Advanced Cost-effective Coal-Fired Rotating Detonation Combustor for High Efficiency Power Generation

DE-FE0031545

Kareem Ahmed[1], Subith Vasu[1], Suresh Menon[2]
[1]University of Central Florida, Orlando, FL
[2]Georgia Tech, Atlanta, GA

PM: Dr. Seth Lawson

Industry Partners: Aerojet Rocketdyne (Dr Scott Claflin)
ISSI (Dr. John Hoke)
AFRL (Dr. Fred Schauer)
Siemens (Timothy Godfrey)

2019 UTSR Meeting

Outline

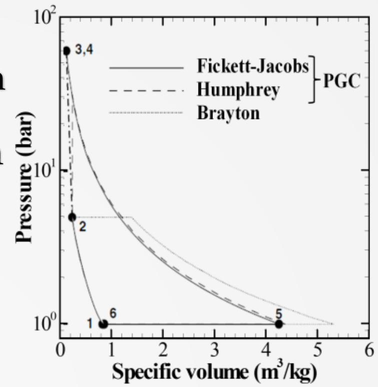
- Background
- Project Objectives
- Technical Approach
- Project Structure and Management
- Project Schedule

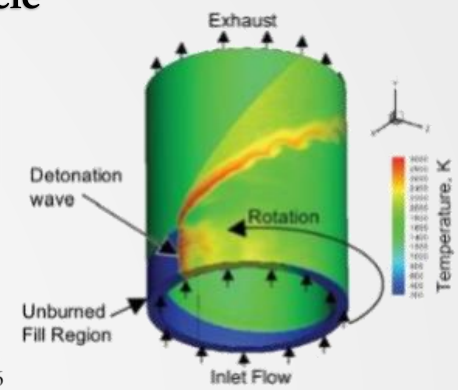
Pressure Gain Combustion

Detonation

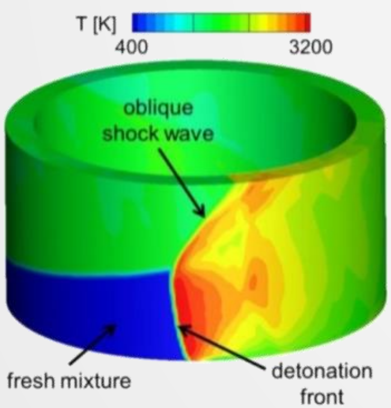
- Exploits pressure rise to augment high flow momentum
- Fundamental mechanism is turbulent flame acceleration
- High flow turbulence intensities and length scales
- Serious challenge for reliable, repeatable and efficient

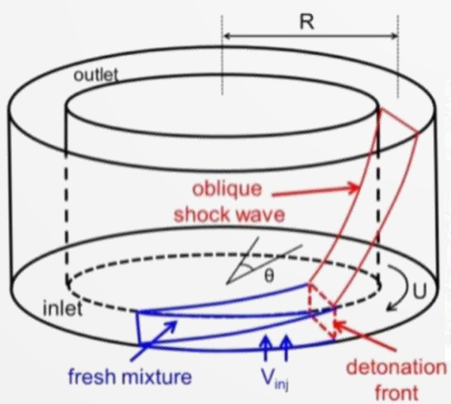
Thermodynamic Cycle

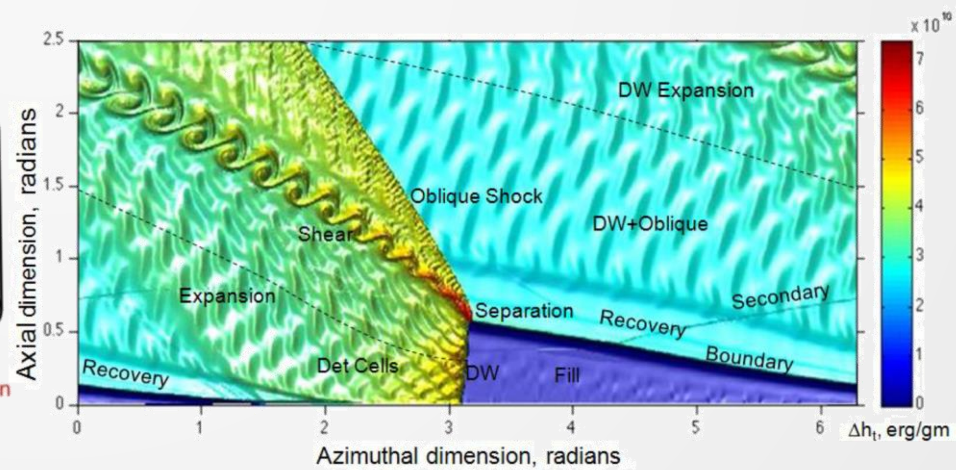




Schwer, *et al.*, AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010







Nordeen *et al.*, *49th AIAA Aerospace Sciences Meeting*, 2011

Why Detonation for Coal ACS?

Origin of Detonation:

- Detonation first discovered during disastrous explosions in coal mines, 19^{th} century.
- Puzzling at first, how the slow subsonic combustion could produce strong mechanical effects. *Michael Faraday "Chemical History of a Candle" 1848*
- First detonation velocity measurement, Sir Frederic Abel 1869
- Coal particles and coal gas interaction, Pellet, Champion, Bloxam 1872
- Berthelot hypothesized shock wave reaction, detonation, 1870

Museum of Industry, Drummond Mine Explosion, 1873

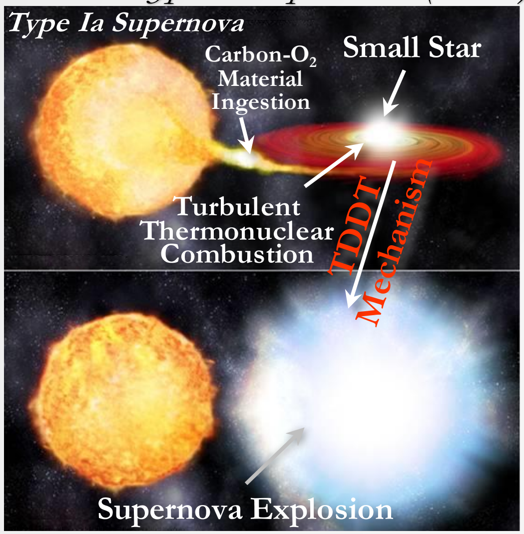
Coal Mine Fast-Flame Deflagration Explosion

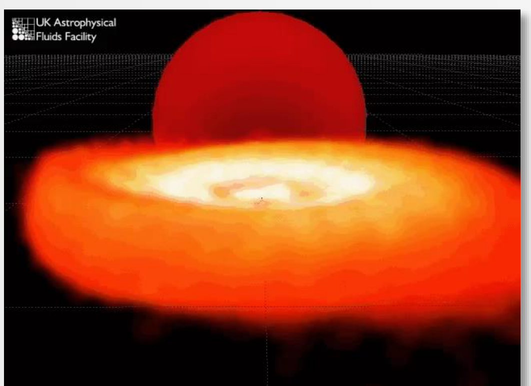
Coal Mine Detonation Explosion

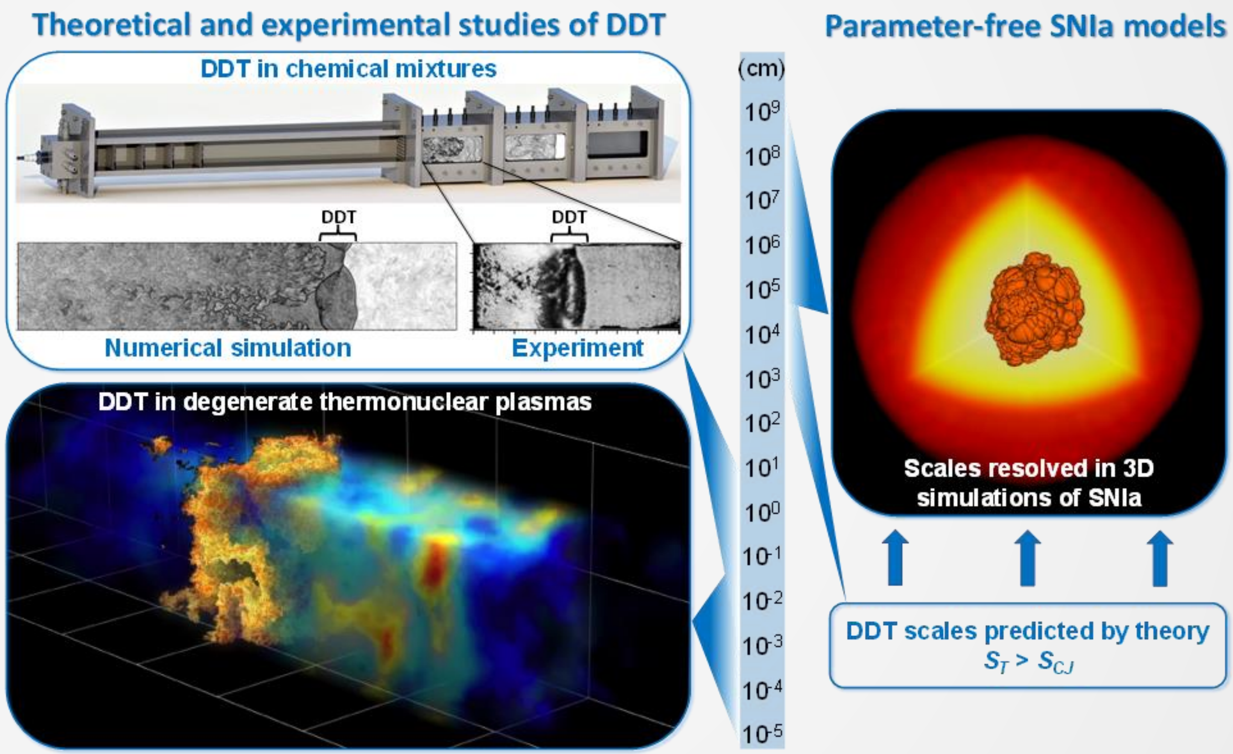
Combustion Physics in Science!

Universal Mechanisms Controlling Terrestrial and Astrophysical Explosions

Relate to Type Ia Supernovae (SNIa) – Thermonuclear Flames







Poludnenko, A., Chambers, J. G, Ahmed, K, Gamezo, V., " A unified mechanism for unconfined deflagration-to-detonation transition in terrestrial chemical systems and type Ia supernovae," Science, Vol. 366, Issue 6465, 2019.

Project Objectives

Explore Advanced Cost-Effective Coal-Fired Rotating Detonation Combustor:

The proposed project aims to characterize the operability dynamics and performance of an advanced cost-effective coal-fired rotating detonation combustor for high efficiency power generation

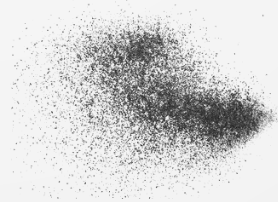
- Development of an operability map for coal-fired RDC configuration
- Experimental investigation and characterization of coal-fired combustor detonation wave dynamics
- Computational investigation and characterization of coal-fired combustor detonation wave dynamics
- Measurement and demonstration of pressure gain throughout the coal-fired RDC operational envelope
- Measurement and demonstration of low emissions throughout the coal-fired RDC operational envelope

Coal

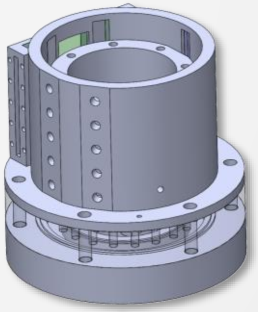
Powder

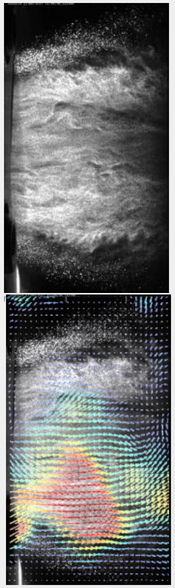
Seeder

Particles



Coal-Fired Rotating Detonation Combustor





Russia: Bykovskii *et al.* 2013

Project Objectives

1. Operability Dynamics for Detonation Wave:
   a. *Coal Injection:* what is the coal particle size, effective volume fraction, and seeding technique? *The focus here will be on effective refraction/burning rate and detonation-solid interaction.*
   b. *Initiation:* is the reaction front that is formed a detonation or a deflagration flame that is acoustically coupled? *The focus here will be on the mechanisms of deflagration-to-detonation transition and composition enrichment syngas and oxy-coal rotating detonation combustion.*
   c. *Directionality:* which direction do the waves rotate and why? why and when do they change direction? *The focus here will be on the conditions and mechanisms of detonation wave direction.*
   d. *Bifurcation:* How many waves are generated and why? *The focus here will be on the driving mechanisms of the form of detonation wave topology.*

2. Performance:
   a. *Pressure Gain:* How much pressure gain is generated under steady and dynamic operability? *The focus here will be on the direct measurement of pressure gain production.*
   b. *Emissions:* what level of emissions coal RDC generate under steady and dynamic operability? *The focus here will be on the direct measurement of emissions along with modeling.*

Project Management

Roles of Participants

DOE ACS Management

University of Central Florida
(Prime Recipient)

Dr. Kareem Ahmed
Dr. Subith Vasu

Aerojet Rocketdyne
(Industry Partner)

Dr. Scott Claflin

Georgia Institute of Technology
(Sub-Recipient)

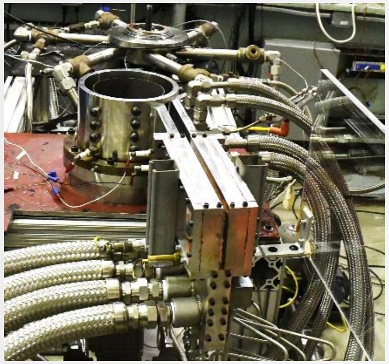
Dr. Suresh Menon

Innovative Scientific Solutions, AFRL
(Industry Partner)

