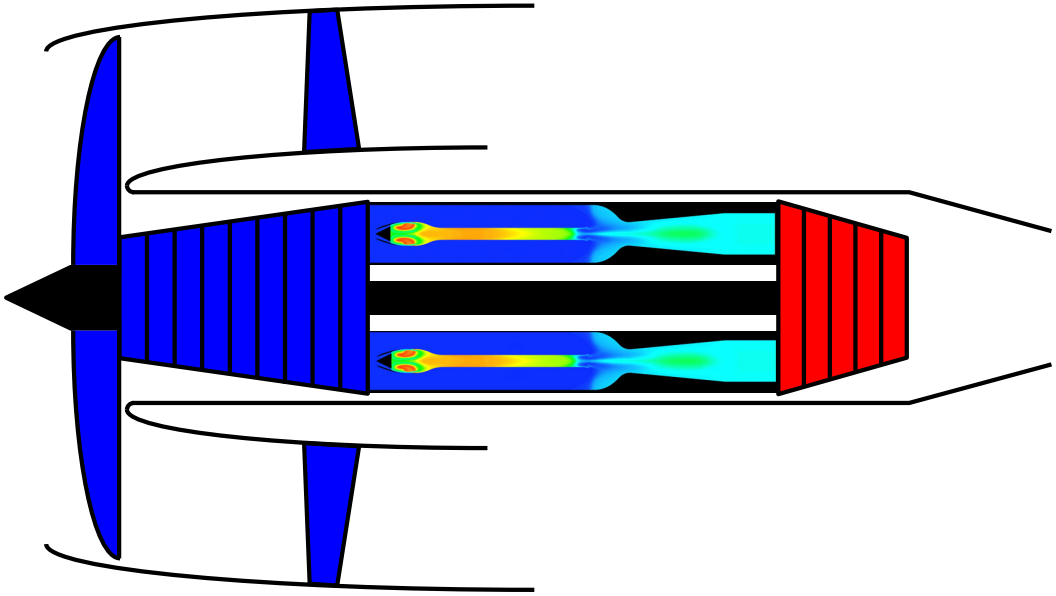


Resonant Pulse Combustors: A Reliable Route to Practical Pressure Gain Combustion

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

Active Flow and Combustion Control Conference 2018

Berlin, Germany
September 19-21, 2018

Acknowledgements

The NASA effort summarized in this presentation contains contributions from (and would not have been possible without) the following individuals

- Shaye Yungster (OAI) - CFD
- Doug Perkins (NASA) - Analysis
- Scott Jones (NASA) - Analysis
- Kevin Dougherty (SAIC) - Experiments
- Robert Pelaez (NASA) - Experiments
- Paul Litke (AFRL) - Experiments
- Andy Naples (ISSI) - Experiments
- Mark Wernet (NASA) - PIV
- Trevor John (Sierra) - PIV

Outline

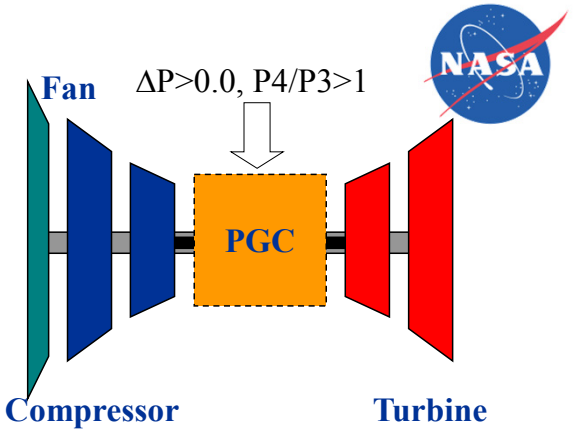
- Motivation
- Experimental Investigations
- Numerical Investigations
- Ongoing and Future Directions
- Related Work
- Concluding Remarks

Pressure Gain Combustion (PGC) Defined:

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.

Context:
Our Focus Is Not the Promotion of Any One PGC Mode
It Is the Practical Utilization of Confinement

