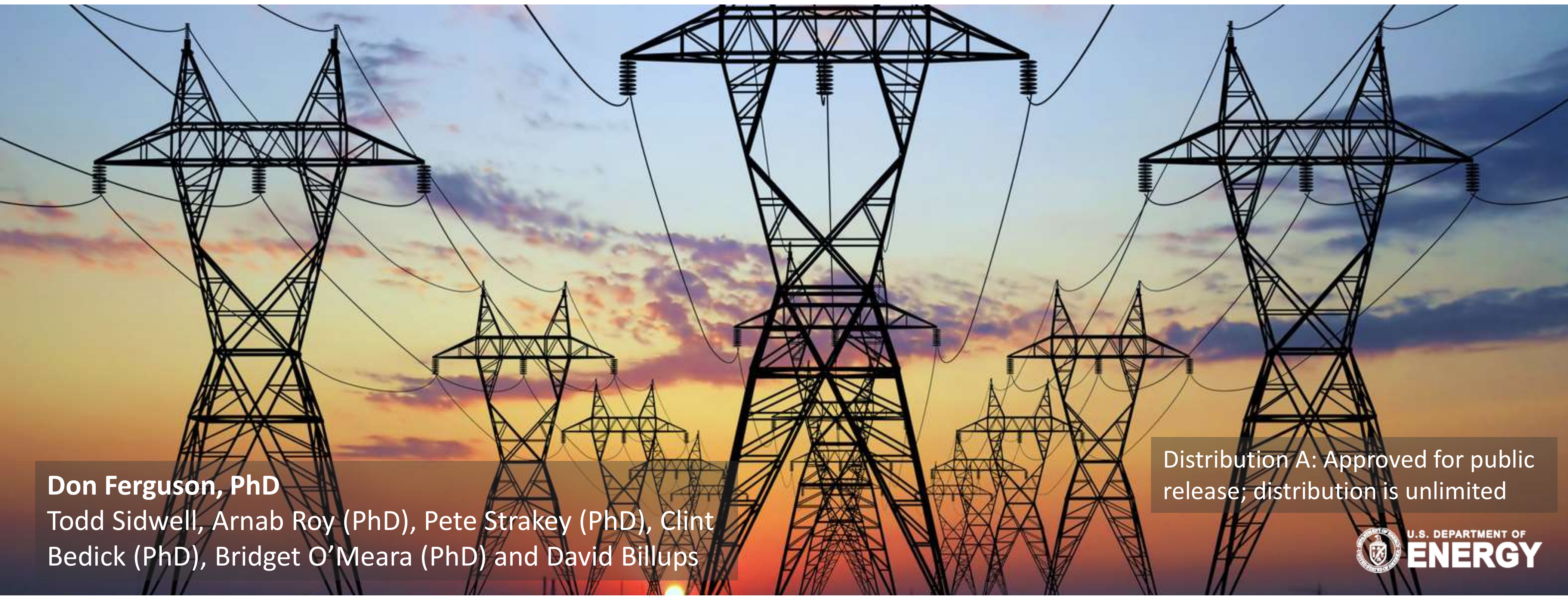
Overview of Pressure Gain Combustion Studies at NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

University Turbine Systems Research Project Review Meeting

Virginia Tech – Blacksburg, VA, November 1-3, 2016

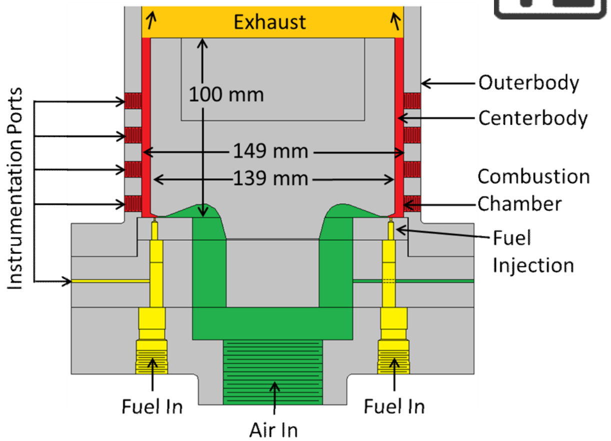


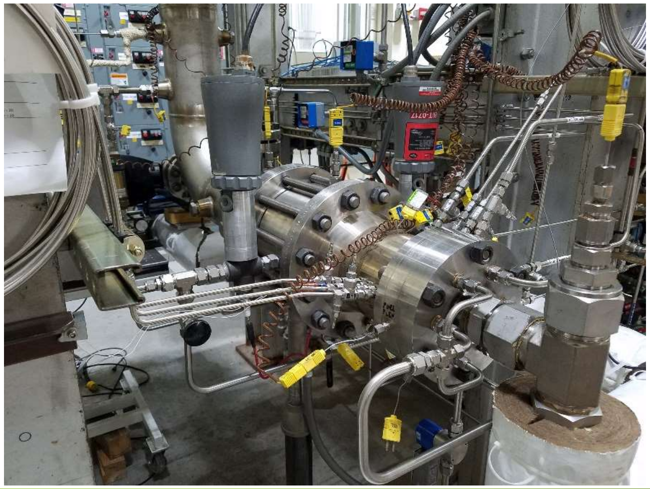
Don Ferguson, PhD
Todd Sidwell, Arnab Roy (PhD), Pete Strakey (PhD), Clint Bedick (PhD), Bridget O'Meara (PhD) and David Billups

U.S. DEPARTMENT OF ENERGY

Overview

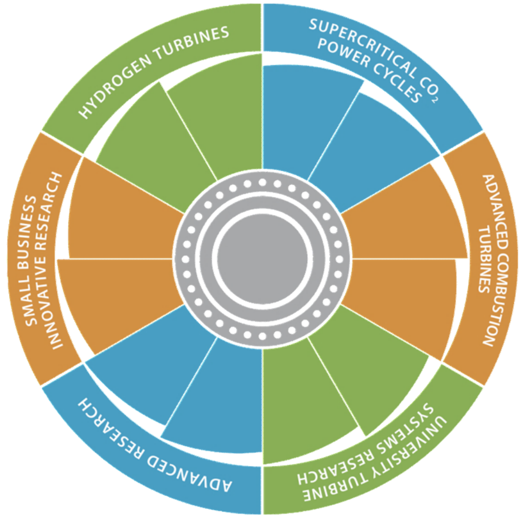
- DOE Program Goals
- CVC Advantages and RDE Challenges
- Lab-Scale and Bench Scale Sector Rig
- Summary





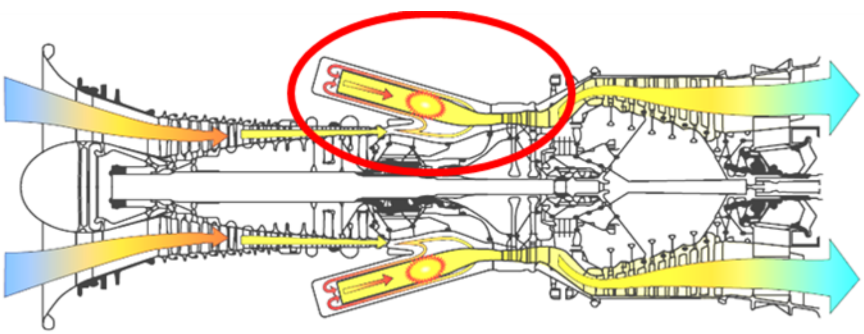
Advanced Gas Turbines Program Goals

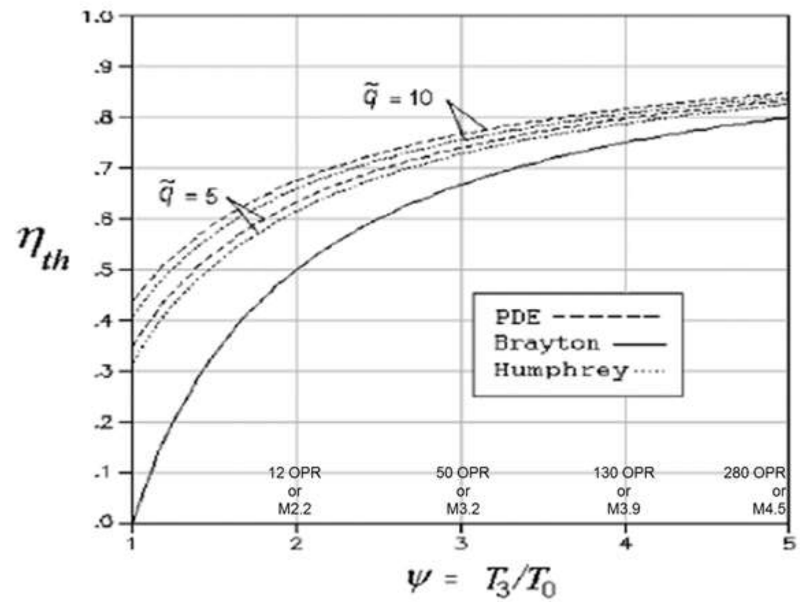
- **Advanced combined cycle turbine**
  - Applicable to natural gas and H2
  - T3 of 3,100º F (~1900 K)
  - Adv. components: pressure gain combustion, advanced transition, air foils w/ decoupled thermal & mechanical stresses
  - Delivers another $20/T reduction in CO2 capture cost
  - NG CC (LHV) efficiency approaching 65%