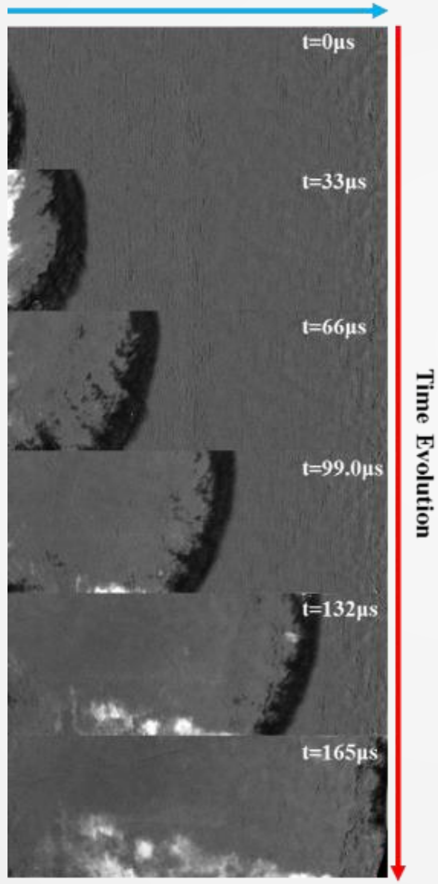
Dr. John Hoke
Dr. Fred Schauer

Research at UCF

Rotating Detonation Engine in Supersonic Flow

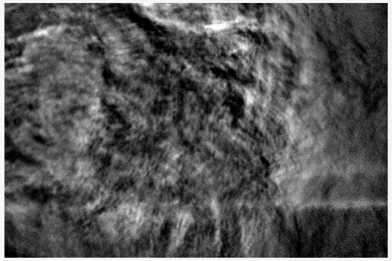


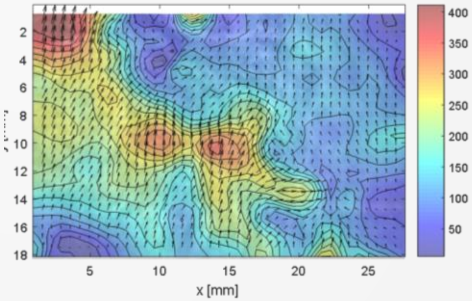
Detonation Propagation in a Premixed Supersonic Flow



J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

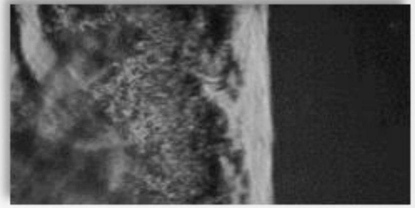
RDE Exhaust Velocimetry



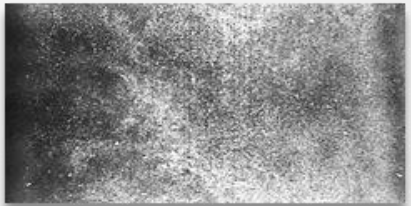


Detonation wave velocimetry and structure conducted at Dr. Ahmed's UCF lab

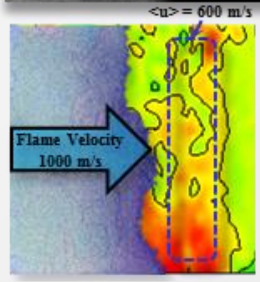
Detonation Shock-Particle-Flame Flow



Aluminum Oxide Particles Flow



Detonation Turbulent Flame

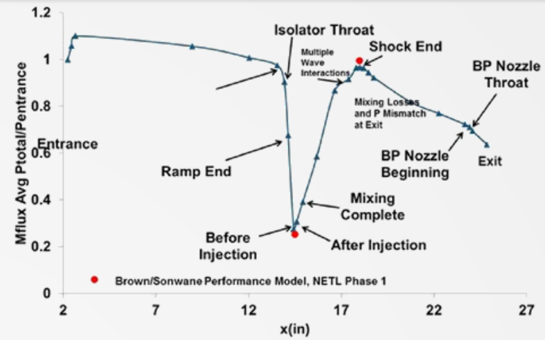


J. Chambers *et al*, ICDERS, 2017

Vision

The goal is to measure stagnation pressure for fundamental understanding of pressure gain within a rotating detonation engine. This will allow for proper understanding of flow field effects.

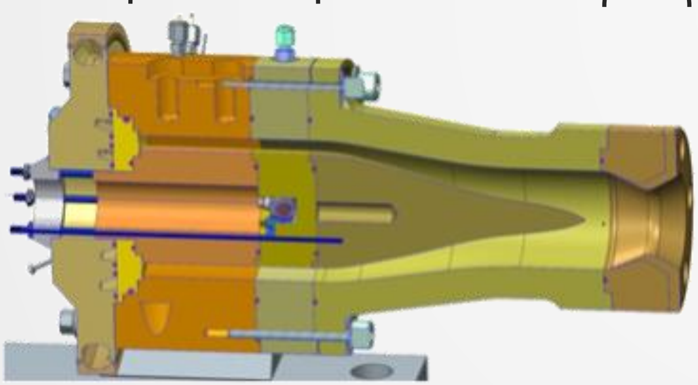
$$\left(\frac{\hat{P}^{o}_{d,ex}}{\hat{P}^{o}_{M}}\right) = \frac{\left(\frac{\hat{P}^{o}_{c,ex}}{\hat{P}^{o}_{c,in}}\right)_{1}}{\left(\frac{\hat{P}^{o}_{M}}{\hat{P}^{o}_{c,in}}\right)_{2}\left(\frac{\hat{P}^{o}_{c,ex}}{\hat{P}^{o}_{d,ex}}\right)_{3}}$$



Computed pressure gain through engine

1 - Combustion Chamber

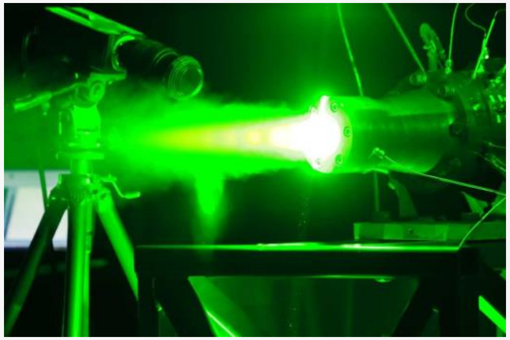
Back-Pressure Nozzle



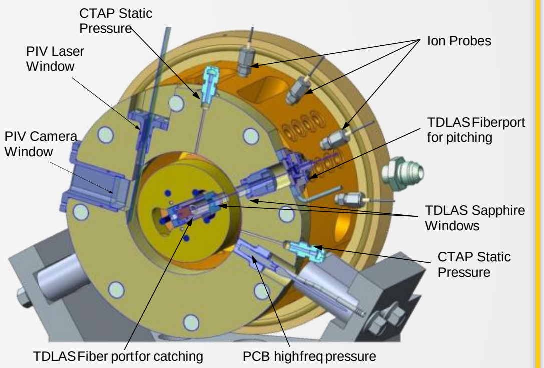
2 - Injector/Isolator

3 - Diffuser

Aerojet Rocketdyne RDE cutout

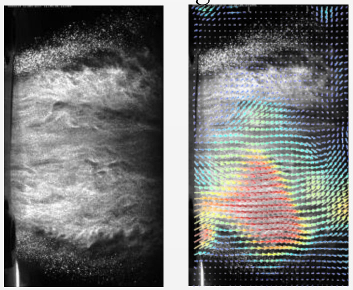


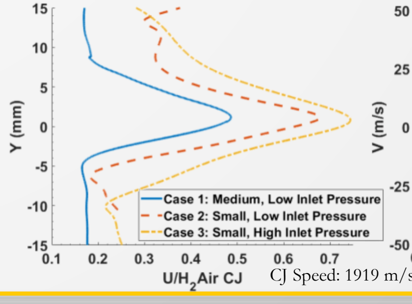
PIV on exit plane of nozzle of the Aerojet RDE



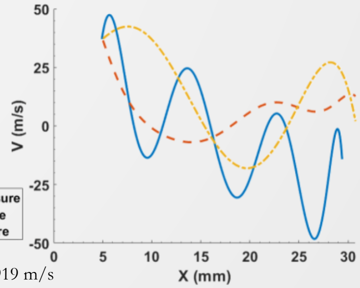
Entire CAD of Aerojet RDE cutout sitting on static test fire stand

Mie Scattering Particles



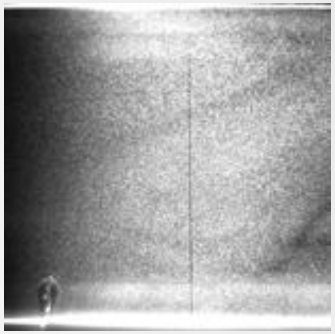


CJ Speed: 1919 m/s

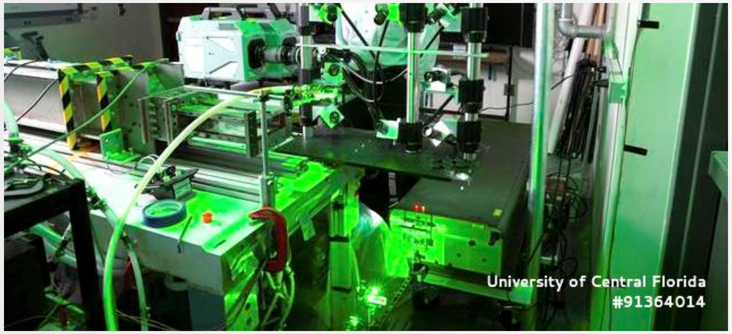


Instrumentation

Advanced Optical Diagnostics

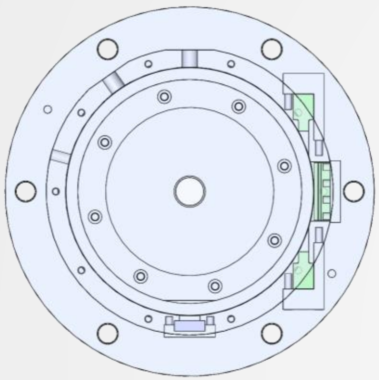


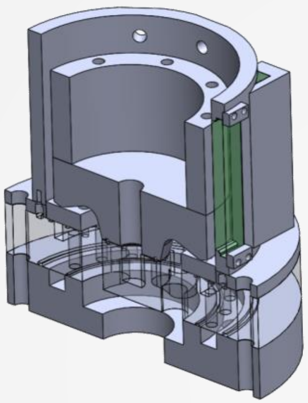
- High-speed PIV system (20kHz, 40kHz, 60kHz, 100kHz)
- High speed cameras 21,000-2,100,000 frames per second
- High-speed chemiluminescence CH*, OH* (40 kHz, 80kHz, 100kHz)
- Light-field focusing system for flow measurements and visualization
- LabVIEW control hardware and software
- Dynamic pressure transducers (PCB)
- Codes: DMD, POD, PIV, Physics-Based Models (Matlab/Fortran)

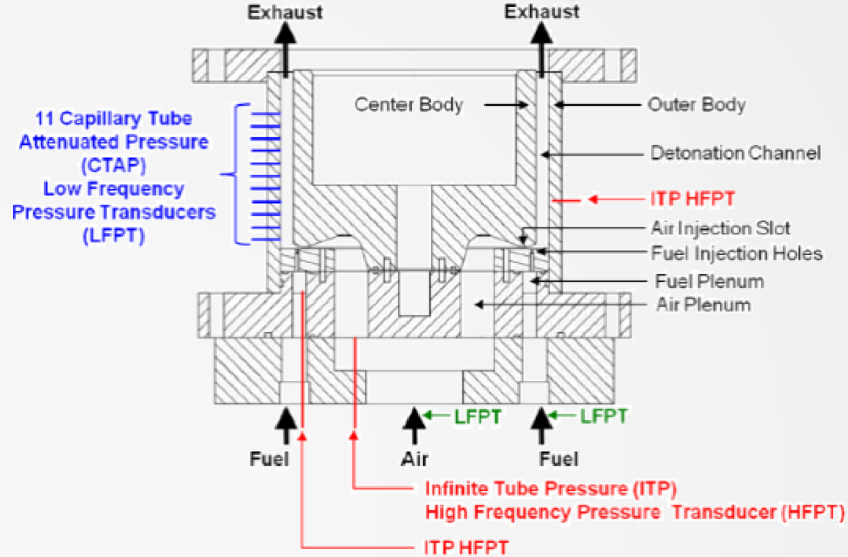


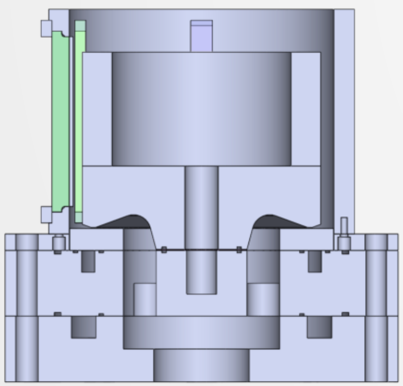
Rotating Detonation Engine

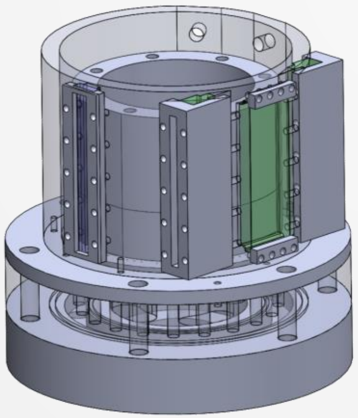
Rotating Detonation Engine: *Modeled After the AFRL RDE and the NETL (Don Ferguson)*

