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

DE-FE0031545

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

NATIONAL ENERGY TECHNOLOGY LABORATORY

2020 Transformative Power Generation Meeting

Outline

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

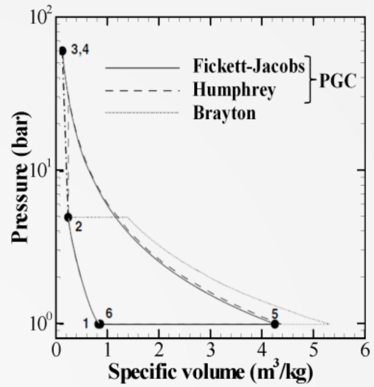
Detonations

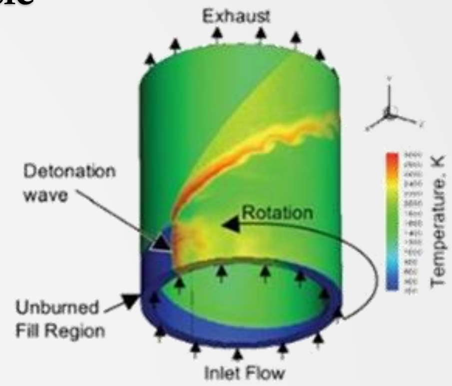
Pressure Gain Combustion

Detonation

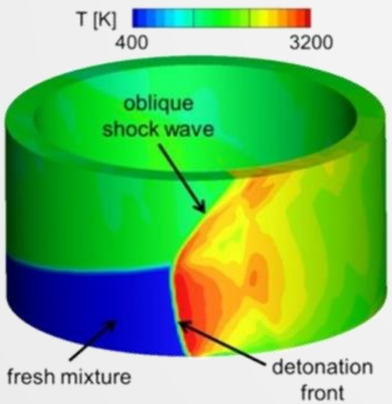
- Exploits pressure rise to augment high flow momentum
- Fundamental mechanism is turbulent flame acceleration
- High flow turbulence intensities and length scales
- Serious challenge for reliable, repeatable and efficient

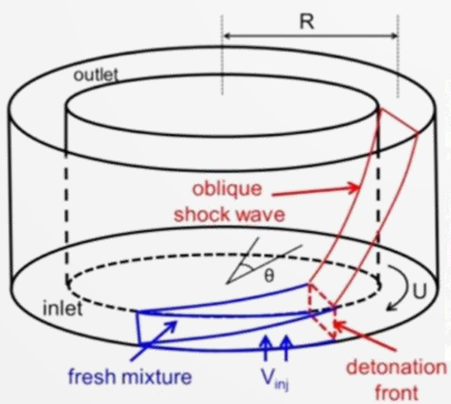
Thermodynamic Cycle

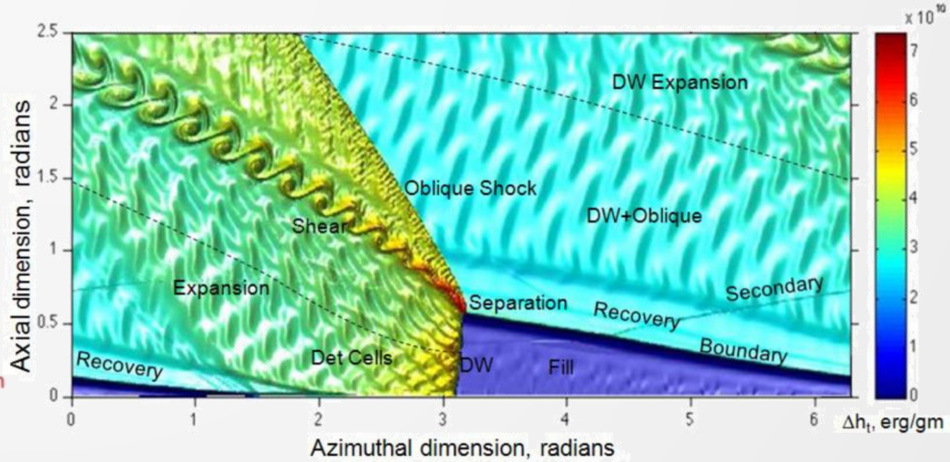




Schwer, *et al.*, AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010







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, 19th 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

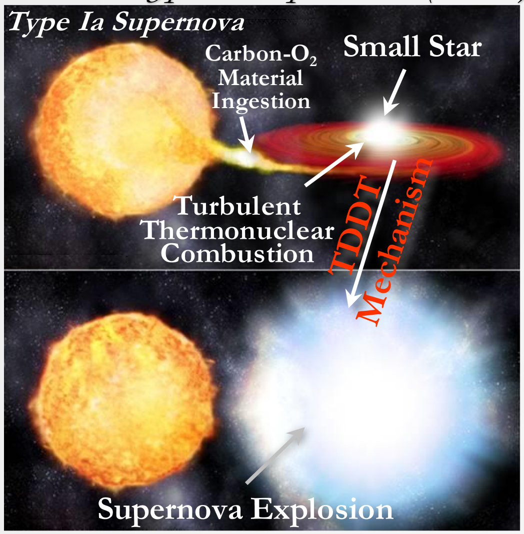
Coal Mine Fast-Flame Deflagration Explosion

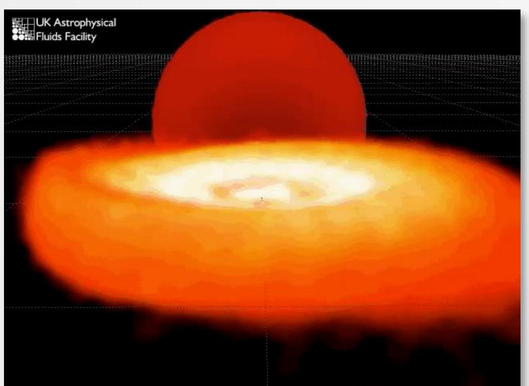
Coal Mine Detonation Explosion

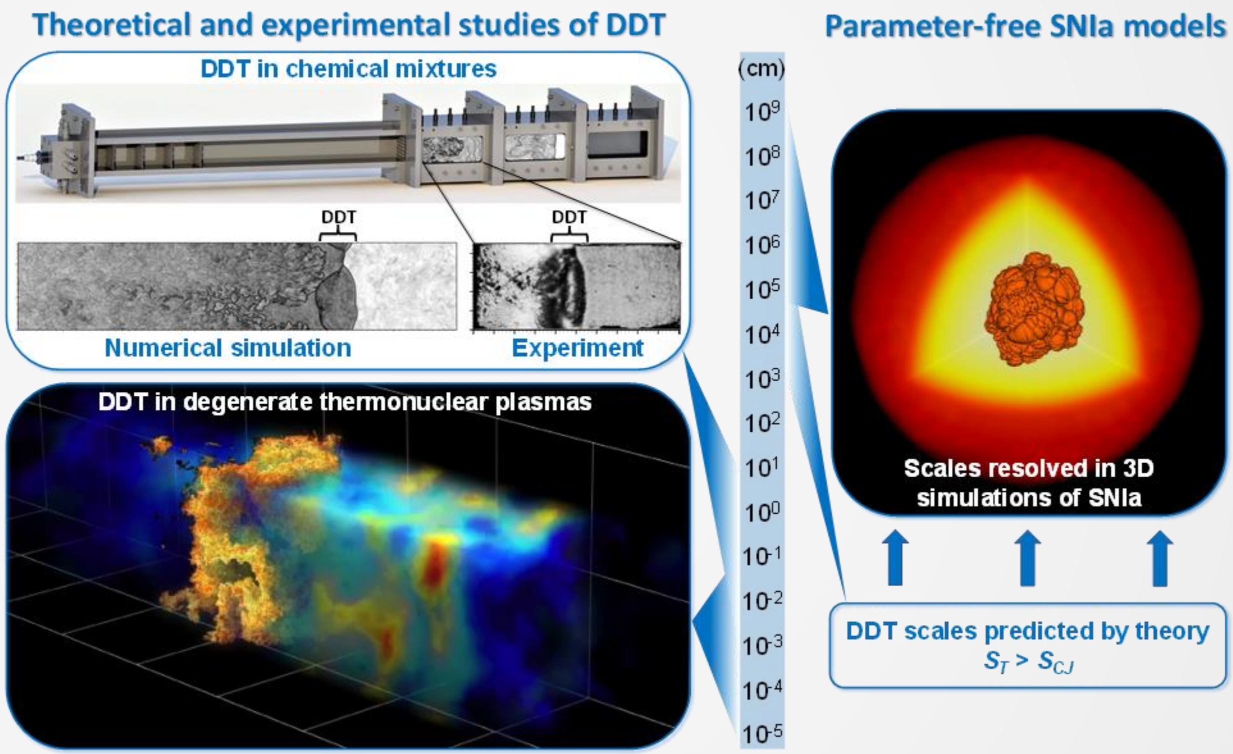
Combustion Physics in Science!

Universal Mechanisms Controlling Terrestrial and Astrophysical Explosions

Relate to Type Ia Supernovae (SNIa) – Thermonuclear Flames





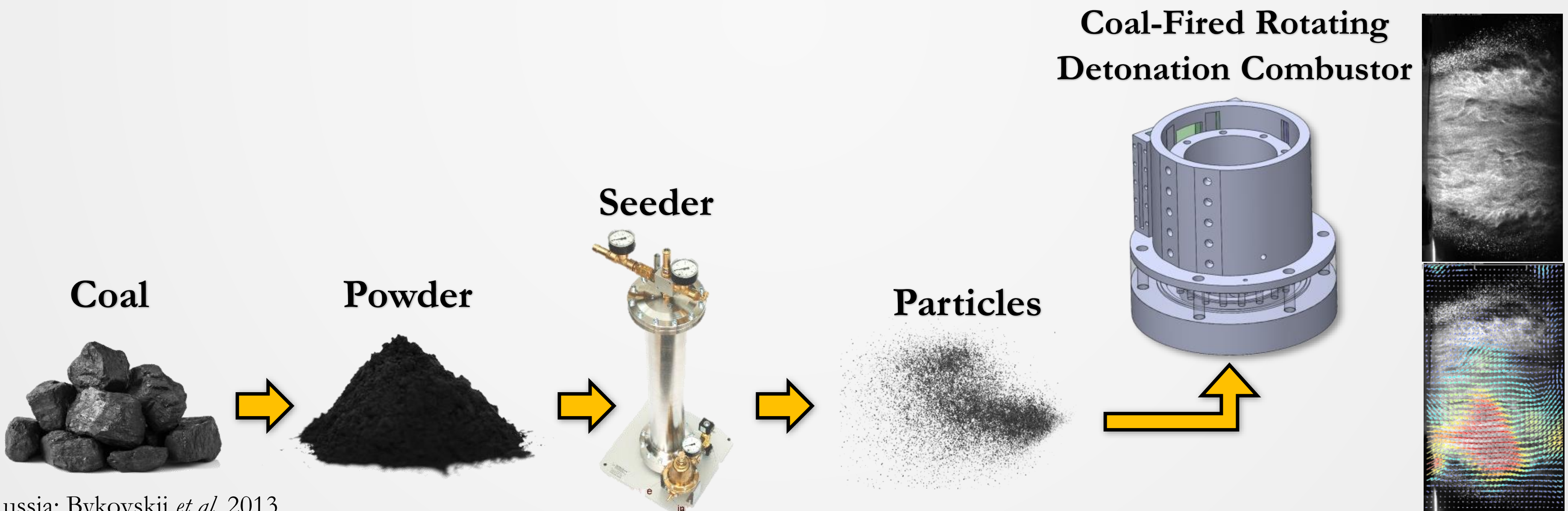


Poludnenko, A., Chambers, J. G, Ahmed, K, Gamezo, V., " A unified mechanism for unconfined deflagration-to-detonation transition in terrestrial chemical systems and type Ia supernovae," Science, Vol. 366, Issue 6465, 2019.

