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

DE-FE0031545

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ISSI (Dr. John Hoke)
AFRL (Dr. Fred Schauer)
Siemens (Timothy Godfrey)

2021 DOE/FE Spring R&D Project Review Meeting

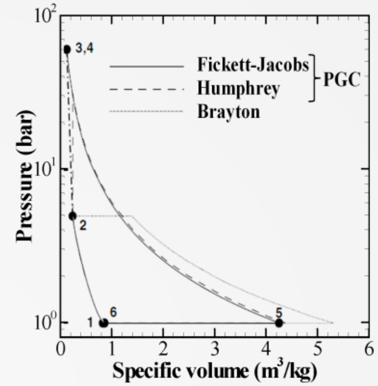
Outline

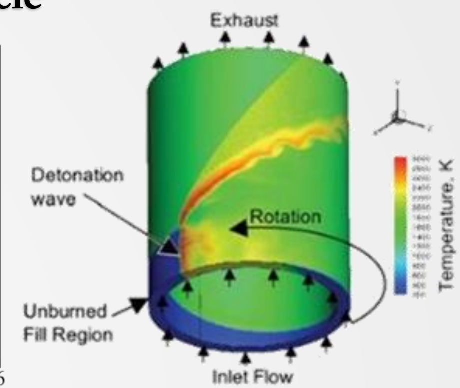
- Background
- Project Objectives
- Technical Approach
- Results and Discussion
- Conclusion

Detonations

Pressure Gain Combustion

Thermodynamic Cycle

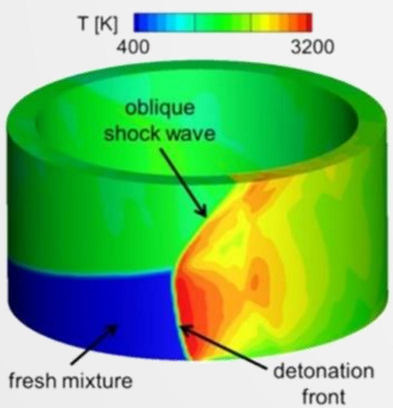


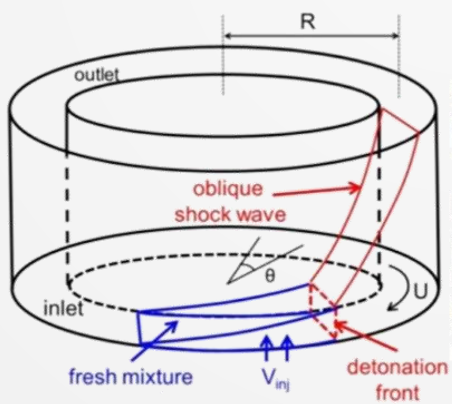


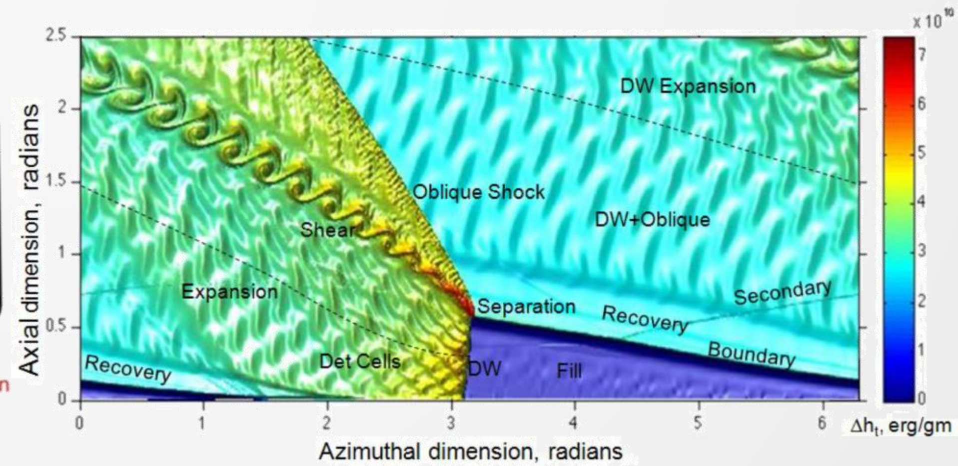
Schwer, *et al.*, AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010

Detonation

- Exploit pressure rise to augment high flow momentum
- High flow turbulence intensities and length scales
- Serious challenge for reliable, repeatable and efficient







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

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

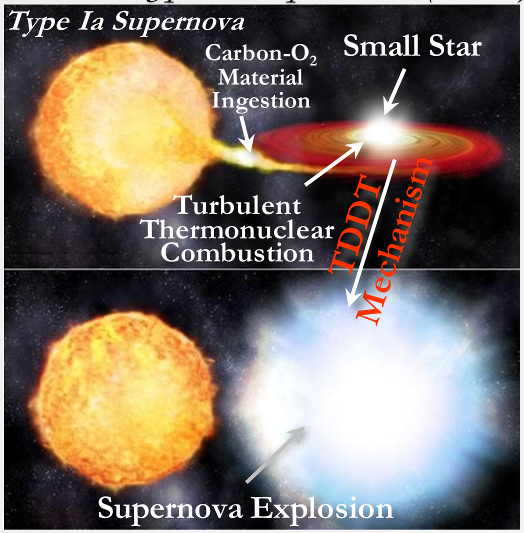
Coal Mine Fast-Flame Deflagration Explosion

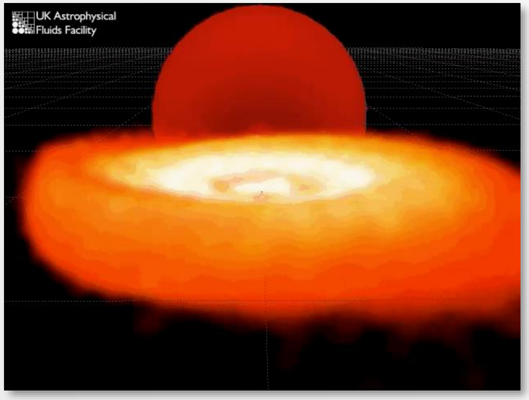
Coal Mine Detonation Explosion

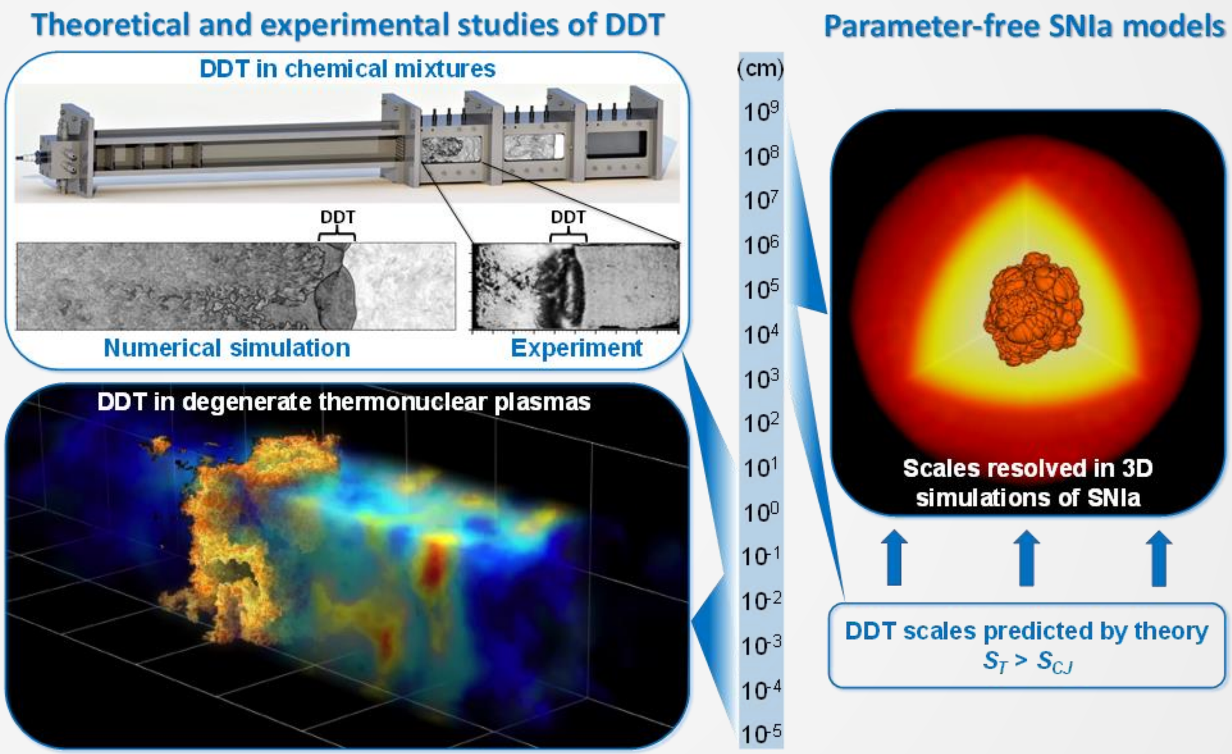
Combustion Physics in Science!