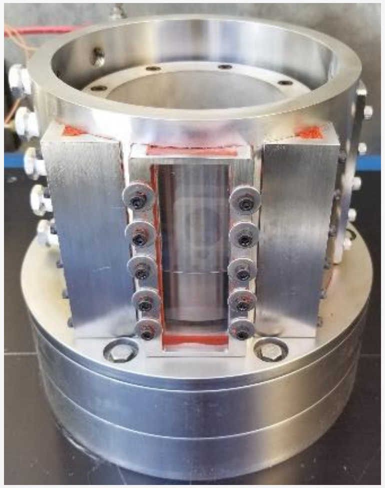


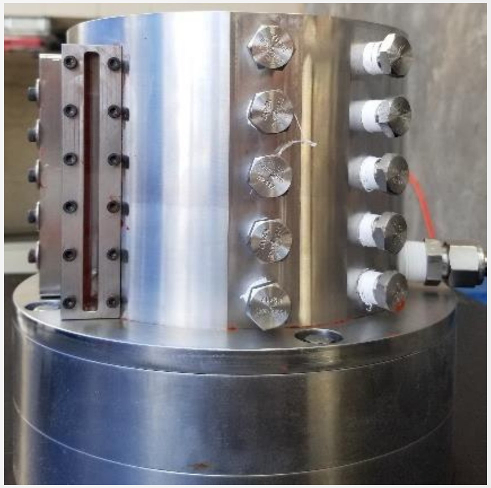










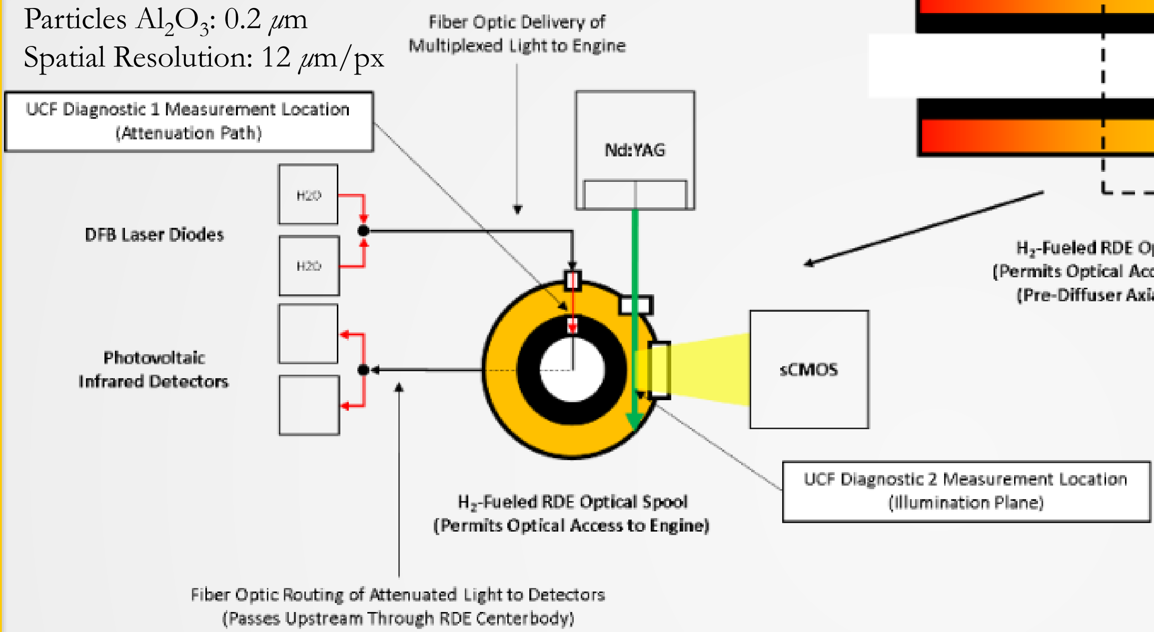


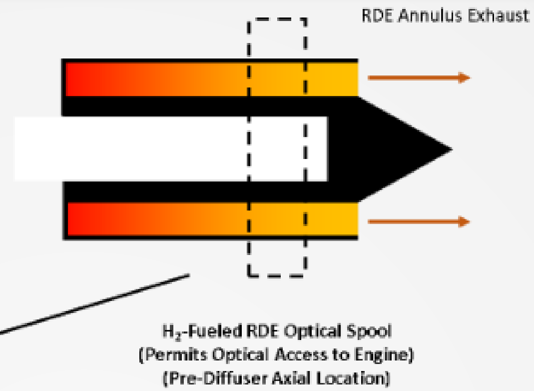
J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

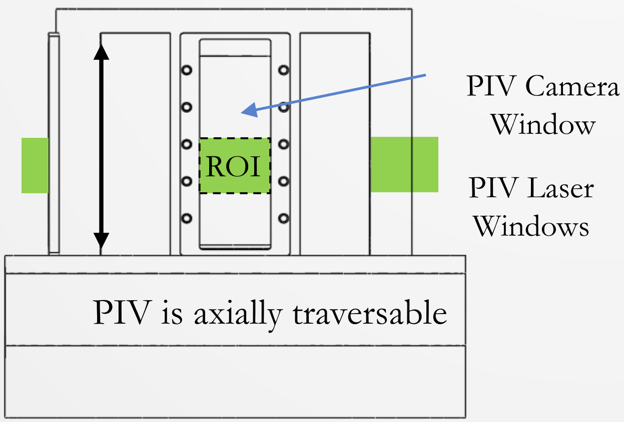
Optical Setup

PIV and TDLAS

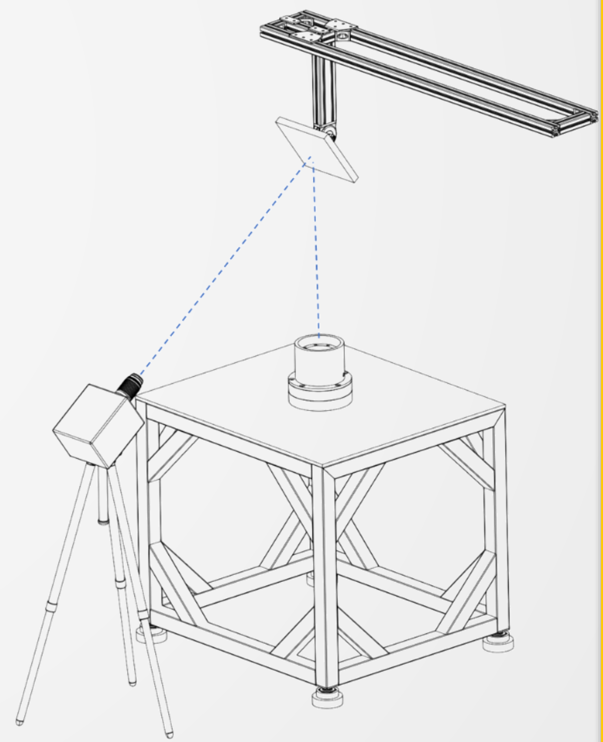
Interframe Time: 1 μs
Particles Al_2O_3: 0.2 μm
Spatial Resolution: 12 μm/px

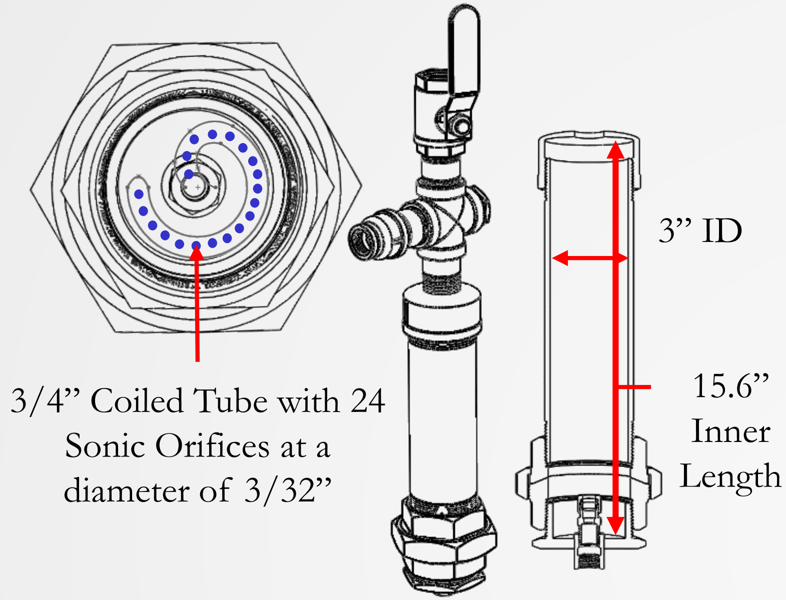


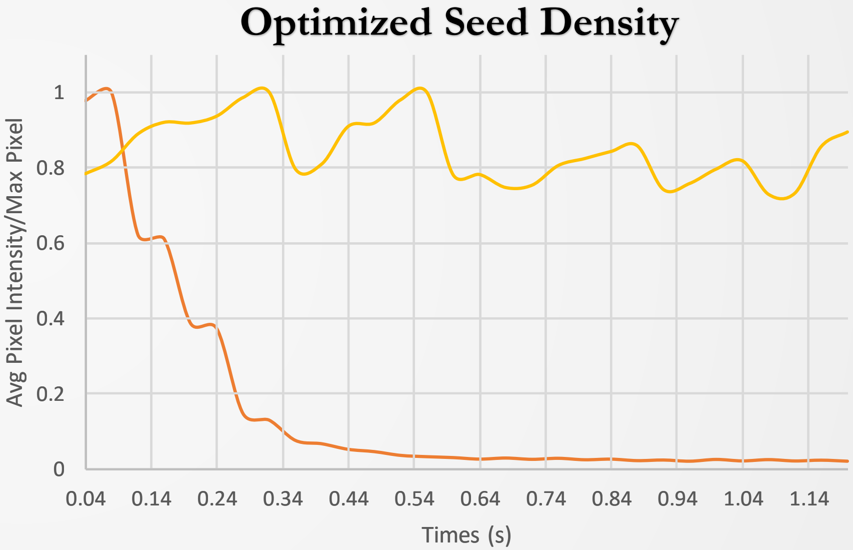




AFT Imaging

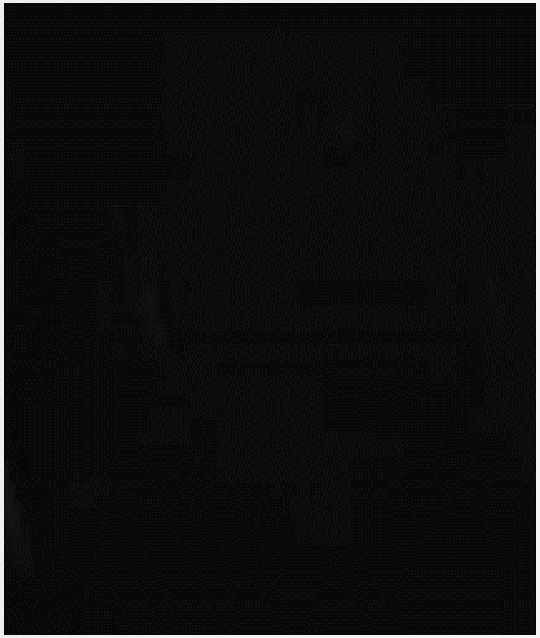



3/4" Coiled Tube with 24 Sonic Orifices at a diameter of 3/32"
3" ID
15.6" Inner Length

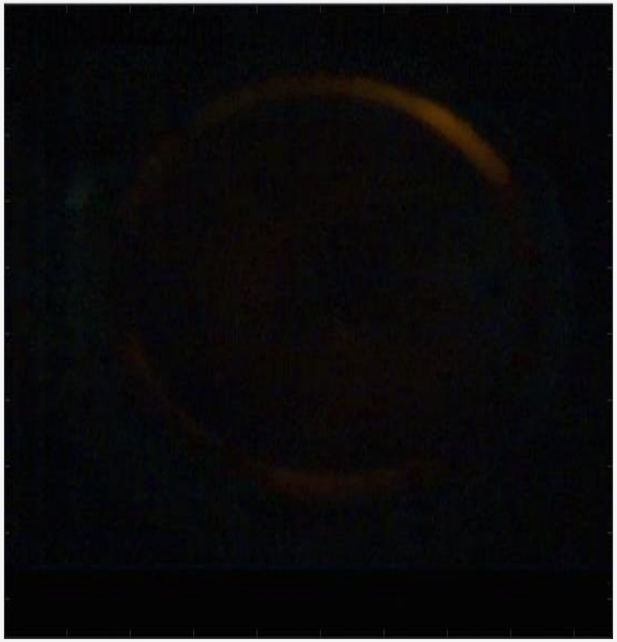

Optimized Seed Density
Avg Pixel Intensity/Max Pixel
0
0.2
0.4
0.6
0.8
1
0.04
0.14
0.24
0.34
0.44
0.54
0.64
0.74
0.84
0.94
1.04
1.14
Times (s)

