Rotating Detonation Rocket Engines (RDRE)

DOE UTSR Pressure Gain Combustion Panel

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RDRE Team

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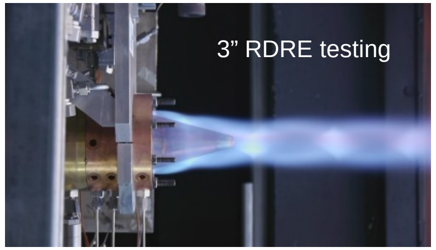
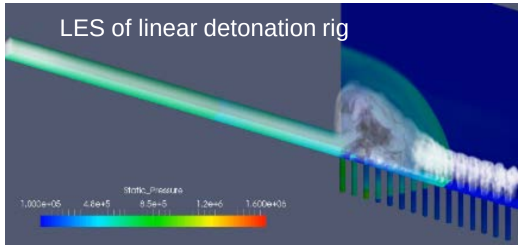
RDRE Program Scope

- **Objectives:**
  - Advance understanding & demonstrate advantage of RDREs for Air Force missions (boost engines, pre-combustion devices, & spacecraft propulsion)
  - Focus RDRE propulsion development into a systematic, national approach
- **Areas being addressed by joint Basic/Applied Research effort:**
  - **Thermodynamic cycle analysis:** *Ideal improvement*
  - **System analysis:** *Air Force system improvement*
  - **Injection & loss mechanisms:** *Physics understanding to allow for functional devices*
  - **Detonation Physics:** *Demonstrate for practical in-space propellants*
  - **Technical gap closure:** *Heat transfer, scaling, nozzle coupling, etc.*
  - **Lab scale demonstration:** *Show that benefits can be achieved for lab-scale devices*
  - **Modeling & Diagnostic Development:** *Accurate simulations verified by diagnostics*
- **Approach:** Layered experiments tied to multi-fidelity modeling and simulation


3” RDRE testing


AFRL Linear detonation rig


LES of linear detonation rig

Overview of Past Year

- **Over 500 plus firings on a CH_4-O_2 RDRE**
    - 6 injector configurations
    - Demonstrated broad operability
- **Developed robust image processing toolbox to understand wave dynamics**
- **Developed modeling & simulation capability from 1D to full 3D LES**
    - Demonstrated ability to simulate entire engine from propellant plenums through nozzle expansion
- **Designed/built linear detonation rig experiment to investigate injector dynamics (November testing)**
- **Completed preliminary engine trade study for in-space application**
- **Ideal thermodynamic cycle analysis for rocket applications**

RDRE Specifications

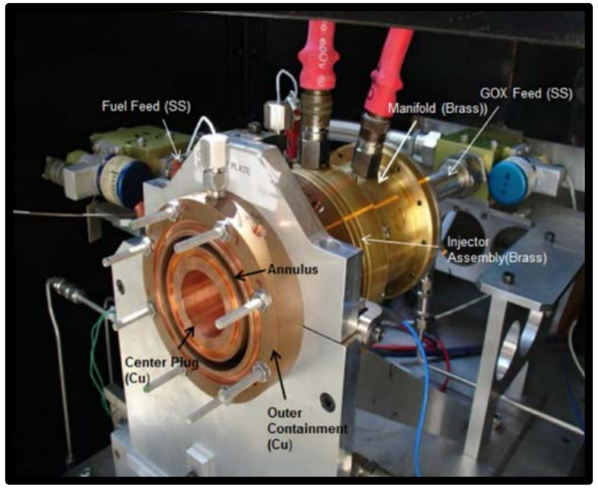
Specifications

- 3” (73.5 mm) annulus with a 0.2” (5 mm) gap
- 3” (73.5 mm) long annular channel
- Propellants: gas-gas, CH_4/GO_2
- Pre-detonator: CH_4/GO_2

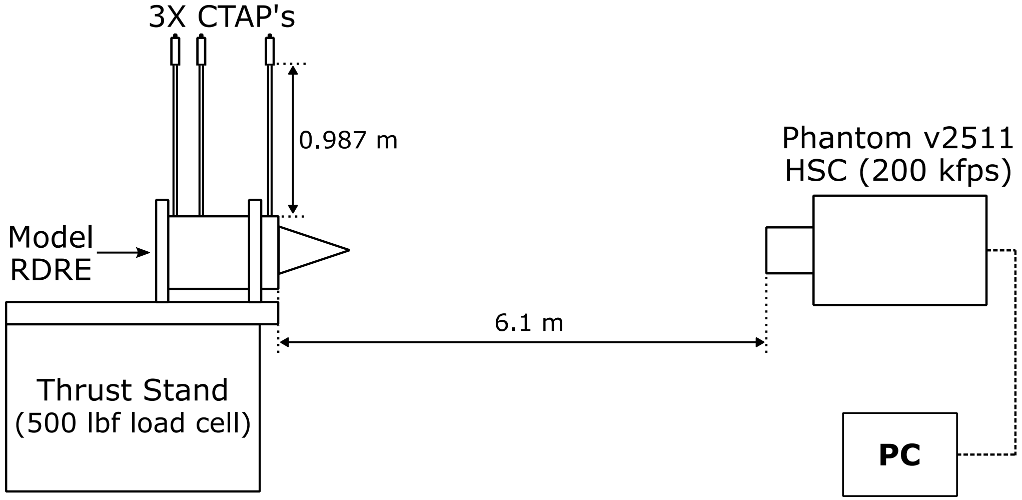
Measurements

– Thrust, Isp
– Mass flow (fuel/ox.)
– CTAP chamber pressure (3 axial locations)
– Plenum pressures (fuel/ox.)
– 200 kfps visible imaging (direct into annulus)

