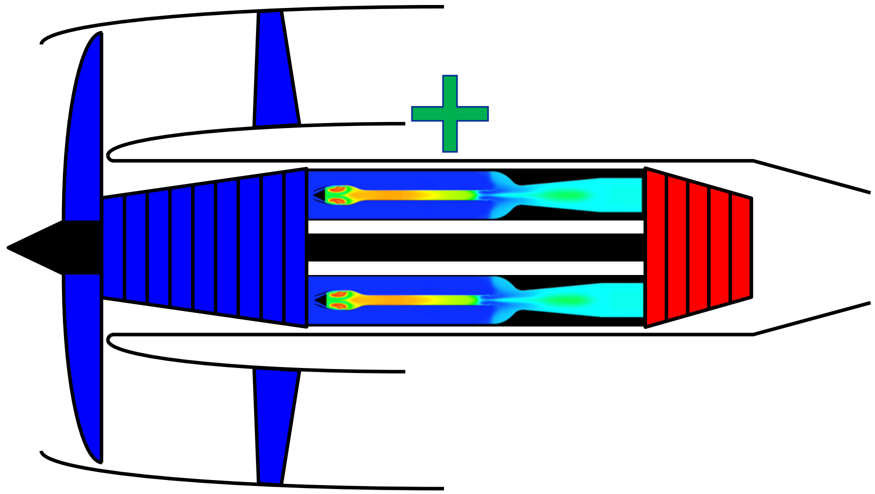


Pressure-Gain Combustion for Gas Turbines

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

INSPIRE Capstone Symposium
September 26-27, 2024
Florence, Italy

Outline

- Motivation/Background
- Quantitative Benefit Examples
- Approaches to Implementation (How It’s Done)
- Technology Challenges
- Closing Remarks

Some Preliminary Facts

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

The U.S. Consumes (Converts) **93,590,000,000,000,000** BTU of Energy Each Year

- *83% from fossil fuels (petroleum, natural gas, coal)*
- *74% from petroleum and natural gas*

Resulting Issues

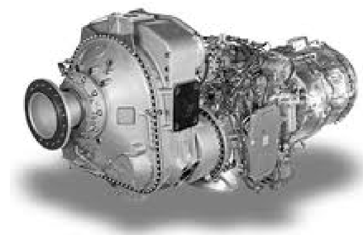
- *Pollution*
- *Climate Change*

The Response

- *Alternative fuels (biomass, etc.)-5% of total converted*
- *Alternative conversion systems (wind, solar, hydro, etc.)-4% of total converted*
- *Conservation/* ***EFFICIENCY*** *(use less)*

Equivalent to 5.6 gallons of gasoline used by every U.S. citizen EVERY DAY!

Pressure Gain Combustion Is All About This Response



Gas Turbines Constitute an Astonishing 17% of Energy Conversion

- *3.4% from aviation*
- *13.4% from power generation (and growing as coal plants are replaced with combined cycle plants)*

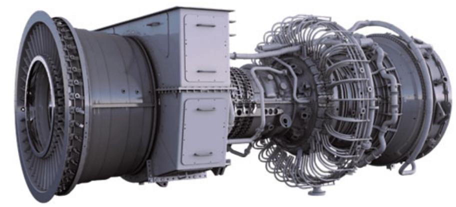
A mere **1%** Improvement in thermodynamic efficiency saves as much energy as increasing our commercial wind turbine output by **17%**.

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

Furthermore

Our Most Ambitious Carbon-Free or Carbon-Neutral Goals Envision:

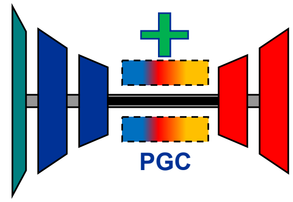
- *Hydrogen fueled gas turbines for power generation*
  Hydrogen fuel is a good way to store excess solar and wind energy



- *Sustainable Aviation Fuels (SAF) in commercial aircraft gas turbines*
- *Hybrid electric commercial aircraft with gas turbine cores*

- *Hydrogen fueled commercial aircraft with gas turbine engines*

Bottom Line:
Gas Turbines Remain Critical to Our Green Future
High Efficiency is Essential



Pressure Gain Combustion is Part of the Solution

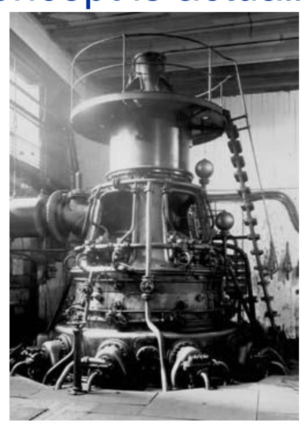
PGC†: A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure.*

†The term "Pressure-Gain Combustion" is credited here to the late J.A.C. Kentfield

*Conventional combustion incurs a total pressure loss

The concept is actually old…

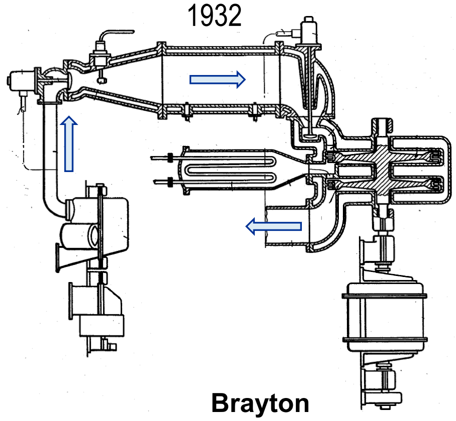
Holzwarth Explosion Turbine 1914



The Implementation Approaches, Analysis Tools, and Design Capabilities Are New

Fundamental Thermodynamics: A Review

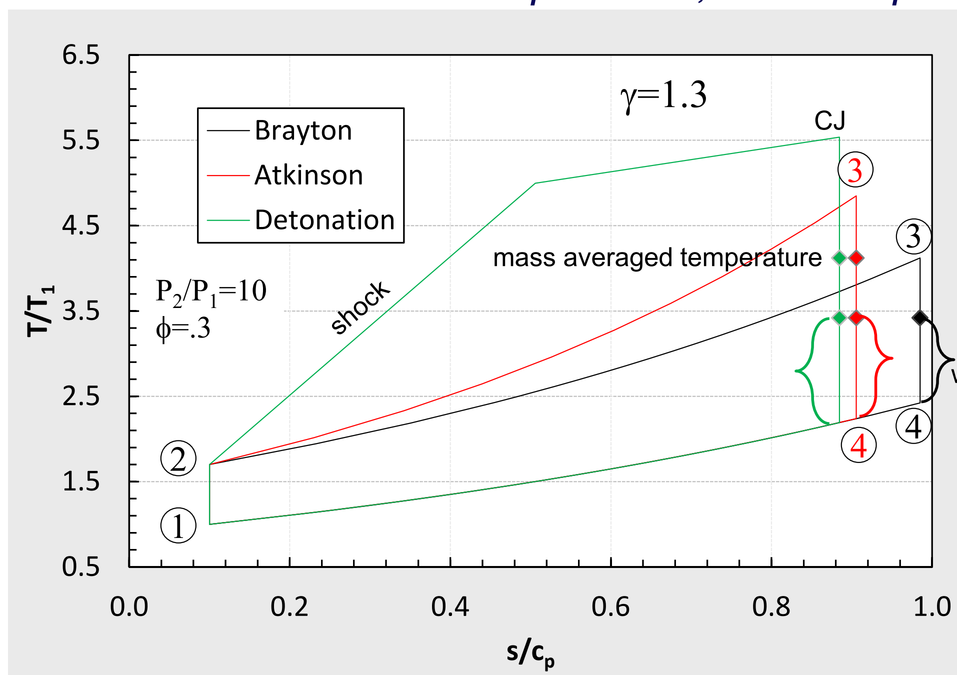
Explosion Turbine (Holzwarth)
1932



Brayton
1-2: Isentropic (adiabatic) Compression
2-3: Isobaric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

Atkinson
1-2: Isentropic (adiabatic) Compression
2-3: Isochoric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

Identical Mechanical Compression,& Heat Input

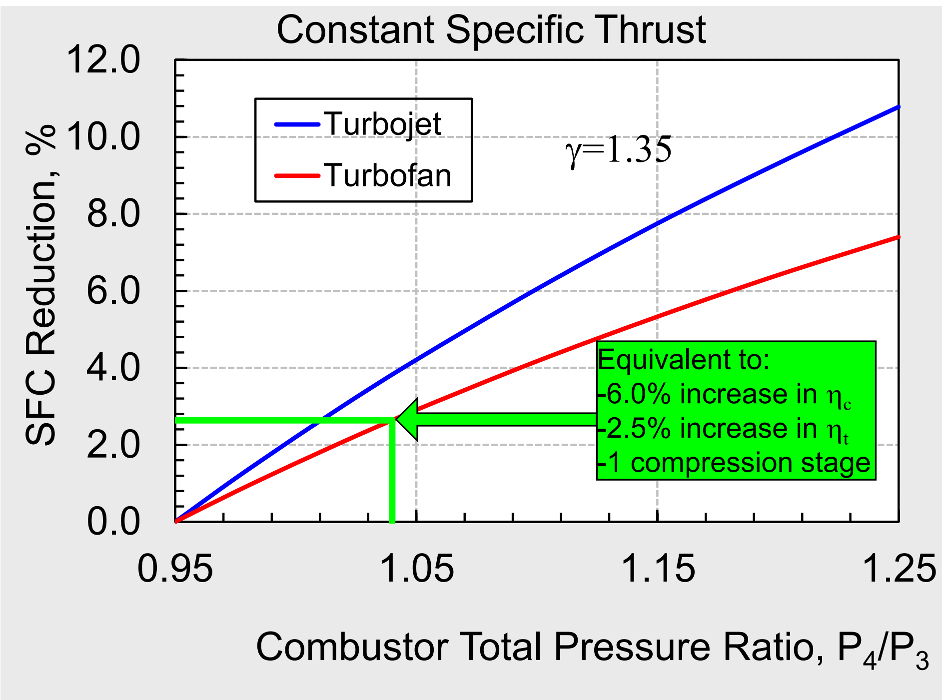


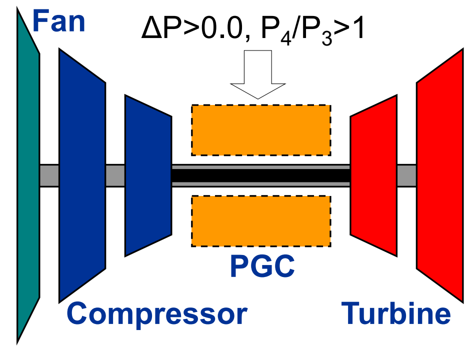
- PGC expands by gasdynamic conversion to kinetic energy (e.g. blowdown)
- Flow to turbine is fundamentally unsteady, and/or spatially non-uniform