Universal Mechanisms Controlling Terrestrial and Astrophysical Explosions

Relate to Type Ia Supernovae (SNIa) – Thermonuclear Flames





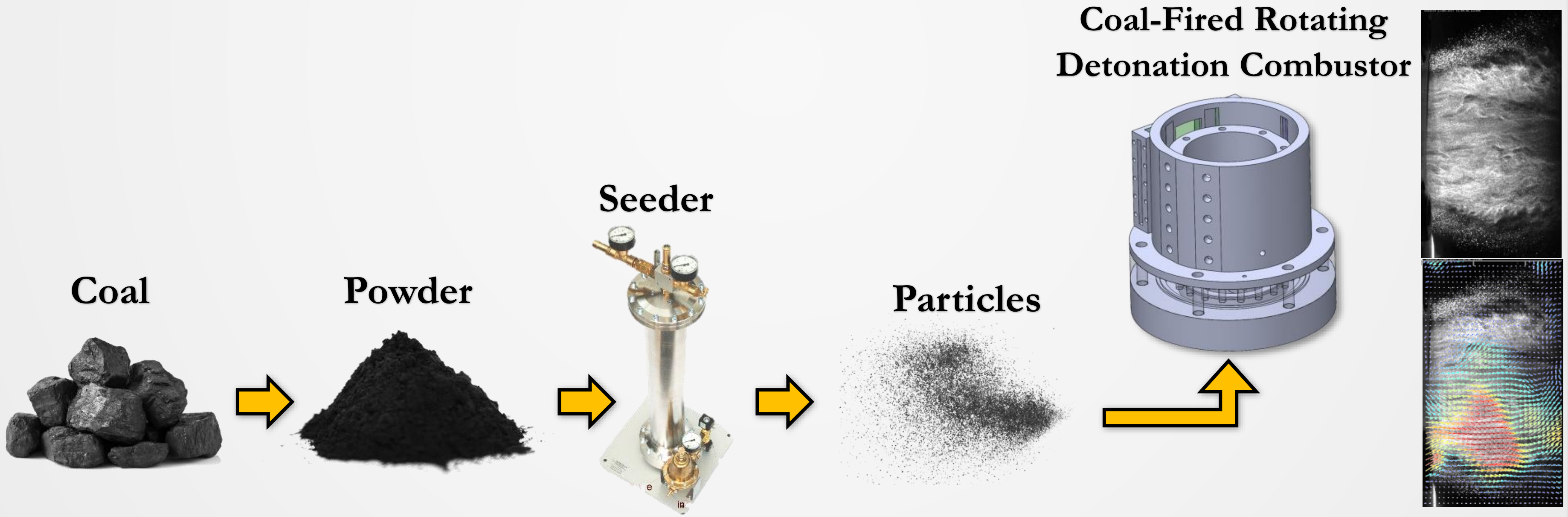


Poludnenko, A., Chambers, J. G, Ahmed, K, Gamezo, V., " A unified mechanism for unconfined deflagration-to-detonation transition in terrestrial chemical systems and type Ia supernovae," Science, Vol. 366, Issue 6465, 2019.

Project Objectives

Explore Advanced Cost-Effective Coal-Fired Rotating Detonation Combustor:
Characterize the operability dynamics and performance of an advanced cost-effective coal-fired rotating detonation combustor for high efficiency power generation

- Operability map of coal-fired RDC (Experiments and computations)
- Measurement and demonstration of coal-fired Performance

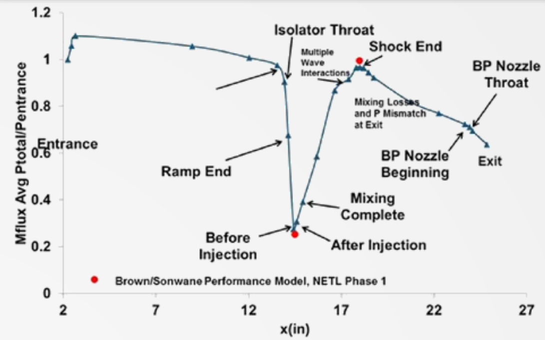


Russia: Bykovskii *et al.* 2013

DOE – NETL: Aerojet Rocketdyne and University of Central Florida

The goal is to measure stagnation pressure for characterizing the performance of rotating detonation engines.

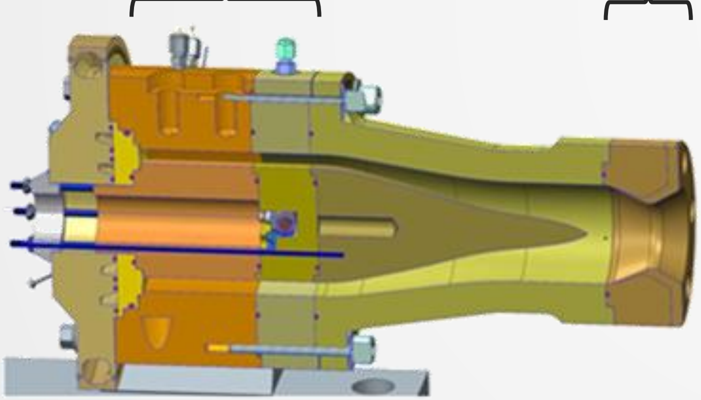
$$\left(\frac{\hat{P}^{o}_{d,ex}}{\hat{P}^{o}_{M}}\right) = \frac{\left(\frac{\hat{P}^{o}_{c,ex}}{\hat{P}^{o}_{c,in}}\right)_{1}}{\left(\frac{\hat{P}^{o}_{M}}{\hat{P}^{o}_{c,in}}\right)_{2}\left(\frac{\hat{P}^{o}_{c,ex}}{\hat{P}^{o}_{d,ex}}\right)_{3}}$$



Computed pressure gain through engine

1 - Combustion Chamber

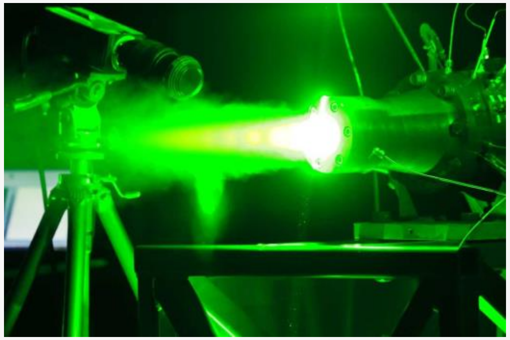
Back-Pressure Nozzle

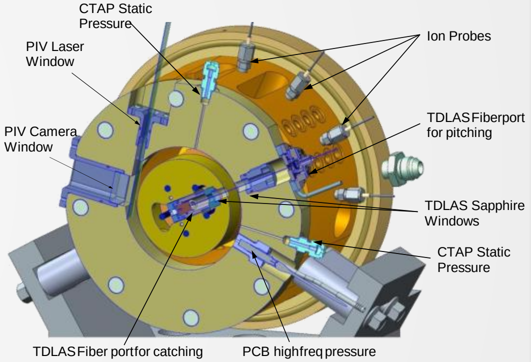


2 - Injector/Isolator

3 - Diffuser

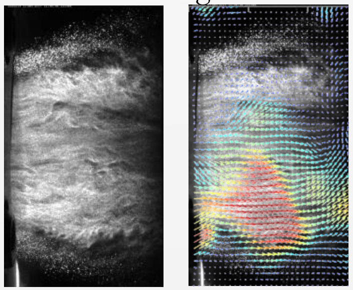
Aerojet Rocketdyne RDE cutout

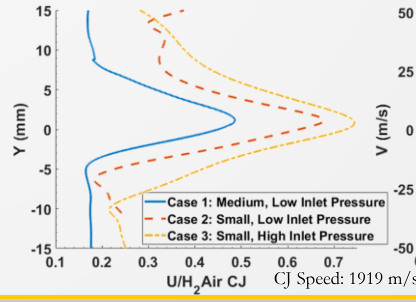

PIV on exit plane of nozzle of the Aerojet RDE



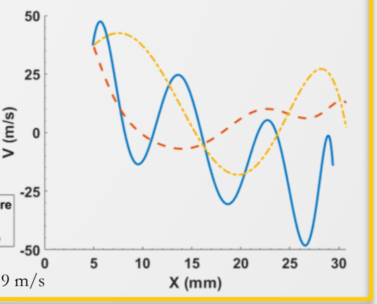
Entire CAD of Aerojet RDE cutout sitting on static test fire stand

