Experimental and Computational Investigation of Valve Motion in a Resonant Pulse Combustor

Daniel E. Paxson & Hugh D. Perkins
NASA Glenn Research Center
Cleveland, Ohio

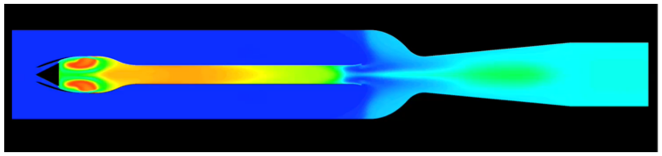
Shaye Yungster
HX5, LLC, NASA Glenn Research Center
Cleveland, Ohio

SciTech 2024
62nd AIAA Aerospace Sciences Meeting
Orlando, FL
January 8-12, 2024

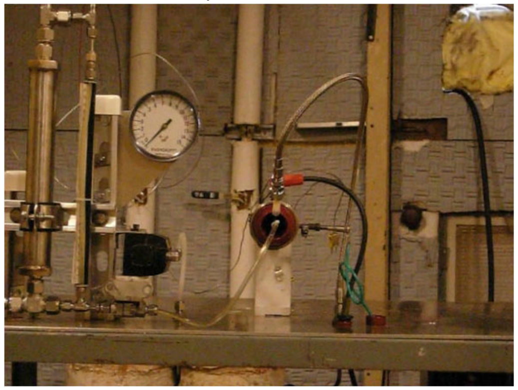
Motivation

- Resonant Pulse Combustors (RPC) represent a promising approach to Pressure Gain Combustion (PGC) for gas turbine application
  - Demonstrated, indisputable pressure gain (3-5%)
  - Low overall equivalence ratio capability when combined with ejector technology
  - Liquid fuel operation (including kerosene)
  - Low emissions potential
  - Only one moving part
- The air valve is a major technology challenge for RPC
  - State-of-the-art passively actuated reed valves are high-performing, but short-lived due to the harsh environment
- A recent effort to design, fabricate, & test a longer lasting valve for high pressure operation yielded a poppet-style configuration
  - Subsequent testing yielded poor pulse combustor operation
  - No pressure gain, not self-sustained

CFD Animation of an Ejector Enhanced Resonant Pulse Combustor



Operational Video

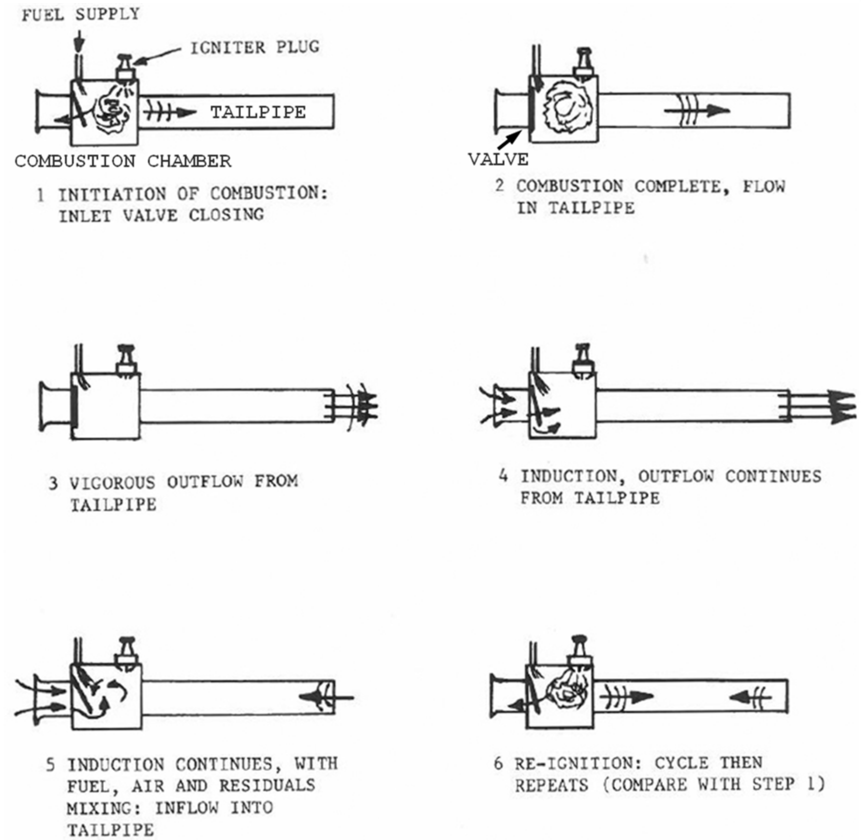


Damaged Reed Valve

This Work Describes an Experimental and Computational Study of the In-Situ Motion of Both Valves to Ascertain Essential Attributes for High Performance and Long Life