Motivation

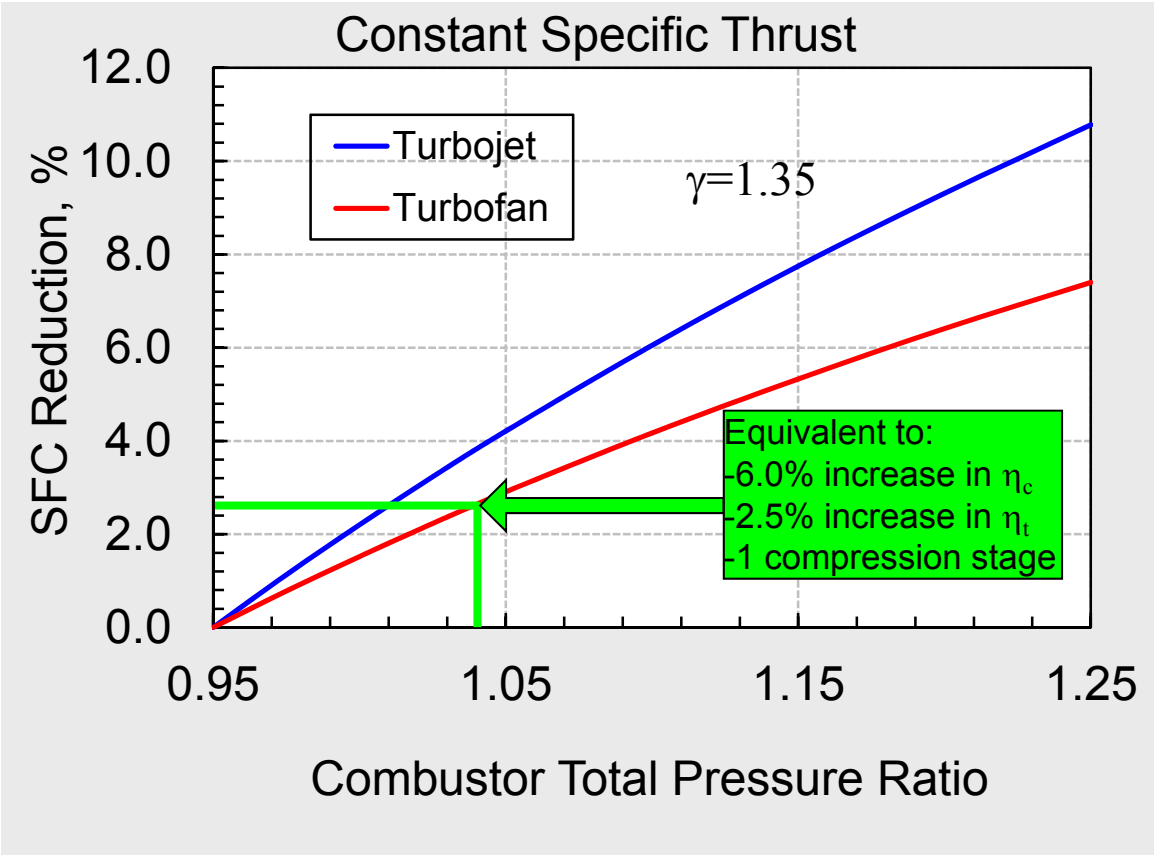


PGC for Gas Turbines

Two specific engines considered

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

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



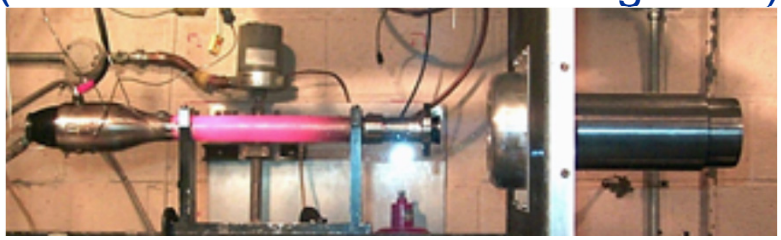
Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
$T_{combustor\ exit}$ (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

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
- 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

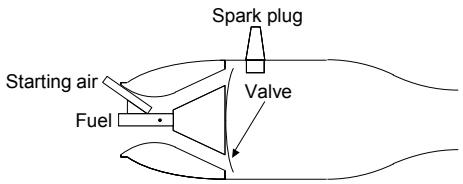
CAVEAT:

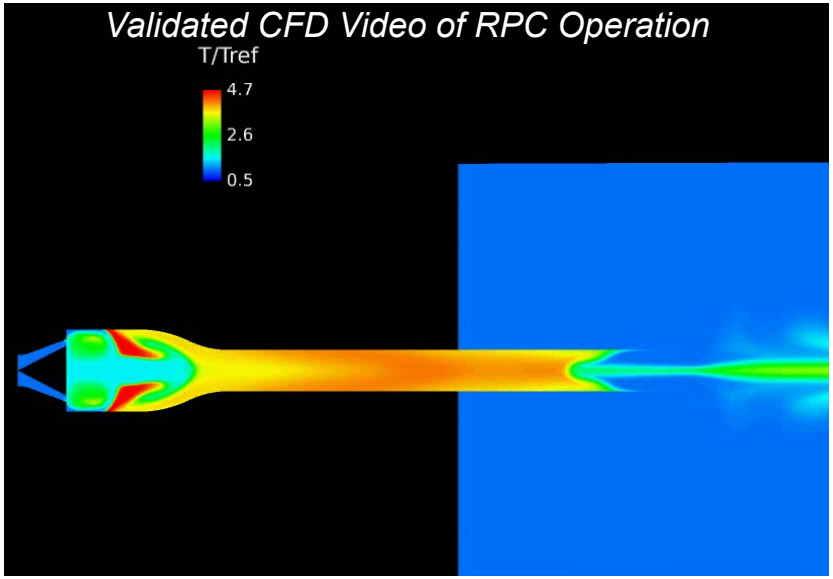
- Only Modest Pressure Gain is Possible
  - Confined (not constant) volume combustion

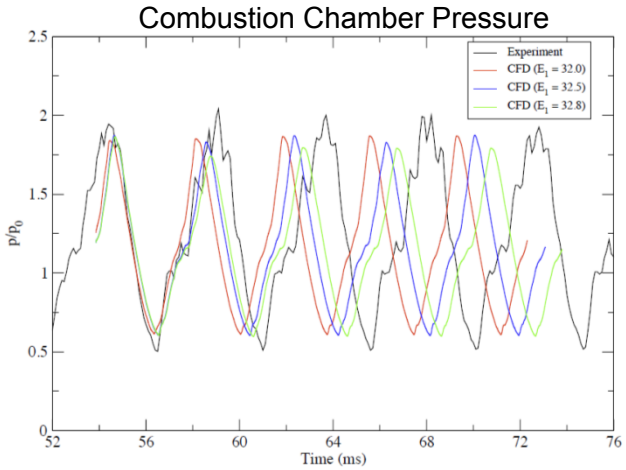
Practically: Features May Outweigh Caveat – Even Compared to Other PGC Approaches

