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

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PM: Dr. Seth Lawson

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

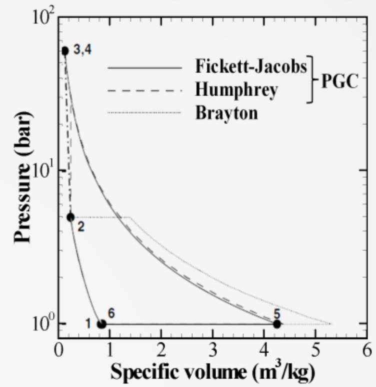
Kickoff Meeting
February 12th, 2018

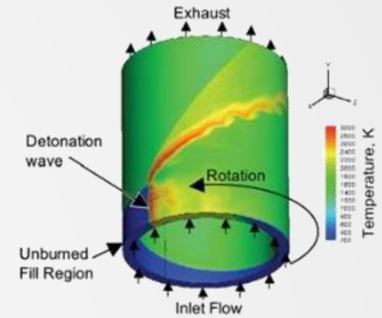
Outline

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

Pressure Gain Combustion

Thermodynamic Cycle





Schwer, Douglas, and Kailas Kailasanath. "Numerical investigation of rotating detonation engines." 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010

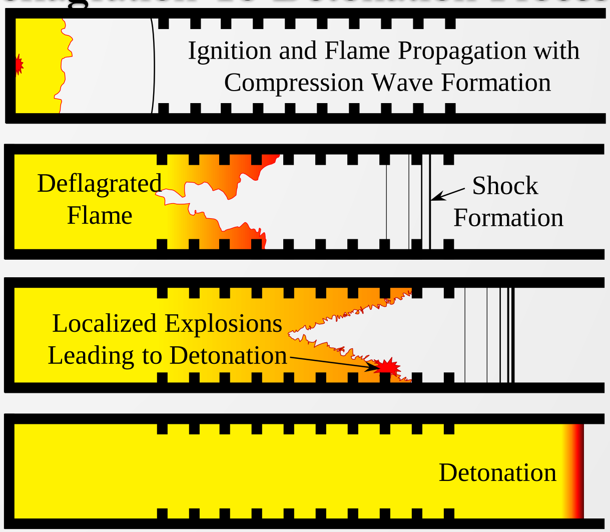
Detonation

- 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

Deflagration-To-Detonation Transition Process

1. Ignition of a deflagration flame
2. Turbulent flame acceleration due to turbulent mixing
3. Transition:
   - Reflected shock (*Oran et al.*)
   - Localized vortical explosion (*Zeldovich gradient mechanism*)
   - Boundary layer turbulence (*Oppenheim*)
   - Turbulence-Driven DDT (active research at *UCF*)
4. Formation of a self-sustaining detonation wave