Constant Pressure vs Constant Volume Combustion

- **Conventional gas turbines rely on Constant Pressure Combustion (Brayton cycle)**
  - Deflagration-slow combustion
  - High temperature with constant pressure.
- **Constant Volume Combustion (PDE, Humphrey Cycle)**
  - Detonation-fast combustion
  - High temperature with ***INCREASED*** pressure produces more available work

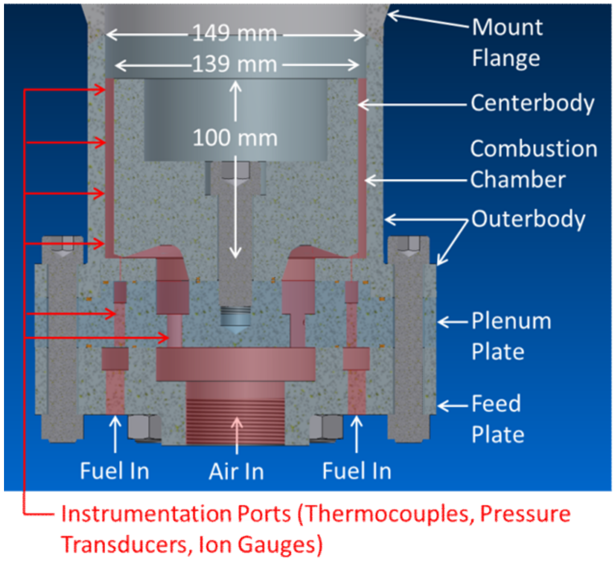




Continuous detonation produces more available work from the same heat input (compared to a conventional combustion system) resulting in a system with greater efficiency.

NETL PGC Research Focus

- **Low loss inlet / injector**
  - Reduce impact from shockwave and backflow due to detonation.
  - Design driven by computational modelling and bench scale experiments



Air Force Research Laboratory 5.6" RDE modified for NETL High Pressure Combustion Lab

- **Combustion Efficiency**
  - Inlet/Injector must rapidly mix fuel-air to ensure complete combustion and maintain low emissions (NOx, CO)

- **Transition quasi-steady exhaust flow to maintain turbine efficiency**
  - Conventional turbines designed for steady flow may require "transitioning" the quasi-steady flow from the RDE.

NETL PGC Computational / Experimental

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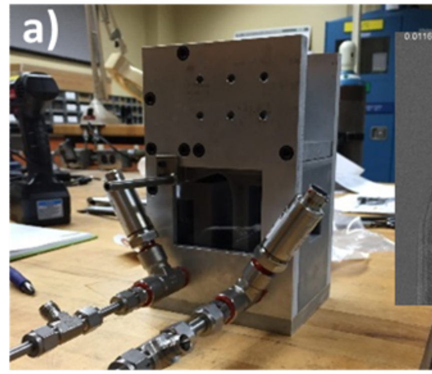
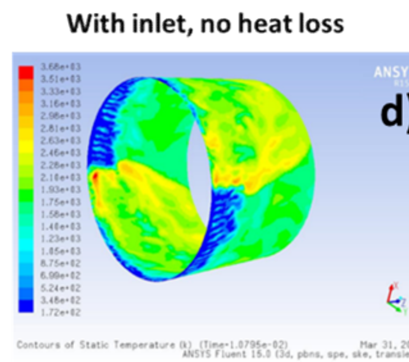
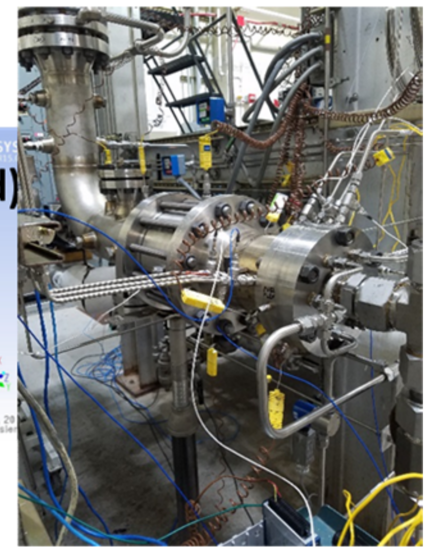
- **Fundamental studies of detonation/shock waves and low loss injectors.** (a-single injector rig, b-shock wave in, (not shown)-linear RDE analog)
- **Lab-scale RDE with variable back-pressure, fuel composition and preheat.** (c-RDE installed in high pressure combustion test facility)
- **Computational studies utilizing experimental studies to anchor code and drive design decisions.** (d-non-premixed, two wave simulated RDE)

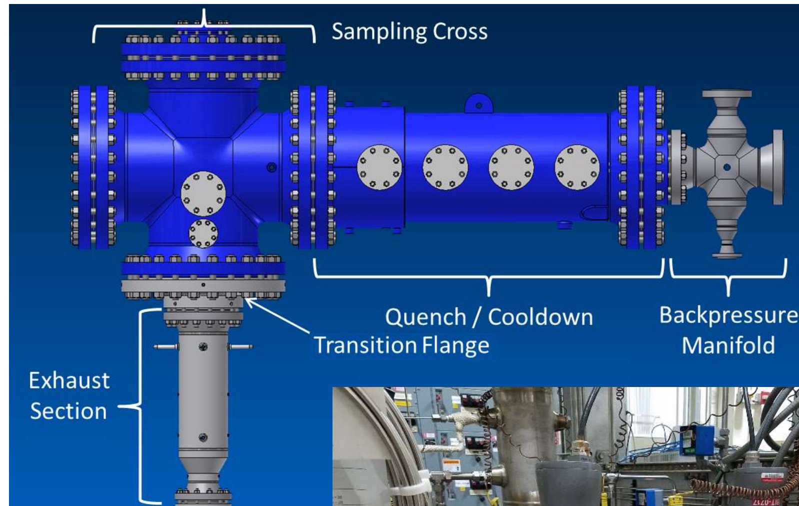


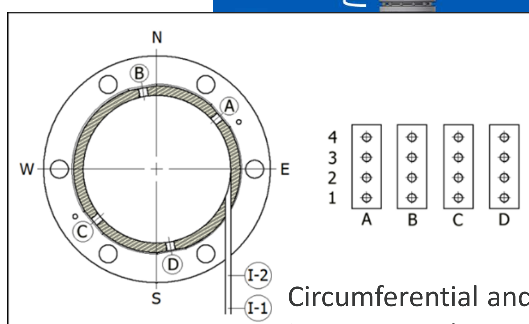




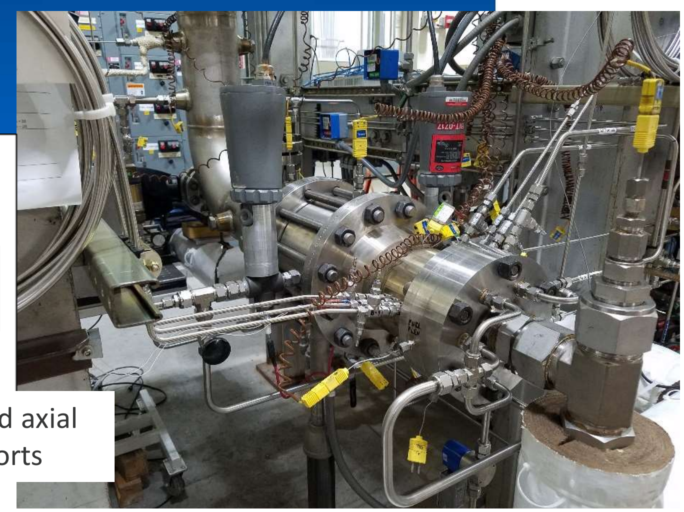
NETL Lab Scale RDE

- **Rig capability**
  - Natural gas, hydrogen, propane, ethane (0.1 kg/sec)
  - Air (1.2 kg/sec)
  - 20 atm, 800 K air preheat
- **Experimental focus**
  - Flow rate
  - Equivalence ratio
  - Fuel Composition (H2 / NG)
  - Air Preheat (600 K)
  - Operating Pressure