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

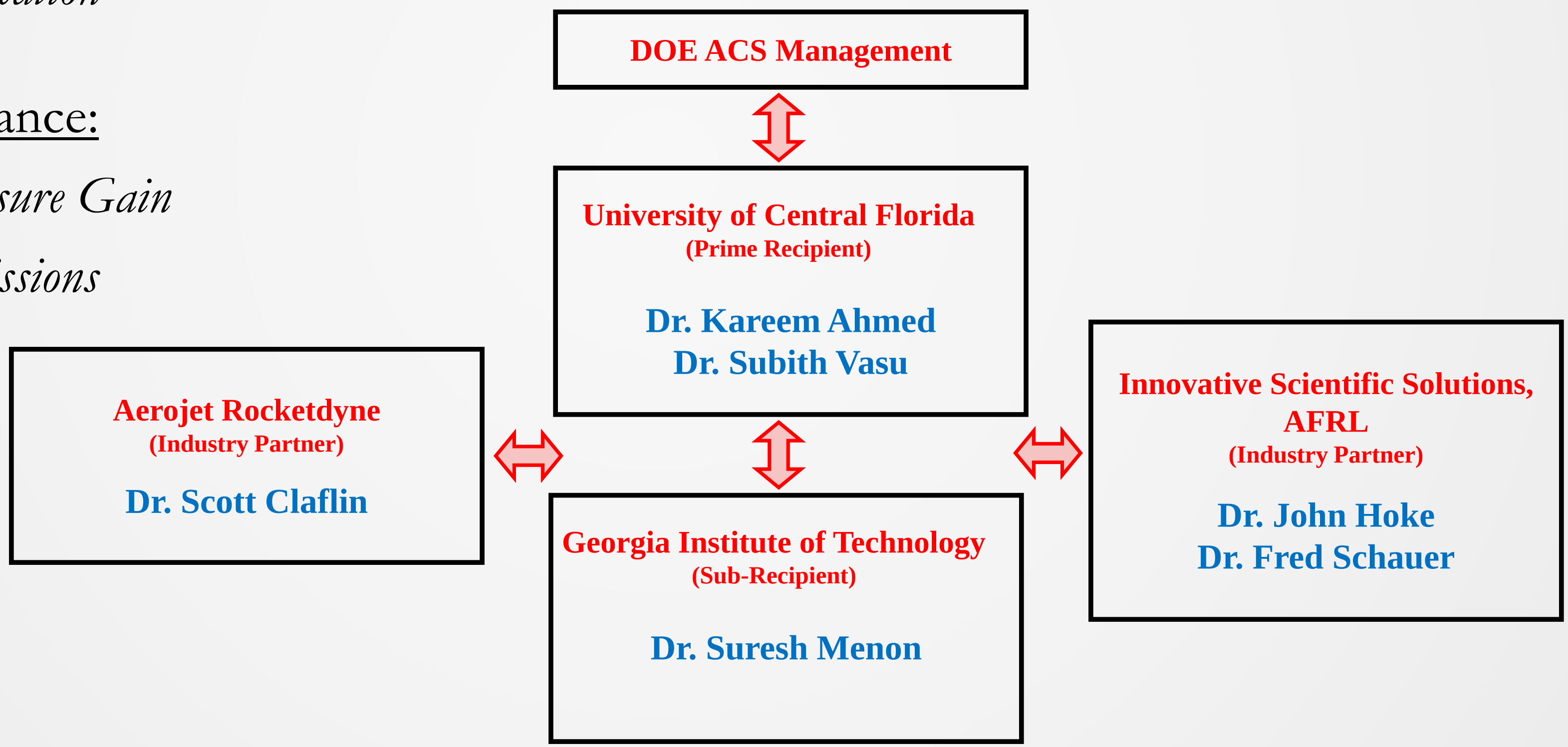


Russia: Bykovskii *et al.* 2013

Project Objectives

1. <u>Operability Dynamics for Detonation Wave:</u>
   a. *Coal Injection*
   b. *Initiation.*
   c. *Directionality*
   d. *Bifurcation*

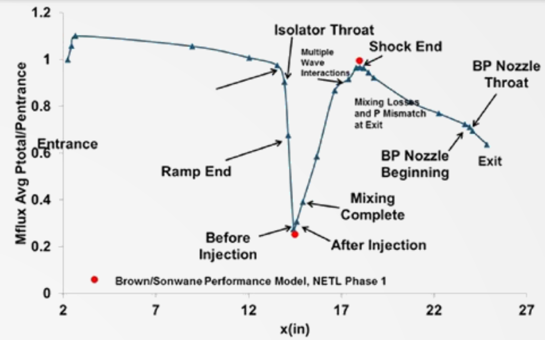
2. <u>Performance:</u>
   a. *Pressure Gain*
   b. *Emissions*



DOE – NETL: Aerojet Rocketdyne and University of Central Florida

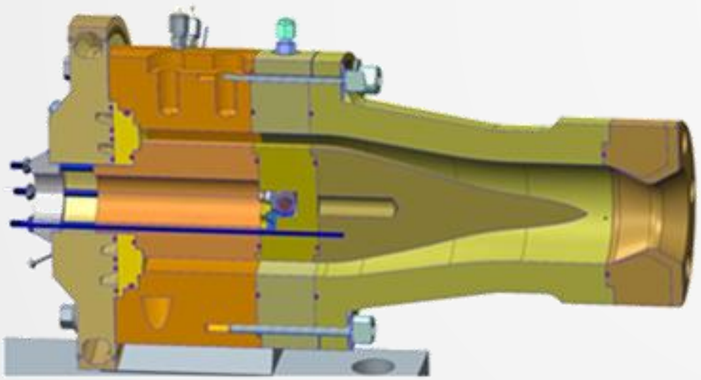
Vision

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.

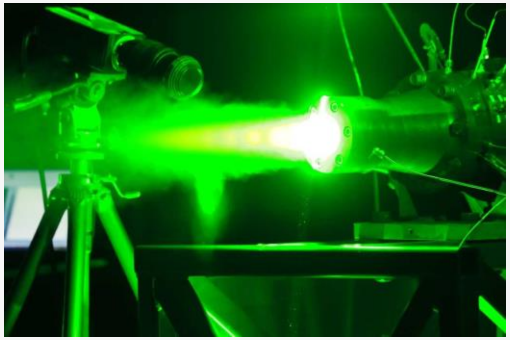


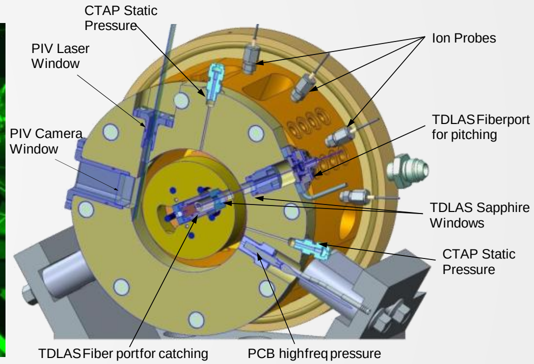
Computed pressure gain through engine

$$\left(\frac{\hat{P}^o_{d,ex}}{\hat{P}^o_{M}}\right) = \frac{\left(\frac{\hat{P}^o_{c,ex}}{\hat{P}^o_{c,in}}\right)_1}{\left(\frac{\hat{P}^o_{M}}{\hat{P}^o_{c,in}}\right)_2\left(\frac{\hat{P}^o_{c,ex}}{\hat{P}^o_{d,ex}}\right)_3}$$



