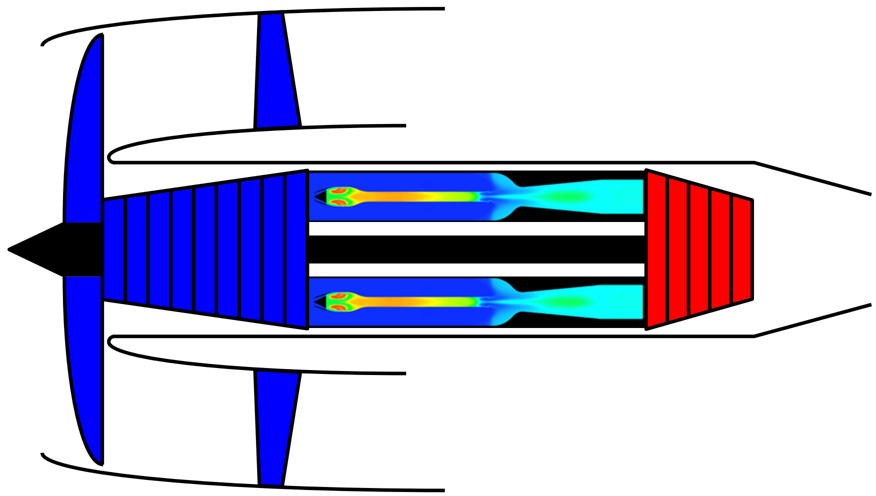


Resonant Pulse Combustors:
A Reliable Route to Practical Pressure Gain Combustion

Dan Paxson
NASA John H. Glenn Research Center
Cleveland, OH

Fundamentals and Applications of Pressure Gain Combustion

AIAA Online Short Course
September-October, 2022

Acknowledgements

Most of what follows represents NASA GRC research in Resonant Pulse Combustion (RPC) since 2000. The following individuals contributed significantly to the work

- Shaye Yungster (HX5) - CFD
- Doug Perkins (NASA) - Analysis
- Scott Jones (NASA) - Analysis
- Kevin Dougherty (SAIC, retired) - Experiments
- Robert Pelaez (NASA) - Experiments
- Mark Wernet (NASA) - PIV
- Trevor John (Sierra) – PIV
- Jack Wilson (ASRC, retired)

Partnership with the Air Force Research Laboratory has been invaluable to the research. The following individuals contributed significantly to the work

- Fred Schauer (AFRL) - Experiments
- John Hoke (ISSI) - Experiments
- Paul Litke (AFRL) - Experiments
- Andy Naples (ISSI) - Experiments

Additionally, colleagues from other organizations have contributed substantially to this technology.

- Rob Miller (University of Cambridge)
- Ephraim Gutmark (University of Cincinnati)
- William Roberts (King Abdullah University of Science and Technology)

Outline

- Motivation
- How Do They Work?
- Experimental Investigations
- Numerical Investigations
- Ongoing and Future Directions
- Related Work
- Concluding Remarks

Some Preliminary Facts

Sources: Bureau of Transportation Statistics, Department of Energy/Energy Information Administration, Environmental Protection Agency

The U.S. Consumed (Converted) **97,330,000,000,000,000** BTU of Energy in 2021

- *79% from fossil fuels (petroleum, natural gas, coal)*
- *68% from petroleum and natural gas*

Resulting Issues

- *National & Economic security*
- *Pollution*
- *Climate Change*

The Response

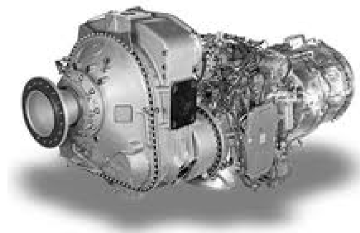
- *Alternative fuels (biomass, etc.)*
- *Alternative conversion systems (wind, solar, hydro, etc.)*

(12% — the two items above)

- *Conservation/* ***EFFICIENCY*** *(use less)*

Equivalent to 6.7 gallons of gasoline used by every U.S. citizen EVERY DAY!

Today's Presentation Is All About This Response

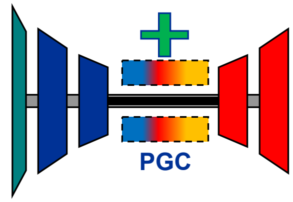




Gas Turbines Constitute an Astonishing 15% of Energy Consumption

- *3.7% from aviation*
- *11.8% from power generation (and growing if coal gasification and/or combined cycle plants are more fully implemented)*

A mere **1%** improvement in the thermodynamic efficiency of our gas turbine fleet is equivalent to installing nearly **20,000** commercial wind turbines.

Two Reasonable Conclusions:
Technologies to Improve Gas Turbine Performance Are Important
Those Applicable to Both Aviation and Ground Power are Critical



Pressure Gain Combustion is One Such Technology

PGC[†]*: A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure*[*] *and allowing work extraction by expansion to the initial pressure.*

[†]The term “Pressure-Gain Combustion” is credited here to the late J.A.C. Kentfield

*Conventional combustion incurs a total pressure loss

Resonant Pulse Combustors (RPC) Are a Practical Implementation of PGC

(When Combined With Ejectors)

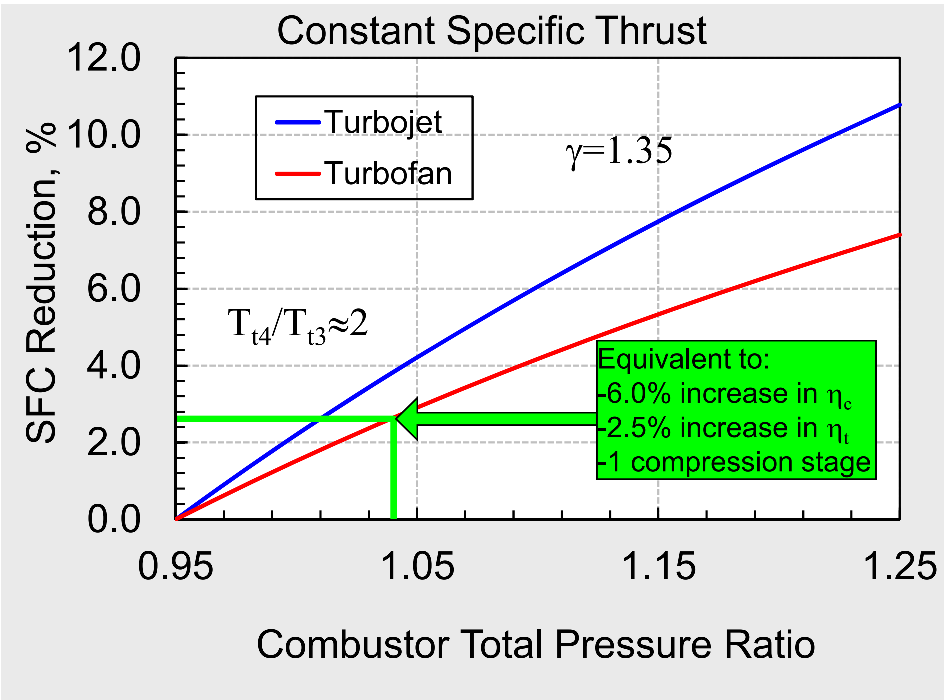
Motivation

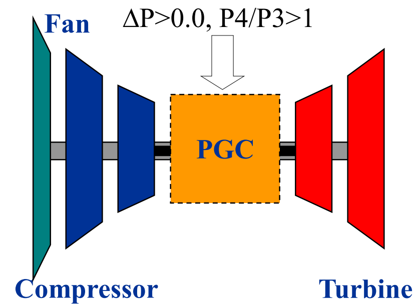
PGC for Gas Turbines

Two specific engines considered

T_{t4}, T_{sp} fixed for turbofan (BPR varied)

T_{sp} fixed for turbojet (T_{t4} varied)



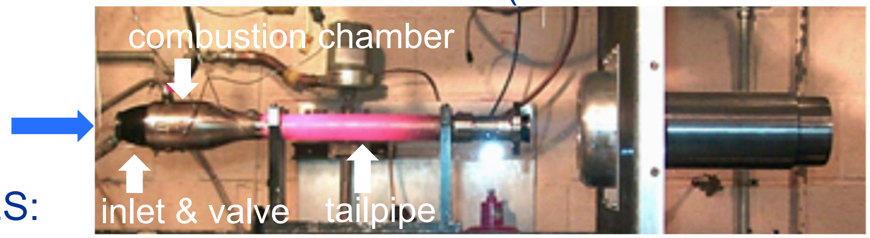


Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
$T_{combustor\ exit}$ (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

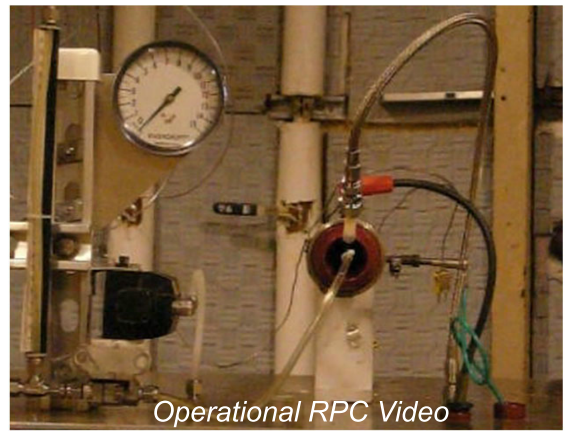
Many Other Studies Available
- AIAA-2013-3623
- AIAA-2004-3396
- Etc.