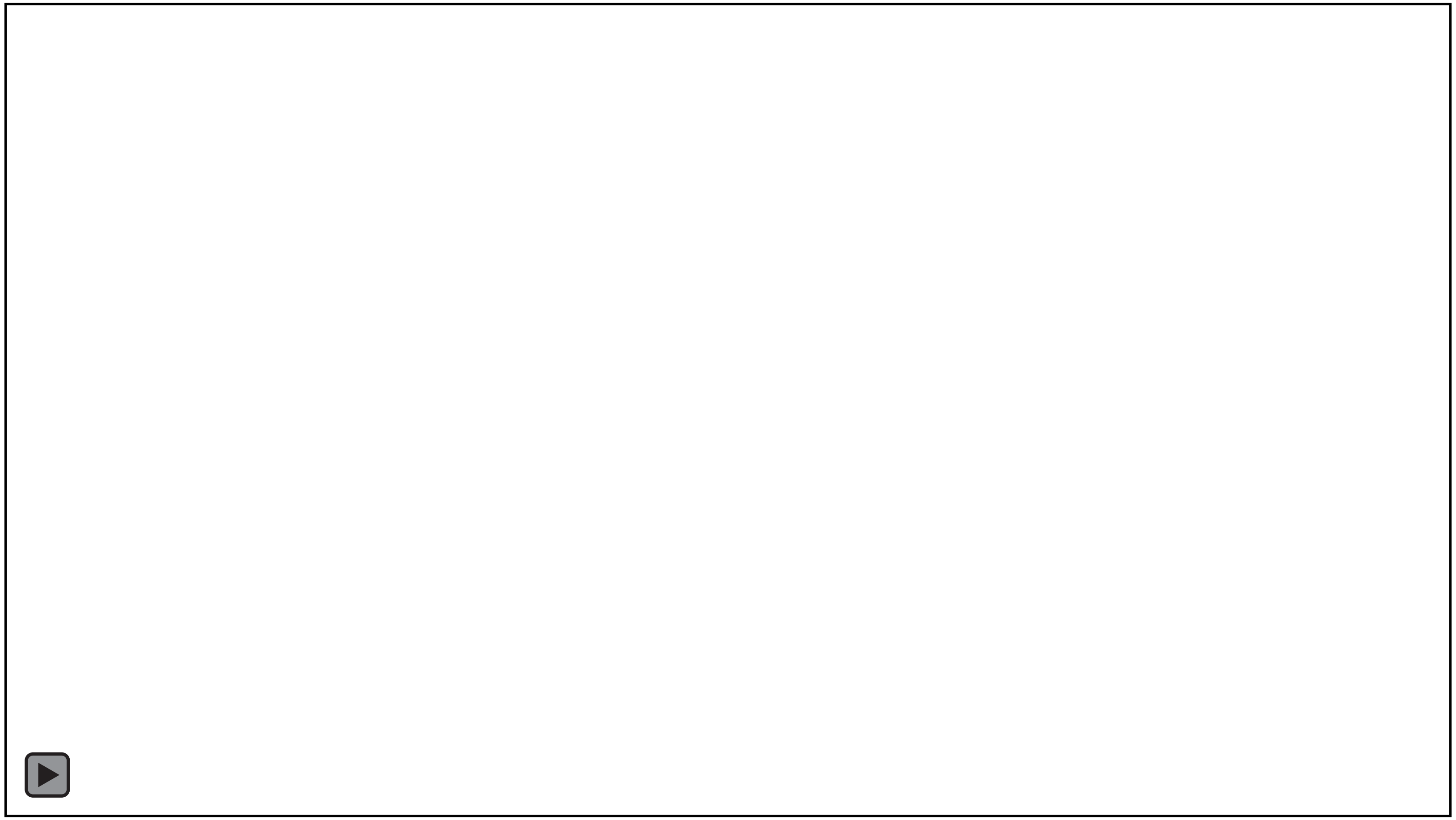
View of RDRE (Smith and Stanley, 2016)



Schematic View



RDRE Operation

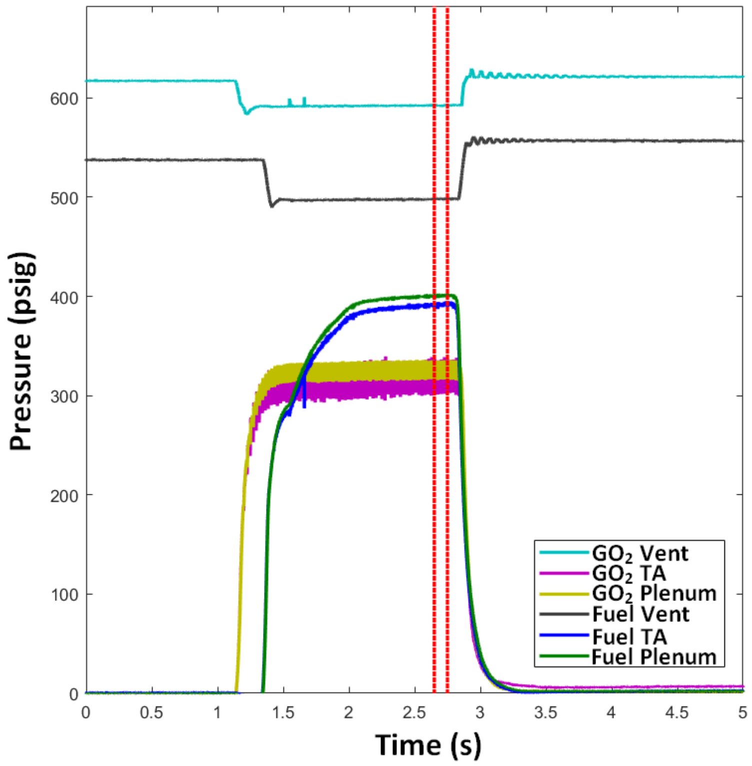


CH4-GOX

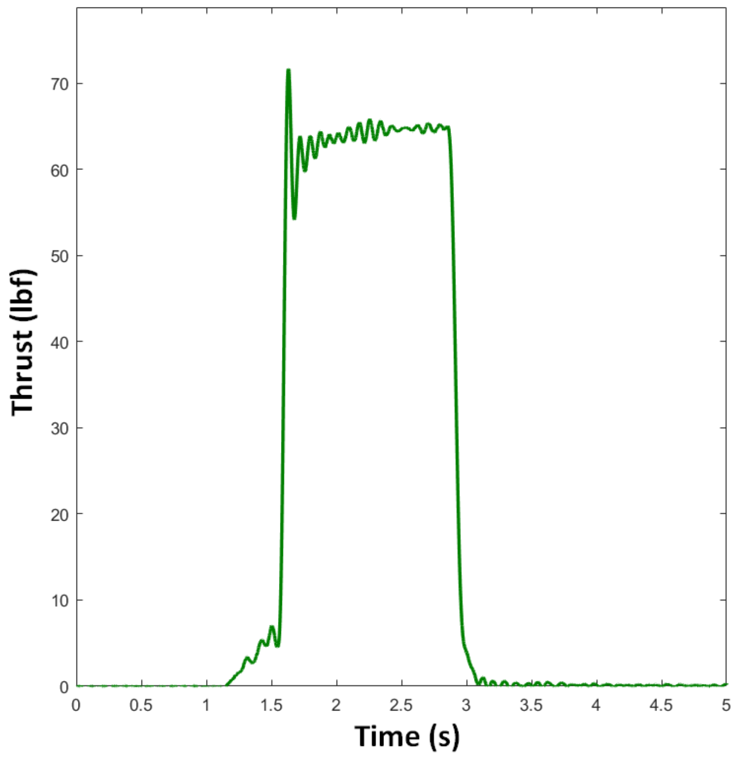
$\phi = 1.1$, $m_{tot} = 0.94$ lbm/s: Test 210