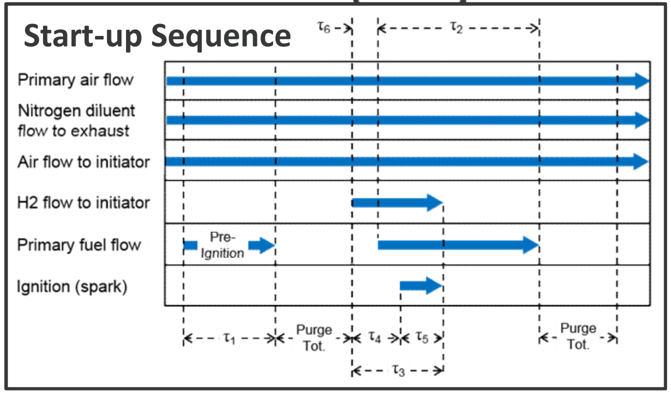


Circumferential and axial Instrumentation ports

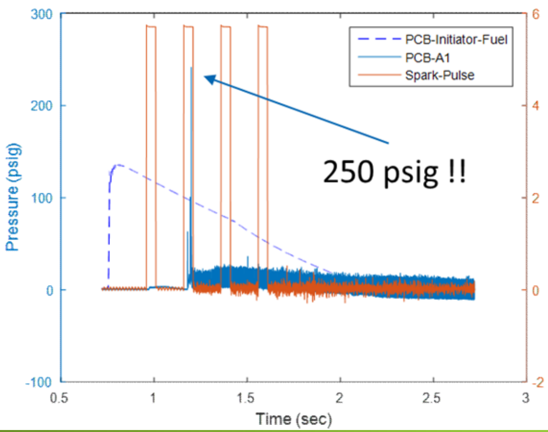


Start-Up Issues

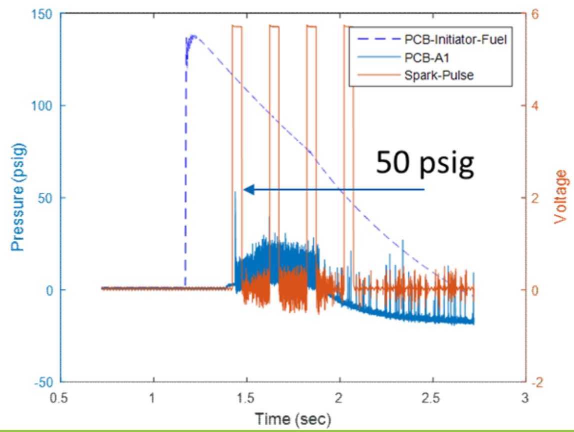
- With a contained exhaust start-up dynamics can be severe.
  - Reactants originally introduced with delayed ignition
- Flow through initiator had a larger than expected impact.
- Vary flow rate and spark timing to reduce start-up to manageable level.
- Added multiple torches immediate downstream of RDE

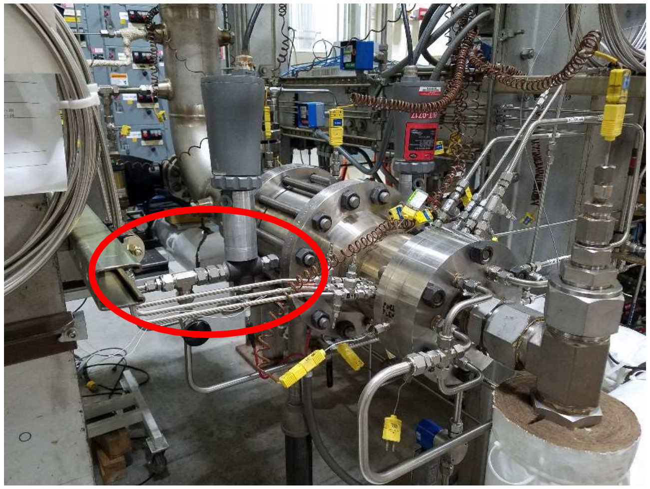


phi=0.8, P_{op} = 1.1 atm
Total flow=30000, Pulse Delay = 0.2 sec



phi=0.8, P_{op} = 1.1 atm
Total flow=30000, Pulse Delay = 0.25 sec





Summary of Test Conditions

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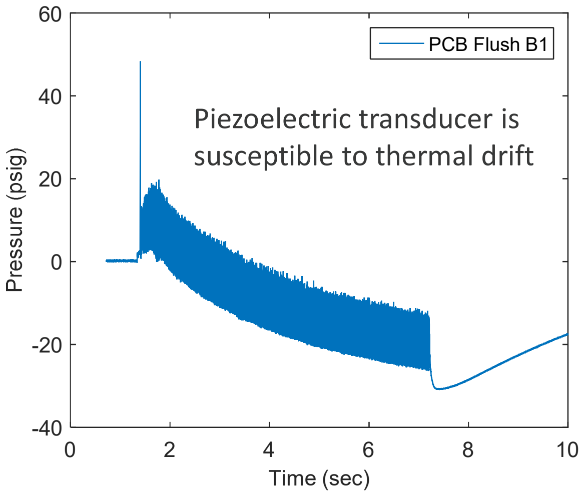
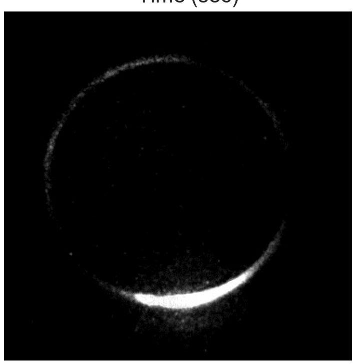
Experiment Date	Preheat (F)	Initial Combustor Pressure (psig)	Run# - APACS (DAQ)	Eq. Ratio Range (target)	RDE Orientation	Comment
3/17/2016	140	1psig	21:31 (21:31)	0.60-1.0	Vertical	Nominal; DO NOT USE TEMPERATURE DATA
3/23/2016	140	1psig	1:7,11,12 (1:7,11,12)	0.8	Vertical	Nominal; APACS Data logged from Run#2; DO NOT USE (DAQ) - 1,12
3/23/2016	140	3psig	8 to 10 (8:10)	0.8	Vertical	Backpressure; With air purge and diluent flow
5/3/2016	390	5psig	1 to 7 (1:7)	0.6-1.0	Vertical	Preheat + Backpressure
5/3/2016	390	1psig	8:12,20:23 (8:12,20:23)	0.60-1.0	Vertical	Preheat
5/11/2016	170	1psig	1:8 (1:8)	0.75-1.0	Vertical	
5/11/2016	390	1psig	9:16(9:16)	0.75-1.0	Vertical	Preheat; DO NOT USE (DAQ) - 11, 15
5/12/2016	140	1psig	1(1)	0.8	Vertical	Nominal
5/26/2016	140-160	1psig	1:27(1:27), 28:29 (29:30)	0.65-0.95	Vertical	Nominal; Nox measured 1st time, Run#28 (14:12:10PM) missing from APACS
8/24/2016	150	1psig	1:12(1:12)	0.8-1.0	Horizontal	Nominal (No Ignition - 2,3,6)
8/25/2016	150	1psig	1:6,17(1:6,17)	0.8-1.0	Horizontal	Nominal
09/08//2016	170	1psig	1:2(1:2)	0.8	Horizontal	Nominal
09/08//2016	170	5psig	3:14(3:14)	0.7-1.0	Horizontal	Backpressure; (Hard start - 3,4,10)

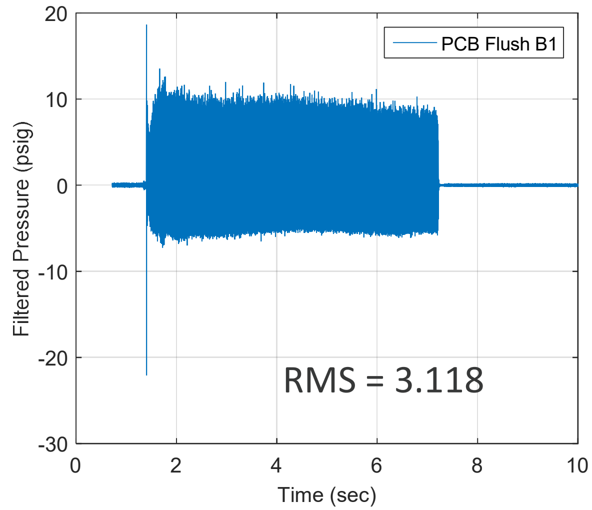
- **Hydrogen – air preheated temperature 140 – 390 F**
- **Eq. Ratio range ~ 0.6 – 1.0**
- **Air flowrates ~ 25,000 - 40,000scfh**