Motivation

Resonant **P**ulse **C**ombustor-RPC
(aka 'Confined' Volume Deflagration)



FEATURES:
- Self-sustained operation
  - No spark plugs (other than for starting)
- Only one moving part
- Relatively low unsteadiness amplitudes
  - Lower thermal and mechanical stresses
  - Effluent easier to smooth
  - Fewer potential issues for downstream turbomachinery
- Readily operates with liquid fuels (gasoline, ethylene, kerosene)
- Effective lean operation (low T_{t4}'s) with bypass ejectors
- Unequivocally a pressure gain device
  - Only known PGC system to operate under static conditions



CAVEAT:
- Only Modest Pressure Gain is Possible
  - Confined (not constant) volume combustion

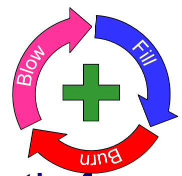
Practically: Features May Outweigh Caveat – Even Compared to Other PGC Approaches

How Do They Work?

RPC Basic Thermodynamics

Like all PGC Devices RPC’s:

- Are periodic
- Are fixed volume
- Produce work availability directly from chemical energy

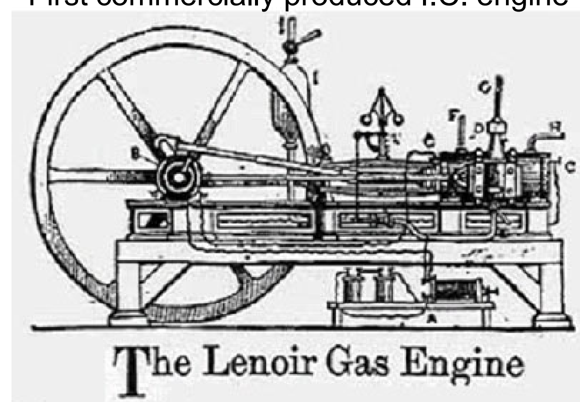


Often described as:
A Lenoir-like Cycle Executed Without Pistons

Lenoir Cycle:

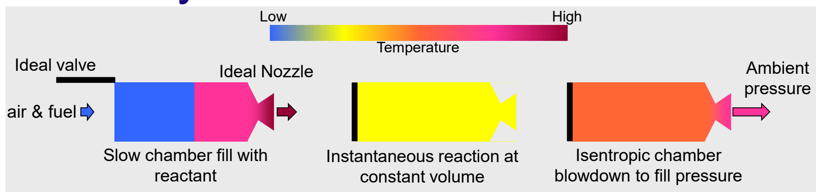
- Isochoric Heat Addition
- Isentropic Expansion
- Isobaric Heat Rejection

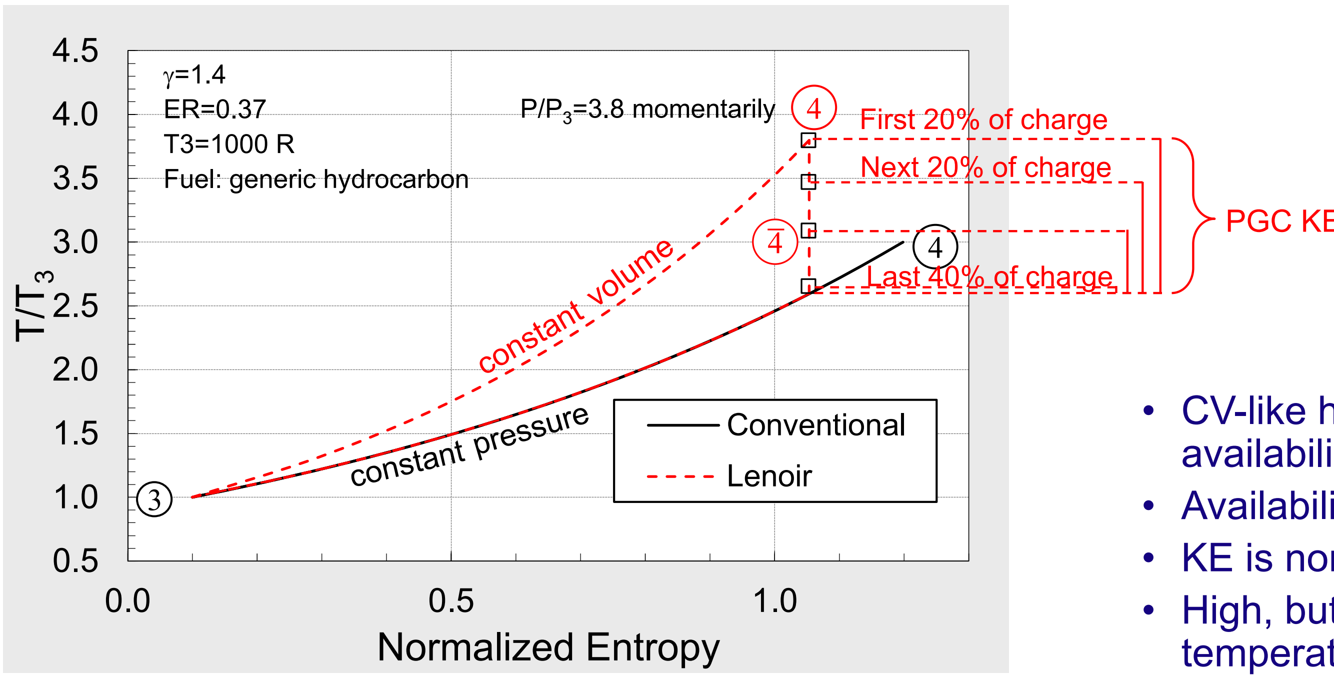
Patented 1860
First commercially produced I.C. engine



Basic Thermodynamics – Non Piston Lenoir Cycle

Notional RPC Device





Confinement During Combustion Is Good

RPC Features

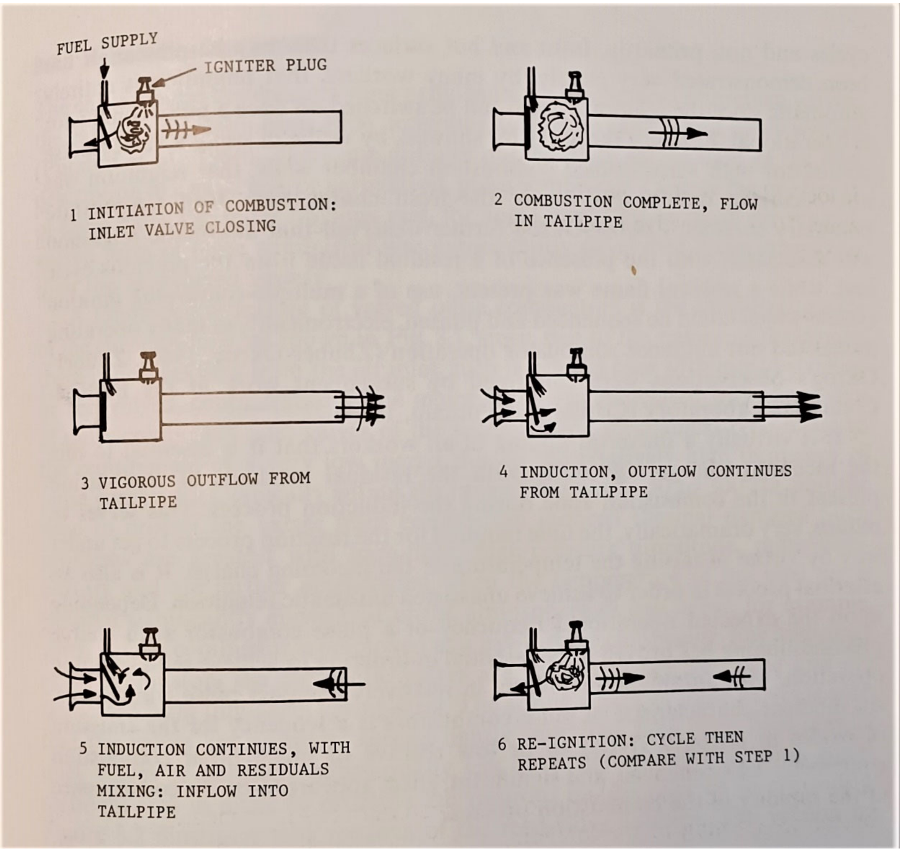
- CV-like heat addition produces availability
- Availability manifested as KE
- KE is non-uniform (unsteady)
- High, but brief pressures & temperatures
- Same mass averaged temperature as conventional heat addition

How Do They Really Work?

