Integrating a Rotating Detonation Combustor with a Power Generating Gas Turbine to Realize the Pressure Gain

Ajay K Agrawal, PI, University of Alabama
Joseph Meadows, co-PI, Virginia Tech
DOE Program Monitor: Richard Dalton

Graduate Students: Shaon Talukdar and Piyush Raj

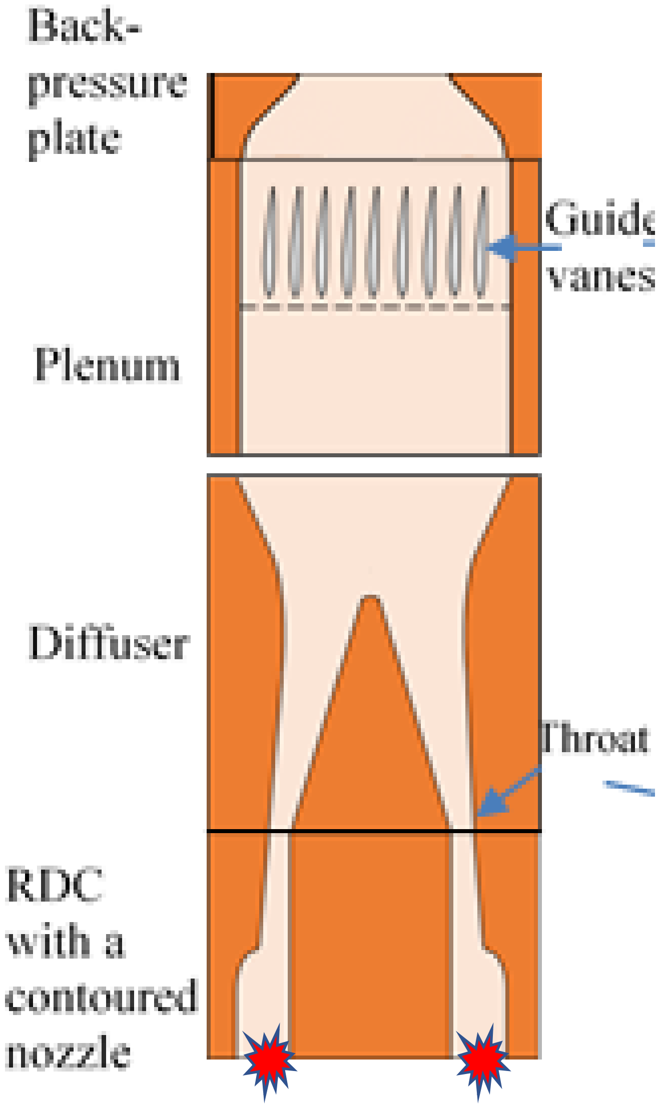
2023 UTSR Meeting
State College, PA, November 01, 2023

AEROJET ROCKETDYNE

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

VIRGINIA TECH

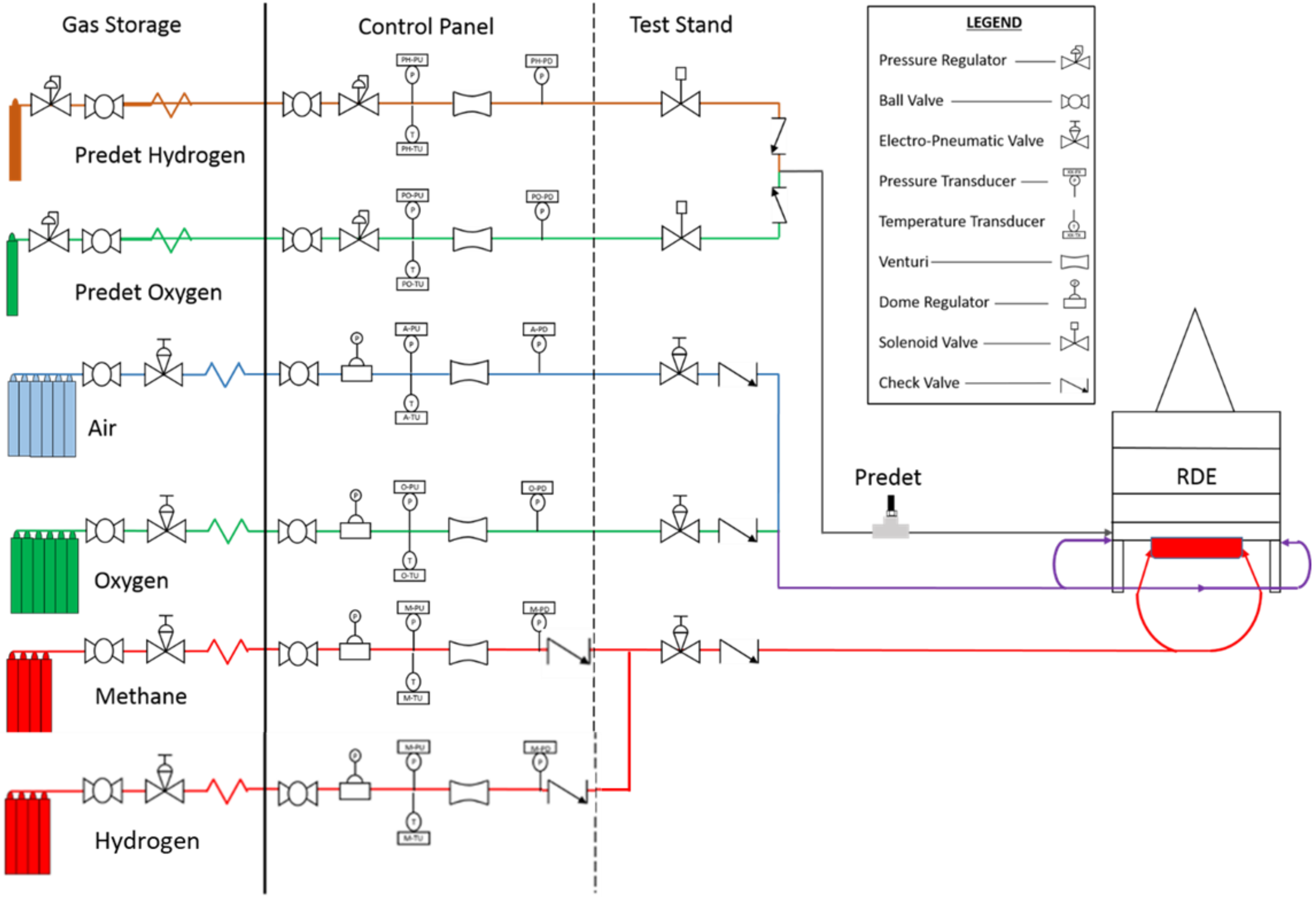
Project Objective

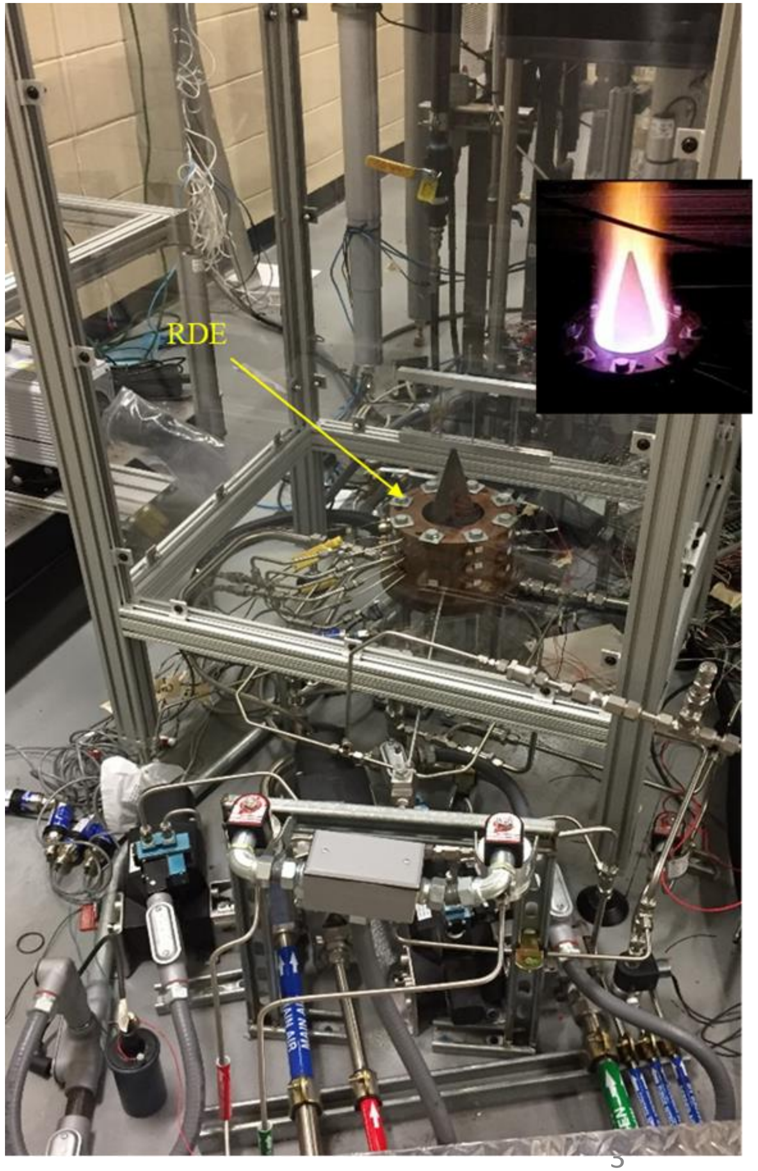


- Integrate rotating detonation combustor (RDC) with turbine inlet to extract maximum work in power generating gas turbines.

- Note that gas turbines are designed to operate with relatively small pressure, temperature, and flow fluctuations at the inlet

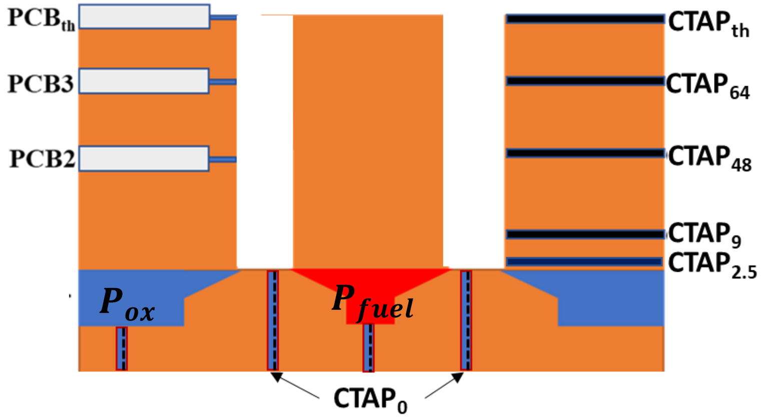
Reactant Supply System and Annular RDE Test Stand

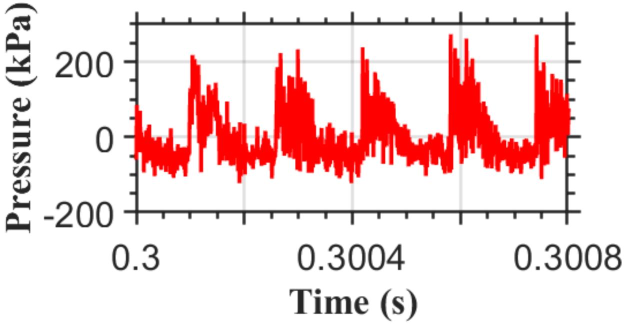


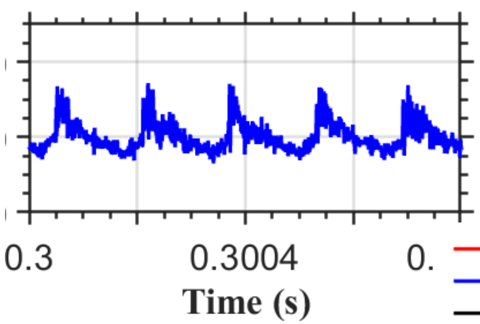


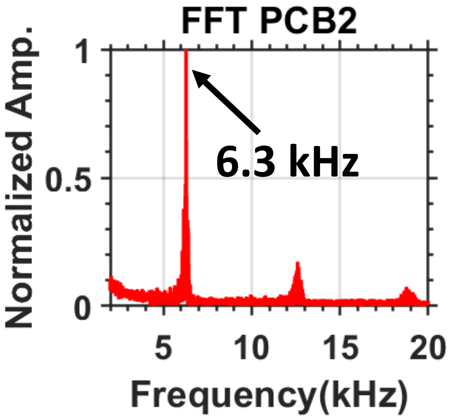
- Wave Speed ≈ 2000 m/s, Max Flow Velocity > 1000 m/s
- 10 cm Diameter RDC Power Output: Up to 10 MW

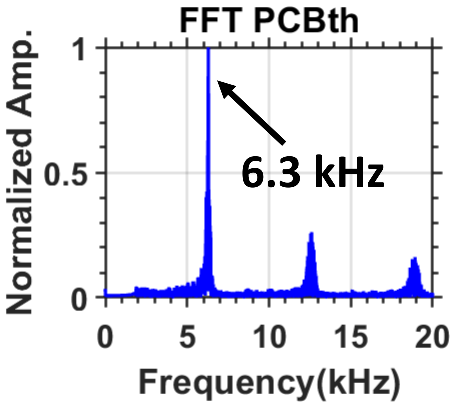
Integration Challenges

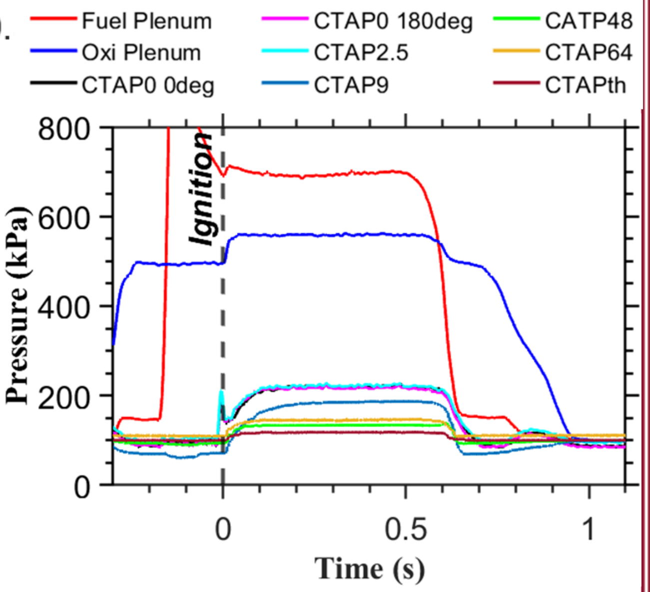






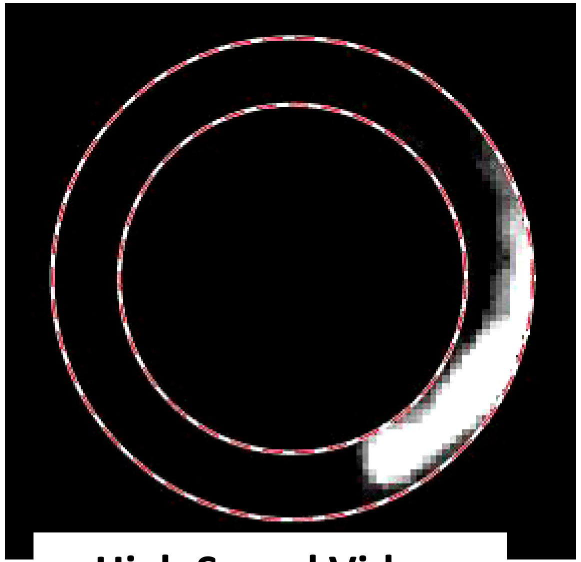






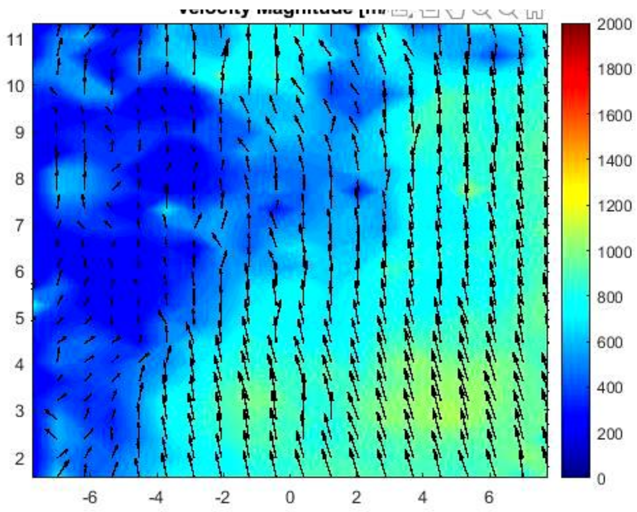
Operating Conditions

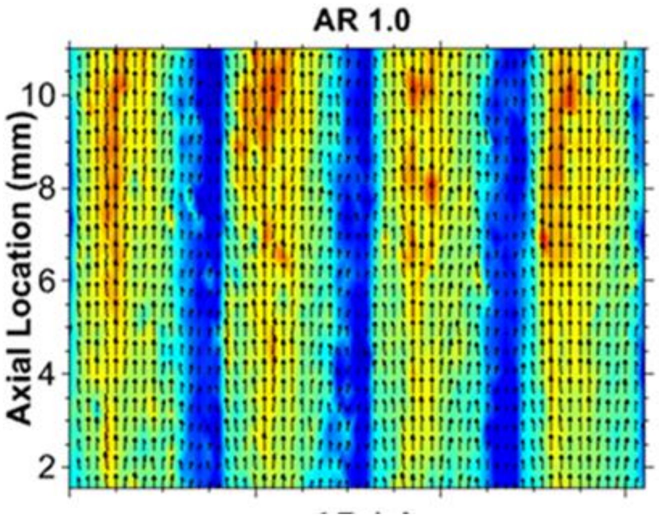
$\dot{m}_{total}$ (kg/s)	$X_{O_2}^{Ox}$ (%)	ER	A_c/A_{inj}	A_c/A_{th}
0.32	67	1.0	10.5	1.0

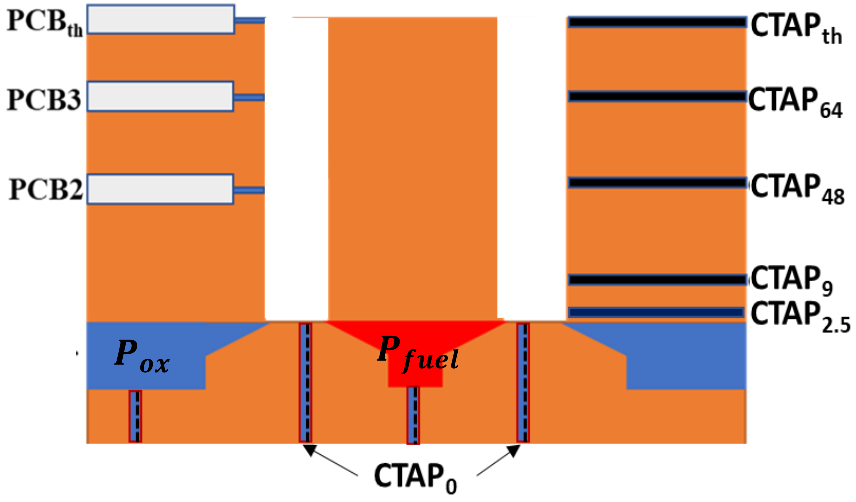


High Speed Video

100 kHz PIV, Region of Interest: RDC Exit







RDC with Constant Annulus Area

RDC Operational Mode

CJ Speed (m/s)	*CJ Freq. (kHz)*	*RDC Freq. (kHz)*	*% CJ*
2250	7.2	6.3	88

Pressure Measurement (kPa)

P_{ox}	P_{fuel}	$CTAP_0$	ΔP_{inj}	$CTAP_{th}$	P_t
530	680	220	330	117	209

Pressure Gain/Loss

Injector	Pressure Gain
-60.0 %	-79% to -62.0%

- Large pressure drop across the injector (60%)
- Substantial pressure drop across the combustor (2-19%).
- Pressure oscillations (at 6.3 kHz) remain at the RDC exit
- Unsteady and spatially non-uniform (hydrodynamically and thermally) RDE exit flow with high periodicity.
- RDC exit flow contains oblique shock wave.
- Oblique shock wave – turbine hardware interactions create complex flow structures, including reflected shock waves affecting upstream detonation itself.
- Gas turbines are designed to operate with relatively uniform flow at the inlet.