Mie Scattering Particles

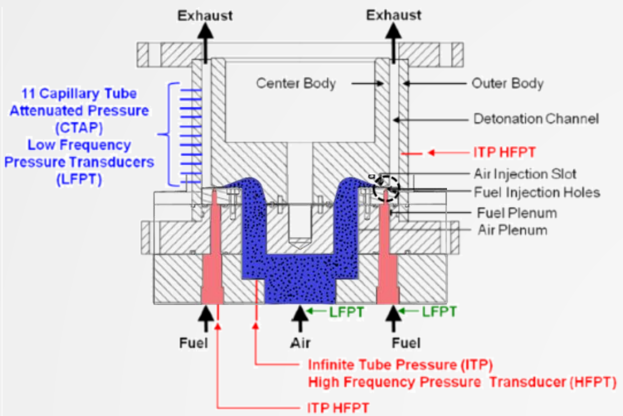




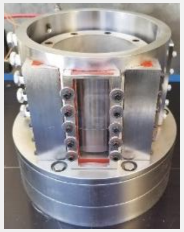
CJ Speed: 1919 m/s

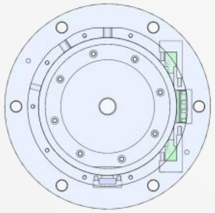


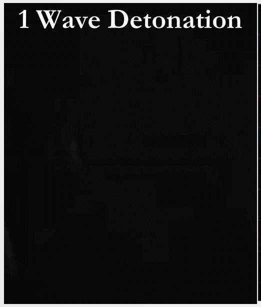
Rotating Detonation Engine: *Modeled After the AFRL RDE and the NETL (Don Ferguson)*

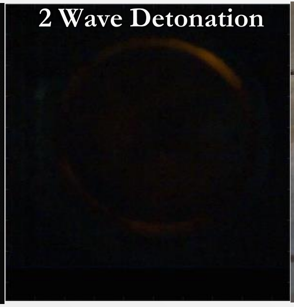


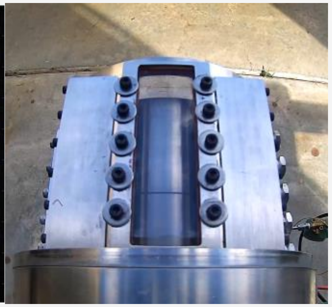
J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.



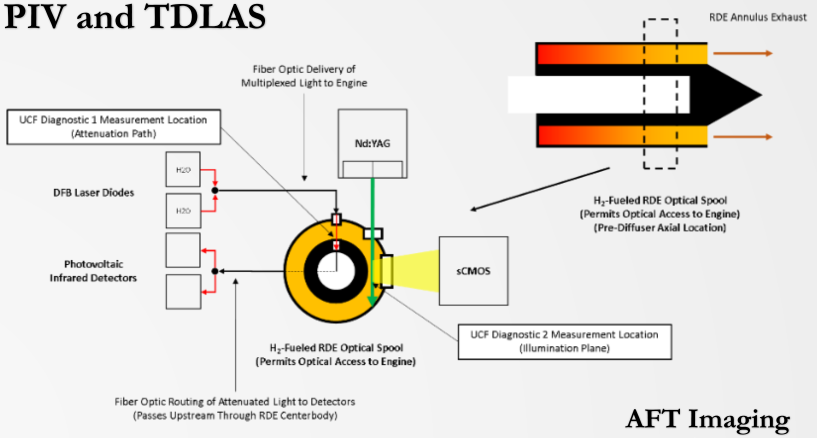


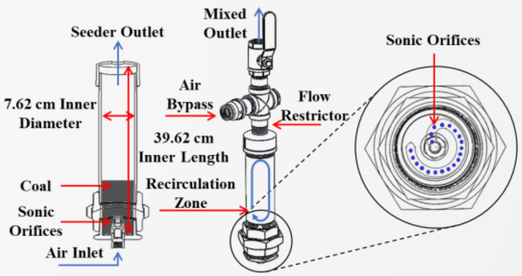




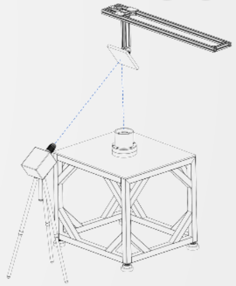


PIV and TDLAS

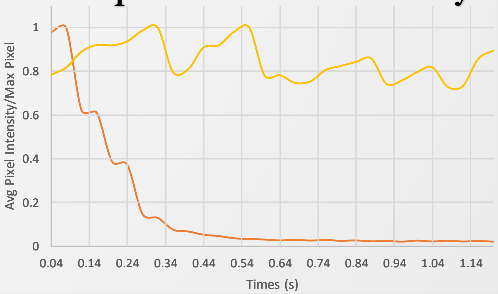




AFT Imaging

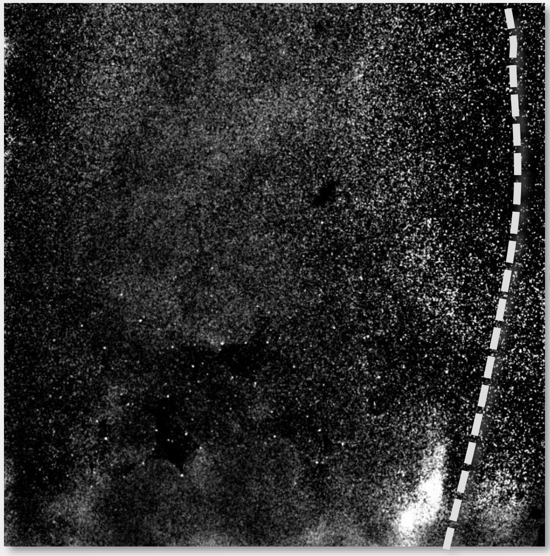


Optimized Seed Density



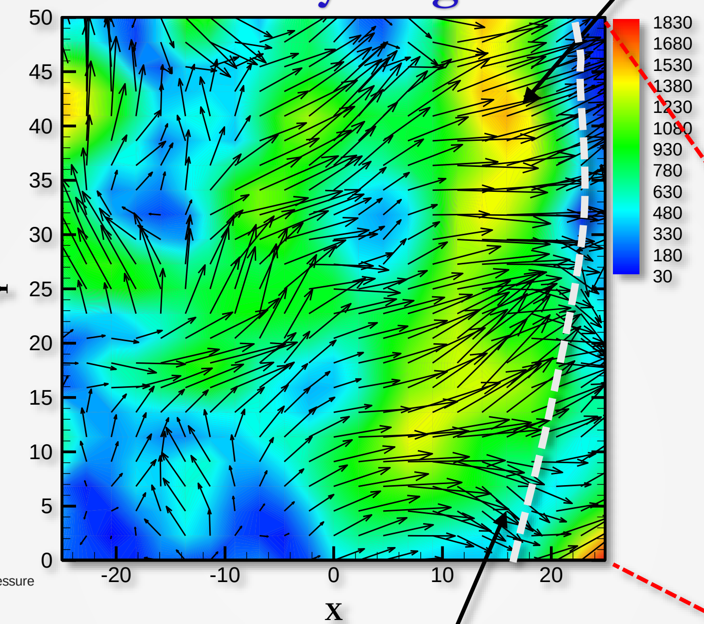
RDE Detonation Velocity Measurements

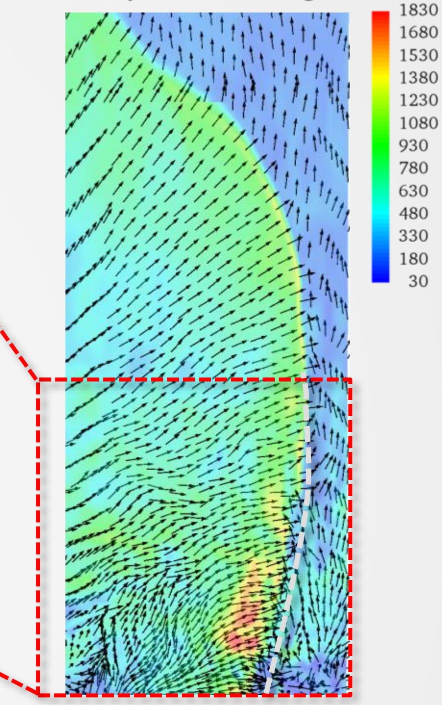
Mie Scatter

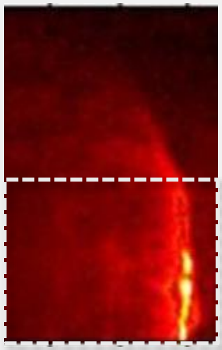


Dunn, I.B., Thurmond, K., Ahmed, K.A. and Vasu, S., 2019. Experimentation of Measuring Pressure Gain Combustion within a Rotating Detonation Engine. In *AIAA Scitech 2019 Forum* (p. 1010).