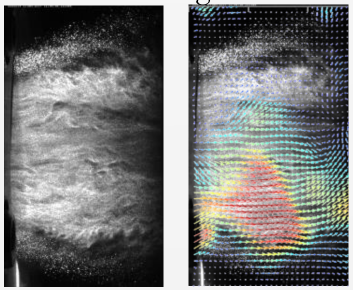
Aerojet Rocketdyne RDE cutout

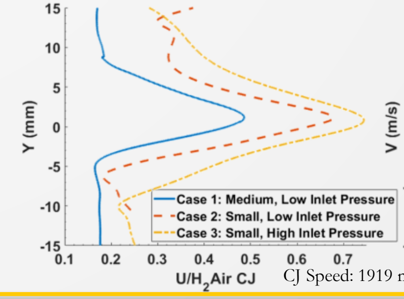

PIV on exit plane of nozzle of the Aerojet RDE

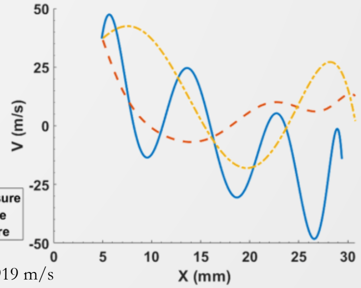


Entire CAD of Aerojet RDE cutout sitting on static test fire stand

Mie Scattering Particles



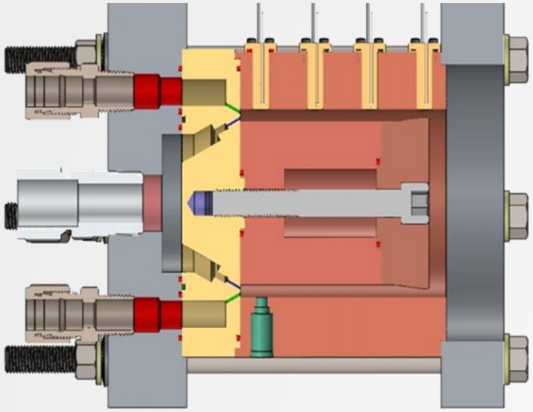


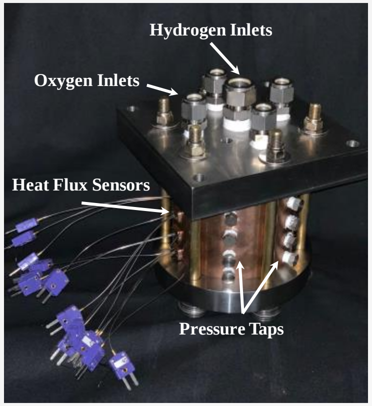


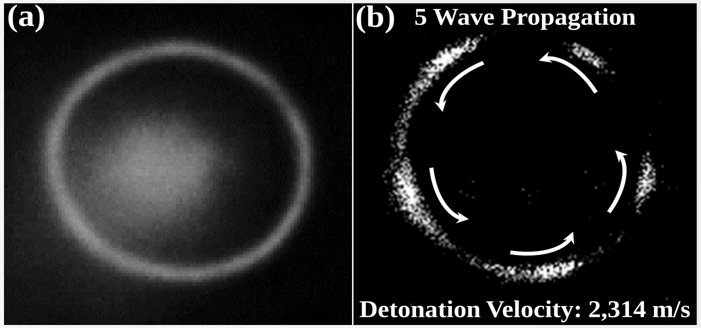
CJ Speed: 1919 m/s

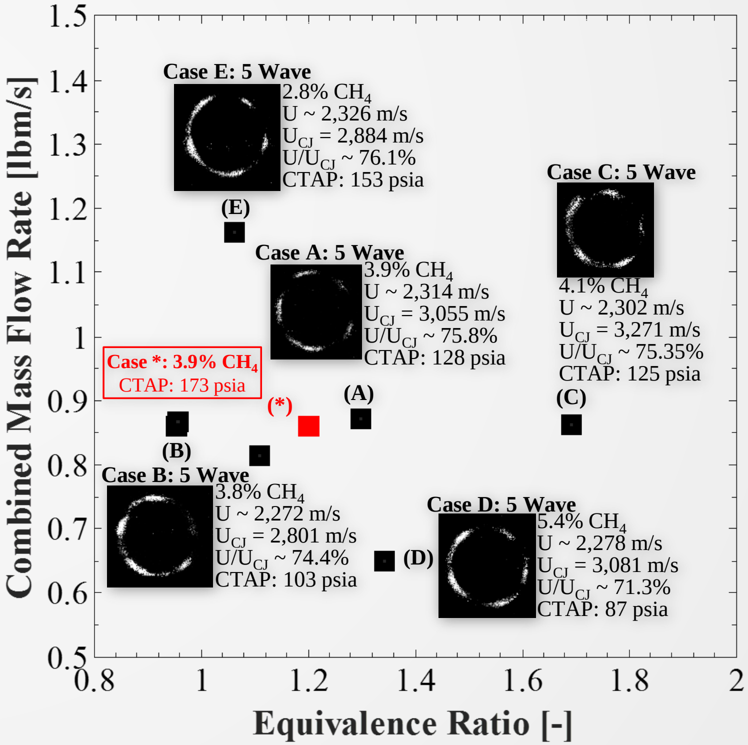
First Demonstration of H_2-O_2 Rotating Detonation Rocket Engine

Improved Performance and Reduced Cost and Weight



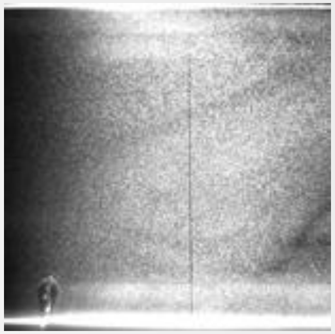




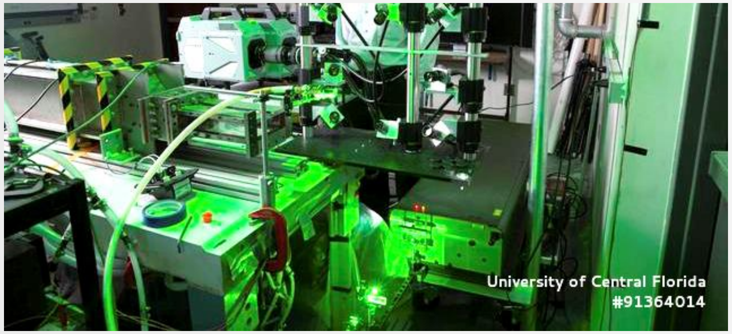


Sosa, Burke, Ahmed, Micka, Bennewitz, Danczyk, Paulson, Hargus Jr., “Experimental Evidence of H2/O2 Propellants Powered Rotating Detonation Rocket Engine,” Combustion and Flame, 2020.

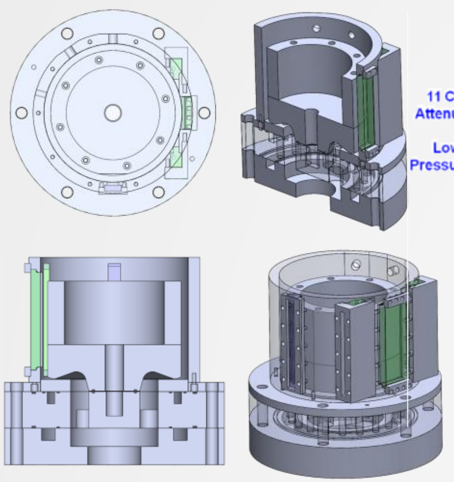
Advanced Optical Diagnostics

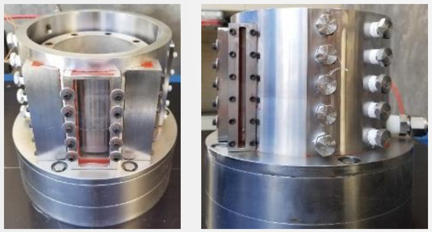


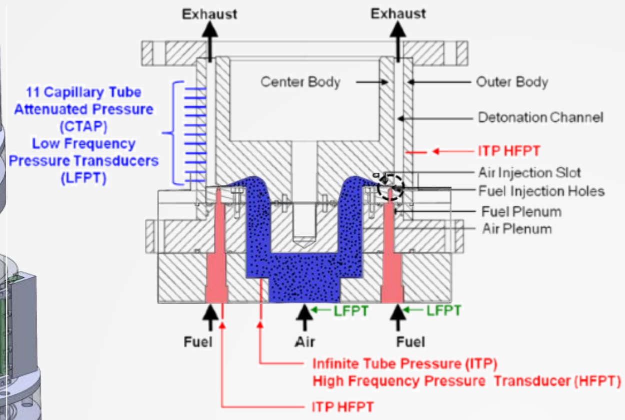
- High-speed PIV system (100kHz – 1 MHz)
- High speed cameras 21,000-2,100,000 frames per second
- High-speed chemiluminescence CH*, OH* (100kHz – 1 MHz)
- Light-field focusing system for flow measurements and visualization
- LabVIEW control hardware and software
- Dynamic pressure transducers (PCB)
- Codes: DMD, POD, PIV, Physics-Based Models (Matlab/Fortran)



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

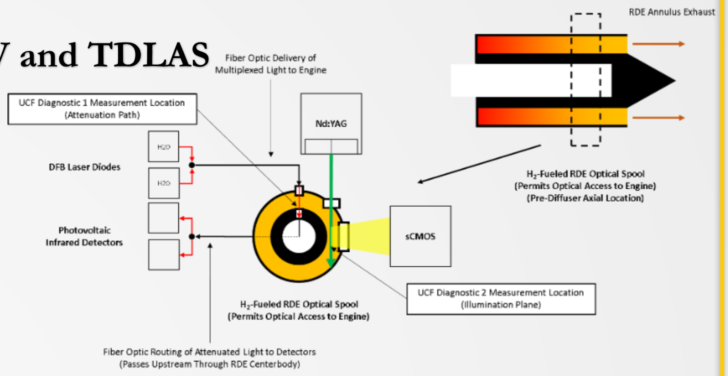




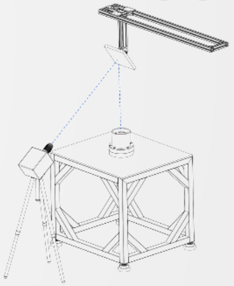


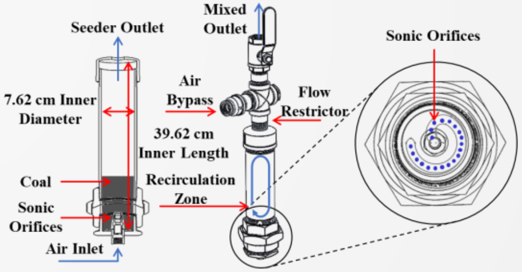
J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

