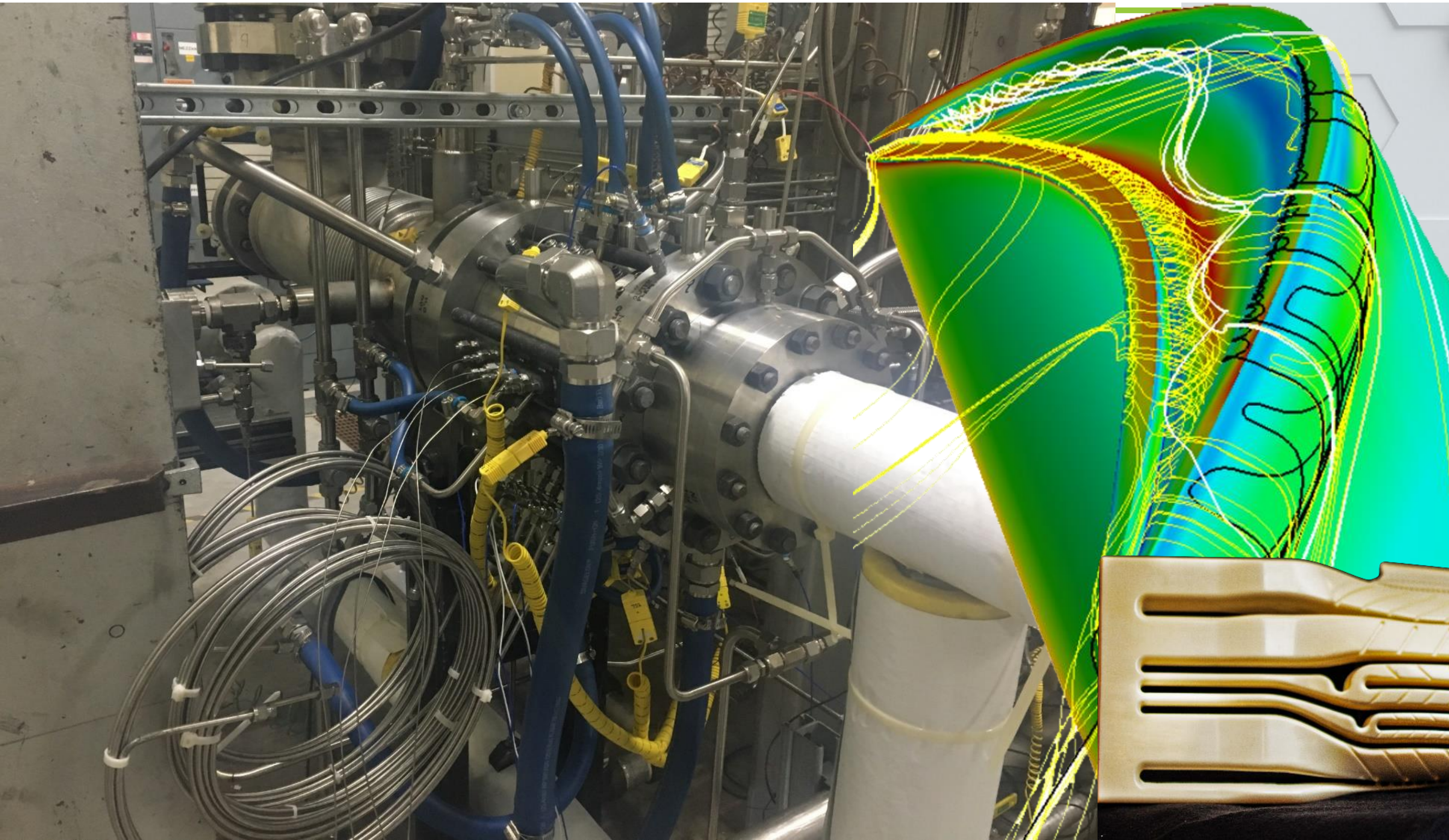
Pressure Gain Combustion Technology Development for Gas Turbine Engines

Solutions for Today | Options for Tomorrow



2021 UTSR Virtual Review Mtg
Nov 8-10, 2021

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DOE's Advanced Turbines Program

Technology Manager: Rich Dennis

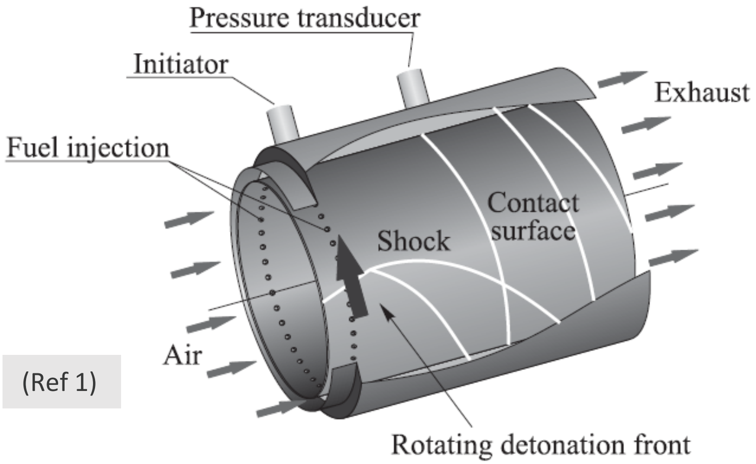
Objective – Developing revolutionary, near-zero emission advanced turbine technologies through research, development in the areas of combustion, aerodynamics / heat transfer and materials.

Key Technology Areas

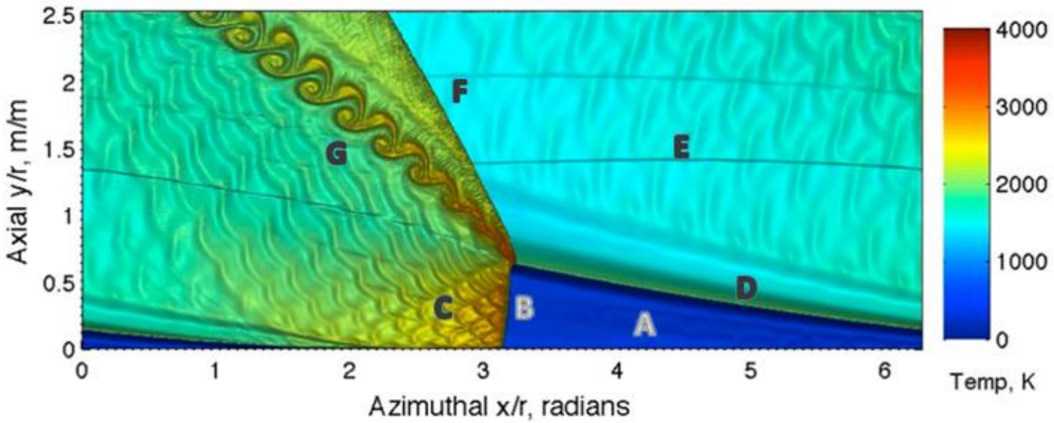
- **Advanced Combustion Turbines** - Component development for turbine systems fueled with coal-derived fuels (including hydrogen and syngas) and natural gas in combined cycle applications.
- **Supercritical CO2 Turbomachinery** - Turbine technology for sCO_2-based power cycles.
- **Steam Turbines** - Improving plant performance and load-following capabilities.
- **Modular Hybrid Heat Engines** - Novel modular hybrid heat engines, based on gas turbine technology, that are cleaner, more efficient, and better load-following capabilities.
- **Pressure Gain Combustion** - Utilizing combustion control strategies to extract additional work availability from coal-derived fuels (hydrogen and syngas) in turbine-based power cycles.

Rotating Detonation Engines

Application and Advantages



(Ref 1)



A. Fresh Reactants
B. Detonation wave
C. Post-Detonation / Transverse Waves
D. Contact Surface (Def)
E. Product Expansion (Det, Det+Def)
F. Oblique Shock Wave
G. Shear Layer

(Ref 2)

Advantages

- Fuel and air has a bulk axial flow with detonation wave traveling circumferentially, producing a nearly "*constant wave*"
- No moving parts
- Detonation wave, once initiated, is self-sustained.
- Detonation wave not susceptible to flashback and thermoacoustic instabilities
- Short residence time and ability to run lean may decrease NOx emissions

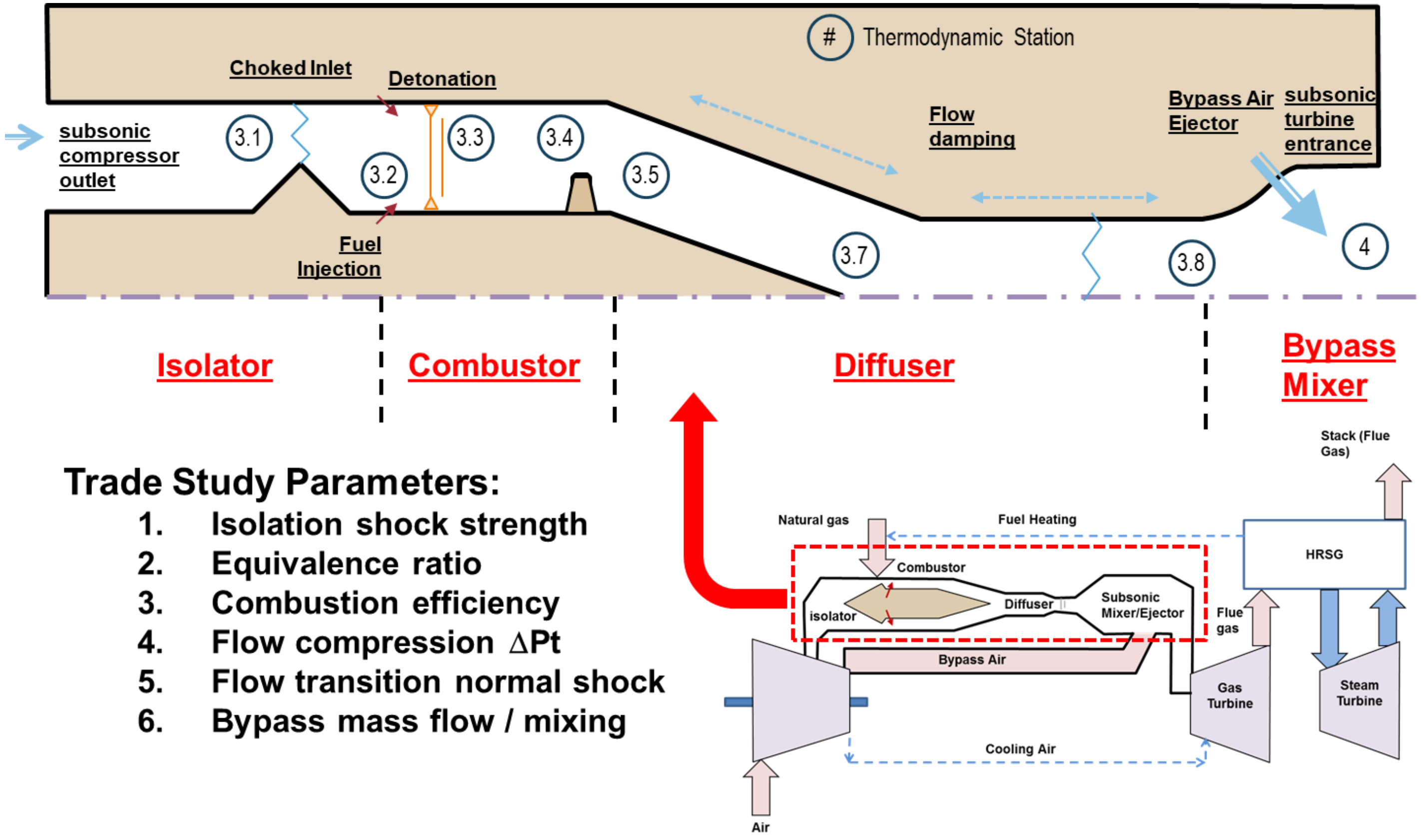
Research Needs

- Low loss fuel/air injection that limits combustor plenum interaction and provides good mixing
- Accurate method for determining pressure gain
- Influence of wave number and speed on performance
- RDE-Turbine integration
- Computational models capable of address component coupling.
- Developing low-cost diagnostics

1. *Wolanski, P., Proc. Comb. Institute, 2013*
2. Nordeen et al, 49th AIAA Aerospace Sciences Meeting, Orlando, FL:, 2011.