Brief Review of the RPC Cycle

- Air enters combustion chamber through open valve
- Mixes with fuel, gets ignited, undergoes a rapid confined combustion process
- Single step, 2 species, ultra-simplified finite rate reaction model
  - Confinement on left from the inlet valve, which rapidly closes as the chamber pressure rises
  - Confinement on right from fluid in the tailpipe with its associated inertia and acoustic waves
- Combustion produces a rapid rise in the chamber pressure
  - Propagates a compression wave down the tailpipe
  - Accelerates the fluid therein
- Accelerated fluid rapidly exits the tailpipe allowing expansion of the combustion chamber
- Chamber pressure eventually drops below the ambient pressure.
- Inlet valve opens and allows a new charge of air and fuel to enter.
- Tailpipe fluid briefly reverses direction
  - New mixture ignited

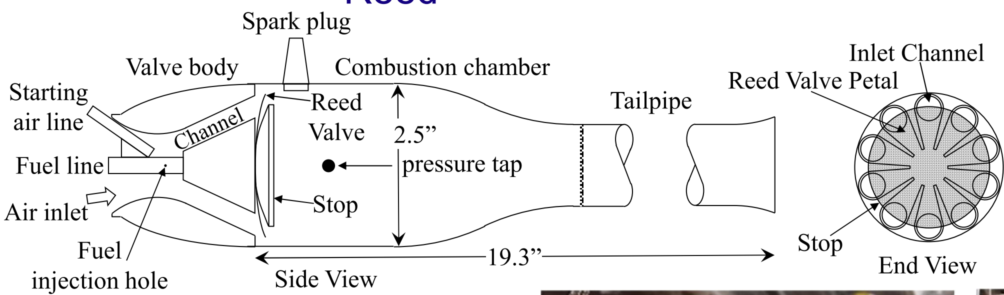


Kentfield, J.A.C, Nonsteady, One-Dimensional, Internal, Compressible Flows, Oxford University Press, 1993

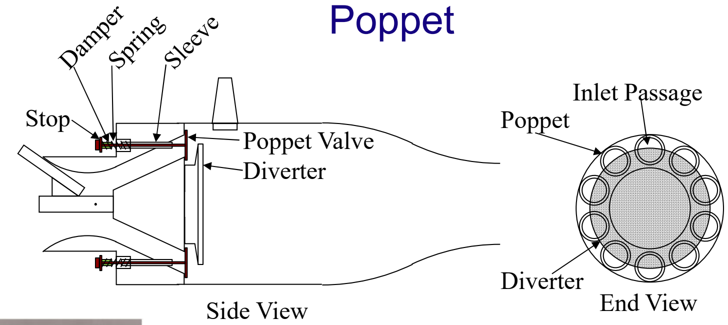
Ignitor Plug and Air Forcing Only Needed For Starting