Example Data Analysis - H2 in Air

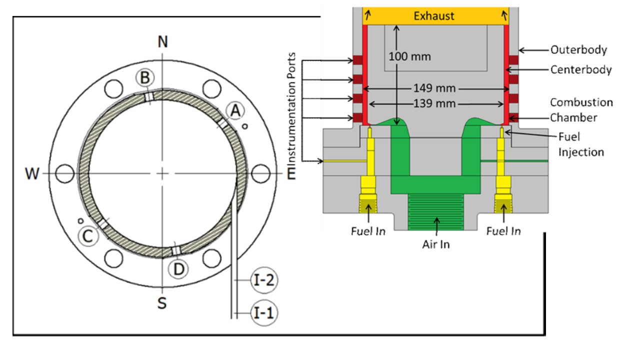


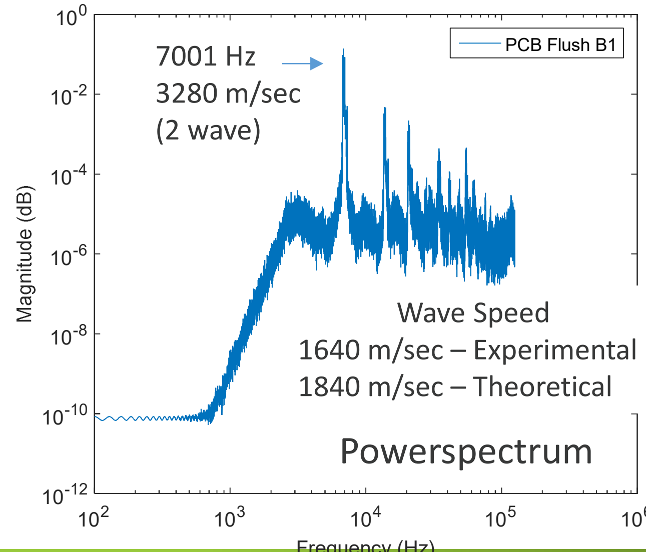


Highpass band butterworth filter to remove thermal drift from dynamic Pressure sensor

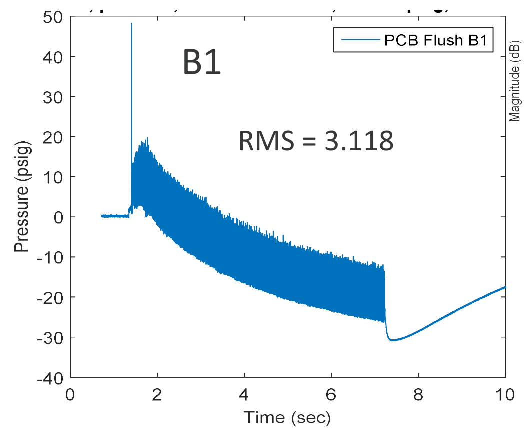


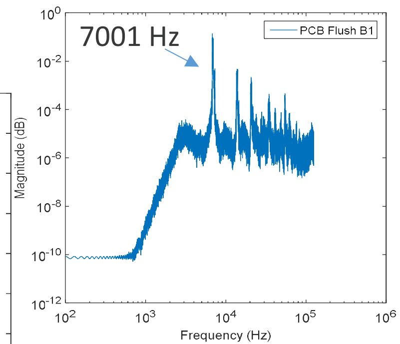
Test#: 9 - 05/26/2016, phi=0.8, Total flow=53000, P = 1.1 psig, Tair = 140F

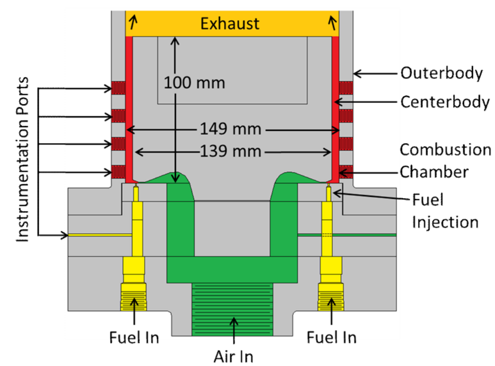


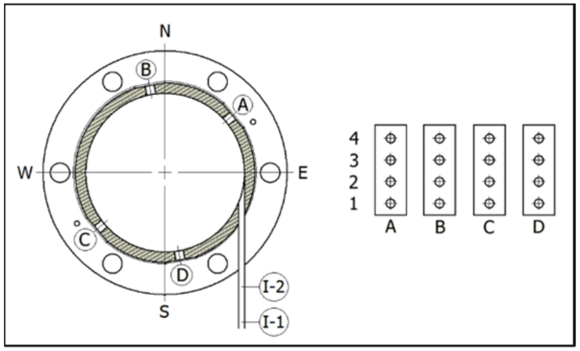


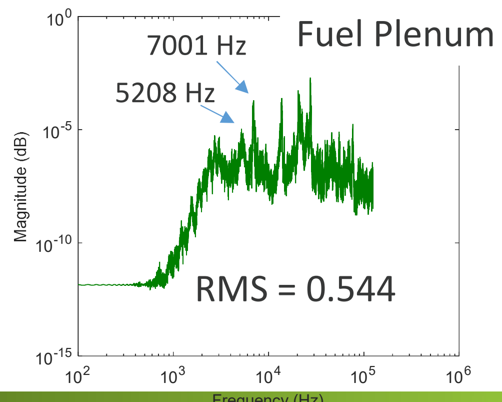
System Distributed Pressure Measurements