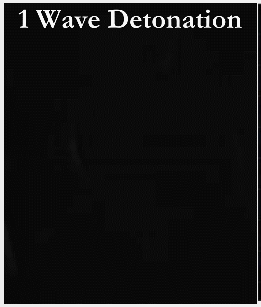
PIV and TDLAS

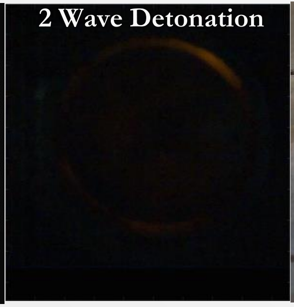


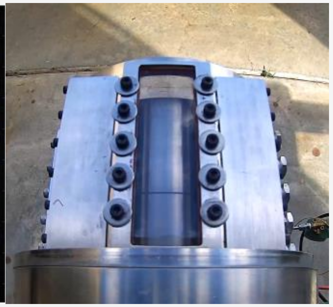
AFT Imaging



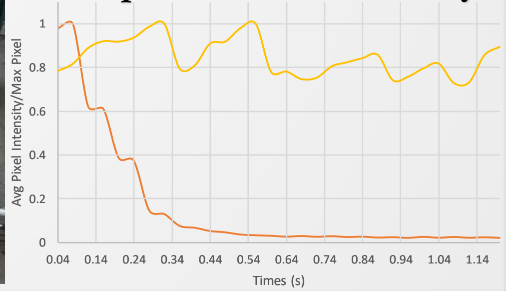




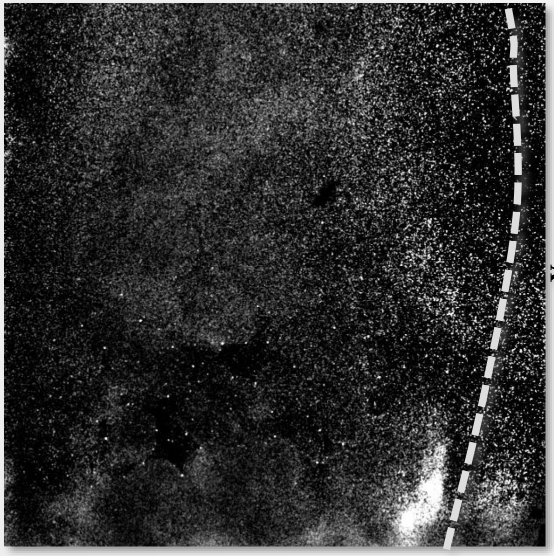




Optimized Seed Density



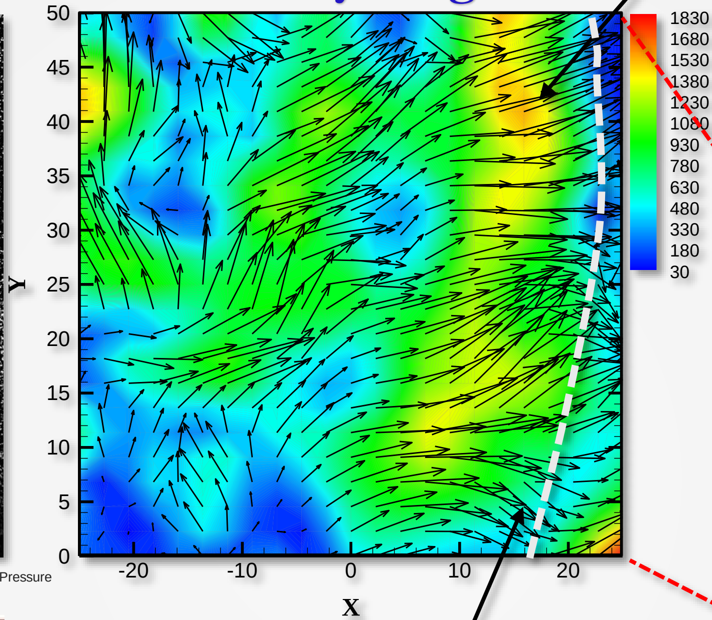
Mie Scatter



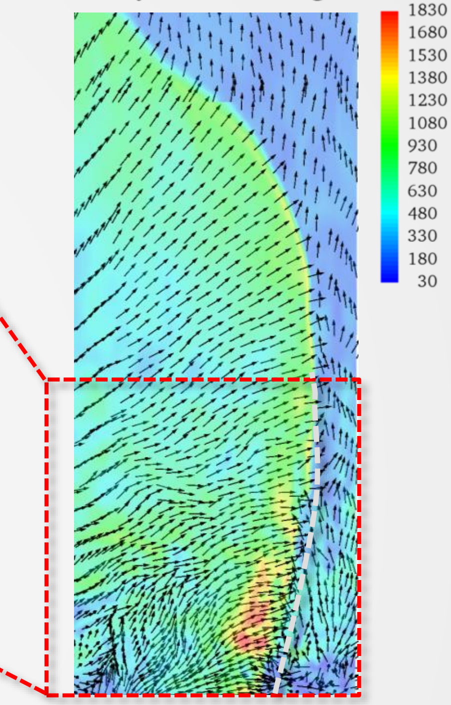
Dunn, I.B., Thurmond, K., Ahmed, K.A. and Vasu, S., 2019. Experimentation of Measuring Pressure Gain Combustion within a Rotating Detonation Engine. In *AIAA Scitech 2019 Forum* (p. 1010).

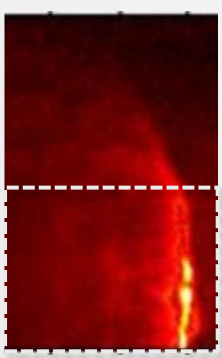
PIV Velocity Magnitude

~1600 m/s



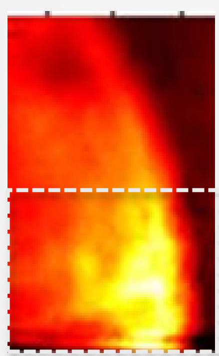
~900 m/s





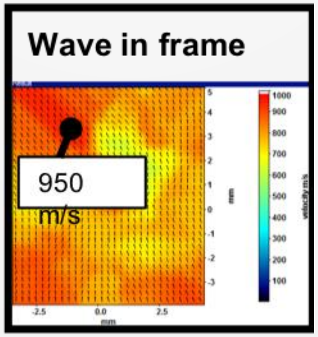
OH*

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

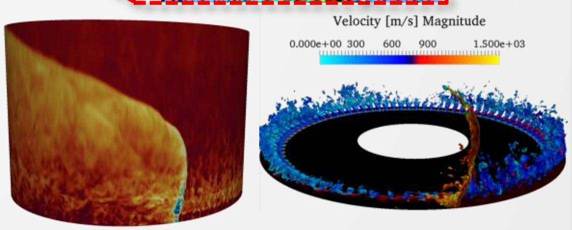


H_2O

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



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



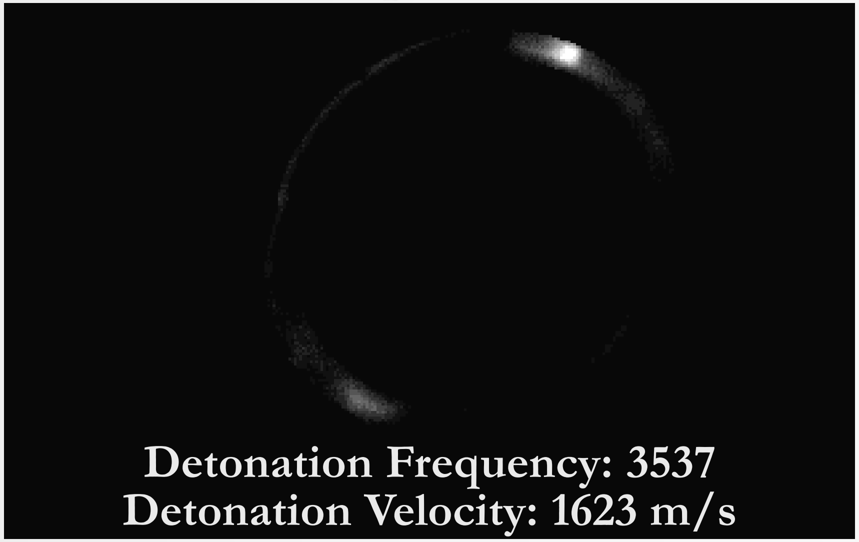
Suresh Menon (LESLIE)

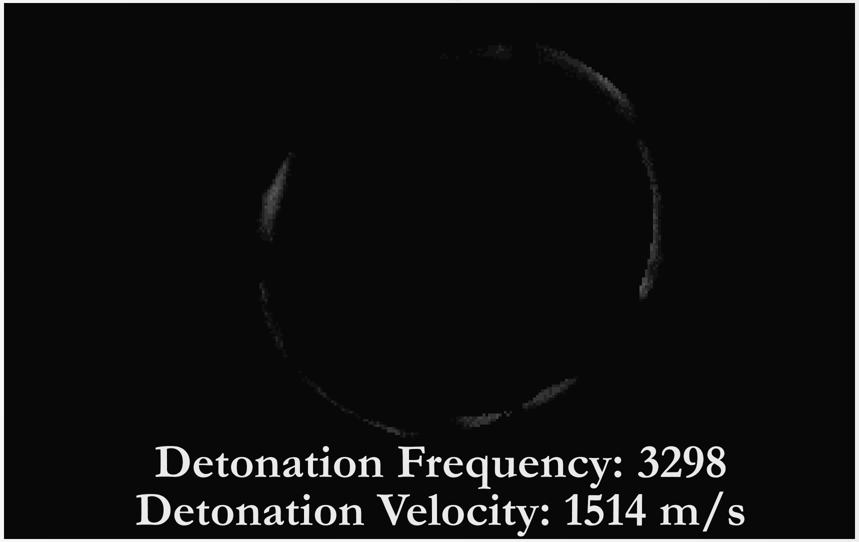
Georgia Tech College of Engineering

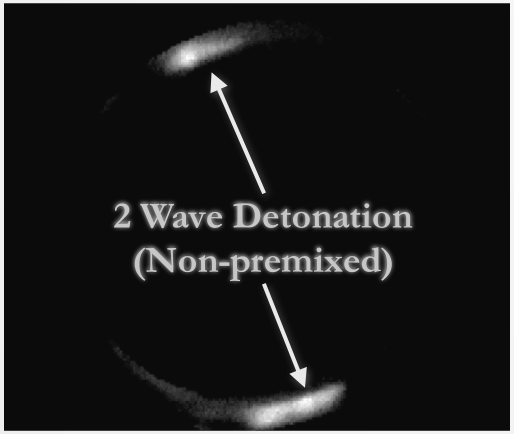
Dynamic Control of Detonation Waves through Partial Premixing

2 Wave Detonation (Non-premixed)

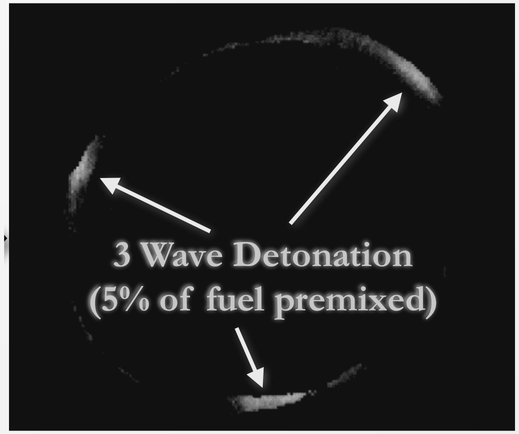
3 Wave Detonation (5% of fuel premixed)







Dunn, I.B., Thurmond, K., Ahmed, K. and Vasu, S., 2019. Wave Dynamics of a Partially Premixed Rotating Detonation Engine. In *AIAA Propulsion and Energy 2019 Forum* (p. 4128).