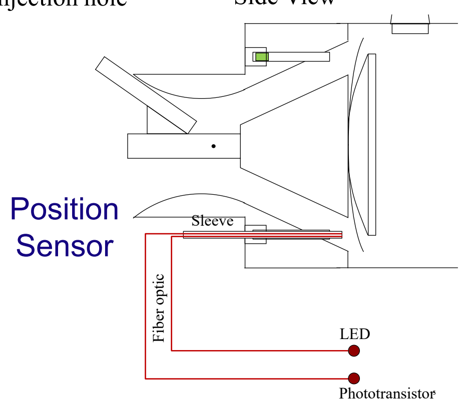
Experiment

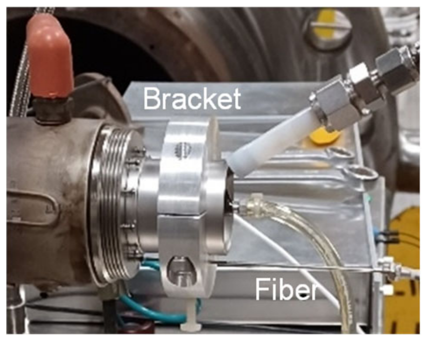
Reed

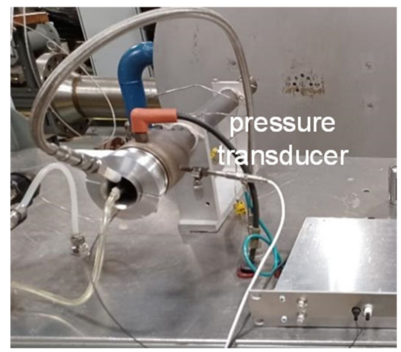


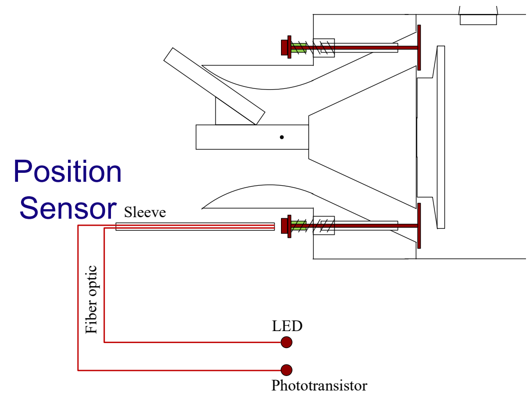
Poppet











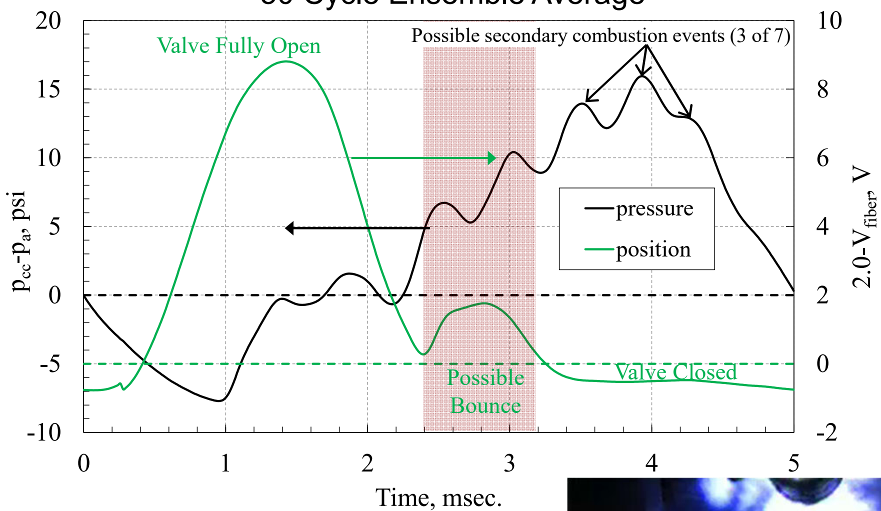
Details

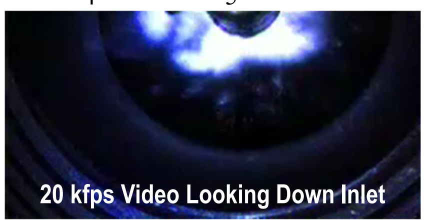
- Identical inlet flow paths upstream of valves
- Reed valve fits on poppet valve body
- Poppet long-life features:
  - Inconel
  - Exterior spring
  - Reduced travel
- LED & Phototransistor are 950 nm
  - Thermal sensitivity makes calibration impossible
  - Valve position is qualitative
- High frequency pressure transducer
  - Senses Chamber pressure
- Fuel is gasoline

