Pressure Gain Combustion for High Speed Propulsion

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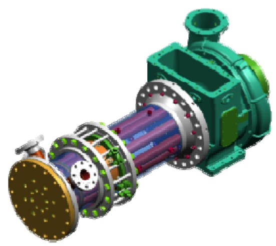

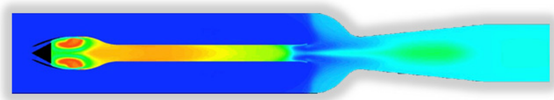

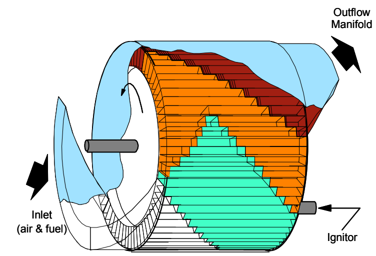

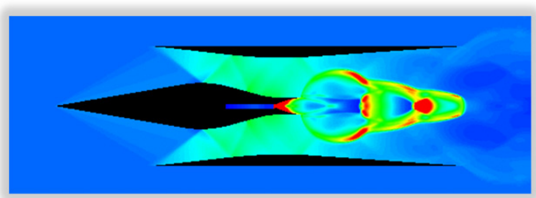

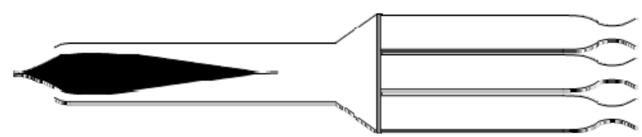

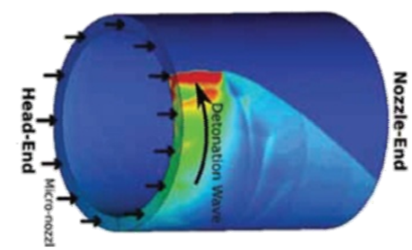

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Emerging Technologies and Cycles
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August 19-22, 2019

Outline

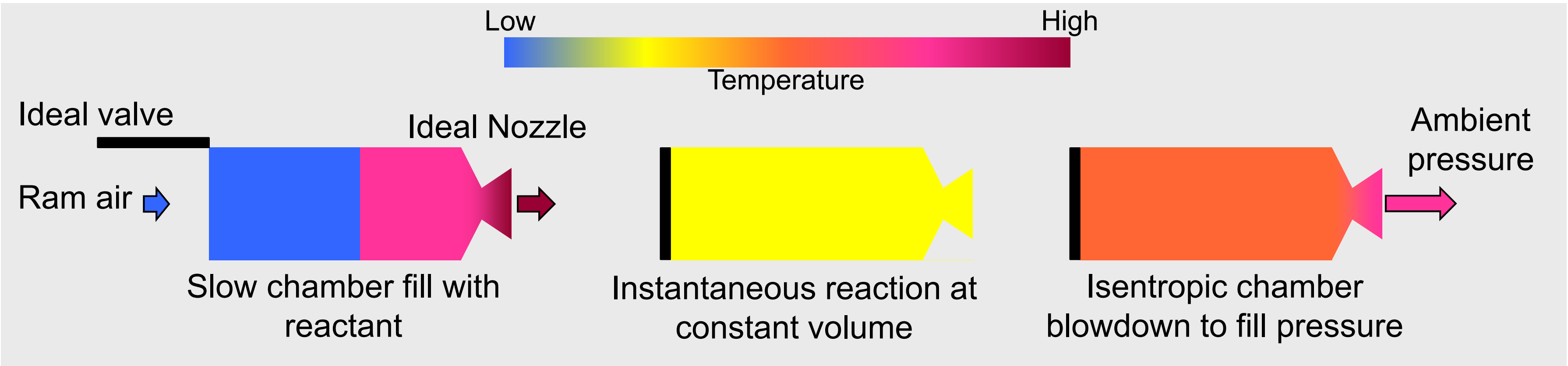
- What is Pressure Gain Combustion (PGC)?
- Why Pursue PGC?
- How is PGC Done in the Real World?
- Challenges
- Community
- Concluding Remarks

What is Pressure Gain Combustion?

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.

- Combustion may be detonative, constant volume, confined volume
- Device is fixed volume (i.e. no pistons)
- Valve at inlet (and possibly exit)

Notional Ram PGC Device



Pressure Rise Provides Increased Availability to Nozzle (or Turbine)

Why Pursue PGC?