Deflagration-To-Detonation Process



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

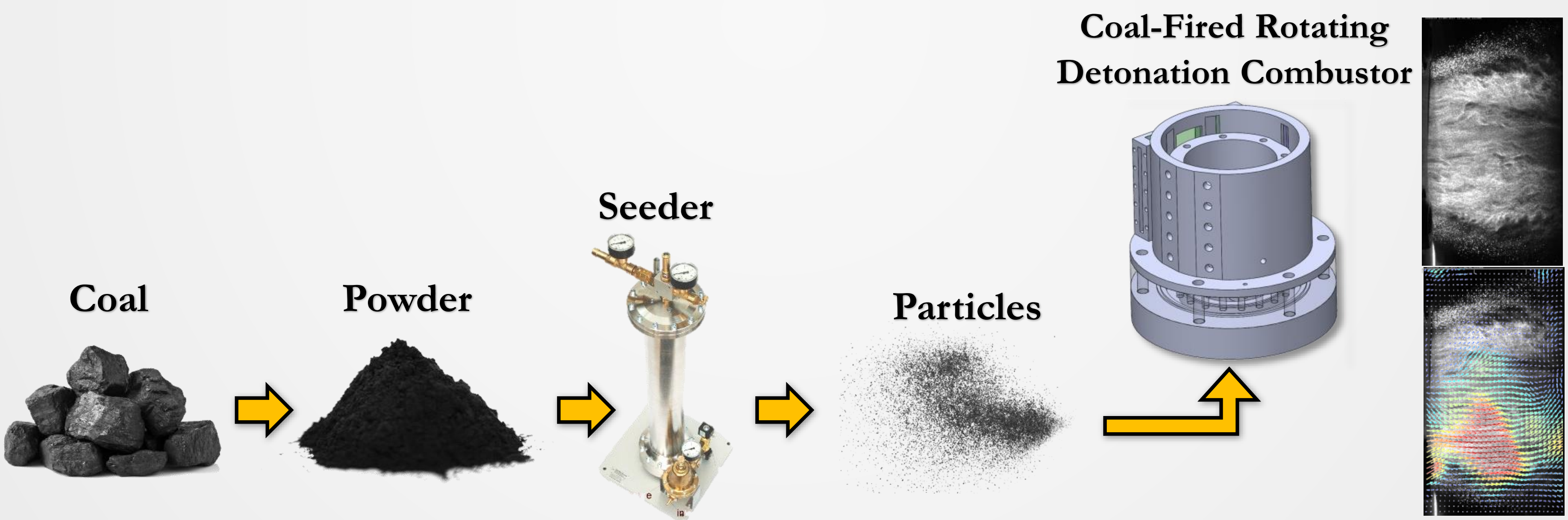
Coal Mine Detonation Explosion

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



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.*

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

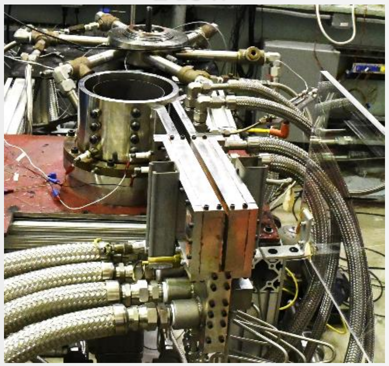
Innovative Scientific Solutions, AFRL
(Industry Partner)

Dr. John Hoke
Dr. Fred Schauer

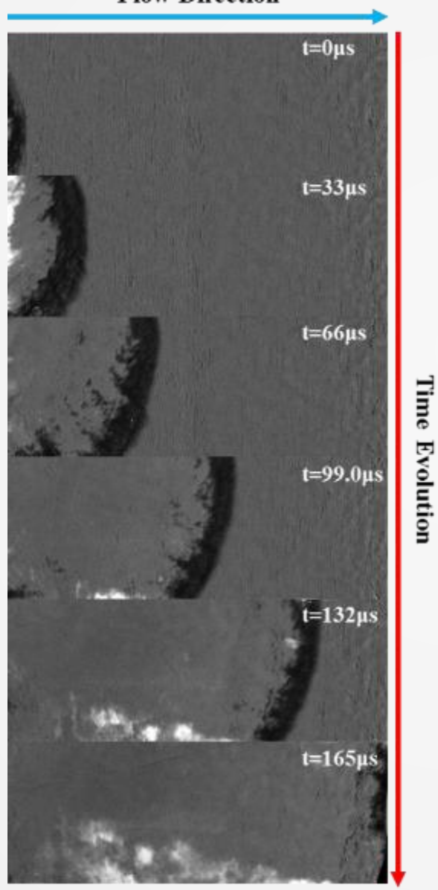
Georgia Institute of Technology
(Sub-Recipient)

Dr. Suresh Menon

Rotating Detonation Engine in Supersonic Flow

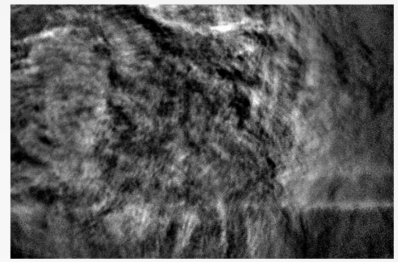


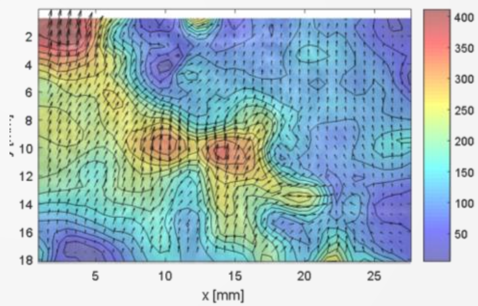
Detonation Propagation in a Premixed Supersonic Flow



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

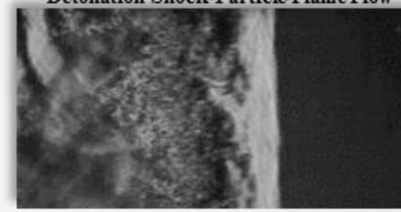
RDE Exhaust Velocimetry





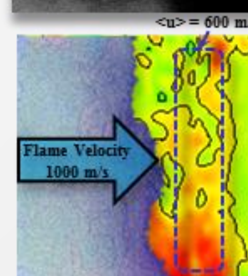
Detonation wave velocimetry and structure conducted at Dr. Ahmed's UCF lab