Setup Allows Simultaneous Chamber Pressure& Valve Motion Measurement

Experimental Results

Reed

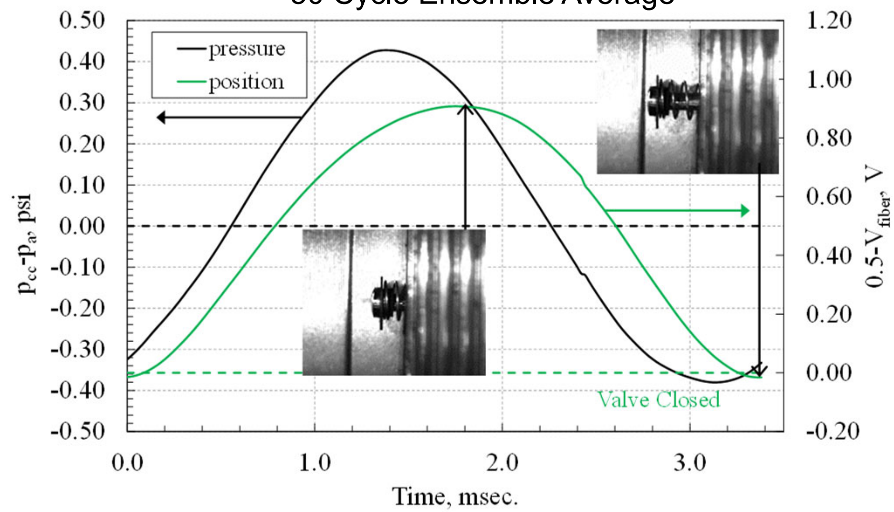




Observations

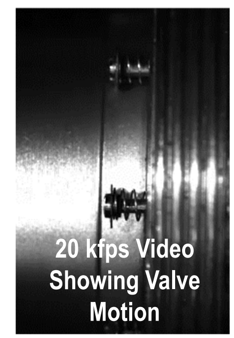
- Self-sustained, self-aspirated operation
  - Spark off, starting air off
- Mean chamber pressure is 3.8 psig
  - Corresponds to 4.6 lb_f static thrust
- 203 Hz. operational frequency
- Valve opens fully to stop

Poppet



Observations

- No self-sustained operation
  - Spark off, starting air **on**
- Mean chamber pressure is 0.0 psig
  - Corresponds to no static thrust
- 292 Hz. operational frequency
- Little valve motion with odd phasing



Additional Poppet Configuration Testing Never Yielded Self-Sustained Operation

Modeling

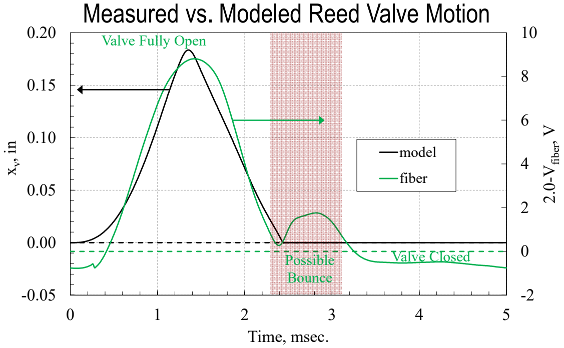
Combined CFD and Simple Mechanics

$$\frac{dv_v}{dt} = \frac{12g_c}{m}\{(p_a - p_{cc})A_p + F_s - f v_v\}$$

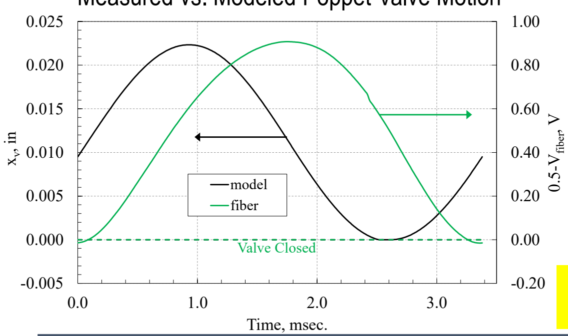
$$F_s = \begin{cases} -kx_v;\ x_v \le 0.17\ in. \\ -100kx_v + 99k(0.17);\ x_v > 0.17\ in. \end{cases}$$