Quantitative Benefits

Pressure Gain Combustion __Theoretically__:

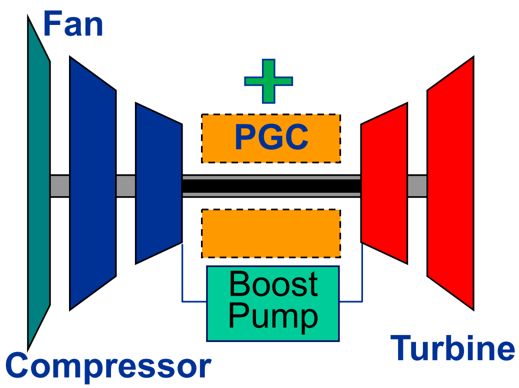
+Increases thermodynamic cycle efficiency
+Reduces SFC / fuel burn
+Reduces CO_2 gas emissions
+Competes with conventional cycle improvements



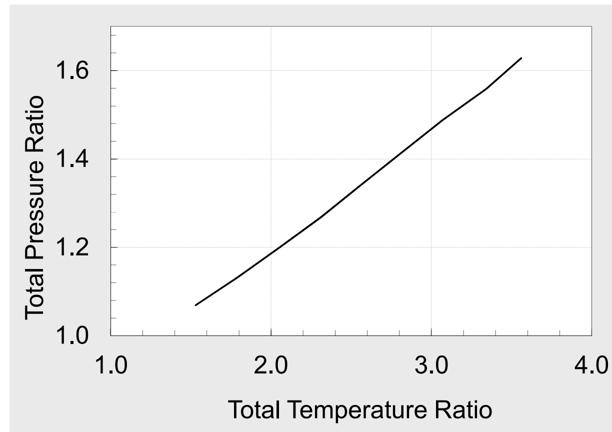


Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
T_{t4} (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

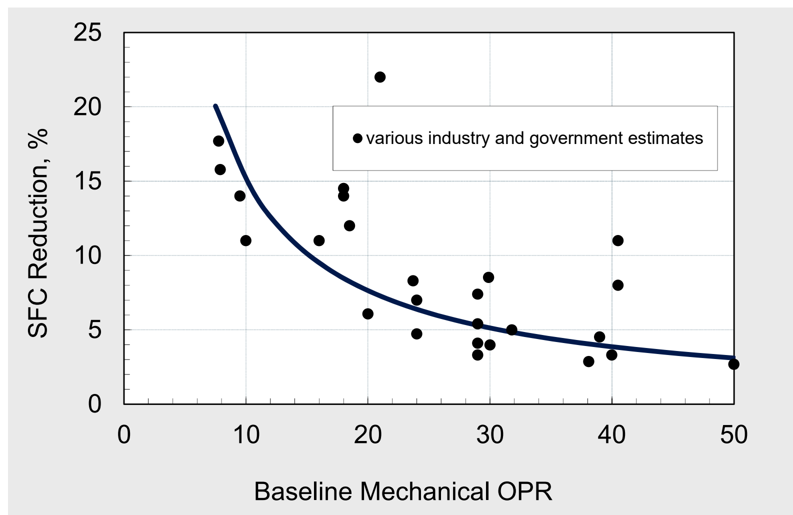
More Quantitative Benefits



Example Modeled PGC Component Performance



- PGC component modeled by various methods
  - Typically assumed detonative or constant volume combustion
  - Temperature ratio indicates fuel added
  - Pressure ratio represents performance
  - Varied loss assumptions
- Results With Engine Cycle Decks Show Promise:
  - Non-ideal turbomachinery
  - Turbomachinery cooling air boost pump added.



These Are Large Reductions!

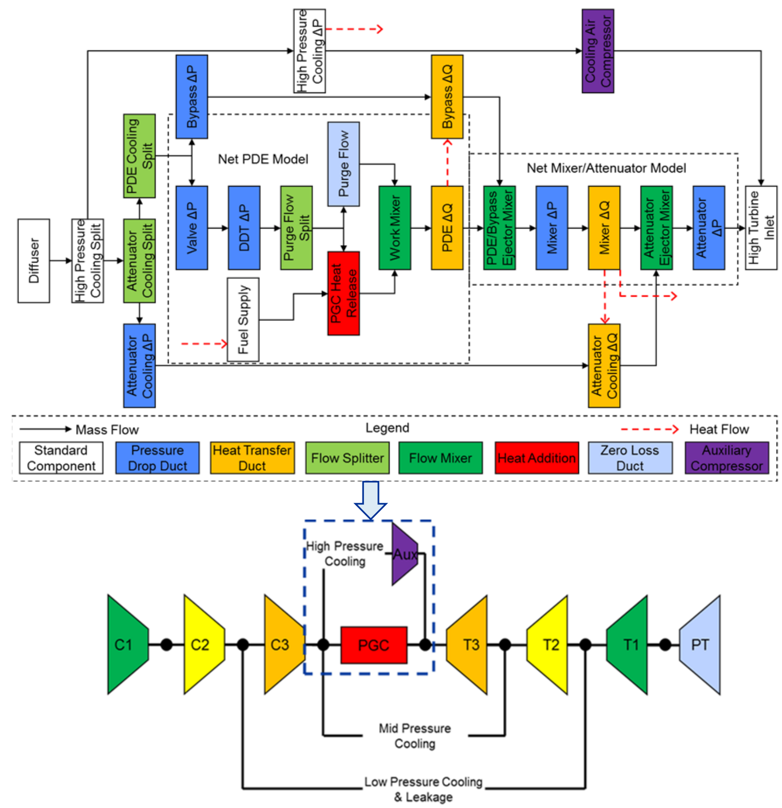
Still More Quantitative Benefits

Combined Cycle Power Generation Employing Pressure Gain Combustion

Department of Energy Award Number DE-FE0024011

All Information Courtesy of United Technologies Research Center

- Detonative PGC component model implemented in NPSS
  - Numerous known loss mechanisms incorporated
- PGC component integrated with other turbomachinery components
- Performance changes of gas turbine propagated through steam cycle.



Power Plant Efficiency: +1.86%
Power Plant Power: +2.97%

Implementation Approaches Since ≈2000

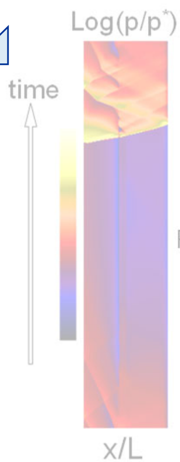
These you know

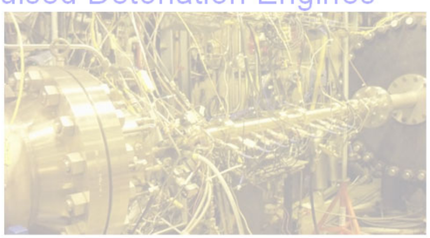
Rotating Detonation Engines

Air Force Research Laboratory

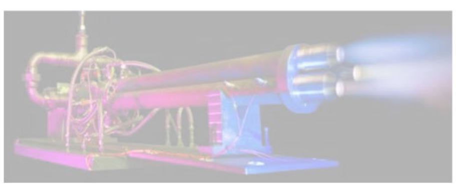
Naval Research Laboratory

Pulsed Detonation Engines



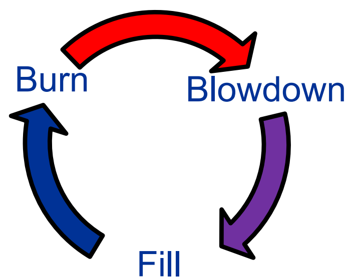


Pratt & Whitney/United Technologies Research Center



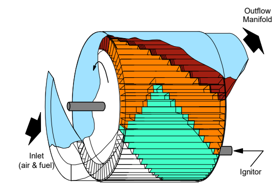
G.E. Global Research Center

All Are Fundamentally Unsteady & Periodic



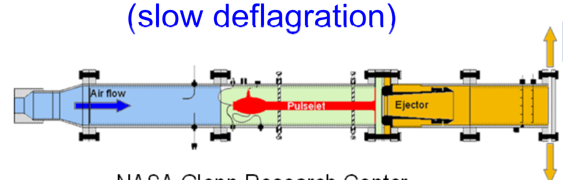
How about these?