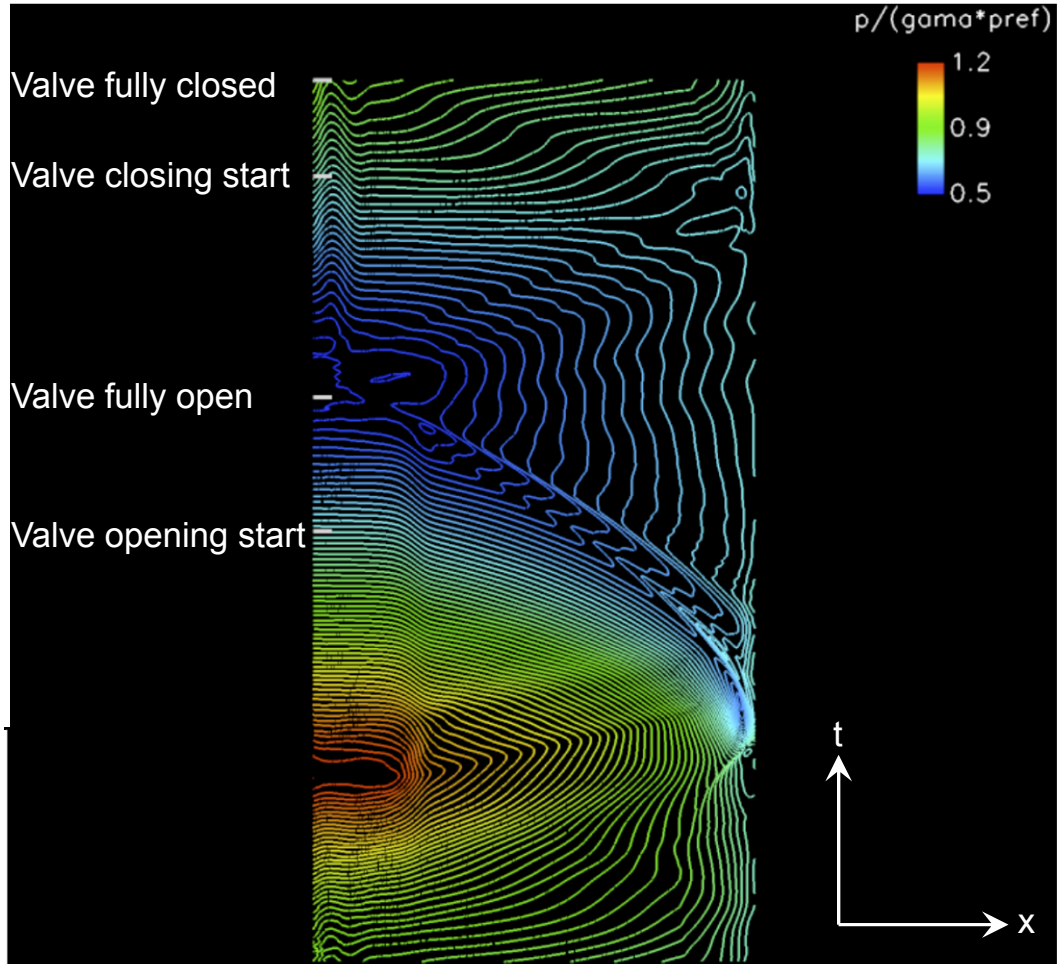
Motivation

Resonant Pulse Combustion Basic Cycle



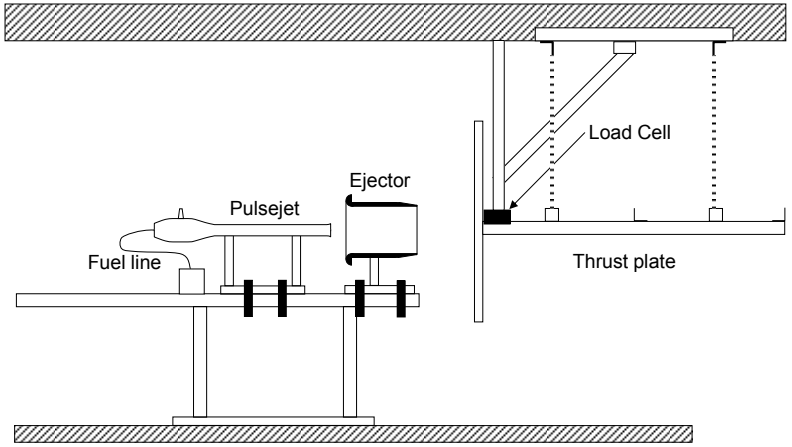




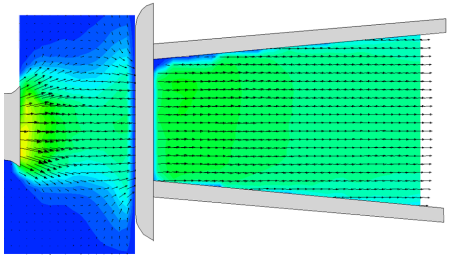


Experimental Investigations

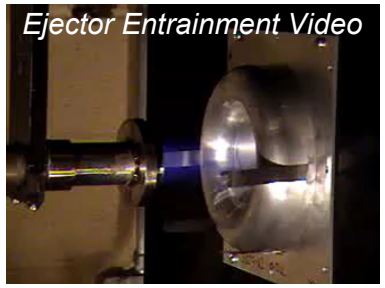
Ejector Mixing and Pumping Optimization



PIV Measured Flowfield Video

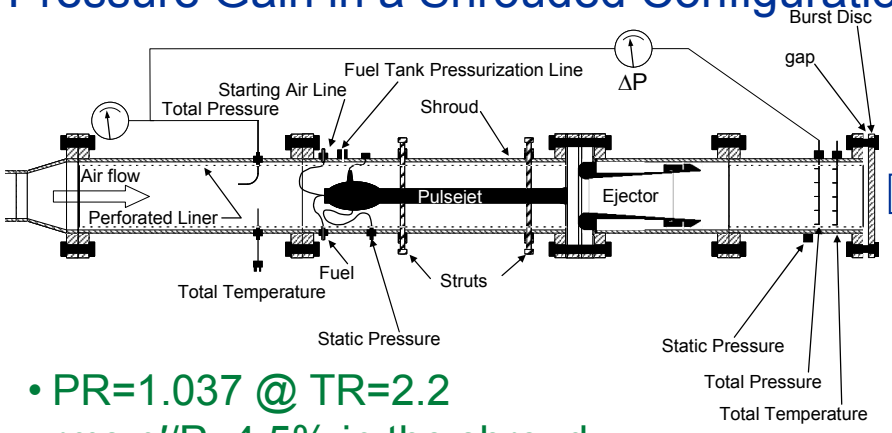


Ejector Entrainment Video



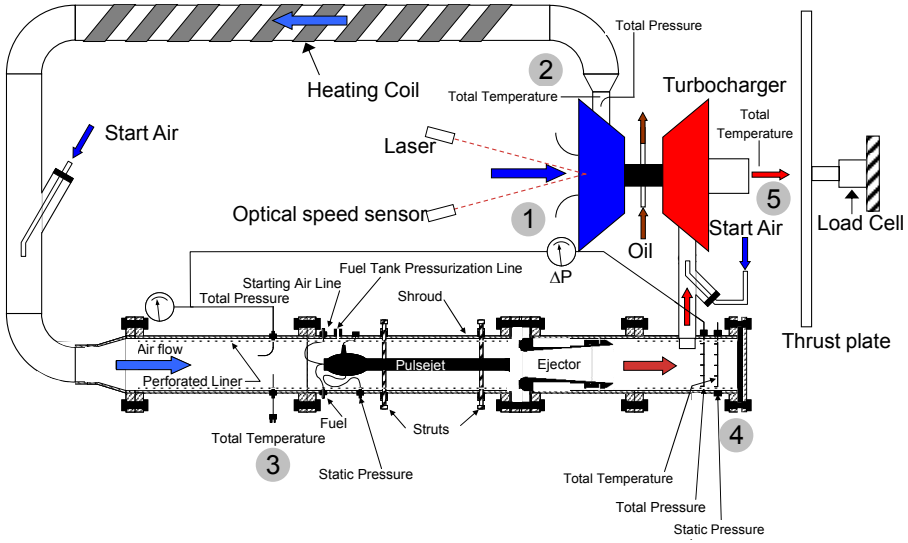
- 18:1 and greater entrainment ratios