PIV Velocity Magnitude

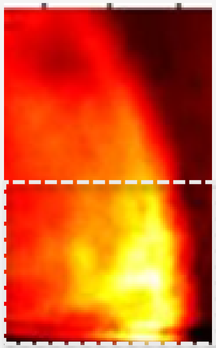






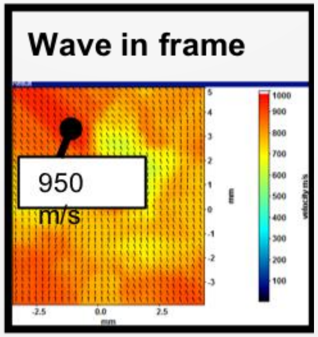
OH*

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

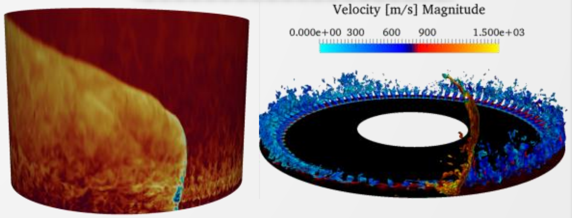


H_2O

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



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

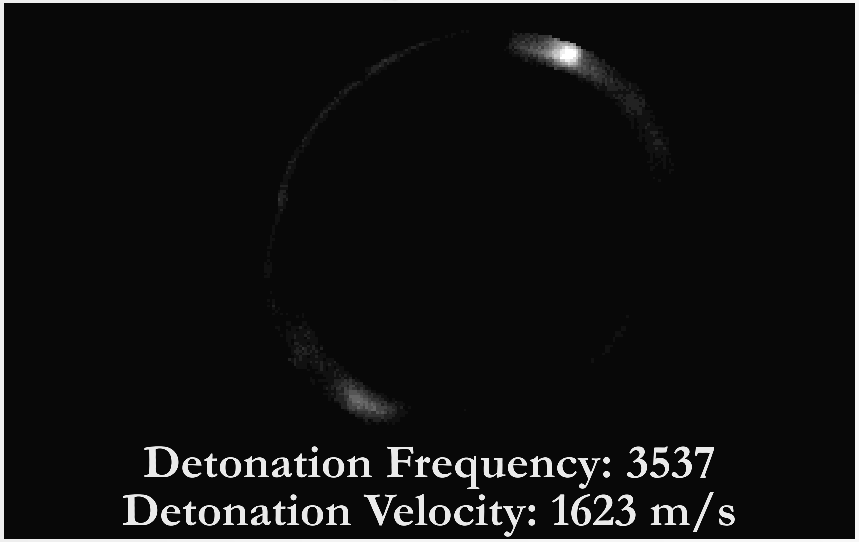


Suresh Menon (LESLIE)

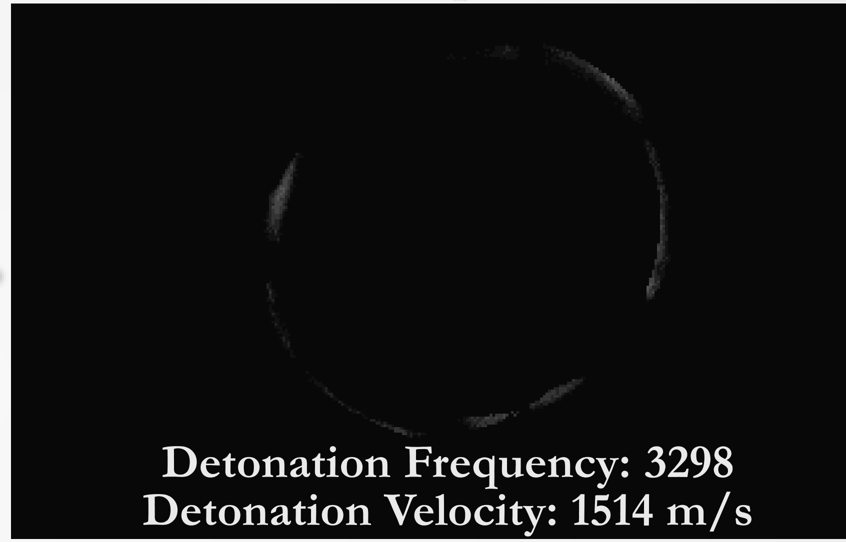
Georgia Tech College of Engineering

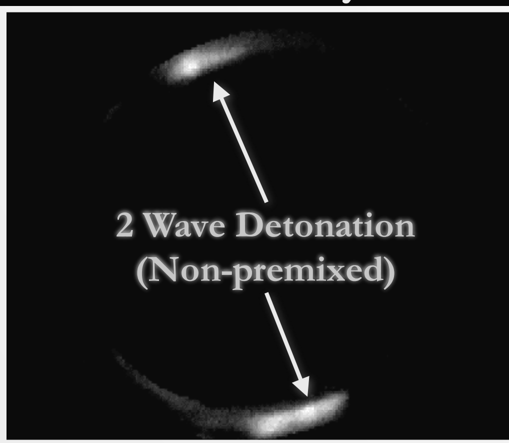
Dynamic Control of Detonation Waves through Partial Premixing

2 Wave Detonation (Non-premixed)

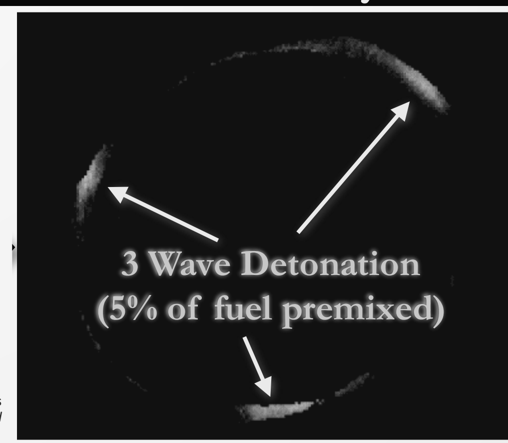


3 Wave Detonation (5% of fuel premixed)





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).



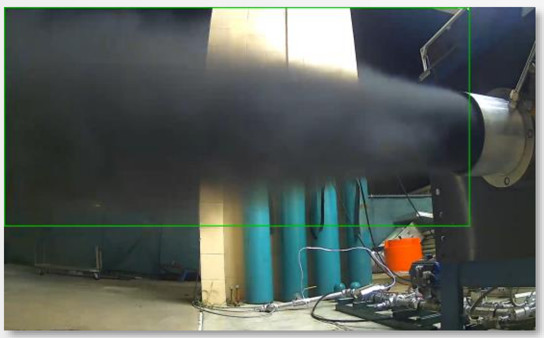
1. Carbon Black (C)
   - Size: 29 nm
   - Volatility: 1.18%

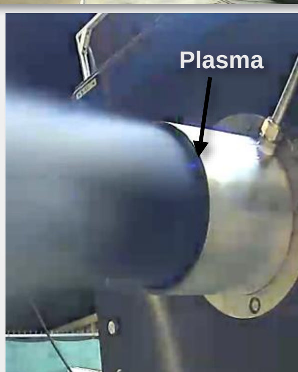
2. Sub-Bituminous Coal ($C_{137}H_{97}O_9NS$)
   - Size: 5 μm (also grounded to 100 nm)
   - Volatility: 10%

Coal RDE Test Fires (carbon)