Internal Combustion Wave Rotor ('Fast' Deflagration)

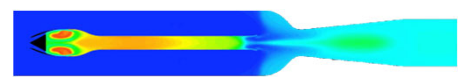


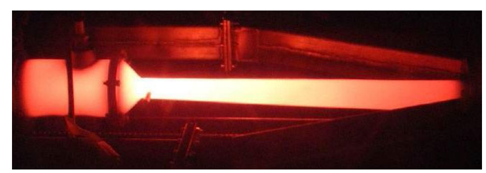
IUPUI/Purdue/LibertyWorks

Resonant Pulse Combustor (slow deflagration)



NASA Glenn Research Center

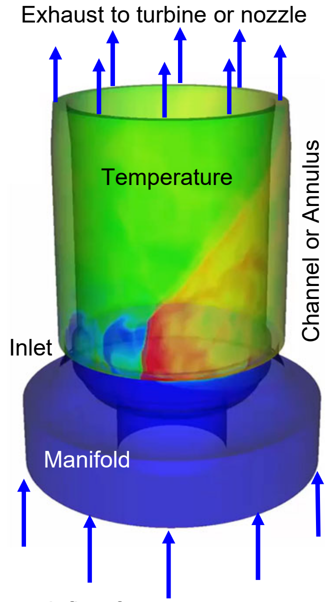




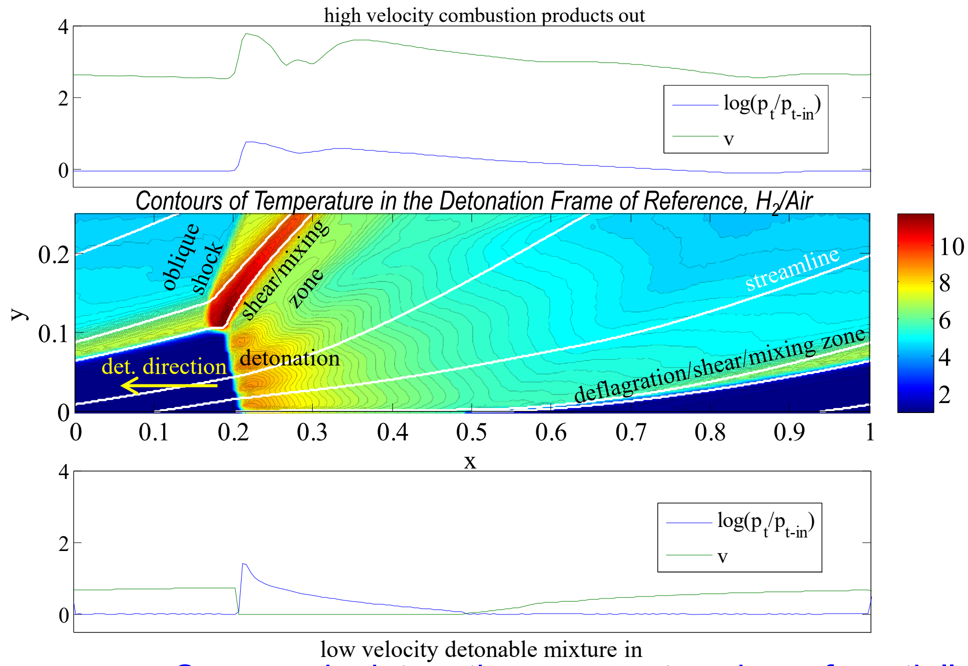
University of Cambridge

Recent Implementation Approaches

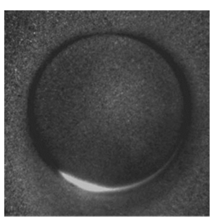
Rotating Detonation Engines or Combustors (RDE, RDC)



CFD RDE Video



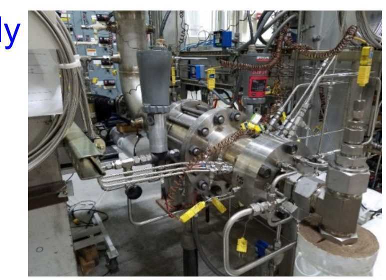
Courtesy AFRL



Experimental Video
Courtesy National Energy
Technology Laboratory

Features:

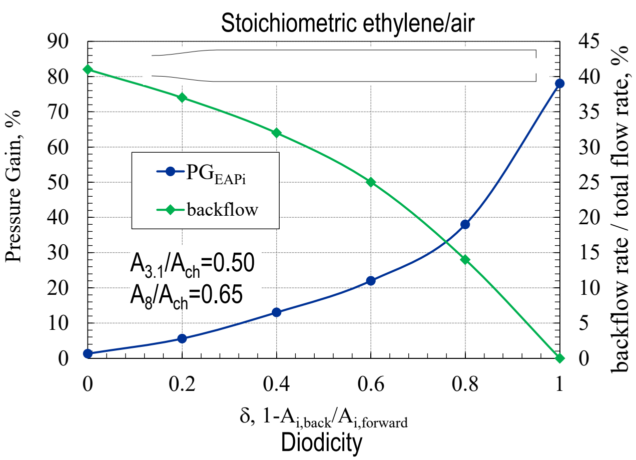
- Supersonic detonation propagates circumferentially
- Fluid travels axially
- No ignition source required (after startup)
- No DDT obstacles required
- Very high frequency operation (kHz)
- Very compact, and conveniently annular
- Inlet is aero-valved to reduce/prevent backflow



Courtesy DOE/NETL

Recent Implementation Approaches

Rotating Detonation Engines or Combustors



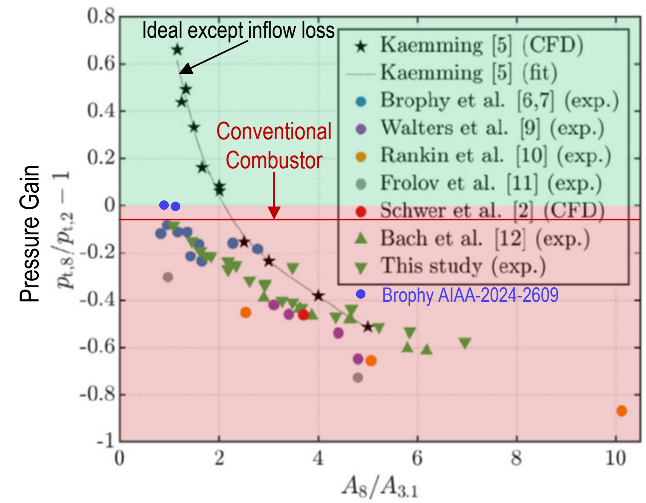
State-of-the Art:

No Pressure Gain Yet

(even at stoichiometric equivalence ratio)

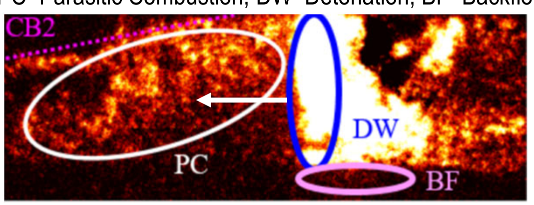
(i.e., T_4/T_3>>2.5 required for gas turbines)

- Unavoidable high fill Mach number
- Energy dissipating backflow into inlet
- High forward flow losses from inlet restrictions
- Poor fuel and air mixing
- Parasitic deflagration prior to detonation
- Coupled nature of all the above



Bach, E., et al, "An Empirical Model for Stagnation Pressure Gain in Rotating Detonation Combustors," Proceedings of the Combustion Institute, V. 38, 2021

PC=Parasitic Combustion; DW=Detonation; BF=Backflow



Chacon, F., Gamba, M., "Study of Parasitic Combustion in an Optically Accessible Continuous Wave Rotating Detonation Engine," AIAA-2019-0473, Jan., 2019.

Bottom Line:

A Promising but Challenging Technology

Proper Inlet Design is Critical

Model Based Design is Essential

LET'S KEEP AT IT!

Recent Implementation Approaches

Pulsed Detonation Engines or Combustors (PDE, PDC)

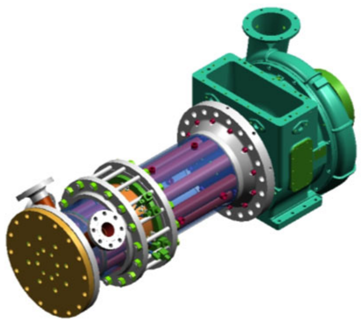


Image and details courtesy G.E. Global Research Center

Courtesy Naval Postgraduate School

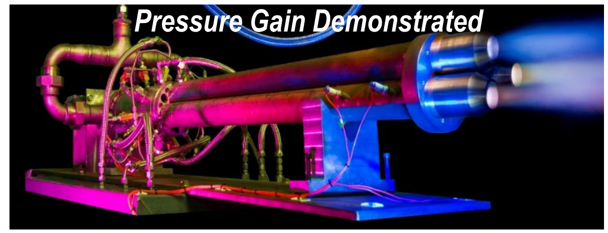
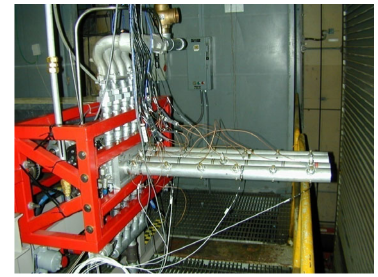
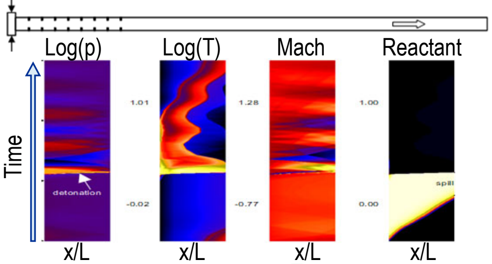


Image and details courtesy G.E. Global Research Center



Courtesy Air Force Research Laboratory



Characteristics:

- Basically a detonative cycle in a linear tube
- Tube is open (or has a throat) at the exit
- Tube is mechanically valved at the inlet
- Detonation propagates in the same direction as the flow

It Does Work!!