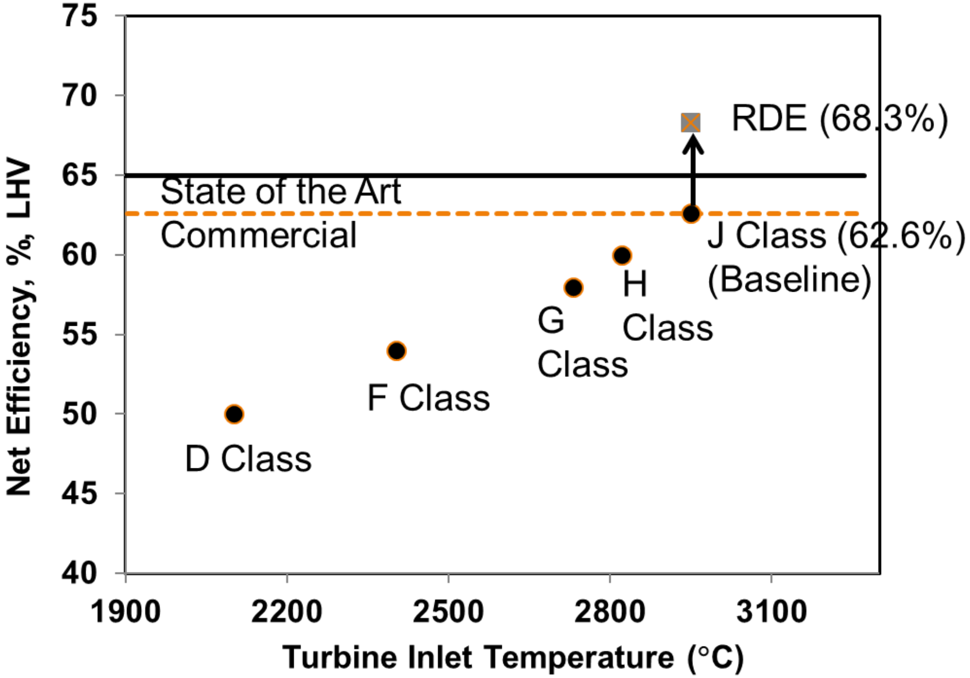
Hybrid RDE-Gas Turbine Cycle

Comparison of NGCC Plant Efficiency with Various Gas Turbines



Trade Study Parameters:

1. Isolation shock strength
2. Equivalence ratio
3. Combustion efficiency
4. Flow compression ΔPt
5. Flow transition normal shock
6. Bypass mass flow / mixing



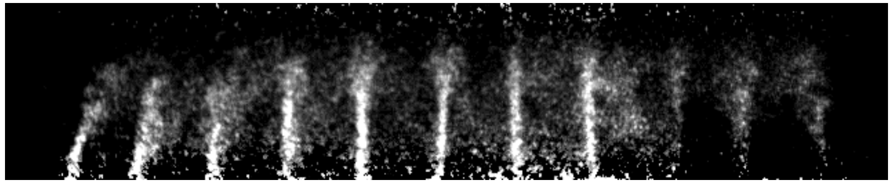
Courtesy: Aerojet Rocketdyne, Inc.

Baseline: MHI's J Class Turbine with 62.6% LHV efficiency (Case 3a, DOE/NETL-341/061013, Walter Shelton, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants)

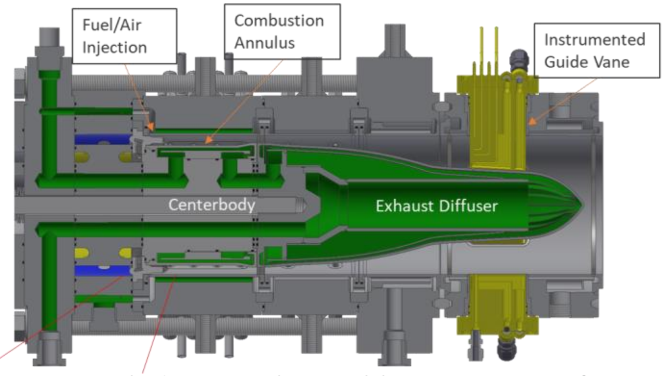
DOE PGC Roadmap

NATIONAL ENERGY TECHNOLOGY LABORATORY

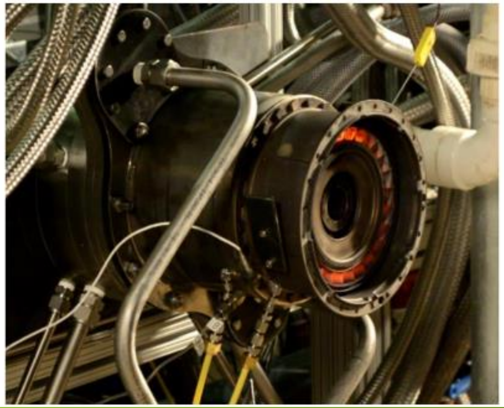
- **Improve fundamental understanding stable continuous wave detonation**
  - Wave directionality, bifurcation, translation speed (~CJ)
  - Det wave influence on operational parameters (i.e fuel injection/mixing)
- **Develop scale laws to better understand the parametric impacts**
  - Flow, pressure temperature, fuel composition (det cell size)
  - Gap width, combustor length, diameter (number of waves)
- **Maximize pressure gain / turbine work availability and reduce emissions**
  - Inlet / exhaust transition configuration (including valves for PDE's)
  - Deflagration, shear layer and downstream shocks
  - CO, NOx emissions
- **Improve modeling capabilities**
  - Simultaneous detonation and deflagration
  - Grid dependences, chemical kinectics
  - Reduced order thermo and chemical models



NETL Characterization of Injector Response using Acetone PLIF



NETL Water-Cooled RDE with variable injection configurations and exhaust treatment.



RDE coupled to T63 Turbine at AFRL
Naples et al., AIAA 2017-1747

EY21 Field Work Proposal

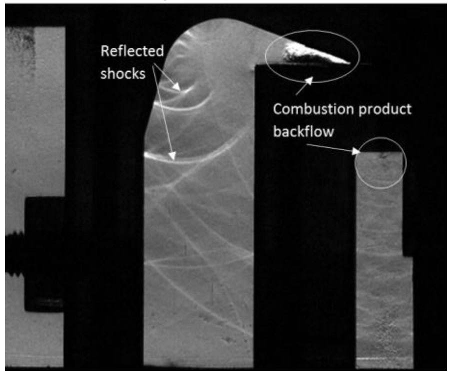
Task 2 – Pressure Gain Combustion - Subtasks

1. **Testing in the NETL Water-Cooled RDE**
   - *The impact of long-duration versus short-duration testing on experimental studies of RDEs.*
   - *Complete installation of axial air injection scheme and exhaust diffuser in the NETL water-cooled RDE in NETL-Morgantown B6.*
   - *Experimental study of optimization of coupled inlet, combustor channel, and diffuser geometry in the high-pressure RDE test rig.*
   - Optimization of exit flow diffuser for improved performance and subsonic turbine integration.
2. **Advanced Diagnostics and Machine Learning**
   - *Incorporation of computer vision system with conventional instrumentation to develop real-time diagnostics.*
   - Accurate quantification of heat flux in the high-pressure, water-cooled RDE.
   - Develop empirical model of dynamic data from RDE using deep learning architecture.
3. **New Modular and Optical RDE**
   - Complete installation of an atmospheric optical RDC at NETL-Morgantown.
4. **High Temperature and Pressure Gas Cell for TDLAS Characterization**
   - *Preliminary design of the high temperature-pressure gas cell in NETL-Pittsburgh for TDLAS development*
5. **Computational Modeling of Pressure Gain Combustion**
   - *Characterization of several advanced inlet designs using a combination of experimental studies and computational modeling.*
   - *Literature review and white paper on use of RDCs for direct power extraction (DPE) cycles.*

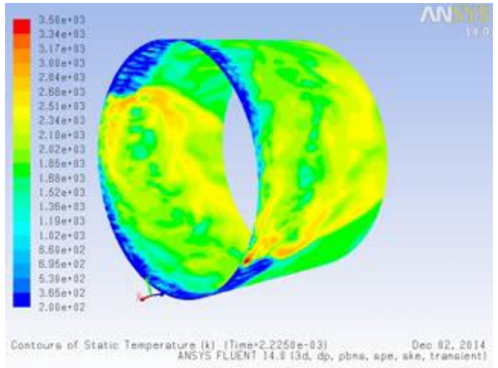
NETL In-House Research Activities

- **RDE Sector / Inlet Test Rig**
  - Rapid evaluation of inlet concepts with correlation to lab-scale combustor.
- **Computational Studies**
  - 1-D injector models coupled to chemical reactor network.
  - CFD
    - Fundamental aspects of detonation
    - Inlet / geometry physics
    - Turbine integration
- **Lab-Scale Experiment**
  - Water-cooled RDE for extended operation
  - Modular RDE with full optical access to the air plenum, combustion channel and exhaust.

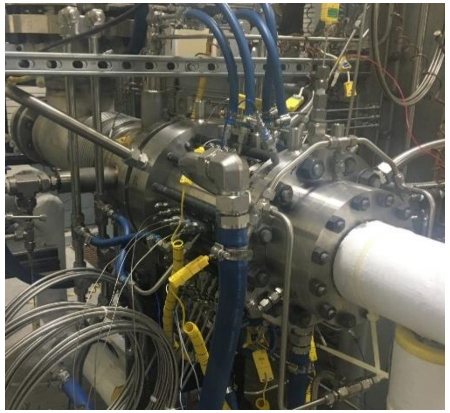
300 slpm air, no He flow



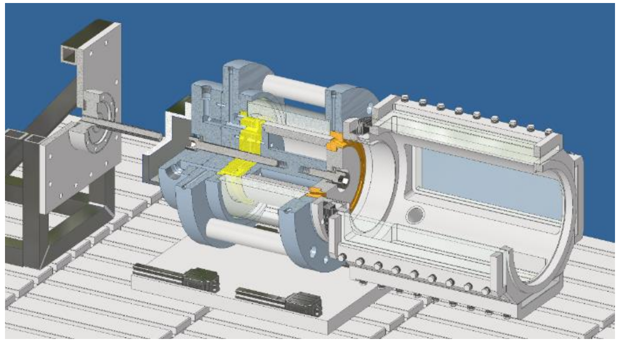
NETL Lab-Scale RDE Inlet Sector Rig



CFD model of RDE with temperature contours (H2/Air)