Non-Reacting

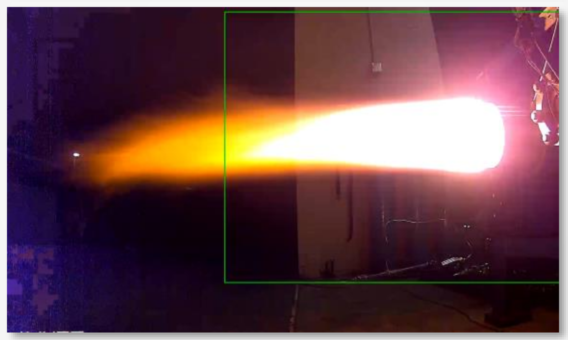
click to play





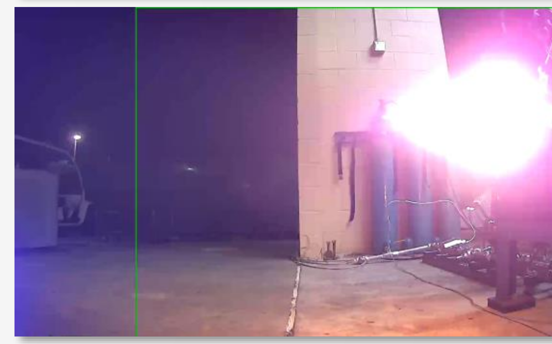
Deflagration

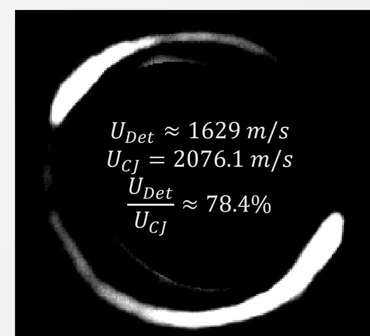
click to play



Detonation

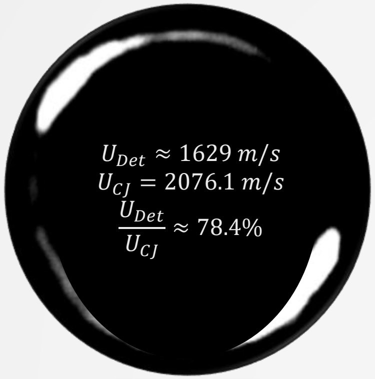
click to play

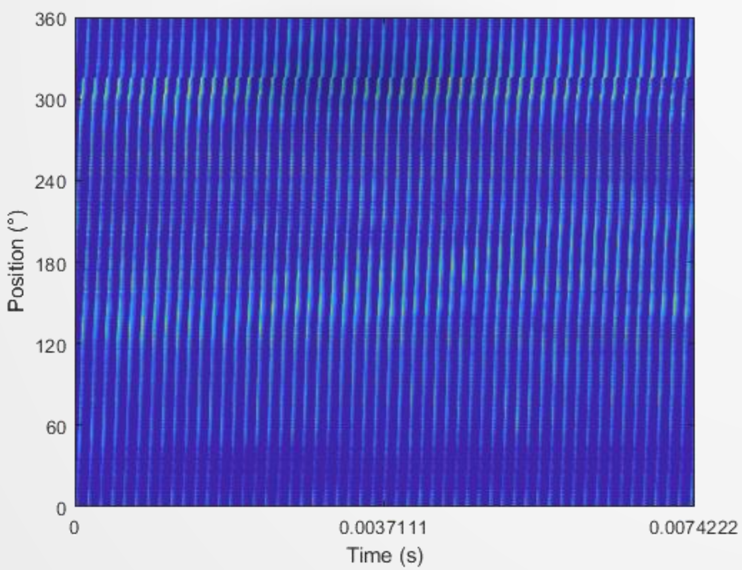




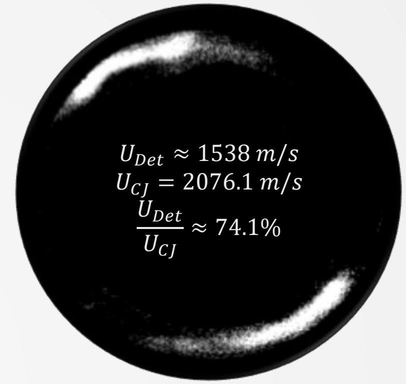
Dunn, I., Menon, S., AHMED, K.A., "Multiphase Rotating Detonation Engine," GT2020-15017, Proceedings of ASME Turbo Expo 2020.

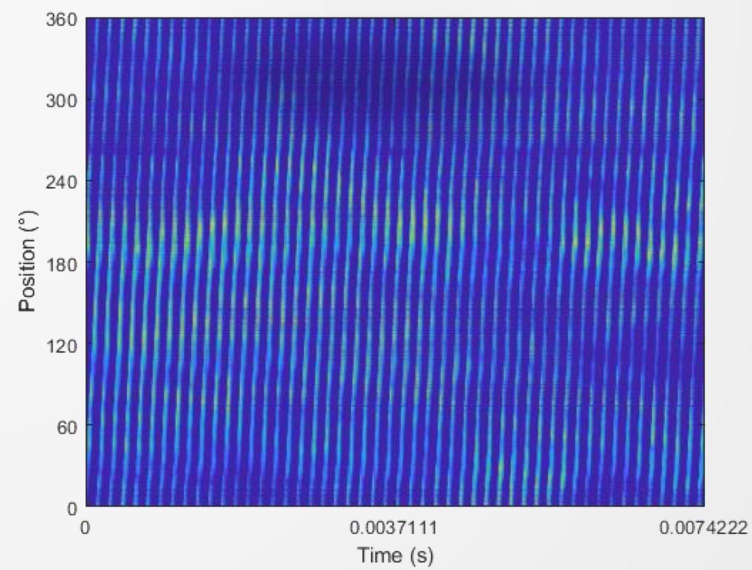
Average Concentration 38% Coal





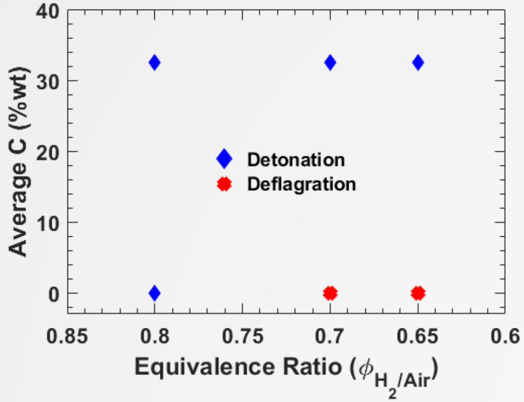
Average Concentration 67% Coal

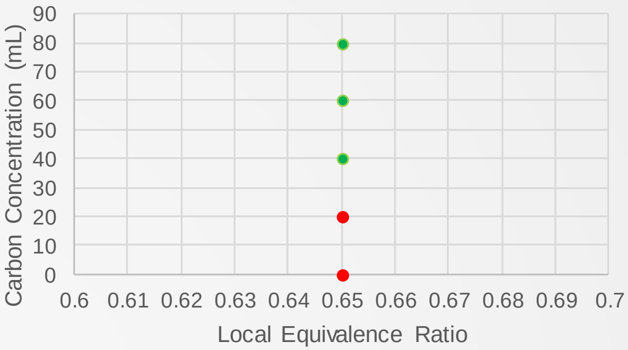


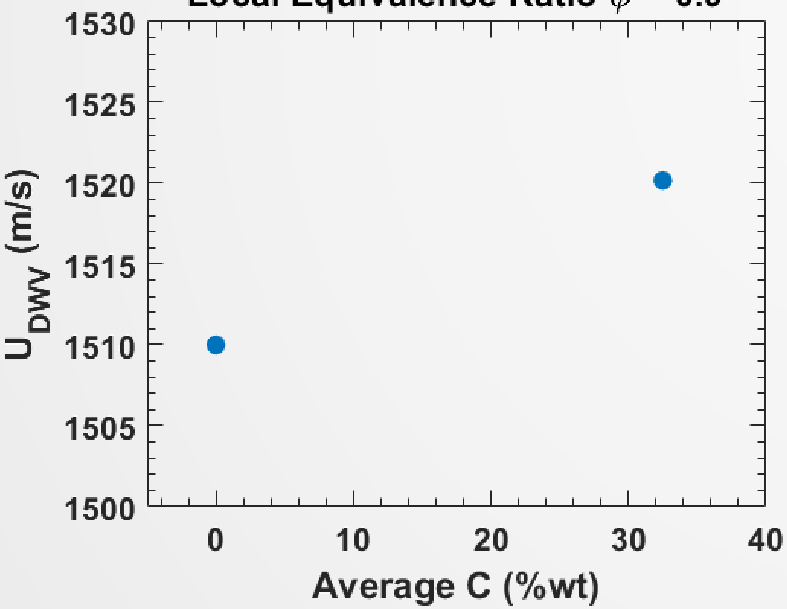


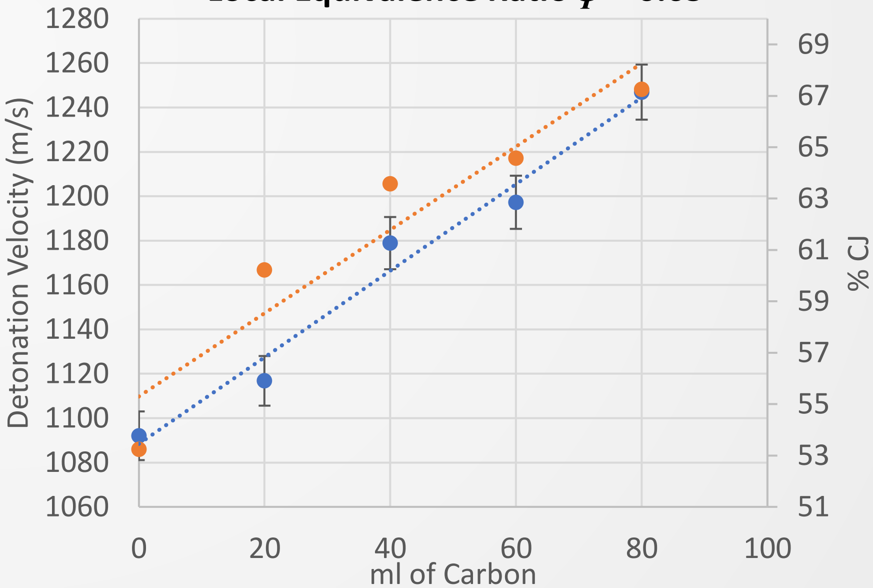
J. Bennewitz, B. Bigler, S. Schumaker, W. Hargus Jr, Automated image processing method to quantify rotating detonation wave behavior, Review of Scientific Instruments 90 (2019)