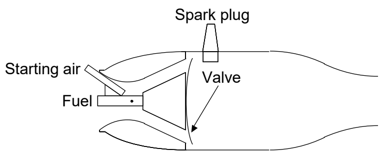
RPC Basic Cycle

Illustrated Schematically

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



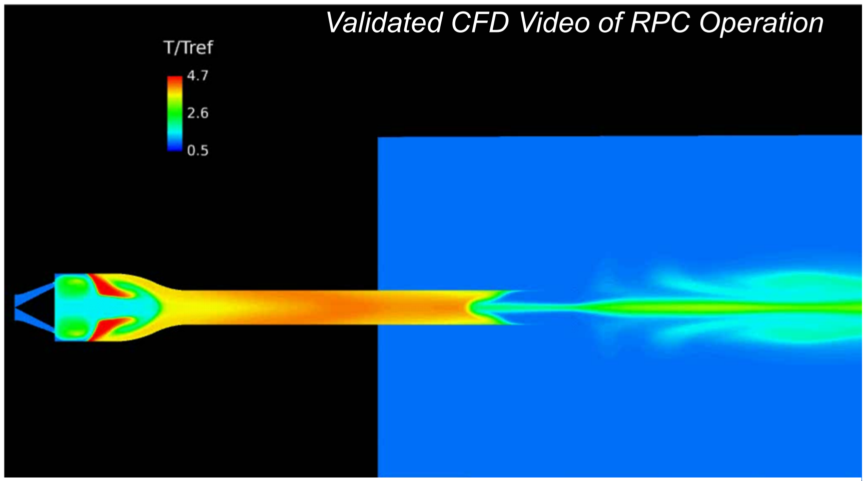
More Complex Than Just Fill→Burn→Blow



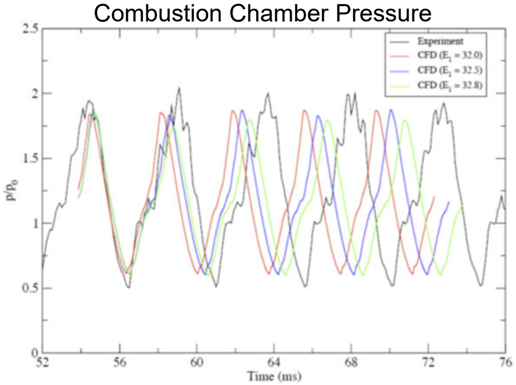
How Do They Really Work?

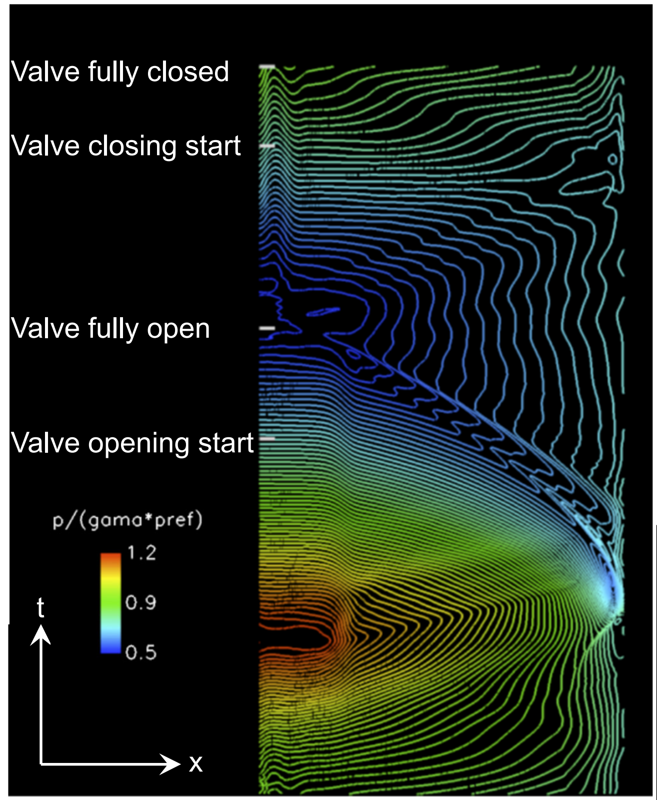
RPC Basic Cycle

Illustrated Using a Validated 2D Axisymmetric Simulation



Combustion Chamber Pressure





RPC Couples:

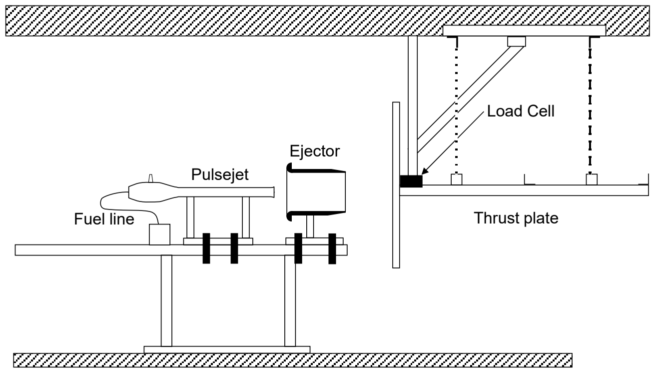
- Strong acoustic resonance (i.e., finite amplitude waves)
- Helmholtz resonance
- Mechanical resonance (in the valve)
- Vortex dynamics
- Chemical kinetics
- Droplet breakup, vaporization, and transport dynamics

Key Takeaways:

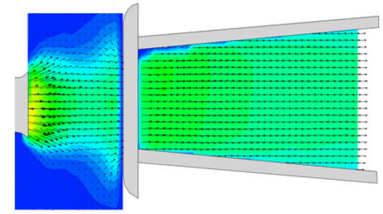
- Geometrically simple but fluidically complex
- Confinement during heat release is only partial (not true CV)
- Optimization is non-trivial

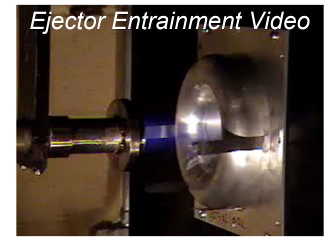
Experimental Investigations

Ejector Mixing and Pumping Optimization



PIV Measured Flowfield Video



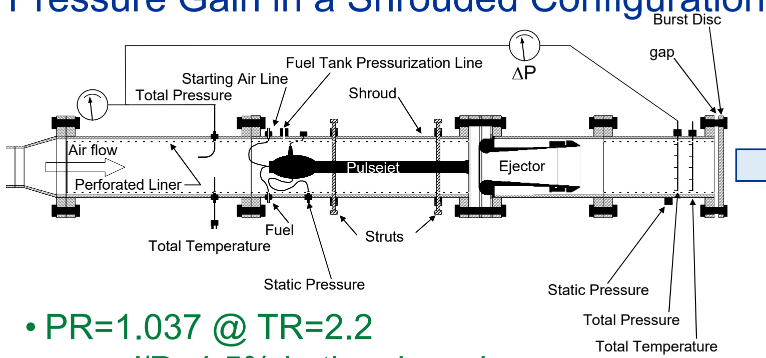


- 18:1 and greater entrainment ratios
- Thrust augmentation ratios up to 2.0
- Velocity fluctuations reduced by 83%

For Gas Turbine Application:

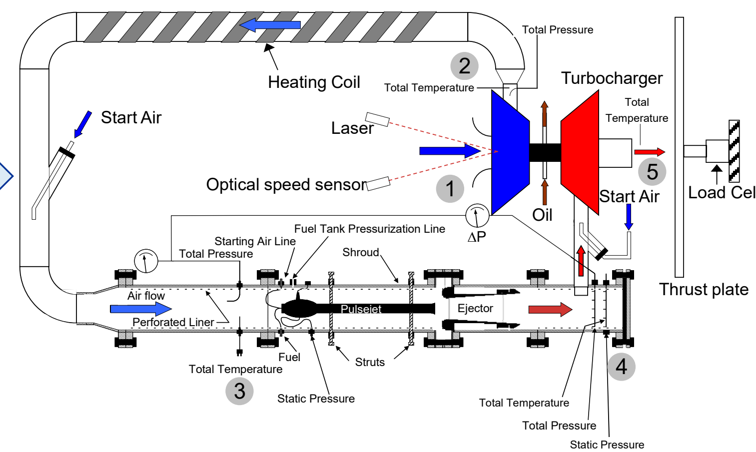
- Low effective equivalence ratios (i.e., limited T_{t4}) required
- RPC difficult to run lean
- Effective bypass strategies are needed

Pressure Gain in a Shrouded Configuration



- PR=1.037 @ TR=2.2
- rms p′/P=4.5% in the shroud
- Successful operation at 2 Atm. inlet pressure

Closed Loop Operation in a Gas Turbine

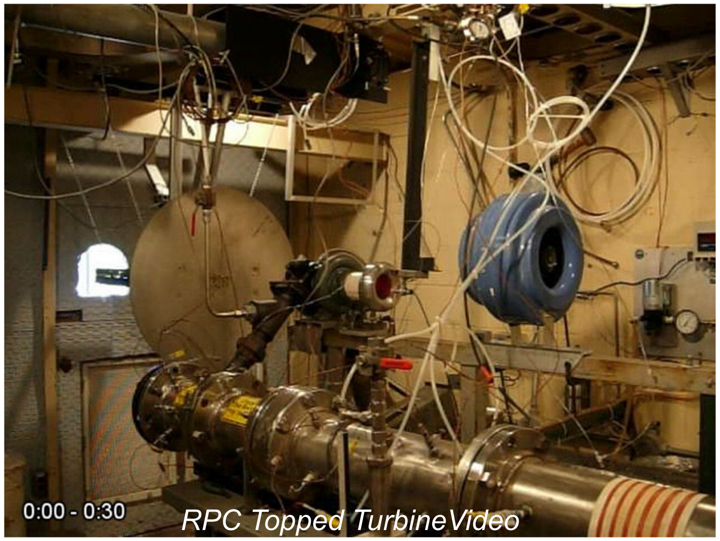


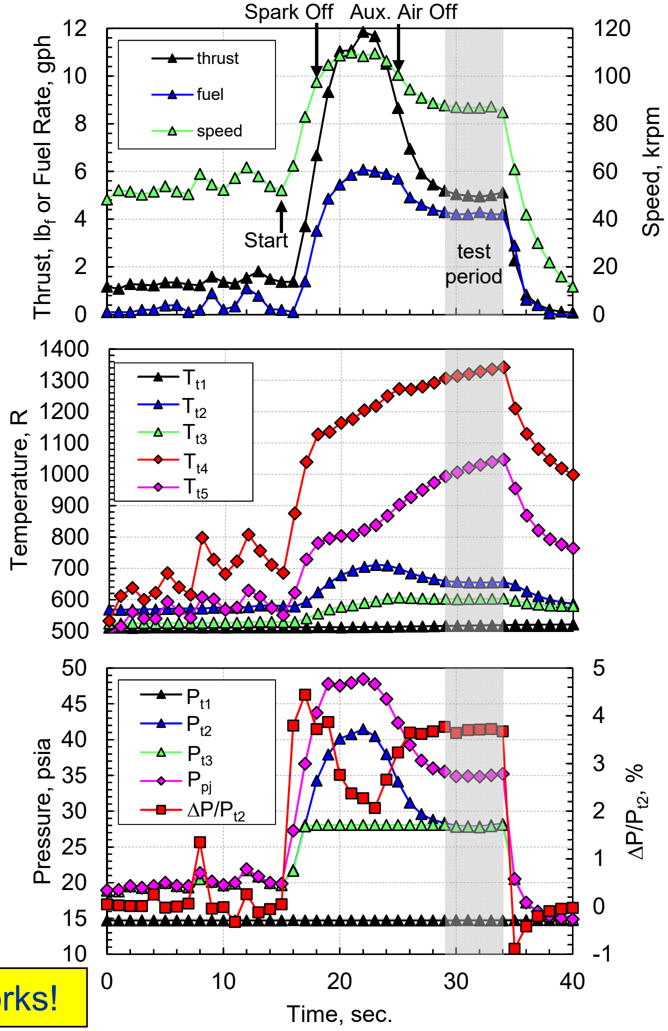
All Work Done With COTS Hobby Scale Pulse Combustor (Pulsejet)

Experimental Investigations

Results:

- True closed loop operation @ SLS
  - All air supplied by compressor
- $(P_{t4}/P_{t3} - 1)$=3.5% @ T_{t4}/T_{t3}=2.2
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine slows and stops with conventional combustor at same T_{Tin}/T_{Cout}
- -20 dB noise reduction across turbine stage
- 4% rms p'/P_{Cout} at turbine inlet





Without Qualification…It Works!

How Do We Make it Work Better? Numerical Modeling

Appropriate Approach Depends on What is Sought

Linear System:

- 0-Dimensional Electrical Circuit Analogy (including transmission line)
    - Operational frequency
    - Techniques for synchronizing 2 or more units

Computational Fluid Dynamics (CFD):

- Quasi-One-Dimensional
    - Operational frequency
    - Performance
    - Limited geometric optimization
- Two-Dimensional Axis-Symmetric
    - Operational frequency
    - Performance
    - Geometric optimization
    - Kinetics
    - Mixing
    - Ejector optimization (and coupling)
- Conjugate CFD & Mechanical
    - Everything above plus valve dynamics

Increasing Fidelity

Increasing Resources

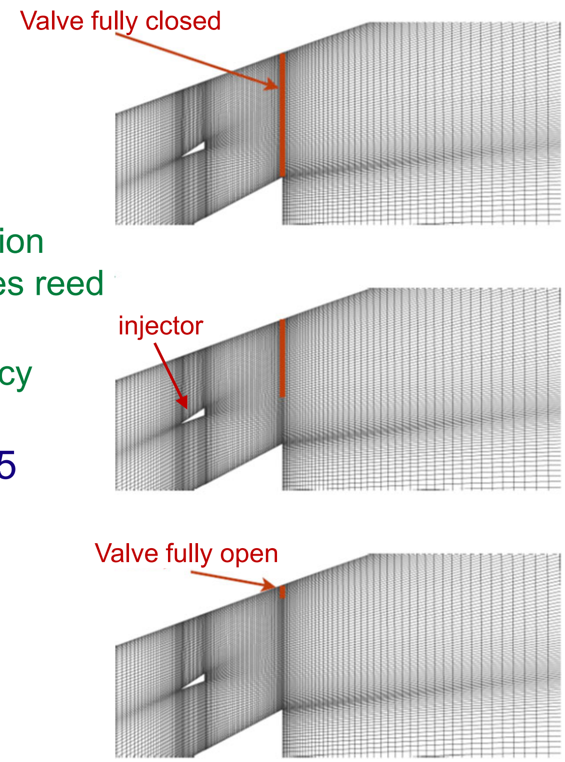
Several Recent Efforts Have Landed Here

Numerical Investigations

What Happens to RPC at Representative P_{t3}, T_{t3}?