NETL Water-Cooled, Pressurized RDC

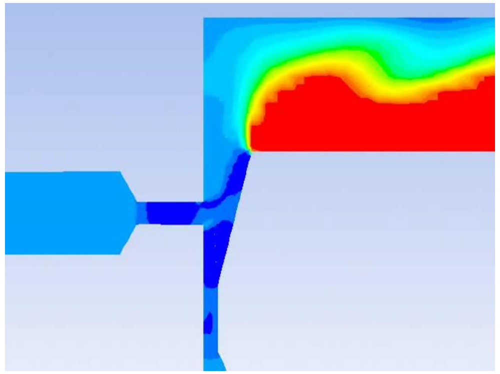


Optical RDE with thrust measurement

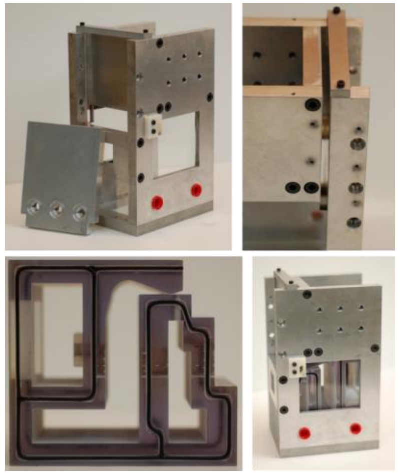
NETL Lab-Scale RDE Injector Study

RDE Injector Experimental Set-up

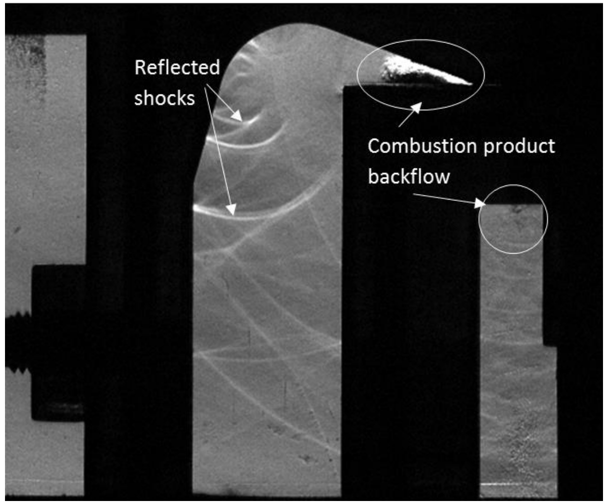
- High pressure region behind detonation wave exceeds inlet supply pressure, interrupting reactant flows or even causing backflow within inlet plenums/injectors
- Inlet flows must recover fast enough to supply fresh reactants to the combustor before subsequent detonation wave arrives (and at correct/consistent stoichiometry, mixedness)



- **RDE Injector Experimental Set-up**
  - RDE "slice" extruded 7.5cm @ 1:1 scale (full RDE with 47cm circumference)
  - Structure created to hold modular, interchangeable geometries
    - Moderate temperatures enables use of 3D printed plastic parts
  - Semi-cold flow approach:
    - Discrete pressure pulses introduced to linear channel ("combustion annulus") via separate H_2/air pre-detonator tube
    - Inert gases within inlet paths (He/air)



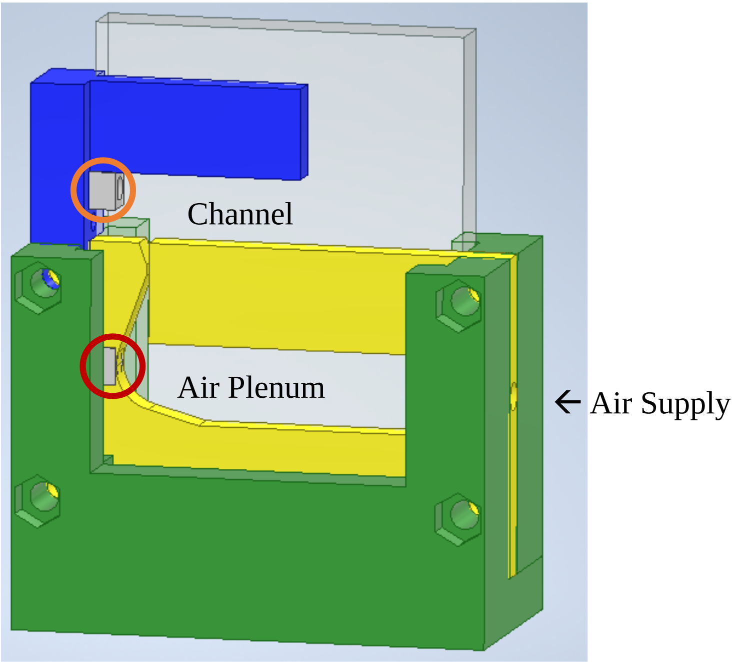
300 slpm air, no He flow



NETL Lab-Scale Inlet Rig Diagnostics

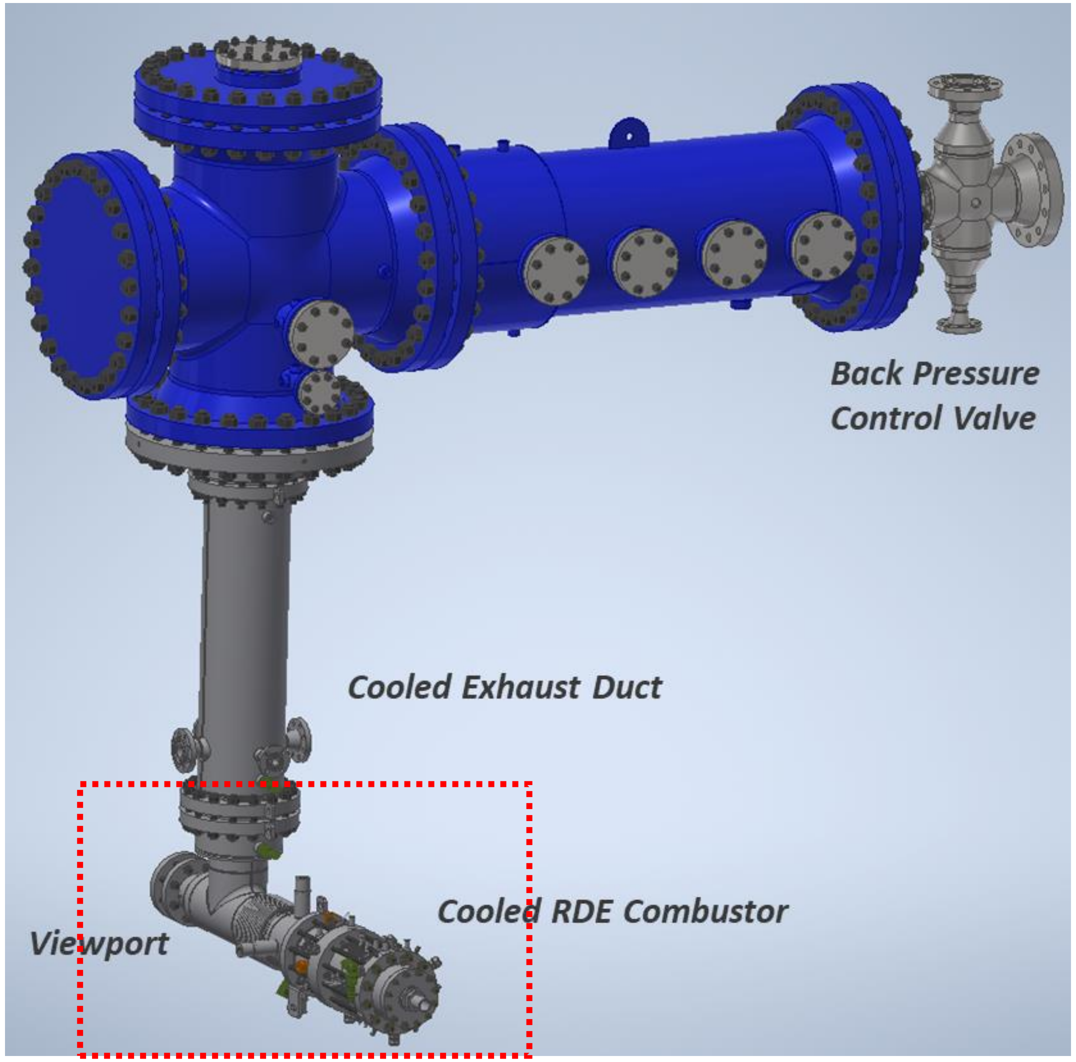
MLEF – Summer Research Project

- **RDE inlet sector rig was used to study four inlet concepts to evaluate flow recovery (interruption / recovery time) and pressure drop**
  - AFRL radial air inlet - gap width of 0.22in (reference)
  - AFRL radial air inlet – gap width of 0.44 in
  - AFRL radial air inlet – gap width of 0.66 in
  - The fourth design is currently unpublished and will not be disclosed in this paper, but its results and analysis will be shown. (Aerostrut Pgain Inlet)



NETL Water-Cooled, High Pressure RDE

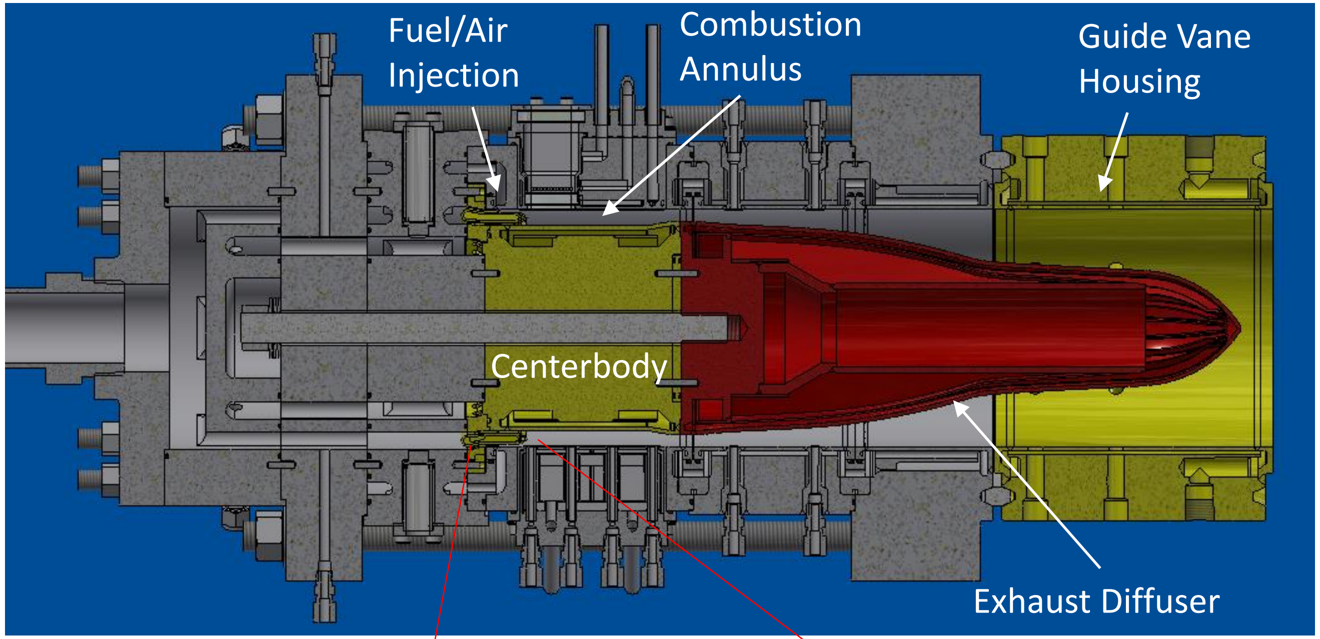
NETL water-cooled RDC without instrumentation package.