- Thrust augmentation ratios up to 2.0
- Velocity fluctuations reduced by 83%

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

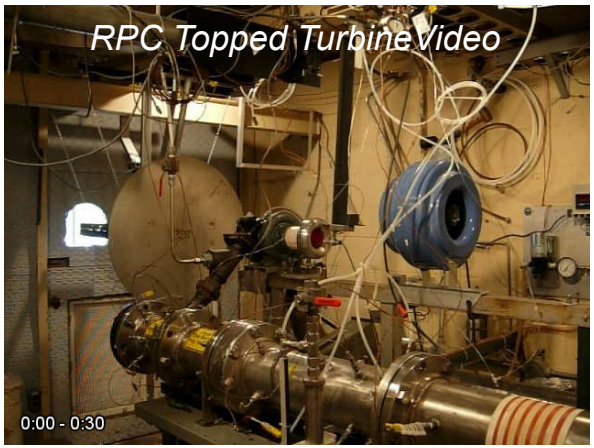


All Work Done With COTS Hobby Scale Pulse Combustor (Pulsejet)

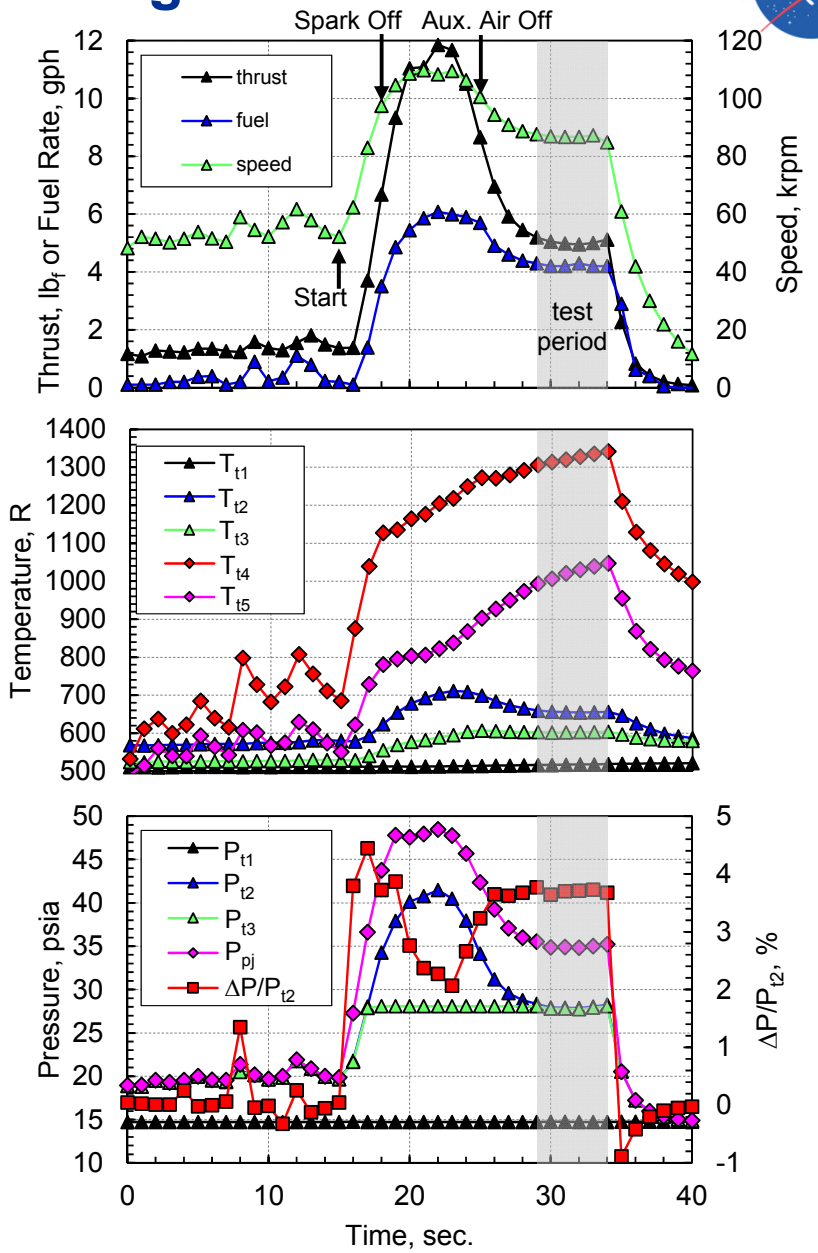
Experimental Investigations

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
- 4% rms p'/P_{Cout} at turbine inlet



Without Qualification…It Works!