Approach:

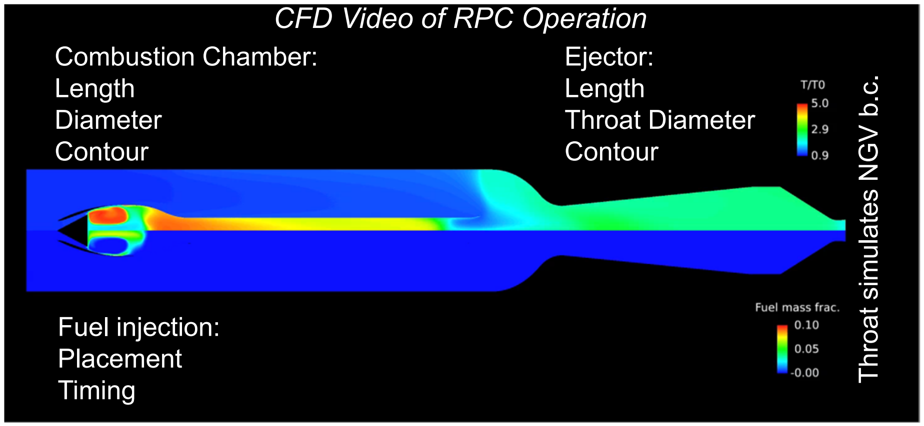
- Use in-house 2D axisymmetric CFD code
  - URANS with several turbulence models
  - Contains detailed chemical kinetics
  - Adiabatic
  - Gaseous Jet-A fueled
  - Successfully applied to PDE, RDE, and SCRAM combustion
  - Pressure actuated, prescribed motion slide valve simulates reed
- Validate on atmospheric tests of experimental RPC
  - Compare thrust, mass flow rate, pressure traces, frequency
- Run at 10 Atm., 990 R inlet conditions
- Optimize for maximum pressure gain at $T_{t4}/T_{t3} \approx 2.0\text{-}2.5$
  - Fuel injector location
  - Inlet geometry
  - Combustion chamber size
  - Combustor length
  - Ejector/mixer parameters (length, position, diameter)
- Monitor emissions
  - Seek lowest index with largest pressure gain
- Seek minimum size



CFD as Predictive Design Tool

Numerical Investigations

Results To Date



Inflow Vortex Motion is Key

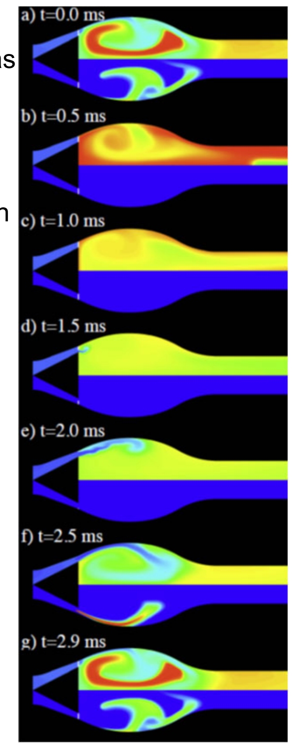
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

Self-ignition via residual hot gas

Rapid confined combustion

Expansion/acceleration

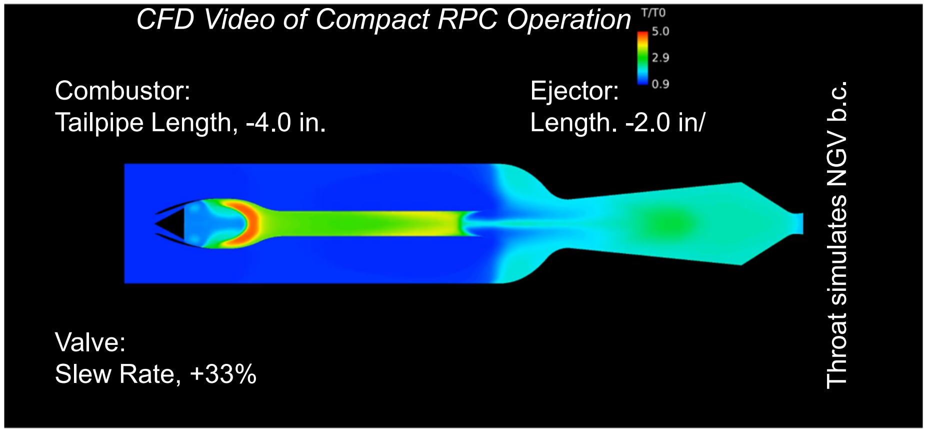
refill

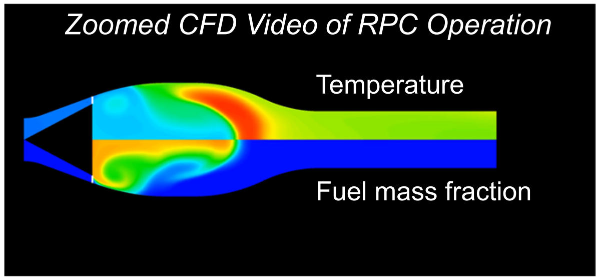


- Emission Index < 10 g_{NOX}/kg_{fuel}
  - Lower pressure gain configurations showed values below 1.0!
- $(P_{t4}/P_{t3} - 1)$=3.3% @ T_{t4}/T_{t3}=2.4
  - A large improvement considering T_{t3}=990 R
- Relatively benign station 4 conditions
  - 7% rms p'/P_{t4}
  - 23% rms u'/u_4
  - 1.7% rms T'/T_{t4}

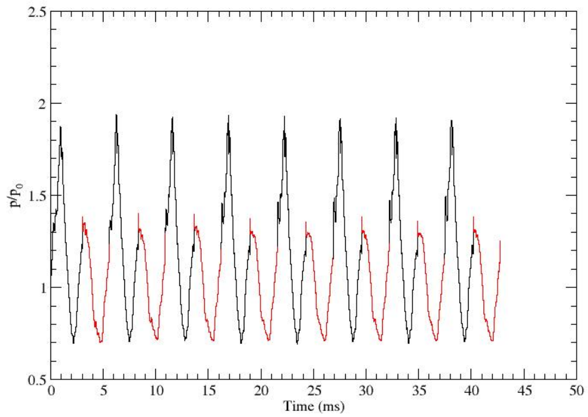
Numerical Investigations

Results To Date



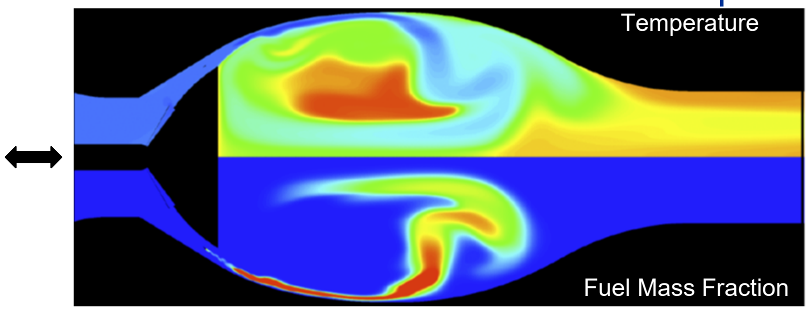


- Emission Index ≈ 13 g_{NOX}/kg_{fuel}
- $(P_{t4}/P_{t3} - 1)$=5.2% @ T_{t4}/T_{t3}=2.1
  - A large improvement
- Odd double period results
  - Large pulse followed by a smaller one
- Results indicate strong acoustic interactions with shroud



Ongoing and Future Directions

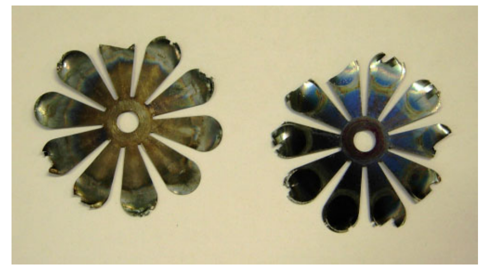
Alternative Valve Concepts



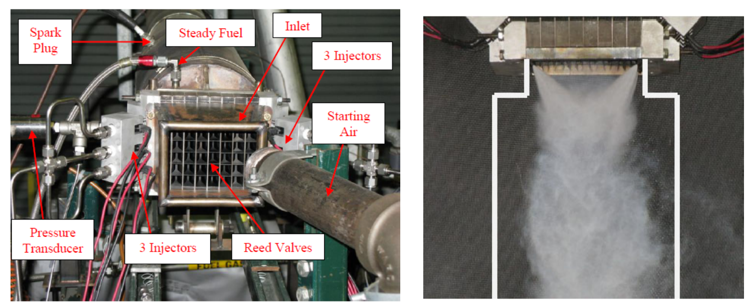
- Minimum length and diameter configuration
  - Computational
- Turbine interaction studies
  - Computational
- Active air and fuel valves
  - Still in planning stages
- High P_3, T_3 testing facilities
  - Still in planning stages
- Gas turbine engine integration studies
  - Aircraft GTE's are length constrained
- Turbine cooling air studies
  - Any PGC system for GTE's must deal with this

