Tags	#rotating detonation engine #alternative rocket propulsion systems
Summary of key points + notes (include methodology)	**Summary:** This invention is a flame-tolerant nozzle which has been incorporated into a gas turbine combustor system. It aims to simplify design, burn a wider range of fuels, and protect the engine structure from flame damage to increase durability and versatility of the engine. It hopes to improve upon existing gas turbine engines and maximize engine performance for energy generation, thrust production, or vehicular use. **Notes:** ● The problem being addressed is that conventional nozzles in gas turbines are complex and have separate air and fuel passages ○ This limits fuel flexibility ○ Risks damage to the engine structure ● Solution ○ Flame tolerant nozzle was developed for gas turbine combustors ■ The benefits of this solution include: ● Simplicity in design (one set of passages for fuel) ○ Fuel and air transfer is simple ● Improved cooling mechanisms ○ Swirling vanes ○ Burner tube ○ Internal fuel flow ● Broader fuel capabaility ○ Low load operation + Flame stablilization ○ Able to smoothly transition between necessary operation modes ● Flame resistance ○ Can use highly reactive fuels due to heat protection ■ Overall this engine:

	● Improved fuel flexibility ● Reduces complexity ● Improves operability ● Lowers emissions (for NOx) ○ The engine components include: ■ Pilot fuel passage: Delivers fuel for pilot flame during low load operation. ■ Transfer passages ● Deliver air for pilot flame. ● Deliver transfer fuel during mode transitions. ● Purge fuel from the nozzle after transfer. ■ Swirling vanes: Pre-mixed fuel and air for improved combustion and flame stability. ● INCORPORATION WITH MY PROJECT? ■ Air-cooled burner tube: Provides extra cooling to protect the nozzle from hot gases. ■ Internal fuel flow: Cools the nozzle tip and passages.
Research Question/Problem/ Need	The need addressed by this invention is a complex design, specific performance with only certain fuels, and flame damage in traditional gas turbine engines.
Important Figures	 Functional schematic of the combustor.

	 Figure 3 Cross-sectional view of combustor engine
VOCAB: (w/definition)	**Flame-tolerant:** able to withstand exposure to flames without significant damage or malfunction **Pre-mixed:** referring to a fuel and air mixture prepared before combustion, leading to cleaner and more efficient burning **Fuel flexibility:** ability of a system to operate efficiently and reliably with different fuel types **Wobbe number:** dimensionless ratio used to characterize the interchangeability of gaseous fuels based on their heating value and specific gravity
Cited references to follow up on	No references included.

Follow up Questions	1. How are the engine features being tested for long-term durability under real-world combustion conditions? 2. How does the nozzle's performance compare to existing technologies for these fuels in terms of efficiency and emissions? 3. WHat is the length of time that the nozzle can realistically withstand a flame holding event before damage? 4. How expensive or easy to manufacture is this engine? Is it comparable, or similarly modeled with the gas turbine engine? 5. What are the emissions created for this model? Does the flame tolerant nozzle offer any other benefits other than heat resistance?