Prior Work

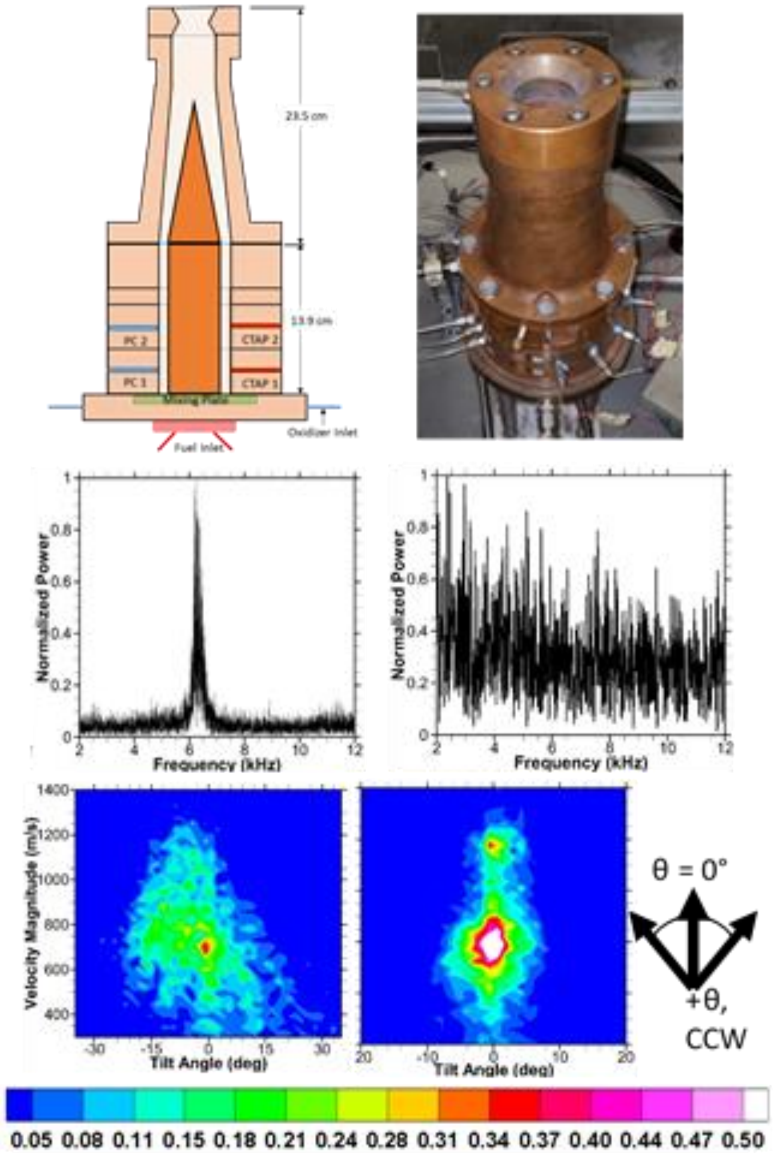
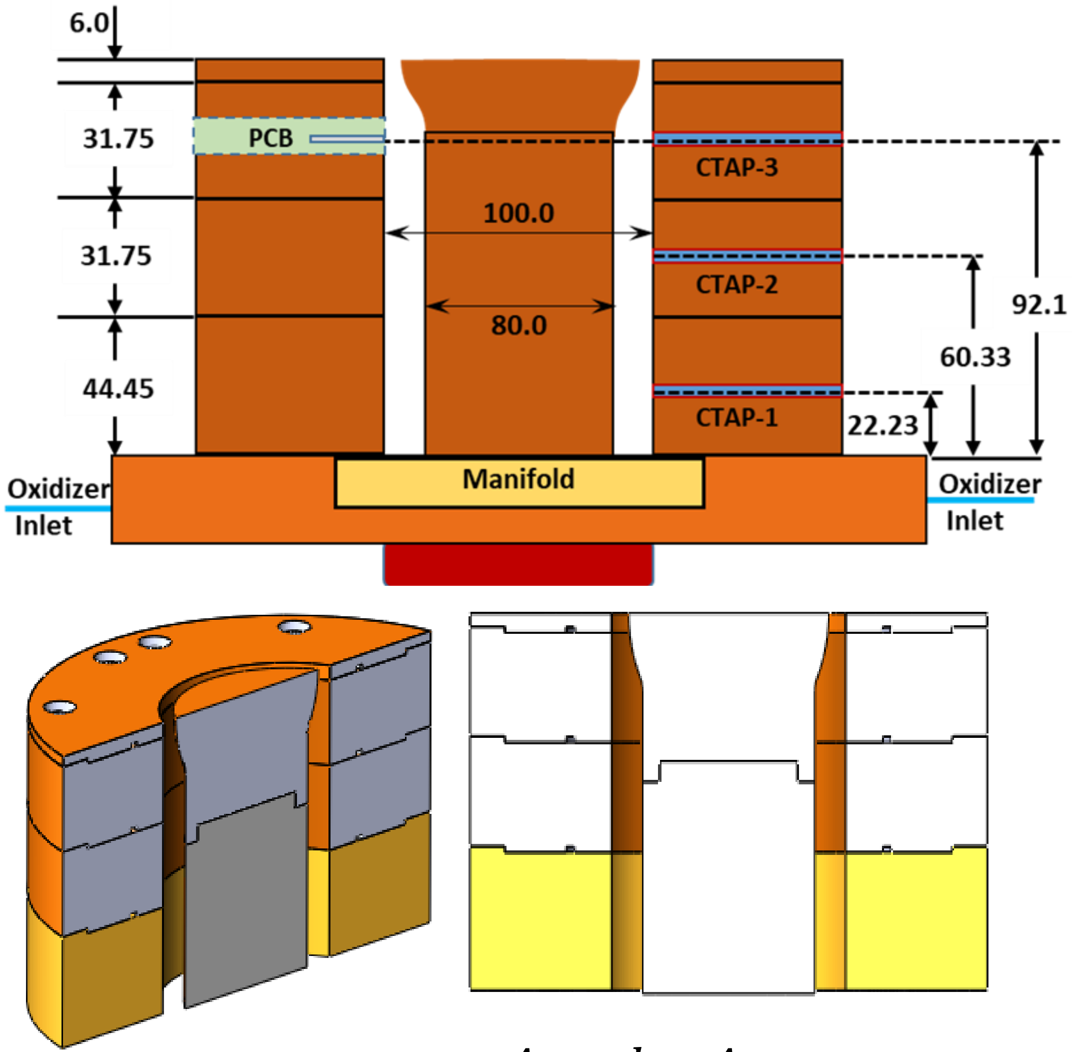
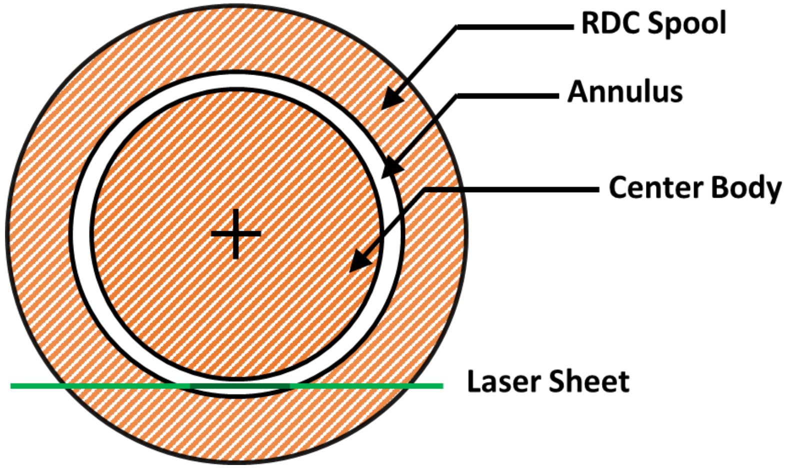


Fig. 4 Schematic (top-left) and photograph (top-right) of RDC with diffuser; FFT of axial velocity without (middle-left) and with diffuser (middle-right); 2D histogram of velocity without diffuser (bottom-left) and with diffuser (bottom-right) [20].

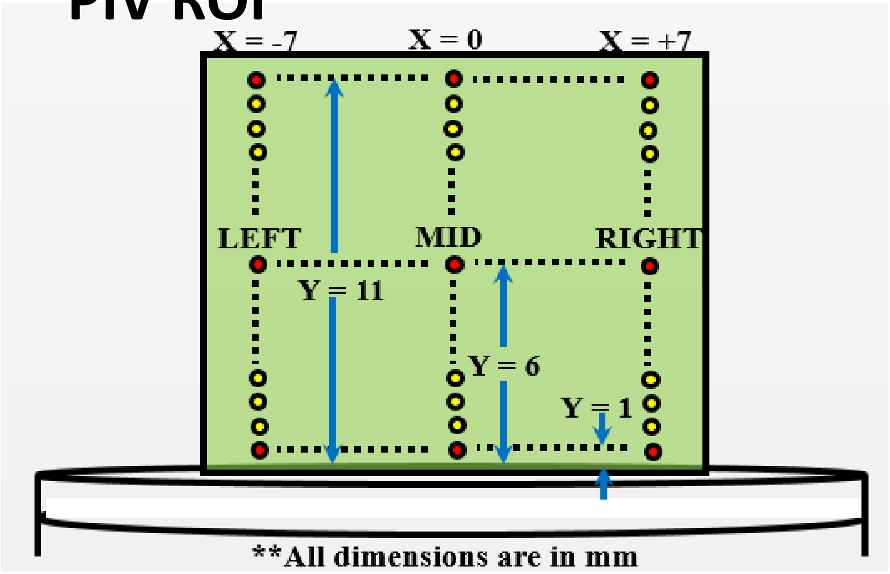
- In our prior work with Aerojet-Rocketdyne, the RDC was integrated with a diffuser as shown.
- Diffuser eliminated the oblique shock wave.
- However, diffuser did not eliminate flow fluctuations; axial velocity varied between 300 m/s and 1,200 m/s.

Mitigation: Place a Nozzle at the RDC Exit





PIV ROI



$$Area\ Ratio\ (AR) = \frac{Annulus\ Area}{Annulus\ Area\ at\ Nozzle\ Throat}$$

RDC Performance Summary

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

Area Ratio (A_c/A_{th})	$\overline{P_{fuel}}$ (kPa)	$\overline{P_{oxi}}$ (kPa)	$\overline{CTAP\ 1}$ (kPa)	$\overline{CTAP\ 2}$ (kPa)	$\overline{CTAP\ 3}$ (kPa)	$\overline{P_{total}}$ (kPa)	%PG	$\overline{PCB}$ (kPa)
1.0	642	631	163	121	122	-	Up to -79	224
1.4	732	619	193	178	194	223	-65	295
1.7	721	594	259	250	260	283	-53	362
2.0	751	685	305	301	313	334	-51	415

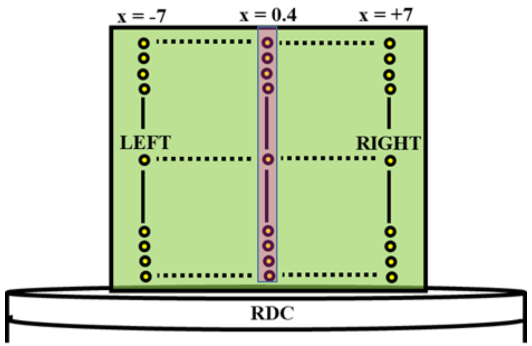
- Assumption: $M_{th} = 1.0$

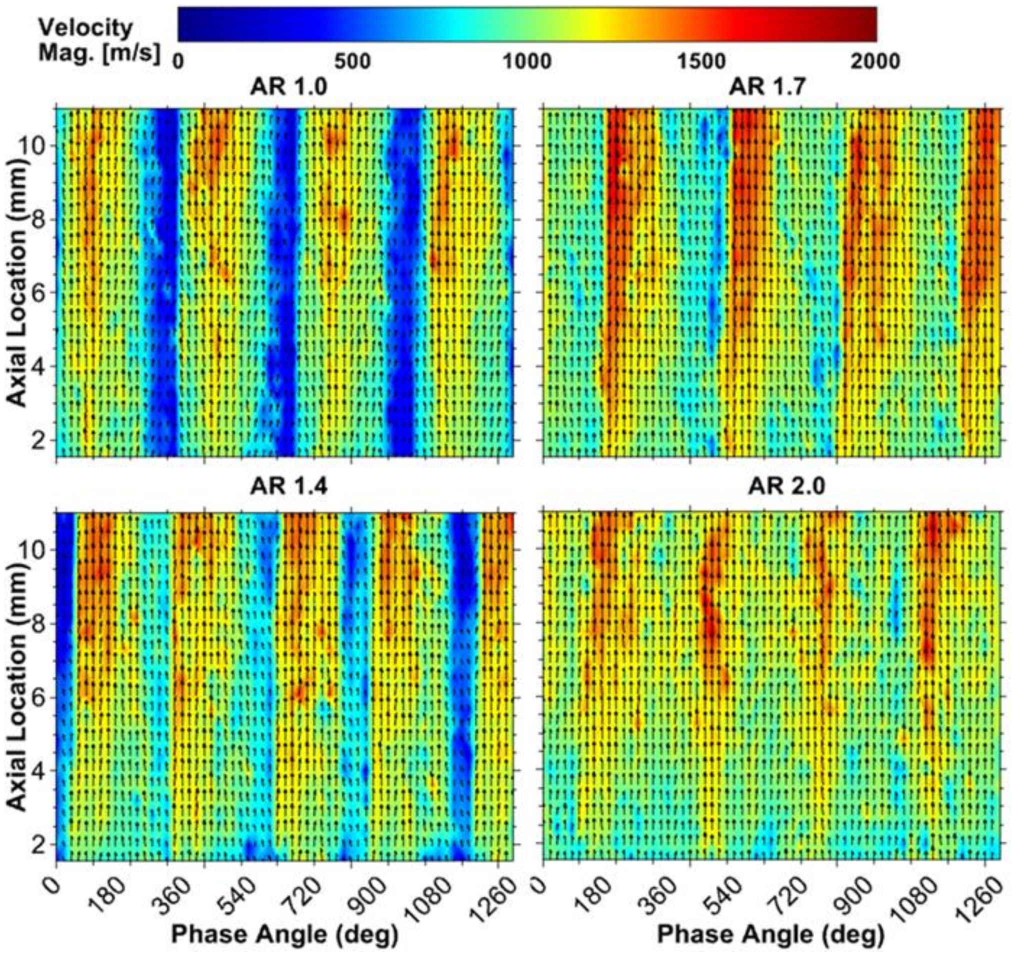
$$Total\ Pressure\ at\ Throat, P_{total} = P_{CTAP}\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

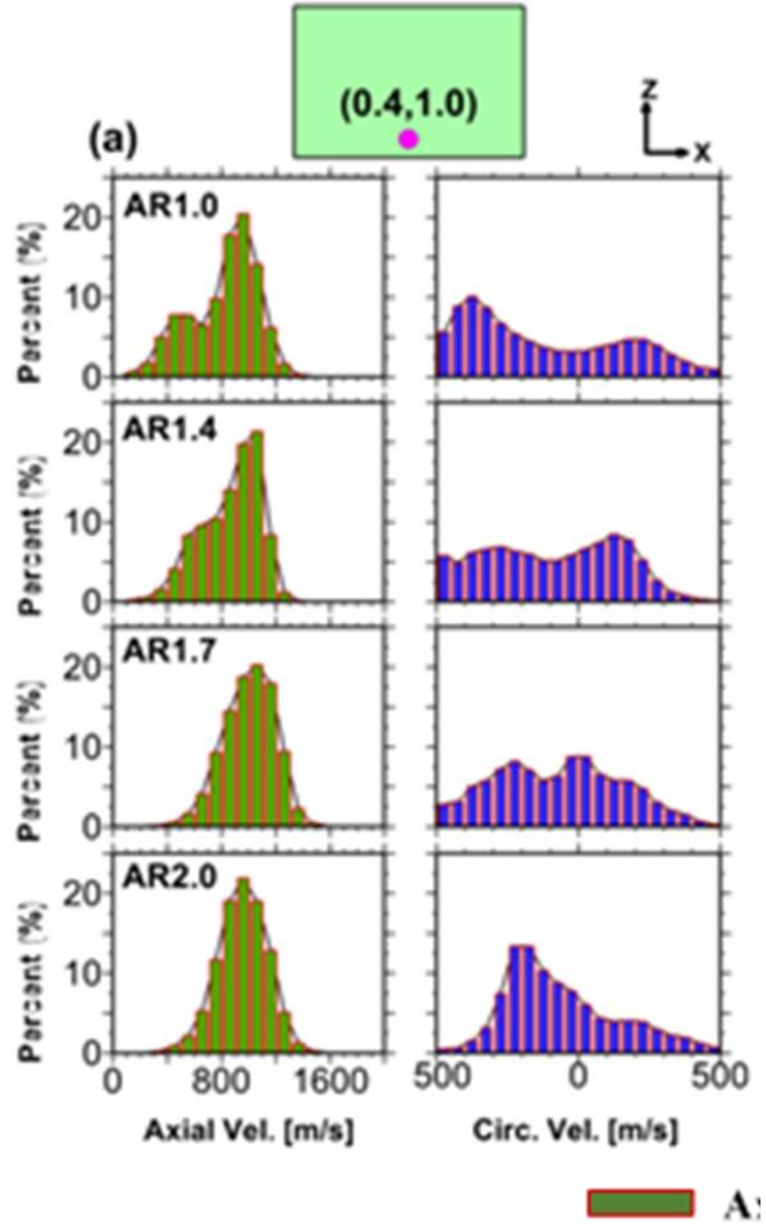
- Pressure Gain Calculation:

$$\%PG = \left(\frac{P_{total}}{(0.86 * P_{ox} + 0.14 * P_{fuel})} - 1\right) * 100$$