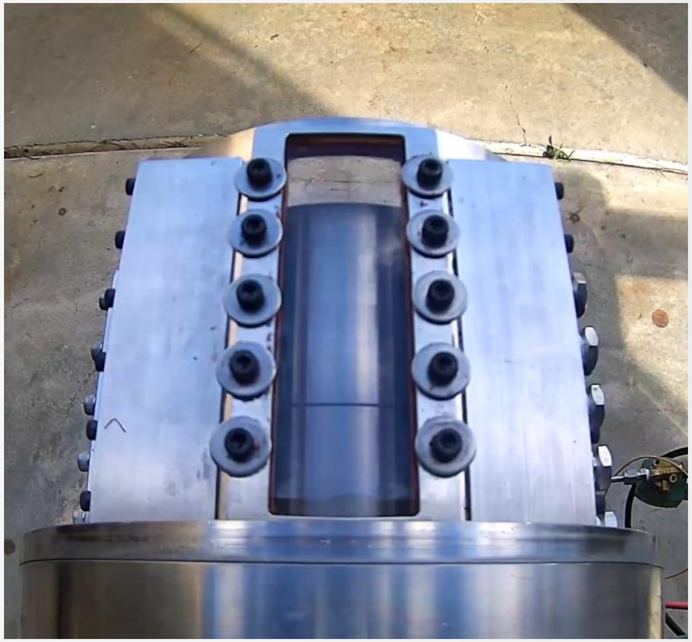
Operation

1 Wave Detonation

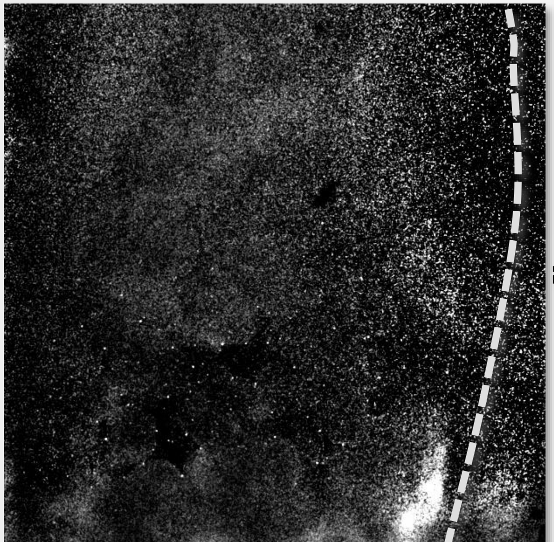


2 Wave Detonation



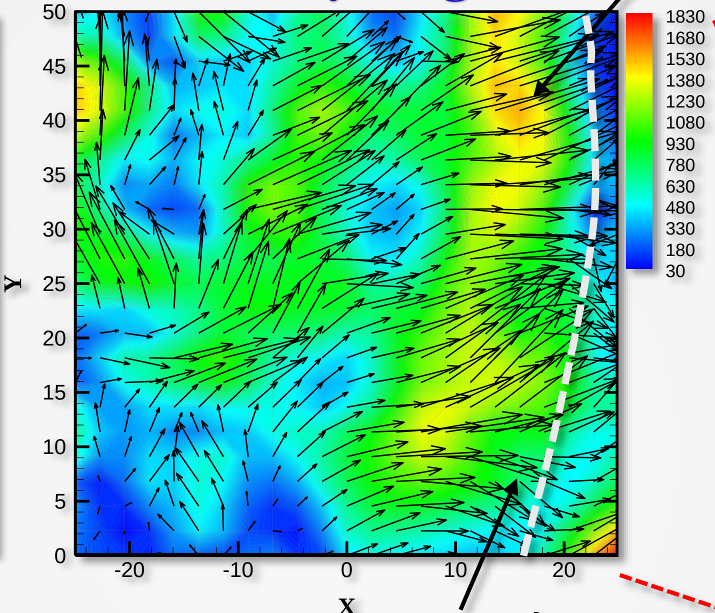


Mie Scatter



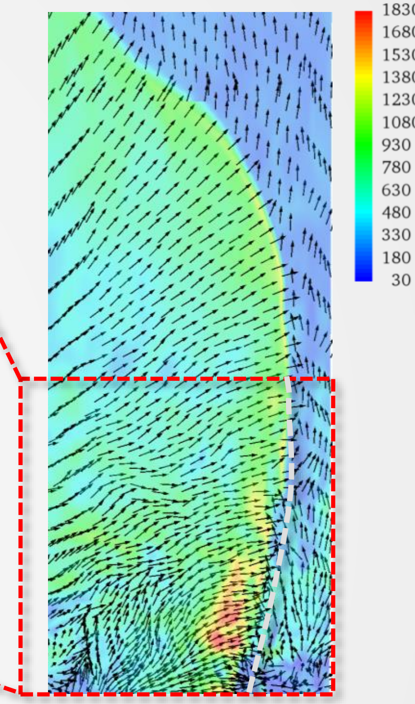
PIV Velocity Magnitude

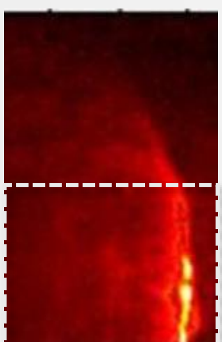
~1600 m/s



~900 m/s

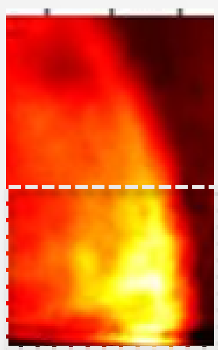
Velocity [m/s] Magnitude





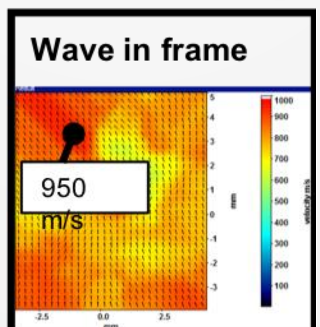
OH*

Brent A. Rankin *et al.*, CNF, 2017

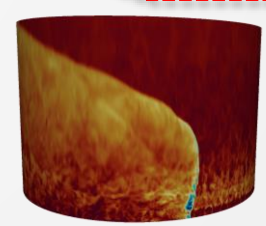


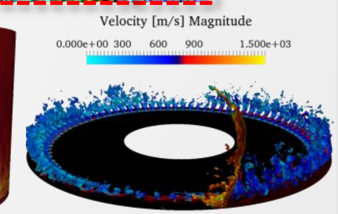
H_2O

Brent A. Rankin *et al.*, PROCI, 2019



Kevin Cho *et al.*, AIAA SciTech, 2019





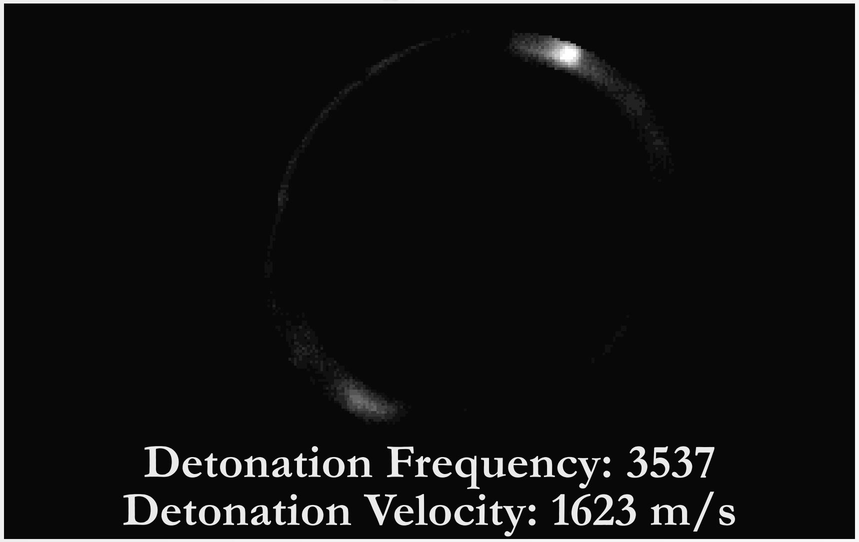
Suresh Menon (LESLIE)

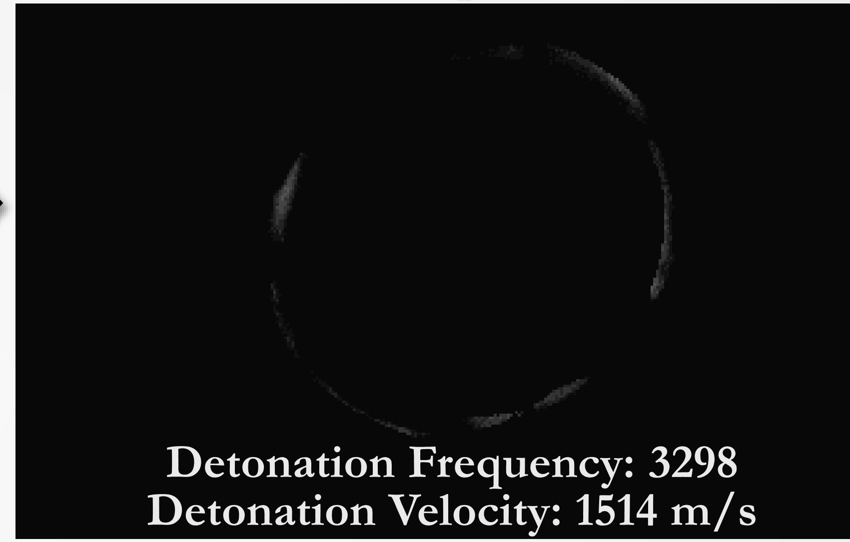
Georgia Tech College of Engineering

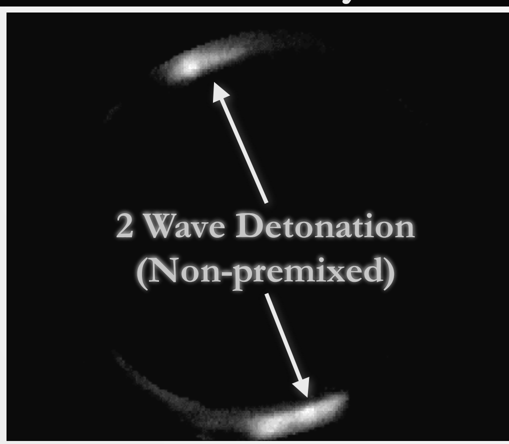
Dynamic Control of Detonation Waves through Partial Premixing

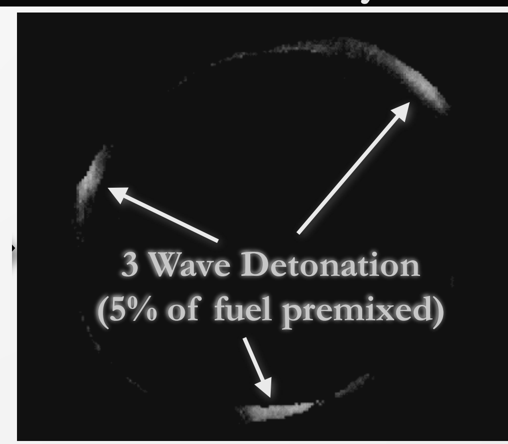
2 Wave Detonation (Non-premixed)

3 Wave Detonation (5% of fuel premixed)



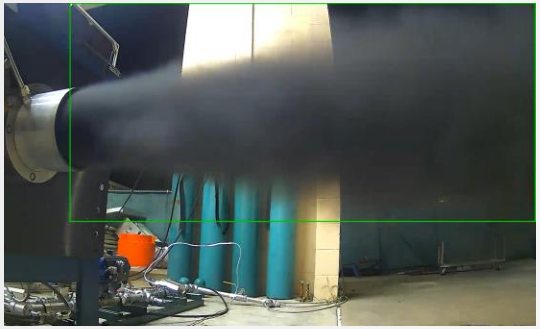




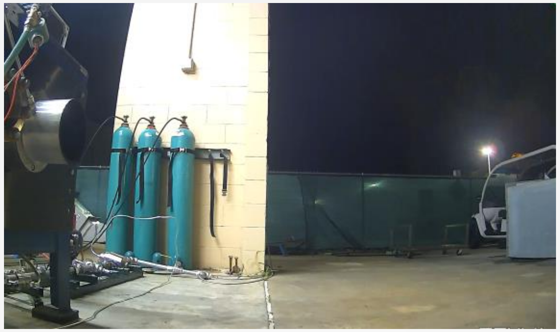


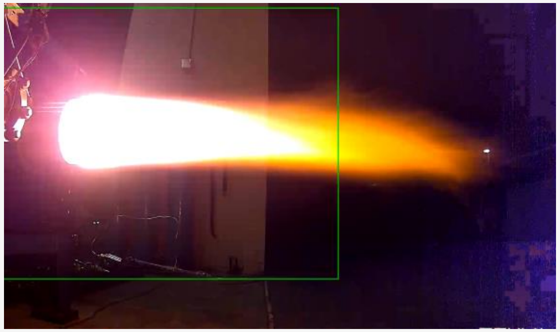
Coal RDE Test Fires (carbon)