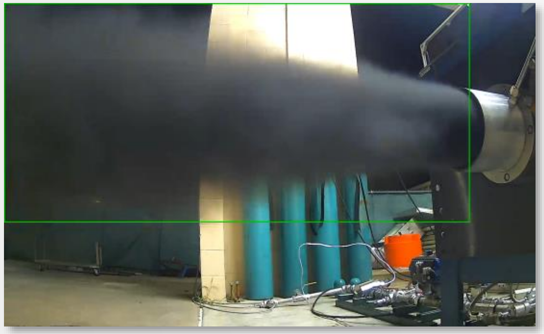
1. **Carbon Black (C)**
   - Size: 29 nm
   - Volatility: 1.18%

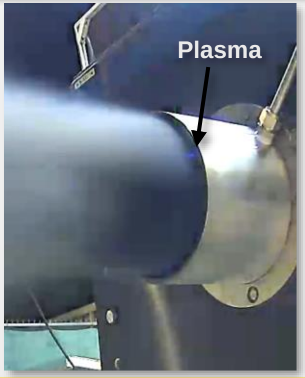
2. **Bituminous Coal ($C_{137}H_{97}O_9NS$)**
   - Size: 5 μm
   - Volatility: 34 to 44%

Coal RDE Test Fires (carbon)

Non-Reacting

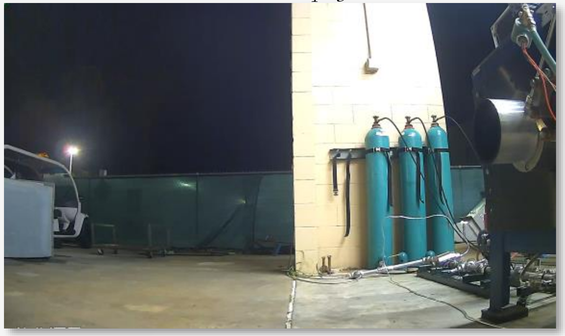
click to play

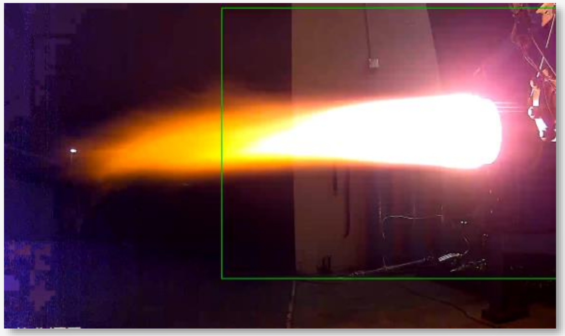




Deflagration

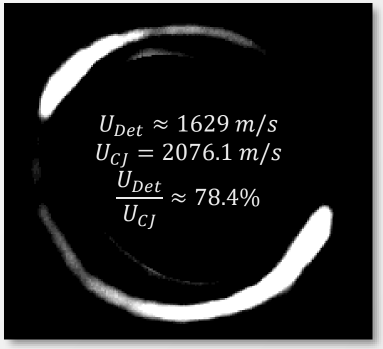
click to play





Detonation

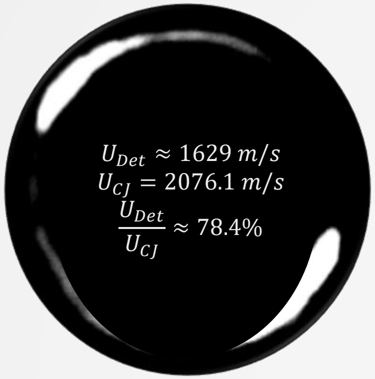
click to play

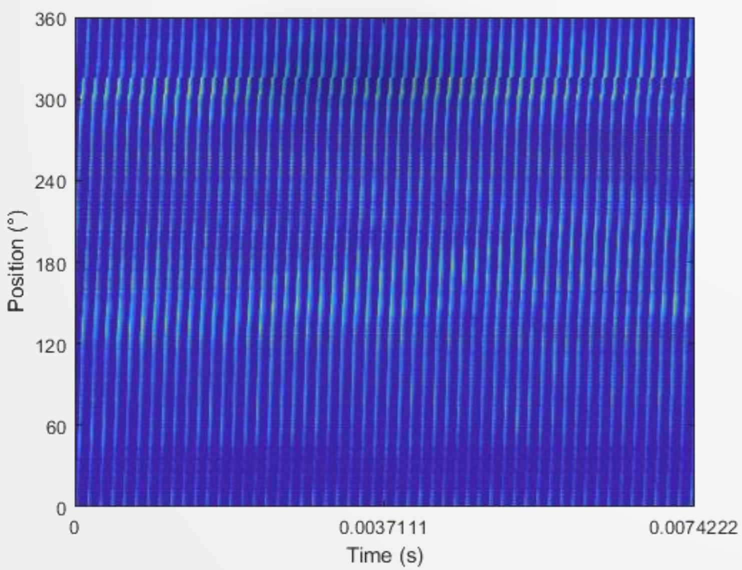


Dunn, I., Menon, S., AHMED, K.A. , "Multiphase Rotating Detonation Engine," GT2020-15017, Proceedings of ASME Turbo Expo 2020.

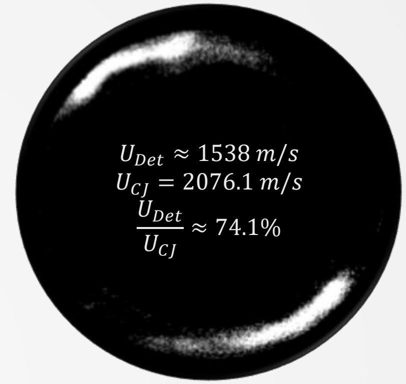
Detonation Wave Dynamics

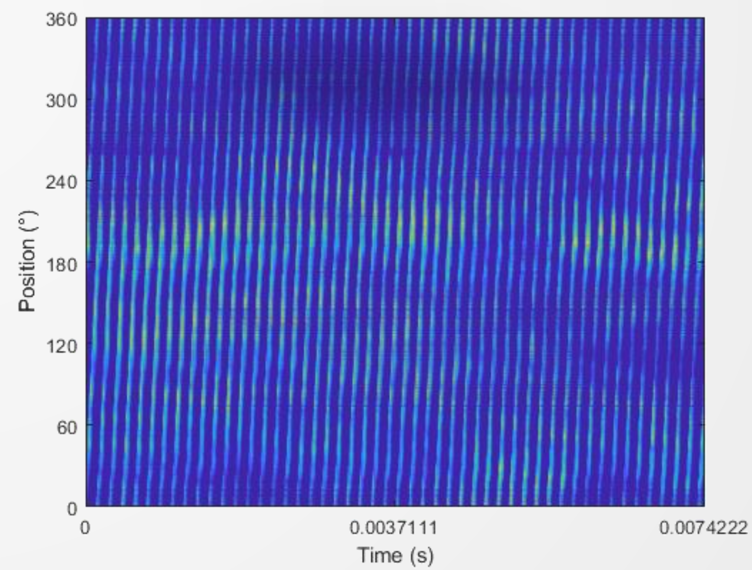
Average Concentration 38% Coal





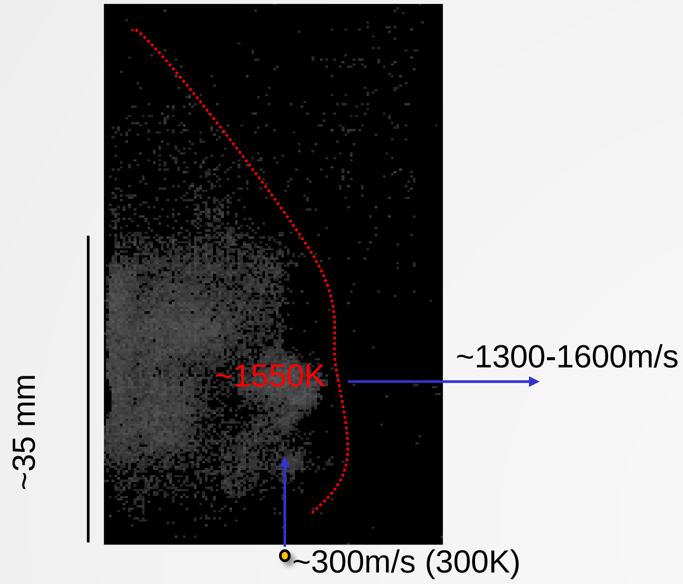
Average Concentration 67% Coal

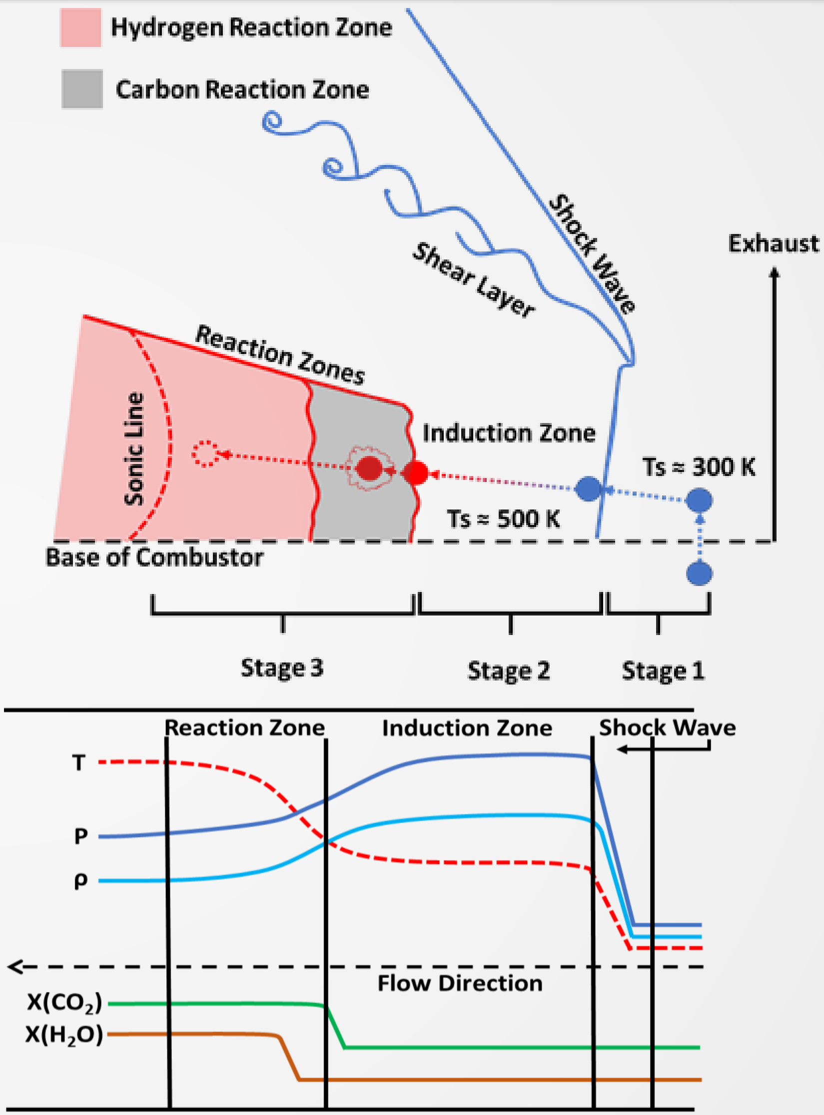




J. Bennewitz, B. Bigler, S. Schumaker, W. Hargus Jr, Automated image processing method to quantify rotating detonation wave behavior, Review of Scientific Instruments 90 (2019)