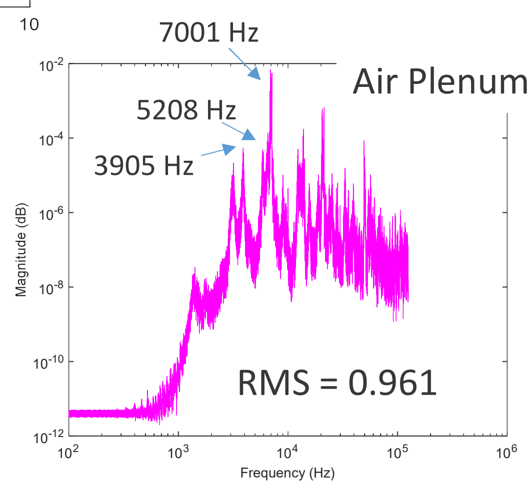


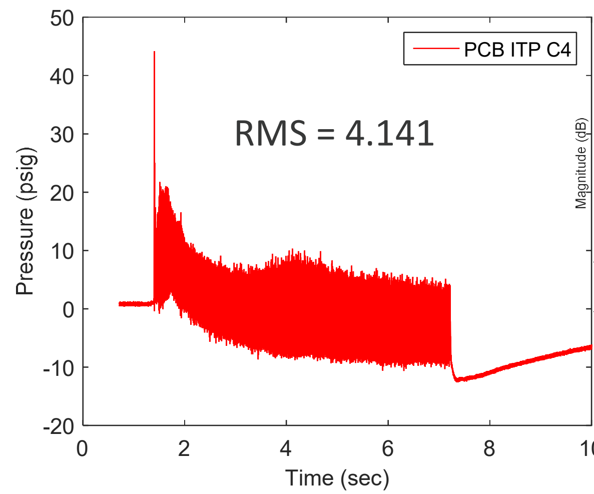


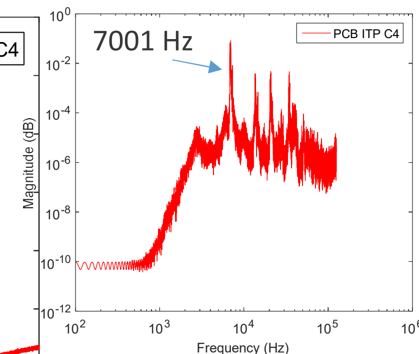






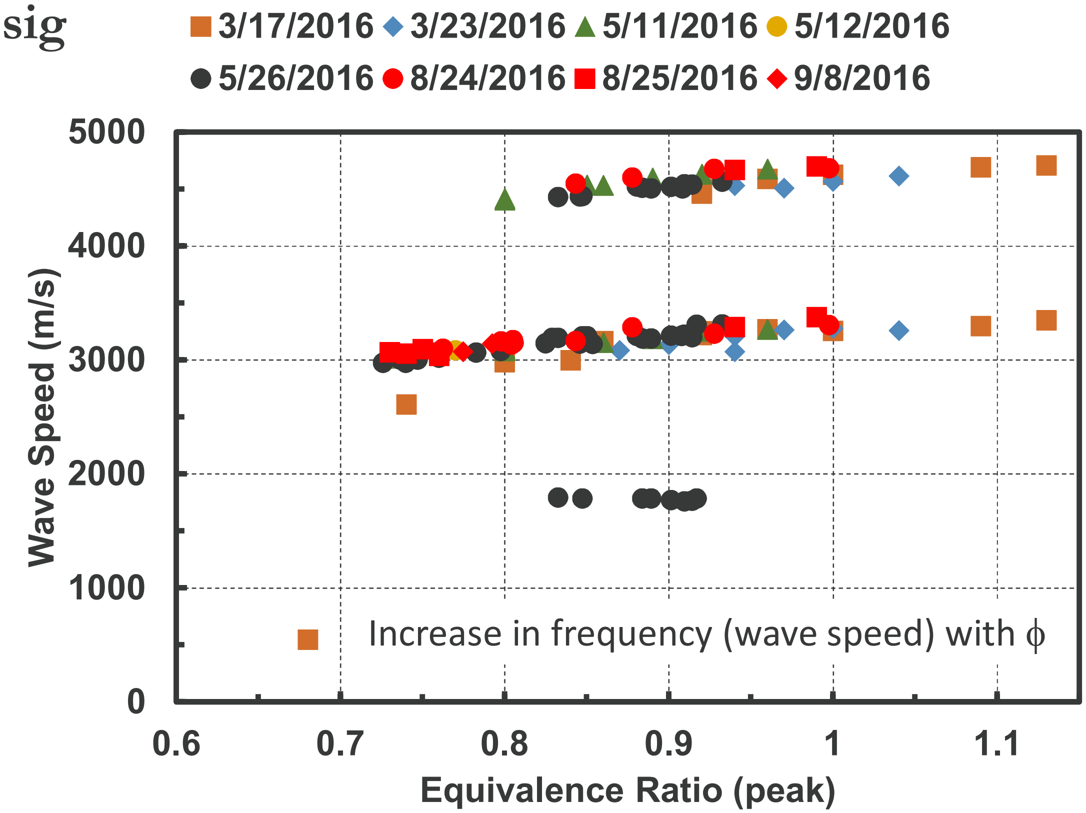


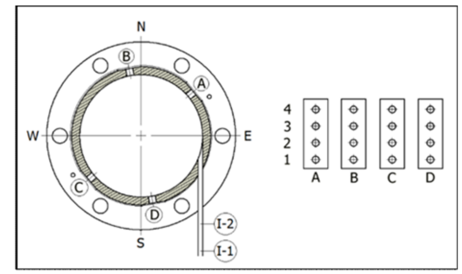


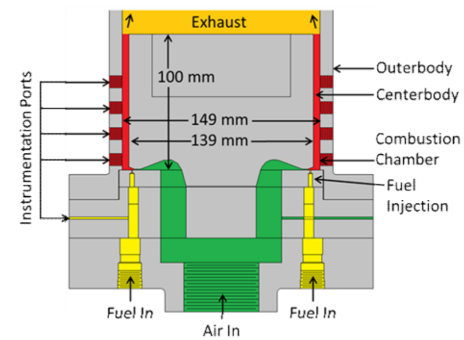


Equivalence Ratio 0.6 – 1.0 / H2 in Air

- Air Flow = 40,000 scfh, Fuel Flow = 10,000 – 15,000 scfh
- Pressure = 1.1 psig





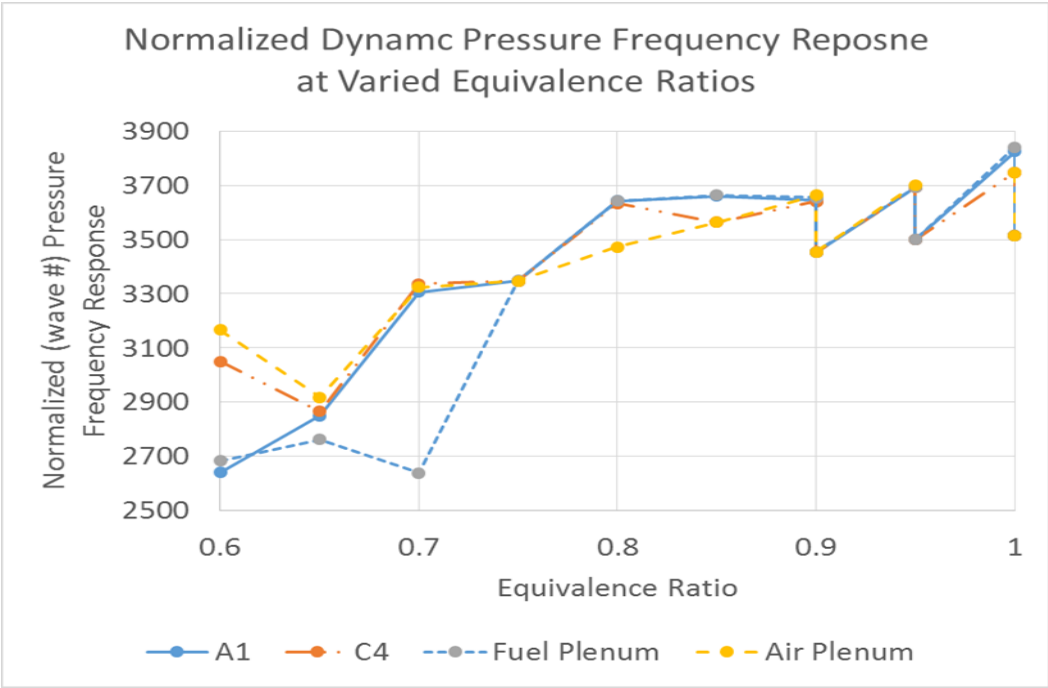


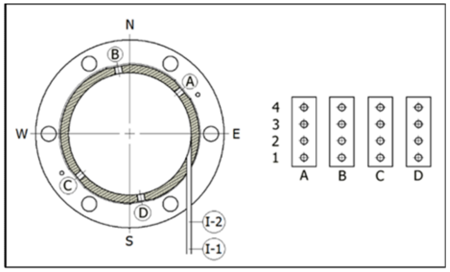
Equivalence Ratio 0.6 – 1.0 / H2 in Air

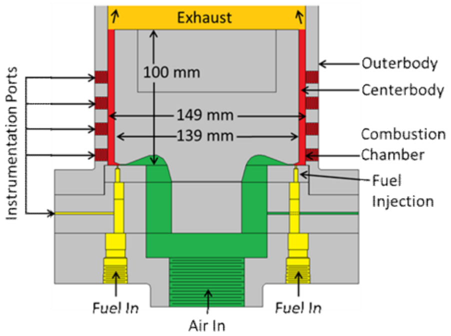
- **Air Flow = 40,000 scfh, Operating Pressure = 1.1 psig**

General Trends

- Increase in frequency (wave speed) with ϕ
- Relative consistency throughout the RDE