Detonation Shock-Particle-Flame Flow



Aluminum Oxide Particles Flow

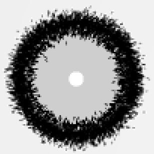
Detonation Turbulent Flame

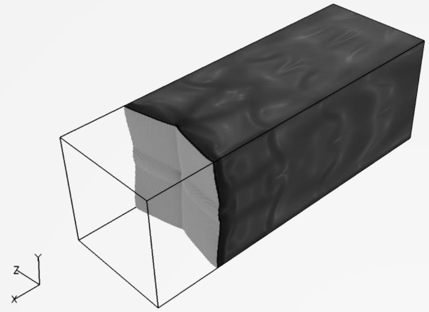


J. Chambers *et al*, ICDERS, 2017

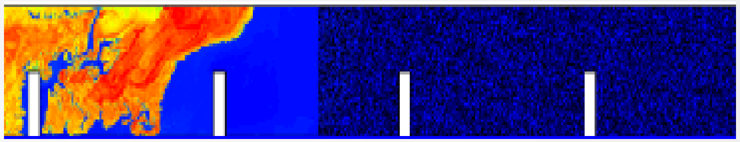
Research in CCL Georgia Tech

Pressure Gain Combustion

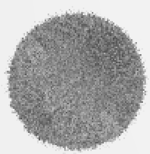


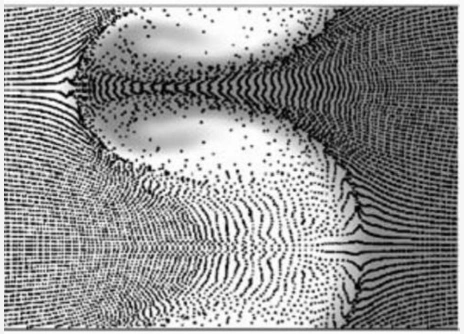


Steady 3D Detonation in a channel



DDT in two-phase channel with obstacles



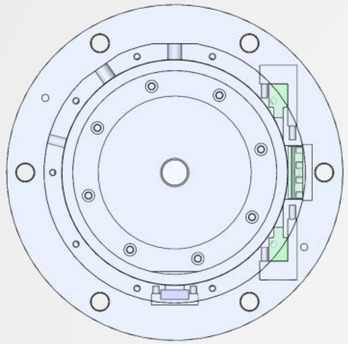


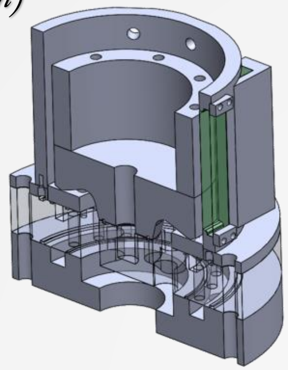
Detonation charge surrounded by inert steel particles

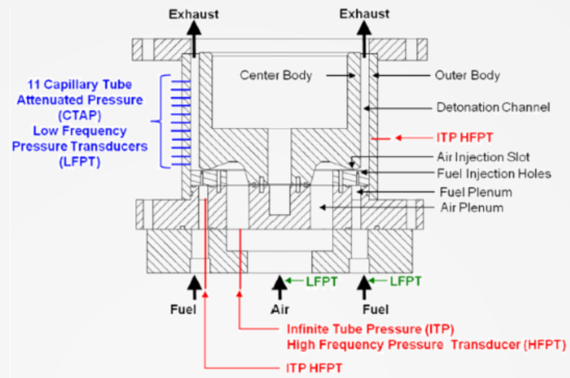
- Research focused on confined and free detonation
- Simulations with inert and reactive (Al) particles
- Condensed phase and gas phase detonation
- Deflagration-to-Detonation Transition (DDT)
- Code LESLIE in AFRL (Eglin) for detonation studies
- http://www.ccl.gatech.edu