Example Test Run

System Pressures



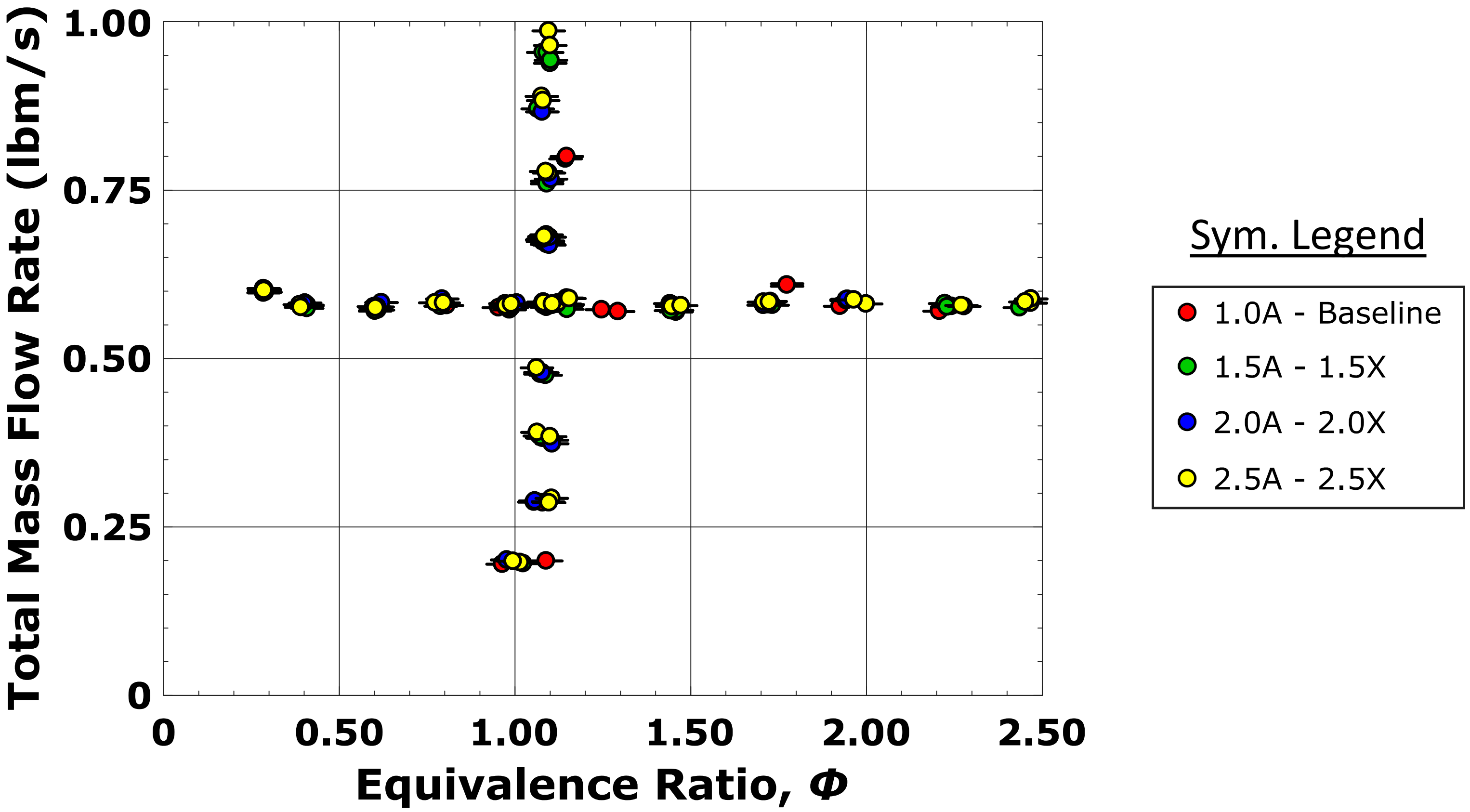
Thrust



- Typical tests consisted of 1.25 s run times
- Reported measurement are from the last 100 ms of the test (bounded by the red lines)

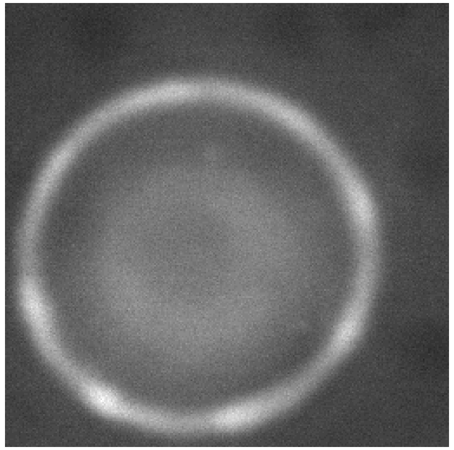
Test Matrix

- Performed the following two flow conditions studies:
  - Equivalence Ratio Sensitivity: φ = 0.30 – 2.5, for $\dot{m}_{tot}$ = 0.58 lbm/s (0.26 kg/s)
  - Total Mass Flow Sensitivity: $\dot{m}_{tot}$ = 0.20 – 1.0 lbm/s (0.09-0.45 kg/s), for φ = 1.1
  - Annulus Mass Flux: 0.1-0.5 lbm/(s-in^2) (80-400 kg/(s-m^2))



High-Speed Image Processing Technique

Raw Image



Corrected Image

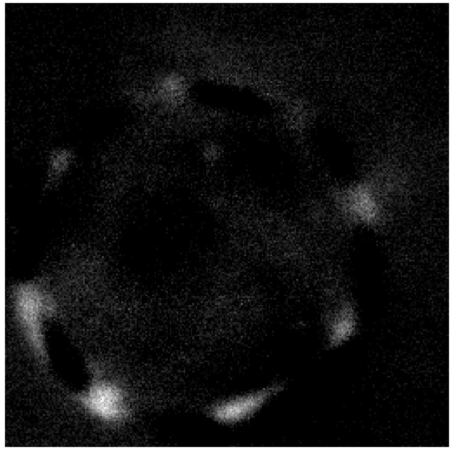
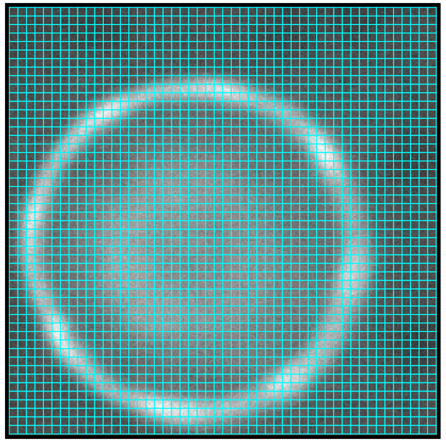


Image Processing Steps

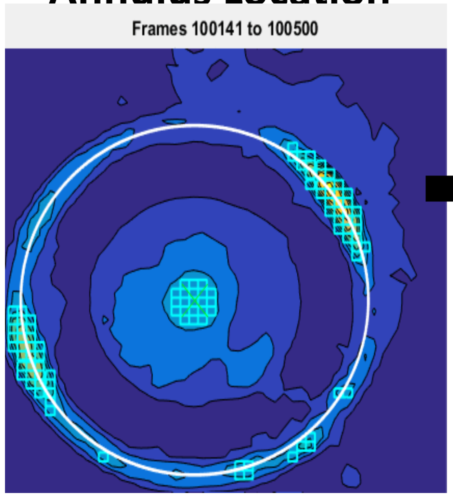
1) Apply Background subtraction.
2) Segment image (256X256 resolution) into 50X50 squares.
3) Quantify $I_{pxl.}$ time trace for each box and find boxes with max. $I_{pxl.}$ amplitude.
4) Fit circle to boxes using Taubin circle fit.
5) Segment circle into 200 angular divisions and again quantify $I_{pxl.}$. $I_{pxl.}$ is now fn(ɵ,t) as *r* dependence is removed.