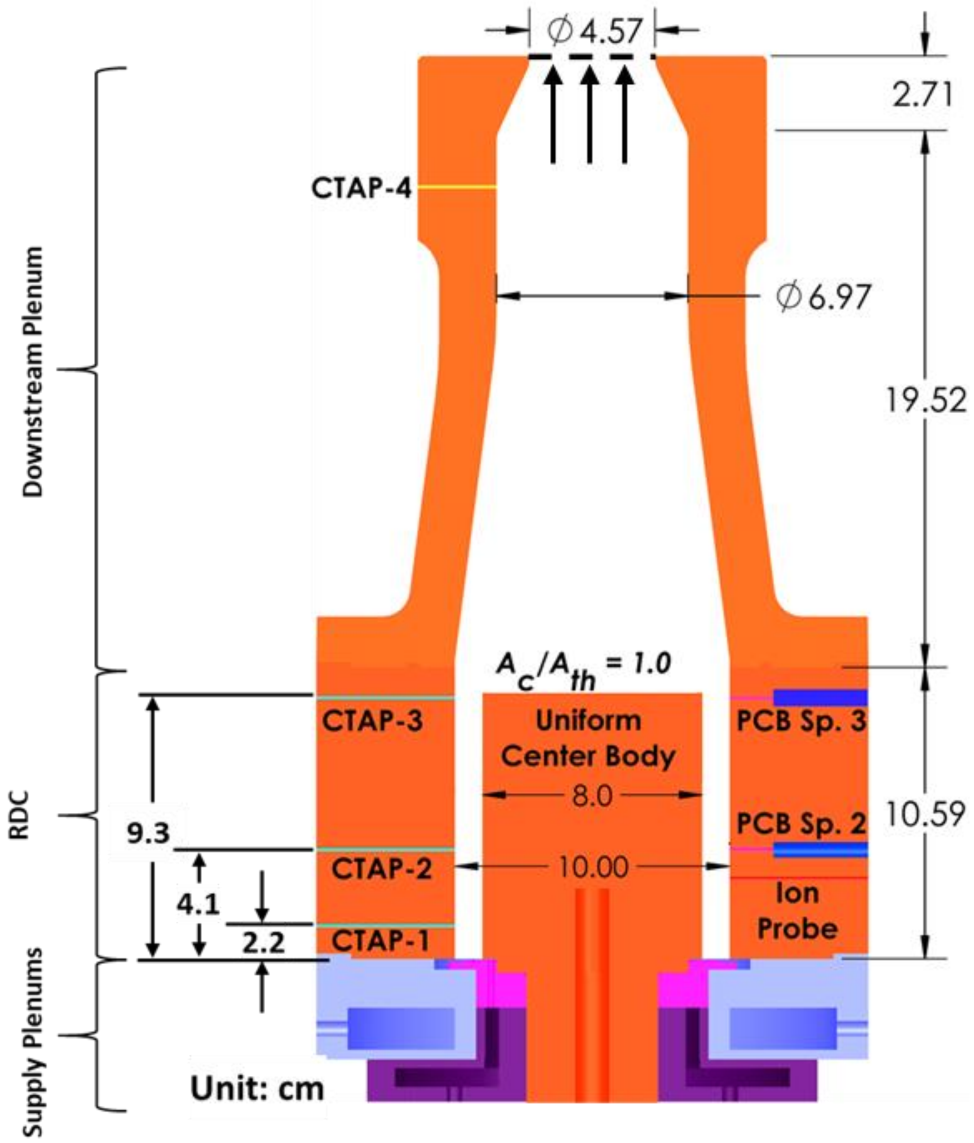
Periodic RDC EXIT Flow

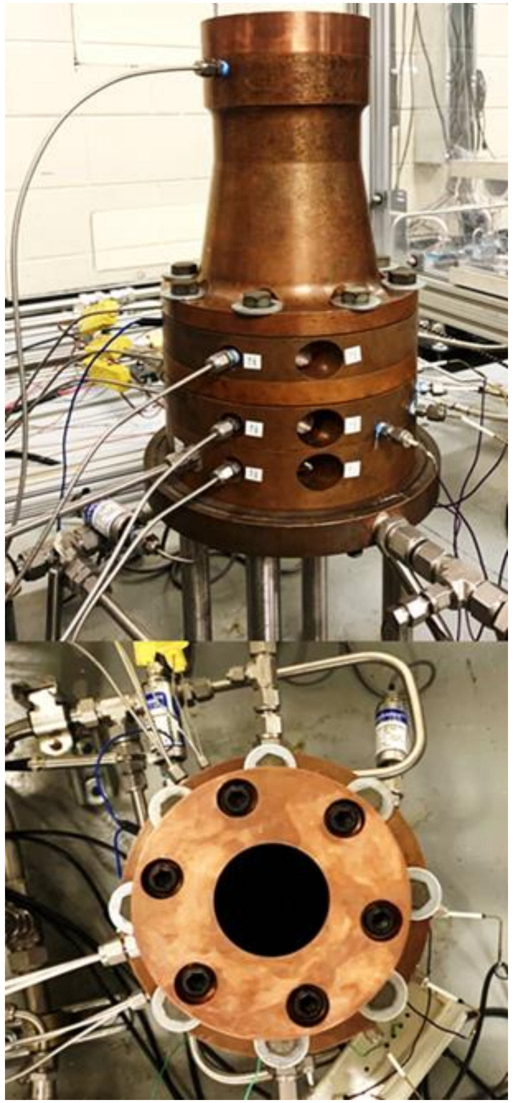


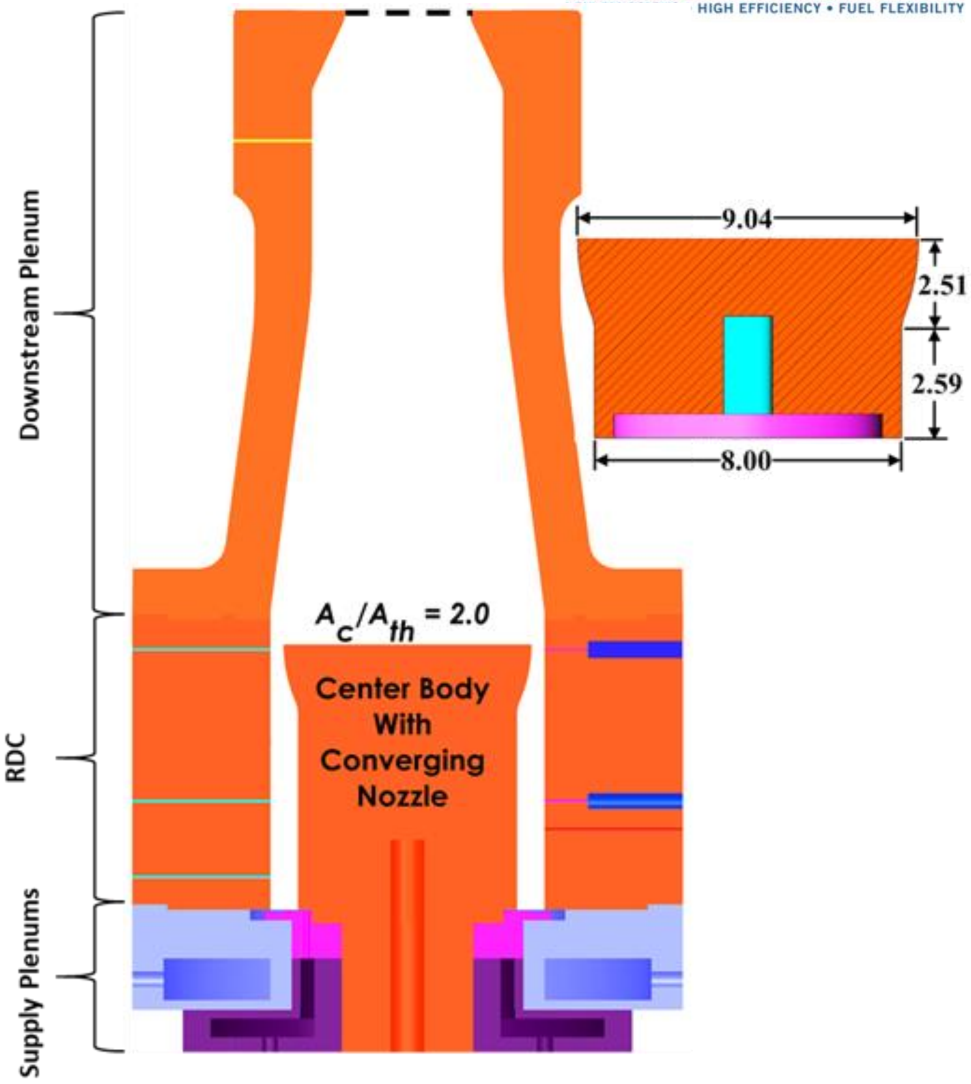




RDC test with backpressure plenum





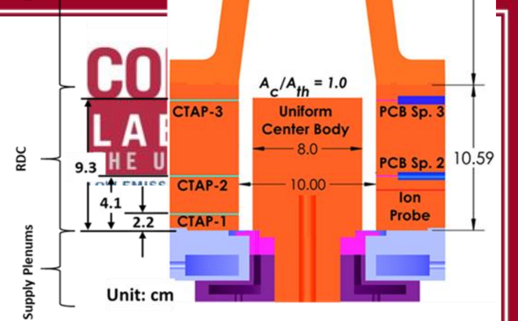


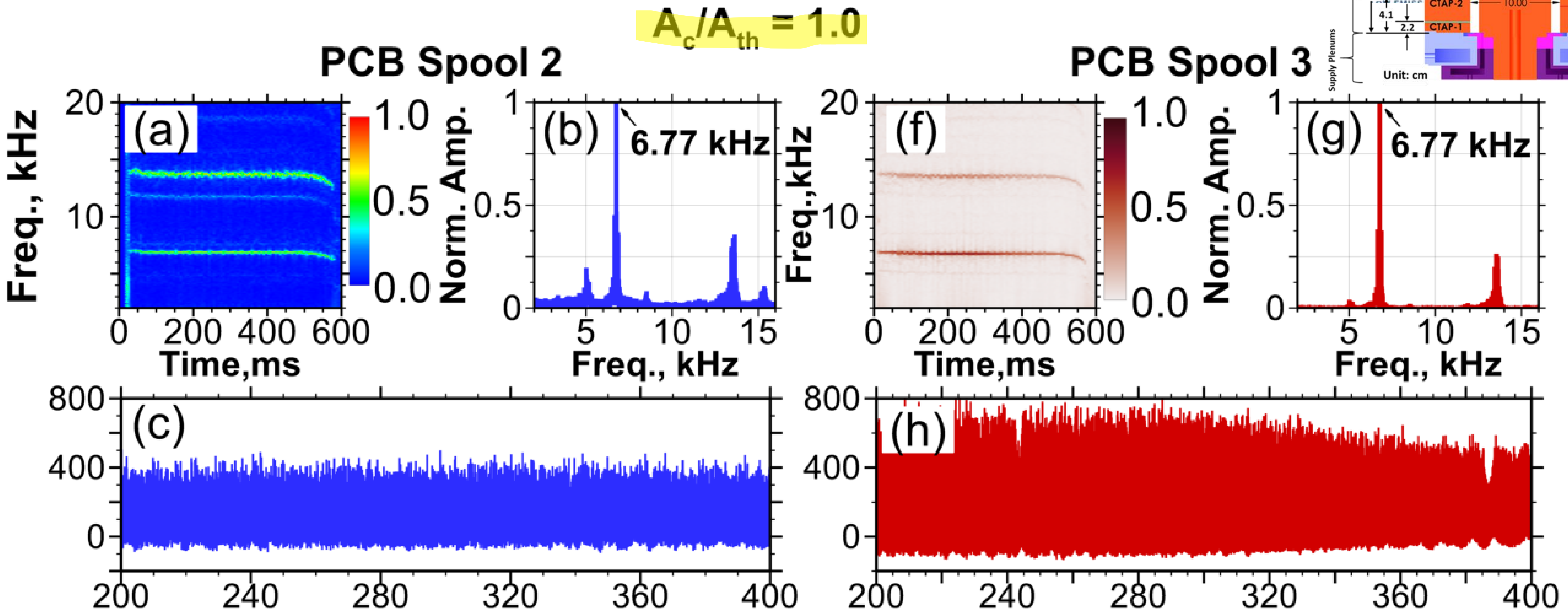
Notice PCB Probe is Placed at the RDC Exit

Test Conditions

Parameter	Value
Backpressure (atm)	1.5-3.5
Total mass flow rate (lbm/s)	0.5, 0.7, 1.0
$A_{combustor}/A_{throat}$	1.0, 2.0
Fuel	CH_4
Oxidizer	O_2/N_2(0.667/0.33 by mole)
Equivalence ratio	1.0

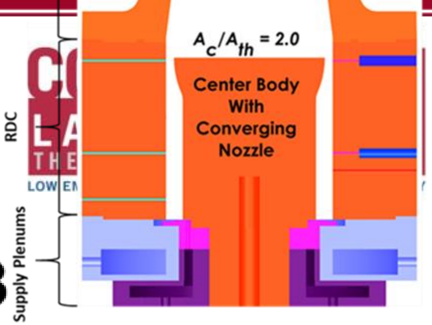
Shock Interactions ($P_{exhaust}$= 3.3 atm)

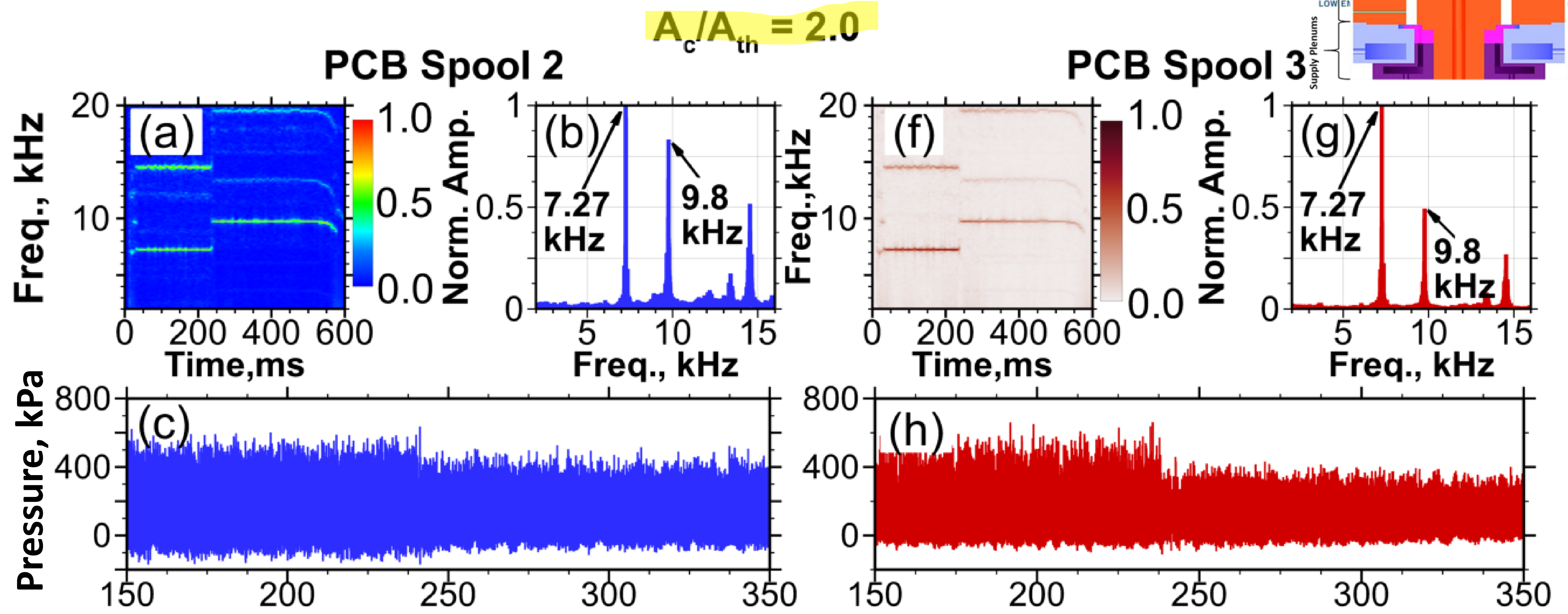




➤Higher pressure oscillations at the exit compared to those inside the RDC indicating coupling with the reflected oblique shock wave.

Combustor Dynamics ($P_{exhaust}$= 3.3 atm)





- Mode shift (single, 7.27 kHz→ double, 9.8 kHz) at ~ 240 ms

Converging nozzle reduces strength of downstream propagating oblique shock & shields RDC from reflected shock

Summary, So Far

Increasing Area Ratio of the converging nozzle (from 1.0 to 2.0) at the RDE exit

- Improves pressure gain (or rather reduces pressure loss) in RDC
- Pressure oscillations decrease, but still remain at the RDE exit
- Flow non-uniformities decrease, but still remain at the RDE exit
- Oblique shock-wave is weaker, but shock still remains at RDE exit

Why not use even higher nozzle area ratio ?

We run into unstable detonation wave modes and shock reflections from the throat

Rapid to gradual (RTG) area profiling alleviates many these challenges

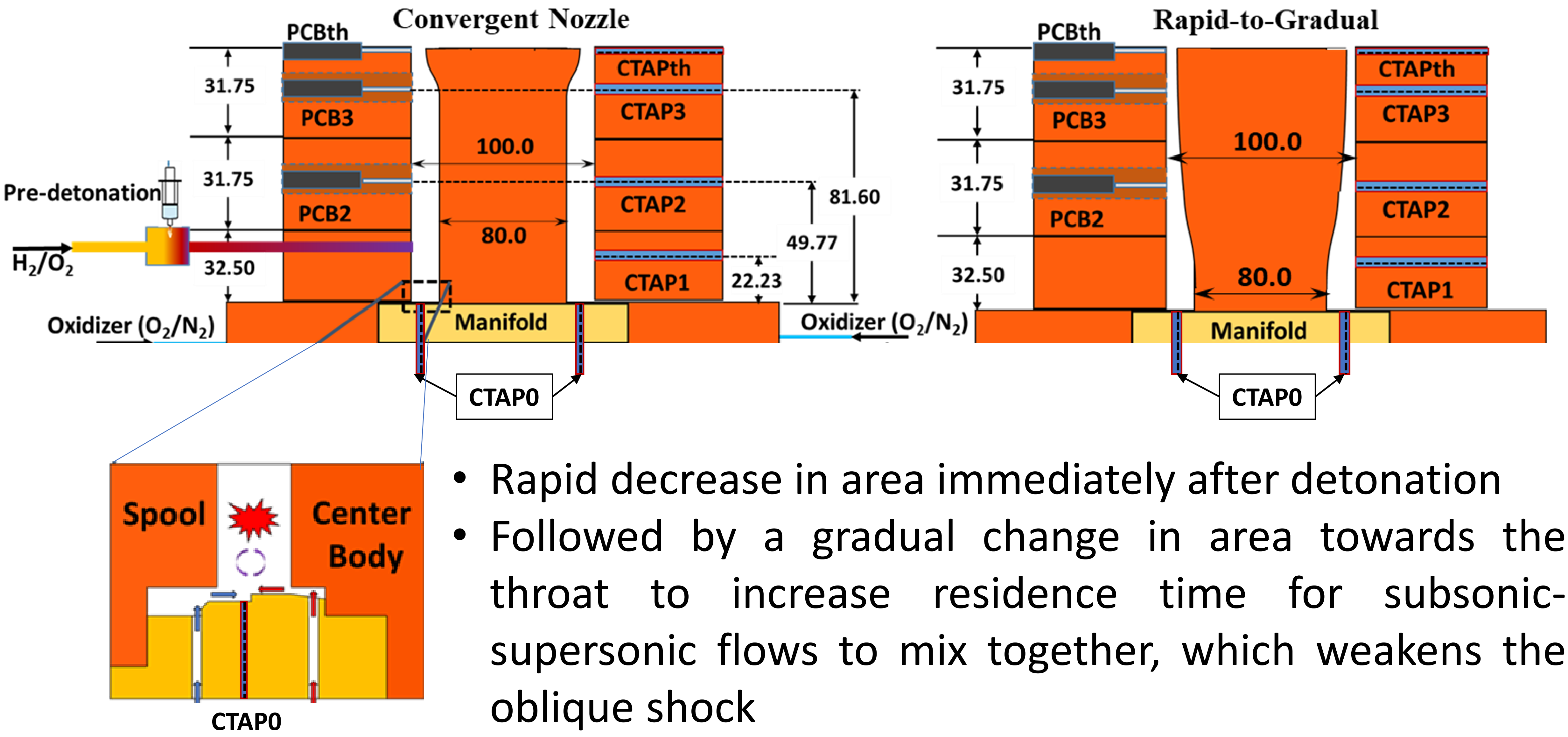
Rapid to Graduate (RTG) Area Profile

Our group introduced this concept in 2021

Bell, K., Schwer, D.A. and Agrawal, A.K., 2021. Effect of Cross-Sectional Area Profiling on the Performance of Disk Rotating Detonation Combustor. In AIAA SciTech 2021 Forum, ***AIAA 2021-1252***.

Bell, K., Schwer, D. and Agrawal, A.K., 2023. Profiling cross-sectional area of a radial rotating detonation combustor to increase pressure gain. ***Aerospace Science and Technology***, 133, p.108096.

RTG Area Profiling



- Rapid decrease in area immediately after detonation
- Followed by a gradual change in area towards the throat to increase residence time for subsonic-supersonic flows to mix together, which weakens the oblique shock

Objectives

- Employs a 3D non-reacting CFD methodology to perform a design of experiment (DoE) study for optimization.
- Objective of the design study:
    - maximizes pressure gain (EAP)
    - minimizes unsteadiness in axial and circumferential velocities.
- Compare results from 3D reacting simulations between the optimized RTG profile and constant cross-section geometry along with the experimental data.