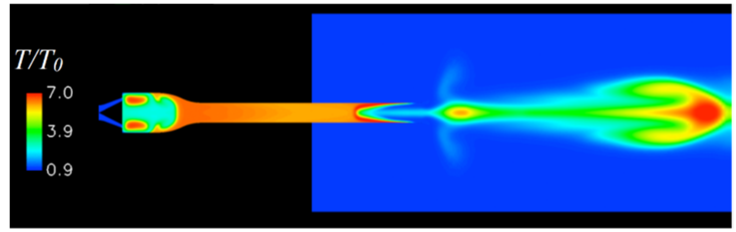
$$\frac{dx_v}{dt} = v_v$$

Measured vs. Modeled Reed Valve Motion



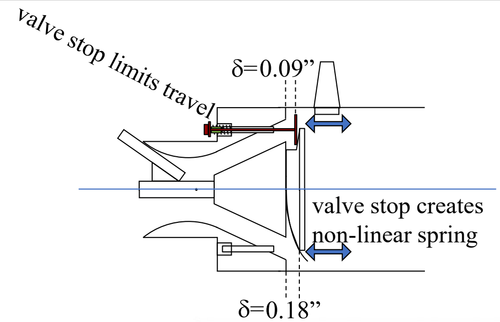
Measured vs. Modeled Poppet Valve Motion

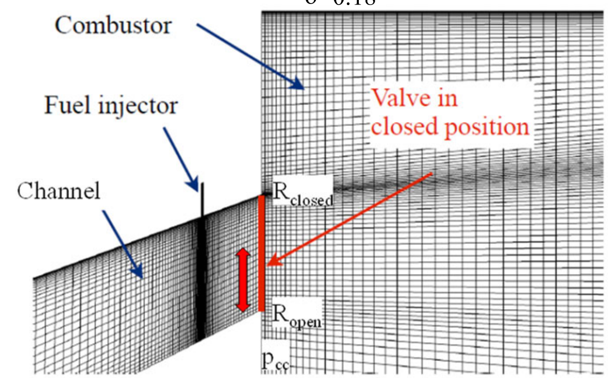




Features

- Ordinary Differential Equation of axial motion developed for each valve
  - Reed valve uses non-linear spring
  - Poppet valve has travel limiter
  - $x_v = f(p_{cc}, v_v, t)$
- Validated with measurements
- Axial valve motion mapped to CFD slider valve motion
  - Valve model integrated into CFD code
- CFD Model (in-house):
  - Axisymmetric, URANS, w/ Turbulence
  - Thermally perfect mixture of gases
  - Fuel is gaseous Jet-A
  - 100,000 grid-points
  - Validated
  - Domain includes RPC and beyond