Cartesian Mesh



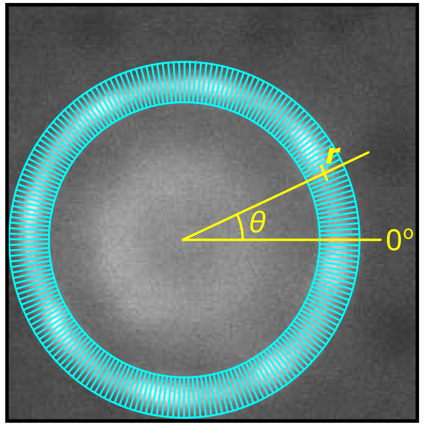
50x50 Grid

Annulus Location



Top 100 Boxes Considered

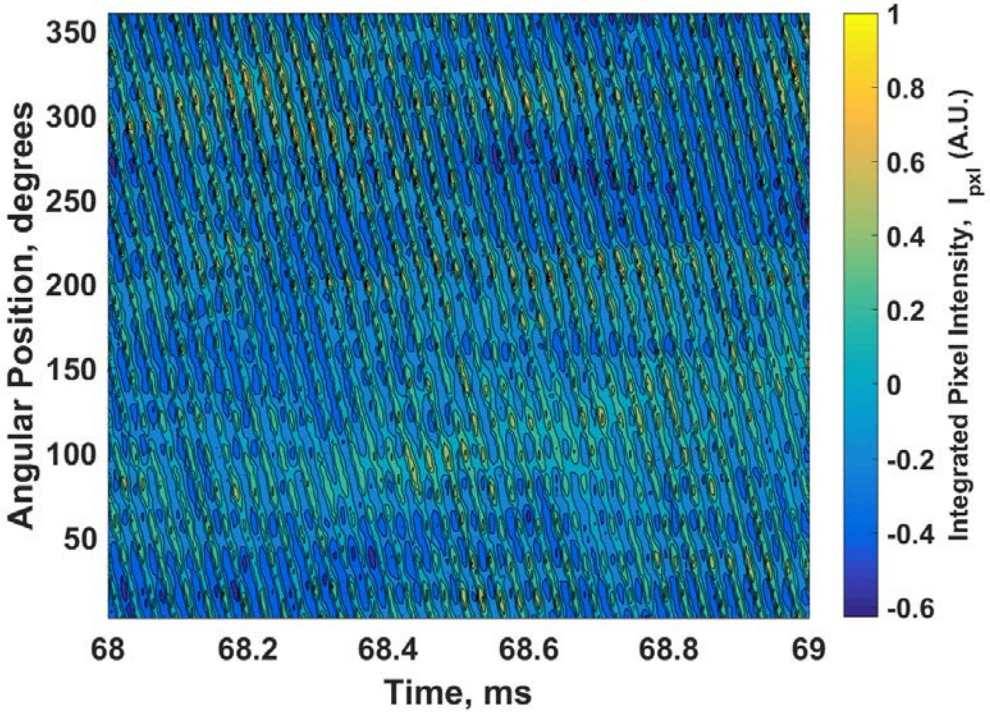
Polar Mesh



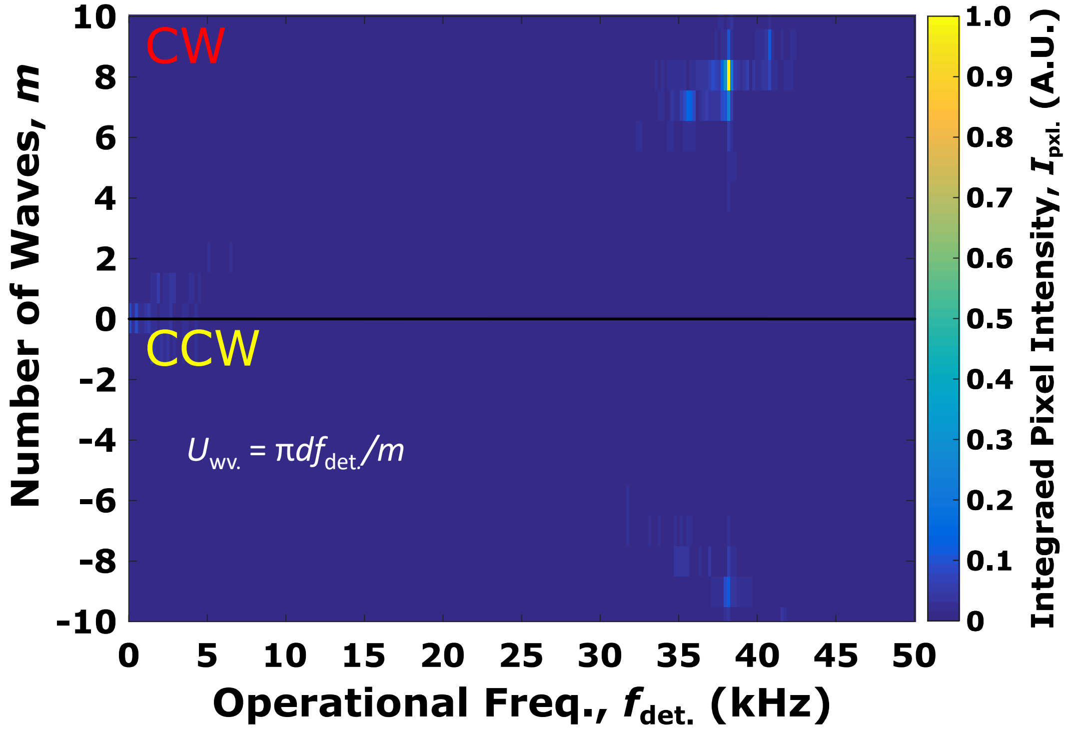
200 Azimuthal Bins

Detonation Surface

Det. Surface (8 Waves CW): Interval 14, Test 86



Example 2-D FFT of Det. Surface (Last Time Interval, 8 CW Waves)



- Wave motion is clear in the clockwise (CW) direction.
- Slope of detonation fronts are directly proportional to wave speed.
- Regions of higher intensity are captured (~270°).

Counter-Propagating Mode Analysis

Test 430

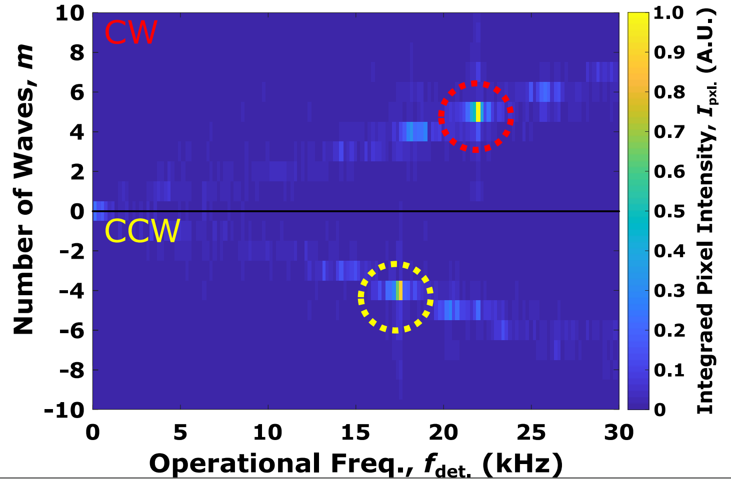
Flow Condition: ϕ = 1.1, $\dot{m}_{tot}$ = 0.2 lbm/s

Injector: 2.5A

- Opposing wave behavior existed with primarily 5 CW dominant mode with a 4 CCW counter-propagating component.