The Edgy Answer

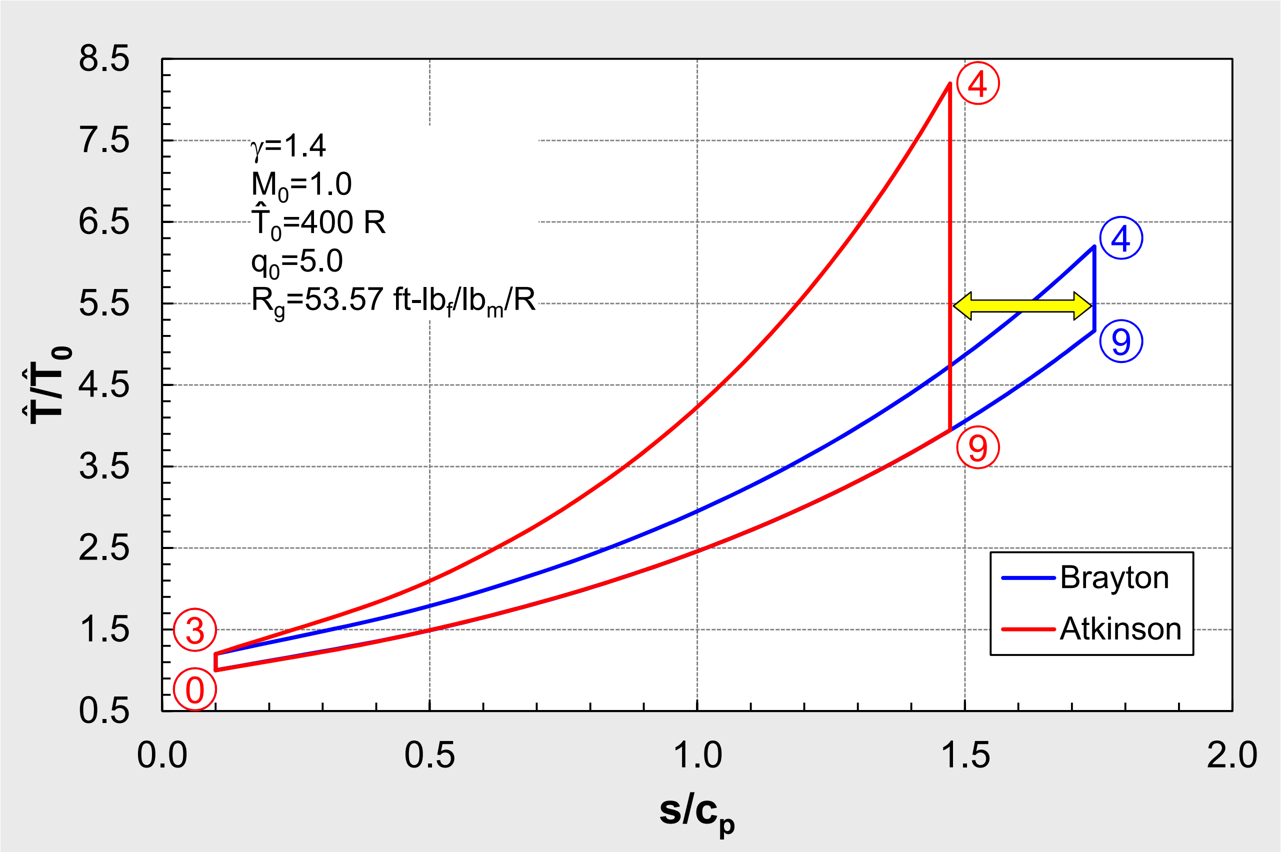
- Most Air Breathing Propulsion & Power Systems Do the Same Thing:
  - *Suck – Squish – Burn – Blow*
- Many Years of R&D Have Relentlessly Focused On:
  - *Suck – Squish – – Blow*
- 90+% of Performance Limiting Entropy Is Produced During:
  - ***Burn***
- **Perhaps It's Time To Think About That…**

Why Pursue PGC?

Better Answer: It is Essentially the Atkinson/Humphrey Cycle Without Pistons

Brayton
0-3: Isentropic Compression
3-4: Isobaric Heat Addition
4-9: Isentropic Expansion
9-0: Isobaric Heat Rejection

Atkinson
0-3: Isentropic Compression
3-4: Isochoric Heat Addition
4-9: Isentropic Expansion
9-0: Isobaric Heat Rejection