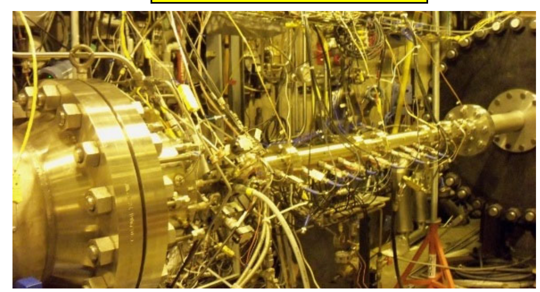


Image and statement courtesy Pratt & Whitney/United Technologies Research Center

"A pulse detonation engine developed by the Pratt & Whitney/United Technologies Research Center ***demonstrates pressure gain*** *at turbine conditions."*
– AIAA 2014 Year In Review

Pros:

- Purge flow avoids parasitic deflagration
- Low fill Mach number increases performance
- Can be mechanically valved to avoid backflow
- Partial filling allows effective low equivalence ratio operation

Cons:

- Detonations must be initiated each cycle
- Required deflagration-to-detonation transition (DDT) ads length
- Low loss, long lasting valves at 100+ Hz. are tough
- Relatively low frequency operation makes nozzles or turbomachinery coupling tricky

Further Research is Warranted
Modeling is Critical

Recent Implementation Approaches

Internal Combustion Wave Rotor (ICWR)

('Fast' Deflagration)

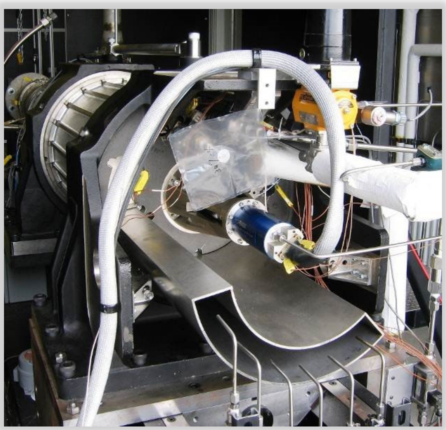
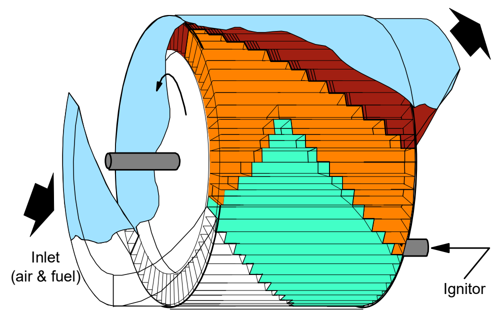
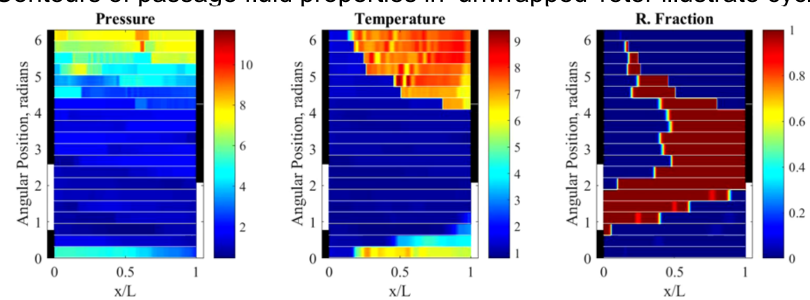


Photo and video courtesy IUPUI and LibertyWorks



Operational rig video

Contours of passage fluid properties in 'unwrapped' rotor illustrate cycle



1D CFD Wave Rotor Video

Characteristics

- Gasdynamic cycle occurs in rotating drum of axially aligned passages
- Inlet & exhaust ducts, housing, and endwalls are stationary

Pros:

- Flow in ducts is nominally steady, though spatially non-uniform
- Rotor is self-cooled
- Rotation provides valving not power extraction
- Valves implemented at both ends
- Closest to true constant volume combustion

Cons:

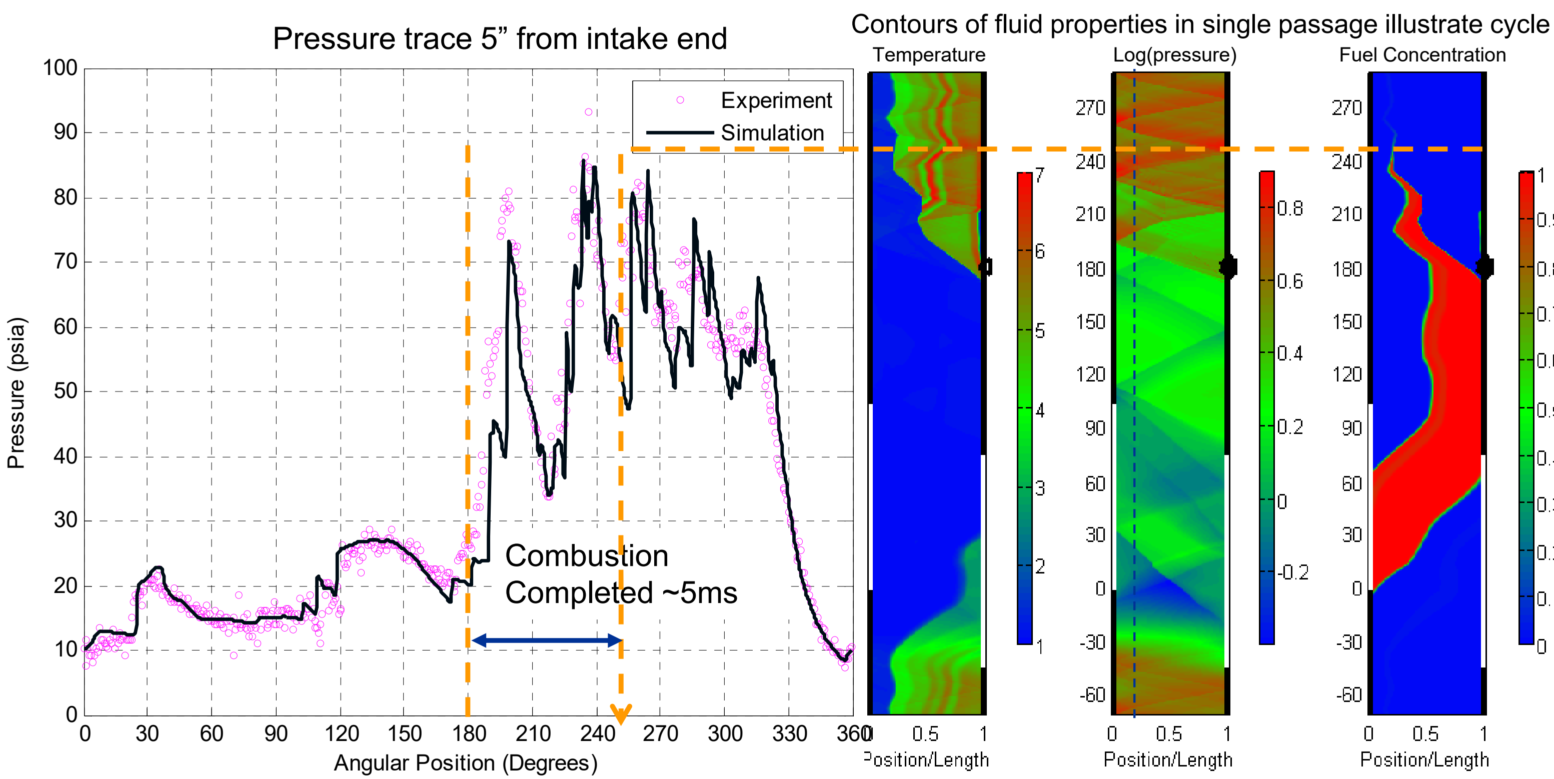
- Rotor-endwall leakage
- Partial admission
- Ignition via transfer ducts

5%-17% Pressure Gain Measured on a 1st Generation, Concept Demonstrator Rig

Recent Implementation Approaches

Internal Combustion Wave Rotor

('Fast' Deflagration)