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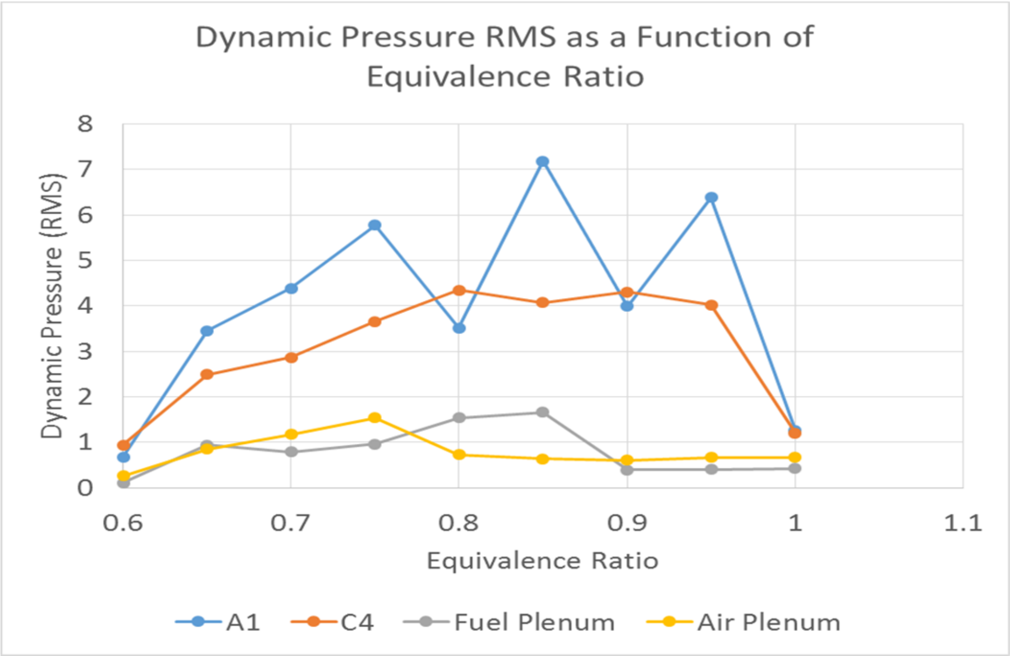
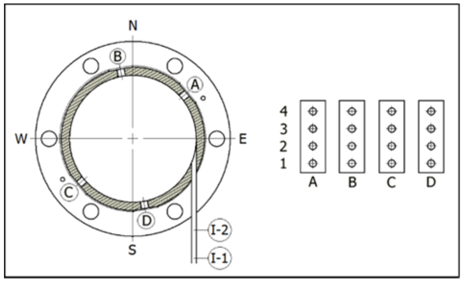
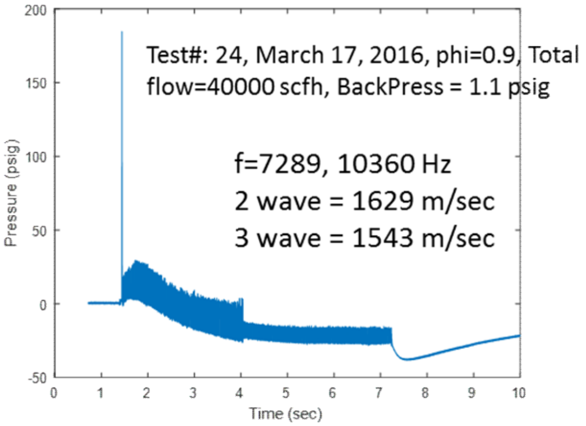




General Trends

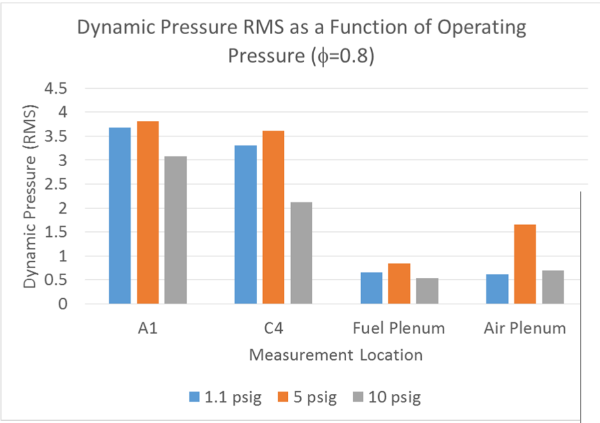
- Increase in RMS with ϕ for A1 and C4
- Max at C4 is less than A1
- Fuel and Air plenum peak at leaner equivalence ratio

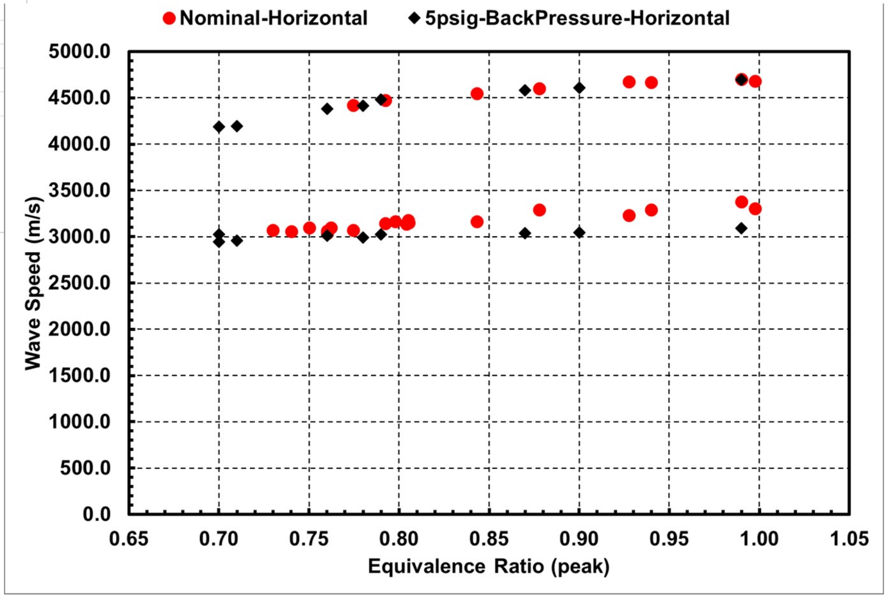
Additional wave beginning at ϕ =0.9



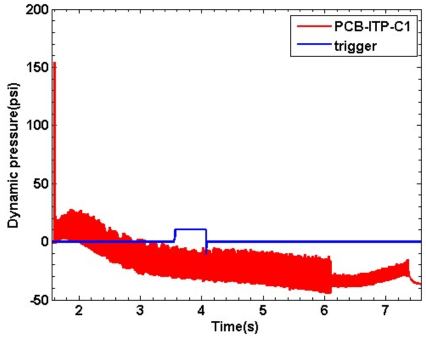
Influence of Increasing Operating Pressure

- H2/Air, 40000 scfh, Air Inlet = 140° C, ϕ = 0.8

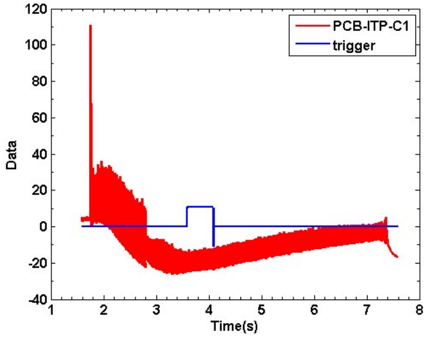




Operating Press 1.1 psig

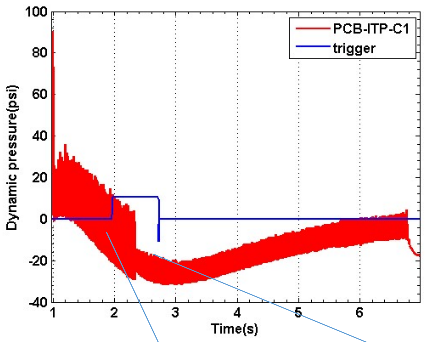


Operating Press 5 psig

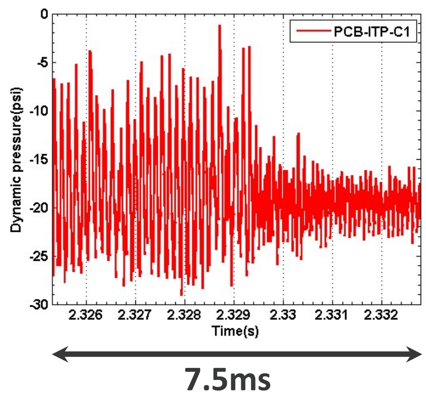


RDE @5psig Operating Pressure

09/08 Run 13 – phi ~ 1.0 (5psig backpressure)



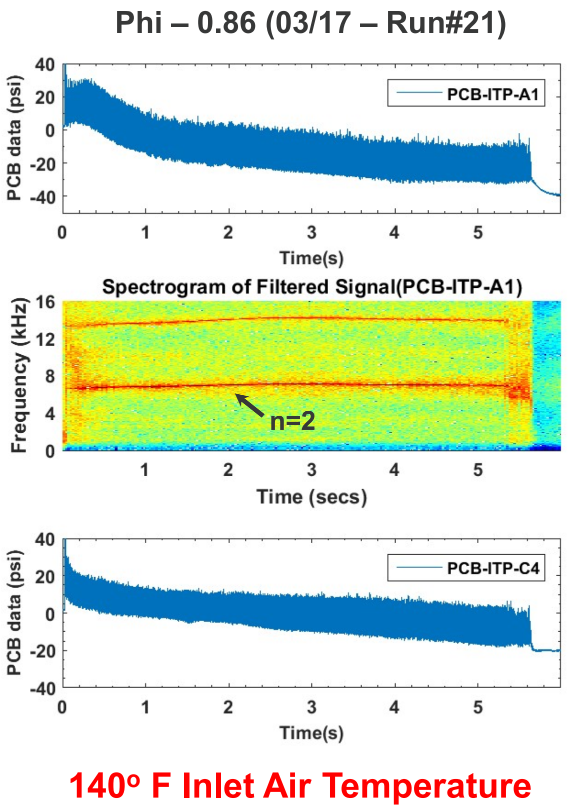
Air Flow = 40,000 scfh
Fuel Flow = 16,500 scfh