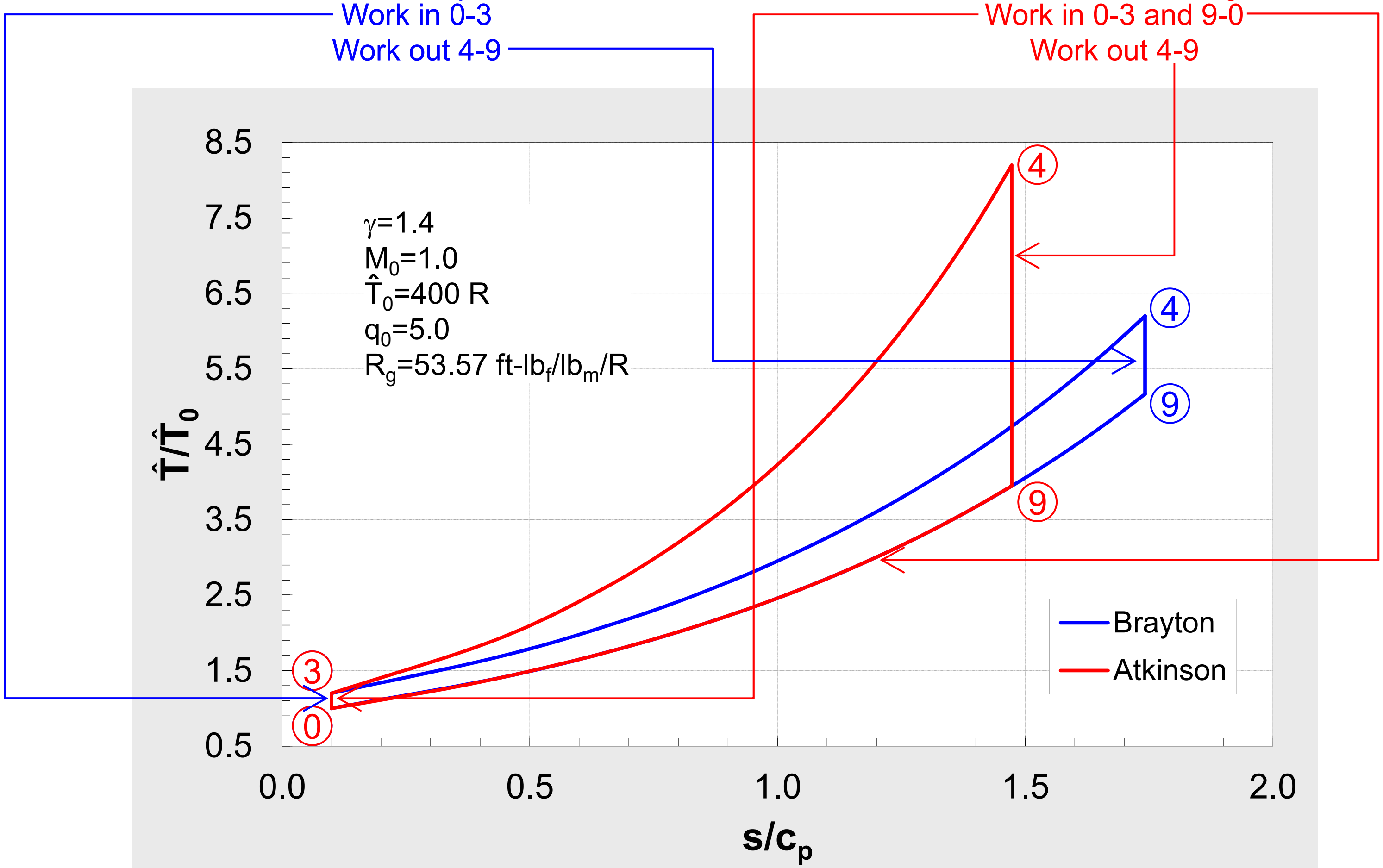
Atkinson Produces Less Entropy For the Same Ram Compression and Heat Addition
(Less Heat Rejected, More Net Work Available)

Why Pursue PGC?

Important Background: The Manner by Which the Cycle is Analyzed Matters

Typical Brayton is Steady Control Volume
Work is $c_p \Delta T$
Work in 0-3
Work out 4-9