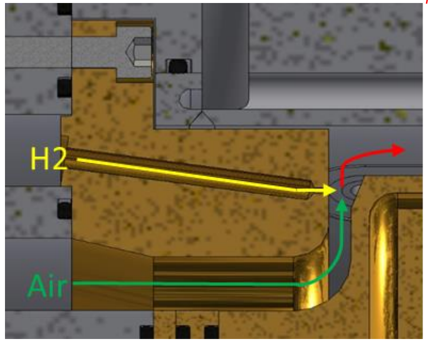


NETL Water-Cooled, High Pressure RDE

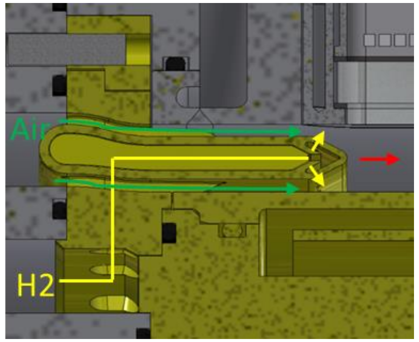
Design Basics and Operational Envelope

- **Modular Geometry**
  - 152.4 mm diameter, 7.62 mm combustion annulus, 152.4 mm length
  - Axial and Radial air injection
  - Accommodate changes to fuel/air routing, injector, centerbody, outerbody, exhaust, instrumentation ports
- **Operating Conditions**
  - Cooling: water @ 150 lpm, 11 Bar
  - Max. shell T. P ≈ 477K, 16 Bar
  - air flow rate @ 600 K – 1 kg/sec
- **Test Conditions (H2/Air – H2/NG/Air)**
  - Tair = 340-475 K, Pcomb = 0-1.5 Bar, mdot = 0.3 – 0.65 kg/sec.
- **Instrumentation (1 MHz sampling)**
  - Dynamic Pressure, OH Chemi, Combustion Ionization
  - High Speed Imaging (60 kHz)





Radial Air Injection

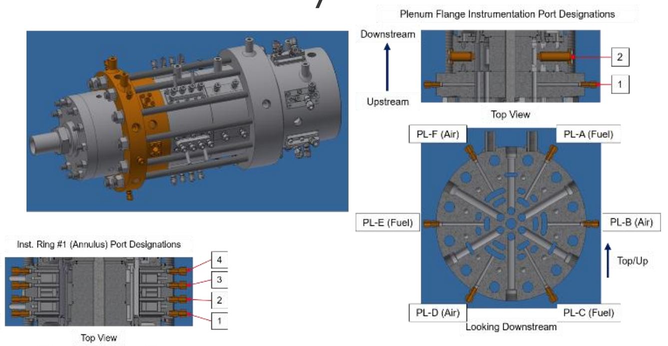


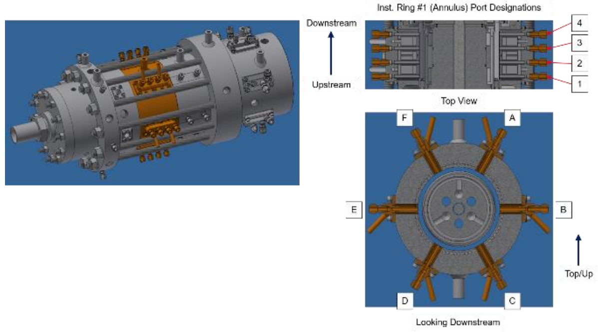
Axial Air Injection

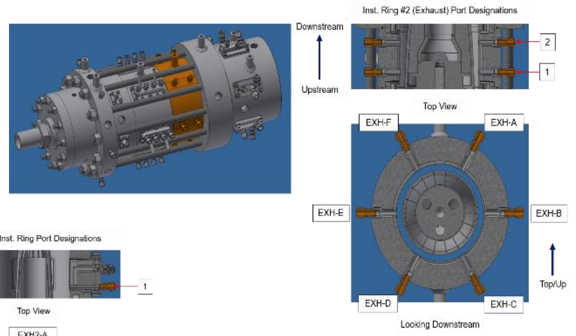
Air Injector Gap Size (mm)
0.56
0.79
1.75
2.8

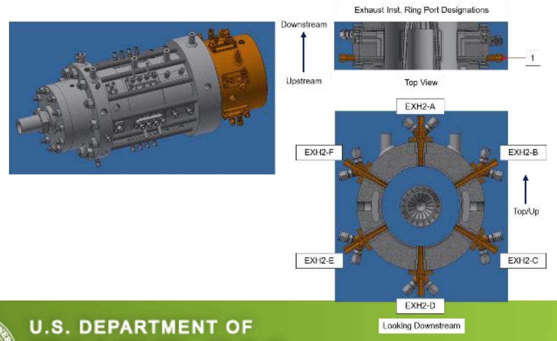
NETL Water-Cooled, High Pressure RDE

Instrumentation and Geometry

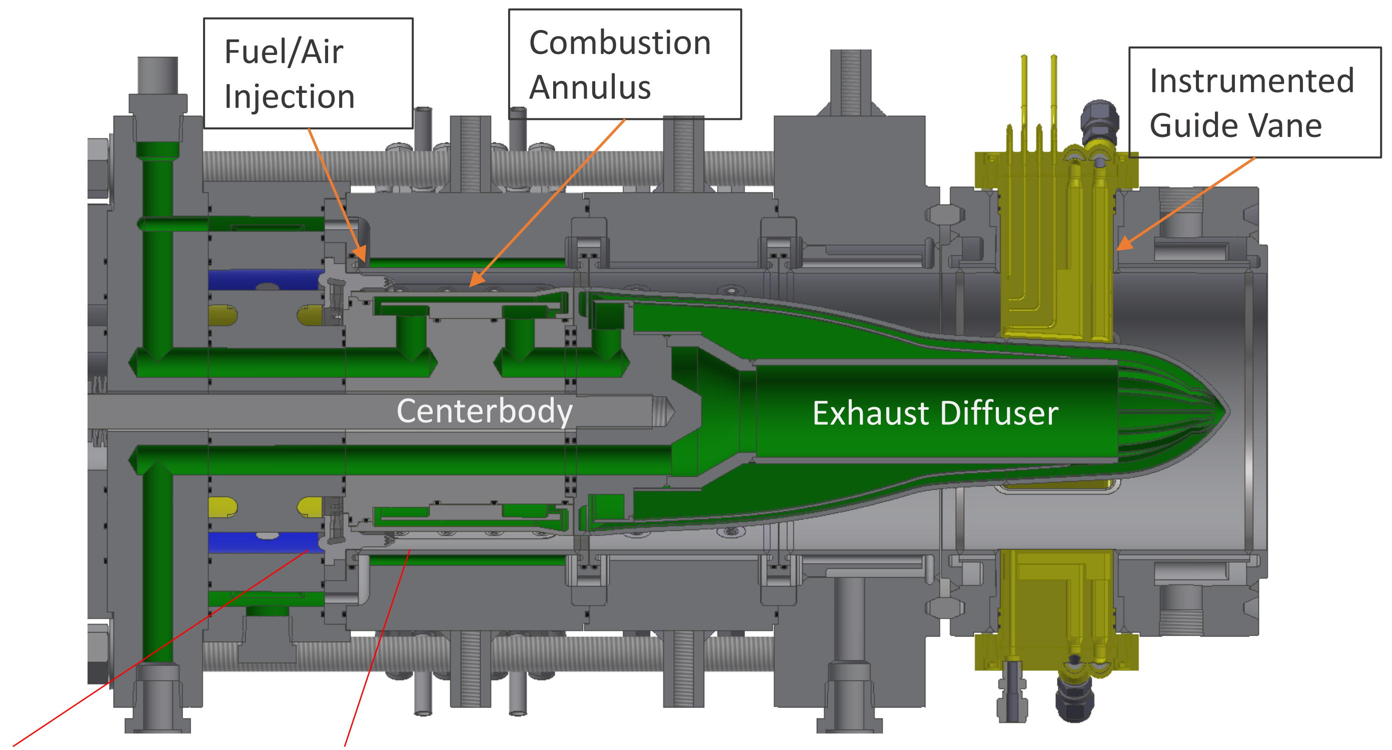


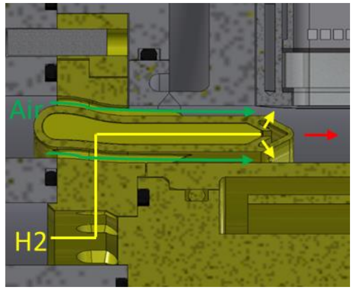




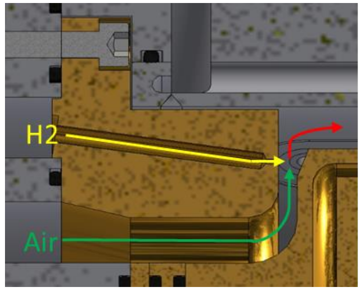


A3.1/A3.2	A8/A3.2
0.36	0.76





Axial Air Injection



Radial Air Injection

Air Injector Gap Size (mm)	A3.1/A3.2	A8/A3.2
0.56	0.06	1.0
0.79	0.09	
1.75	0.2	
2.8	0.32	