Non-Reacting

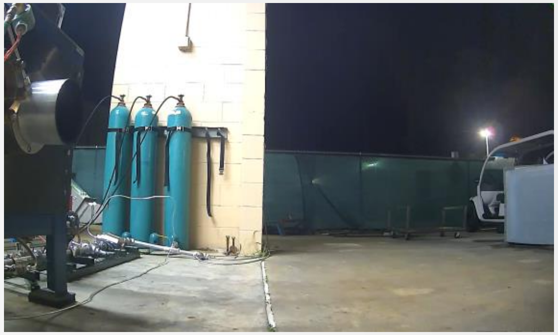


Deflagration



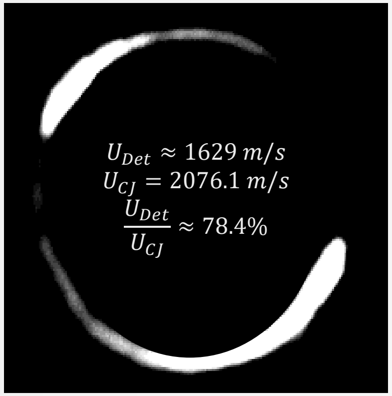


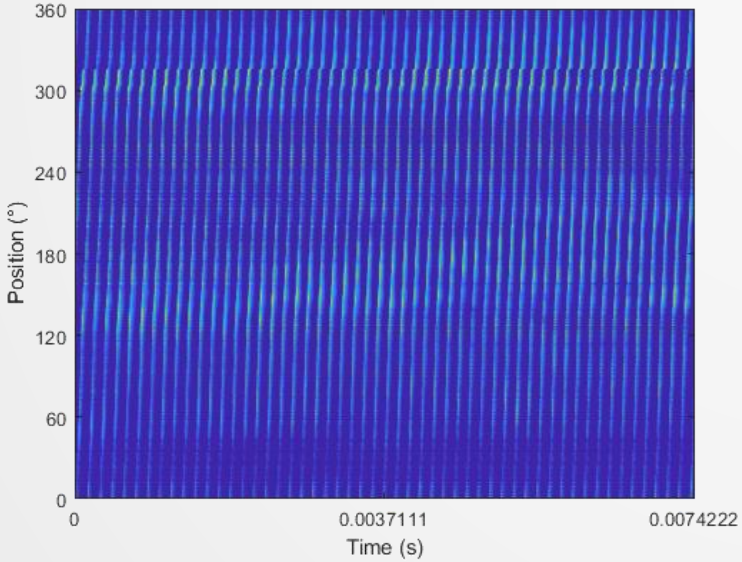
Detonation



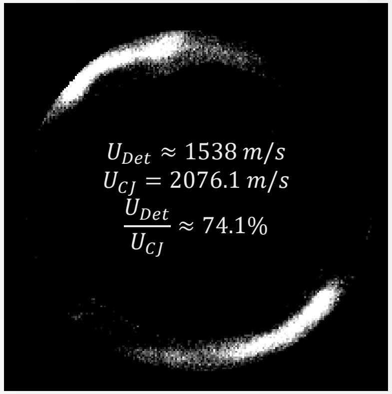
Detonation Wave Dynamics

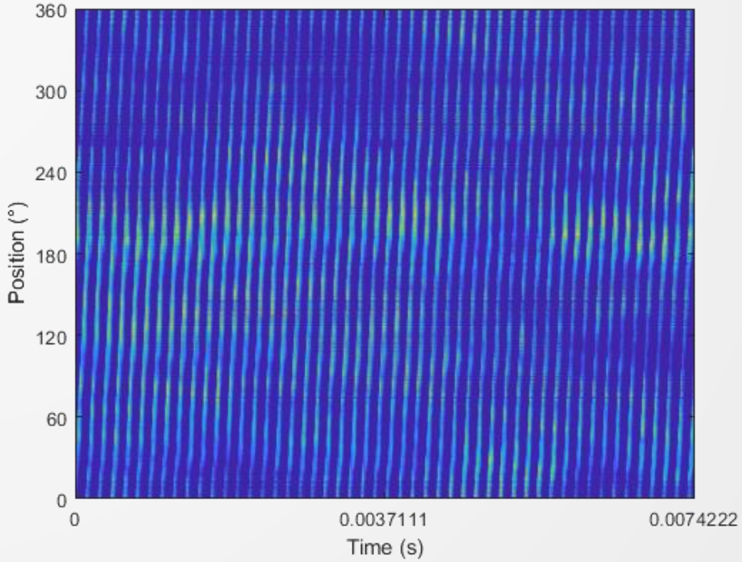
Average Concentration 38% Coal





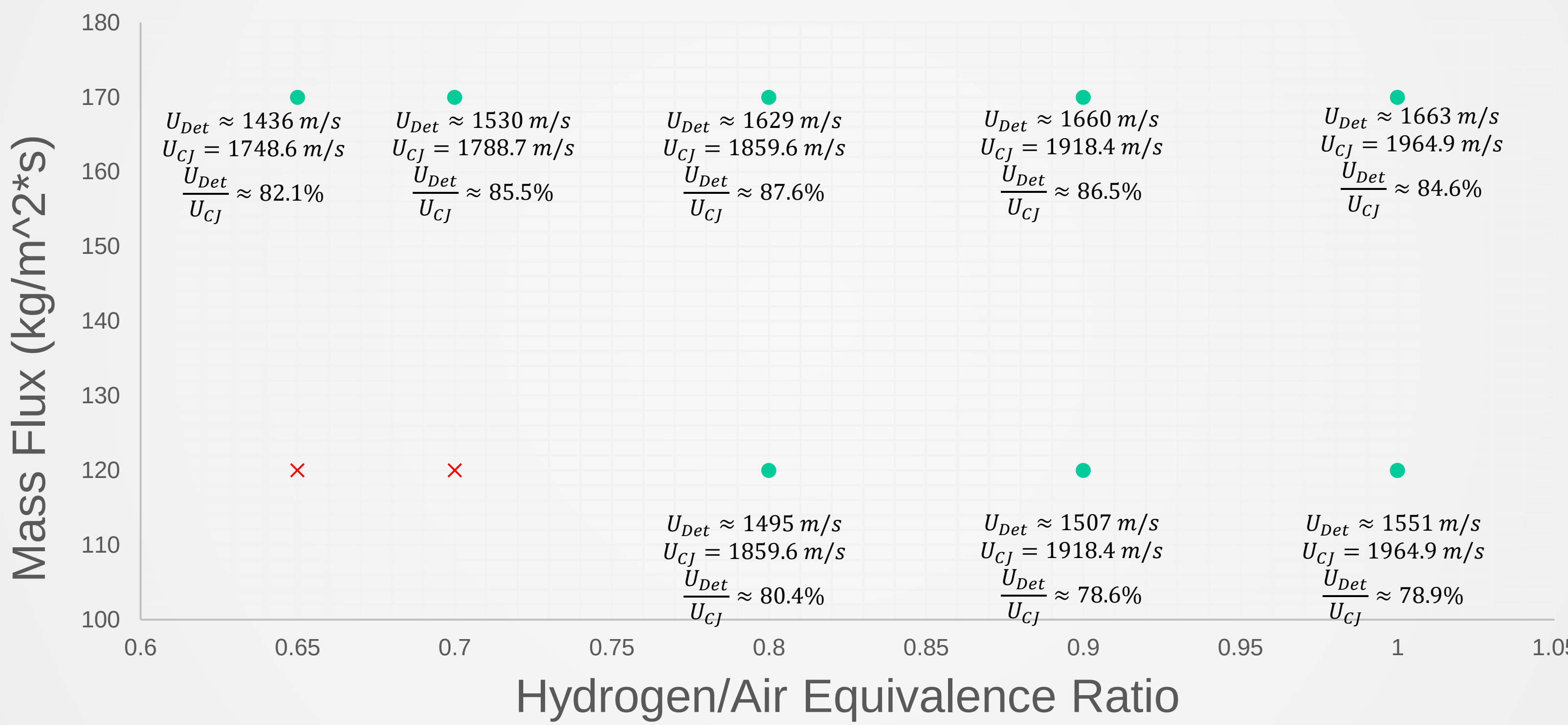
Average Concentration 67% Coal





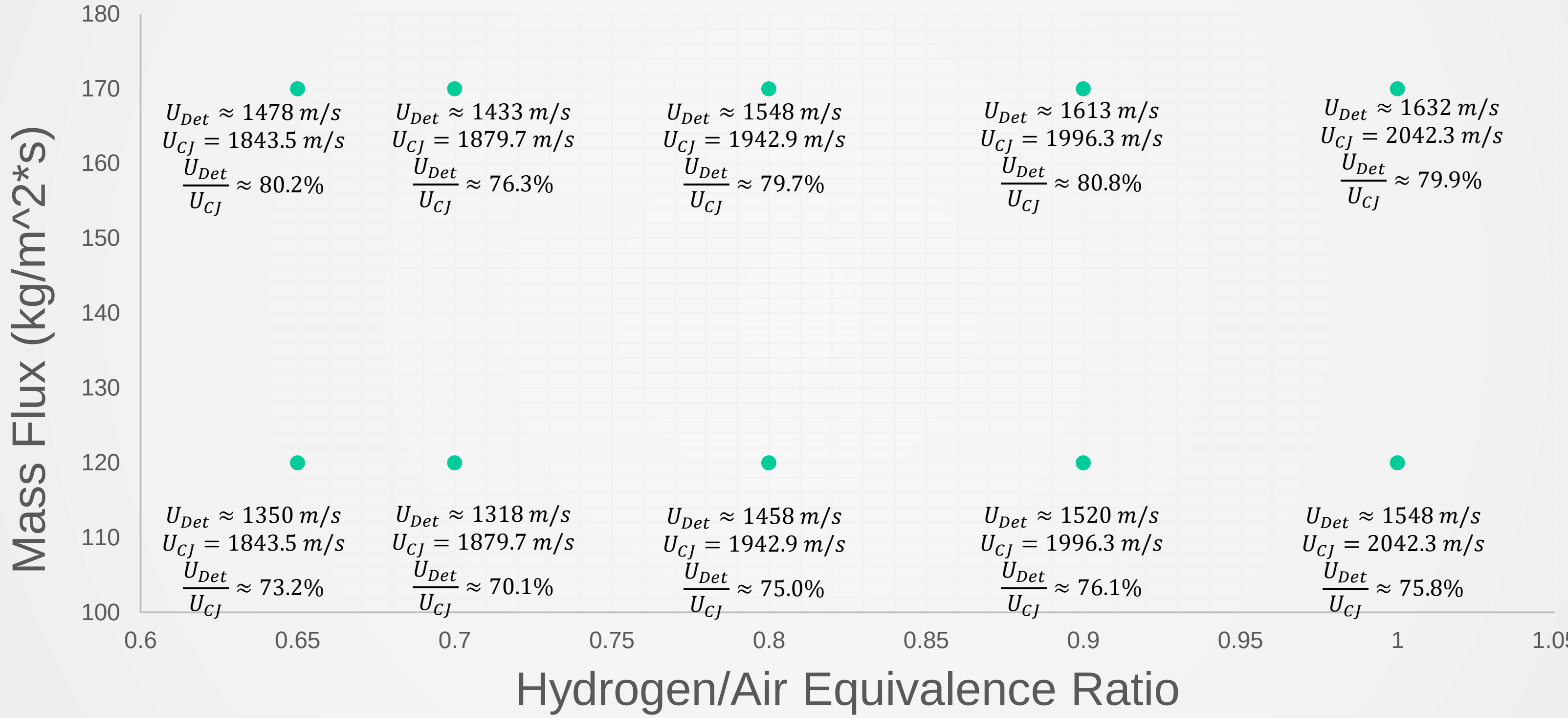
J. Bennewitz, B. Bigler, S. Schumaker, W. Hargus Jr, Automated image processing method to quantify rotating detonation wave behavior, Review of Scientific Instruments 90 (2019)

Baseline

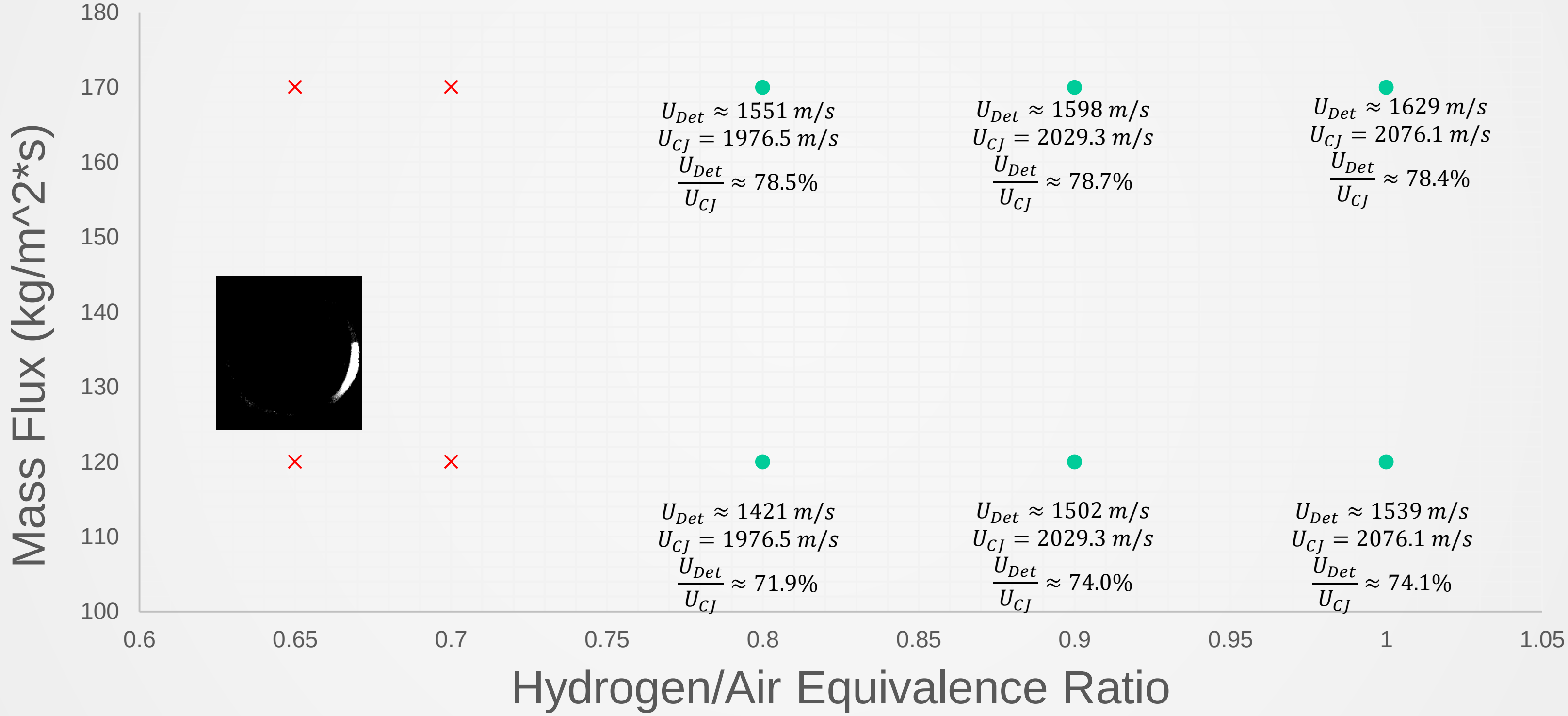


Mass Flux (kg/m^2*s)
Hydrogen/Air Equivalence Ratio
180
170
160
150
140
130
120
110
100
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
$U_{Det} \approx 1436\ m/s$
$U_{CJ} = 1748.6\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 82.1\%$
$U_{Det} \approx 1530\ m/s$
$U_{CJ} = 1788.7\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 85.5\%$
$U_{Det} \approx 1629\ m/s$
$U_{CJ} = 1859.6\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 87.6\%$
$U_{Det} \approx 1660\ m/s$
$U_{CJ} = 1918.4\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 86.5\%$
$U_{Det} \approx 1663\ m/s$
$U_{CJ} = 1964.9\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 84.6\%$
$U_{Det} \approx 1495\ m/s$
$U_{CJ} = 1859.6\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 80.4\%$
$U_{Det} \approx 1507\ m/s$
$U_{CJ} = 1918.4\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 78.6\%$
$U_{Det} \approx 1551\ m/s$
$U_{CJ} = 1964.9\ m/s$
$\frac{U_{Det}}{U_{CJ}} \approx 78.9\%$