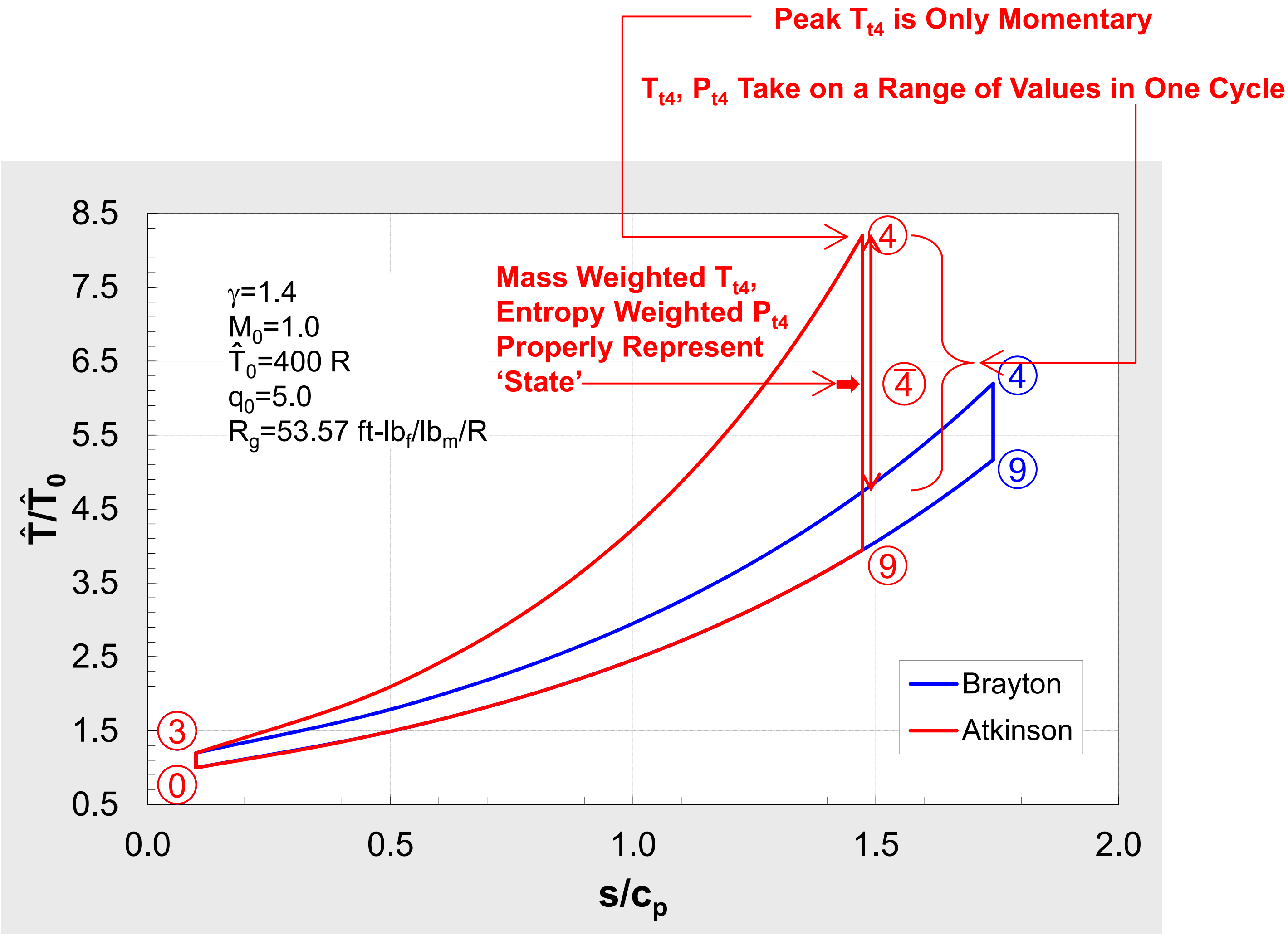
Typical Atkinson is Control Mass
Work is $c_v \Delta T$ and $R_g \Delta T$
Work in 0-3 and 9-0
Work out 4-9



<u>Unsteady</u> Control Volume Analysis is Required for the PGC Atkinson Cycle
(Simple 'States at Stations' is No Longer Sufficient)

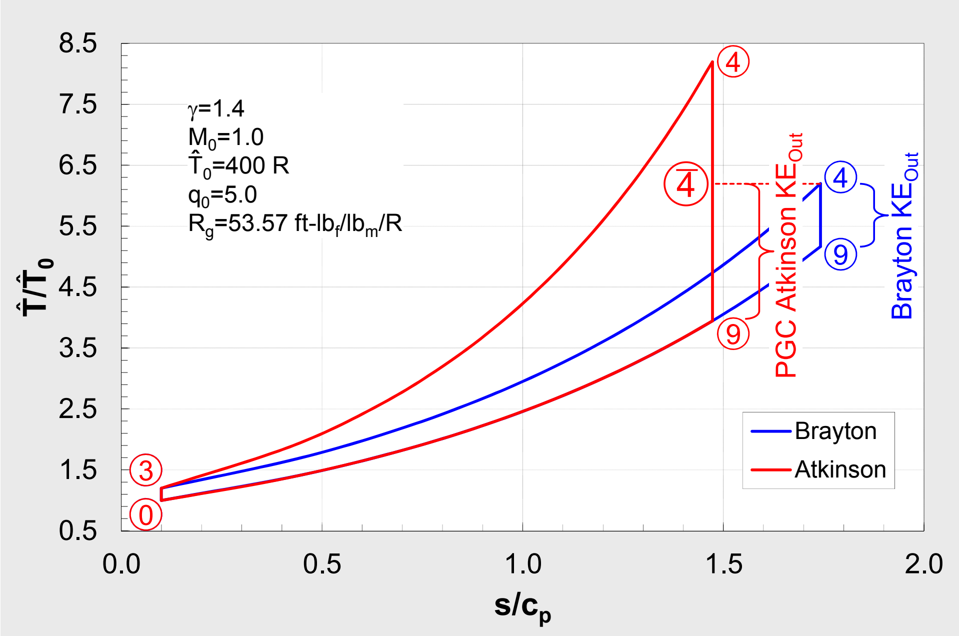
Background

Important Background: Expansion Phase Requires Special Attention



Performance (i.e. Efficiency and Specific Thrust) Requires Evaluation of Flux Integrals