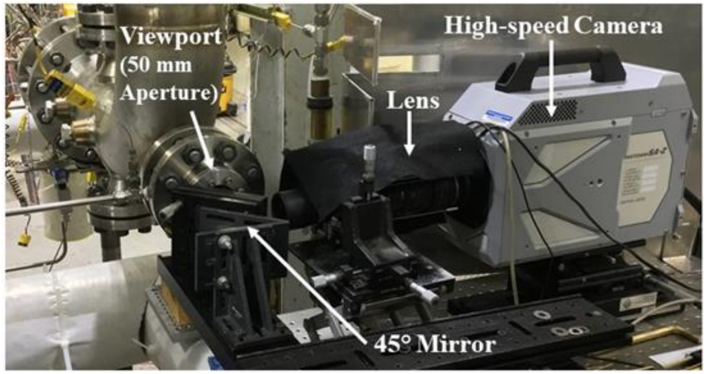
NETL Water-Cooled, High Pressure RDE

Additional Instrumentation and Optical Access

NATIONAL ENERGY TECHNOLOGY LABORATORY

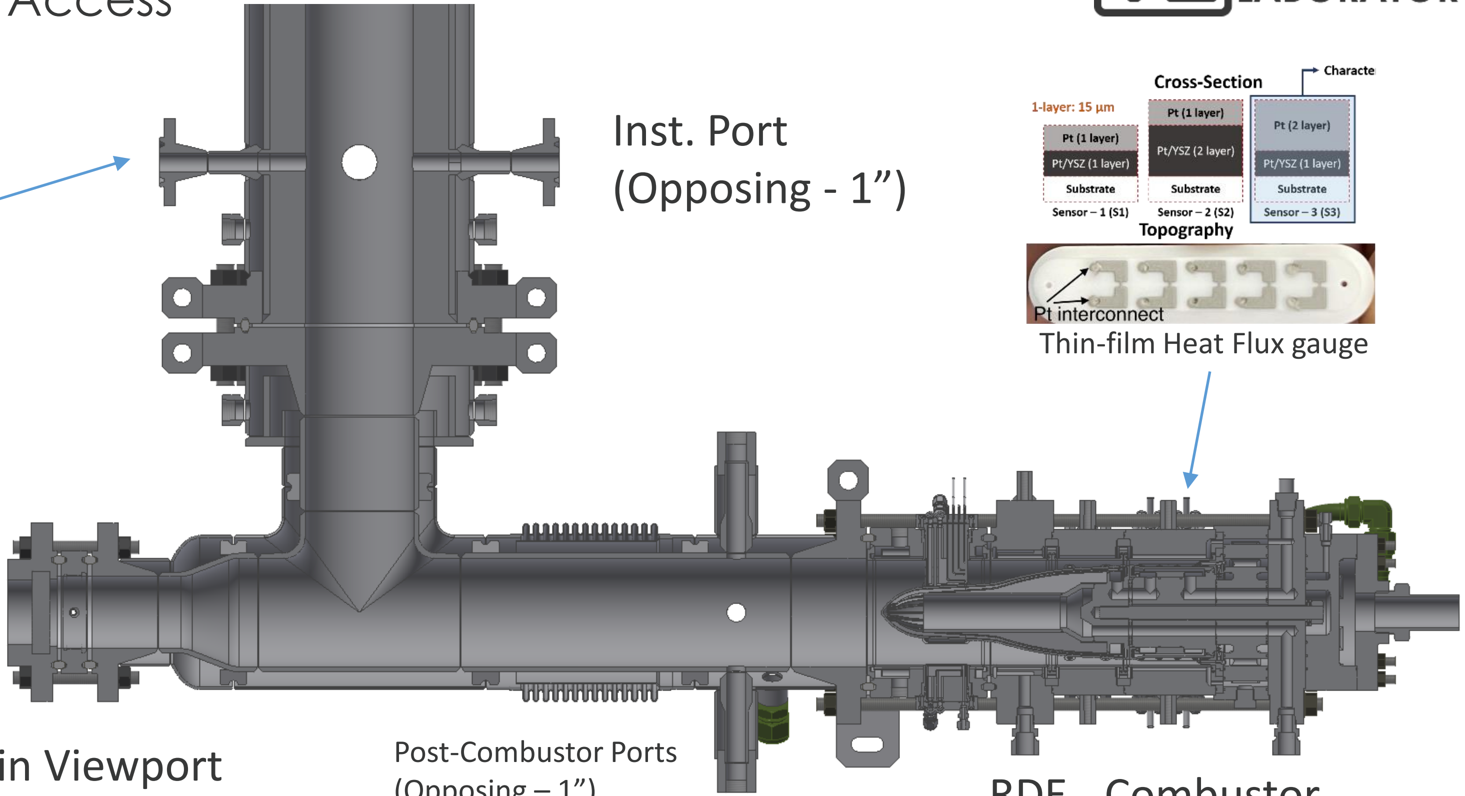
Gaseous Emissions Sampling
- NOx
- O2

Sampling is conducted in real-time during long duration (20-30 sec) tests.



- High speed images (typically ~ 60kfps, capability-1Mfps)
- Computer vision / machine learning

Inst. Port (Opposing - 1”)

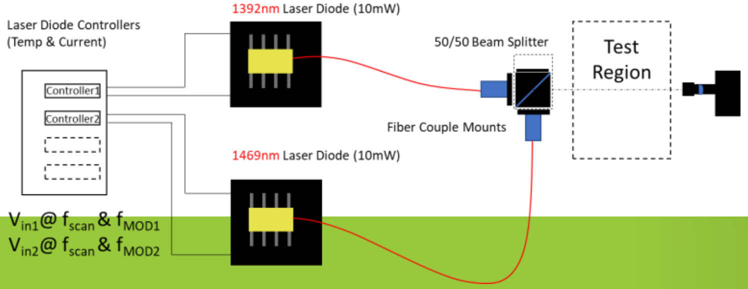


4in Viewport

Post-Combustor Ports (Opposing – 1”)

RDE - Combustor

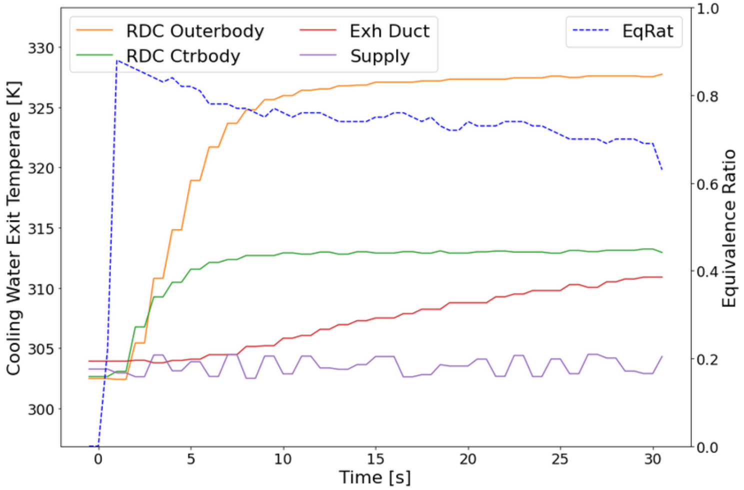
Thin-film Heat Flux gauge

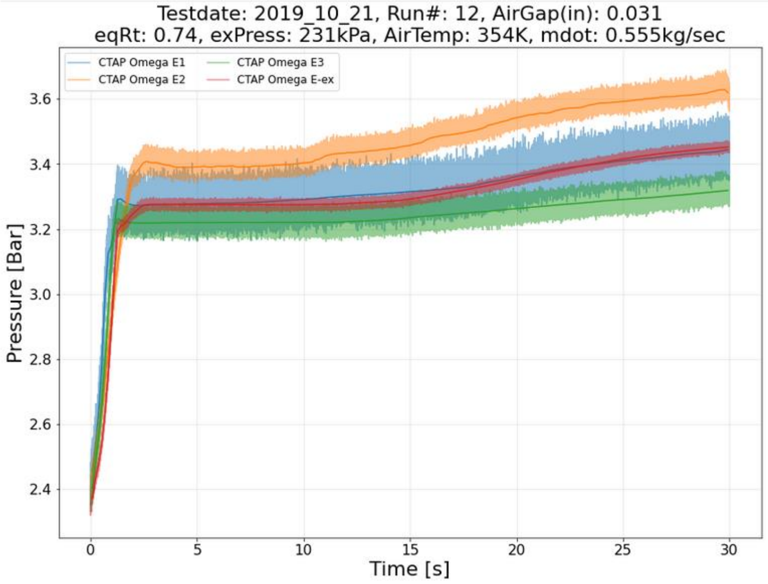


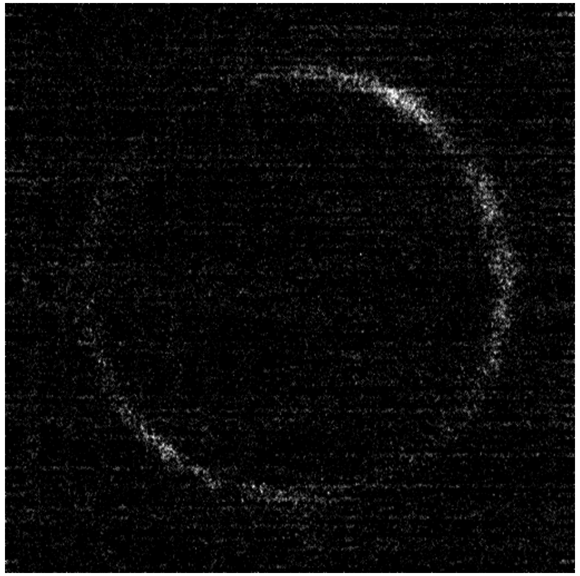
Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Real-time gas temperature
- Water concentration

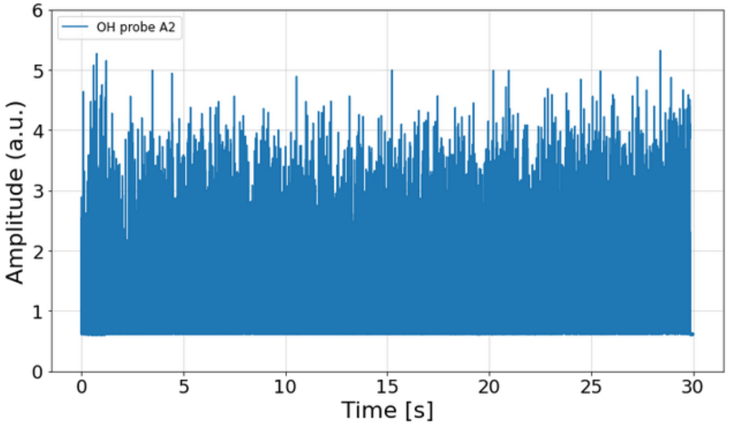
NETL Lab Scale RDC – H2/Air

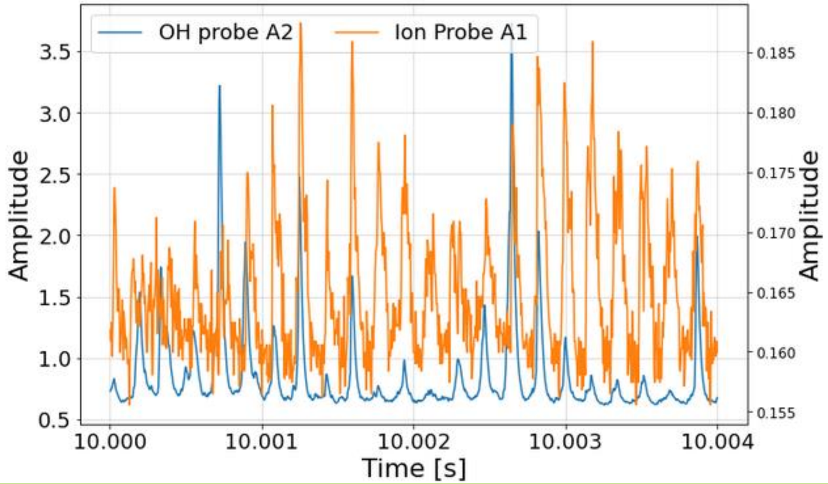
phi=0.74, Total mass flow ~ 0.555kg/sec P = 2.3 Bar, Tair = 354 K