- Intensity of the counter-propagating component is 83% of the dominant.

2-D FFT: Q1 & Q4



Max. Peak Characteristics

Dom. Num. Waves: m = 5

Frequency: $f_{det.}$ = 22.0 kHz

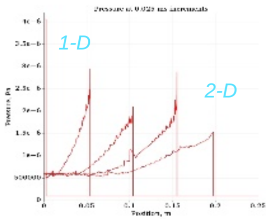
CP Num. Waves: m = -4

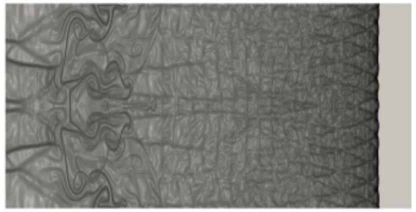
Frequency: $f_{det.}$ = 17.6 kHz

Modeling & Simulation

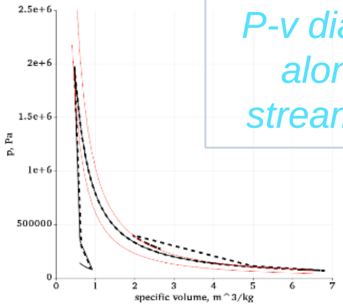
- Extremely difficult to make quantitative measurements in RDREs
- Key to understanding underlying physics is performing high fidelity simulations in concert with validation experiments

- **Exploratory physics studies**
  - In support of detonation physics
  - OD,1D & 2D detonations through premixed gas
- **Thermodynamic cycle analysis**
  - In support of systems analysis
  - Unwrapped (2D-planar) RDRE
- **Injector response**
  - In support of injector design
  - Linear injector array
- **Full engine dynamics**
  - In support of engine design
  - Full 3D axisymmetric configuration
  - Nozzle Effects