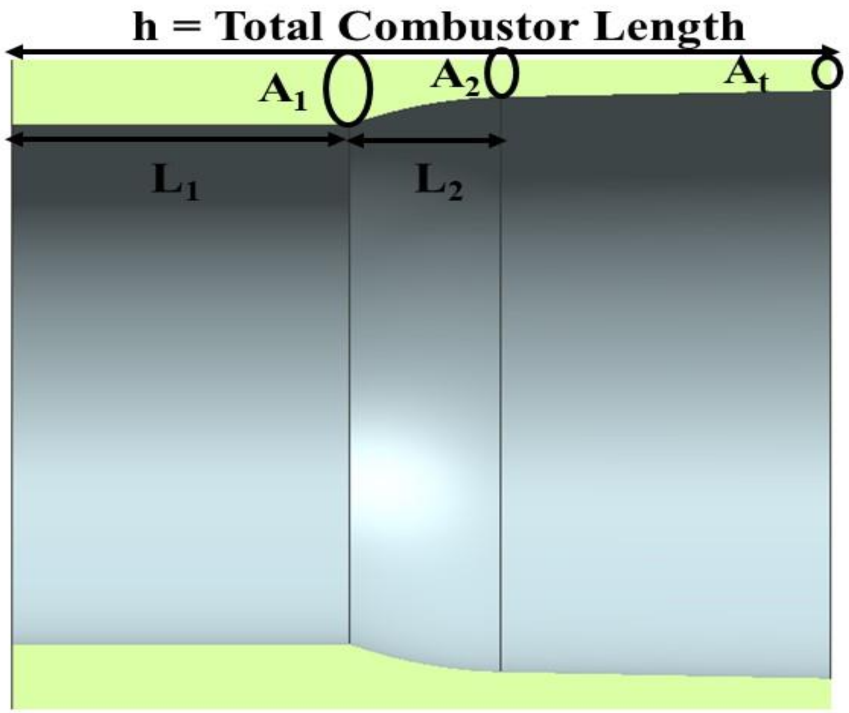
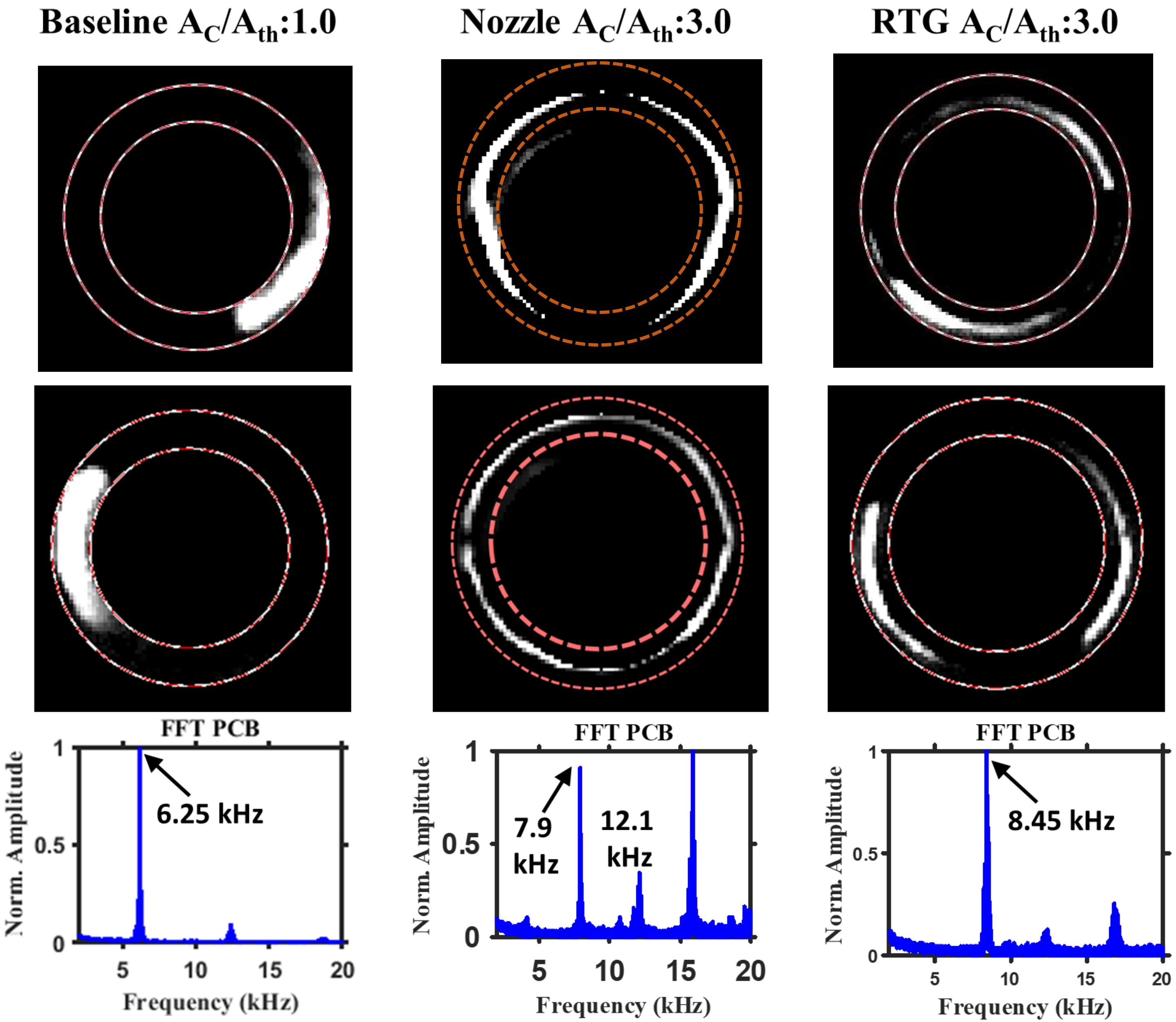


Figure: 3D RTG profile geometry of the RDE

Wave Dynamics of Conventional vs RTG Nozzle

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY



Operating Conditions

$\dot{m}_{total}$ (kg/s)	Fuel	$X_{O_2}^{Ox}$ (%)	φ	A_c/A_{th}
0.32	CH_4	67	1.0	1.0-3.0

Observations

- Baseline (no profile) shows a stable single wave mode operation.
- Convergent nozzles with area ratio >2.0 show unstable operation, two pairs of counter rotating waves for area ratio 3.0.
- RTG profile (area ratio 2.0-3.0) shows stable RDC operation with two corotating waves (8.4-8.7 kHz)

RDC Performance of Conventional vs RTG Nozzles

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

Pressure in kPa

AR	Profile	P_{ox}	P_{fuel}	$CTAP_0$	$\%\Delta P_{inj}$	$CTAP_{th}$	P_{t_th}	$\%PG_1$	$\%PG_2$
3.0	Nozzle	773	942	585	27%	320	520	-34.76	-11.1
	RTG	765	950	570	28%	327	566	-28.44	-0.7

- Assumption: M_{th} = 1.0

$$P_{t\_th} = P_{CTAP\_th}\left(1 + \frac{\gamma - 1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

- **Injector Pressure Drop:**

$$\%\Delta P_{inj} = \left(\frac{(0.86 * P_{ox} + 0.14 * P_{fuel}) - CTAP_0}{(0.86 * P_{ox} + 0.14 * P_{fuel})} - 1\right) * 100$$

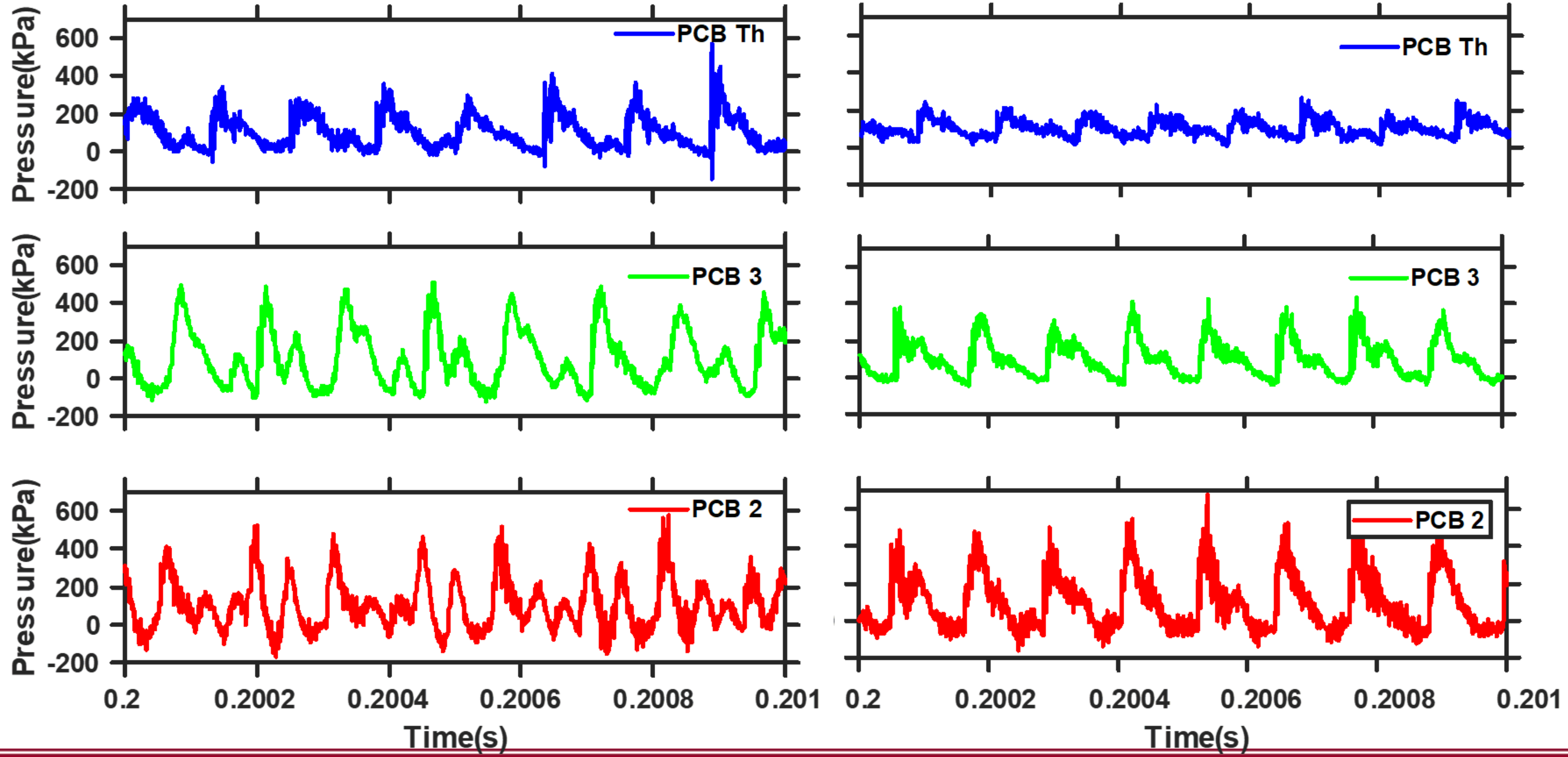
- **Pressure Gain Calculation:**

$$\%PG_1 = \left(\frac{P_{t\_th}}{(0.86 * P_{ox} + 0.14 * P_{fuel})} - 1\right) * 100$$

$$\%PG_2 = \left(\frac{P_{t_{th}}}{CTAP_0} - 1\right) * 100$$

Pressure Oscillations of Conventional vs RTG Nozzle

RTG provides more uniform pressure at the throat

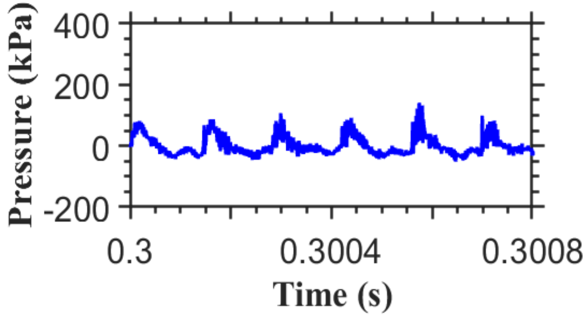


Comparing Pressure Oscillations at the Throat for Conventional vs RTG Nozzle

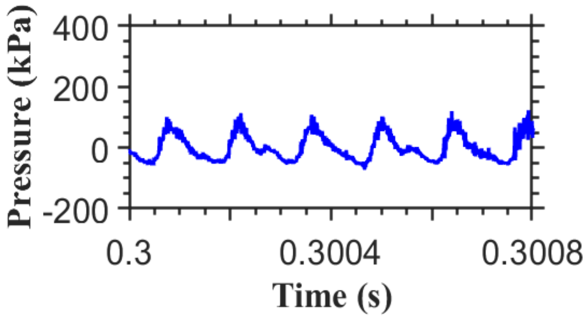
COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

Convergent Nozzle

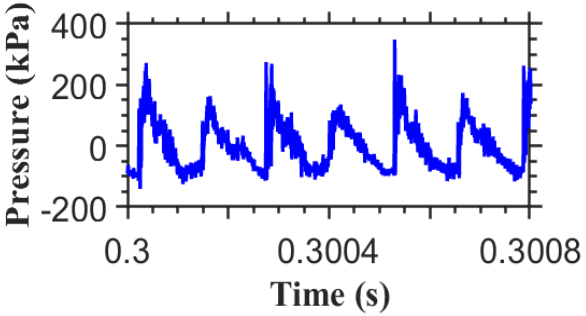
AR 2.0



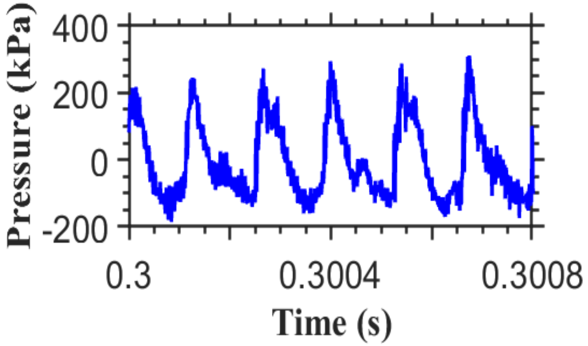
AR 2.5



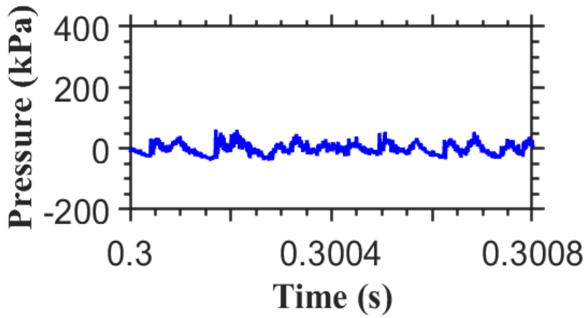
AR 3.0

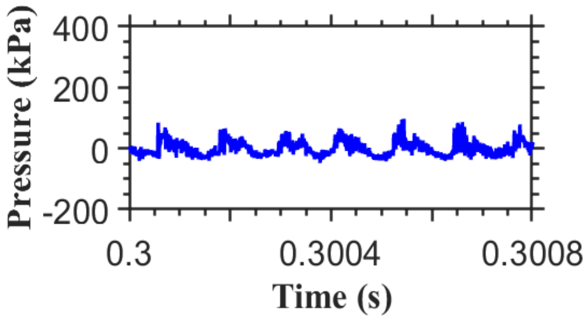


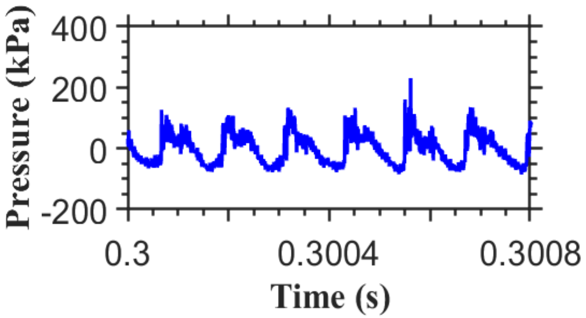
AR 4.0

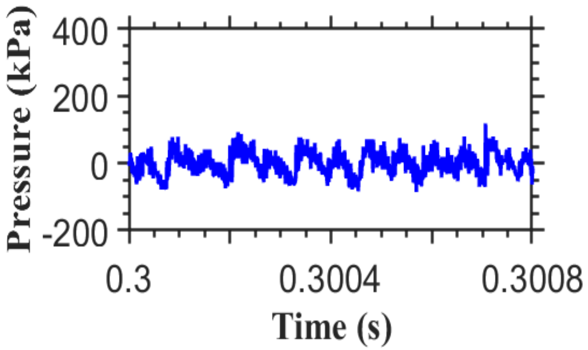


RTG









Benefits of RTG Area Profile

- As AR increases above 2.0, RDC with convergent nozzle demonstrates *unstable wave mode.*

- RDC with RTG profile showed stable two wave mode at higher ARs.

- For a specific AR, RDC with RTG nozzle provides higher performance (pressure gain) compared to an equivalent conventional nozzle.

- Pressure fluctuations at the throat reduce significantly with the RTG nozzle, indicating improved uniformity of the flow leaving the RDC.

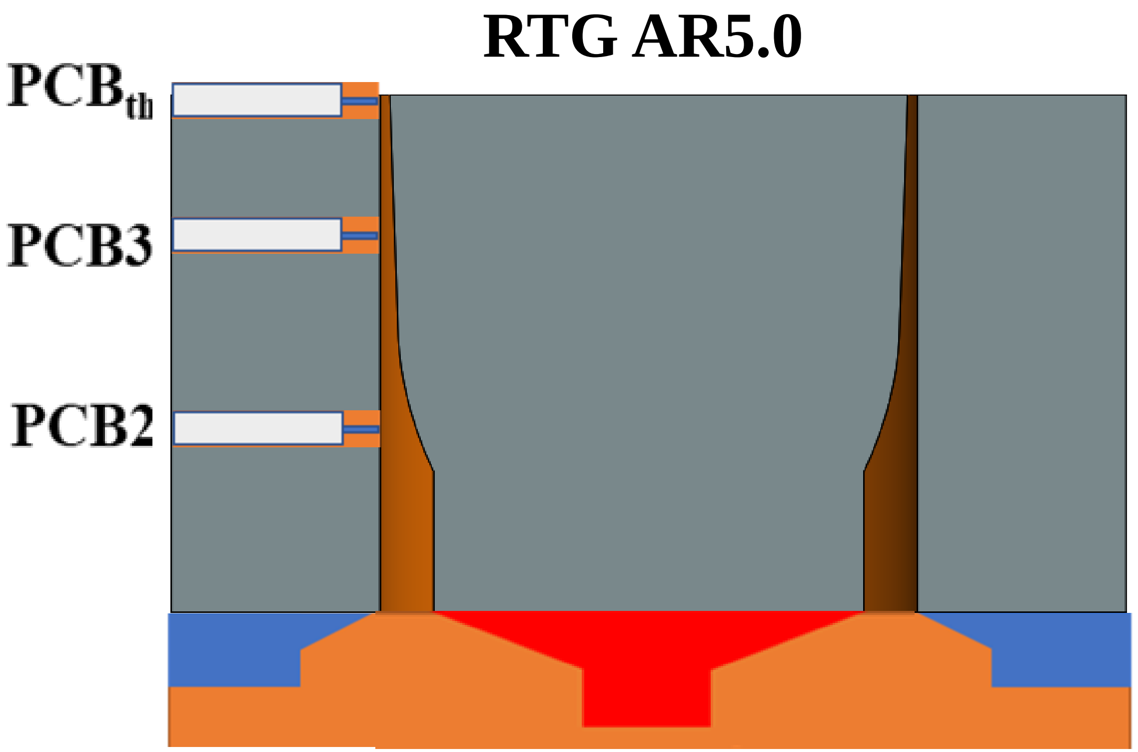
Pushing RTG Nozzle Further to AR5.0

Experiments performed for:

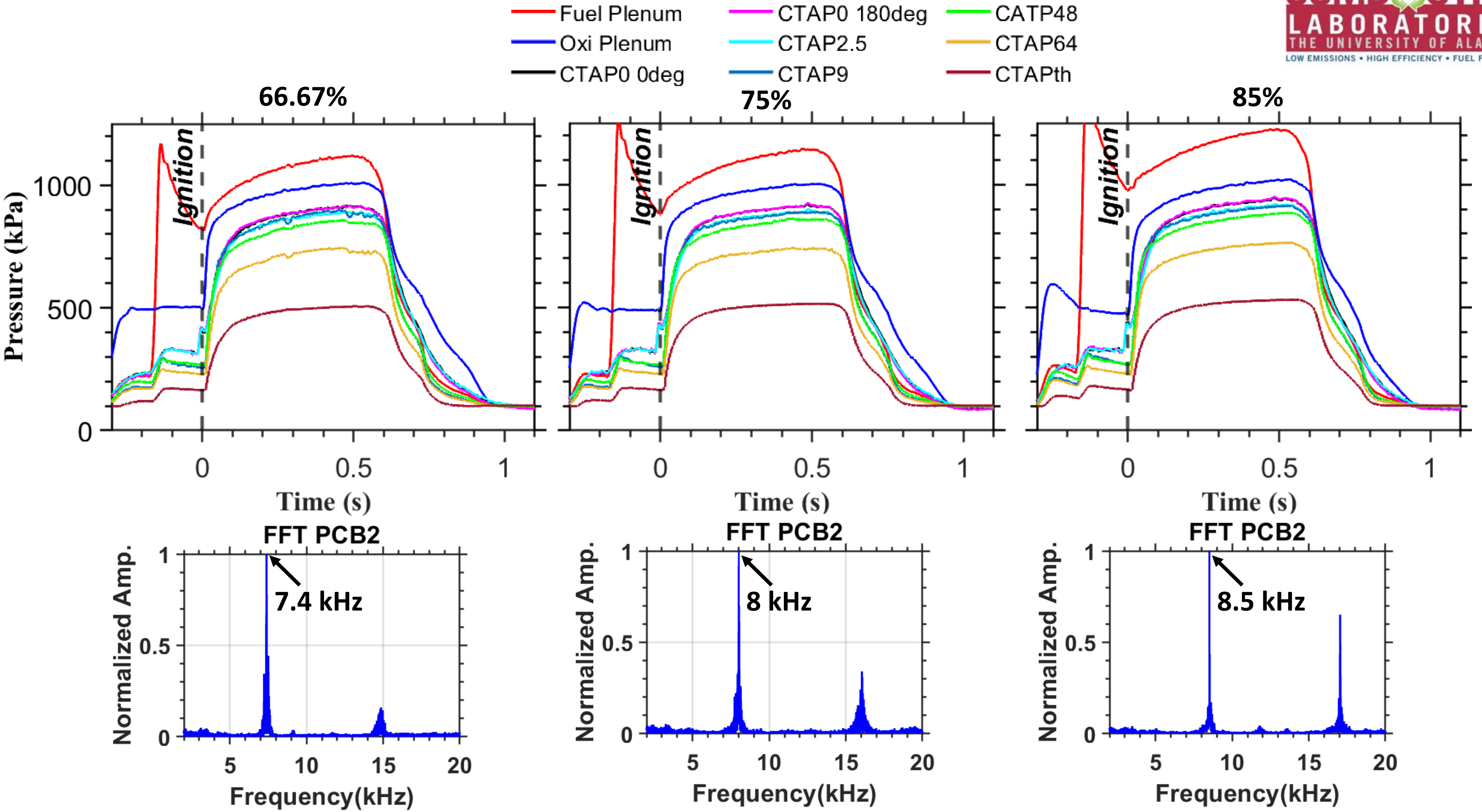
- Varying mass flow rate
  - 0.5, 0.7, 1.0 lbm/s
  - Equivalence ratio = 1.0
  - % O2 = 66.67%