Life Extending Techniques for Existing Reed Valves

(Currently In testing in 2022)



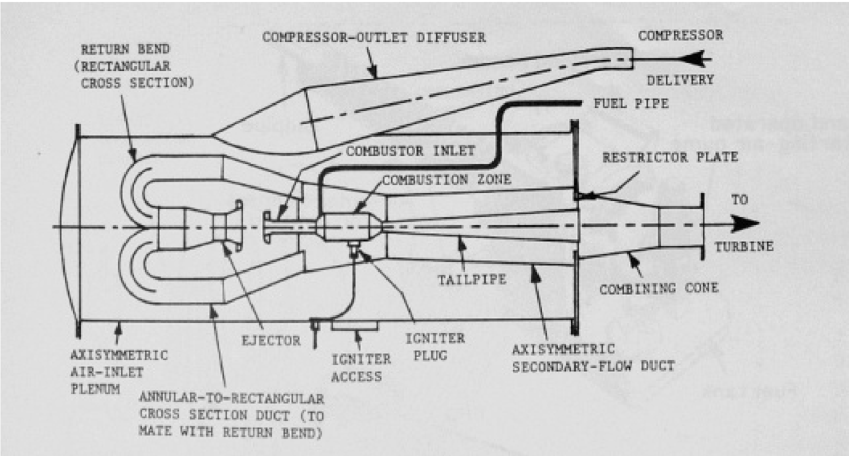
Active Fuel Modulation



AFRL/NASA - 2009

Related Work

Inspiration From the Past



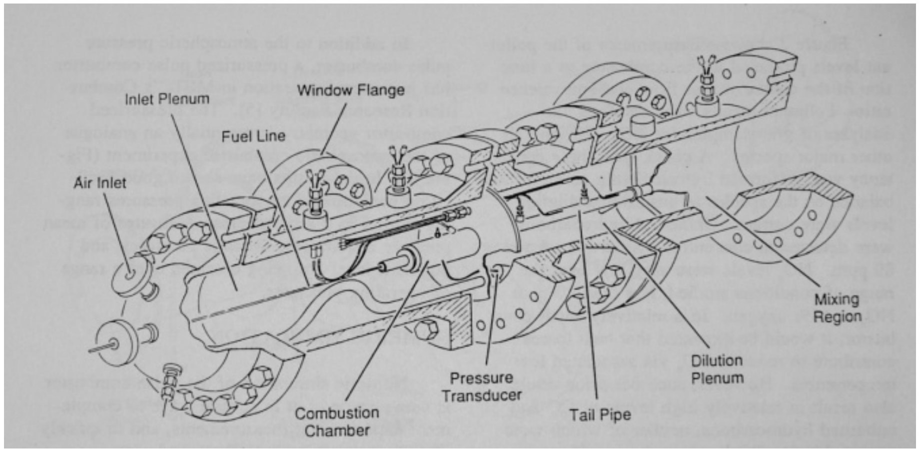
University of Calgary 1989

Excellent Reference!

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

Results:

- Achieved pressure gain
  - Using a valveless design
- Operated closed loop in a gas turbine



DOE National Energy Technology Laboratory, 1993

Gemmen, R.S., et. al., “Achieving Improved Cycle Efficiency Via Pressure Gain Combustors,” ASME 95-GT-63, June, 1995

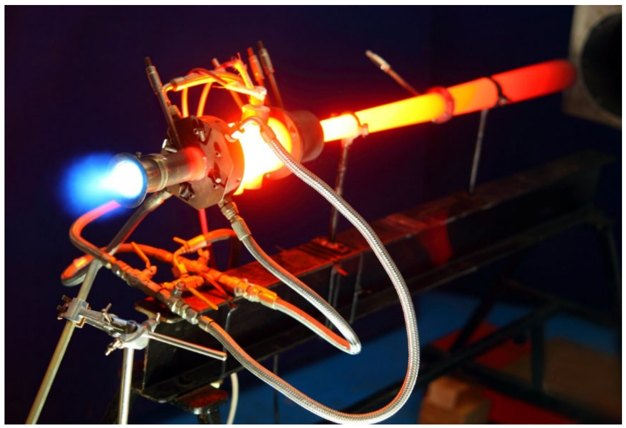
Results:

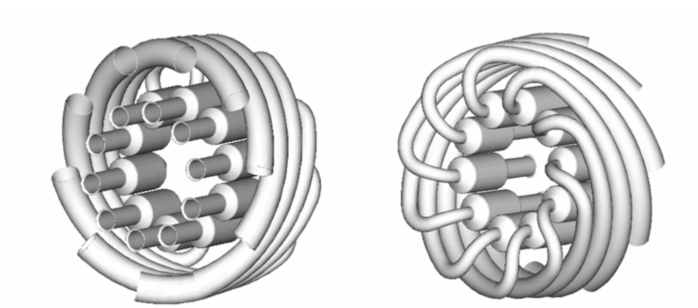
- Achieved pressure gain
  - Using a valveless design
- Operated at high P_{t3}, T_{t3}
- Achieved very low emissions

These Are Just Two of Many Significant Previous Efforts

Recent Related Work

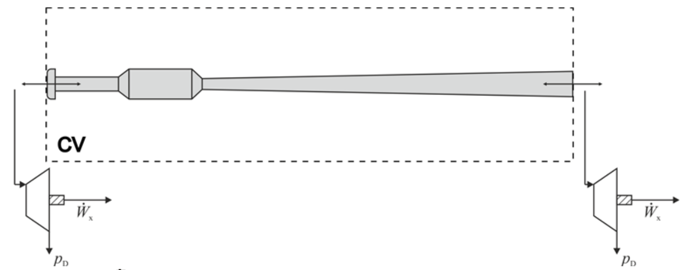
Images Courtesy of Whittle Laboratory and Rolls-Royce, Prof. Robert Miller

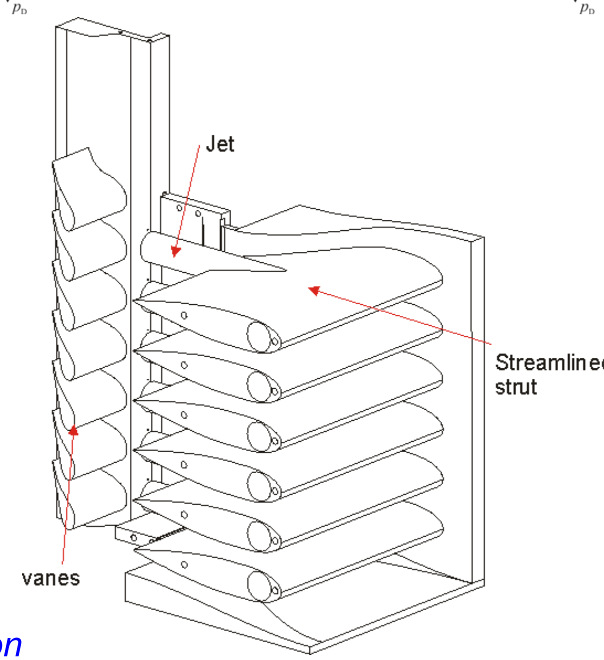




Aerovalved Configurations

- *Engine integration*
- *Defining and optimizing pressure gain*
- *Optimizing combustor/turbine interaction*





Current Related Work

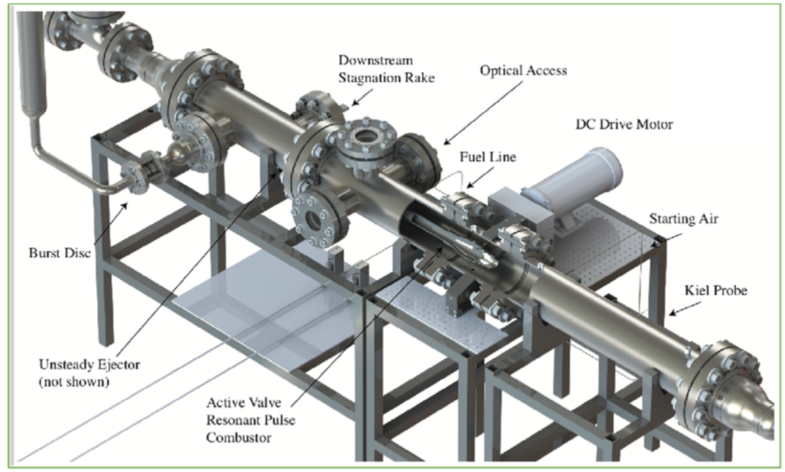
King Abdullah University of Science and Technology, Prof. William Roberts, PI