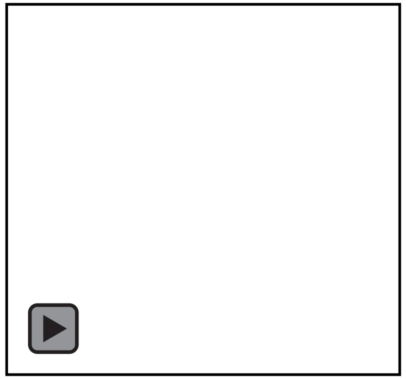


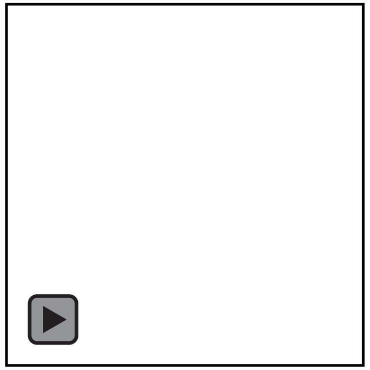


Basic detonation behavior, ignition procedures, fuels, & mesh resolution



P-v diagram along 2 streamlines



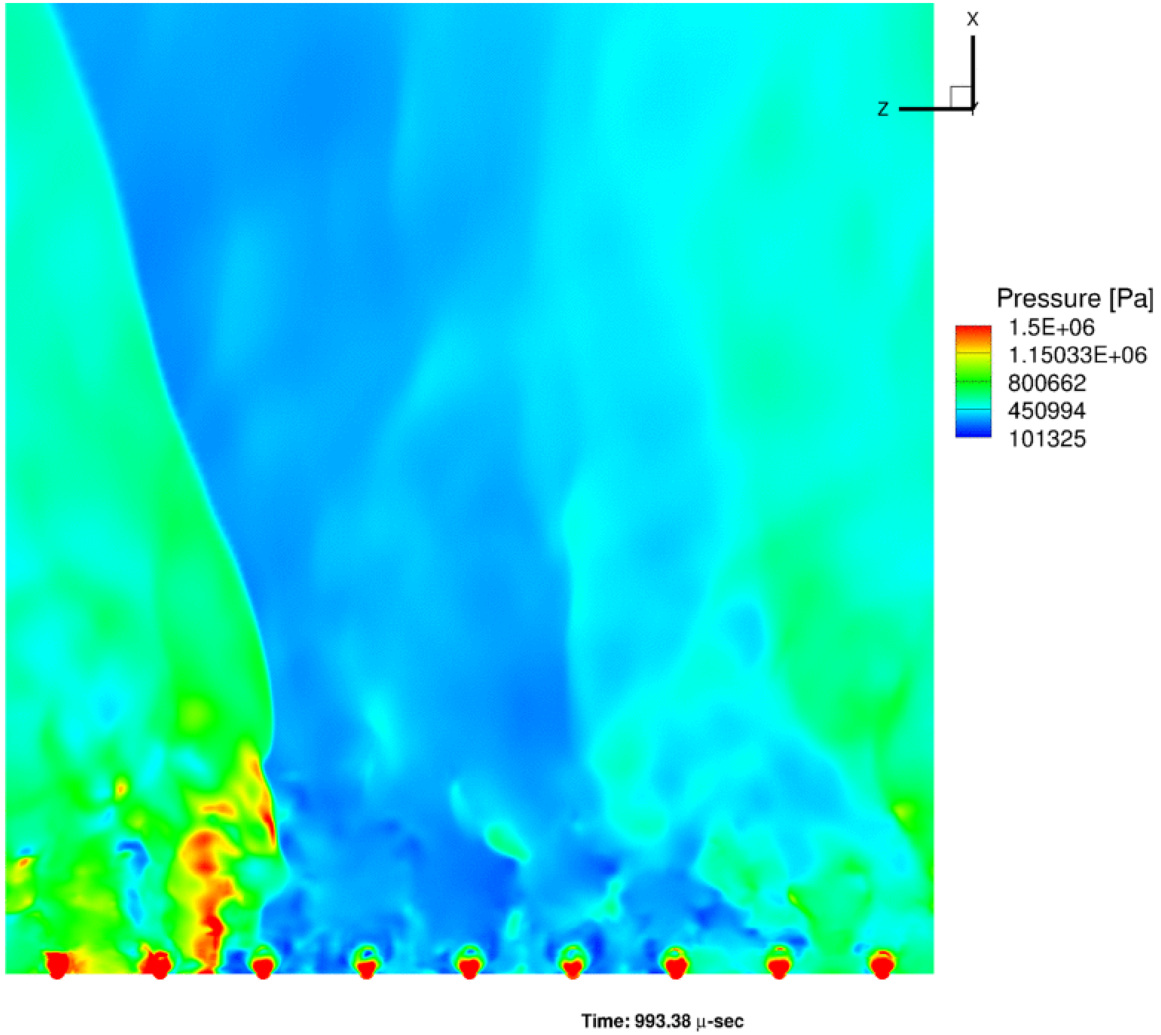


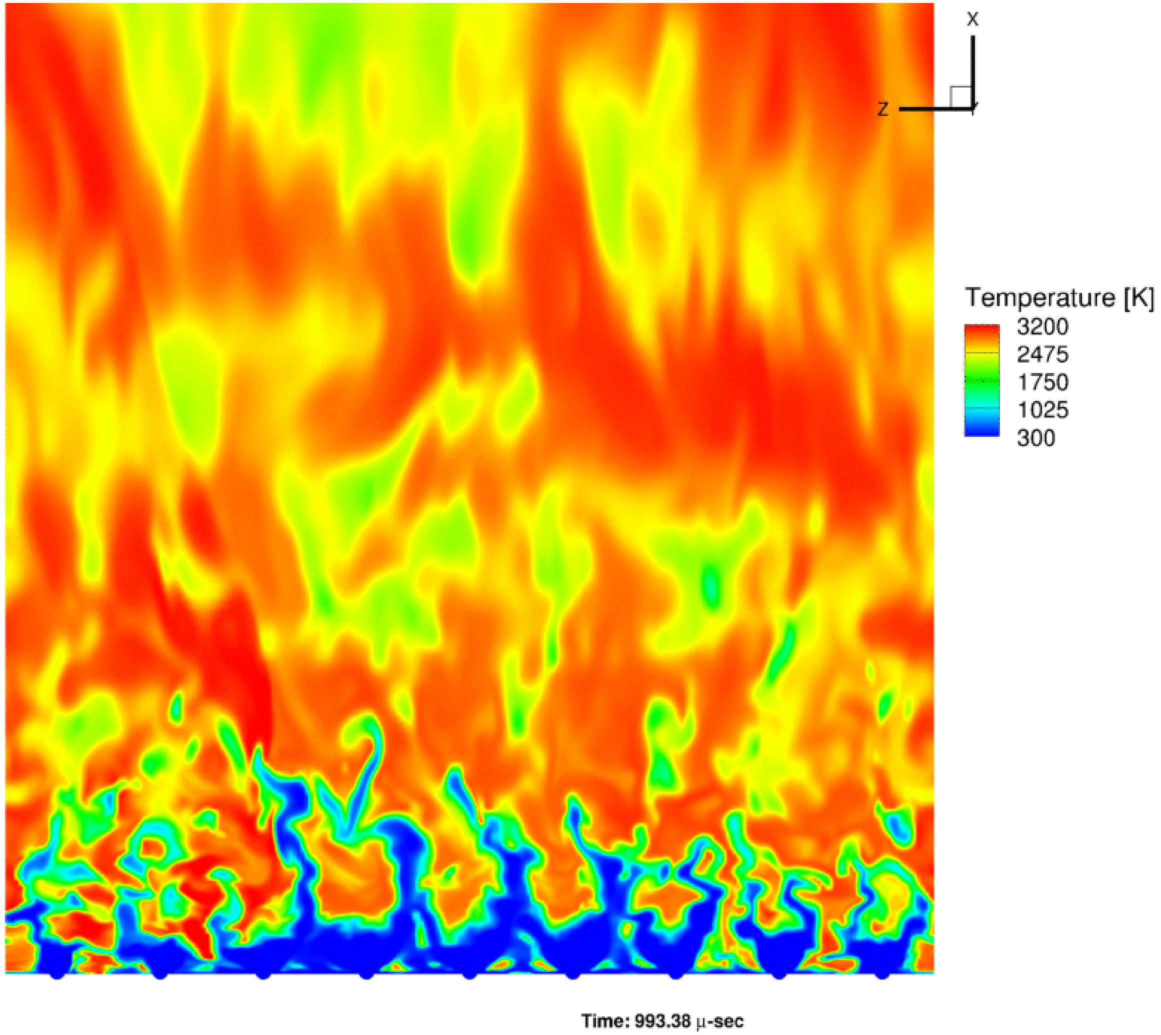
Engine Sector 3D Simulation

- Test 119, 8 Waves
- 9 Injector sector (1 wave)
- $\dot{m}$=0.61 lbm/s, Φ=1.77
- P_{CTap1}
  - Exp: 56.5 psi
  - Sim: 64.2 psi
- Wave Speed
  - Exp: 1132 m/sec
  - Sim: 1580 m/sec

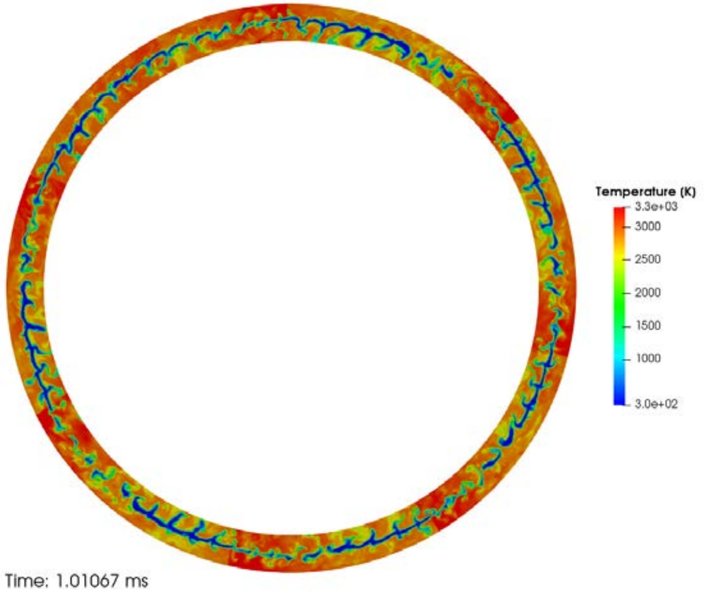
- Isocontours of Pressure
  - White: 7 atm
  - Black: 10 atm
- Temperature Scale
  - 300K to 3600K
- CJ Proprieties
  - T_{det}=3606 K
  - P_{det}=66 atm
  - V_{CJ}=2653 m/s