Average Concentration 38% Coal

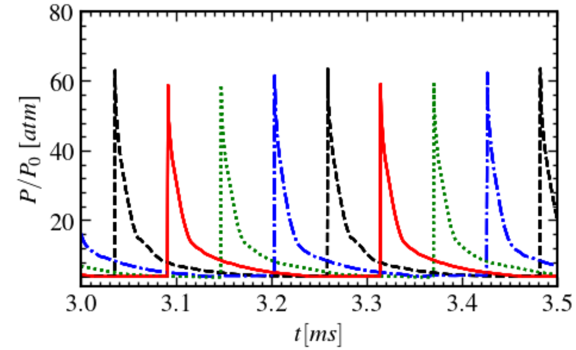


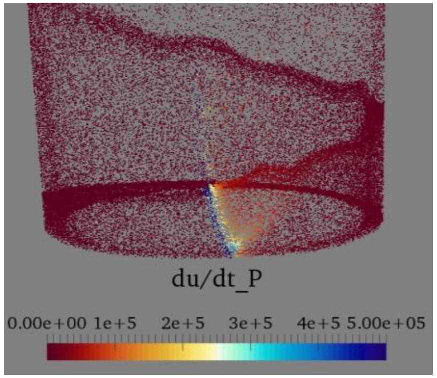
Average Concentration 67% Coal

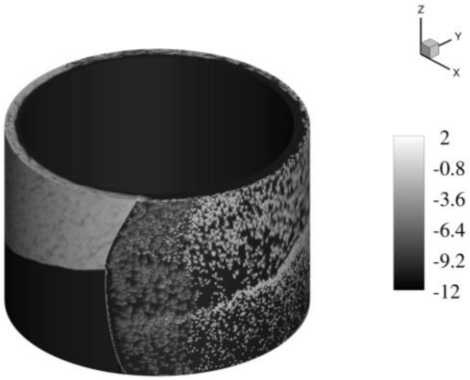


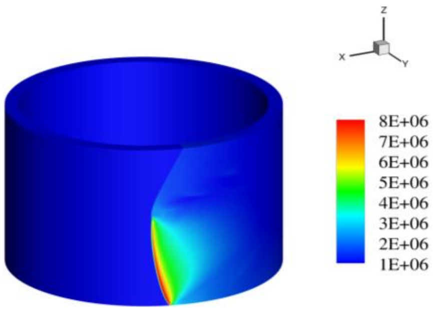
Premixed RDE with Coal Particles

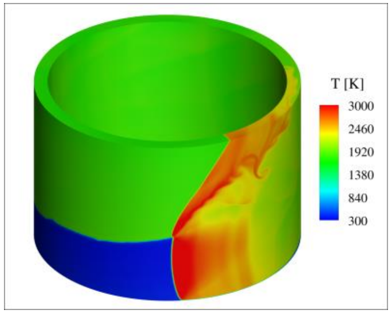
- UCF RDE geometry without injectors and air slot
- 1-step 3-species kinetics [1] for gaseous H2-air, Euleriar Lagrangian Approach, Dilute loading
- Detonation is sustained but EL particle tracking cost is excessive and not practical for parametric studies











[1] Kindracki, Jan, et al. *Progress in Propulsion Physics* 2 (2011): 555-582.

Coal Modeling Formulation

- Mass Transfer: Limited by the reaction kinetics or diffusion of species [1].

$$\frac{dm_c}{dt} = -\dot{m}_c = \frac{d}{dt}\left(\frac{4}{3}\rho_c \pi r_c^3\right)$$

- The net mass transfer for carbon particles is thus defined as:

$$\dot{m}_c = \frac{P_{O_2}}{\frac{1}{k_s} + \frac{1}{k_d}}$$

$$k_s = 0.86\, e^{\left(-\frac{1.495x10^8}{RT_c}\right)}$$

$$k_s = 4.86\phi\left(\frac{D_d}{r_c R T_m}\right)$$

k_s: Kinetic-limited
k_d: Diffusion-limited
T_m: mean gas/particle temperature
ϕ: Mechanism factor
D_d: Diffusion coefficient

- 2-steps infinite-rate gas-phase reactions [2]

$C_g + O_2 \rightarrow CO_2$ *(partial oxidation)*
$C_g + \frac{1}{2}O_2 \rightarrow CO$ *(oxidation)*

1. Baek, S. W., Sichel, M., and Kauffman, C. W. Combustion and Flame 81, 3-4 (1990), 219–228
2. Balakrishnan, K., and S. Menon. *Combustion Science and Technology* 182.2 (2010): 186-214.

Computation Cost for Non-Premixed Detonation Studies

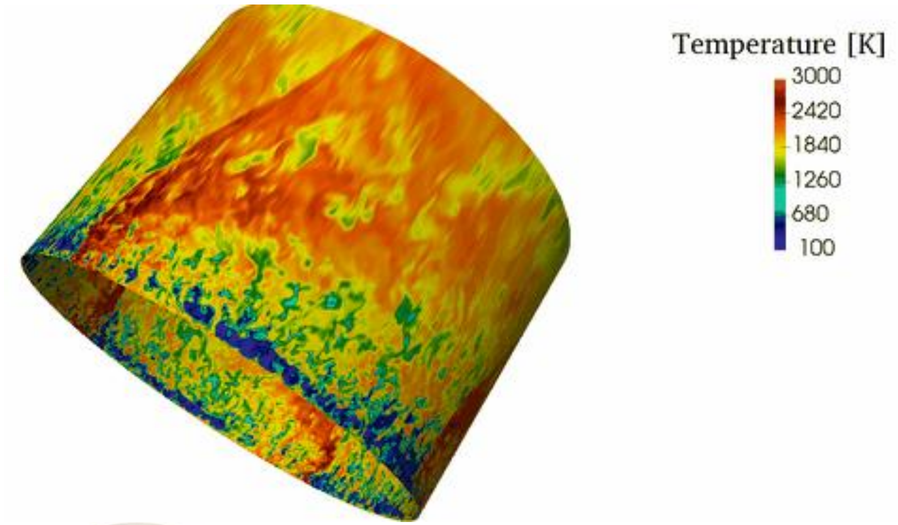
	15 Injectors	*8 Injectors*	*80 Injectors RDE*
Grid	16.2M	8.5M	55M
Blocks	9947	5263	26,560
Cores	1280	1280	3200
Δx_{min}	50 μm	50 μm	50 μm
Δt_{min}	3.0 ns	3.0 ns	3.0 ns
Cost*	~ 24 hours [*]	~ 4 hours [**]	~ 72+ hours [***]

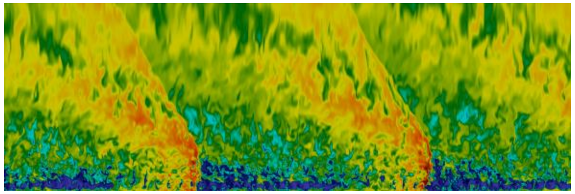
- Cost of full RDE is too excessive using available resources
- Focus on a subset assembly to assess injection/mixing sensitivities
- For example, the 8-injector linear array assembly is reasonably cost effective
  - Can be used for multiple parametric studies with available resources
  - But limitations of the approach needs to be factored into the study

[*,**] Time required for the detonation to propagate through the entire domain
[***] Time required to reach quasi-steady state periodicity

80-Injector Non-Premixed RDE (full rig in UCF)

- Sensitive to initialization
  - High P, T charge
  - 1D H_2/air detonation solution
  - Char. Inflow/outflow, adiabatic walls
- Solution carried long enough to establish rotating detonation
- High mass flow rate in this case results in 4-wave stable system
- Study underway with reduced mass flow to achieve 1 or 2 detonations
- Two-phase cases deferred for later



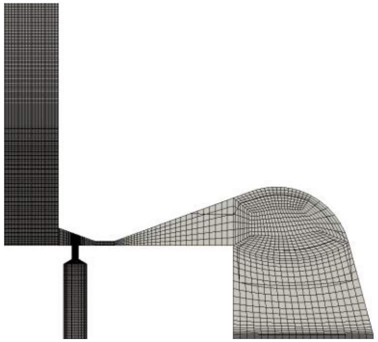


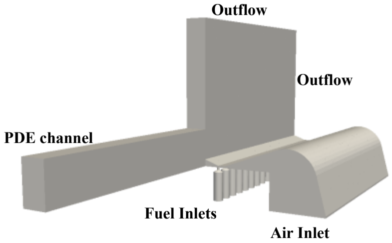
1. Baurle, R., Alexopoulos, G., and Hassan, H. Journal of Propulsion and Power 10, 4 (1994), 473–484.
2. Poinsot & Lele, J. Comp. Phys. 1992

Linear Array Detonation Studies

- 15-injector & 8-injector unwrapped array to isolate two-phase detonation features
- Use pre-detonation tube to create shock-to-detonation-transition (SDT), get a DW into chamber, and then investigate if detonation sustains in a 2-phase mixture
- H_2 injected as before but with different coal-air mixture in the oxidizer stream

Parameter	***Value***
Kinetics	7-steps 7-species H_2/air mechanism [1] 2-steps 3-species infinitely fast $C/\ O_2$ [3]
Coal	Diffusion and kinetics limited mass transfer [2]
$\dot{m}_{air}$	0.15 kg/s
$\dot{m}_{H_2}$	0.0052 kg/s – 15 injectors 0.0027 kg/s – 8 injectors
$T_{in,H_2}, T_{in,Air}$	300 K



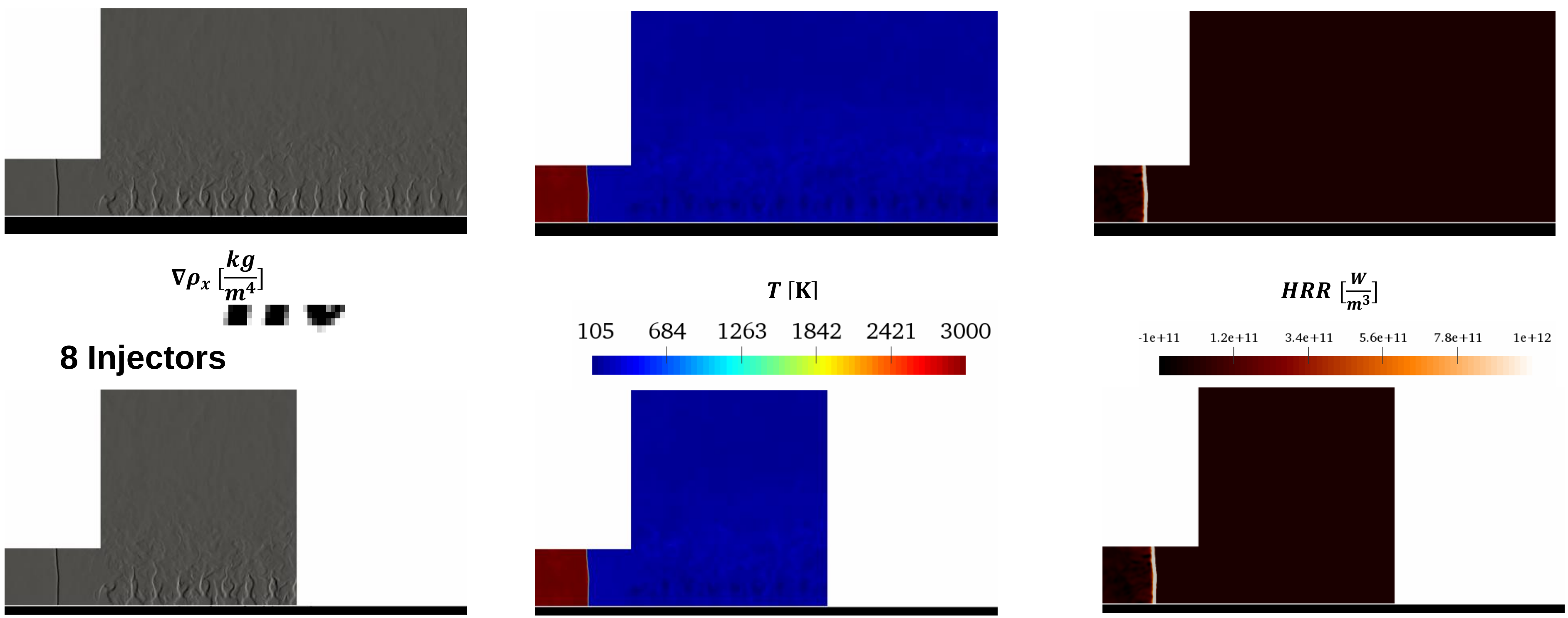


15-injector Array

1. Baurle, R., Alexopoulos, G., and Hassan, H. Journal of Propulsion and Power 10, 4 (1994), 473–484.
2. Baek, S. W., Sichel, M., and Kauffman, C. W. Combustion and Flame 81, 3-4 (1990), 219–228
3. Donahue, L., F. Zhang, and R. C. Ripley. *Shock Waves* 23.6 (2013): 559-573.