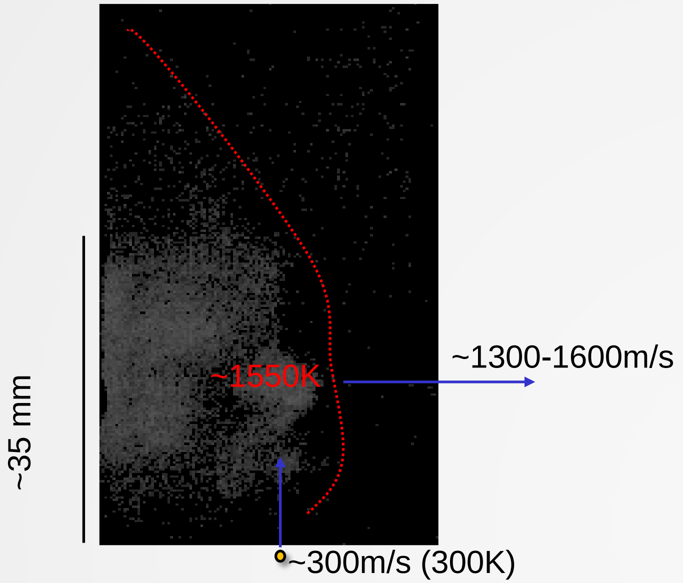
Evidence of Carbon Driving Detonation

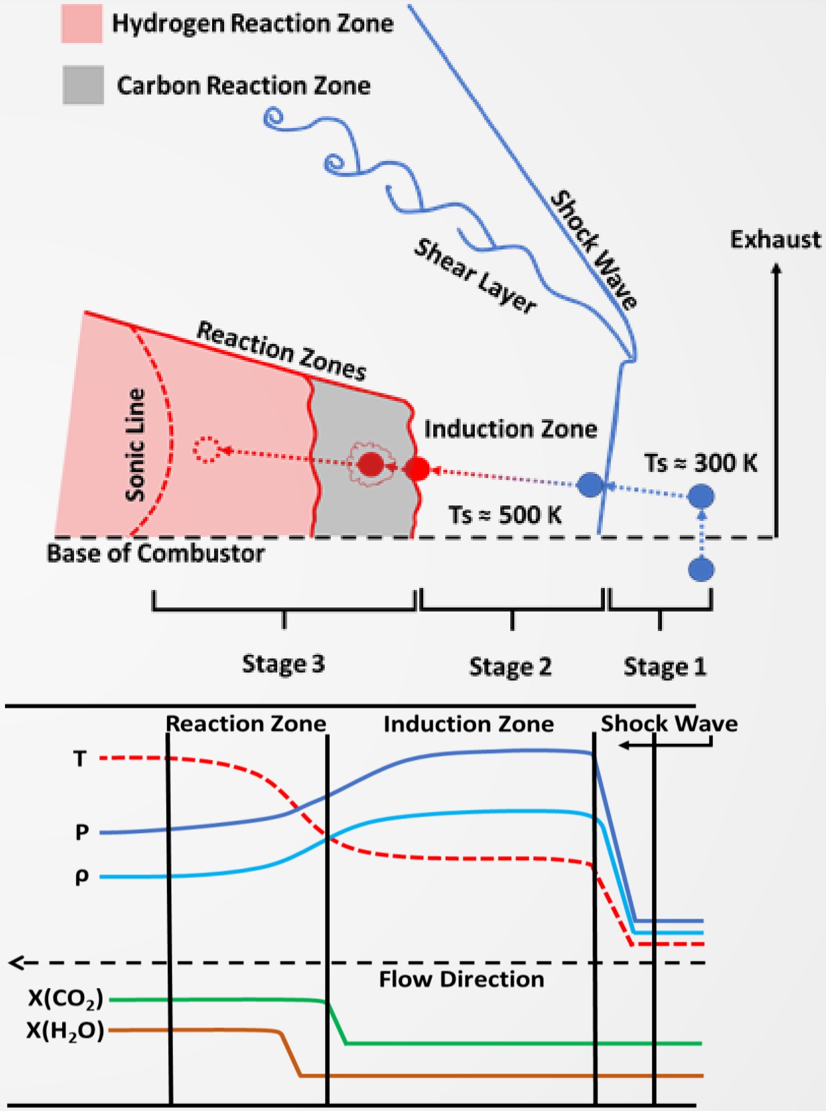




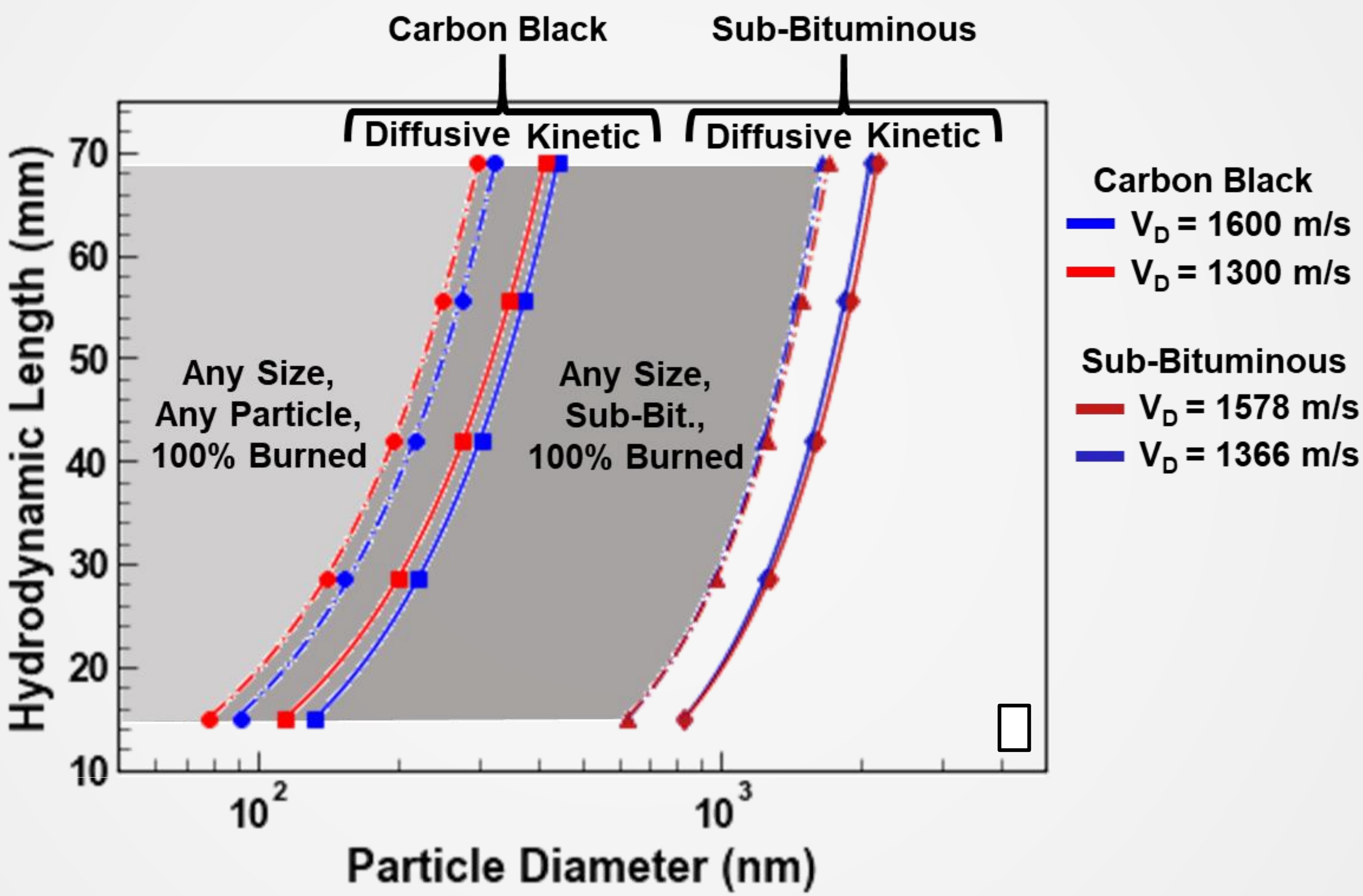




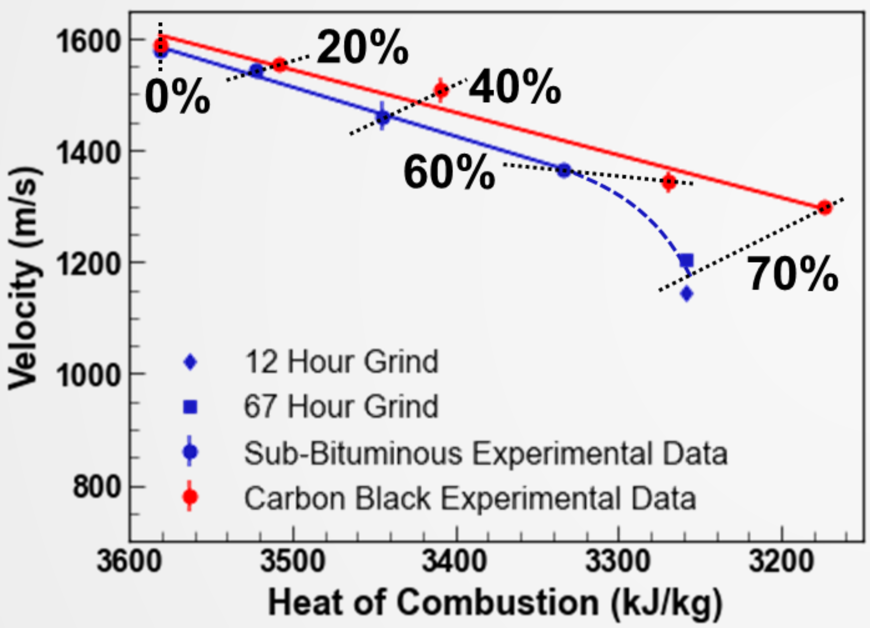


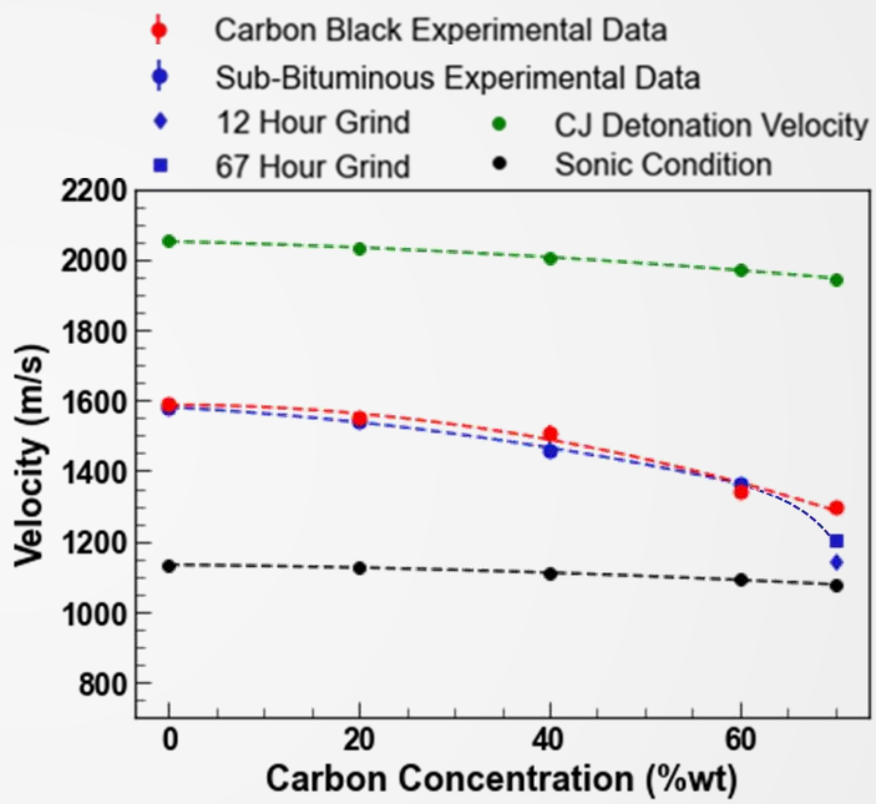


- Stage 1: Leading Shock
- Stage 2: Particle Heating
- Stage 3: Particle Gasification
- Stage 4: Particle Burn Out


Carbon Black
Sub-Bituminous
Diffusive
Kinetic
Diffusive
Kinetic
Hydrodynamic Length (mm)
70
60
50
40
30
20
10
Any Size,
Any Particle,
100% Burned
Any Size,
Sub-Bit.,
100% Burned
10^2
10^3
Particle Diameter (nm)
Carbon Black
V_D = 1600 m/s
V_D = 1300 m/s
Sub-Bituminous
V_D = 1578 m/s
V_D = 1366 m/s

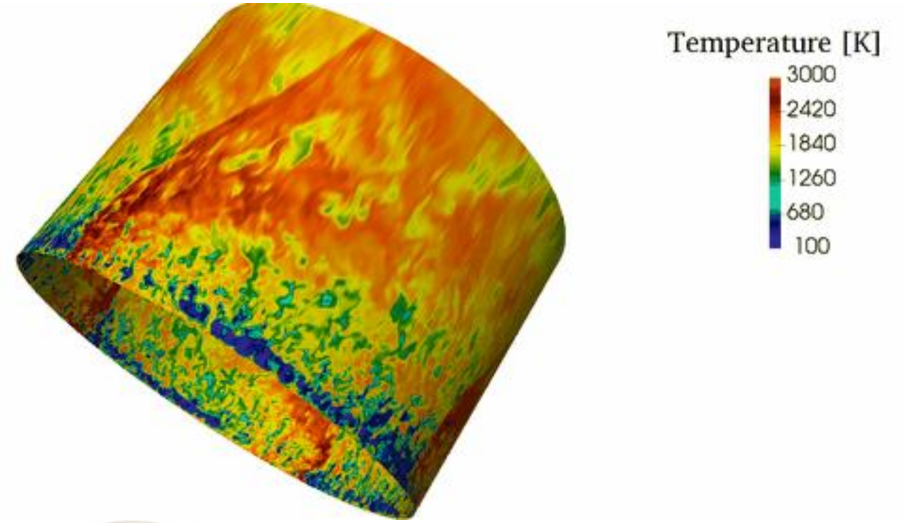
RDE Detonation Velocity Measurements vs. Heat of Combustion

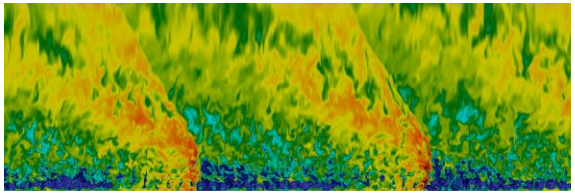




80-Injector Non-Premixed RDE (full rig in UCF)