Passively Actuated CFD Based Pulse Combustor Simulation Developed

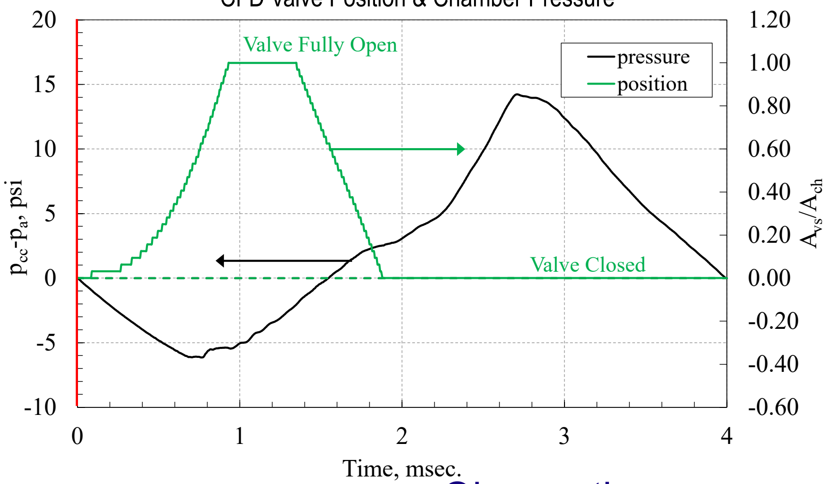
Modeling Results

Reed Valve

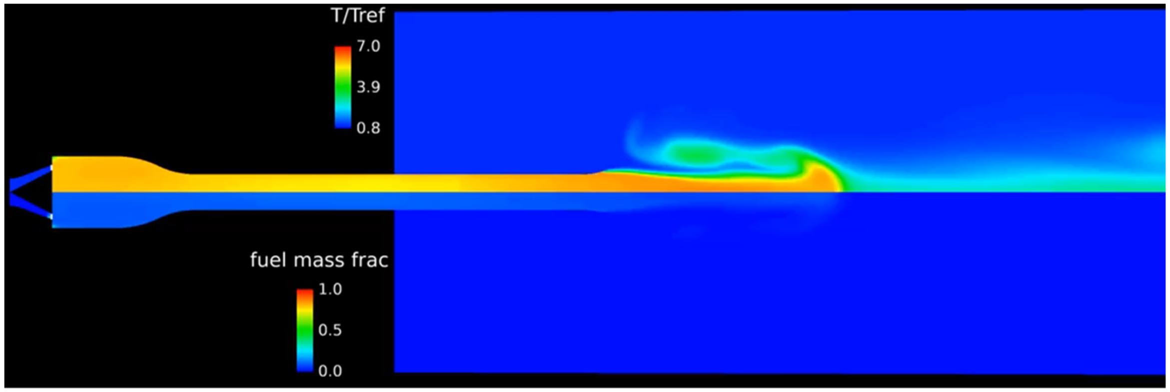
Simulation Initiated With Limit Cycle Solution Using An Idealized Active Valve

Yungster, S., et al, *AIAA Journal of Propulsion and Power*, V. 33, No. 1, 2017, pp. 29-42

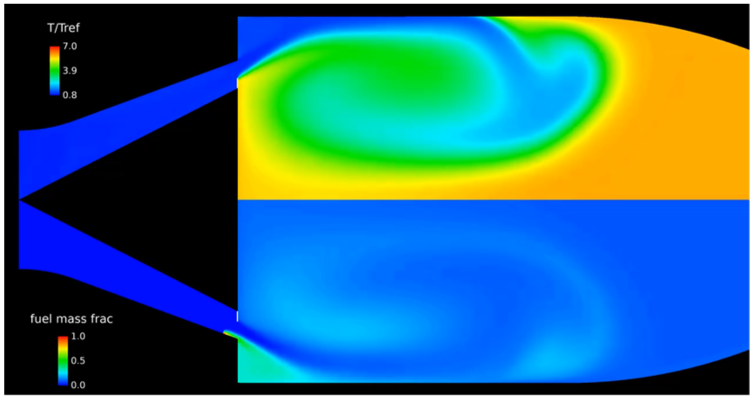
CFD Valve Position & Chamber Pressure



CFD Animation of Full Computational Space



Zoomed CFD Animation of Chamber and Valve



Observations

- Self-sustained, self-aspirated limit cycle operation achieved
- Mean chamber pressure is 2.7 psig
  - 30% below experimental value
  - Just 6% below experimental absolute
  - Very good agreement considering: Jet-A vs. gasoline; gaseous vs. liquid fuel, etc.
- 250 Hz. operational frequency
- Valve position vs. chamber pressure phasing similar to experiment