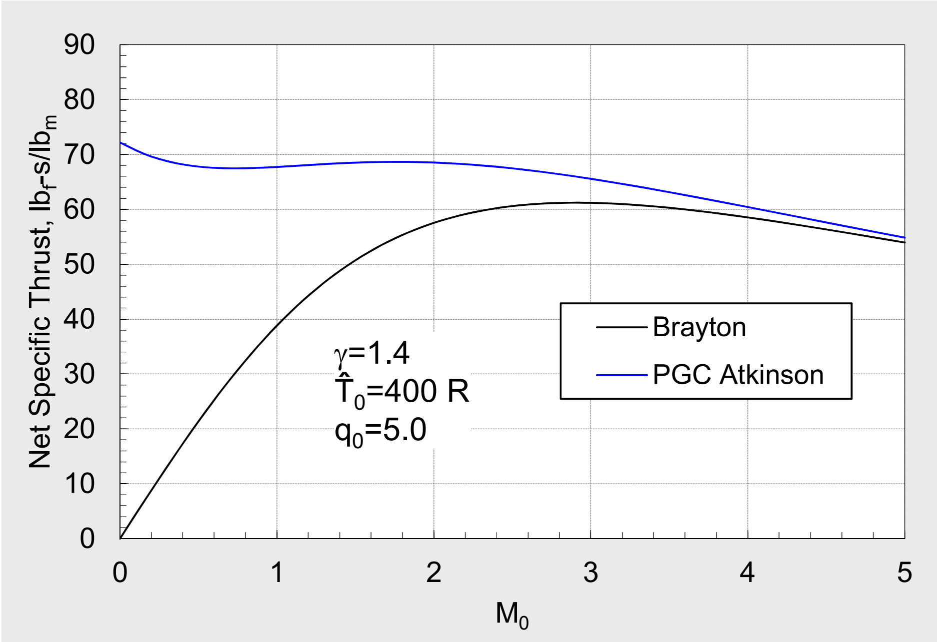
Why Pursue PGC?



Ideal Notional Ramjet Example

For the Same Heat Addition:

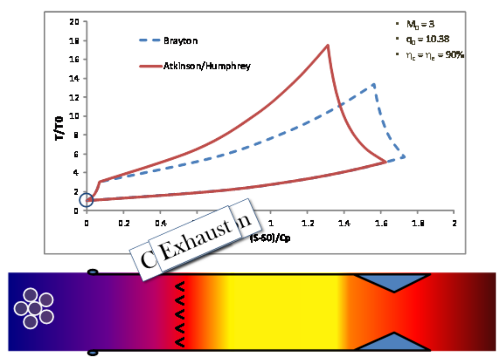
- Same Mass Averaged T_{t4}
- More Kinetic Energy Produced
- Higher Efficiency



Why Pursue PGC?

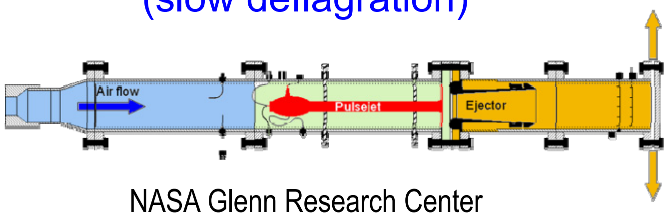
The Ramjet PGC With Losses Illustrated

- $M_0 = 3$
- Hydrocarbon Fuel
  - $\Delta h_v = 18500$ BTU/lb_m
  - ER = 0.8
  - $q_0 = 10.38$
- Component Efficiencies
  - $\eta_c = \eta_e = 90\%$

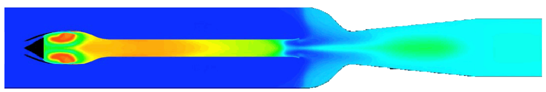


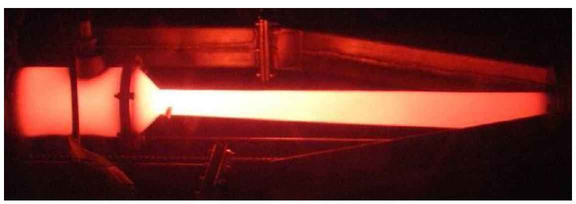
How is PGC Done in the Real World?