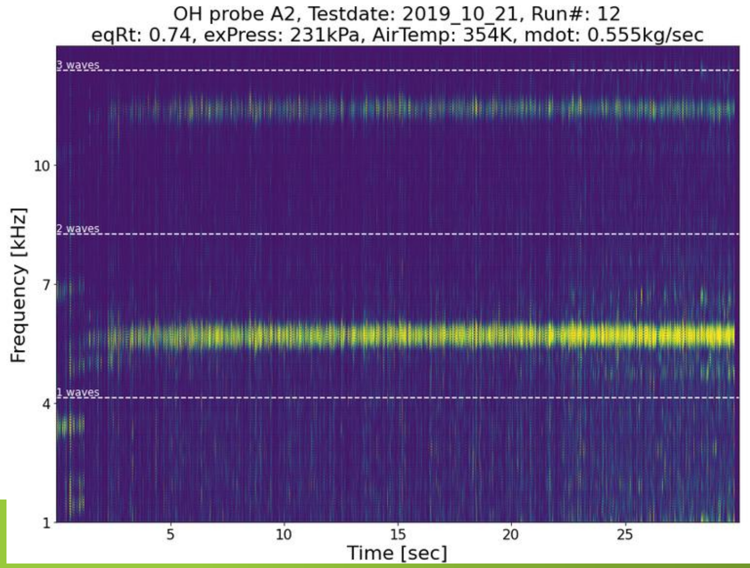






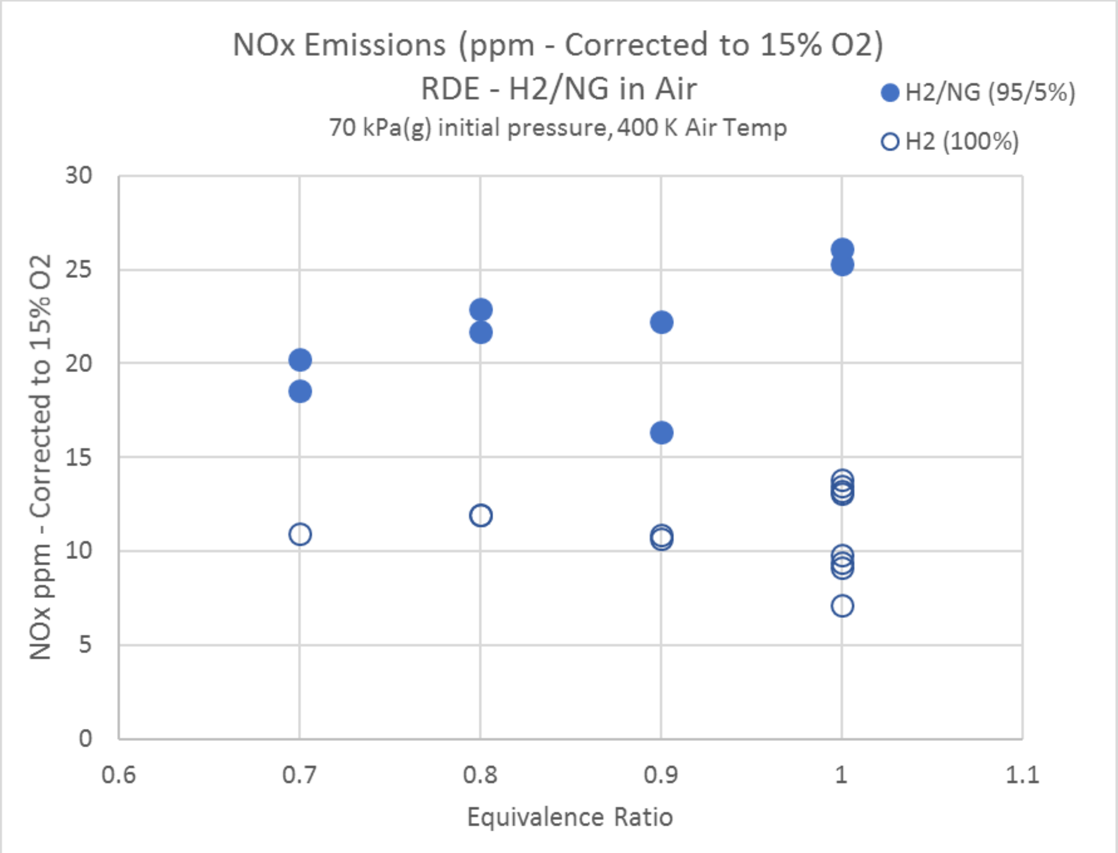




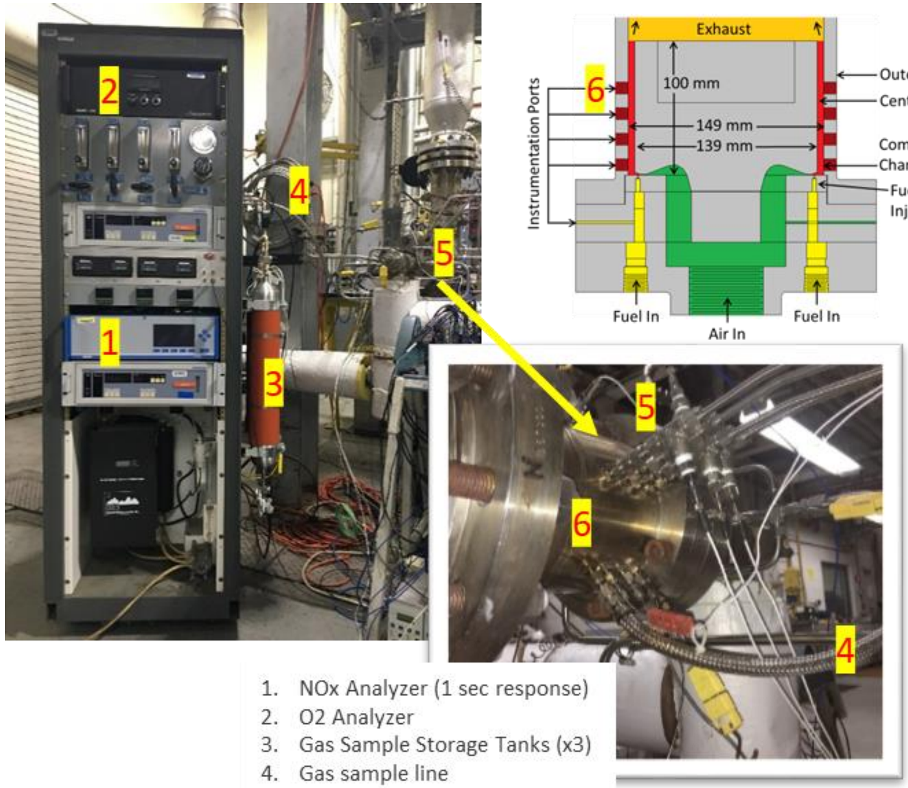


NOx Emission (ppm) – NETL RDE on H2-Air

NOx Emissions (ppm) – Corrected to 15% O2



$$Oxygen\ referenced\ conc. = Measured\ conc.x\ \frac{20.9 - Oxygen\ Reference\ value\ (\%)}{20.9 - measured\ oxygen\ (\%)}$$



1. NOx Analyzer (1 sec response)
2. O2 Analyzer
3. Gas Sample Storage Tanks (x3)
4. Gas sample line
5. RDE
6. Gas sample port

Results shown are from NETL uncooled RDE

Ferguson, Donald H., Bridget O'Meara, Arnab Roy, and Kristyn Johnson. "Experimental Measurements of NOx Emissions in a Rotating Detonation Engine.", AIAA2020-0204, *AIAA Scitech 2020 Forum,* Orlando, FL, January 2020, https://doi.org/10.2514/6.2020-0204.

Real-time sensor for RDE Mode and Wave Speed

Machine Vision – Deep Learning Application

- Train convolutional neural network (CNN) on large pool of images with multiple modes
- Utilize CNN to predict wave mode (wave number and direction of rotation) from a single image
- Machine vision approach is being combined with conventional instrumentation (p’) to add instantaneous wave speed.

NETL images

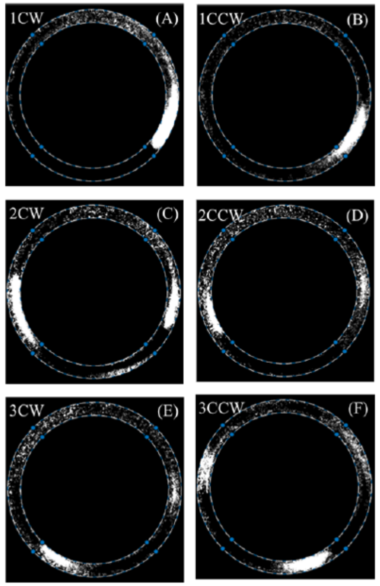
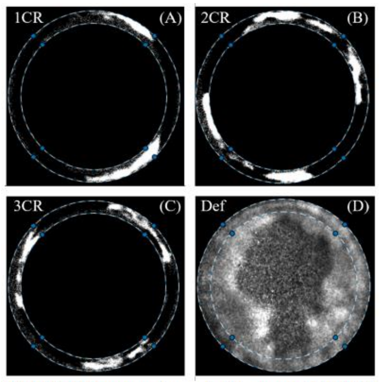


FIGURE 6: Downstream images of modes (A) 1CW, (B) 1CCW, (C) 2CW, (D) 2CCW, (E) 3CW and (F) 3CCW



Purdue images

FIGURE 15: Downstream images of additional modes (A) 1CR, (B) 2CR, (C) 3CR, and (D) Def

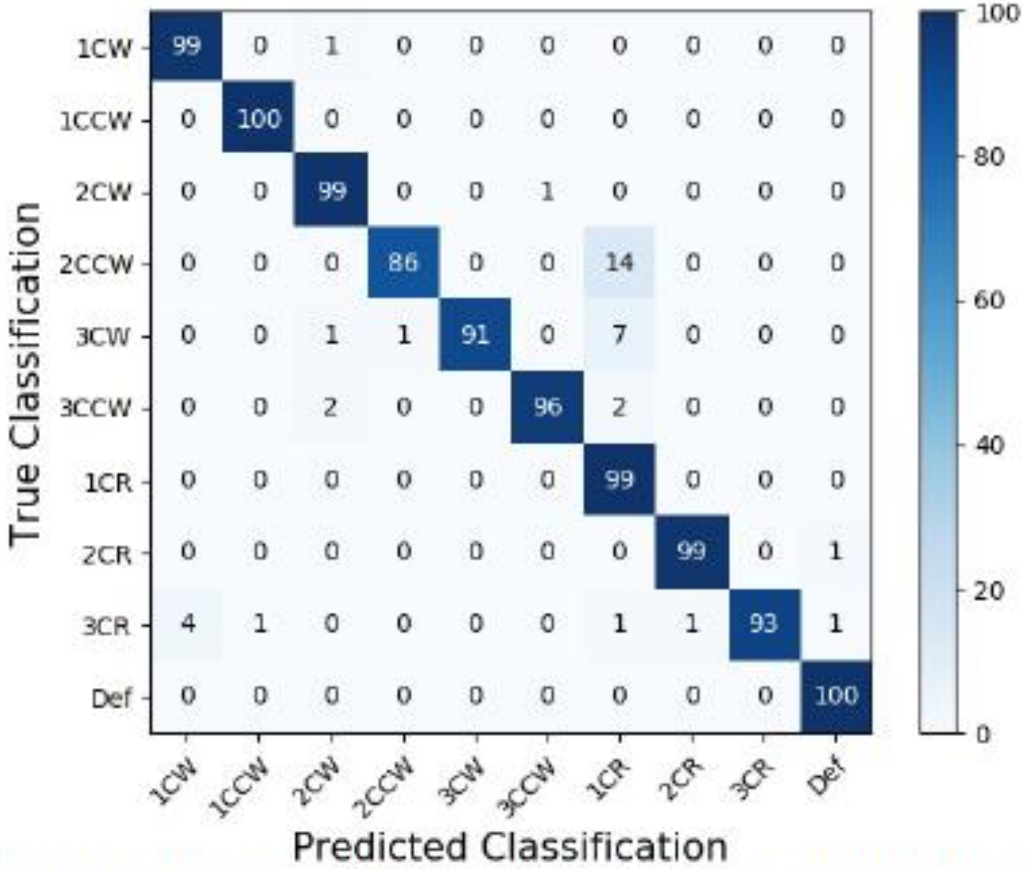


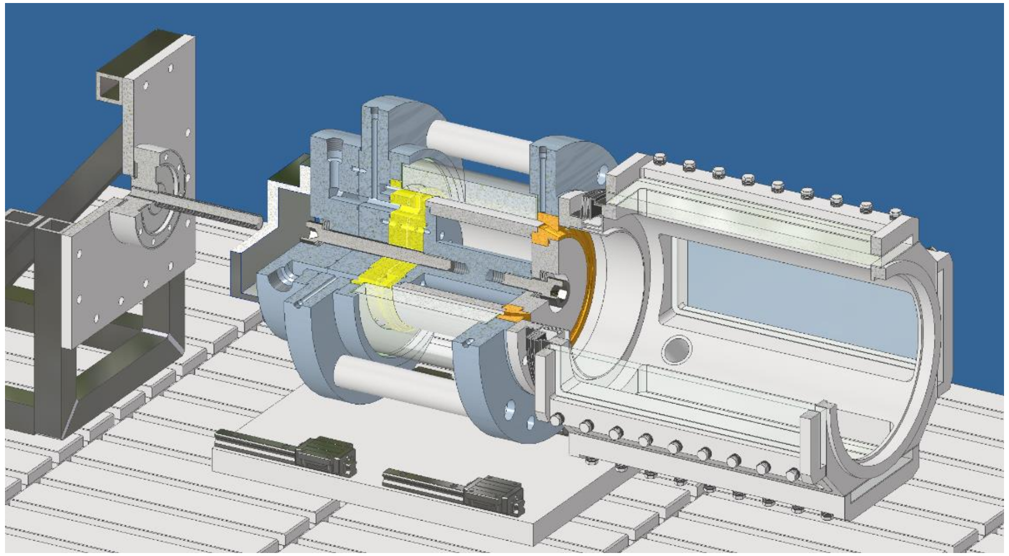
FIGURE 16: Normalized confusion matrix of extended dataset containing counter-rotating waves and deflagrative behaviors