- Varying oxygen content in oxidizer
  - 66.67%, 75%, and 85%
  - 0.7 lbm/s

  Equivalence ratio = 1.0



O2 Variation: Operation of RDC with RTG Profile



RDC Performance Summary: Flow Rate Variation

Pressure in kPa

AR	% O2	P_{fuel}	P_{ox}	$CTAP_0$	$\%\Delta P_{inj}$	$CTAP_{th}$	P_{t_th}	$\%PG_1$	$\%PG_2$
5.0	**66.67**	1107	997	902	10.9%	501	893	**-11.8%**	**-0.2%**
	75.0	1114	982	897	10.5%	507	905	**-9.5%**	**0.81%**
	85.0	1191	995	919	10.6%	521	928	**-9.0%**	**0.85%**

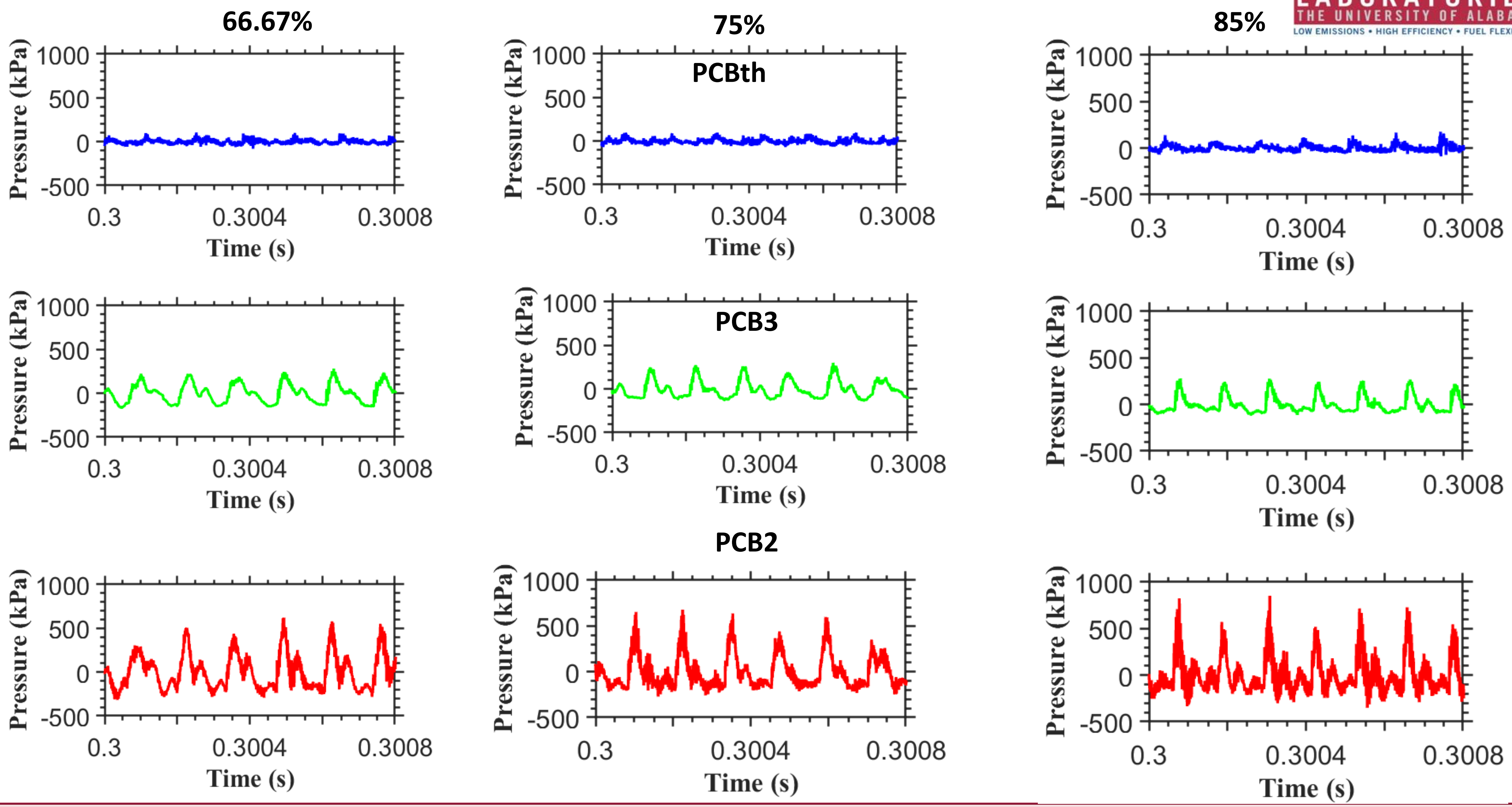
- Pressure Gain Calculation:

$$\%PG_1 = \left(\frac{P_{t\_th}}{(Y_{ox} * P_{ox} + Y_{fuel} * P_{fuel})} - 1\right) * 100$$

$$\%PG_2 = \left(\frac{P_{t_{th}}}{CTAP_0} - 1\right) * 100$$

O2 Variation: Operation of RDC with RTG Profile

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY



Concluding Remarks

- Successful RDC operation requires an integrated approach considering both injectors and downstream components.
- RTG nozzle is superior to conventional nozzle for RDC applications. It provides residence time needed to decelerate supersonic flow and accelerate subsonic flow in the combustor channel.
- RDC can be operated with very high area ratio RTG nozzle
- RTG nozzle eliminates integration problems of RDCs
  - Increased pressure gain, stable wave modes, no shock reflections
  - Highly unform exit flow without oblique shock wave

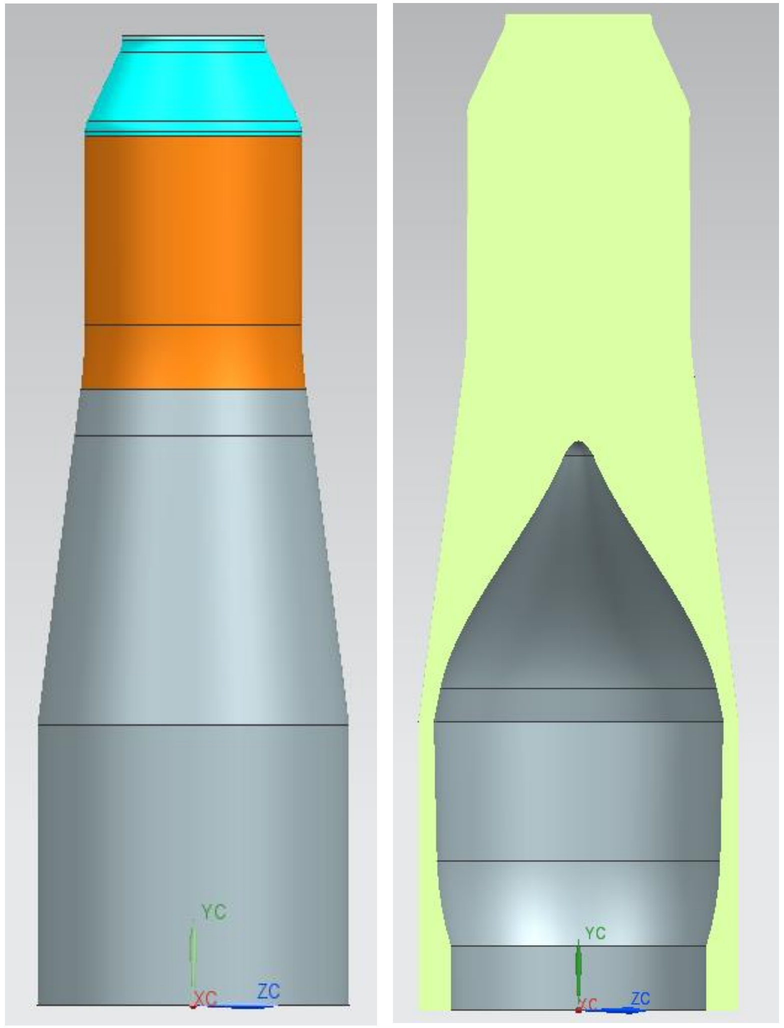
Next question:

- Can we increase the number of waves to further increase the pressure gain?

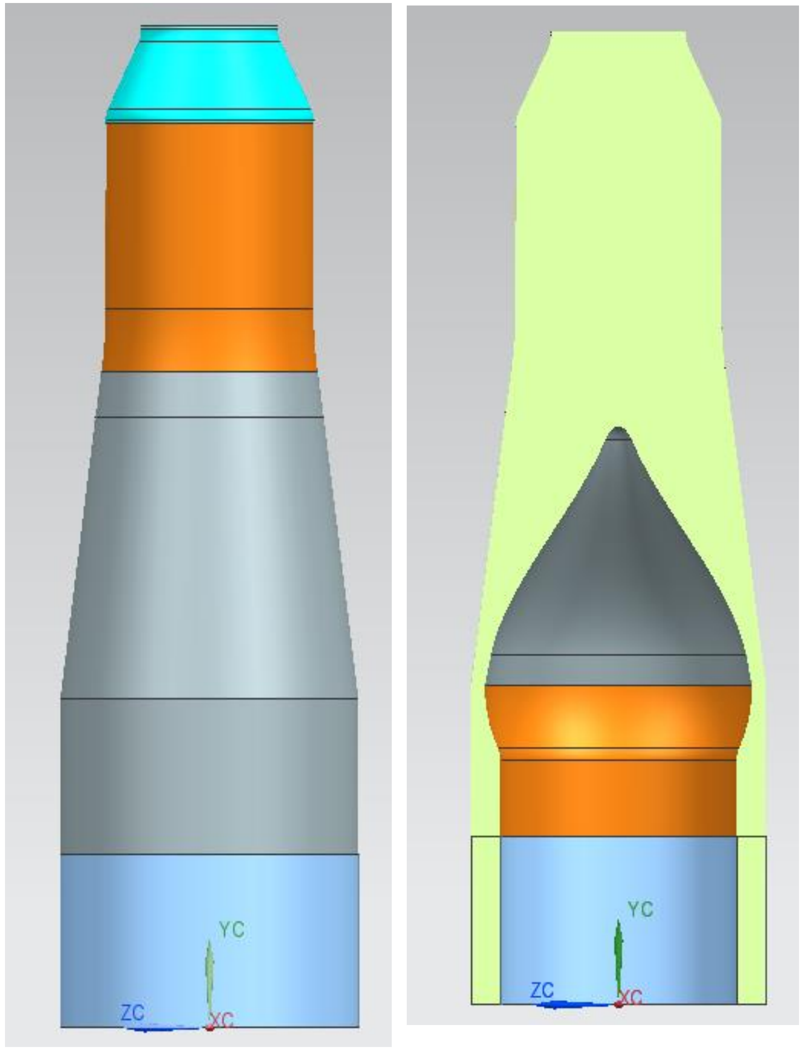
- Large pressure drop across the injector (60%) RTG 5.0: about 10%
- Substantial pressure drop across the combustor (2-19%). RTG 5.0: slight gain
- Pressure oscillations (at 6.3 kHz) remain at the RDC exit RTG5.0: No more
- Unsteady and spatially non-uniform (hydrodynamically and thermally) RDE exit flow with high periodicity. RTG5.0: Likely no more
- RDC exit flow contains oblique shock wave. RTG5.0: No more
- Oblique shock wave – turbine hardware interactions create complex flow structures, including reflected shock waves affecting upstream detonation itself.

RTG5.0: Likely no more

BASELINE DESIGNS WITH PLENUM/DIFFUSER



RTG Nozzle with Downstream Diffuser

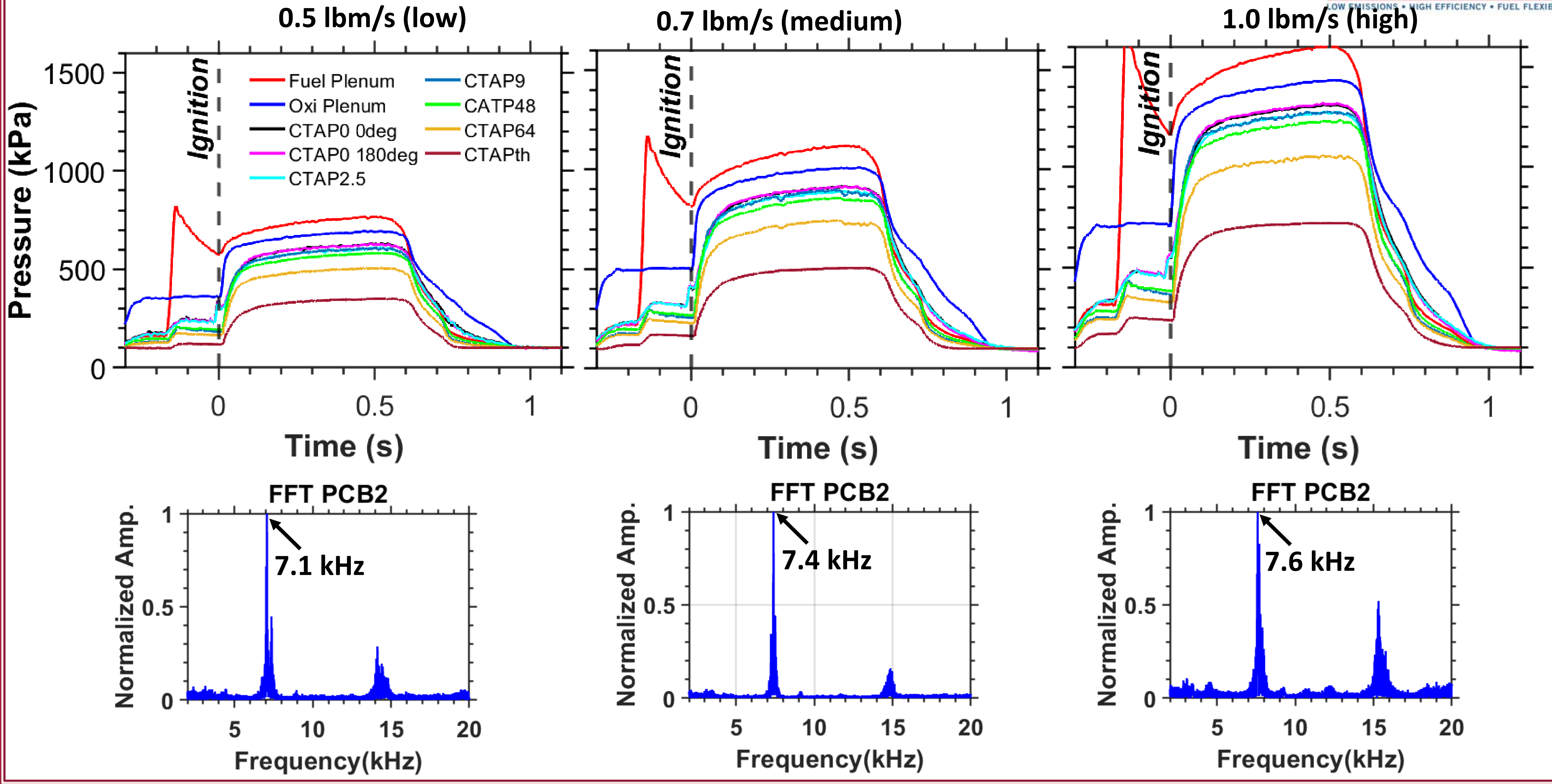


Nozzle Profile

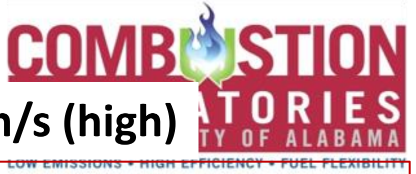
- Baseline RDE design with diffuser and plenum is constructed.
- First design is with RTG profile with throat area ratio of 2.
- Second design is with converging nozzle near the RDE exit with AR = 2.
- 3D reacting simulation is performed to draw comparison analysis between the converging nozzle and RTG profile.

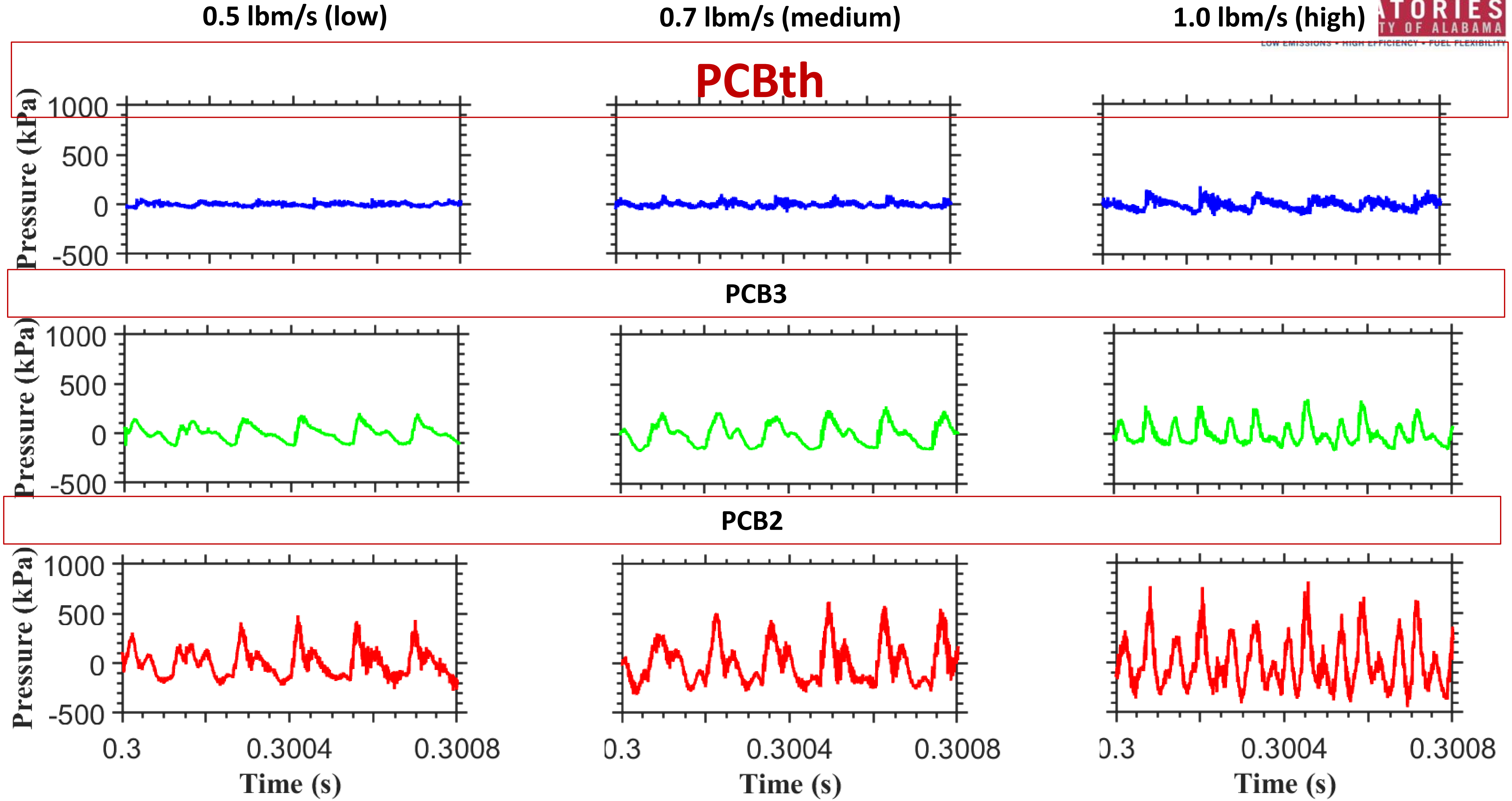
Questions

Flow Rate Variation: Operation of RDC with RTG Profile



Flow Rate Variation: Operation of RDC with RTG Profile





RDC Performance Summary: Flow Rate Variation

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

Pressure in kPa

RTG	Flow Rate (lbm/s)	P_{fuel}	P_{ox}	$CTAP_0$	$\%\Delta P_{inj}$	$CTAP_{th}$	P_{t_th}	$\%PG_1$	$\%PG_2$
5.0	**0.5**	748	678	612	**11.2%**	341	608	**-11.5%**	**-0.7%**
	0.7	1107	997	902	**10.9%**	501	893	**-11.8%**	**-0.2%**
	1.0	1561	1401	1284	**9.7%**	712	1281	**-10.0%**	**-0.2%**