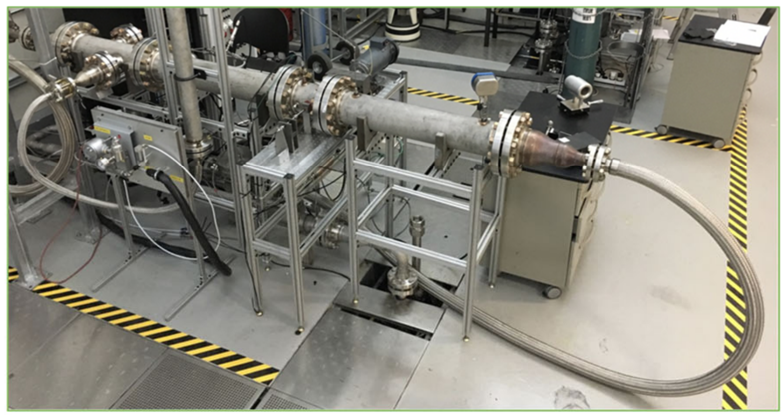
Motivation

- Resonant pulse combustors (RPC) have been widely employed in domestic and industrial heating applications.
- Replacing isobaric combustor with an RPC could significantly increase thermal efficiency.
- Deflagration-based RPC is much easier to integrate with gas turbine components than detonation-based combustor
- Traditional passively-valved RPCs suffer the very short operation durations.

Objectives

- Design a robust actively-valved RPC for very long operation duration
- Understand the stagnation pressure gain, operability, emission of actively-valved RPC operating at different pressures
- Understand the operational principle, stability characteristics, and other physics in the RPC..



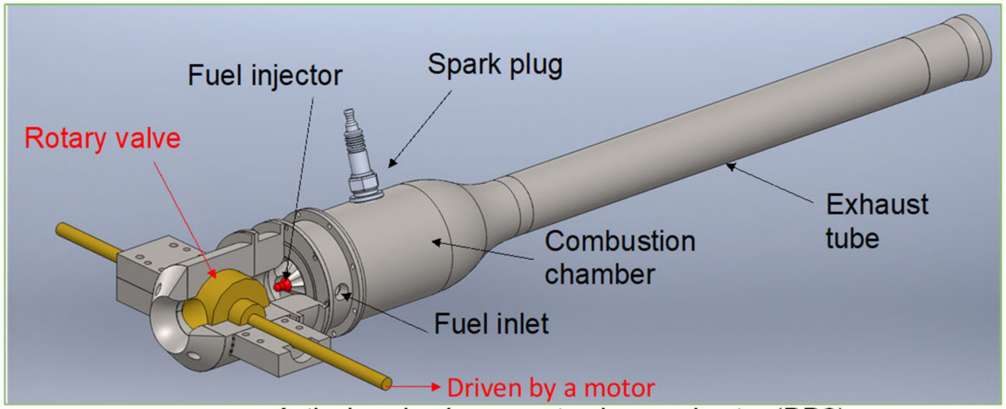


KAUST actively-valved RPC high-pressure test rig

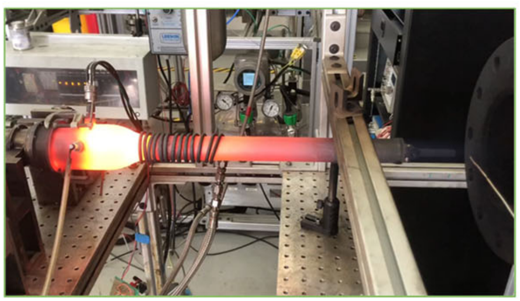
Current Related Work

King Abdullah University of Science and Technology, Prof. William Roberts, PI

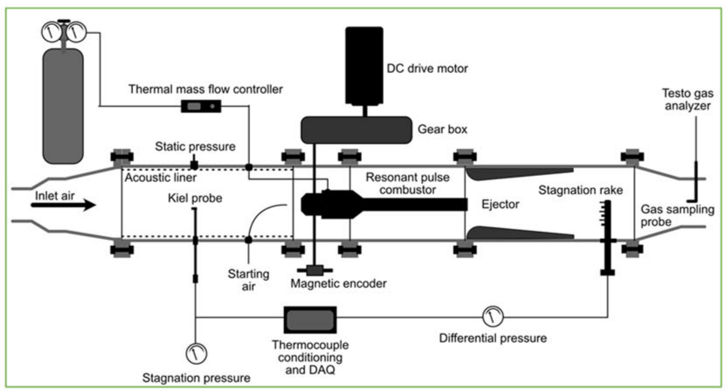
Actively-valved resonant pulse combustor (RPC) for pressure gain combustion



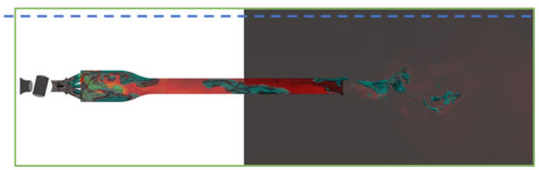
Actively-valved resonant pulse combustor (RPC)



Actively-valved RPC operating under atmospheric conditions



Schematic of the KAUST RPC high-pressure test system



High fidelity large eddy simulation:

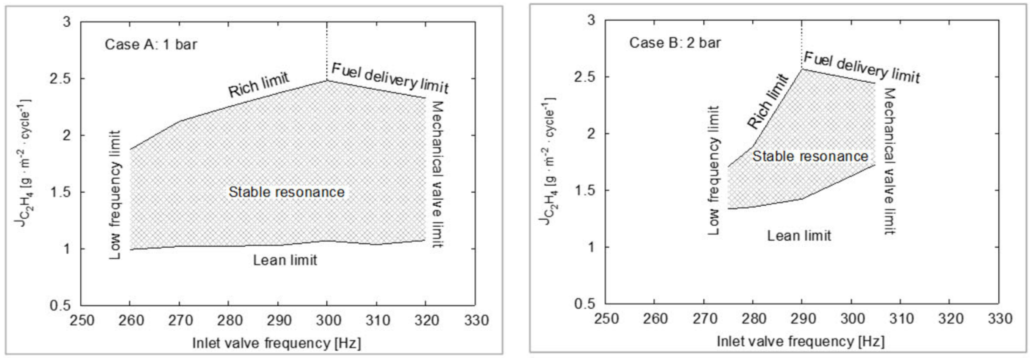
- OpenFOAM
- Moving mesh
- Compressible
- Acoustic/heat release
- Chemical reaction,
- Low dissipation numerical schemes, etc…

Current Related Work

King Abdullah University of Science and Technology, Prof. William Roberts, PI

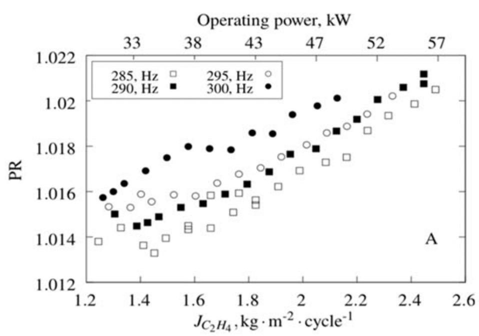
Results

- A novel actively-valved RPC was designed
- This novel RPC is robust enough to assure very long operation duration as well as broad operational range
- Meaningful stagnation pressure gain and low NOx was achieved at different pressures
- Stability characteristics was quantified with a PSD ratio, which can be used for early prediction of blowoff