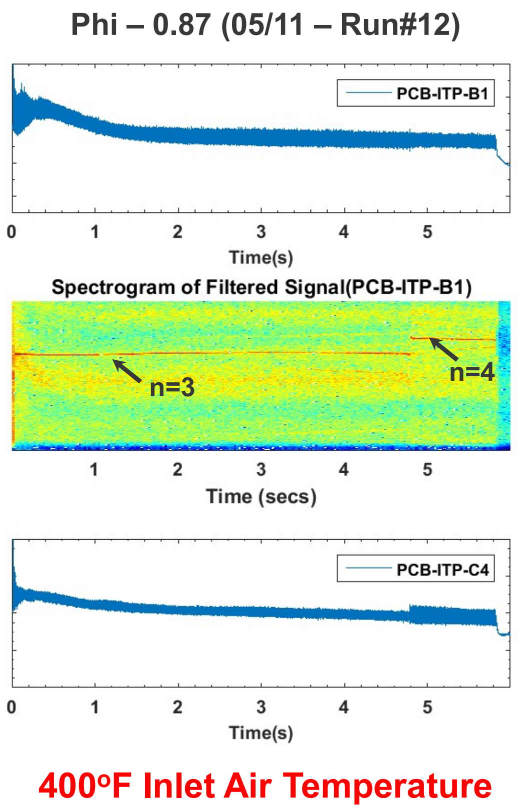


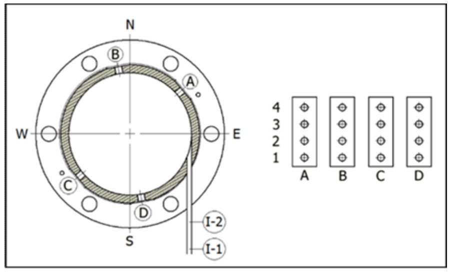
- Start – 0.3575s after trigger, Viewing: 375frames @15fps

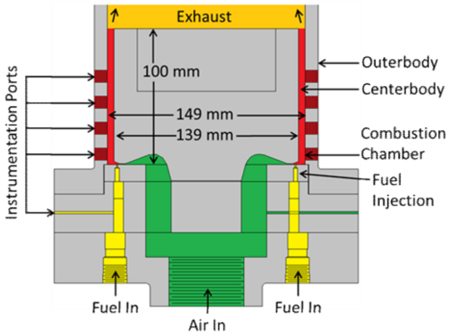
Effect of Inlet Air Temperature

Air Flow = 40,000 scfh
Operating Pressure = 1.1 psig



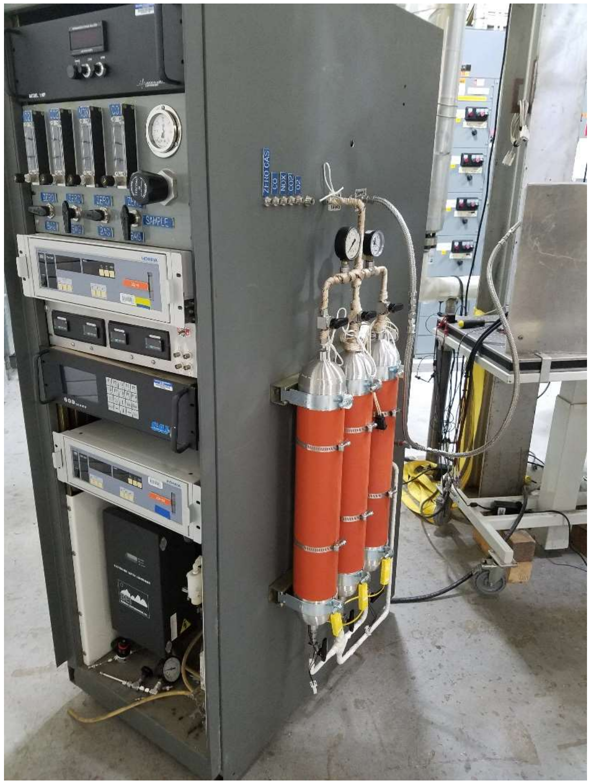






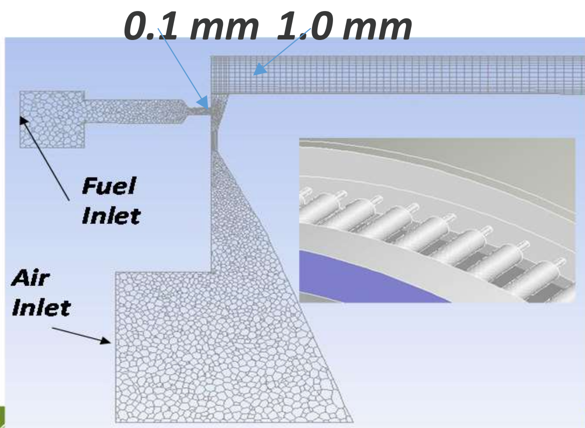
Pending Nox Emissions Measurements

- Delayed by procurement issues
- Slow response NOx Analyzer requires samples be collected through iso-kinetic sample probe and stored in heat gas cylinders in preparation for post-test sampling
- Heated to prevent condensation and loss of water soluble NO2
- Computational Study by NRL suggest combustion physics of detonation vs detonation may or may not have a significant impact on NOx emissions
- Collaborating with AFRL on T63 tests

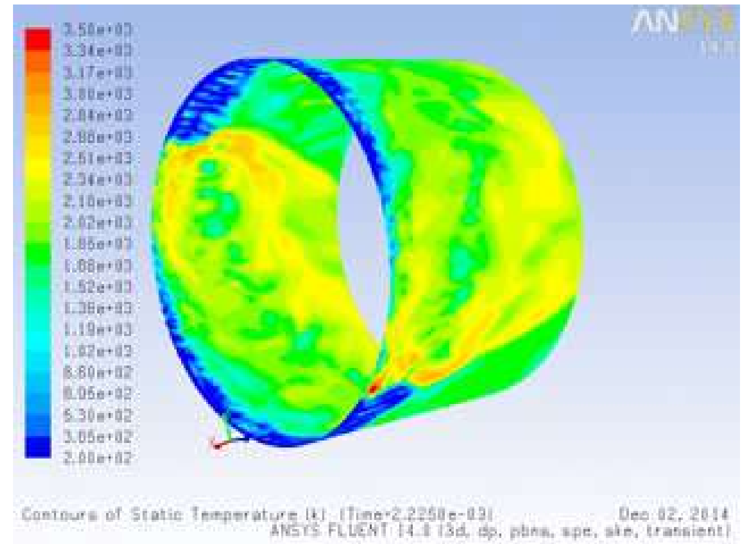


CFD Modeling of NETL RDE

- Validated modeling approach with experimental data from AFRL.
- Developed averaging process.
- Characterized overall thermal efficiency, pressure gain/loss, potential turbine work, etc…
- Examined loss mechanisms.
- Simulated linear RDE experiment.



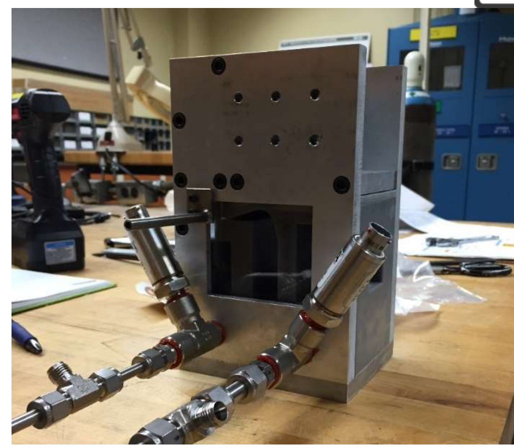
- *Includes air and fuel injectors and partial manifolding*

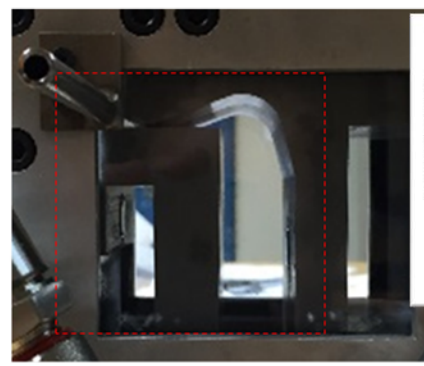


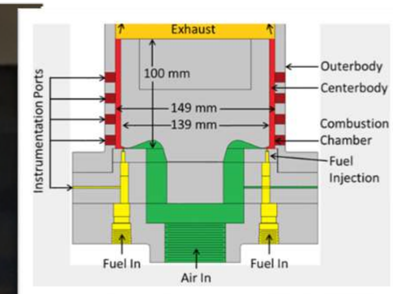
Simulation shows significant interface burning (~40% of fuel). Turbulence chemistry interaction models are not valid for both deflagration and detonation zones.