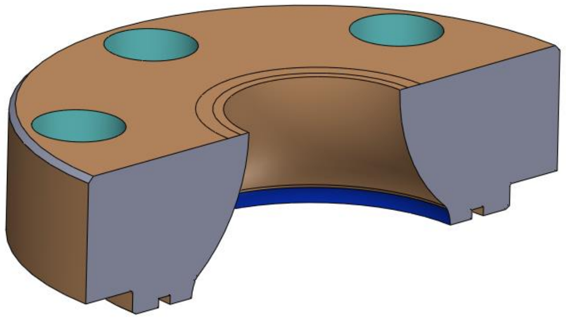
- Pressure Gain Calculation:

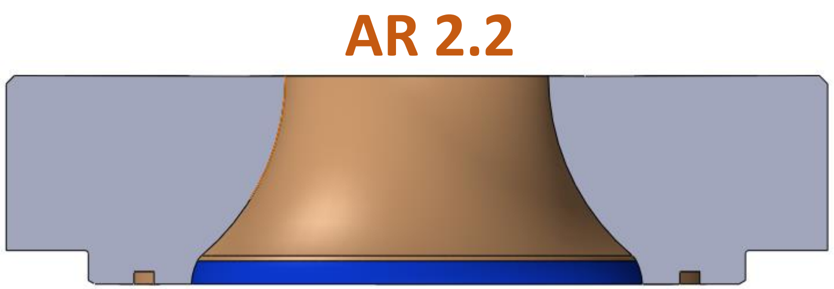
$$\%PG_1 = \left(\frac{P_{t\_th}}{(0.86 * P_{ox} + 0.14 * P_{fuel})} - 1\right) * 100$$

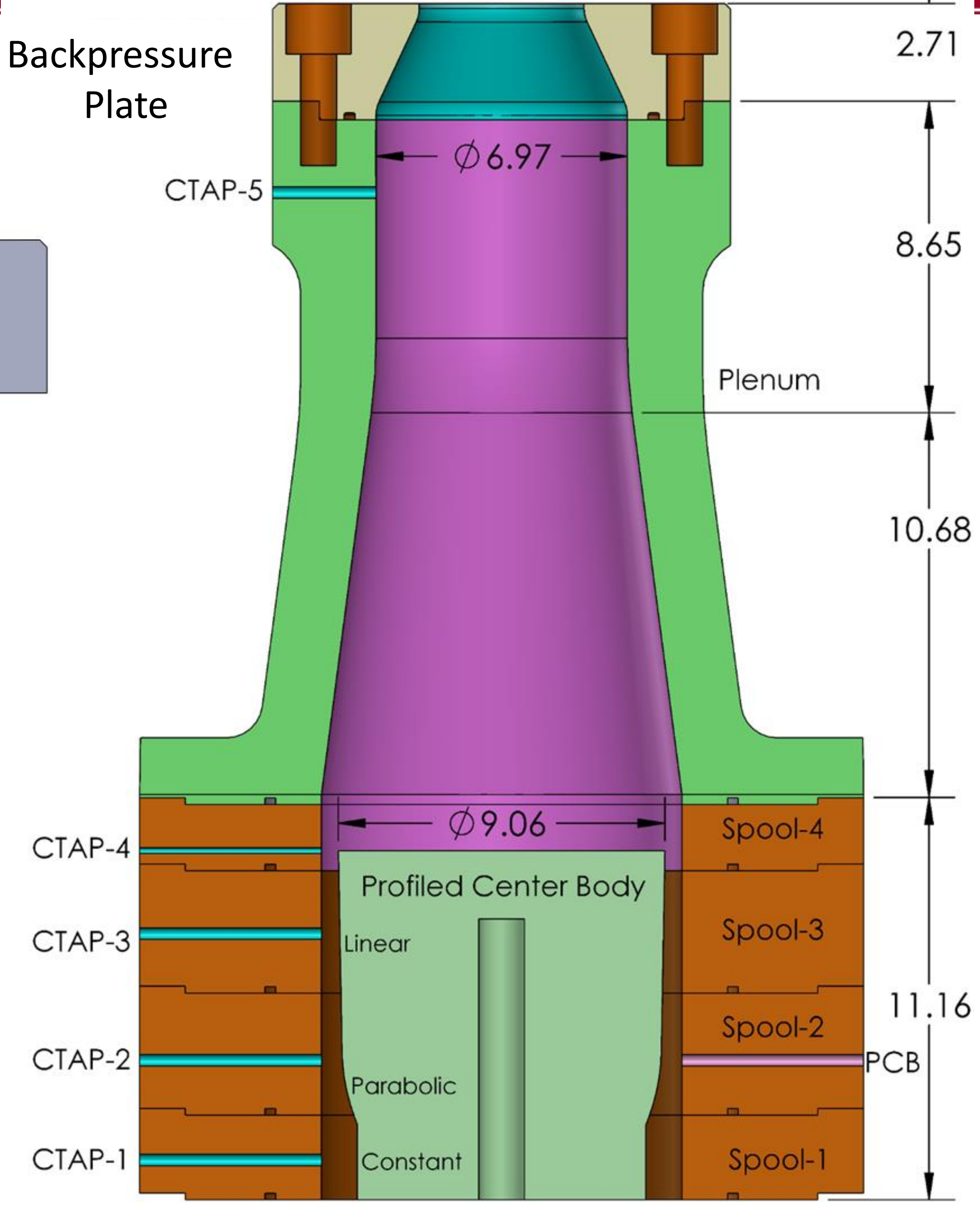
$$\%PG_2 = \left(\frac{P_{t_{th}}}{CTAP_0} - 1\right) * 100$$

Raj, P, & Meadows, J. "Numerical Analysis to Optimize and Study the Impact of Area Profiling on the Performance of a Rotating Detonation Engine." *Proceedings of the ASME Turbo Expo 2023: Turbomachinery Technical Conference and Exposition*. *Volume 3B: Combustion, Fuels, and Emissions*. Boston, Massachusetts, USA. June 26–30, 2023. V03BT04A014. ASME. https://doi.org/10.1115/GT2023-102982

RDC-Downstream Plenum







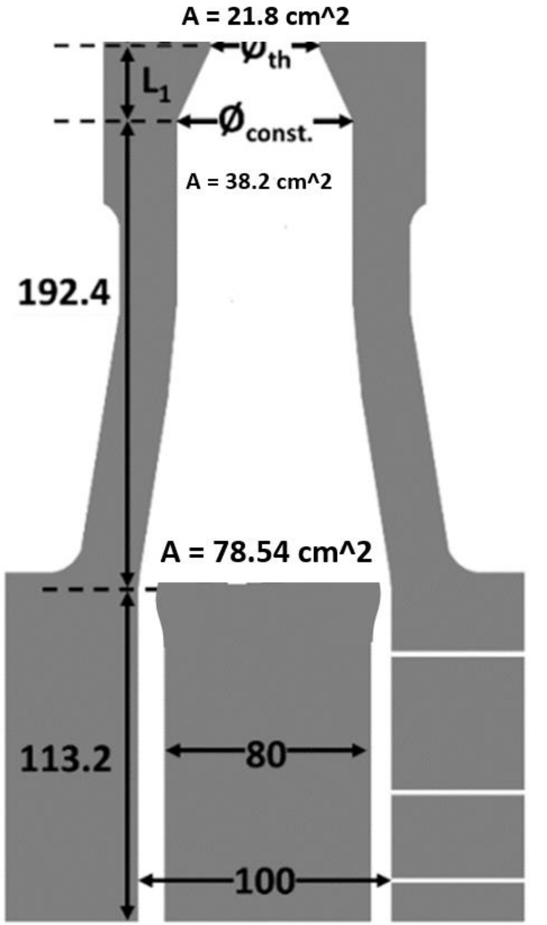
- Backpressure plate:
    - ARs (**1.3**, **1.7**, **2.2**)
- Inner profile:
    - RTG
    - Longer converging nozzle
- Reactants:
    - CH4/O2/Air
    - H2/Air
    - H2/CH4/O2/AIR

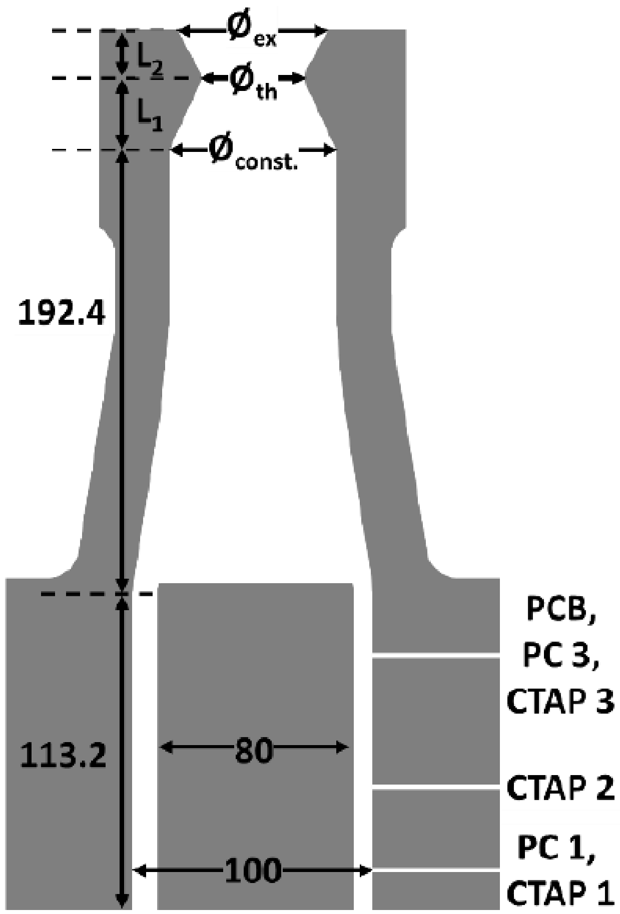
Current back pressurization capability

Exhaust Plenum With Nozzle

RDC Annulus Area = 28.27 cm^2

RDC Throat Area = 14.14 cm^2





Area ratio (AR) is calculated based on annulus area (28.27 cm^2)

CD Nozzle

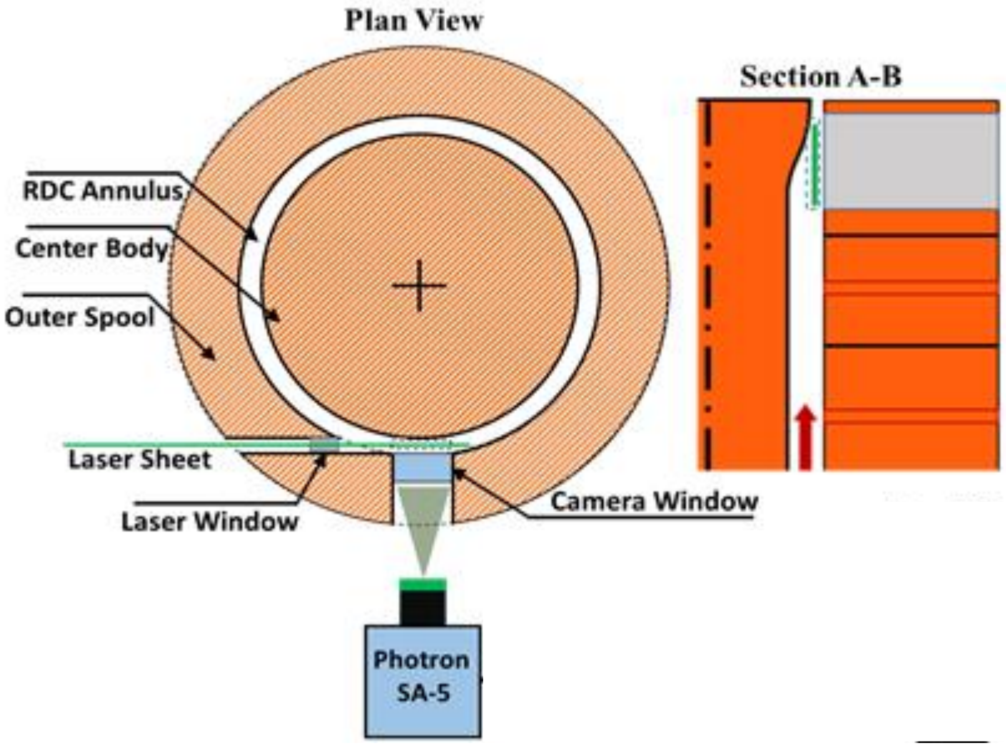
AR_{th} = 1.7 AR_{th} = 2.0

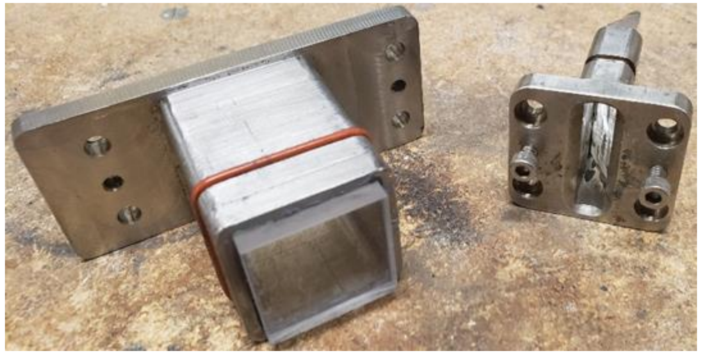
Converging Nozzle

AR_{th} = 1.3 AR_{th} = 2.1

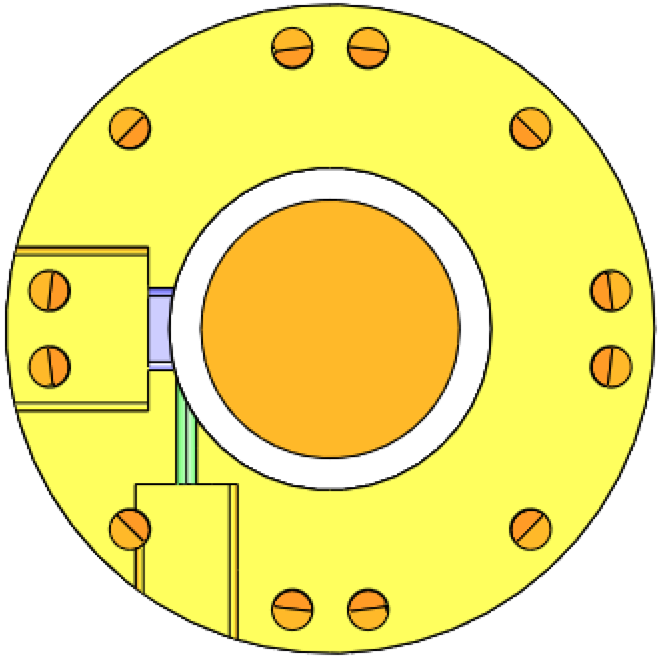
Flow measurements across the Convergent Nozzle

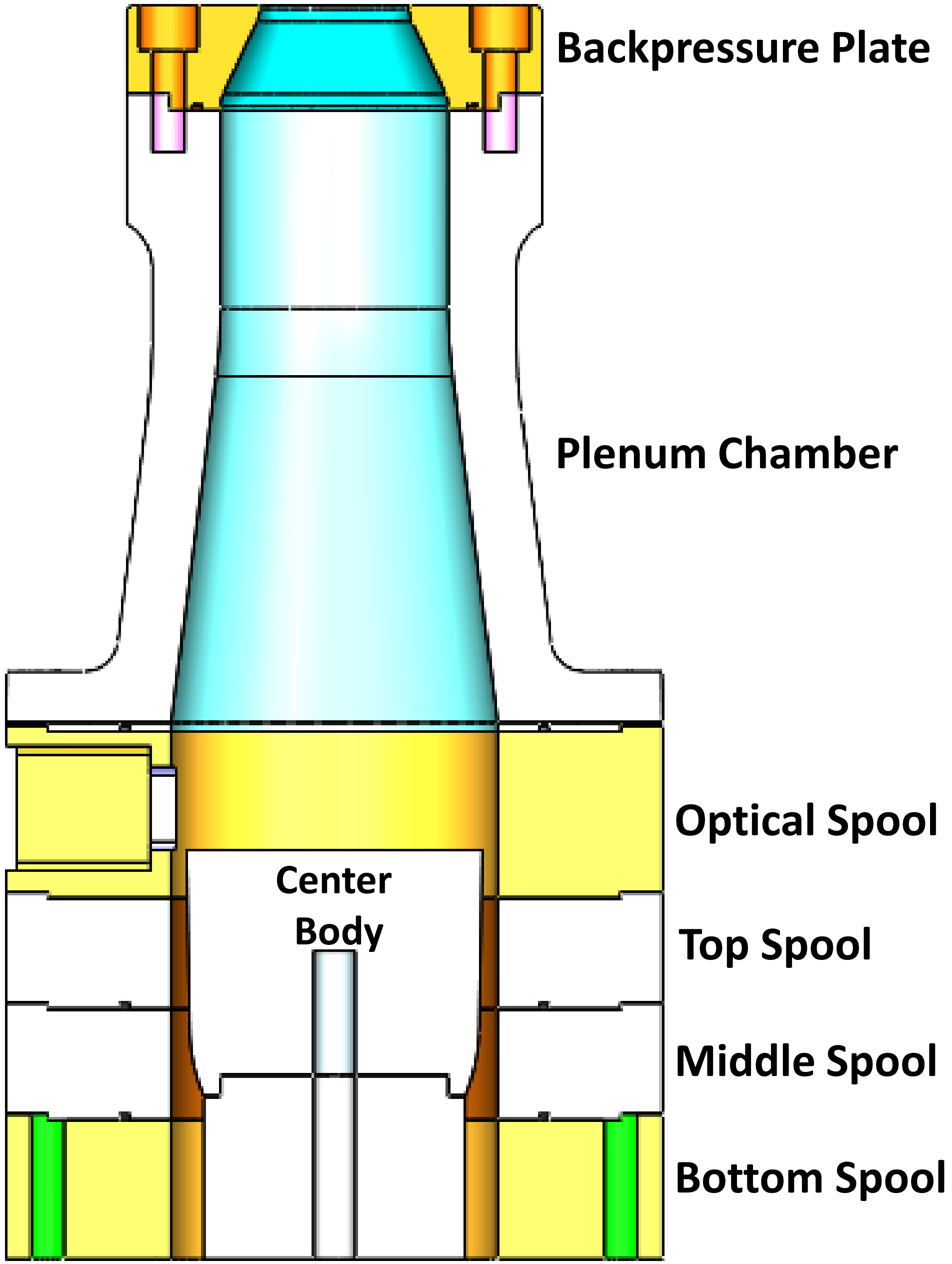
- Use optical spool as third spool
- PIV at RDC exit upstream and downstream
- Previously studied ARs would be tested





RDC-Plenum Assembly w/ Optical Access



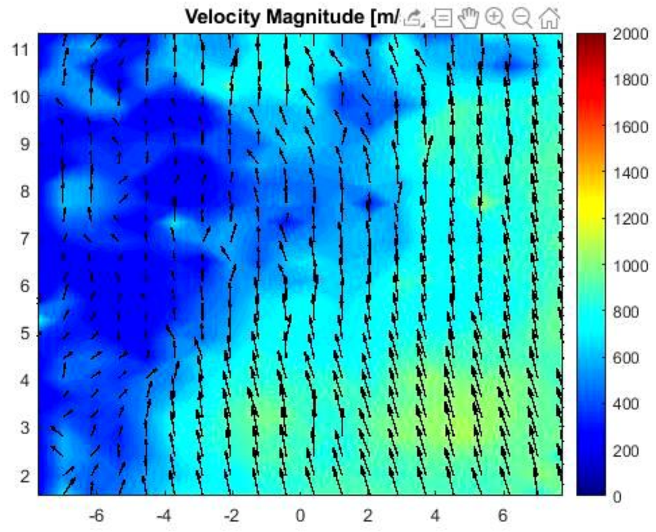


Thank you!

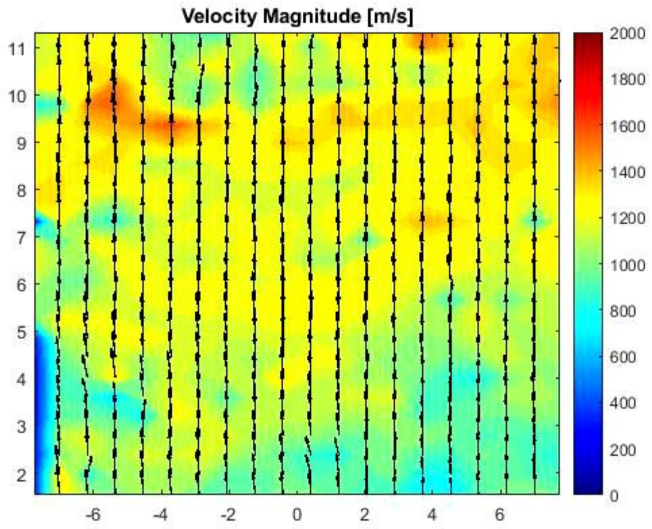
Question?