Resonant Pulse Combustor (slow deflagration)



NASA Glenn Research Center



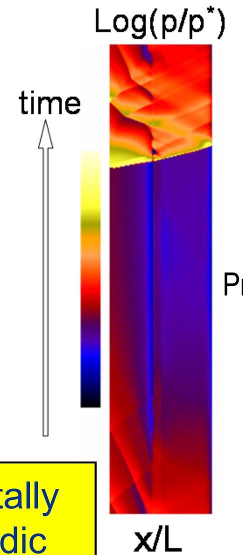


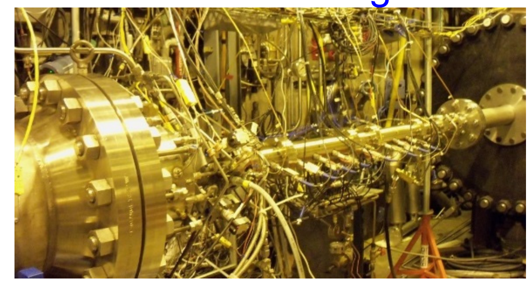
University of Cambridge

All Are Fundamentally Unsteady & Periodic

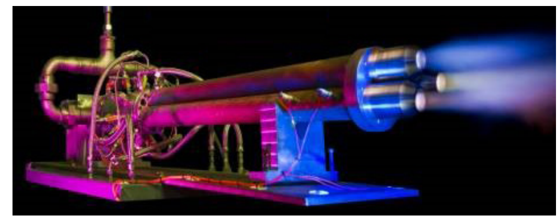
Fill →Burn →Blowdown →Repeat

Pulsed Detonation Engines



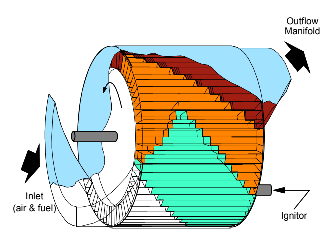


Pratt & Whitney/United Technologies Research Center



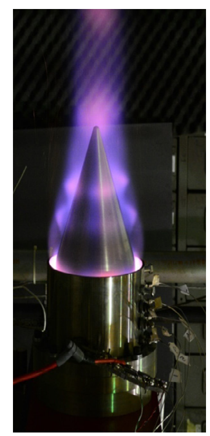
G.E. Global Research Center

Internal Combustion Wave Rotor ('Fast' Deflagration)

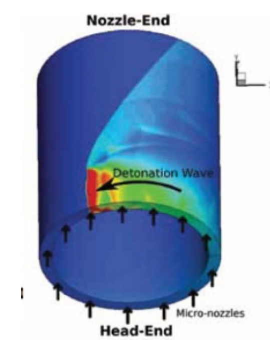


IUPUI/Purdue/LibertyWorks

Rotating Detonation Engines

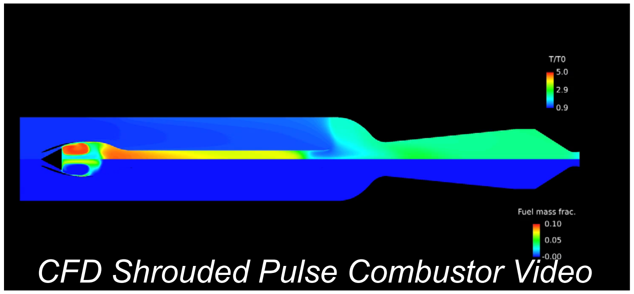


Air Force Research Laboratory



Naval Research Laboratory

How is PGC Done in the Real World?



CFD Shrouded Pulse Combustor Video

Operational Rig Video

Resonant Pulse Combustion (slow deflagration)

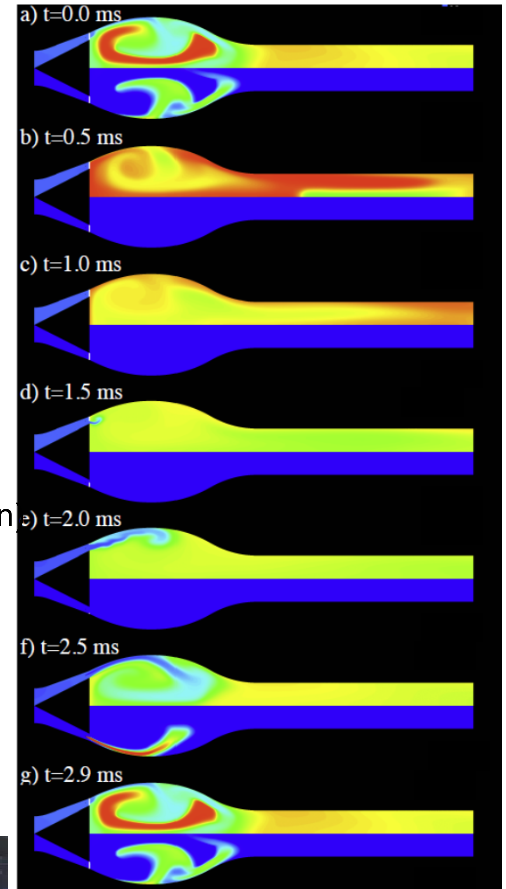
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