With Reacting $d_P = 10\ \mu m$ Particles

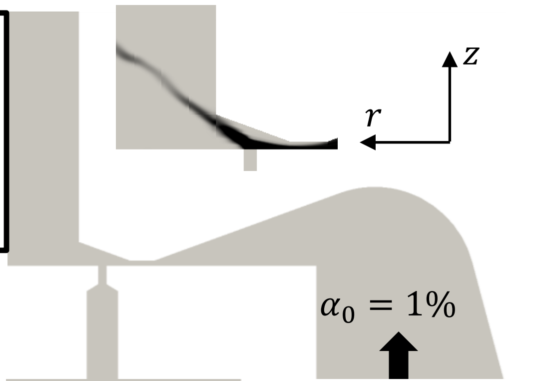
15 Injectors



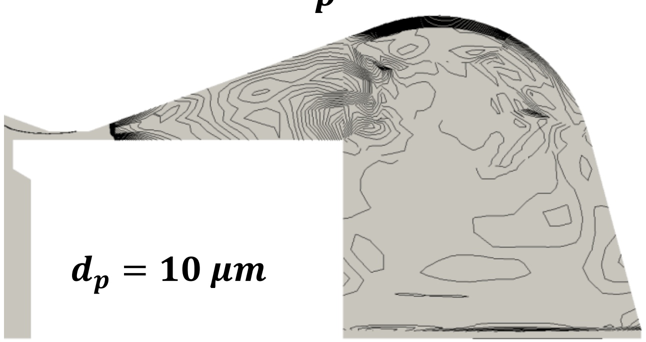
8-injector similar to the 15-injector setup and is much more cost-effective

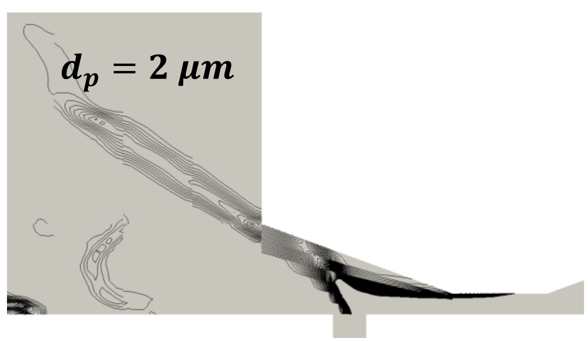
Particle distribution for $d_p = 10\ \mu m$ and $2\ \mu m$

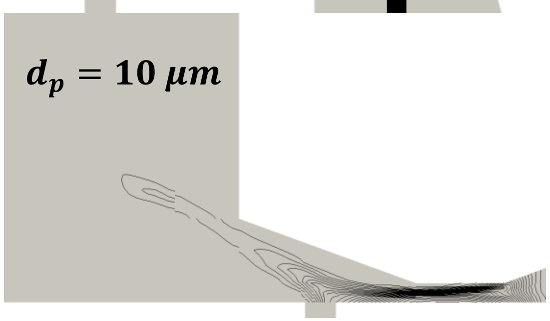
- Many particles for smaller diameter
- Uniform injection still results in non-uniform distribution at throat & in chamber
- Larger variations for smaller particles
- What happens if coal is mixed uniformly?



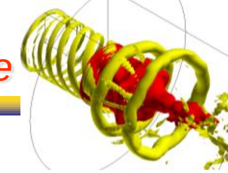
Contour of α_p





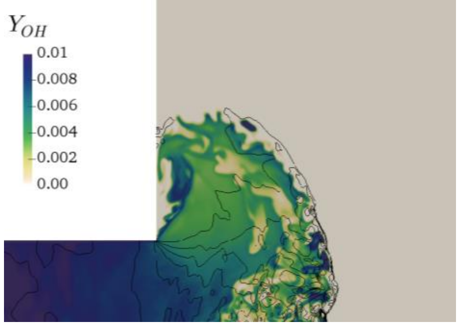


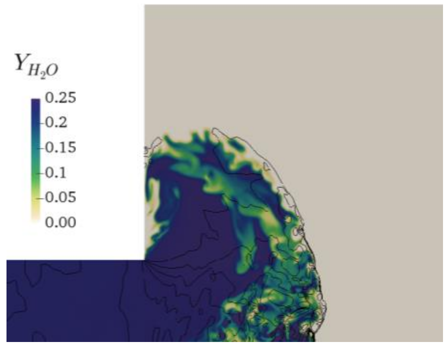
Contour of Number Density



LRDE: Gas-Phase $H_2 - \mathrm{C_g} - \mathrm{Air}$ with 70% $\dot{m}_{H_2}$

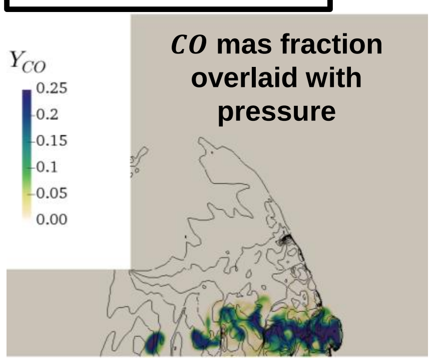
Without C_g



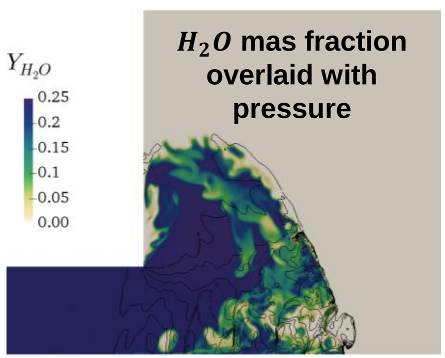


Baseline ϕ_{global} = 1.0

With C_g



CO mas fraction overlaid with pressure



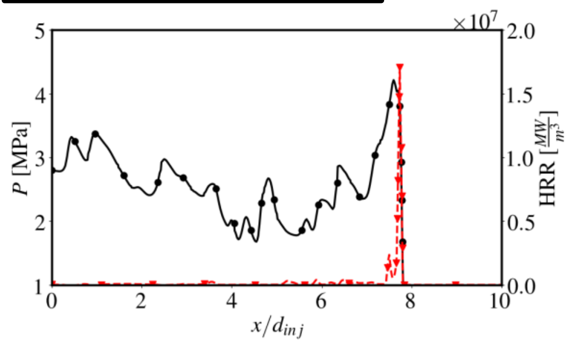
H_2O mas fraction overlaid with pressure

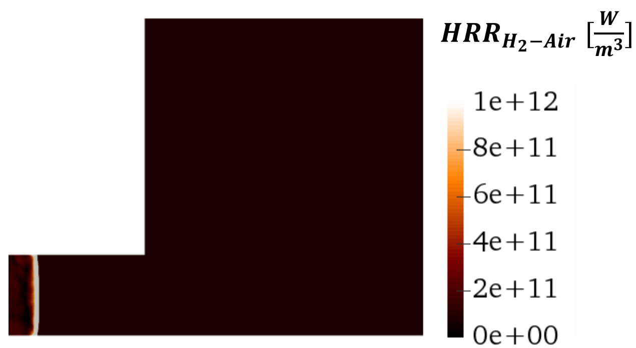
$HRR_{H_2-Air}\ [\frac{W}{m^3}]$

$HRR_{C-O_2}\ [\frac{W}{m^3}]$

LRDE: Gas-Phase $H_2 - C_g - Air$ with 70% $\dot{m}_{H_2}$

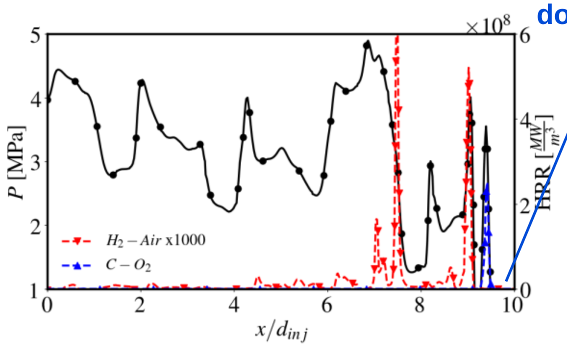
Without C_g

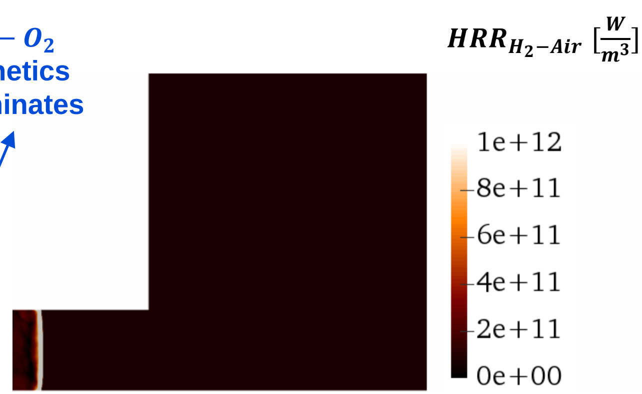




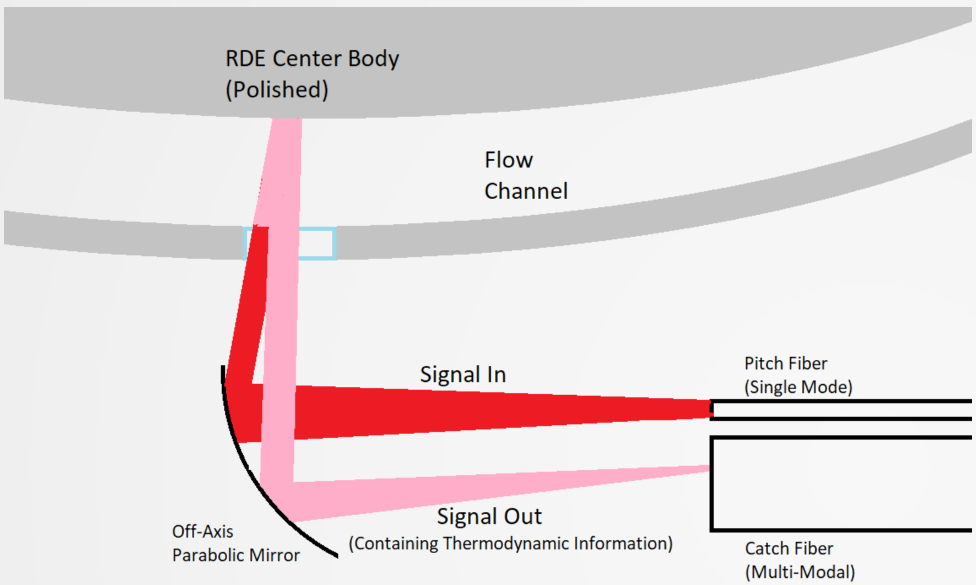
With C_g

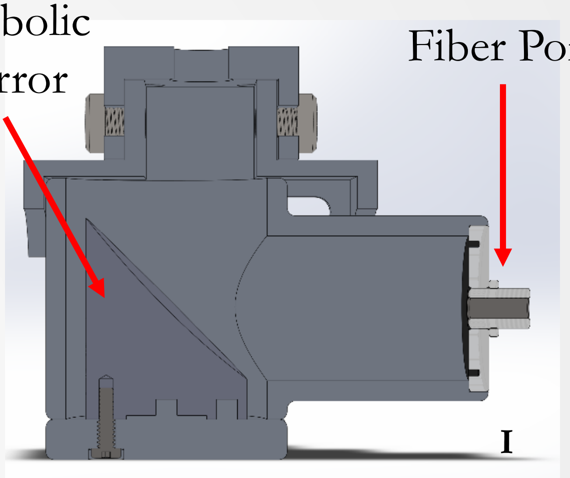
$C - O_2$ kinetics dominates





TDLAS





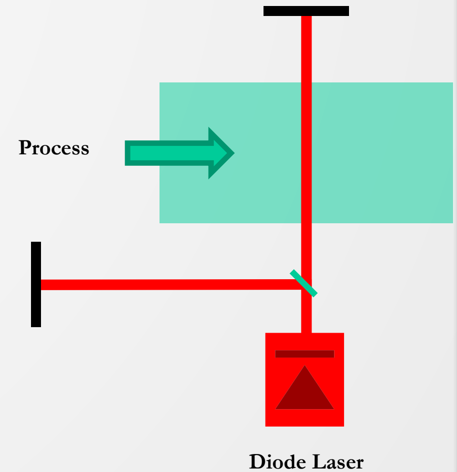
- **Beer-Lambert Law**

$$-\ln\left(\frac{I}{I_0}\right) = \sum_i \sum_j S_{ij}(T) X_j P L \phi_{ij}\left(\nu - \nu_{0_{ij}}\right)$$

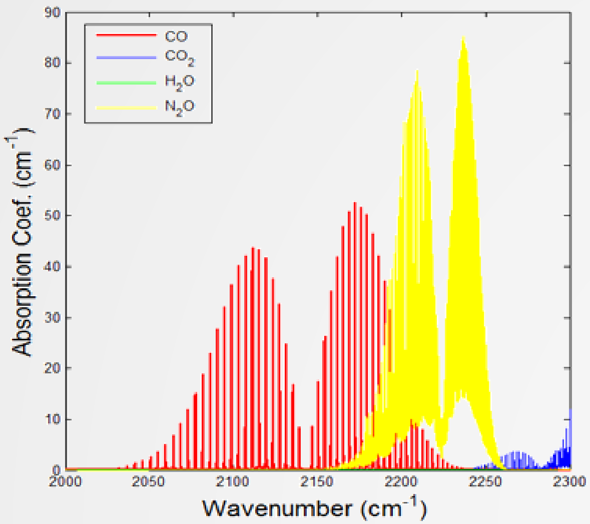
$I = \textit{Transmitted Intensity} \left(\frac{W}{cm^2 sr Hz}\right)$
$I_0 = \textit{Incident Intensity} \left(\frac{W}{cm^2 sr Hz}\right)$
$S_{ij} = \textit{Linestrength} \left(\frac{cm^{-2}}{atm}\right)$
$T = \textit{Static Temperature}$ (K)
$X_j = \textit{Mole Fraction}$
$P = \textit{Static Pressure}$ (atm)
$L = \textit{Path Length}$ (cm)
$\phi_{ij} = \textit{Lineshape Function}$ (cm)