PIV Video

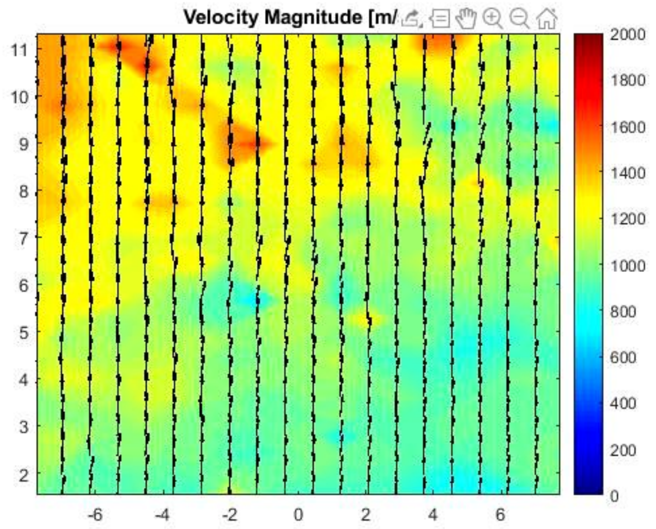
AR 1, CH4, 0.7 lbm/s



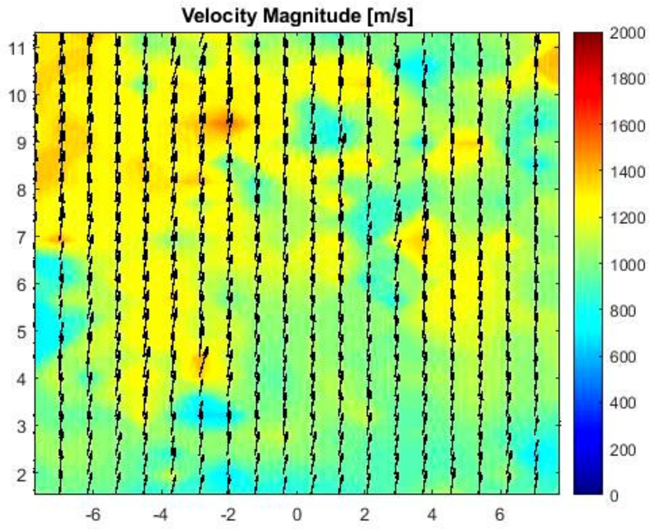
AR 1.7, CH4, 0.7 lbm/s



AR 1.4, CH4, 0.7 lbm/s



AR 2.0, CH4, 0.7 lbm/s



COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

Experimental Condition

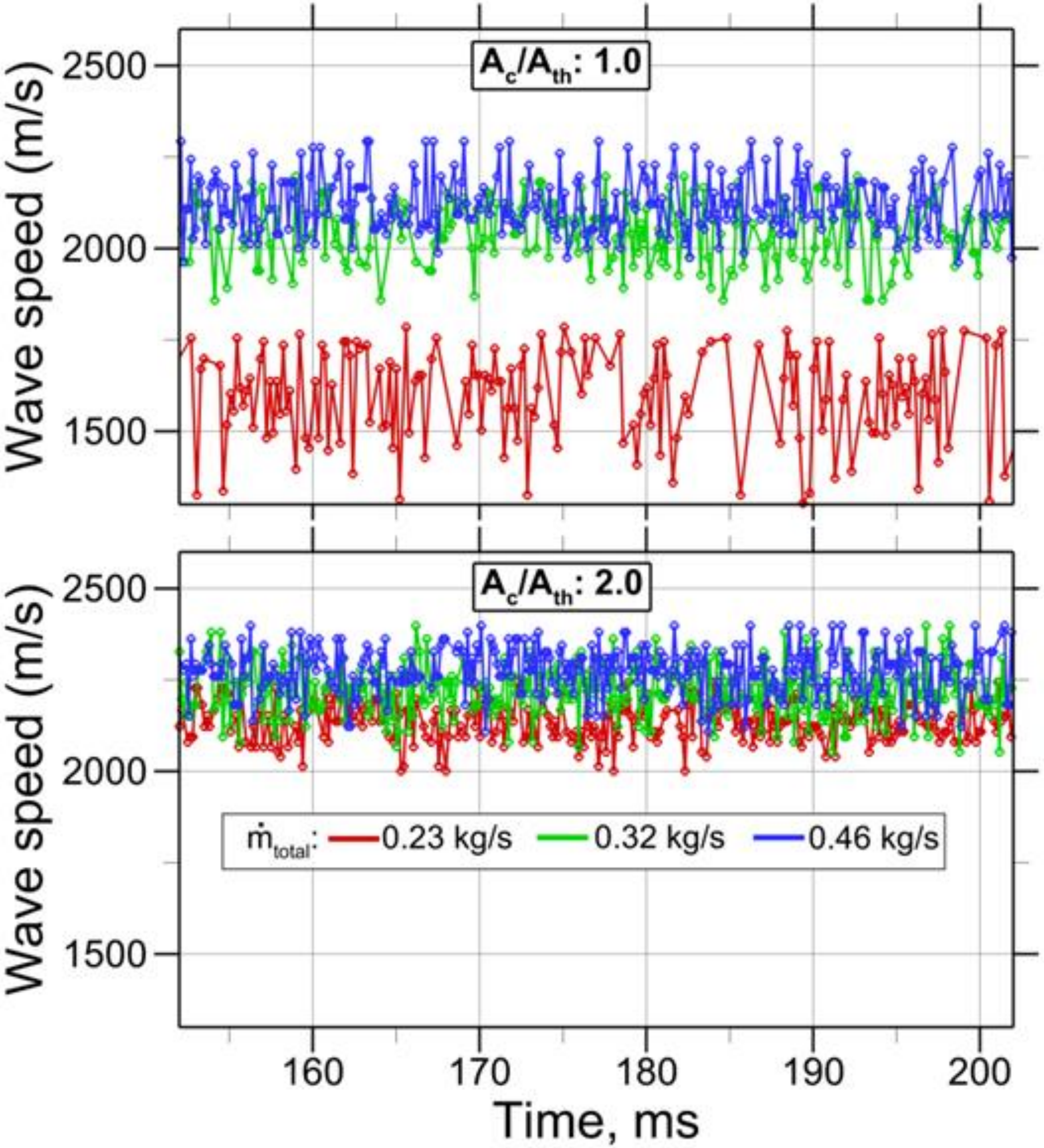
- **Fuel:**
  CH_4
- **Oxidizer:**
  O_2/N_2 (66.6/33.3 %V)
- **Total Mass Flow Rate:**
  0.7 lbm/s
- **Global Equivalence Ratio:**
  1.0

Start Time: ~105 ms after SOI

Video Duration in Actual Test: 0.6 ms

Video Frame Rate: 10 frame/s

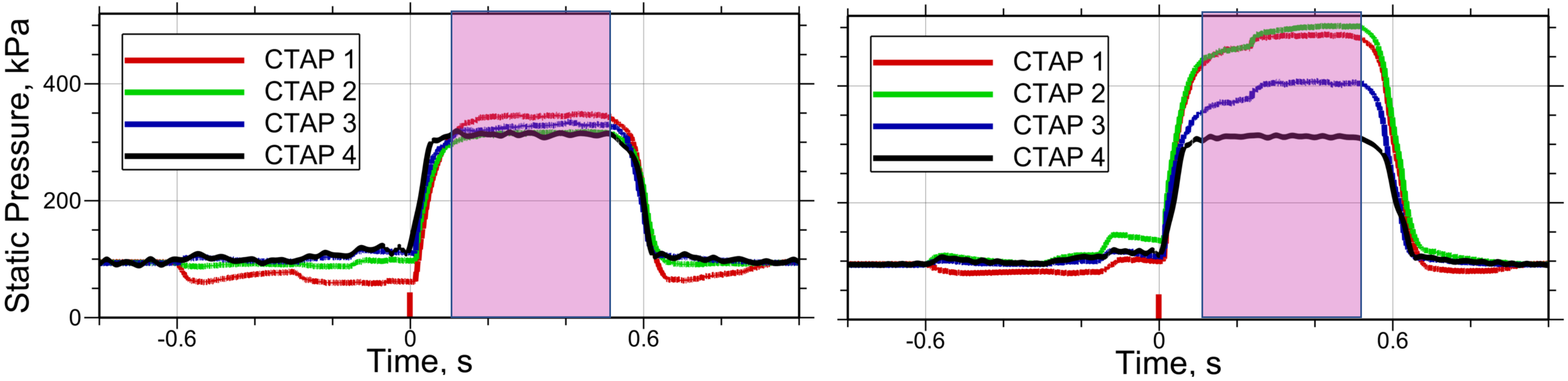
Wave Speed



A_c/A_{th}: 1.0
A_c/A_{th}: 2.0
Wave speed (m/s)
2500
2000
1500
Wave speed (m/s)
2500
2000
1500
$\dot{m}_{total}$: 0.23 kg/s 0.32 kg/s 0.46 kg/s
160
170
180
190
200
Time, ms

CTAP Measurement

$A_c/A_{th} = 1.0$ $\dot{m}_{total}$ = 1.0 lbm/s $A_c/A_{th} = 2.0$



$\dot{m}_{total}$	A_c/A_{th}	P_{oxid}	CTAP 1	CTAP 2	CTAP 3	CTAP 4
0.5	1.0	379	170	148	145	155
	2.0	479	242	236	195	157
0.7	1.0	595	243	216	210	205
	2.0	710	334	332	276	210
1.0	1.0	920	346	318	333	327
	2.0	980	477	484	393	330

% Oxygen	Pressure	$CJ\ Speed\ (m/s)$	$CJ\ Freq.\ (kHz)$	$RDC\ Freq.\ (kHz)$	$\%\ CJ$
66.67	100	**2220**	**7.1**		
66.67	600 (0.5 lbm/s)	**2285**	**7.27**	7.1	**97.5**
66.67	1000 (0.7 lbm/s)	2303	**7.33**	**7.4**	
66.67	1500 (1 lbm/s)	2317	**7.38**	**7.6**	
75%	1000 (0.7 lbm/s)	2360	**7.52**	**8.0**	
85%	1000 (0.7 lbm/s)	2417	**7.69**	**8.5**	

Data Acquisition Capabilities

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

- **Probe Measurement**
  - Pressure at upstream and downstream of sonic nozzle at 1 kHz
  - Temperature at upstream of sonic nozzle at 1 kHz
  - RDC Pressure measurement
    - Plenum Pressure (CTAP) at 1 kHz
    - Injection Plane Pressure (CTAP) at 1 kHz
    - Wall Static (CTAP) and Dynamic (PCB) at 1 kHz and 1 MHz
    - Throat measurement (CTAP and PCB) at 1 kHz and 1 MHz
    - Dynamic pressure (PCB) at 1 MHz
  - Ionization Probe Measurement at 1 MHz
- **High Speed Video/Imaging**
- **OH*/CH* Chemiluminescence**
- **Particle Image Velocimetry (PIV) at 100 kHz**
- **Rainbow Schlieren Deflectometry (RSD) at 300 kHz**

Key Findings

- The exhaust flow field of baseline case shows **high temporal and spatial flow non-uniformity** in both axial and non-axial directions. However, a significant improvement of flow non-uniformity was achieved by placing a convergent nozzle at the annulus exit.

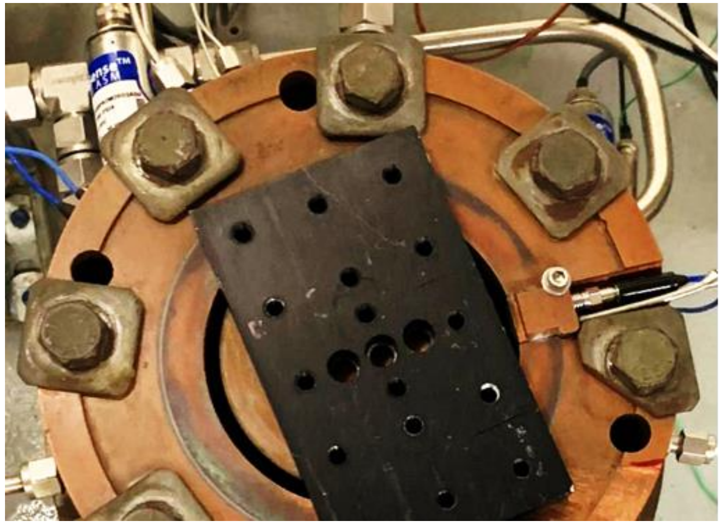
- Even with a convergent nozzle of AR2.0, the flow at the exit throat is not fully choked, showing conventional exhaust nozzles might not be suitable for RDC flows.

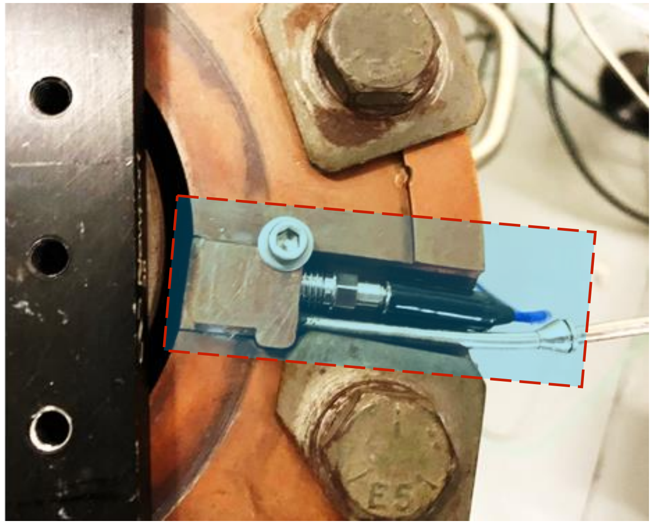
- Instead**, profiling the entire RDC channel** could effectively choke the flow since it provides a longer residence time for mixing subsonic/supersonic flow segments.

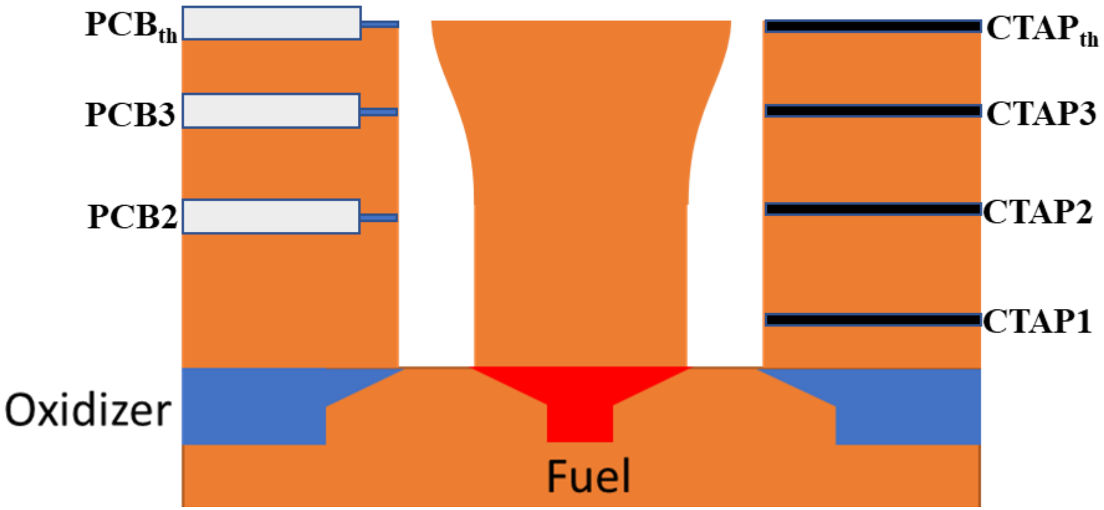
Presentation Overview

- Operation of RDC for two exit configurations integrated with a downstream pressurized plenum.
- **High speed probe (PCB/Kulite) measurement at RDC throat as a measure of unsteadiness.**
- Inner wall profiling of RDC channel to improve performance and reduce flow unsteadiness at the RDC exit.
- Upcoming plans.

Throat Measurement



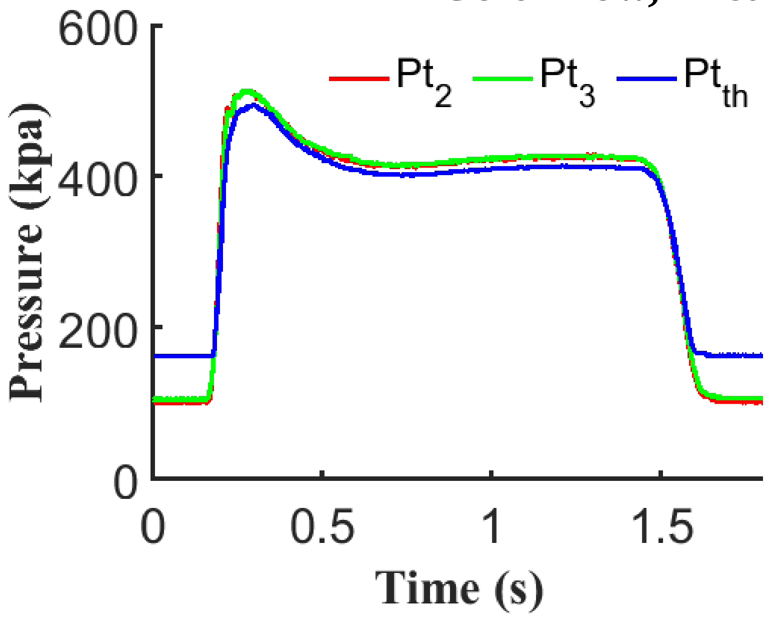


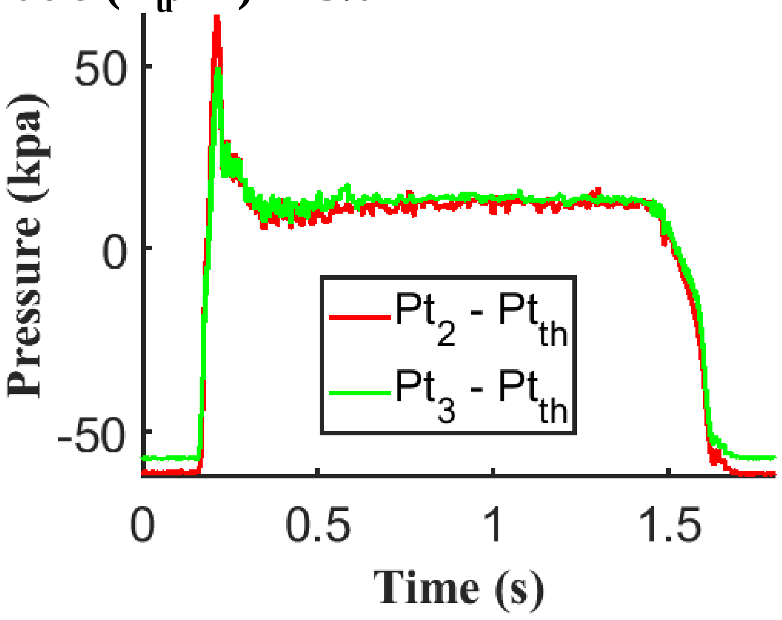


- PCB measurements along the RDC channel shows the behavior the unsteadiness as the flow moves downstream.
- Direct pressure measurements (CTAP and PCB) at the throat.
- Assess **NPS method** (proposed by Brophy) using **cold flow and hotfire** RDC testing.