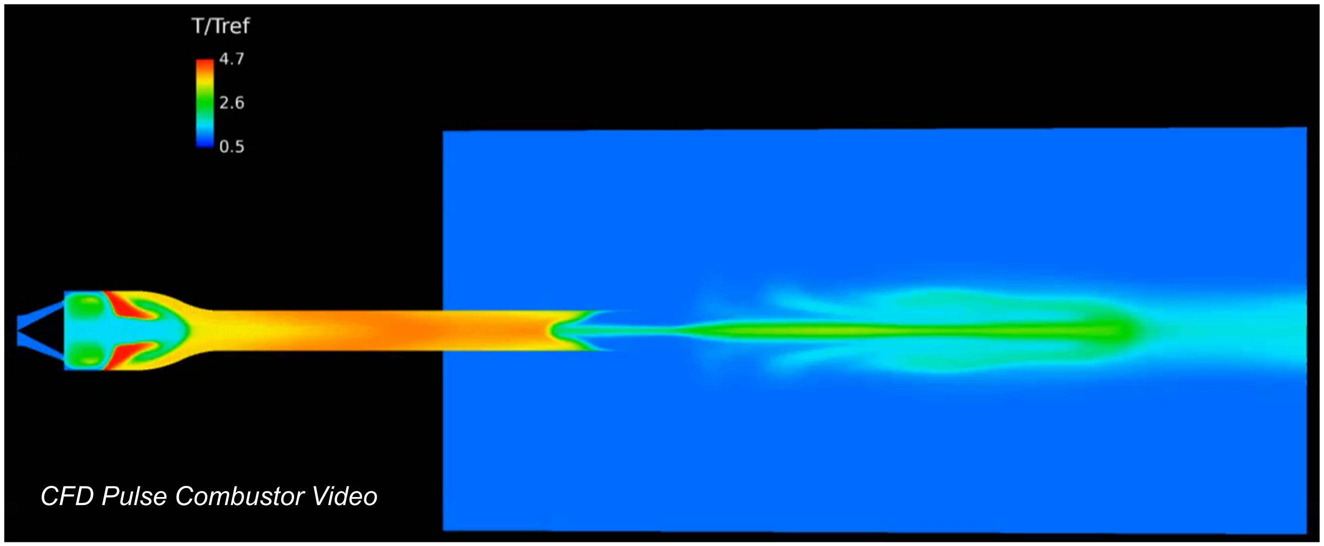


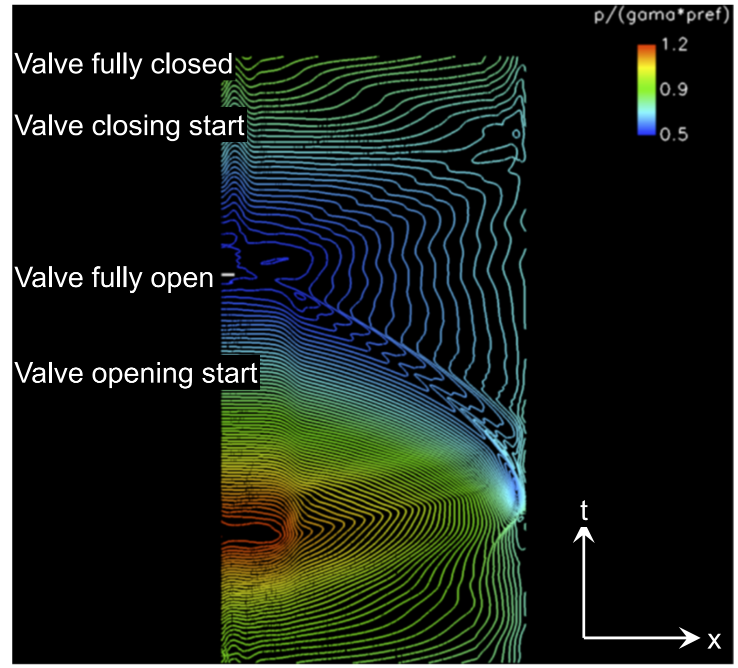
Pressure trace and contour plot courtesy IUPUI and LibertyWorks

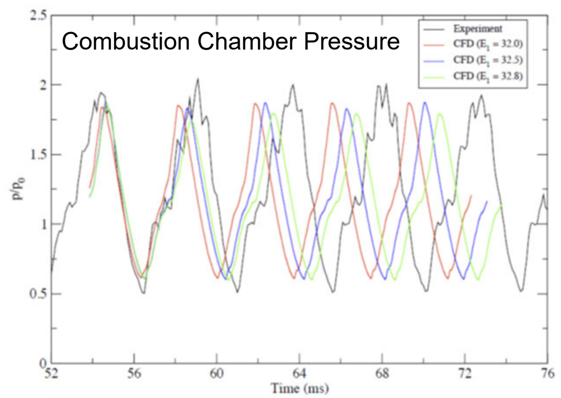
Again, Validated Models Are Essential for Design, Performance Assessment, and Diagnostics

Recent Implementation Approaches

Resonant Pulse Combustor (RPC)

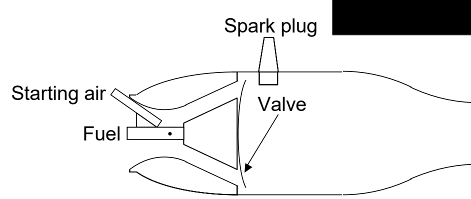






Successful cycles balance coupled:

- Gasdynamic waves
- Large vortex dynamic
- Chemical kinetics
- Helmholtz phenomena



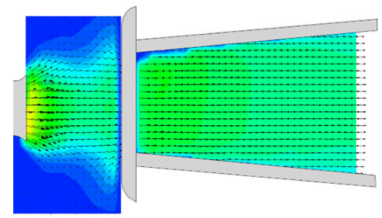
Pressure Gain=50%+!!

Recent Implementation Approaches

RPC as Gas Turbine Combustor

Effluent is too hot and impulsive for direct turbine coupling:

- Add optimized unsteady ejector
- Entrain bypass flow
- Mix efficiently
- Pump

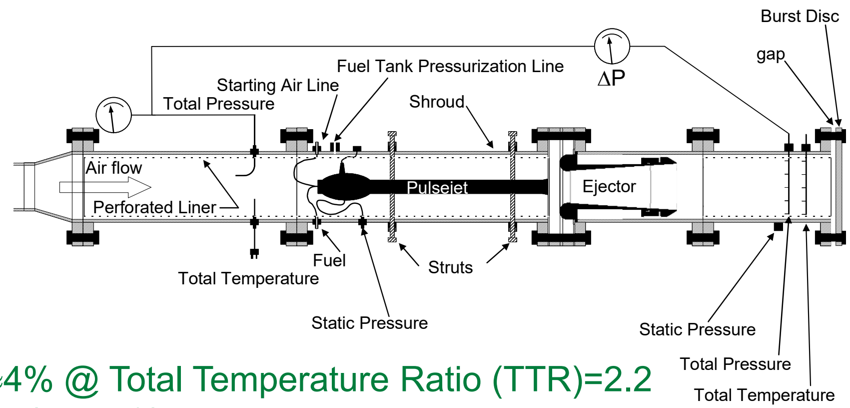


PIV Measured Ejector Flowfield Video

Ejector Enhanced Resonant Pulse Combustor

Pros:

- Demonstrated pressure gain
- One moving part
- Readily operates with liquid fuels
- Relatively benign fluctuations



Cons:

- Relatively limited theoretical potential
- Long
- Volumetrically inefficient

- PG≈4% @ Total Temperature Ratio (TTR)=2.2
- rms p′/P=4.5% in the shroud
- Successful operation at 2 Atm. inlet pressure

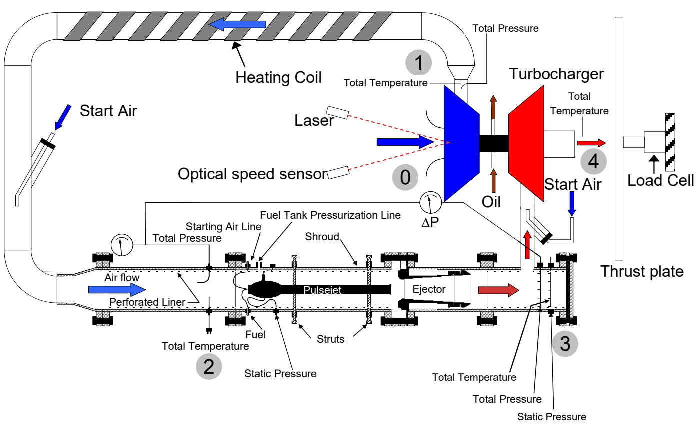
All Work Done With COTS Hobby Scale Pulse Combustor

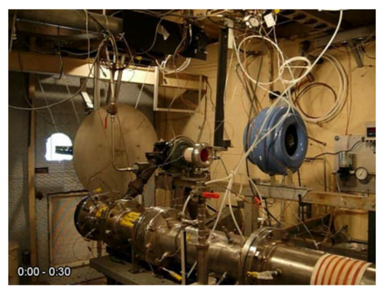
Recent Implementation Approaches

RPC as Gas Turbine Combustor

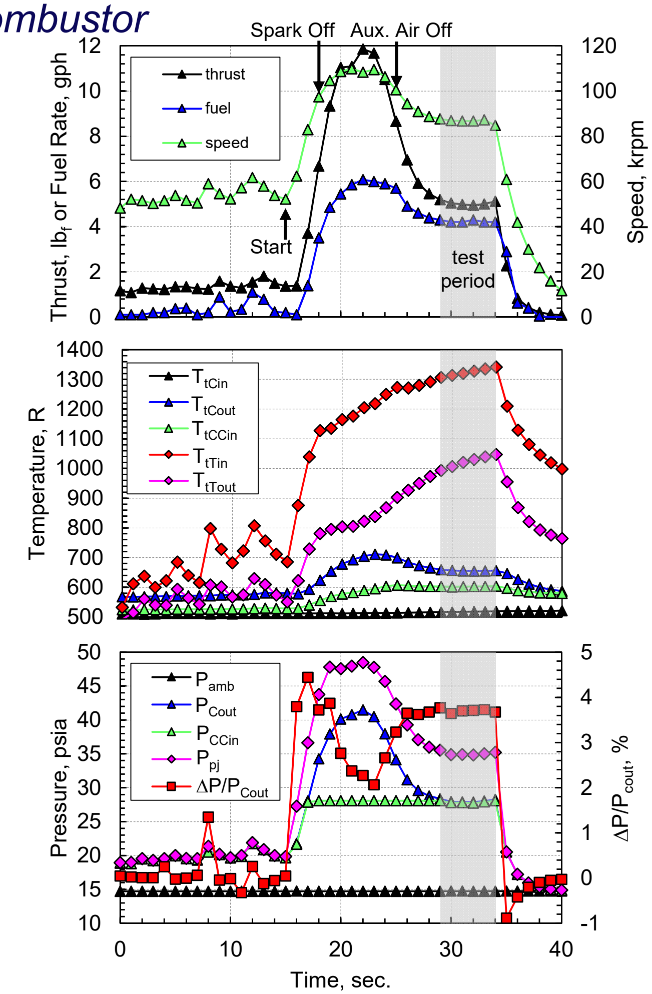
Lab Demo Results:

- True closed loop operation @ SLS
  - All air supplied by compressor
- $(P_4/P_3 - 1)=3.5\%$ @ $T_4/T_3=2.2$
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine stops with conventional combustor at same T_4/T_3
- -20 dB noise reduction across Turbine
- 4% rms p'/P_4 at turbine inlet





Operational Rig Video

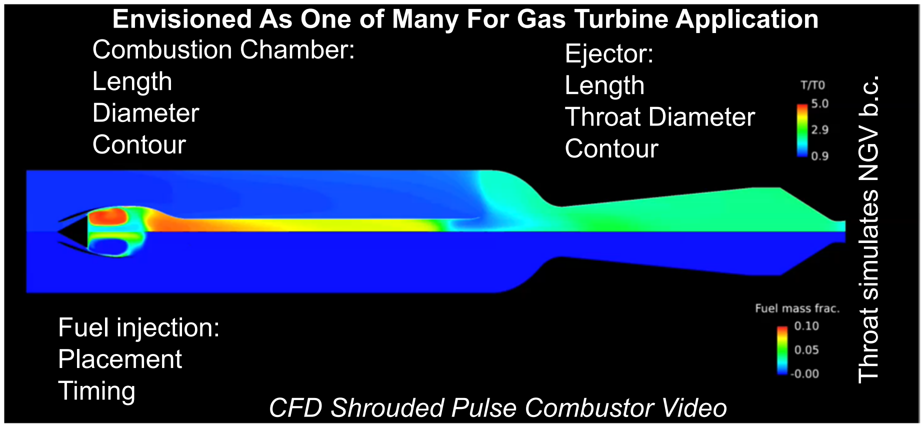


It Works!

Recent Implementation Approaches

RPC as Gas Turbine Combustor

High P_3, T_3 Operation and Optimization Through Simulation



Inflow Vortex Motion is Key

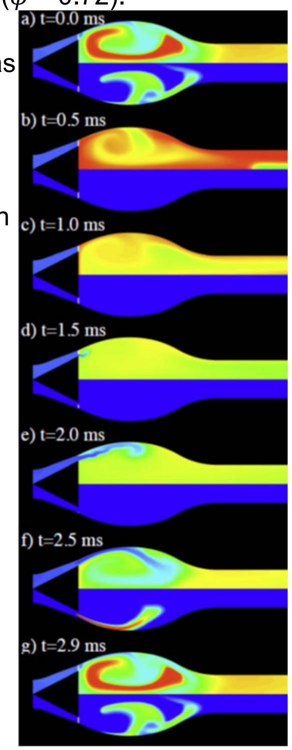
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

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}

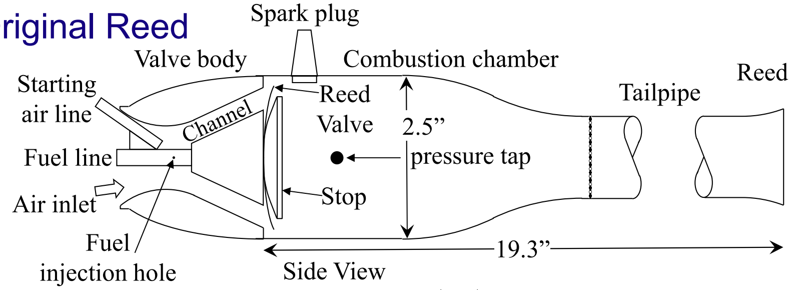
Validated Models Are Essential For Design, Performance Assessment, and Diagnostics

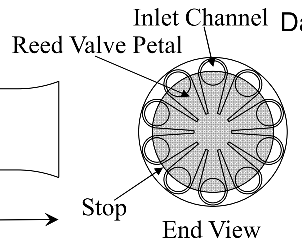
Recent Implementation Approaches

RPC as Gas Turbine Combustor

Passive Valve Optimization Through Experiment & Simulation

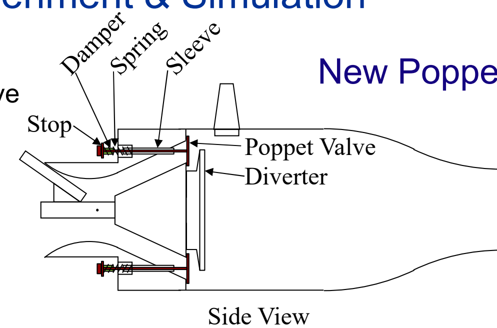
Original Reed

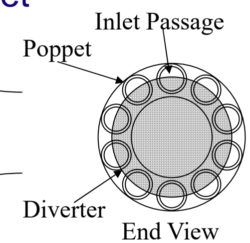




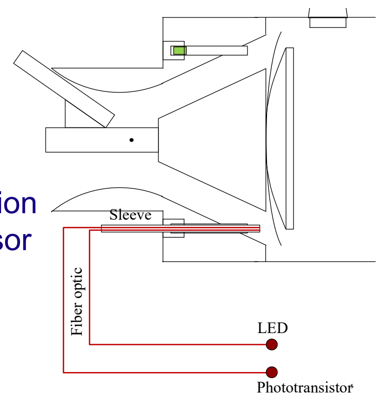
Damaged reed valve

New Poppet

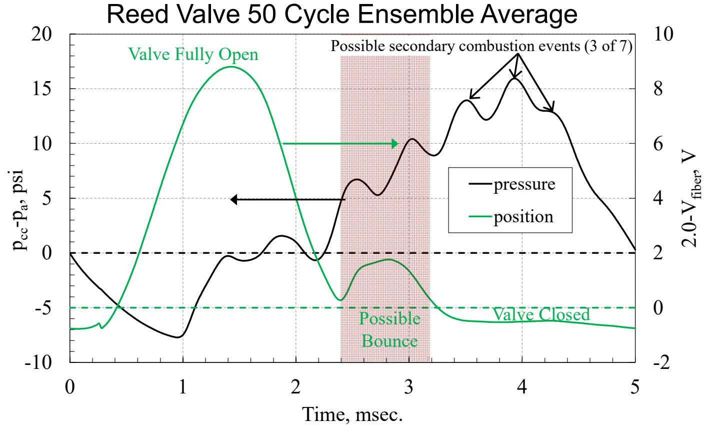




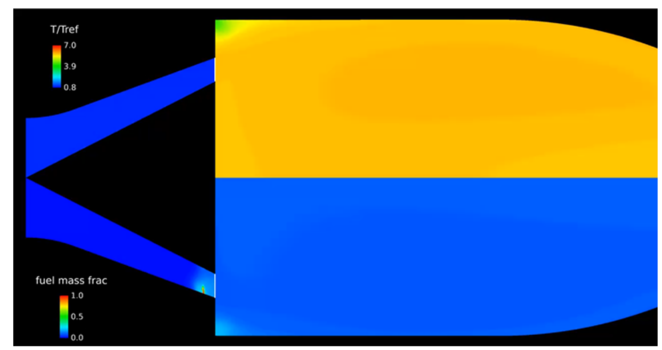
Position Sensor



Reed Valve 50 Cycle Ensemble Average



Zoomed CFD Animation of Chamber and Modeled Reed Valve



Outcomes

- Poppet valve unsuccessful
  - No self-sustained operation
- Significant insights gained for motion requirements