NETL RDE Inlet Sector Rig

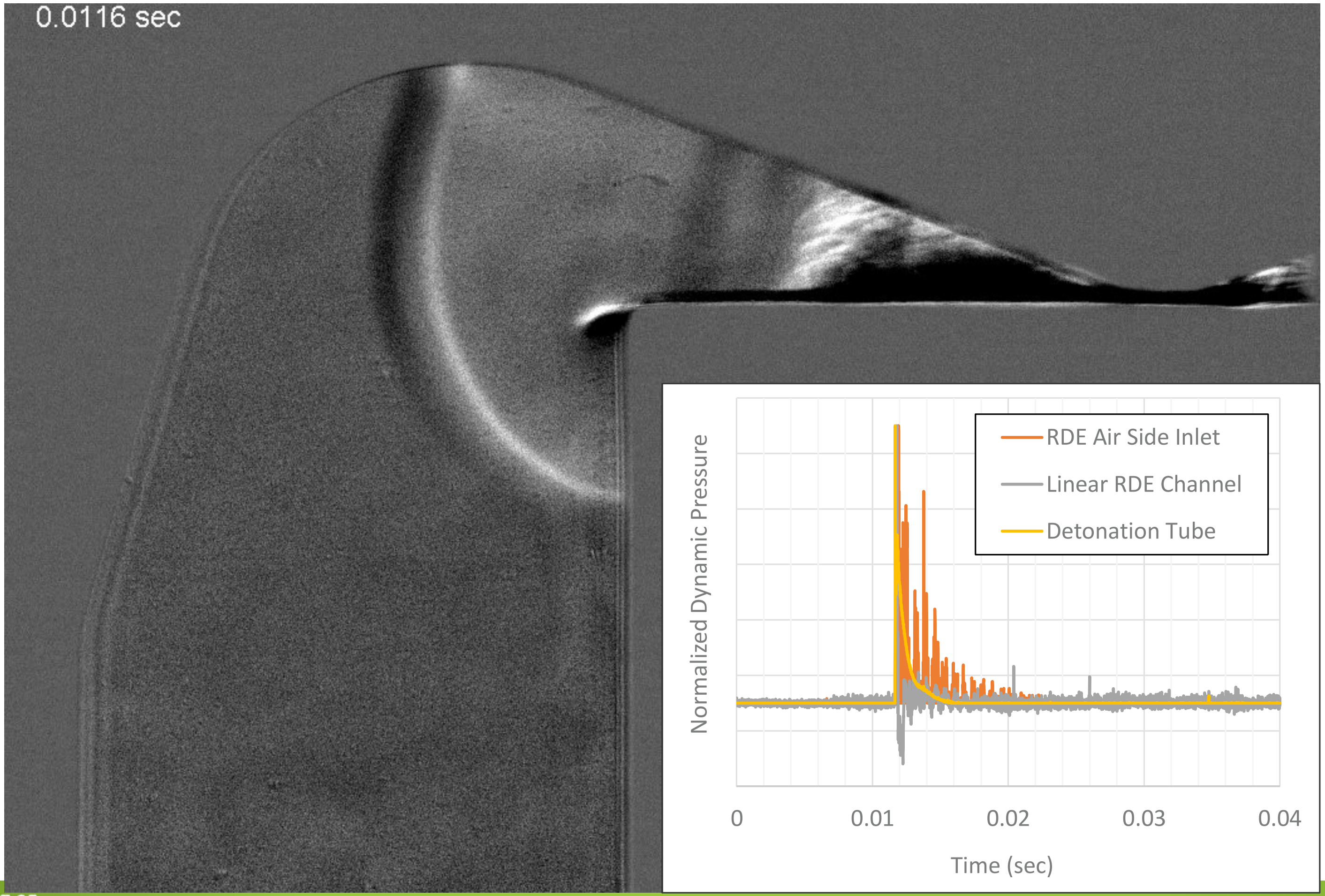
- **Linear RDE apparatus designed and fabricated to facilitate development of improved inlets**
  - Inlet and plenum optically accessible from multiple sides
  - H2/air detonation tube connected to end of linear RDE channel
  - 3D printed inlet geometries for rapid evaluation of designs
  - Rapidly propagating pressure wave creates characteristic backflow and recovery behavior seen in full-scale, fired RDE
  - Qualitative and quantitative data can be collected non-intrusively
  - Diagnostics include dynamic pressure measurements and high-speed Schlieren imaging to evaluate inlet dynamics, acetone PLIF for fuel/air mixing within channel





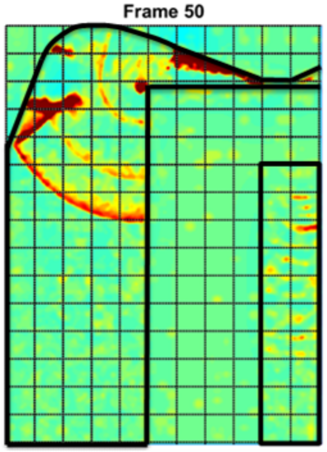


Focused Schlieren of Inlet Dynamics



Effects of Detonation on Inlet

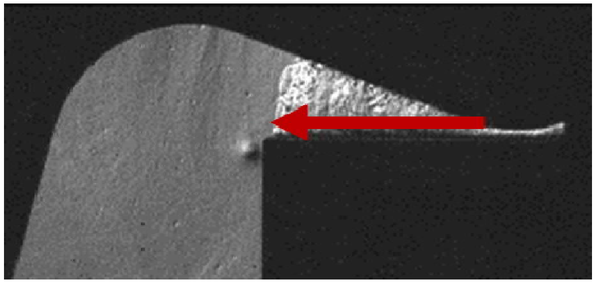
- **Shockwave**
  - Interruption time is the time required for the nominal pressure in the plenum to overcome the resultant pressure from the detonation.
  - No refueling occurs during this period of time
  - Contributes to inhomogeneity in ϕ



Shock wave in inlet air plenum

- **Mass flow**
  - Recovery time is the amount of time that the injectant flow takes to force recirculated exhaust products out of the inlet.

0.044" Gap



Some of the Inlet Designs Tested

Inlet Design	Recovery Time (ms)	Interruption Time (ms)	Backflow Length (L_{max})
0.022” Gap – Air Plenum	0.300	0.0740	0.675”
0.022” Gap – Fuel Plenum	0.320	0.0833	0.969”
0.044” Gap	0.430	0.0860	0.942”
0.066” Gap	0.600	0.0860	1.155”

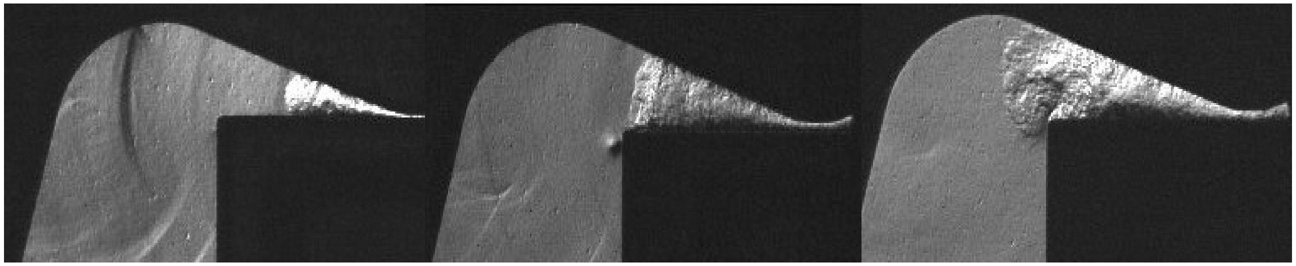


Figure 42. Maximum backflow shown for 0.022” gap (left), 0.044” gap (middle), and 0.066” gap (right)

Summary

- **Engineering scale rig operating at elevated back pressure and natural gas**
  - New Horizontally mounted rig for greater optical accessibility
  - Water cooled rig for extended operations

- **Linear bench scale sector rig for fundamental studies related to upstream pressure wave and backflow issues**

- **Computational models intended for parametric studies validated by experimental studies**

Acknowedgements

- This research is funded by the US Department of Energy –Office of Fossil Energy through Advanced Combustion and Advanced Turbine Systems.

- The authors would like to thank Richard Dennis, Dan Driscoll & Patcharin Burke at DOE NETL for continued project support

- The authors would also like to thank Mark Tucker and Jeff Riley for doing all the hard work.

Questions?

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