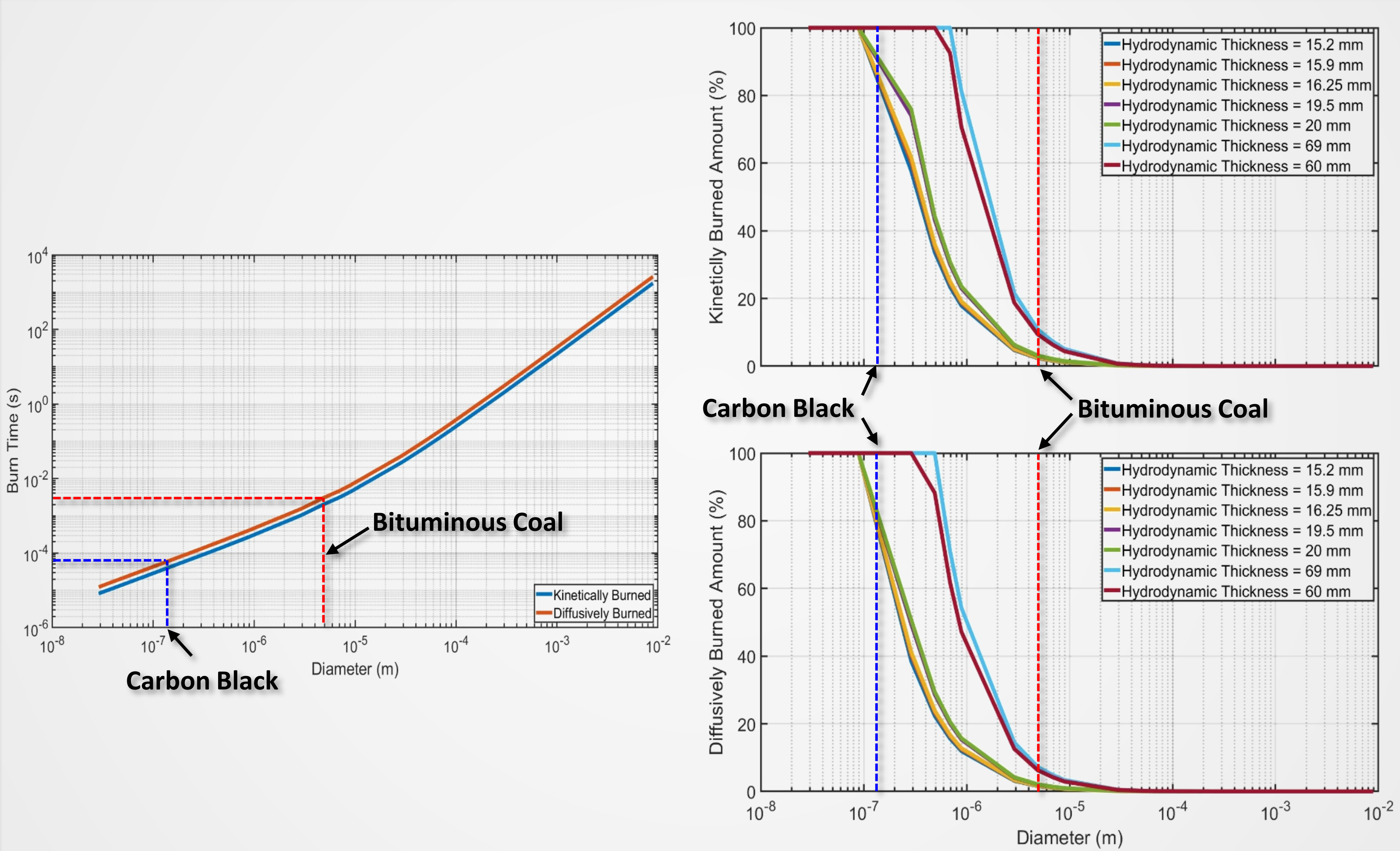
ZND Overlay with Detonation Structure



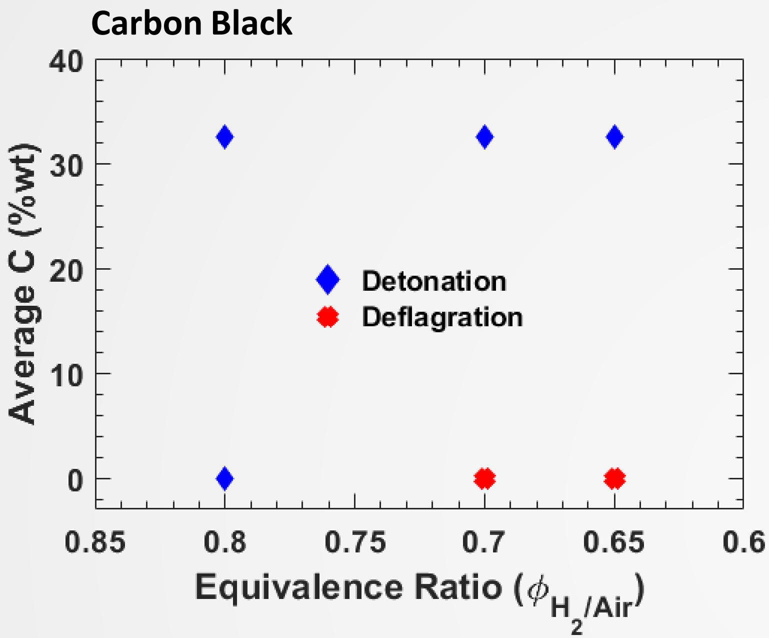


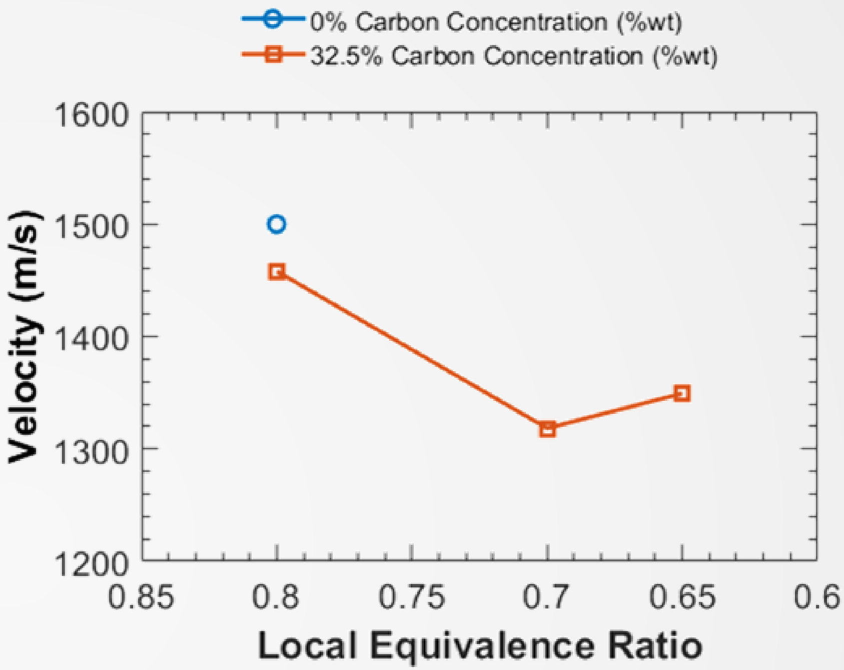
- Stage 1: Leading Shock
- Stage 2: Particle Heating
- Stage 3: Particle Gasification
- Stage 4: Particle Burn Out