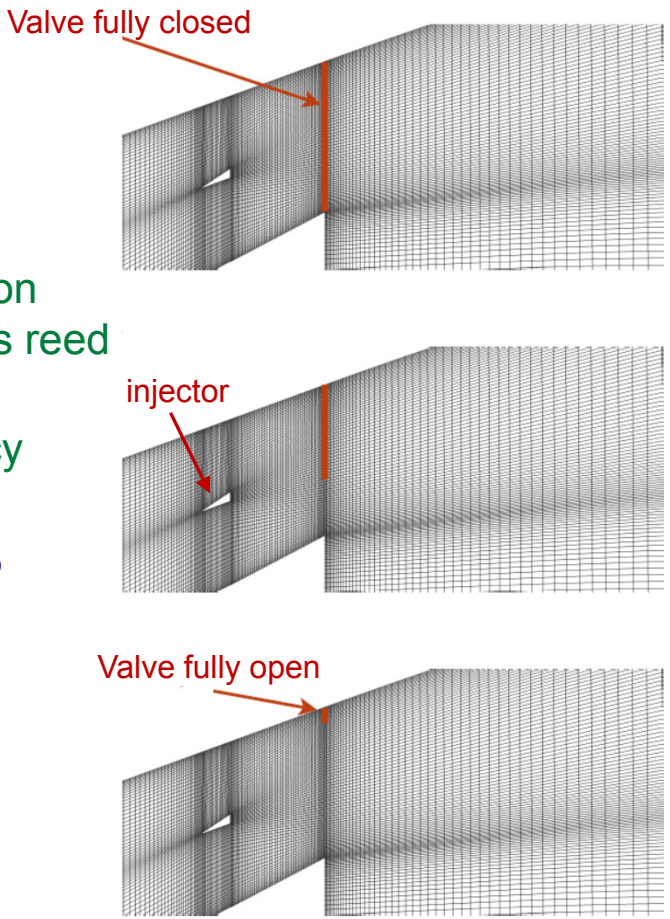


Numerical Investigations

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

Approach:

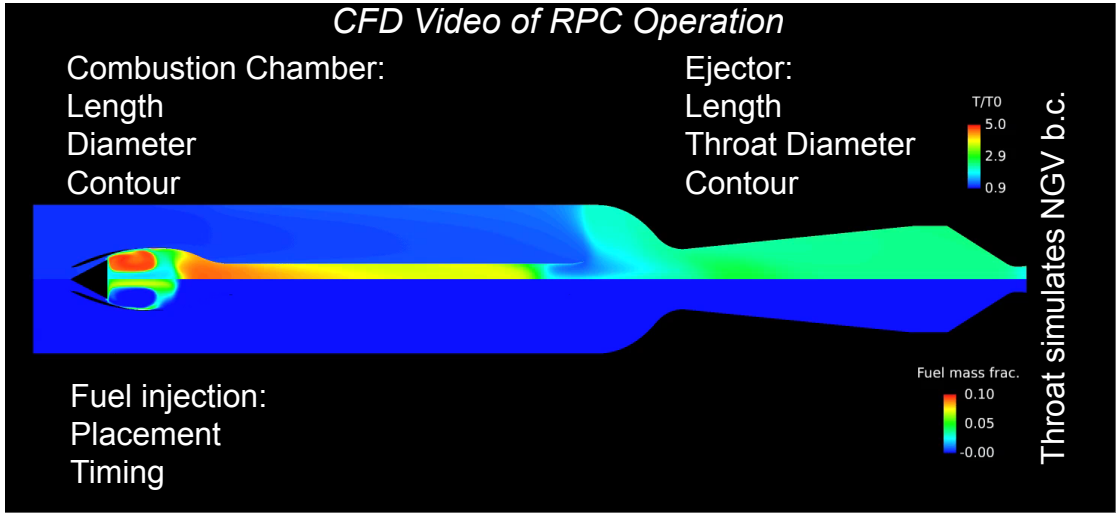
- Use in-house 2D axisymmetric CFD code
  - Turbulent
  - Contains detailed chemical kinetics
  - Adiabatic
  - Gaseous Jet-A fueled
  - Successfully applied to PDE, RDE, and SCRAM combustion
  - Pressure actuated, prescribed motion slide valve simulates reed
- Validate on atmospheric tests of experimental 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



- 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}

Inflow Vortex Motion is Key

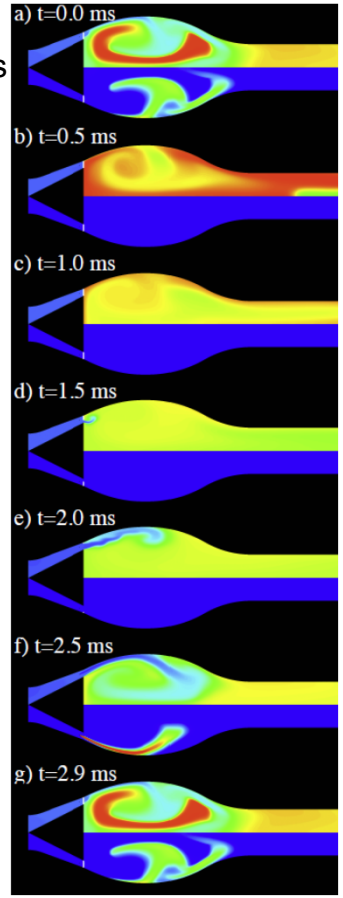
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