Self-ignition via residual hot gas

Rapid confined combustion

Expansion/acceleration (blowdown)

refill



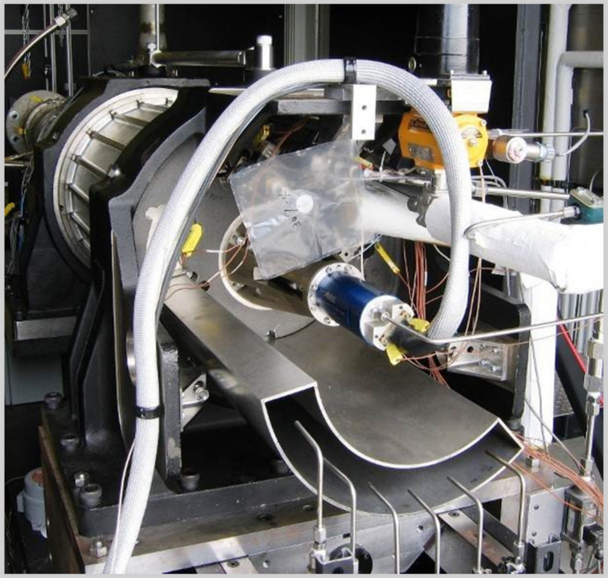
Characteristics

- Self-sustaining
- Self-aspirating (operates statically)
- Liquid fueled
- Few or no moving parts
- Relatively low mechanical/thermal stress
- Limited performance potential (confined, not constant volume combustion)
- Unequivocally demonstrated p-gain

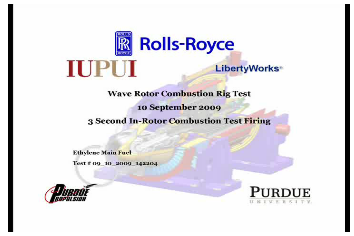

Operational Rig Video

How is PGC Done in the Real World?

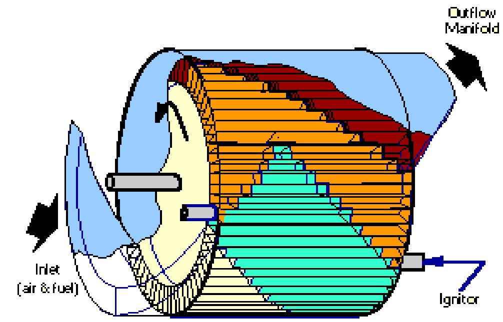
Internal Combustion Wave Rotor
(‘Fast’ Deflagration)



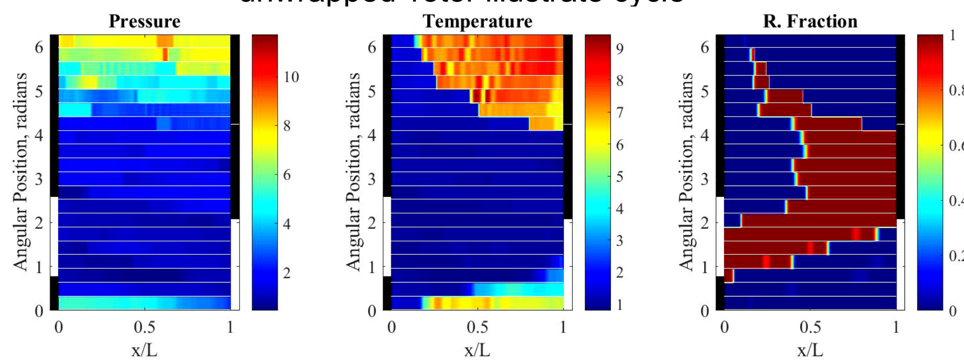
Photo, movie, courtesy IUPUI and LibertyWorks