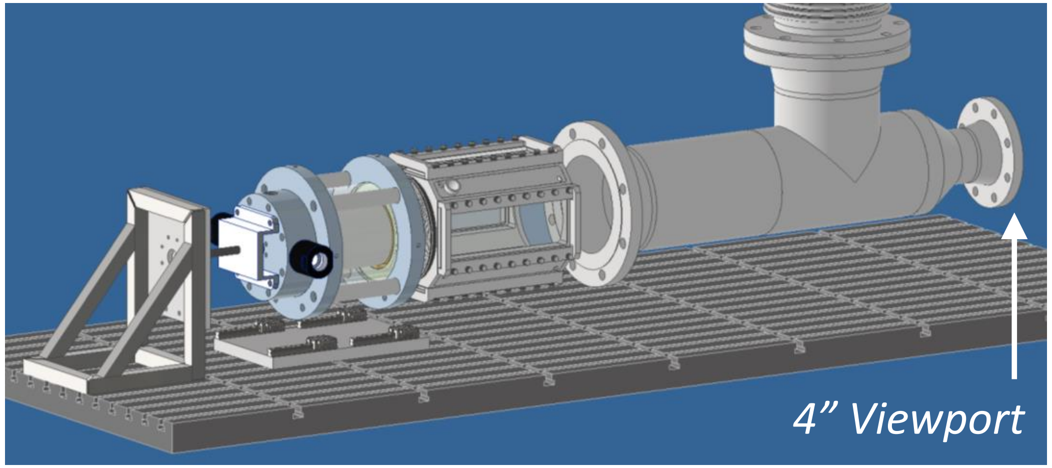
Johnson, Kristyn B, Donald H Ferguson, Robert S Tempke, and Andrew C Nix. “Application of a Convolutional Neural Network for Wave Mode Identification in a Rotating Detonation Combustor Using High-Speed Imaging.”, GT2020-15676 In ASME 2020 Turbo Expo. Virtual, Online: ASME Turbo Expo, 2020.

NETL Optical and Modular RDE (mRDE)

Combustor-Plenum interactions and Combustion Stability

- **Optical Access**
  - Air plenum, combustor and exhaust
- **Thrust measurement with ducted exhaust**
  - Provides performance metric through Equivalent Available Pressure (EAP)
  - Working to develop performance metric for turbomachinery
- **Testing conditions**
  - Hydrogen-Air (sonic nozzle flow measurement)
  - Short duration (~ 3 sec)
  - m_{air} = 0-0.61 kg/sec
- **Full diagnostic compliment**
  - OH Chemi, TDLAS, high speed PLIF/PIV, P, T and chemi ionization (ion probe)

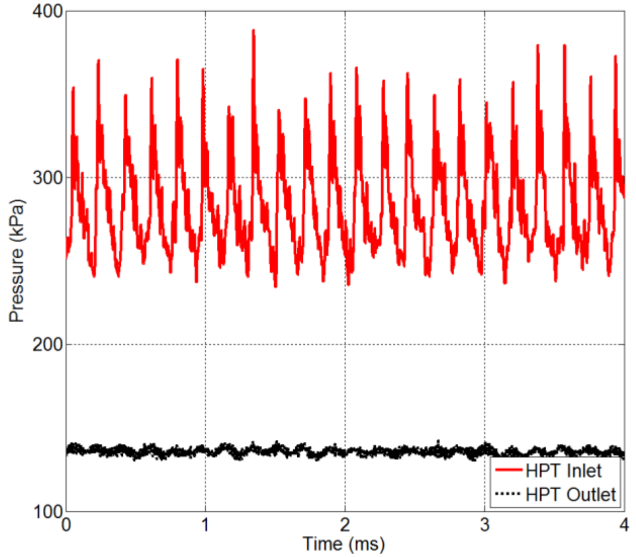




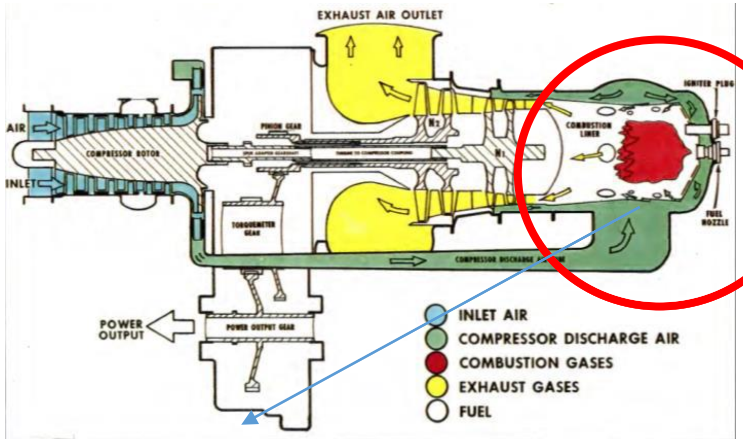
Impact of Unsteadiness on Turbine Efficiency

RDE-Turbine Integration

- **Turbine / Engine Integration**
  - AFRL test of T63 gas turbine stock combustor replaced with RDE

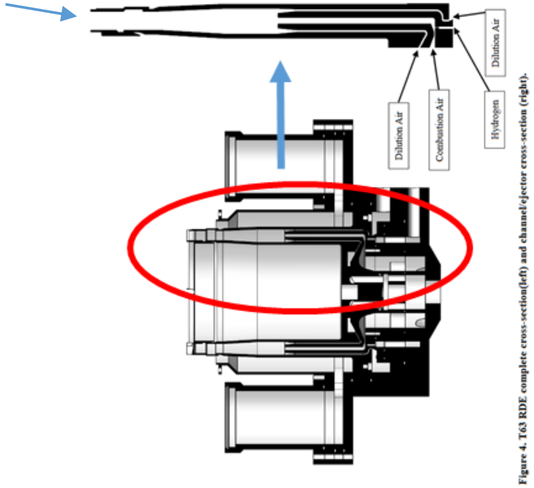


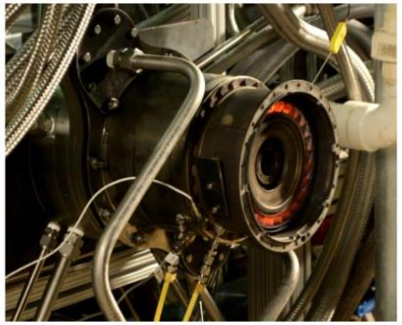
Dynamic pressure measurement upstream and downstream of high pressure turbine for RDC test.



T63 Gas Turbine reverse flow design with aft-engine combustor replaced with RDE.

Turbine Interface



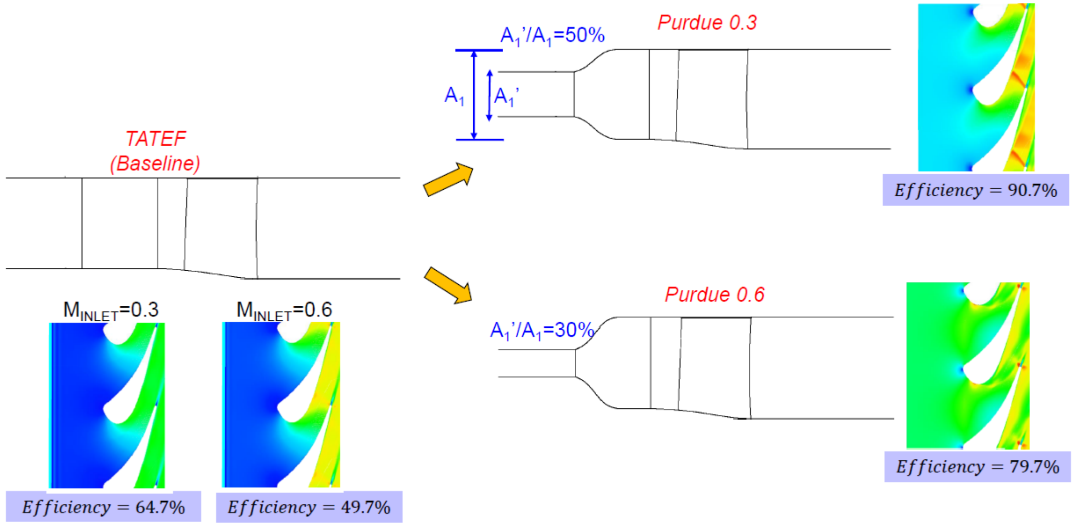


Naples et al., “Rotating Detonation Engine Implementation into an Open-Loop T63 Gas Turbine Engine”, AIAA SciTech 2017

Analysis of Turbine Exposed to Inlet Fluctuations

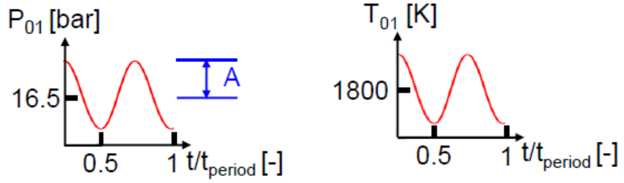
RDE-Turbine Integration (Purdue University)