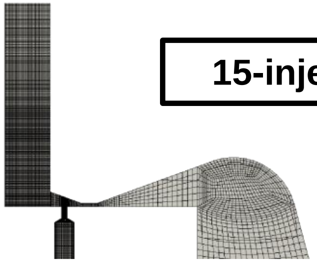
- Sensitive to initialization
  - High P, T charge
  - 1D H_2/air detonation solution
  - Char. Inflow/outflow, adiabatic walls
- Solution carried long enough to establish rotating detonation
- High mass flow rate in this case results in 4-wave stable system
- Study underway with reduced mass flow to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



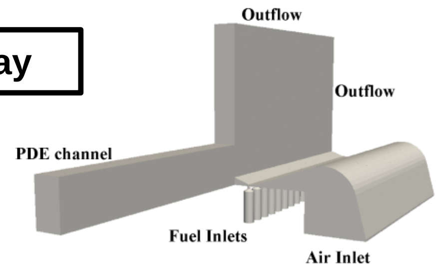


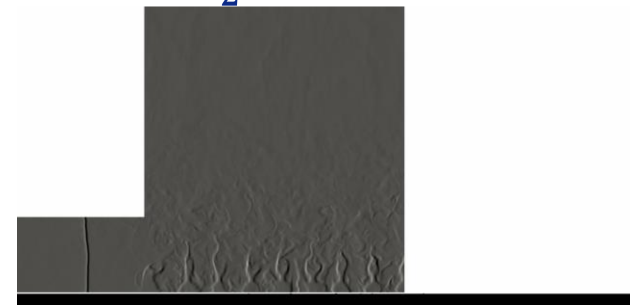
1. Salvadori, M., Dunn, I.B., Sosa, J., Menon, S. and Ahmed, K.A., 2020. Numerical Investigation of Shock-Induced Combustion of Coal-H2-Air mixtures in a Unwrapped Non-Premixed Detonation Channel. In AIAA Scitech 2020 Forum (p. 2159).
2.Baurle, R., Alexopoulos, G., and Hassan, H. Journal of Propulsion and Power 10, 4 (1994), 473–484.
3. Poinsot & Lele, J. Comp. Phys. 1992