Critical Valve Motion and Fluid Coupling Physics Captured

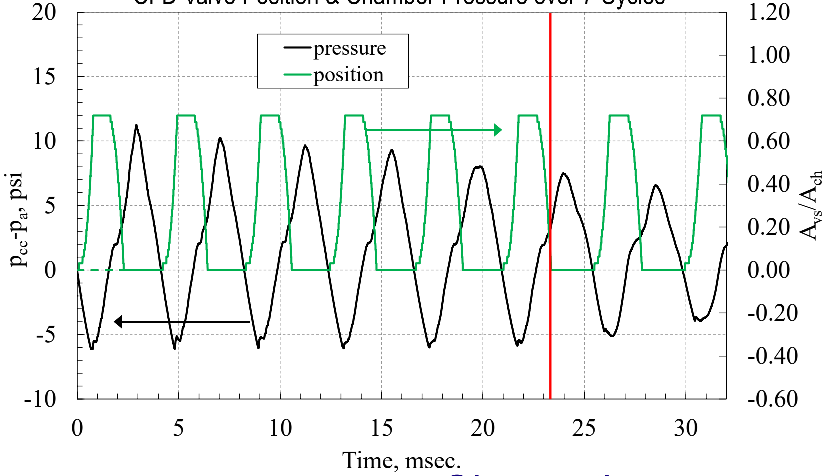
Modeling Results

Poppet Valve

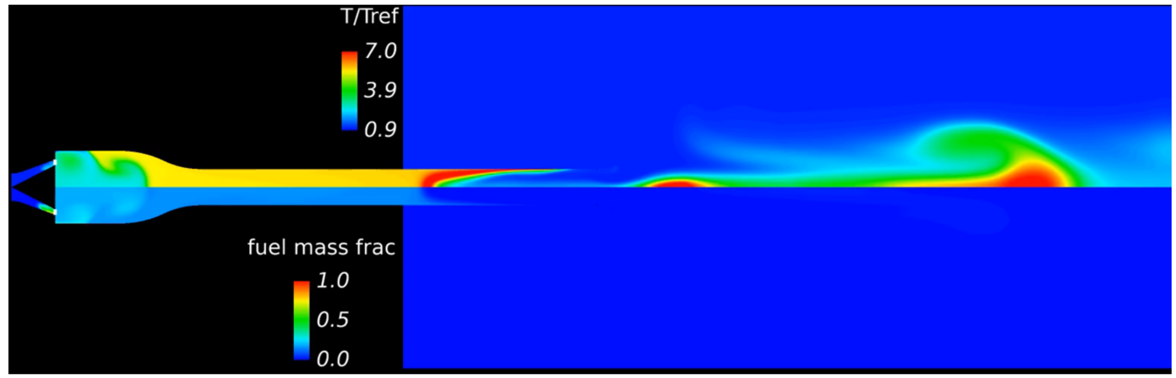
Simulation Initiated With Limit Cycle Solution Using An Idealized Active Valve

Yungster, S., et al, *AIAA Journal of Propulsion and Power*, V. 33, No. 1, 2017, pp. 29-42

CFD Valve Position & Chamber Pressure over 7 Cycles



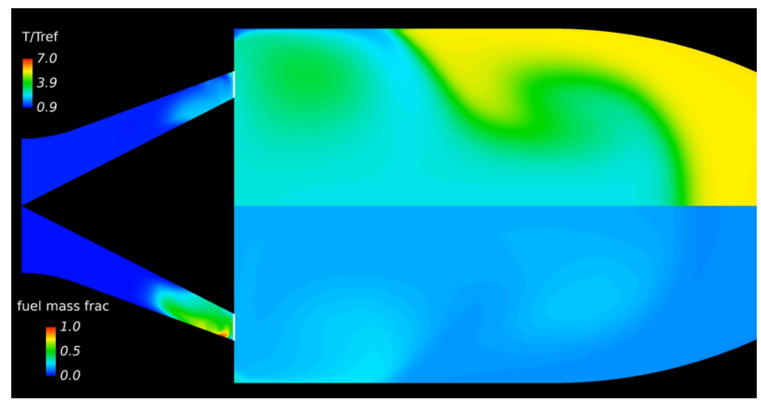
CFD Animation of Full Computational Space



Observations

- Cycle is slowly decaying
  - Pressure amplitude declines with each cycle
- Mean chamber pressure is 1.0 psig on 7th cycle
  - 73% below experimental value
- 240-220 Hz. operational frequency
- Significant backflow
- Fuel flow is not reduced in model
  - Venturi not simulated
  - More rapid decay likely if modeled

Zoomed CFD Animation of Chamber and Valve



Critical Valve Motion and Fluid Coupling Physics Captured
Greatly Reduced Performance With Eventual Failure Likely

Summary

- Operation of a liquid fueled, passively valve Resonant Pulse Combustor (RPC) was examined experimentally and computationally
- Two passive valve types were examined:
  - Traditional, short-lived reed valve
  - Newly fabricated, longer-life poppet valve
- Valve motion in relationship to chamber pressure was measured
  - Reed valve motion yielded self-sustained, pressure gain operation
  - Poppet valve required forced air to operate and yielded no pressure gain
- Valve motion was modeled and implemented in a CFD simulation of the RPC
  - Reed valve simulation yielded self-sustained, pressure gain, limit cycle operation
  - Poppet valve simulation yielded continually decaying operation with little pressure gain
- Poppet valve does not have the travel range or the non-linear spring action needed for success
- High performance, long-lived RPC valves will likely require:
  - Actively actuated, feedback-controlled, rotary or chopper valve systems
  - Redesigned inlet flow paths to accommodate active valves

Thank You for Viewing