Analysis of turbine stage: steady flow

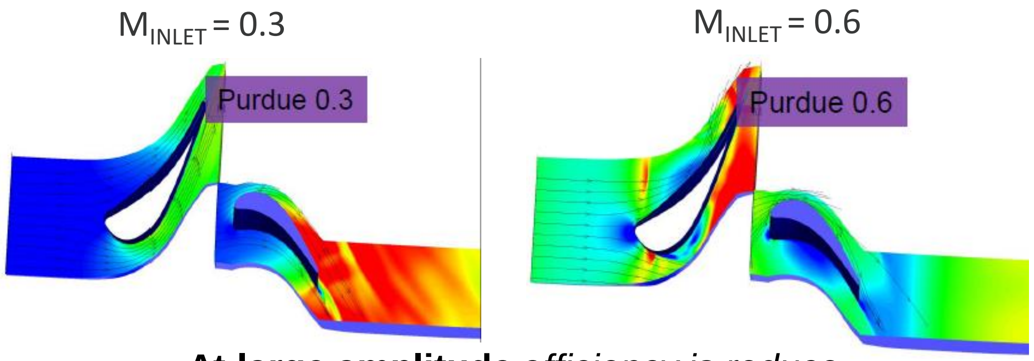


Turbine stage exposed to inlet fluctuations

Boundary conditions



- Imposed at several frequencies and amplitudes

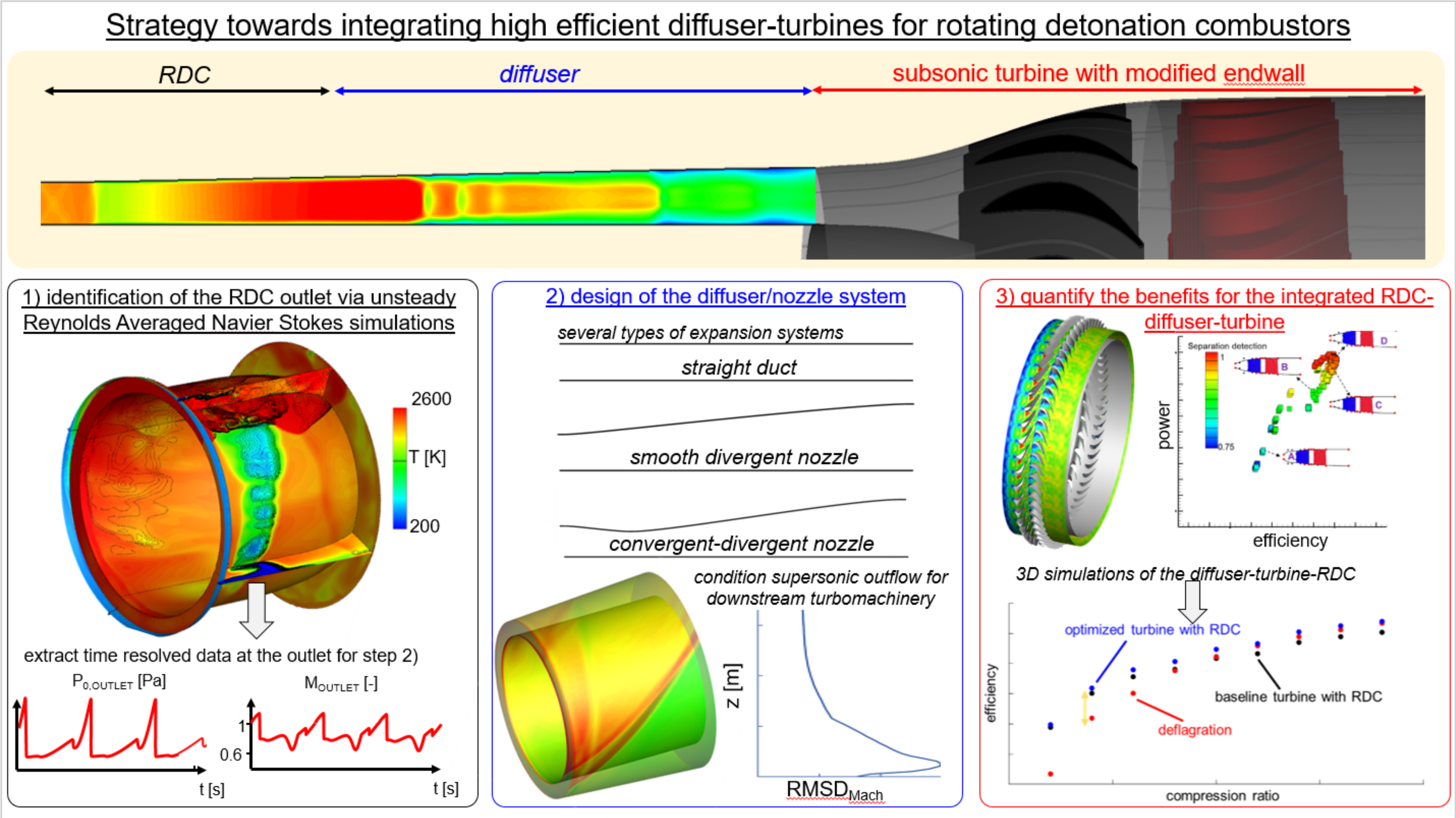


At large amplitude *efficiency is reduce*

75.4% from 90.7% 71.7% from 79.7%

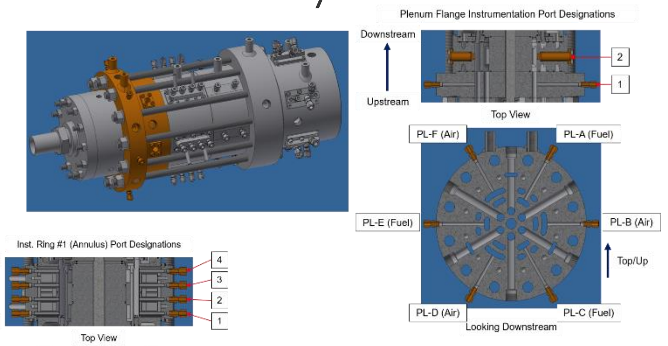
Turbine Integration – High efficiency Diffuser

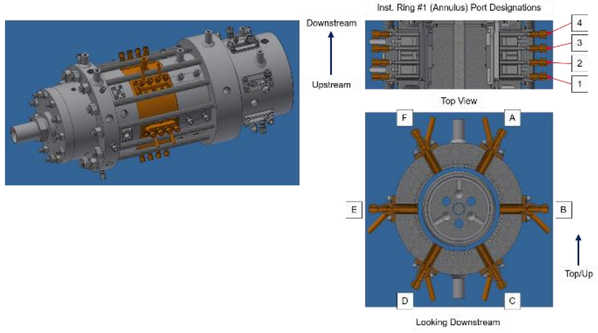
RDE-Turbine Integration (Purdue University)

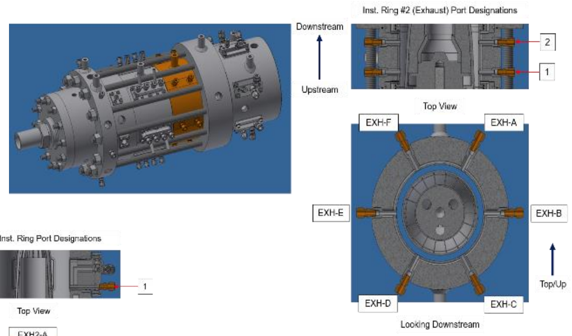


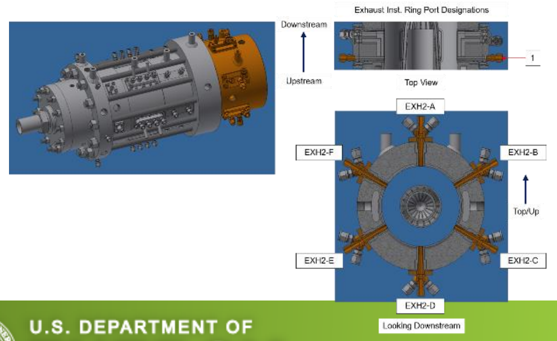
NETL Water-Cooled, High Pressure RDE

Instrumentation and Geometry

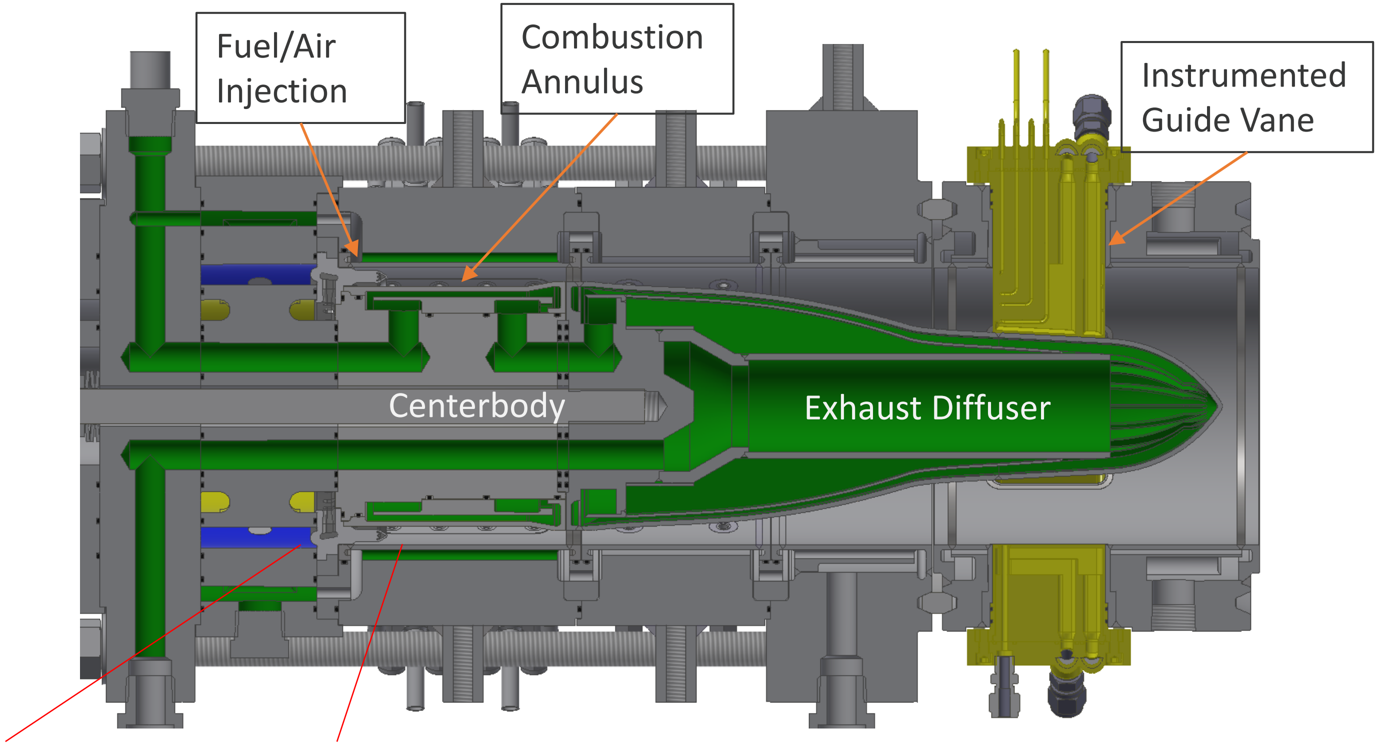


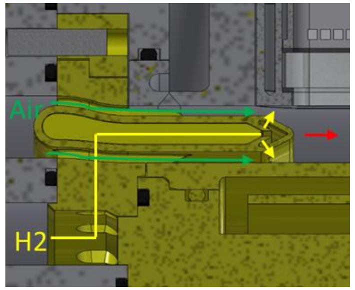




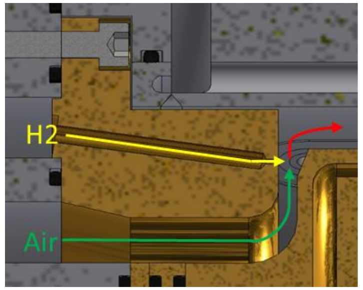


A3.1/A3.2	A8/A3.2
0.36	0.76





Axial Air Injection



Radial Air Injection

Air Injector Gap Size (mm)	A3.1/A3.2	A8/A3.2
0.56	0.06	1.0
0.79	0.09	
1.75	0.2	
2.8	0.32	

Summary

- **Rotating Detonation Combustion / Engines has the potential for producing significant gains in cycle efficiency through near constant volume combustion.**
  - Research has focused on Hydrogen-Air combustion
- **Challenges exist**
  - Reducing the pressure drop across the inlet, maintaining combustion stability, understanding performance characteristics, compressor / turbine integration
- **DOE continues to provide support for PGC and collaborates with other funding agencies when appropriate.**
- **Consideration for Pressure Gain Combustion in new hybrid cycles.**


NATIONAL ENERGY TECHNOLOGY LABORATORY
Thank You.
Questions??
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