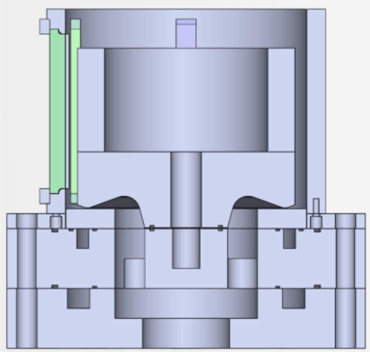
Coal Rotating Detonation Combustor

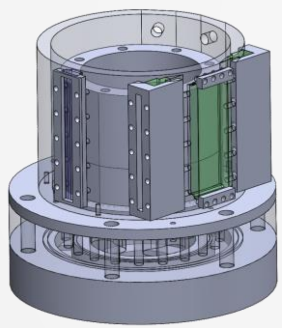
Coal Rotating Detonation Combustor: *Modeled After the AFRL RDE and the NETL (Dr. Don Ferguson)*

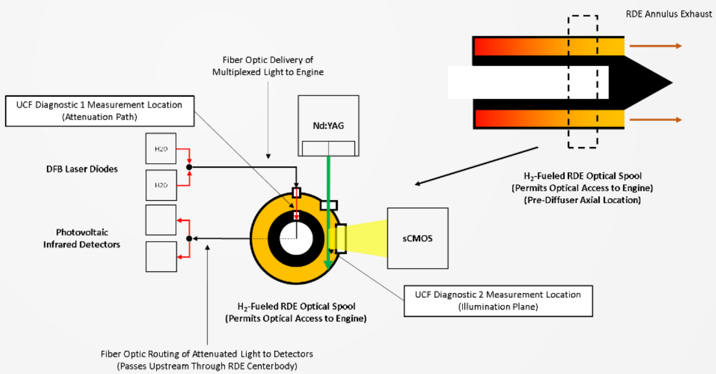






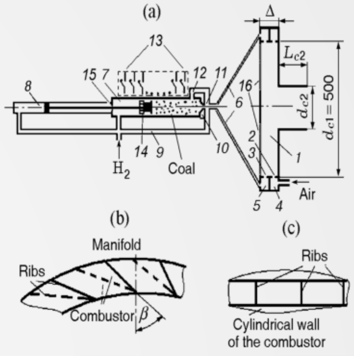


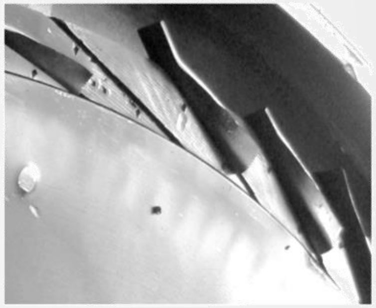


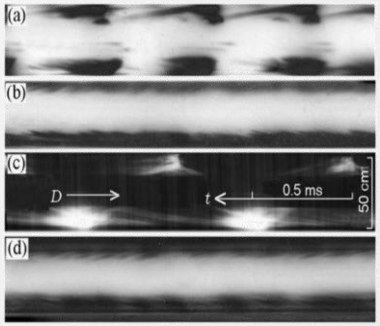


J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

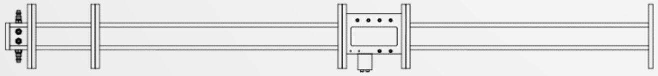
Russia: Bykovskii *et al.* 2013



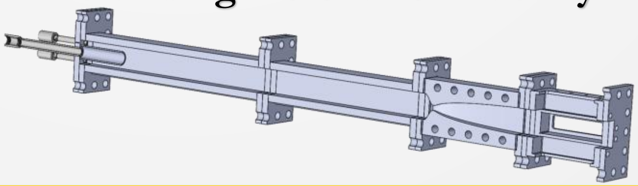




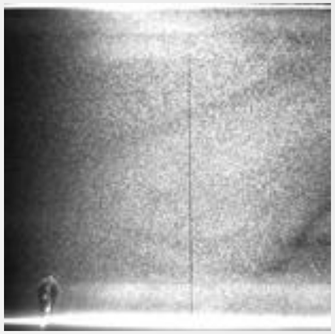
Deflagration-to-Detonation Facility



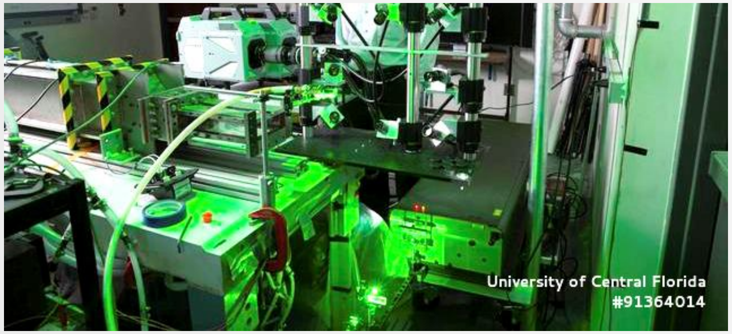
Standing Detonation Facility



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)