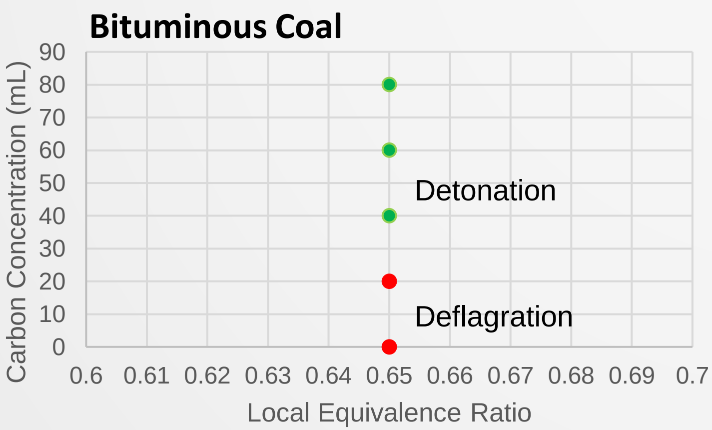
Particle Reaction



First Evidence of Carbon Driving Detonation



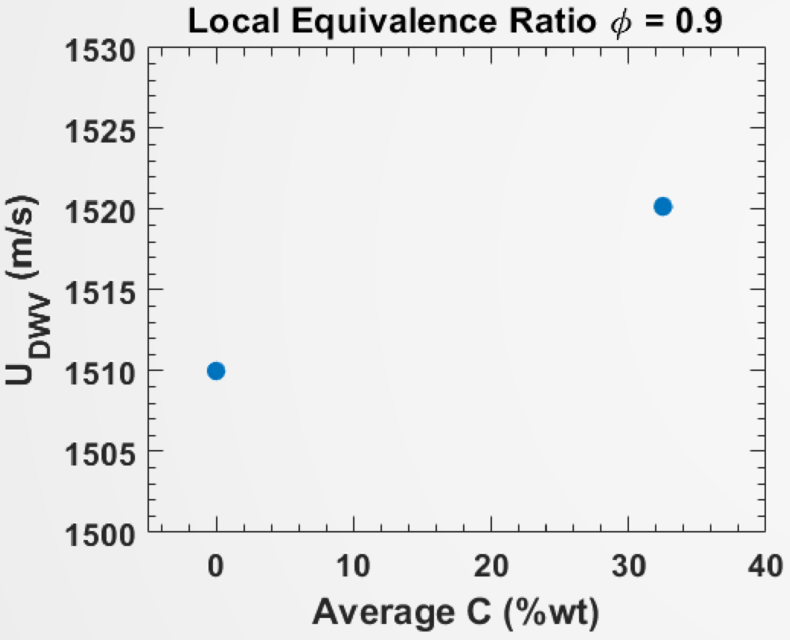




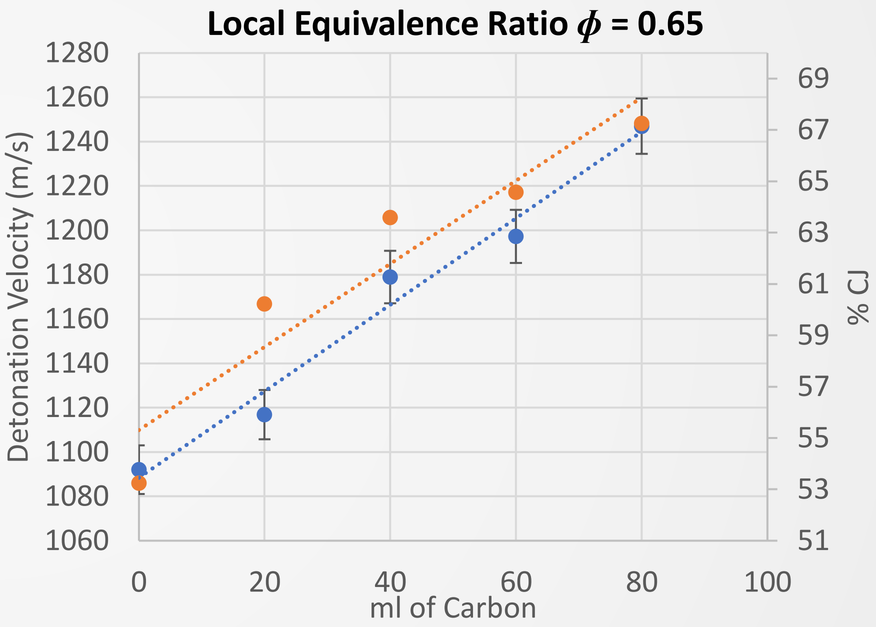
Dunn, I. , Menon, S., AHMED, K.A. , "Multiphase Rotating Detonation Engine," GT2020-15017, Proceedings of ASME Turbo Expo 2020.

Second Evidence of Carbon Driving Detonation

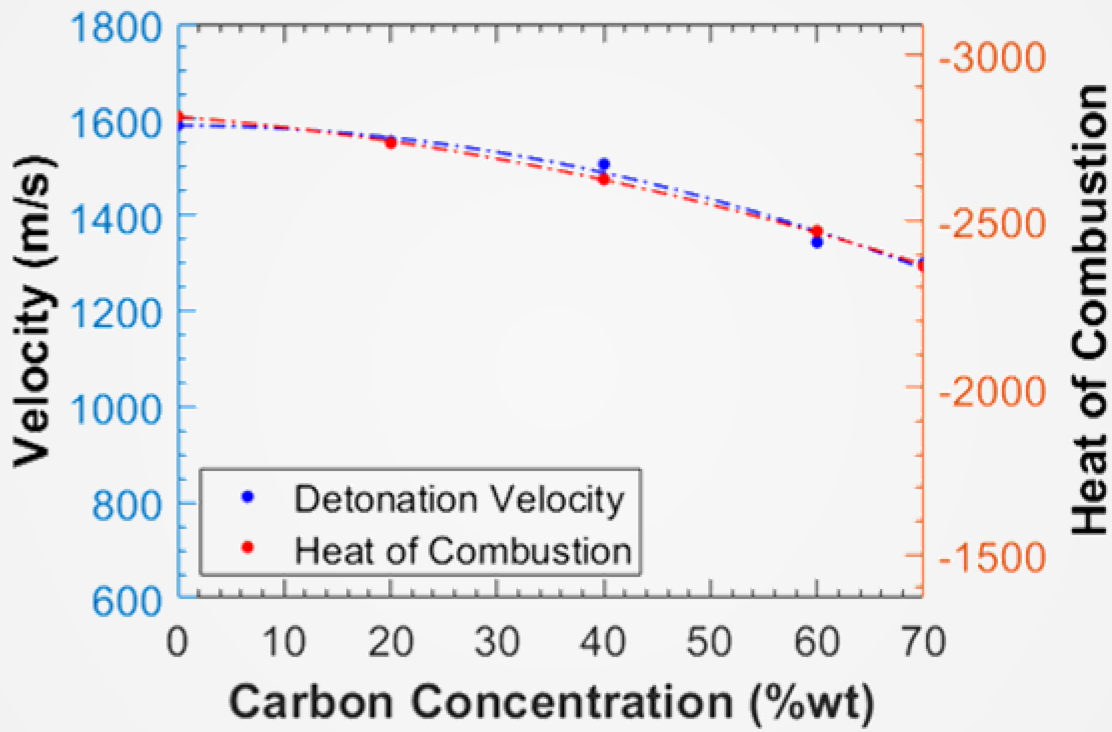
Carbon Black



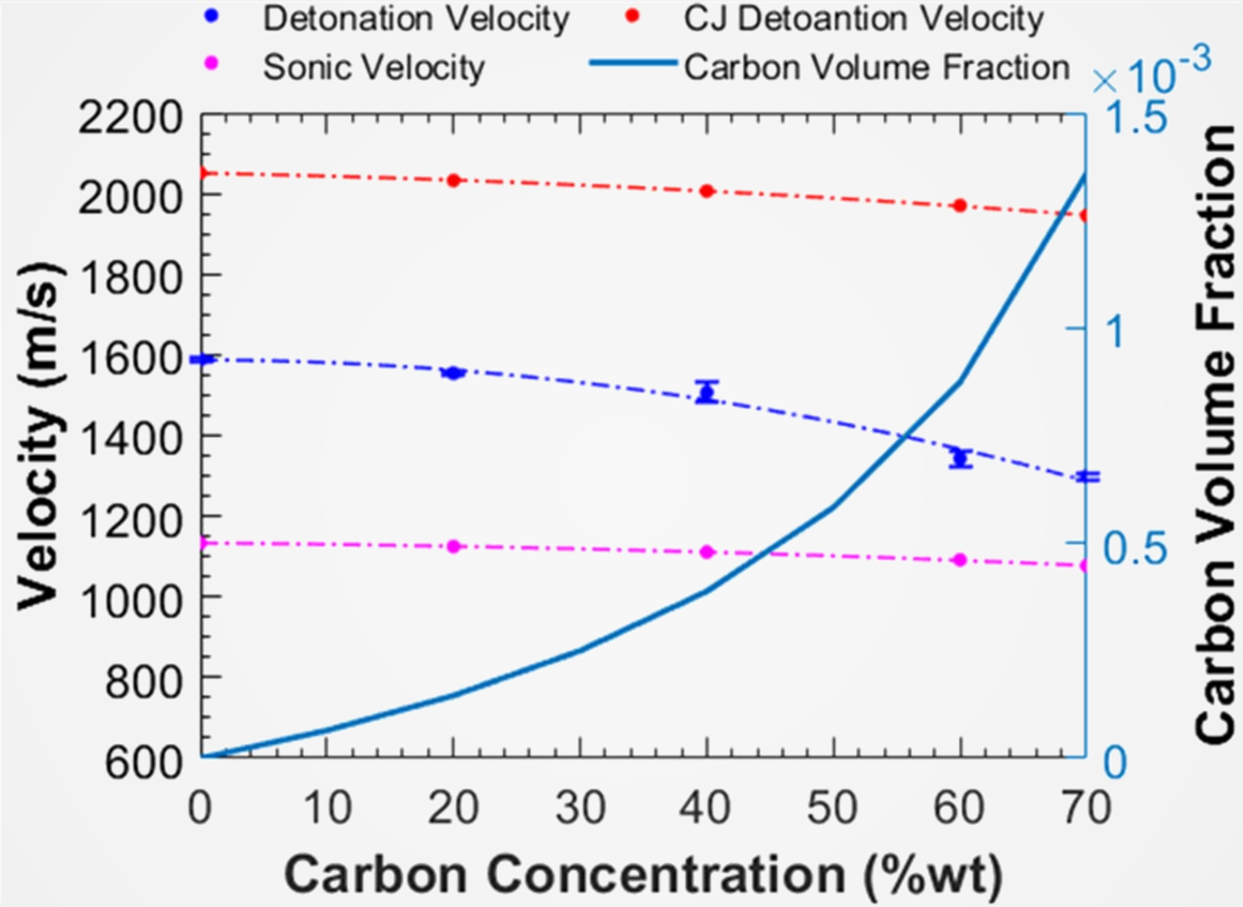
Bituminous Coal



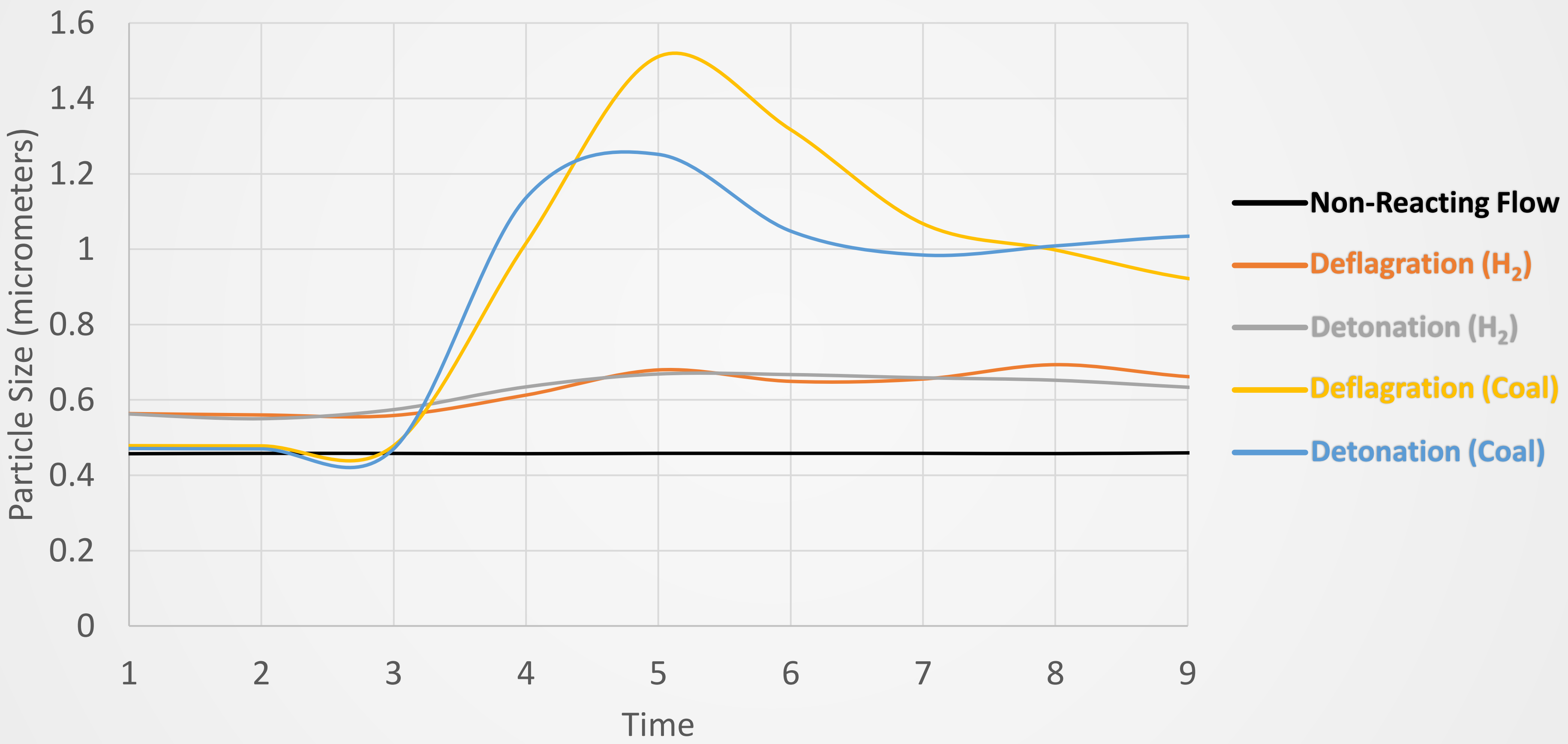
RDE Detonation Velocity Measurements vs. Heat of Combustion