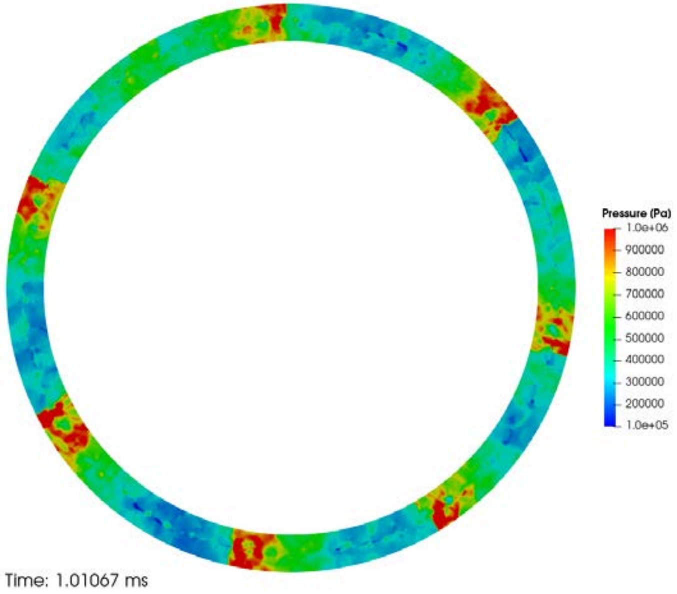
3D Centerline Values

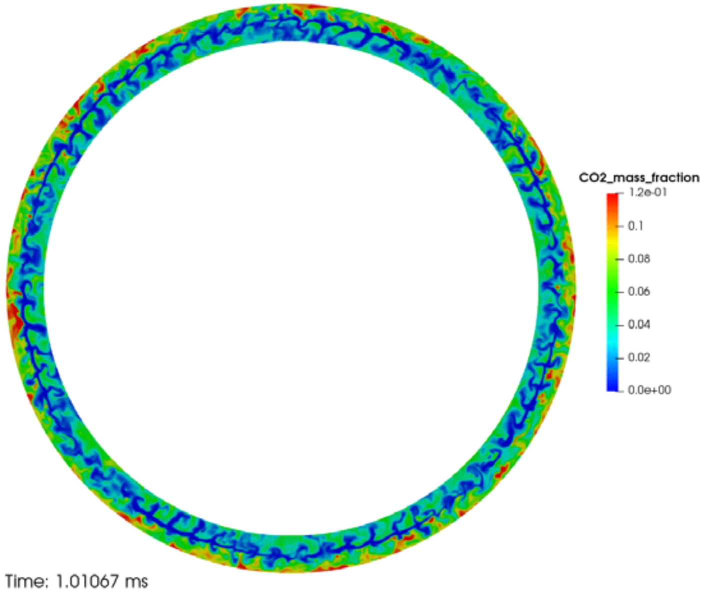




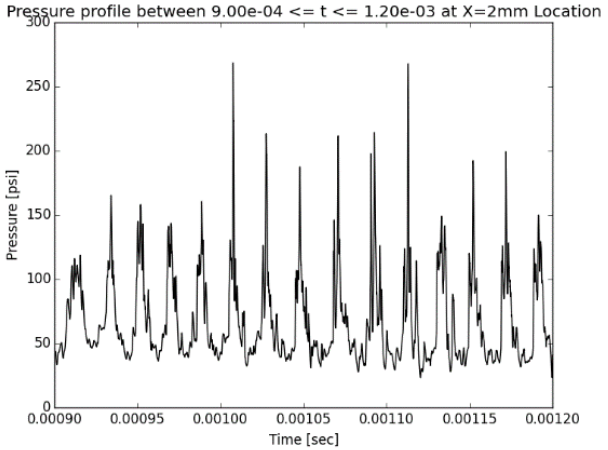
Full 3D Simulation







- Code: AHFM (VISP Version)
- Chemistry: Modified Westbrook & Dryer
- Domain: Plenums through expansion
- Grid Size: 78 Million
- Cores: 15,048
- Sim Time: 1.28 m-sec
- CPU Hours: 722K



- Test 104
- $\dot{m}$=0.58 lbm/s, Φ=1.15
- Experiment vs Simulation:
  - Waves: 9 vs 7
  - P_{CTap1}: 53.9 vs 59.4 psi
  - Speed: 1047 vs 1593.2 m/s
  - Freq: 42.2 vs 50 kHz

Counter-Propagating Mode Analysis

- **Past year key takeaways:**
  - Experiments have demonstrated broad operability for gas-gas RDREs
  - LES simulations of full engine are feasibly, relatively affordable and have the potential to provide critical insight into mixing, key detonation features, and loss mechanisms
  - Detonations obtained to date vary significantly from ideal homogenous CJ detonations
  - Wave speed deficit relative to CJ tied to inhomogeneous mixing field and less then full heat release coupling with the detonation
- **Future:**
  - Investigate how detonation structure affects engine efficiency through closely coupled experimentation and simulations
  - Improved injection methods (low loss & improved mixedness) & loss mechanisms via 2nd generation hardware
  - Increased chamber pressures
  - Increased instrumentation and diagnostics

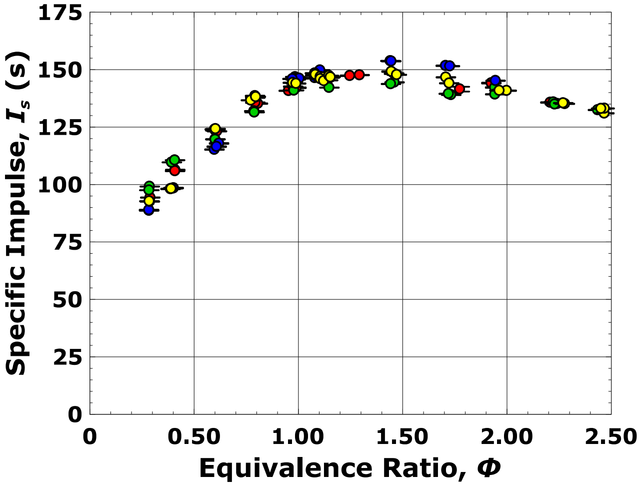
Questions?

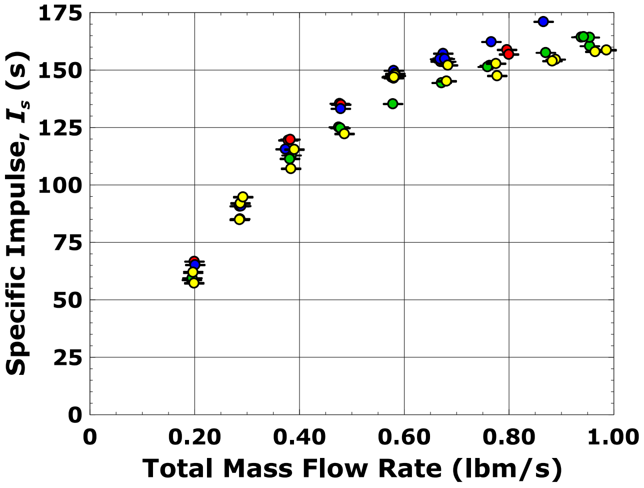
Typical 2D Simulation

- CH4-O2, Φ=1, 1atm backpressure
- 2D premixed with high pressure shutoff inflow
- Code: GEMS
- Chemistry: FFCM-1 reduced for these conditions
- Grid Points: 1.4 million (0.2mm per cell)