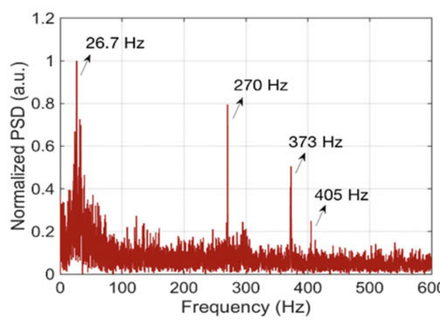


Stability envelope of the RPC under different pressures

Out-shroud

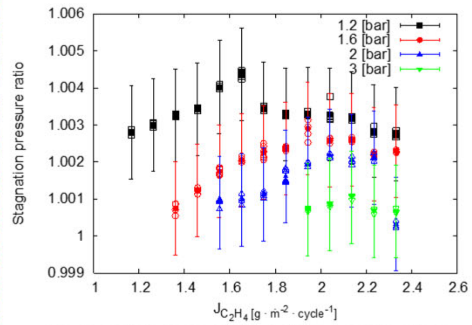


Pressure ratio (PR) as a function of ethylene flow rate

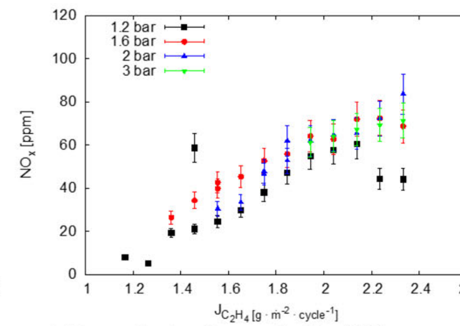


Power spectrum density (PSD) at near blowoff condition

In-shroud



Stagnation pressure gain as a function of ethylene flow rate at different pressures

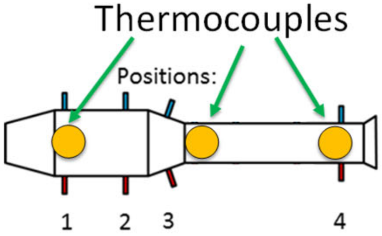


NOx emission (corrected to15% oxygen) as a function of ethylene flow rate at different pressure

Current Related Work

University of Cincinnati, Profs. E. Gutmark and V. Anand, PI's

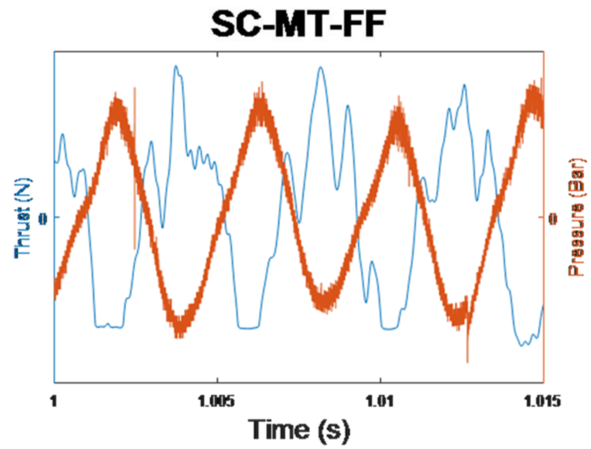
Effects of Geometric Parameters on Performance



- Instrumentation
  - 4 PCBs
  - 4 Ion Probes
  - 3 Thermocouples
  - 1 Load cell

Variables:

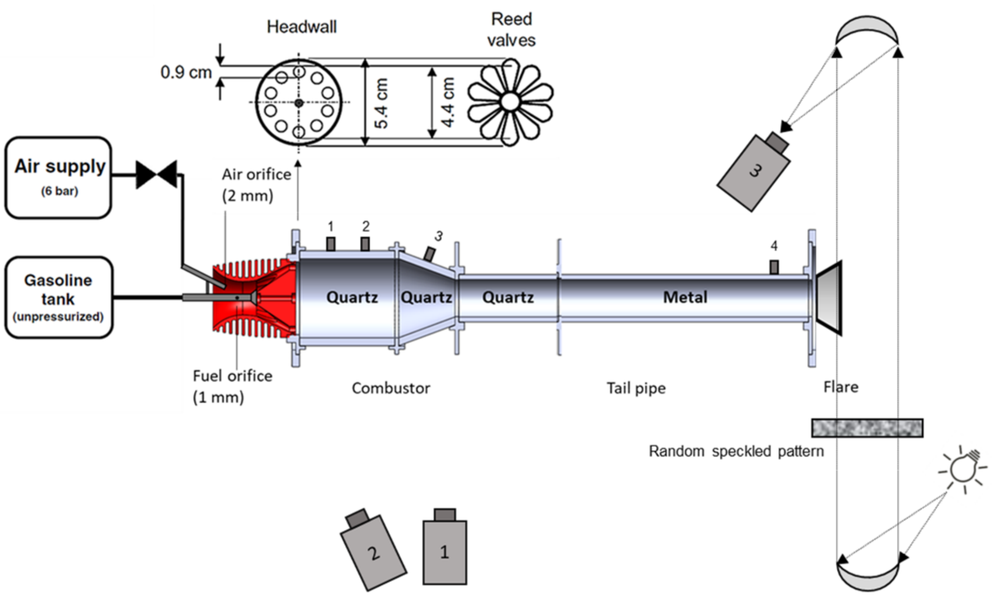
- Combustor Length (diameter = 5.9 cm)
  - Short (SC) = 13.1 cm
  - Long (LC) = 15.7 cm
- Tail Pipe Length (diameter = 2.7 cm)
  - Short (ST) = 25.4 cm
  - Medium (MT) = 40.7 cm
  - Long (LT) = 56 cm
- End Flare (3 cm)
  - On (FN)
  - Off (FF)

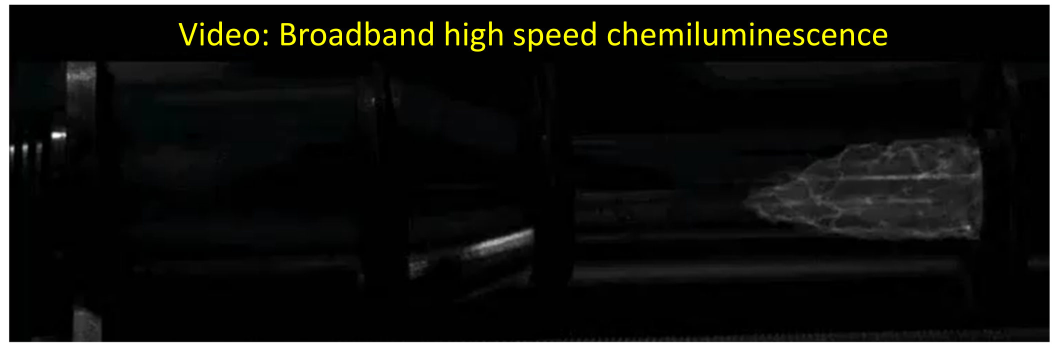


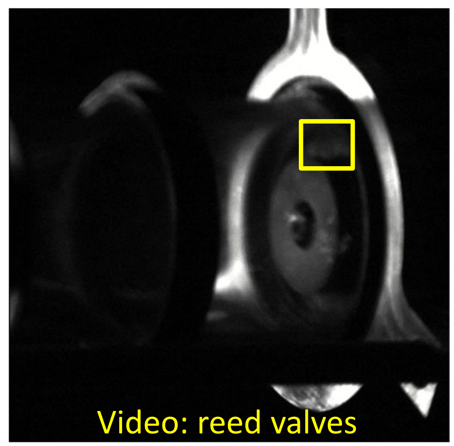
Current Related Work

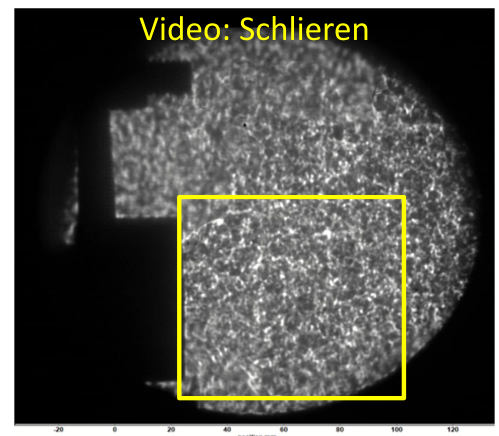
University of Cincinnati, Profs. E. Gutmark and V. Anand, PI's

Experimental Flow Visualization









Concluding Remarks

Resonant Pulse Combustion (RPC):

- Represents a promising approach for achieving practical Pressure Gain Combustion (PGC)
- Has features which are well suited for gas turbine applications
  - Relatively low unsteadiness
  - Demonstrated approaches to achieving requisite overall lean operation
  - Few moving parts
  - Relatively low thermal and mechanical stresses
  - Self-sustaining
  - Low emissions potential
- Is a remarkably well-developed concept
  - Liquid fueled operation
  - Demonstrated pressure gain
  - Demonstrated benefit to gas turbines
- Has potential for high P_{t3}, T_{t3} operation
- Can be practically and accurately simulated using CFD
- Presents multiple opportunities for improvement and optimization that are achievable with current technology

PGC Through RPC Warrants Additional R&D

END