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

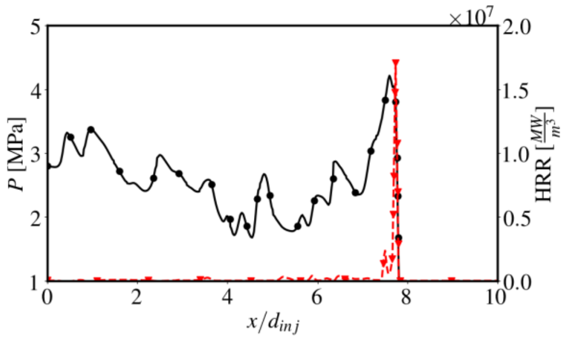


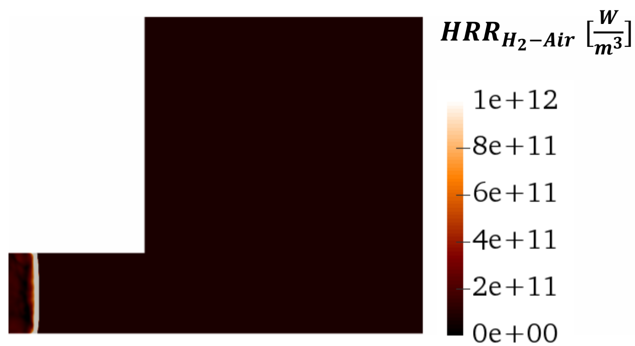
15-injector Array





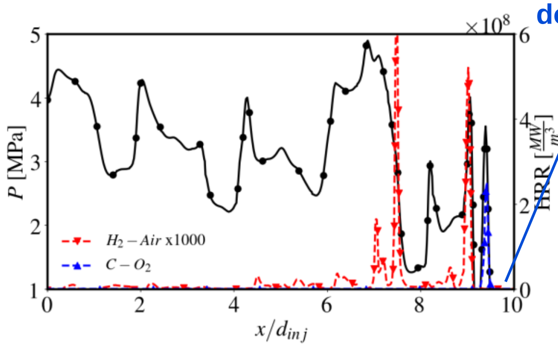
Without C_g

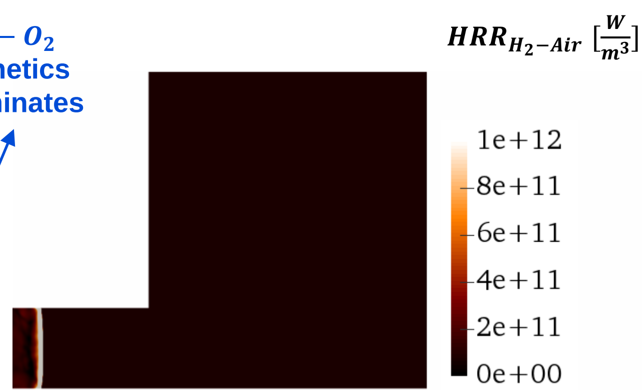




With C_g

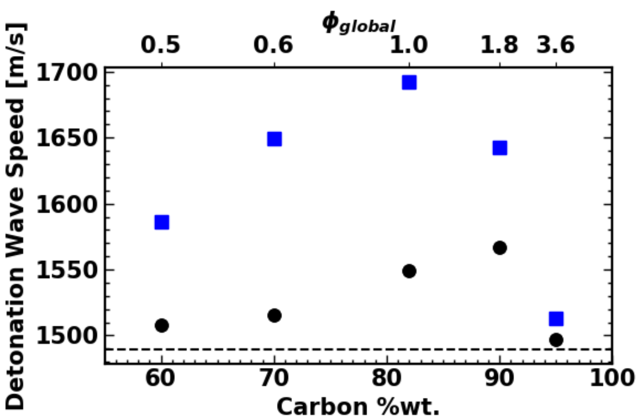
$C - O_2$ kinetics dominates

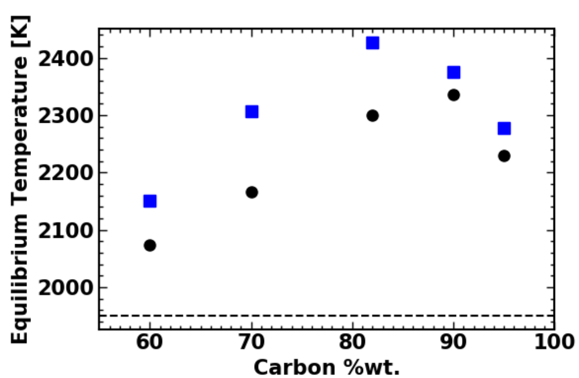


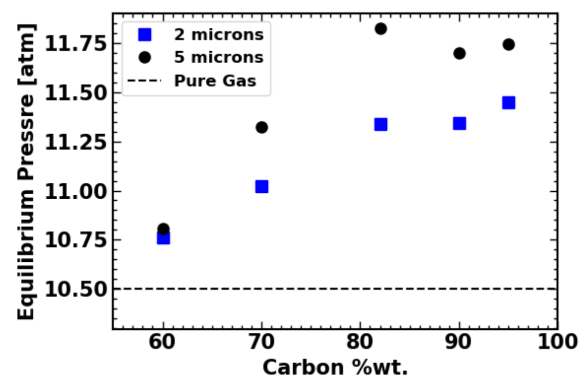


Results: Carbon Enhances Detonation

- As carbon loading is increased,
  - Detonation wave speed increases
  - Final pressure rises
  - Final temperature rises
- For dense loadings, though, detonation wave speed decreases due to lower heat release.
- As carbon particle size decreases, both final temperature and detonation wave speed increase. However, final pressure decreases (though not significantly) because of greater heat release.

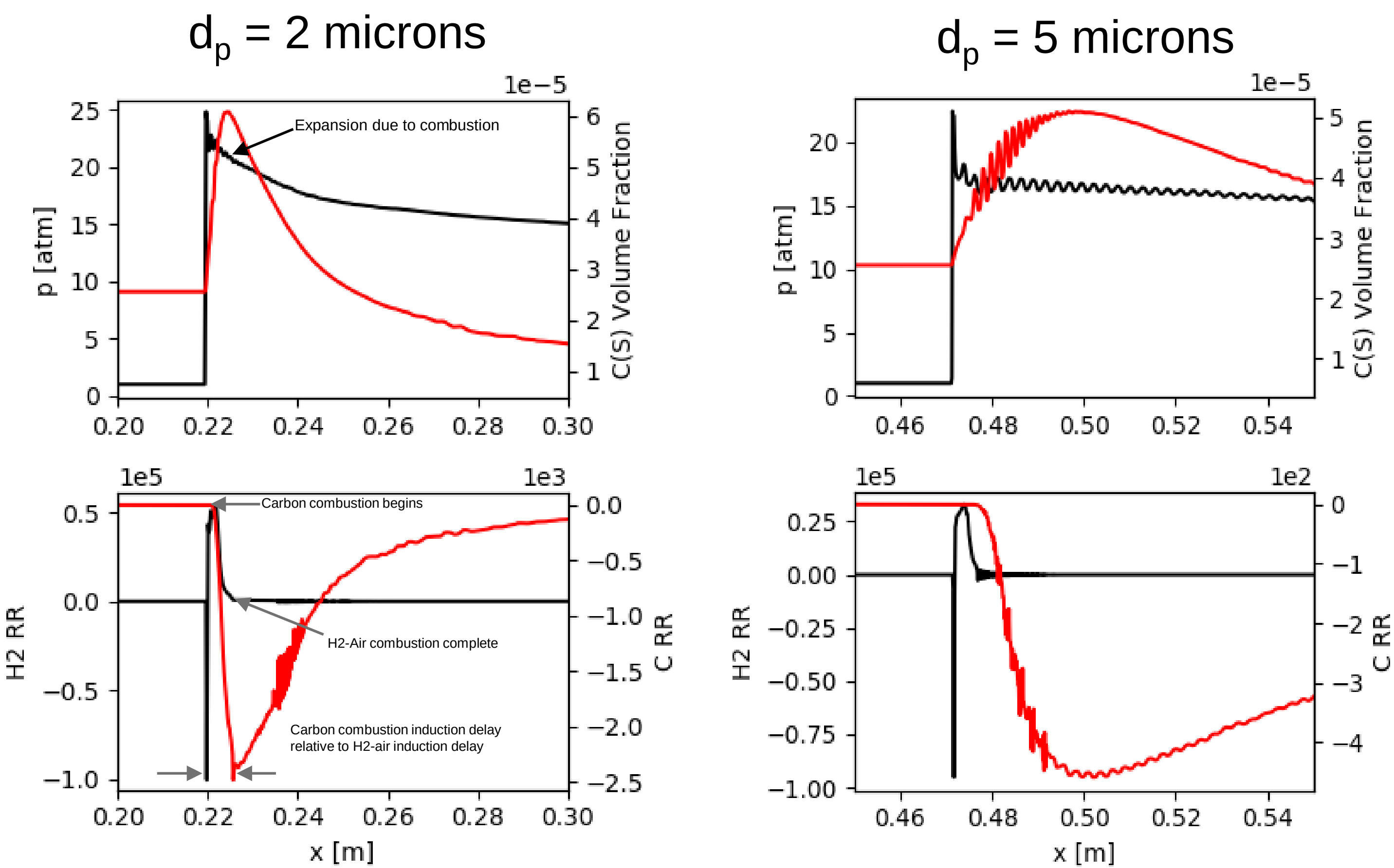






Results: Why is Carbon Enhancing Detonation?

- **Carbon enhances detonations when carbon combustion initiates within a certain length (and time).**



Conclusion

- **Demonstrated multiphase rotating detonation waves with carbon particles in a Rotating Detonation Engine**

- **Evidence of carbon driven rotating waves are experimentally shown through detonability and wave speed**

- **Heat of combustion correlates to the carbon concentration and the wave speed at fixed equivalence ratio**

- **Mechanisms of the carbon particle shock interaction and subsequent reactions are presented**