Passive Valve Motion Is Complex and Punishing

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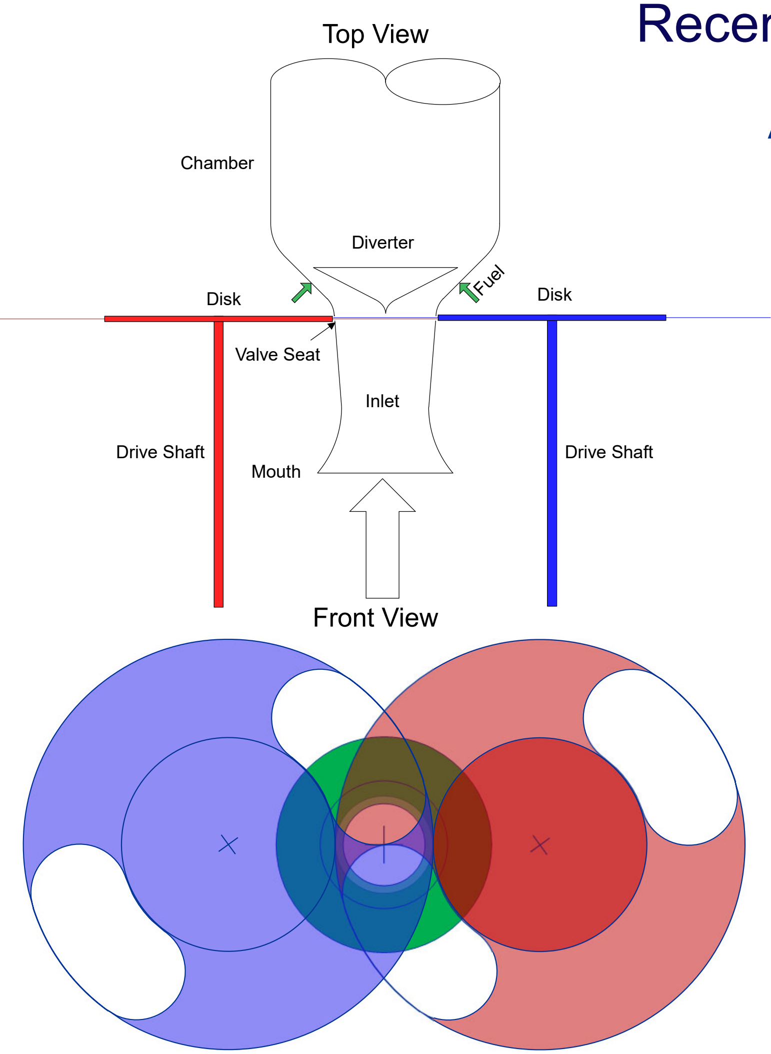
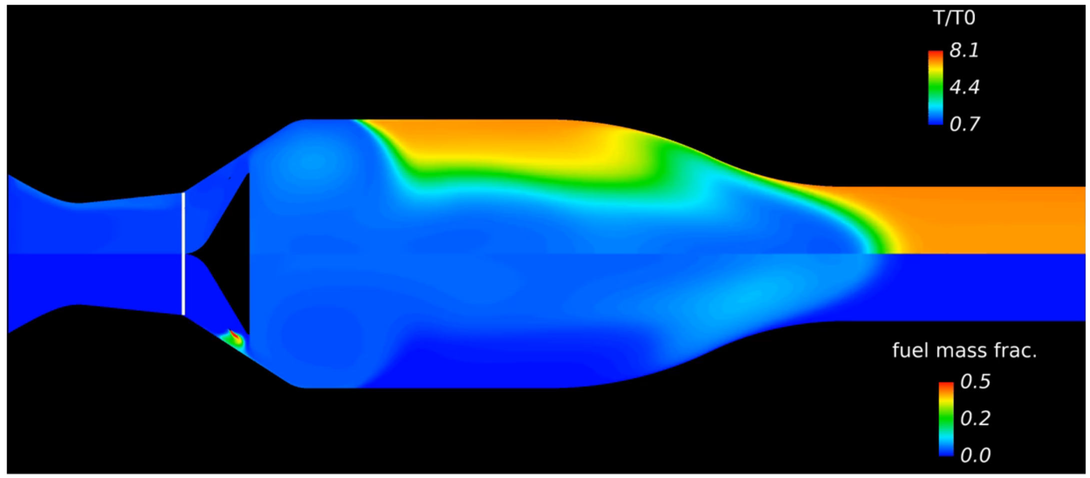
Active Rotary Valve Optimization



Preliminary CFD Simulation with gaseous propane



Characteristics:

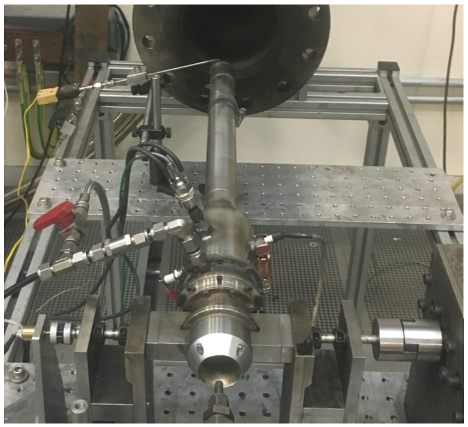
- Rapid opening and closing without slamming
- Open dwell time is variable
- Improved performance
- Adaptable to multiple-combustor can configurations

A Potential Path Froward for RPC Concepts

Recent Implementation Approaches

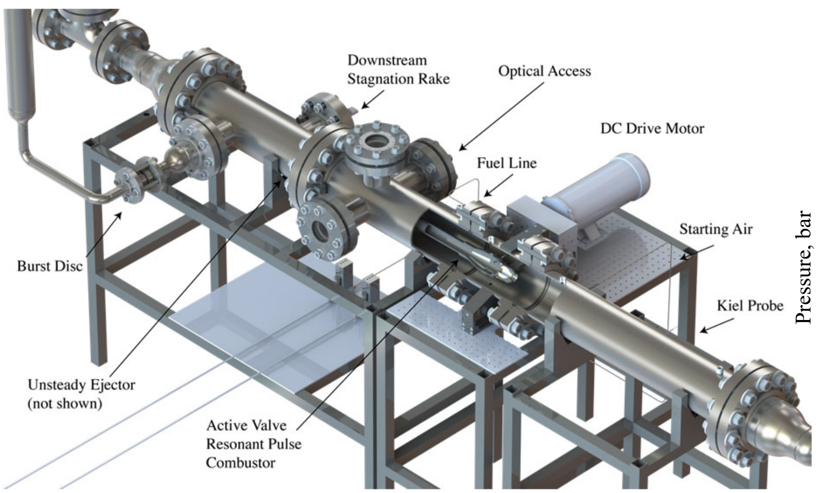
RPC as Gas Turbine Combustor

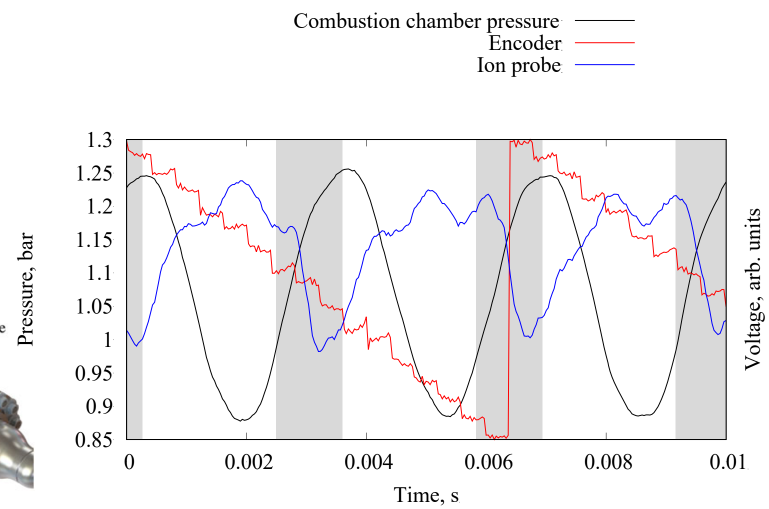
Images Courtesy of King Abdullah University of Science and Technology, Prof. William Roberts



Active Air Valve System
- *Successful self-sustained, self-aspirated operation*
- *Successful operation for long periods*