Self-ignition via residual hot gas

Rapid confined combustion

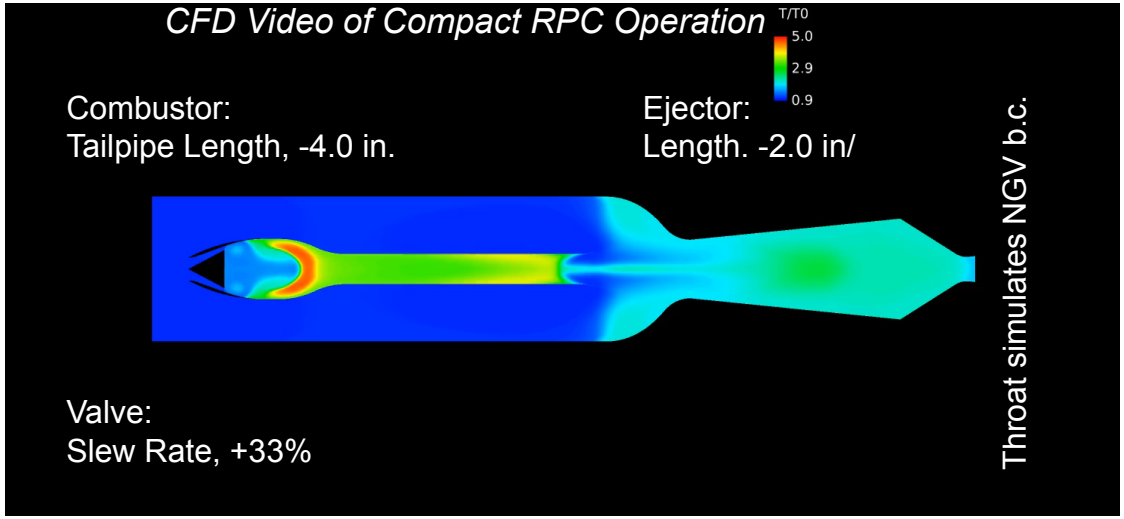
Expansion/acceleration

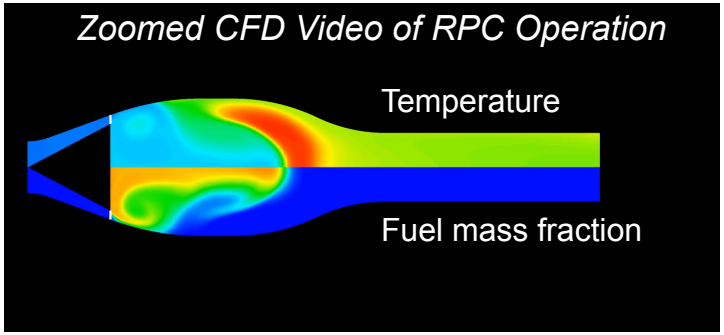
refill



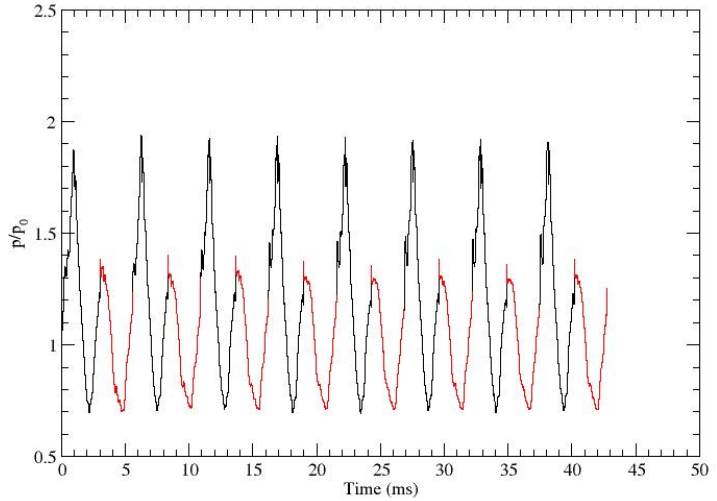
Numerical Investigations

Results To Date



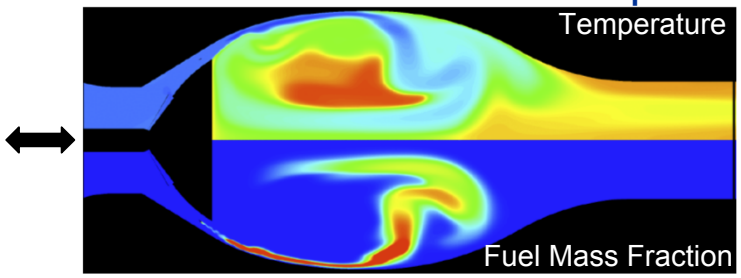


- Emission Index ≈ 13 g_{NOX}/kg_{fuel}
- $(P_{t4}/P_{t3} - 1)$=5.2% @ T_{t4}/T_{t3}=2.1
  - A large improvement
- Odd double period results
  - Large pulse followed by a smaller one
- Results indicate strong acoustic interactions with shroud

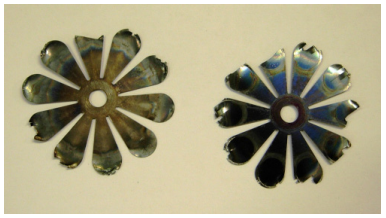


Ongoing and Future Directions

Alternative Valve Concepts

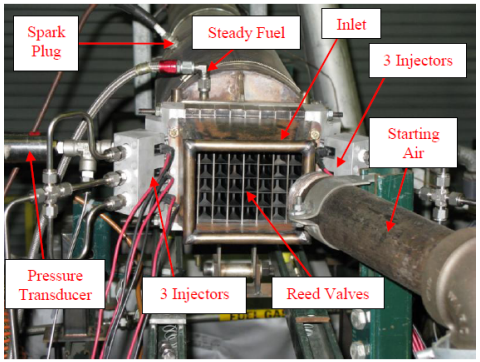


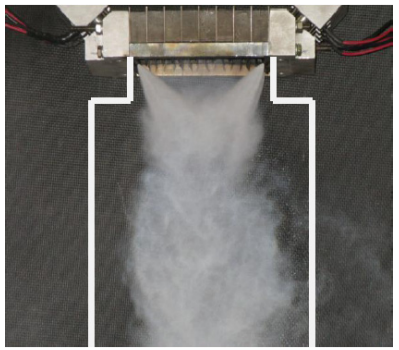
Life Extending Techniques for Existing Reed Valves