RDE Detonation Wave Speed

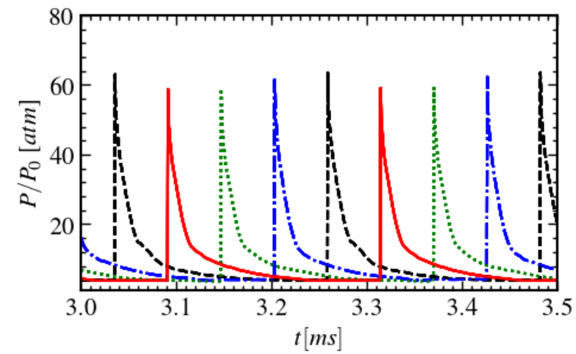


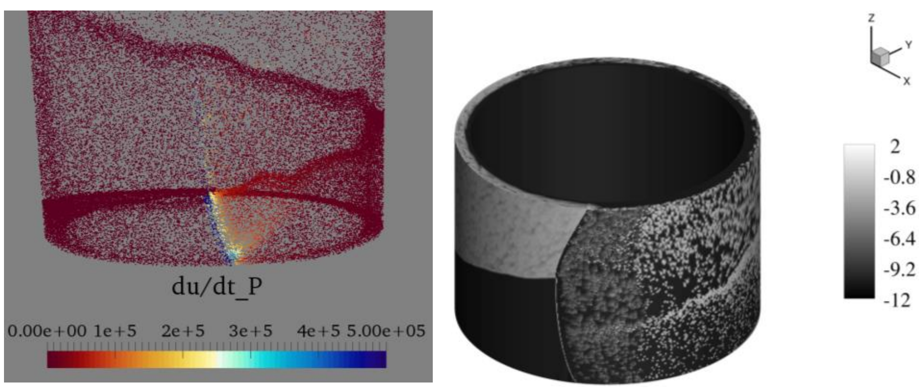
Exhaust Particulates (Bituminous Coal)

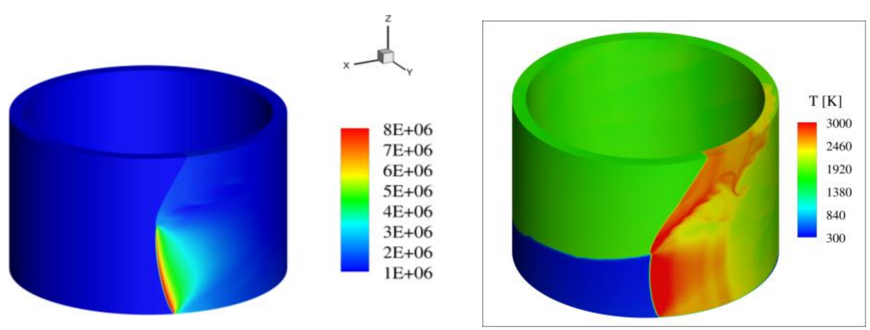


Premixed RDE with Coal Particles

- 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.

Salvadori, M., Dunn, I.B., Sosa, J., Menon, S. and Ahmed, K.A., 2020. Numerical Investigation of Shock-Induced Combustion of Coal-H2-Air mixtures in a Unwrapped Non-Premixed Detonation Channel. In *AIAA Scitech 2020 Forum* (p. 2159).

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

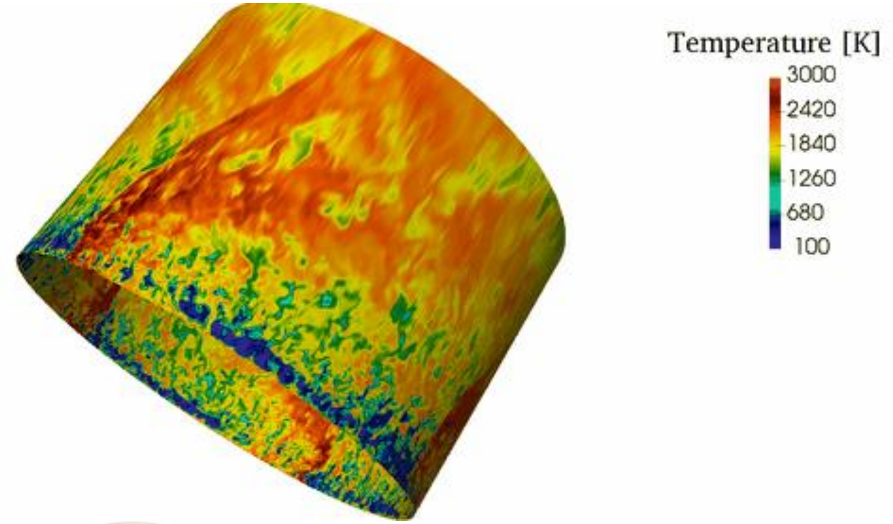
- 2-steps infinite-rate gas-phase reactions [2]

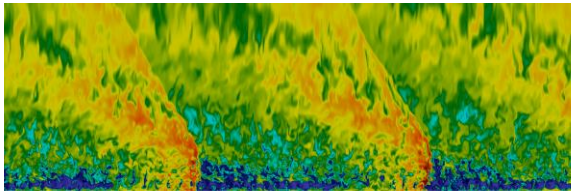
$C_g + O_2 \rightarrow CO_2$ *(partial oxidation)*
$C_g + \frac{1}{2}O_2 \rightarrow CO$ *(oxidation)*

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.

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



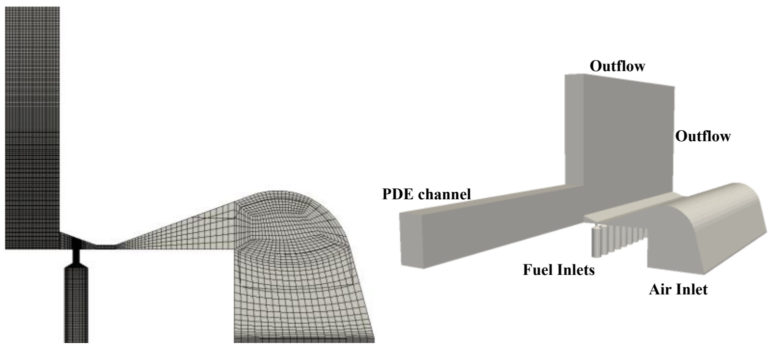


1. Baurle, R., Alexopoulos, G., and Hassan, H. Journal of Propulsion and Power 10, 4 (1994), 473–484.
2. Poinsot & Lele, J. Comp. Phys. 1992

Linear Array Detonation Studies

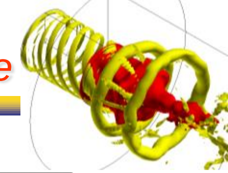
- 15-injector & 8-injector unwrapped array to isolate two-phase detonation features
- Use pre-detonation tube to create shock-to-detonation-transition (SDT), get a DW into chamber, and then investigate if detonation sustains in a 2-phase mixture
- H_2 injected as before but with different coal-air mixture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



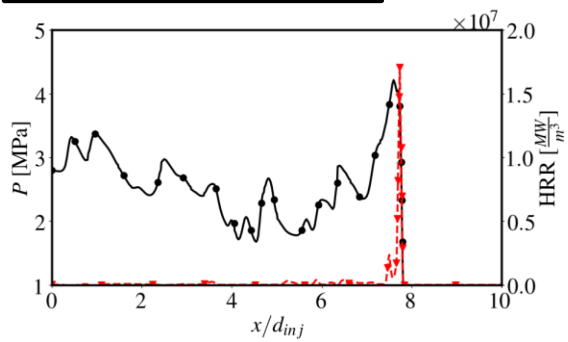
15-injector Array

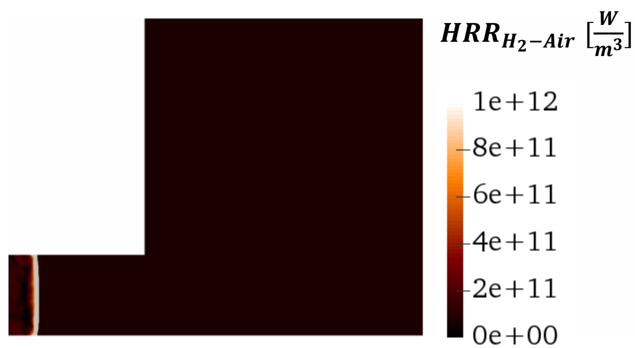
1. Baurle, R., Alexopoulos, G., and Hassan, H. Journal of Propulsion and Power 10, 4 (1994), 473–484.
2. Baek, S. W., Sichel, M., and Kauffman, C. W. Combustion and Flame 81, 3-4 (1990), 219–228
3. Donahue, L., F. Zhang, and R. C. Ripley. *Shock Waves* 23.6 (2013): 559-573.



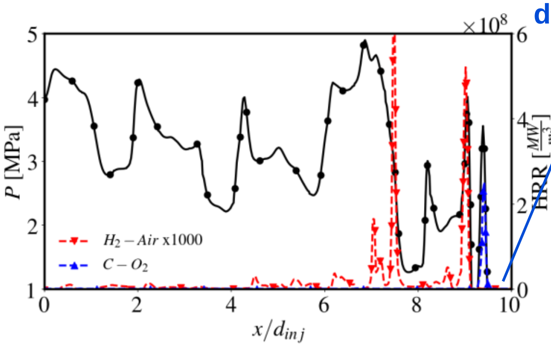
LRDE: Gas-Phase $H_2 - C_g -$ Air with 70% $\dot{m}_{H_2}$

Without C_g





With C_g



$C - O_2$ kinetics dominates