Shrouded High Pressure Test Bed
- *Heated air*
- *Extensive diagnostics*

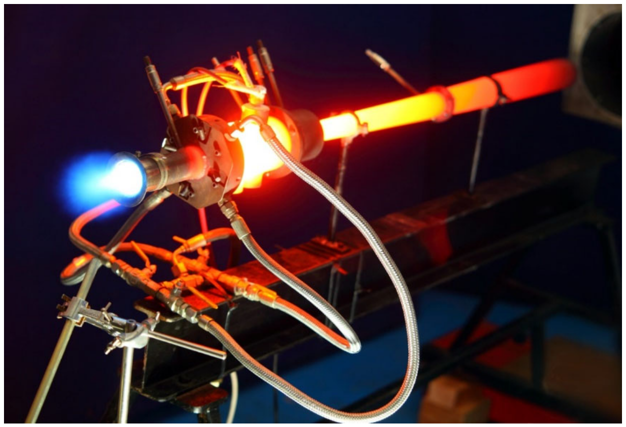


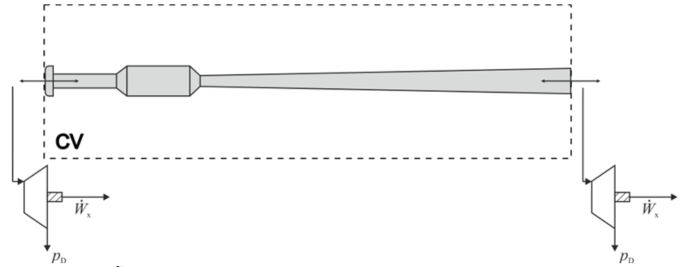


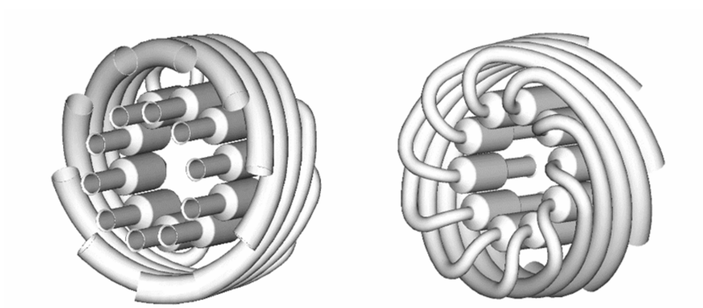
Recent Implementation Approaches

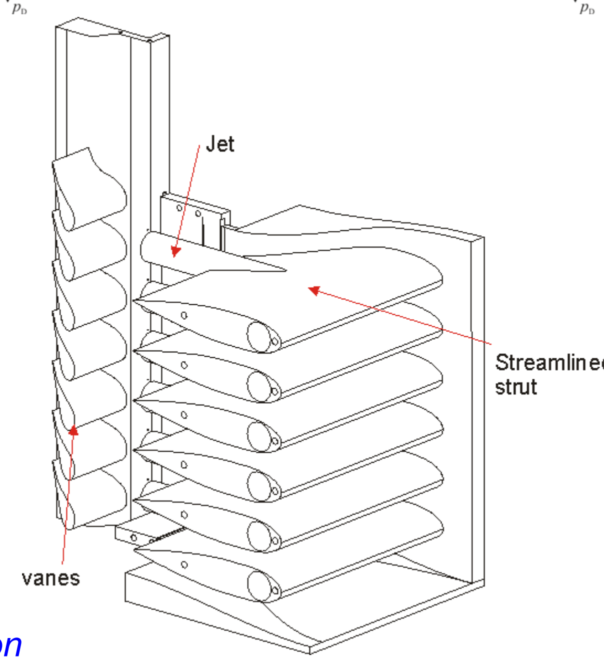
RPC as Gas Turbine Combustor

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









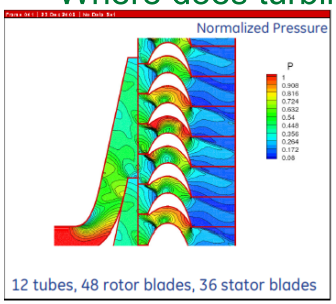
Aerovalved Configurations

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

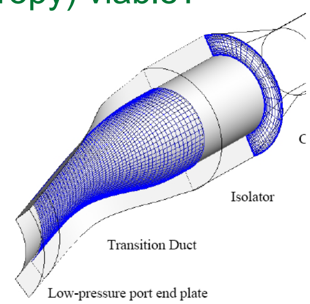
Technology Challenges

(aka What Makes it Fun!)

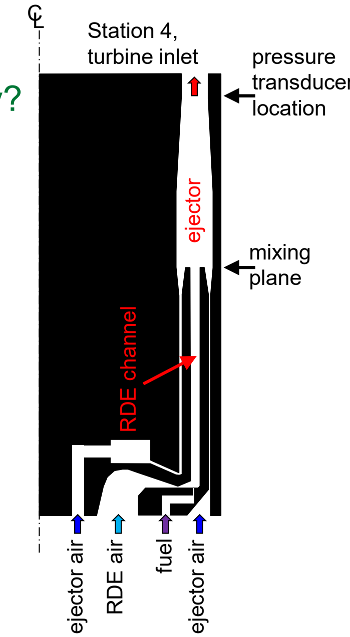
- Turbine/PGC Component Interactions
  - −How is turbine performance quantitatively affected by non-uniformity?
  - −Can unsteadiness-tolerant turbines be designed?
  - −Is efficient bypass mixing (with associated entropy) viable?
  - −Where does turbine cooling flow come from?



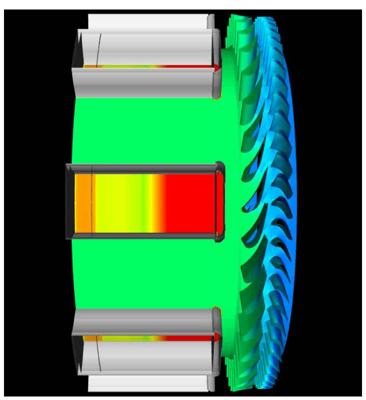
2D CFD Video Courtesy G.E. Global Research Center



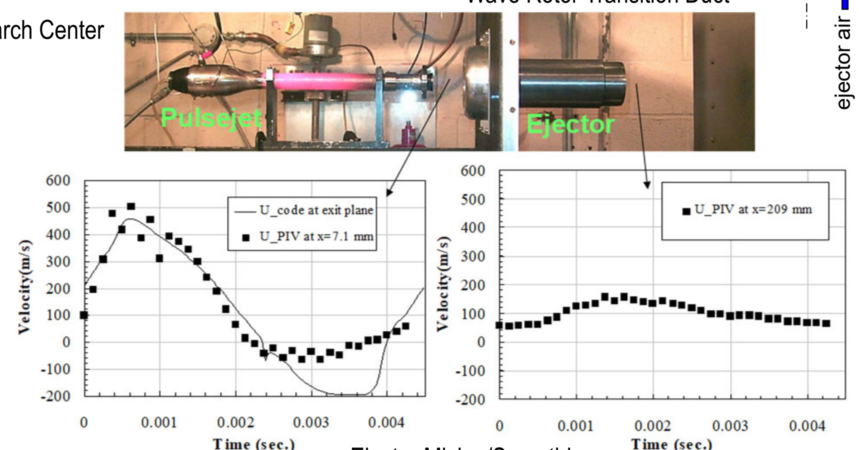
Wave Rotor Transition Duct



RDE Bypass Ejector for Mixing/Smoothing



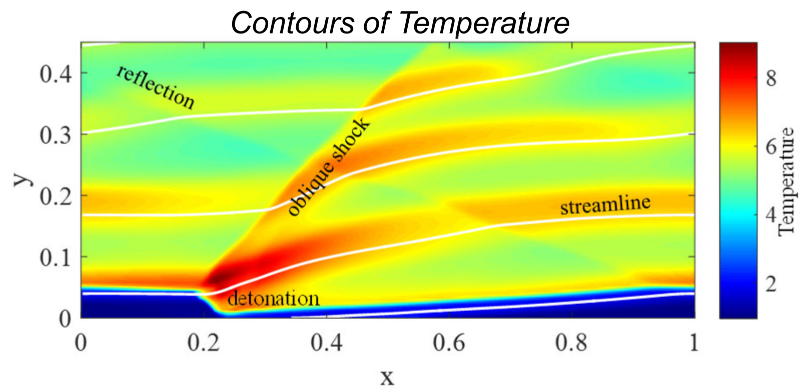
3D CFD Video



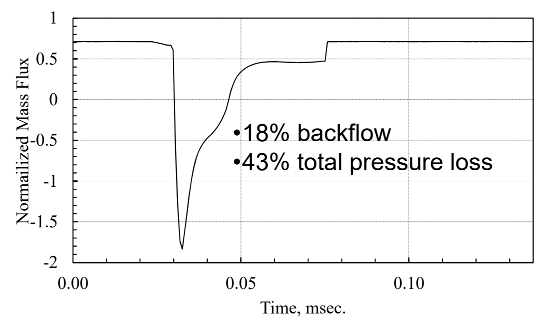
Ejector Mixing/Smoothing

Technology Challenges
(aka What Makes it Fun!)

- Inlet Valves
  - All PGC methods require robust mechanical or aero-valve systems which:
    1. Prevent backflow into inlet and/or seal
    2. Have low loss to forward flow
    3. Operate at high frequency
    4. Don't fail
    5. Tolerate high thermal and stress loads (though they are at least intermittent)



1950's era RPC Reed Valves After 15 sec. Operation in Gas Turbine



Computed Inlet Plane Mass Flux of a Research RDE Using Validated CFD

Technology Challenges

(aka What Makes it Fun!)

- Thermal Management
  - PGC devices have high associated thermal loads
  - Detonative devices have very high associated thermal loads
- Instrumentation and Measurement
  - High frequency, large amplitude range, harsh environment tolerant capabilities required
  - Methodologies for assessing meaningful averages for P_{t4}, T_{t4} *(Hint: time-average won't work)*
- Controls and Actuation
  - Some PGC devices do not operate (well) passively
- Modeling and Validation
  - PGC environment is computationally challenging (fundamentally unsteady, multiple time scales, chemical kinetics uncertain, turbulence models uncertain)
  - Validation is difficult due to instrumentation limits and lack of canonical flows
- Emissions?
  - Some approaches are problematic due to near stoichiometric operation, exceptionally high temperatures, and long residence time.
  - Several approaches have shown competitive levels due to rapid expansion following reaction

Recent Research Efforts Have Yielded Substantial Progress in All Areas
No Show Stoppers Identified to Date

Concluding Remarks

Gas turbines for propulsion and power are part of our low carbon future

Pressure Gain Combustion is a promising technology for improving gas turbine efficiency

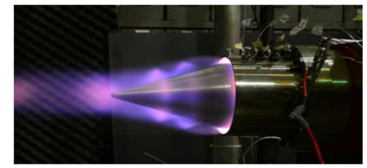
- *Competitive with conventional improvement strategies*
- *Targets improvement at the major source of entropy generation*

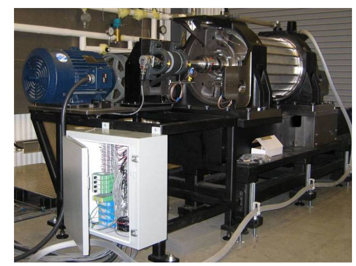
There are numerous promising implementation strategies under investigation

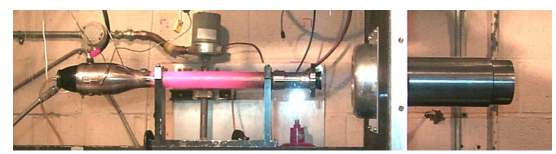
- *Rotating Detonation Engine*
- *Pulse Detonation Engine*
- *Internal Combustion Wave Rotor*
- *Resonant Pulsed Combustion*
- *Aero or mechanical valves*
- *Valves fore and aft, or just fore*
- *Mixing, bypass, lean, etc. operational modes to achieve acceptable TR*

There are technology challenges however:

- *None have yet been identified as insurmountable*
- *Analysis tools have advanced significantly*
- *Understanding has increased dramatically*







"Great things are done by a series of small things brought together."
- Vincent Van Gogh

QUESTIONS?

"Nothing in this world can take the place of persistence. Talent will not: nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education will not: the world is full of educated derelicts. Persistence and determination alone are omnipotent."

-Calvin Coolidge