- 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

Active Fuel Modulation

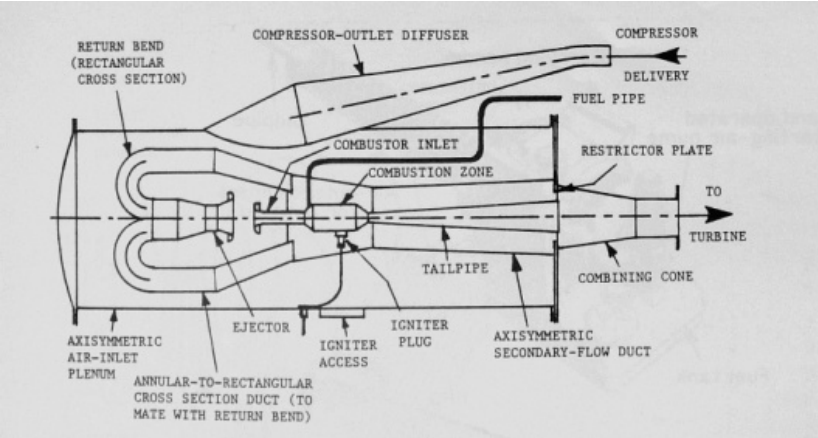




AFRL/NASA - 2009

Related Work

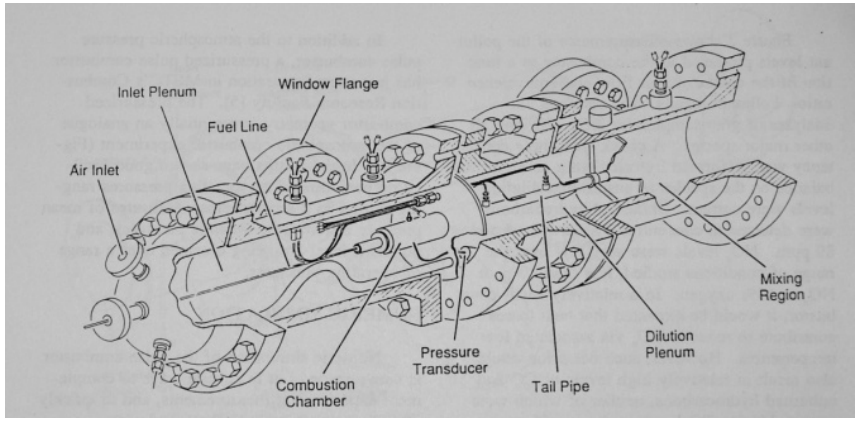
Inspiration From the Past



University of Calgary 1989
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

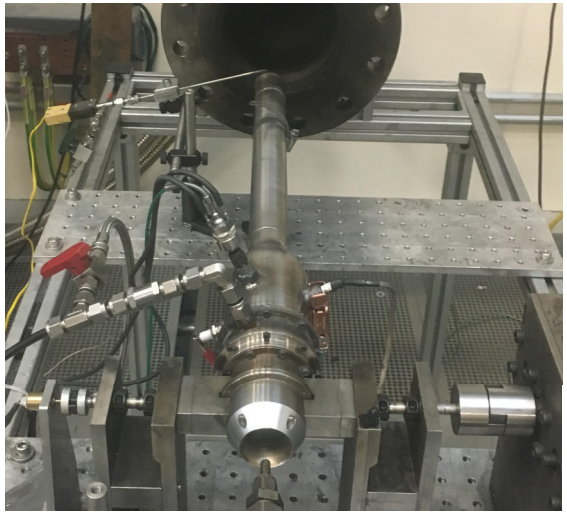
Results:

- 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

Current Related Work

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

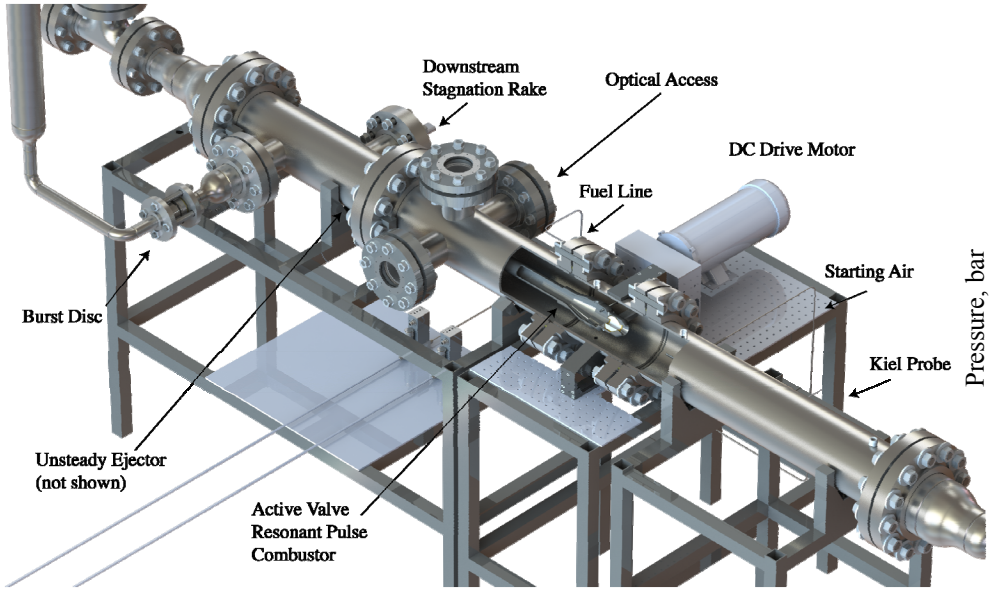


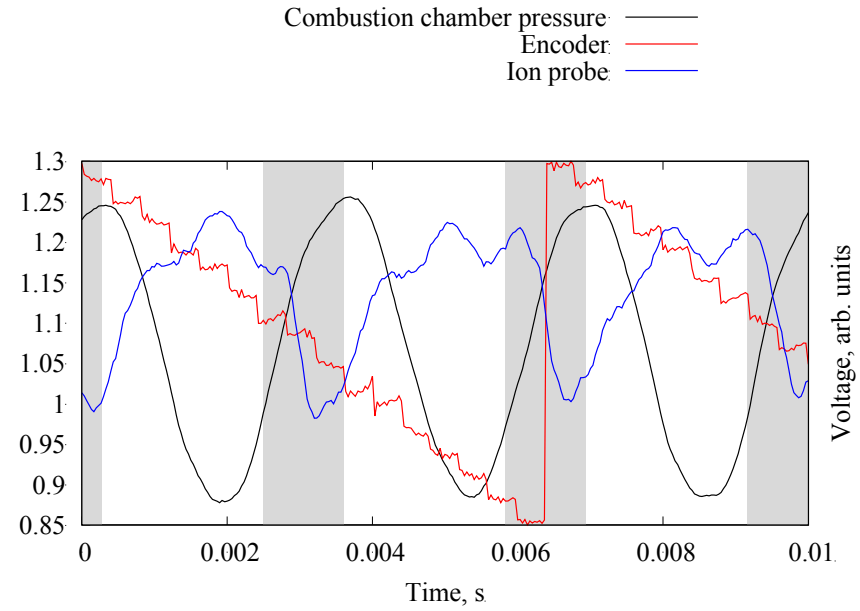
Active Air Valve System

- *Successful self-sustained, self-aspirated operation*
- *Successful operation for long periods*