- **TDLAS Overview**
  - **Beer-Lambert Law (Detail)**
    - Equation of Radiative Transfer → Limiting Case of Dominant Stimulated Absorption
    - Valid at each optical frequency ν across targeted region of EM spectrum

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

$I = Transmitted\ Intensity\ \left(\frac{W}{cm^2 sr Hz}\right)$

$I_0 = Incident\ Intensity\ \left(\frac{W}{cm^2 sr Hz}\right)$

$S_{ij} = Linestrength\ \left(\frac{cm^{-2}}{atm}\right)$

$T = Static\ Temperature\ (K)$

$X_j = Mole\ Fraction$

$P = Static\ Pressure\ (atm)$

$L = Path\ Length\ (cm)$

$\phi_{ij} = Lineshape\ Function\ (cm)$

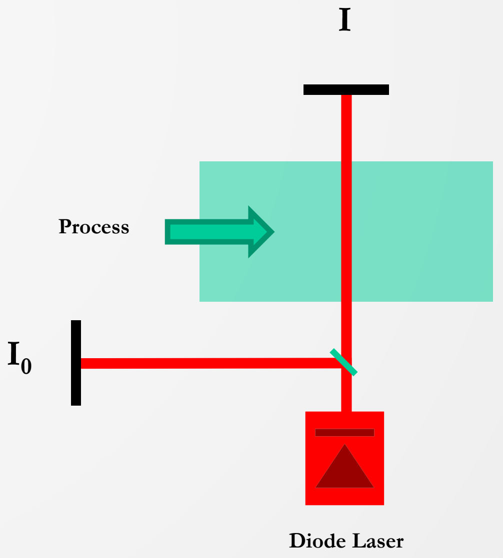
$\nu = Optical\ Frequency\ (Hz)$

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

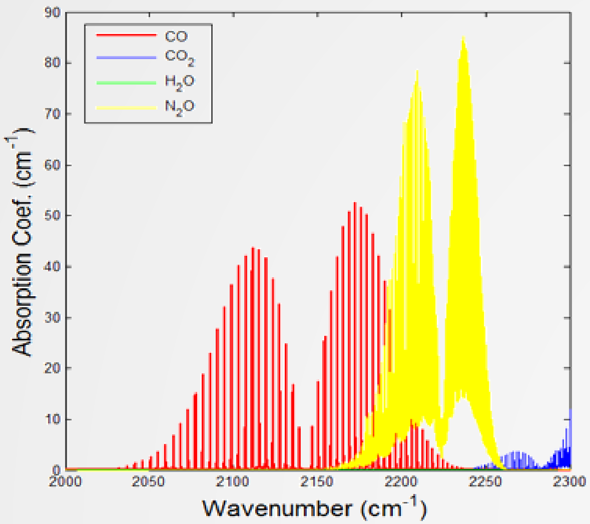
Subscripts

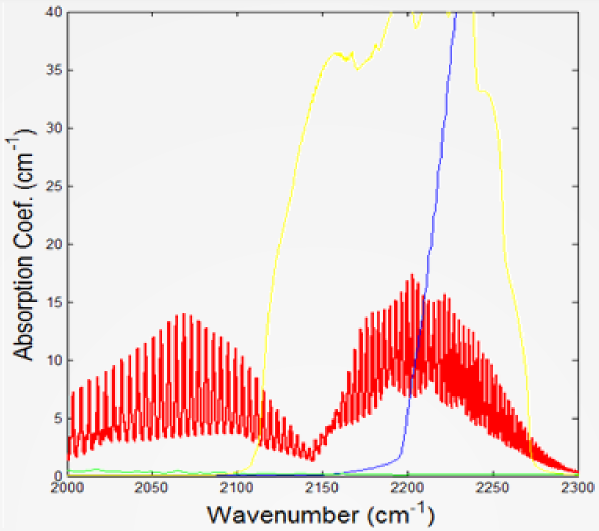
$i = Quantum\ Transition$

$j = Atomic/Molecular\ Species$



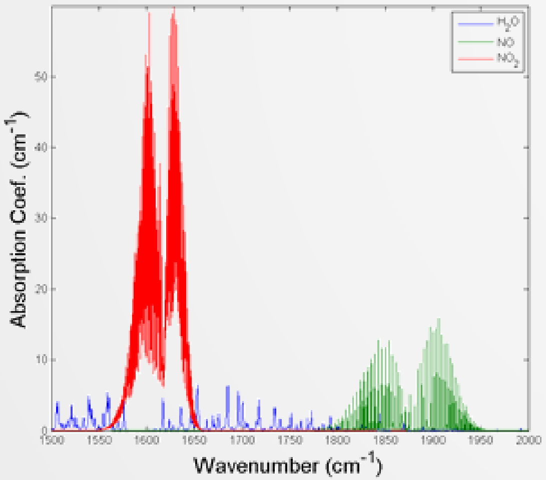
Experimental Measurements: TDLAS for NOx, CO

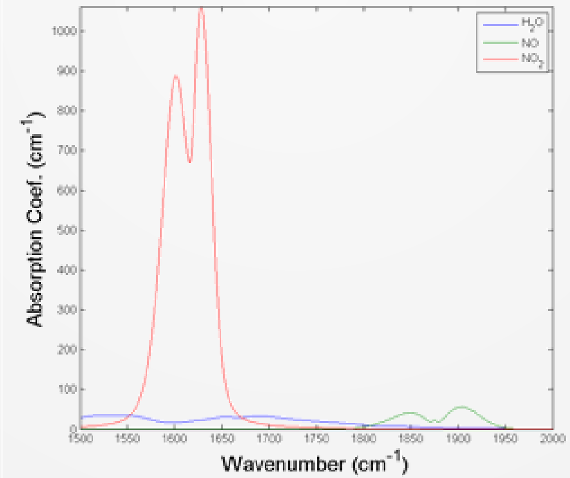




<u>Spatio-temporally resolved for understanding evolution of emissions</u>

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

Team Members by Task

Task	Responsible Team Member(s)
1: Project Management and Planning	Dr. Ahmed, Dr. Vasu, Dr. Menon
2: COAL-RDC: Operability Map	Dr. Ahmed
3: COAL-RDC: Dynamic Behavior – Experimental Investigation	Dr. Ahmed
4: COAL-RDC: Dynamic Behavior – Computational Investigation	Dr. Menon
5: COAL-RDC: Pressure Gain Evaluation	Dr. Ahmed, Dr. Vasu
6: COAL-RDC: Emissions Evaluation	Dr. Vasu, Dr. Ahmed

Tasks

- **Task 1.0 – Project Management and Planning**
- **Task 2.0 – Establish Coal-RDC Operability Map**
  - 2.1 – Identify Key Non-Dimensional Parameters