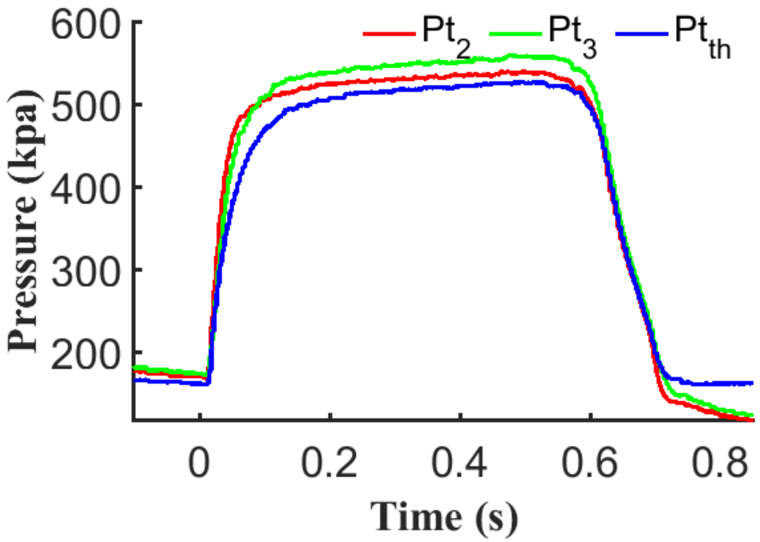
Total Pressure Using NPS Method: Cold Flow Vs Hotfire

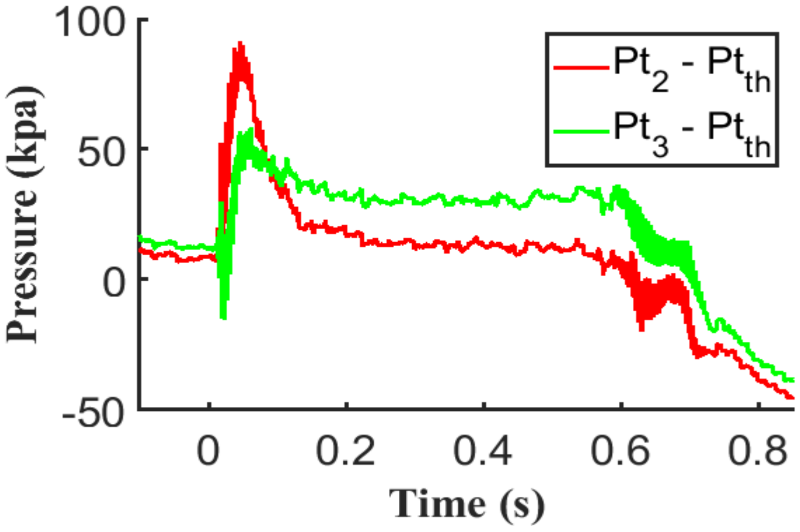
Cold Flow, Area Ratio (A_u/A^*) = 3.0

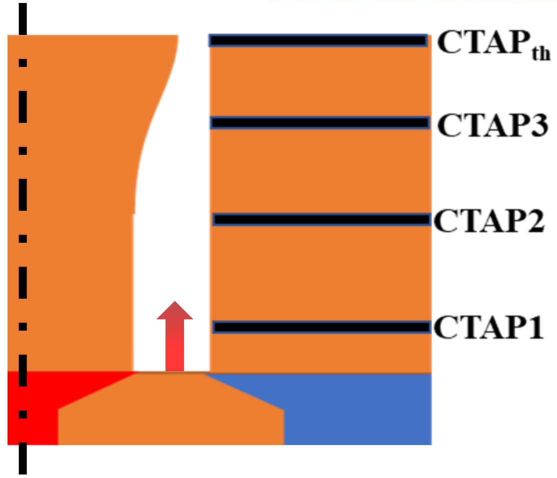




Hotfire, Area Ratio (A_u/A^*) = 3.0







For throat:

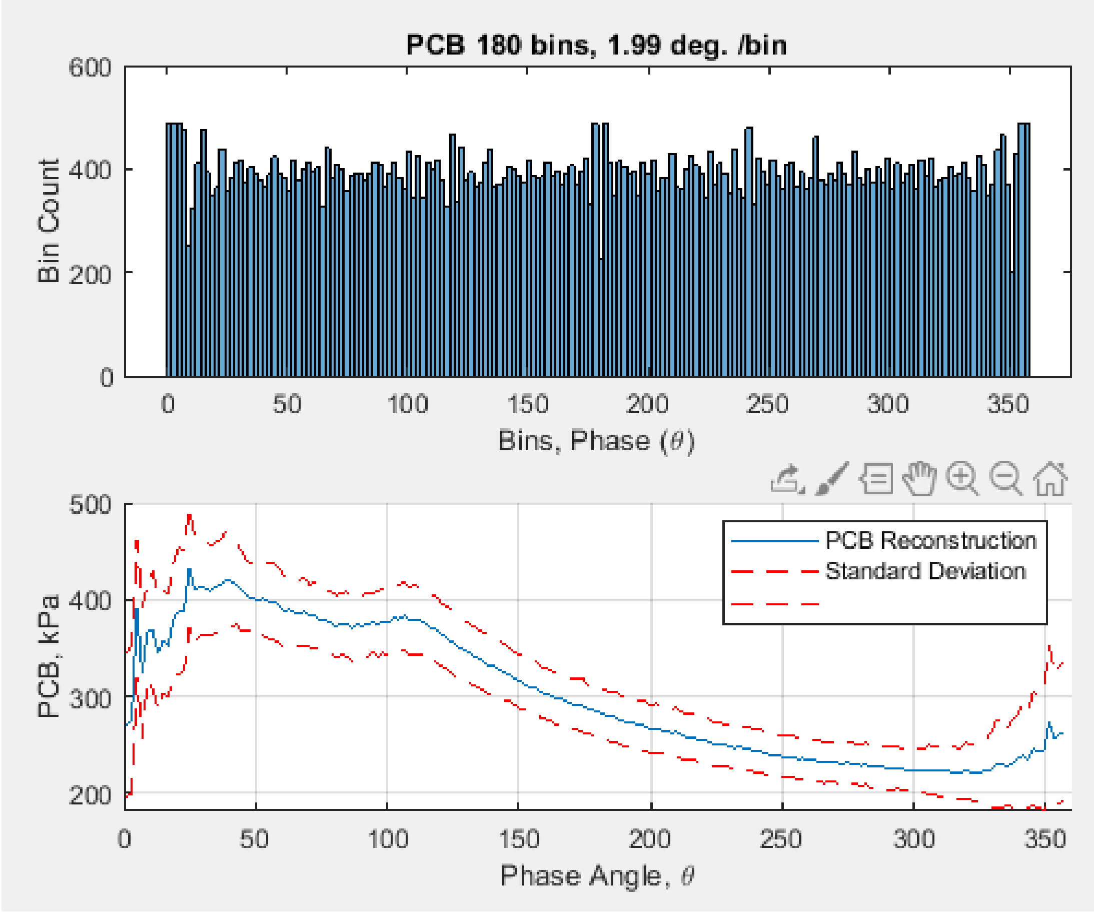
$$P_{t\_th} = P_{CTAP\_th}\left(1 + \frac{\gamma - 1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

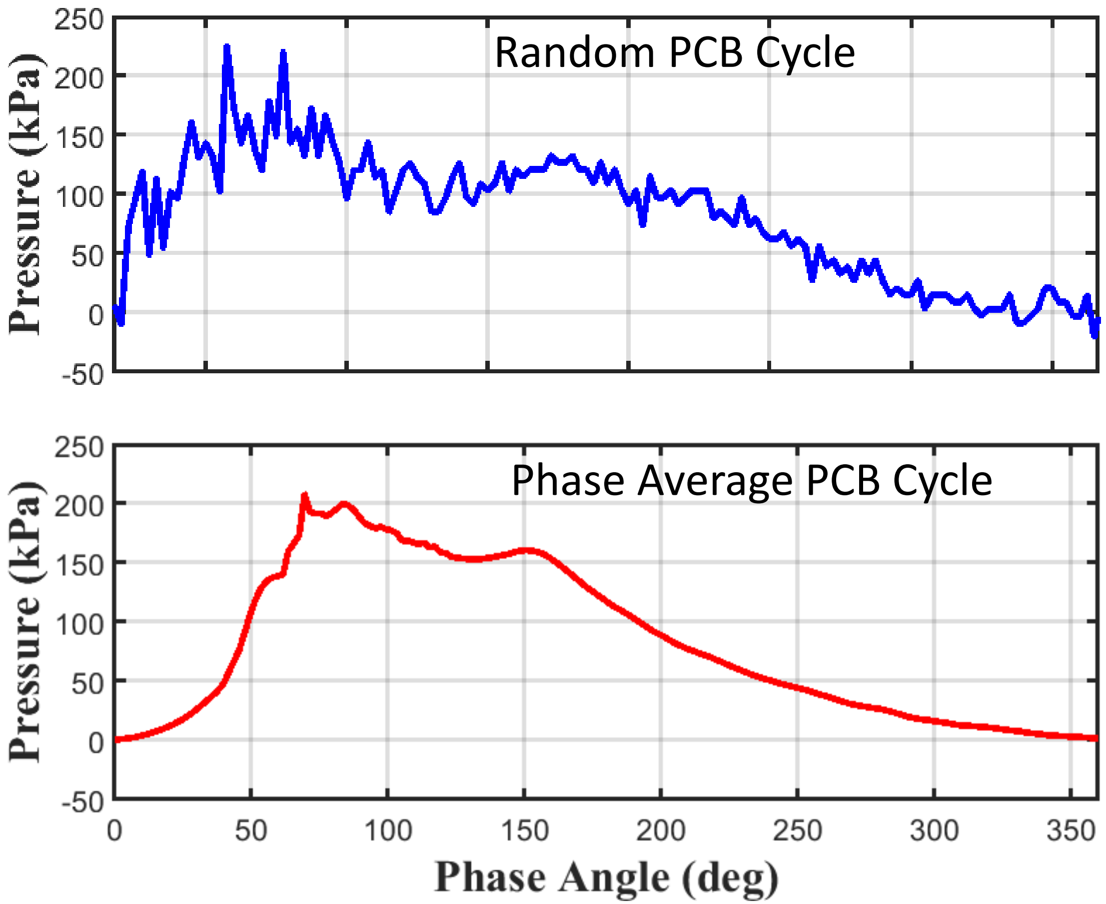
For other axial locations:

$$P_{tx} = P_{CTAPx}\left(1 + \frac{\gamma - 1}{2} M_x^2\right)^{\frac{\gamma}{\gamma-1}}$$

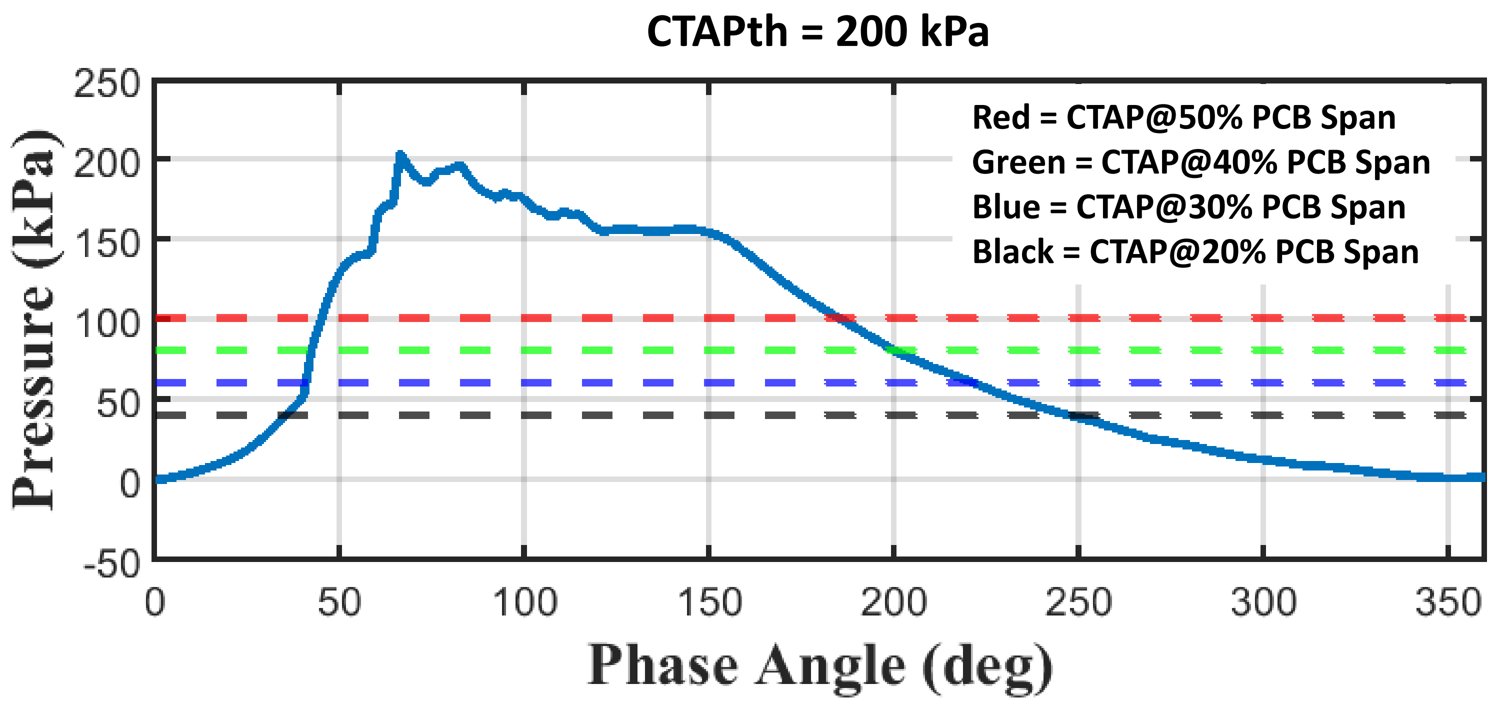
- M_2 and M_3 are calculated using area ratio (A_u/A^*) relationship
- $\gamma_{coldflow}$ = 1.4 and $\gamma_{hotfire}$ = 1.22 (CJ)

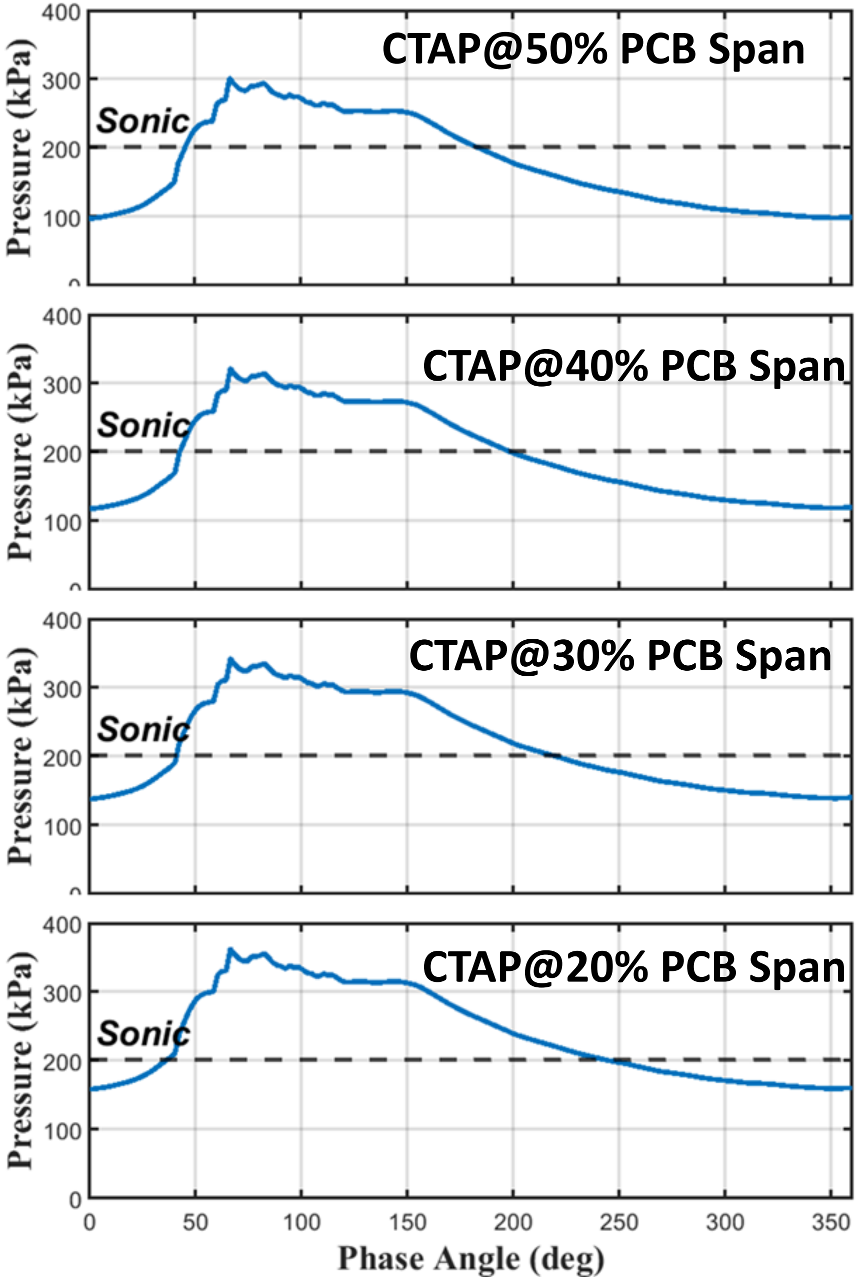
Phase Averaged PCB Cycle





CTAP+PCB for Nozzle (AR2.0)

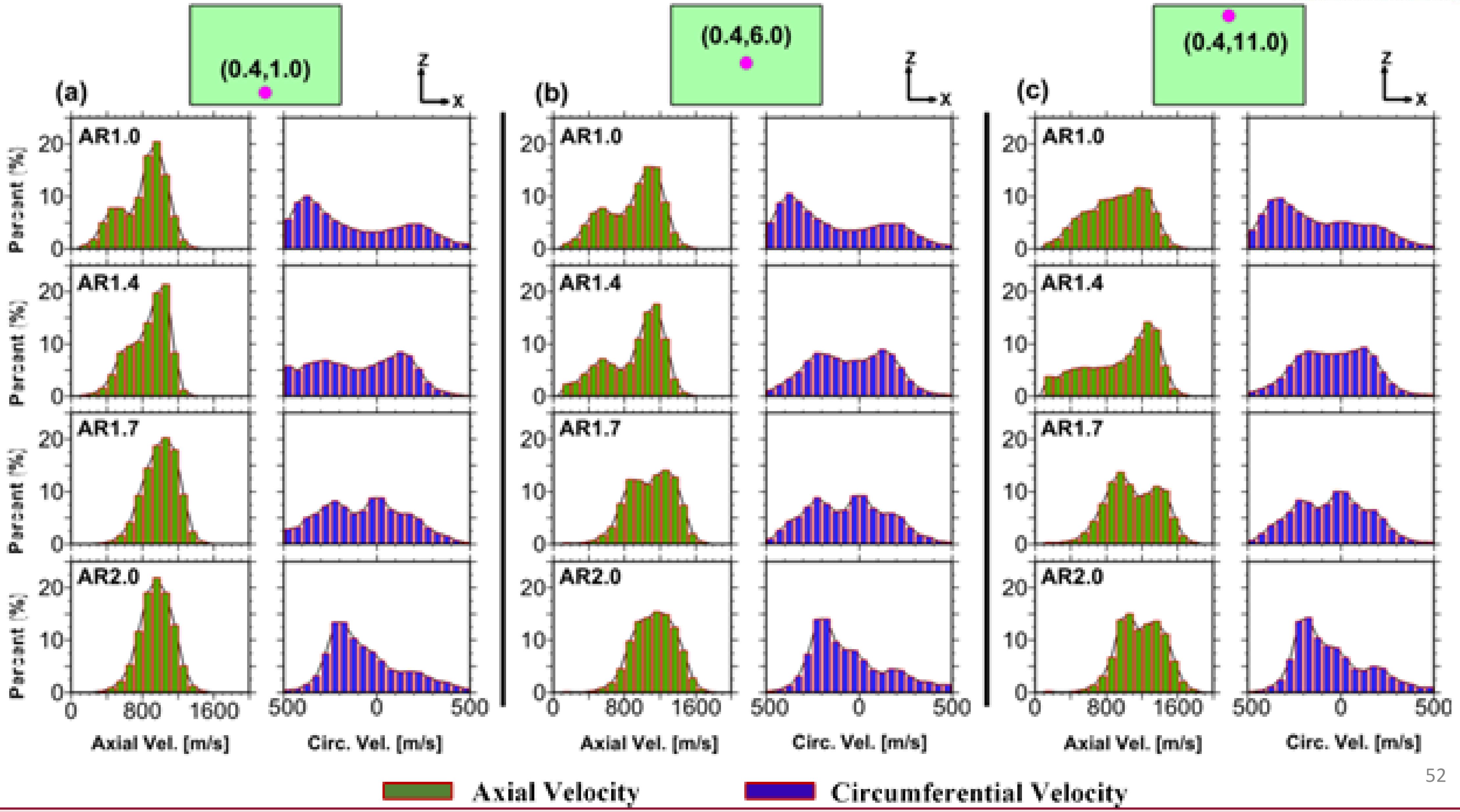




Key Findings - Initial

- For cold flow and $A_u/A^* \geq 3.0$, Mach-corrected method shows a good agreement between total pressure at throat and any other upstream location, manifesting a choked flow at nozzle throat.
- For hotfire, there is ~50 kPa difference between $\boldsymbol{P_{t\_th}}$ and $\boldsymbol{P_{t2}}$.
- This deviation could be attributed to:
  - The flow is *not fully choked* at the nozzle throat for hotfire case.
  - The upstream flow is transonic (sub-/supersonic), and hence the M_u calculation assuming subsonic upstream flow results further error.

Flow Statistics for Full 600 ms Test



Pressure Measurement