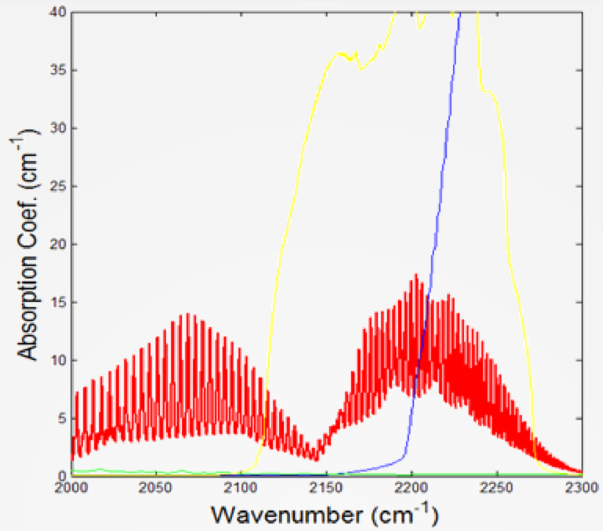
$\nu = \textit{Optical Frequency}$ (Hz)
$\nu_{0_{ij}} = \textit{Line Center Optical Frequency}$ (Hz)

Subscripts
$i = \textit{Quantum Transition}$
$j = \textit{Atomic/Molecular Species}$



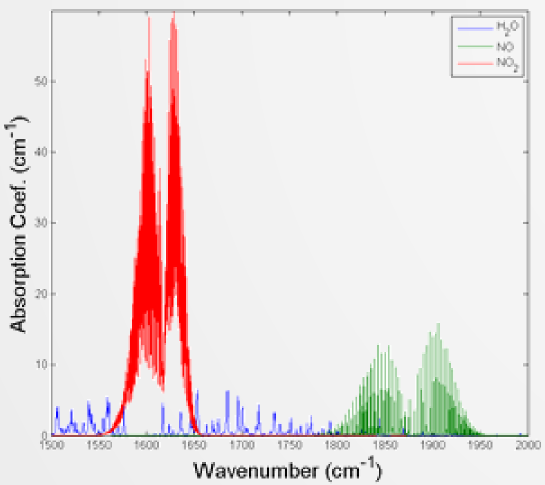
Experimental Measurements: TDLAS for NOx, CO

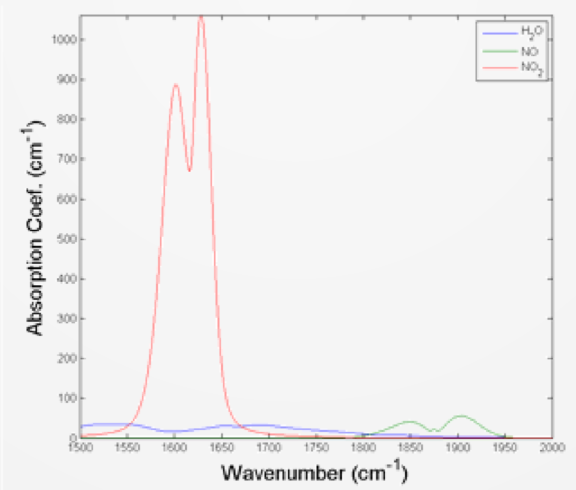




<u>Spatio-temporally resolved for understanding evolution of emissions</u>

Carbon Monoxide (target) and common interfering species (CO_2, H_2O, N_2O) absorption features at T = 296 K and P =1 atm (**Left**); and T = 1500 K and P = 40 atm (**Right**).





NO, NO_2, and interfering water absorption features at T = 296 K and P = 1 atm (**Left**); and and P =40atm (**Right**). Note the marked increase in absorption for NO and NO_2 at high pressures and the minimal water interference around 1600cm^{-1} and 1900cm^{-1}.

Diagnostics will be validated using shock tube and high temperature cells

Characterization of Materials

Experimental minimum tube diameter and K_{ST}-factor

Dust	Size µm	K_{ST} bar·m/s	d_{min} m
U.S. W. Sub-Bituminous coal[a]	≤ 100	59[b]	0.6
Cornstarch	10	160	0.3
Anthraquinone	$22 \times 6 \times 6$	274	0.14
Aluminum	$36 \times 36 \times 1$	359	0.12

Note: *a* - Gardner et al. (1986); *b* - Fangrat et al. (1987).

F. Zhang *et al.*, *Journal of Shock Waves*, 2001

Potential:

Carbon Black (very fine)

Cannal Coal (Russians coal of choice)

Aluminum Iodate Hexahydrate (for doping)

Liquid Isopropyl nitrate (for doping, need a new injection scheme

Bituminous Coal, Anthracite Coal, Carbon Black

(All coal sizes as low at 75 micrometers with the exception of carbon black. Carbon black can be found as low as 18 nanometers)

Anthraquinone Powder, Aluminum Nanoparticles, Liquid Isopropyl nitrate

Combustible Solid Particles (C3)

Bit Coal

Asbury provides LOW SULFUR Bituminous Coal commonly known as Bit Coal. This material is ground and screened to specifications commonly used for foundry sand addition, brake linings and other industrial applications.

Chemistry

	TARGET MIN	TARGET MAX	C3 TYPICAL	D4 TYPICAL
% SULFUR	0	1	0.71	0.74
% VOLATILE	34	44	37.4	38.6
% MOISTURE	0	7	5.2	3.4
% ASH	0	10	8	7.1
% FIXED CARBON	50	60	54.6	54.3

The percentages above/below are "Targets" and not meant to be a guarantee.

Sizing

Product	US Standard Sieves in % Mesh						
	+16 (1.18mm)	+20 (850 Microns)	+30 (600 Microns)	+40 (425 Microns)	+100 (150 Microns)	+200 (75 Microns)	-200 (75 Microns)
C3 Target	0	2 - 9	6 - 18	8 - 15	27 - 36	------------	max 27.5
C3 Typical	0	7.5	16	14.9	32	12.7	16.9
D4 Target	------------	0 - 1	1 - 12	5 - 16	28 - 46	14 - 27	12 - 40
D4 Typical	------------	0.3	3.9	7.2	37.3	21	30.3

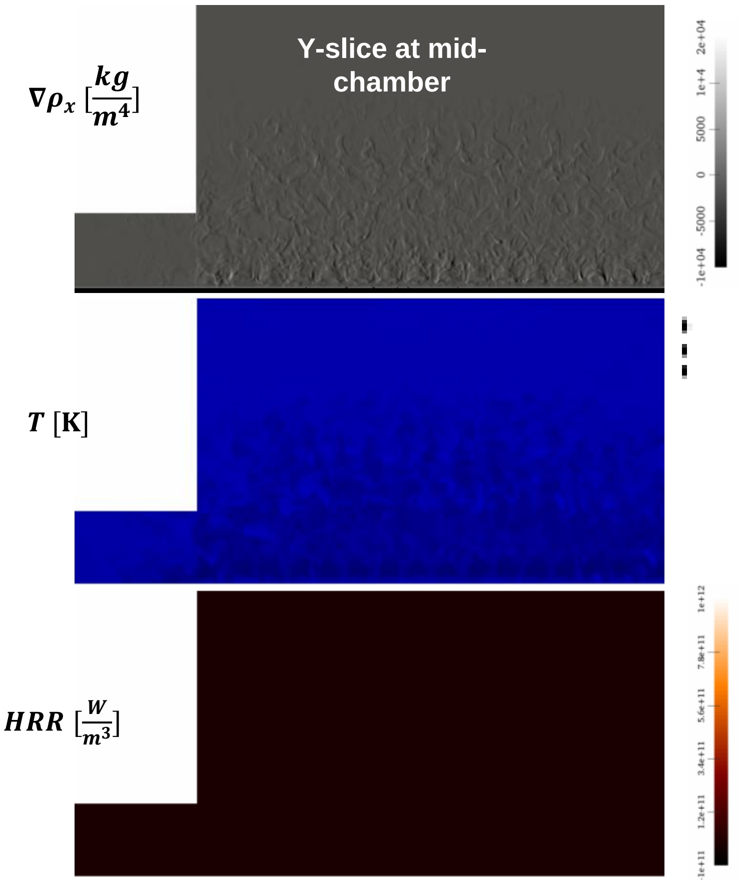
- Packaging includes 50 lb bags or 2000 lb super sacks.
- Export Packaging and containerization available.
- Shipping to any port destination.

In the US or abroad…

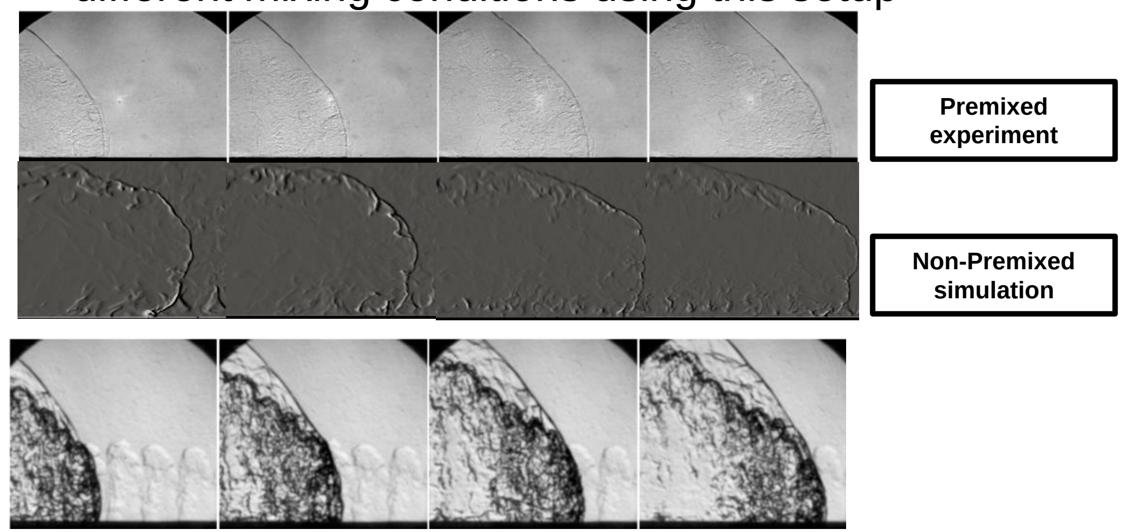
Let Asbury handle your Bit Coal requirements

ASBURY CARBONS
An ISO 9001 Corporation
ASBURY GRAPHITE MILLS, INC.
405 Old Main Street • PO Box 144 • Asbury, New Jersey 08802
Phone: 908.537.2155 • Fax: 908.537.2908
www.asbury.com

15-injector Linear Array with H2-air Detonation



- A detonation enters the chamber and transition to a non-premixed detonation front above the injectors
- Gas-phase detonation successfully achieved
- Multiple detonation traverses can be studied for different mixing conditions using this setup



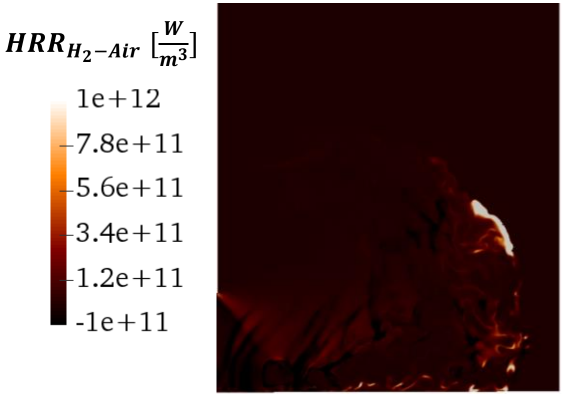
Burr, Jason R., and Kenneth Yu. *53rd AIAA/SAE/ASEE Joint Propulsion Conference*. 2017.

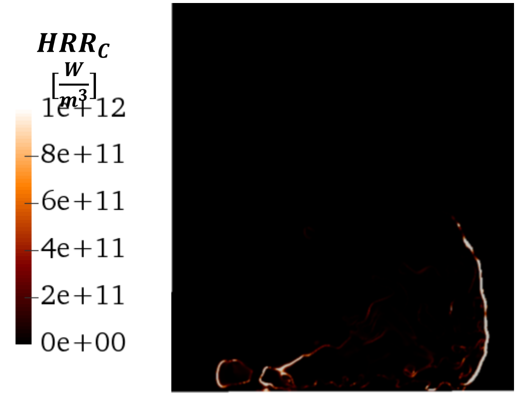
Gas-Phase $H_2 - \mathrm{C_g} - \mathrm{Air}$ Combustion

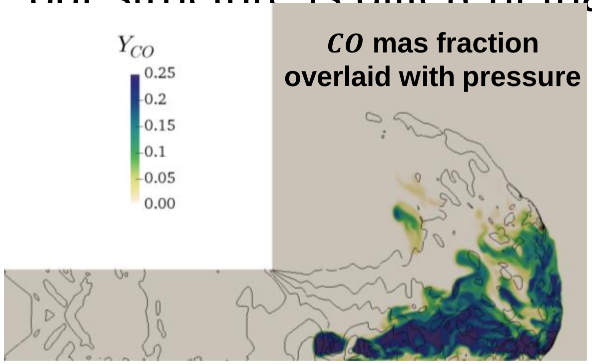
- Ideal case: coal gasified and premixed with air @600 K
- H_2 injection is unchanged as before.
- Gas-phase reaction of $C_g - \mathrm{O}_2$ starts when the local T reaches 950 K [1] - mimics carbon particle ignition
- Detonation propagated mainly due to coal combustion but structure is different than pure H2-air case

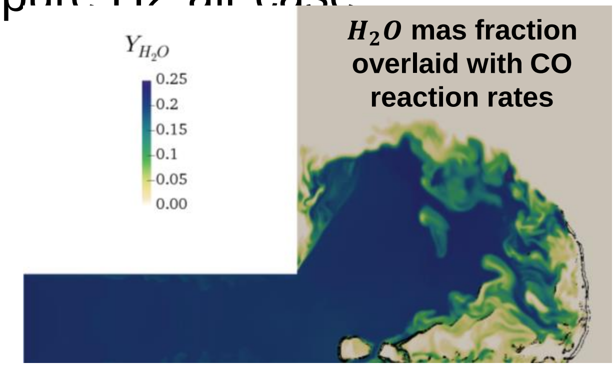
8 Injectors Grid

$C_g + O_2 \rightarrow CO_2$
$C_g + 0.5O \rightarrow CO$









1.Donahue, L., F. Zhang, and R. C. Ripley. *Shock Waves* 23.6 (2013): 559-573.