Shrouded High Pressure Test Bed

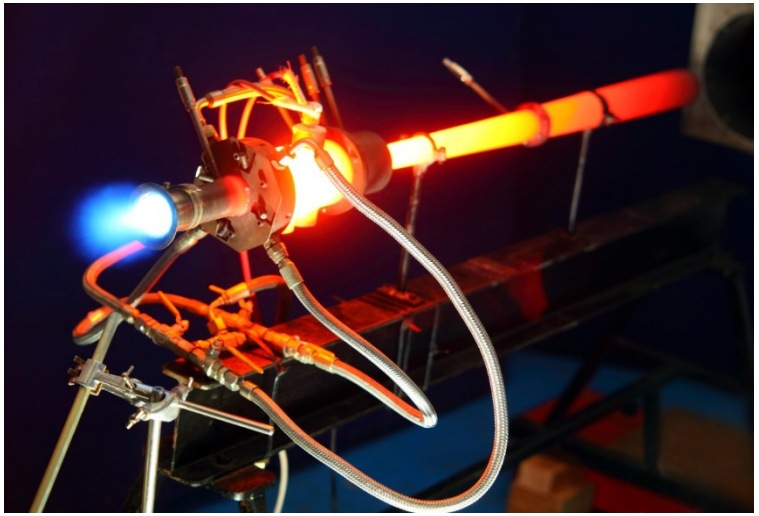
- *Heated air*
- *Extensive diagnostics*

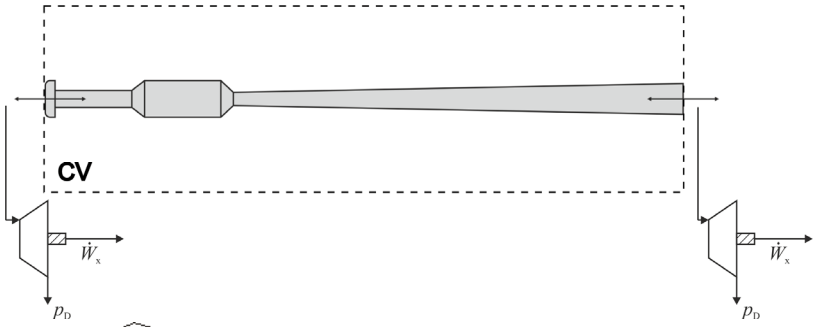


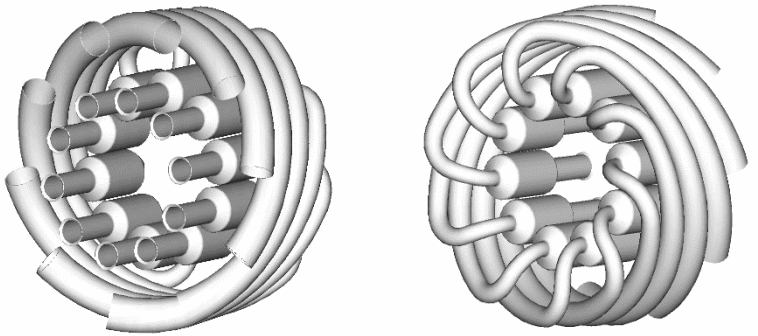


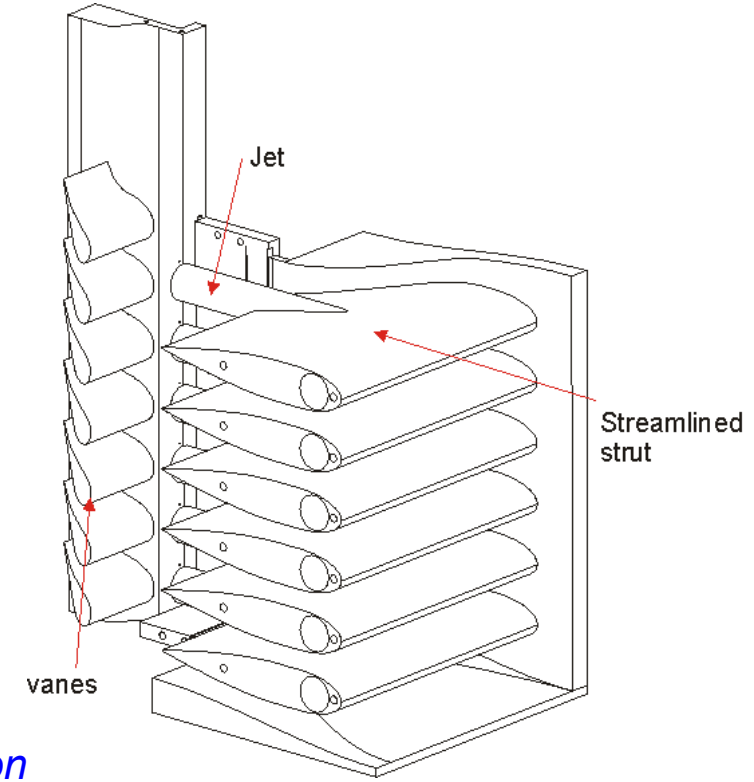
Current Related Work

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









Aerovalved Configurations

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

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
- Presents multiple opportunities for improvement and optimization that are achievable with current technology

RPC Could Be the Gateway to Making PGC Mainstream

END