  - 2.2 – Conduct Coal-RDC Testing to Explore Non-Dimensional Parameter Space
  - 2.3 – Construct Non-Dimensional Operability Map
- **Task 3.0 – Conduct Experimental Investigation on Coal-RDC Dynamic Behavior**
- **Task 4.0 – Conduct Computational Investigation of Coal-RDC Dynamic Behavior**
  - 4.1 – Establish Computational Model for RDC
  - 4.2 – Conduct Computational Simulations on Baseline RDC for Validation
  - 4.3 – Evaluate Coal Kinetics and Employ Reduced Kinetics in Computational Simulations
  - 4.4 – Simulate Shocked Coal Combustion
- **Task 5.0 – Evaluate Pressure Gain in Coal-RDC**
  - 5.1 – Validate Pressure Gain Diagnostics in High Pressure Shock Tube Tests
  - 5.2 – Conduct Coal-RDC Tests to Characterize Evolution of Total Pressure
  - 5.3 – Enhance Operability Map: Inclusion of Pressure Gain
- **Task 6.0 – Evaluate Emissions in Coal-RDC**
  - 6.1 – Validate Emissions Diagnostics in High Pressure Shock Tube Tests
  - 6.2 – Conduct Coal-RDC Tests to Characterize Evolution of Pollutant Species
  - 6.3 – Enhance Operability Map: Inclusion of Pressure Gain and Emissions

Schedule

Task	Year 1				Year 2				Year 3				Participants
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1. Project Management													All
2. Operability Map													Ahmed
2.1													
2.2													
2.3													
3. Experimental Investigation													Ahmed
4. Computational Investigation													Menon
4.1													
4.2													
4.3													
4.4													
5. Pressure Gain Evaluation													Ahmed, Vasu
5.1													
5.2													
5.3													
6. Emissions Evaluation													Vasu, Ahmed
6.1													
6.2													
6.3													