Injector Area Study

Isp

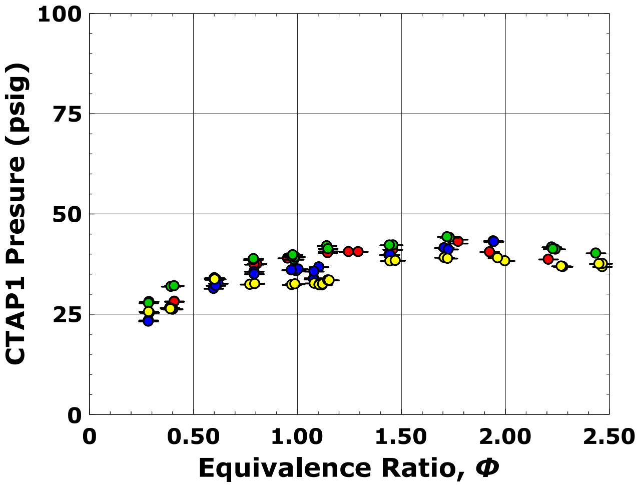


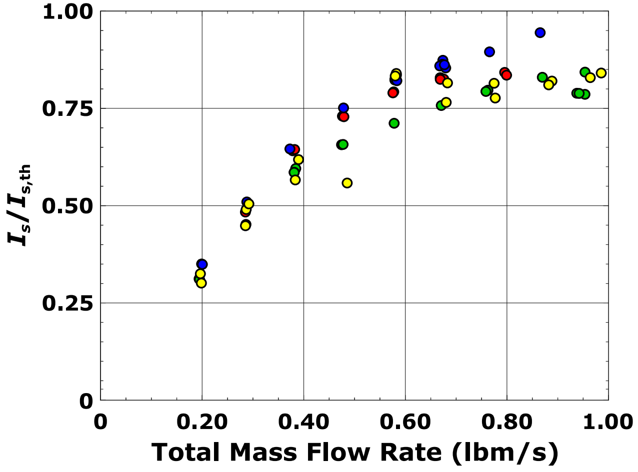


Sym. Legend

- 1.0A - Baseline
- 1.5A - 1.5X
- 2.0A - 2.0X
- 2.5A - 2.5X

Pressure



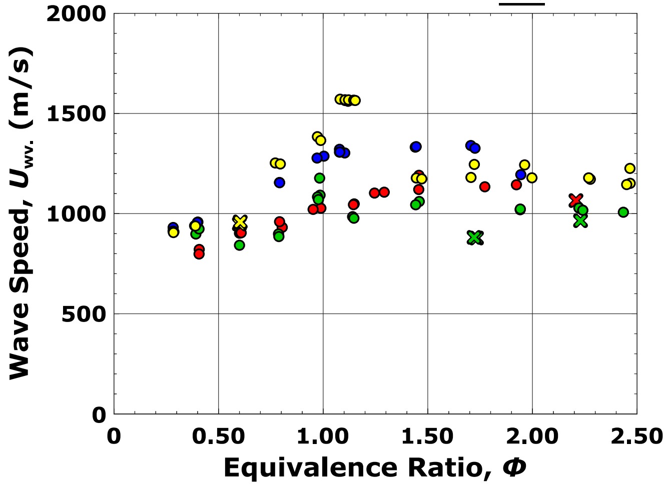


$I_s/I_{s,th}$

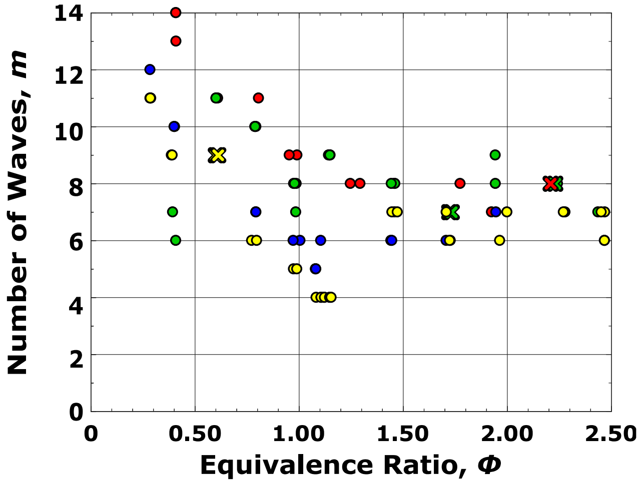
- Detonation achieved from 0.30 to 2.50 equivalence ratio and down to m_{tot} = 0.2 lbm/s (0.09 kg/s).
- Peak performance occurred at φ = 1.1 for all injector geometries, where I_s = 150 s.
- No appreciable change in performance observed for the various injector geometries.

Injector Area Study: Wave Modes

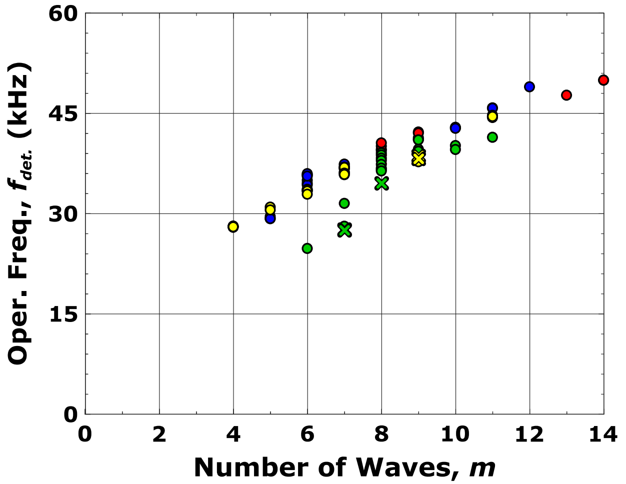
Wave Speed, $U_{wv.}$



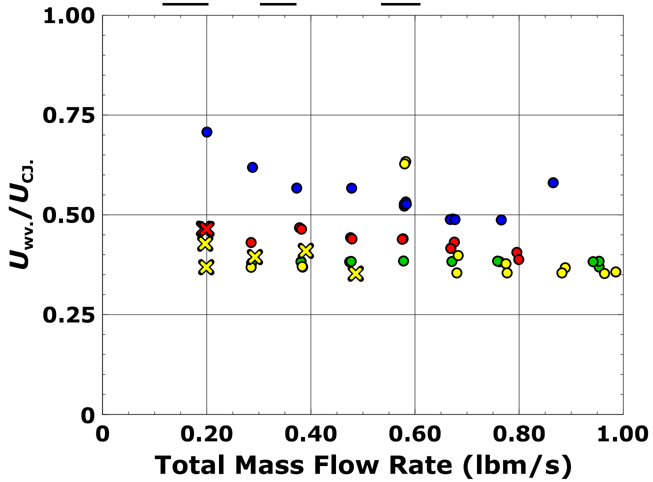
Number of Waves, *m*



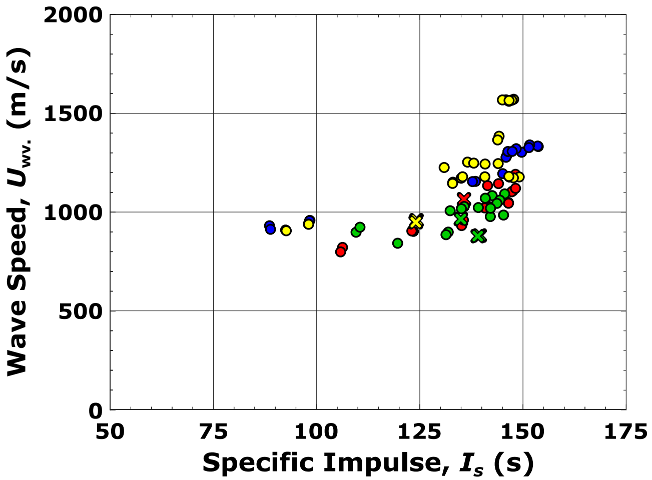
Oper. Freq. vs. Num. Waves



$U_{wv.}/U_{CJ.}$ – m_{tot} Study



Wave Speed vs. Isp



Sym. Legend

- 1.0A - Baseline
- 1.5A - 1.5X
- 2.0A - 2.0X
- 2.5A - 2.5X