Operational Rig Video



Contours of passage fluid properties in ‘unwrapped’ rotor illustrate cycle



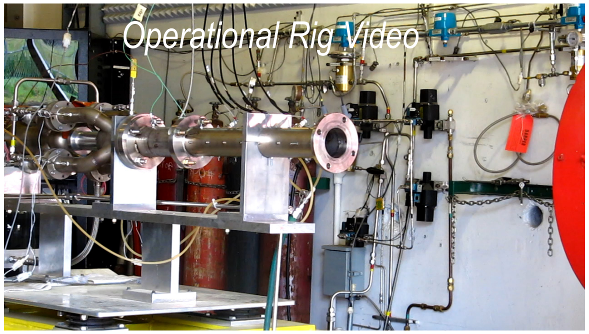
1D CFD Wave Rotor Video

Characteristics

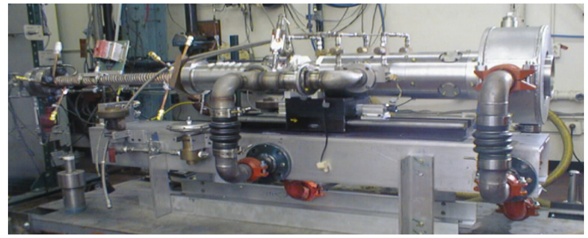
- Flow in ports is nominally steady
- Self-cooling is possible
- Very high frequency ignition source required
- High performance potential
- Low stress valve design
- Requires sealing between rotor and endwall
- Closest to true constant volume combustion

How is PGC Done in the Real World?

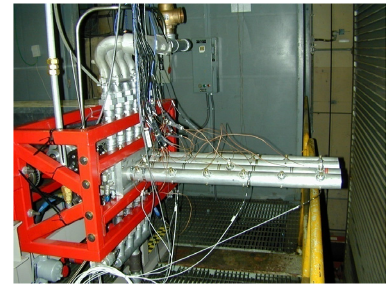
Pulsed Detonation Engines



Courtesy Naval Postgraduate School



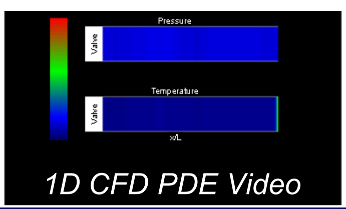
Courtesy Boeing Corporation



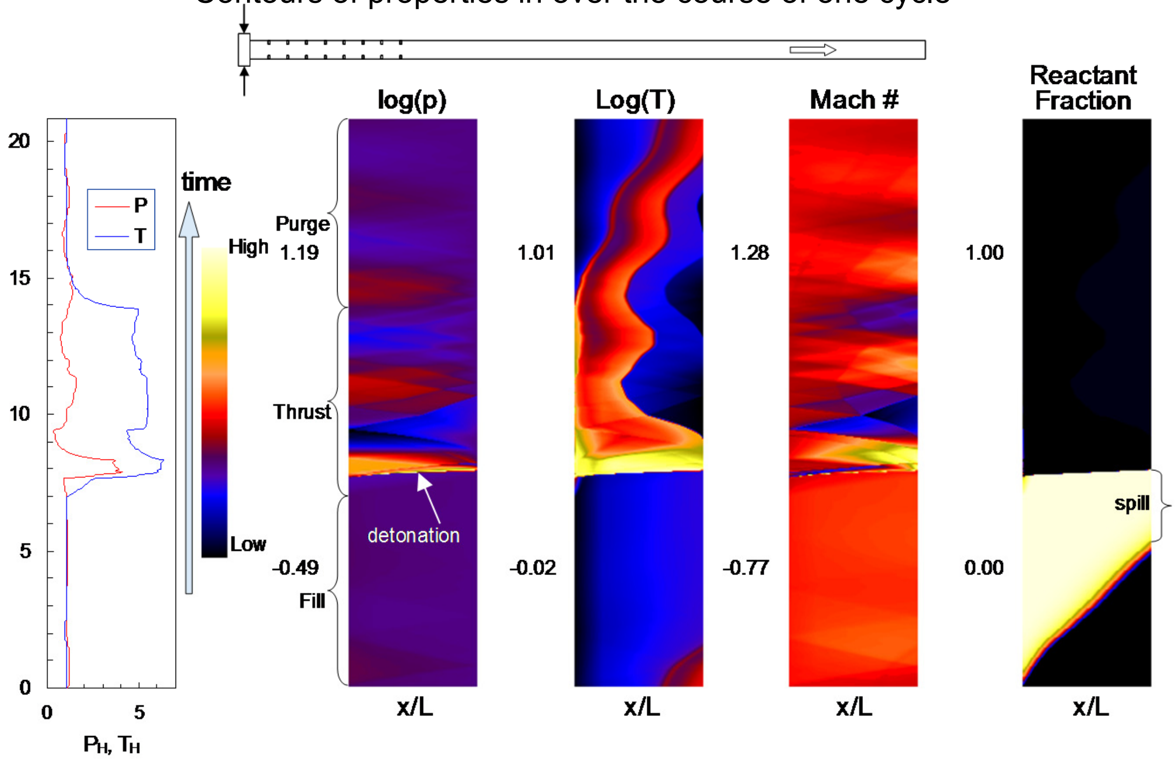
Courtesy Air Force Research Laboratory

Characteristics

- Supersonic detonation approximates CV
- Ignition source required
- Deflagration-to-detonation transition obstacles required
- High performance potential
- High frequency valves required
- Highly non-uniform effluent



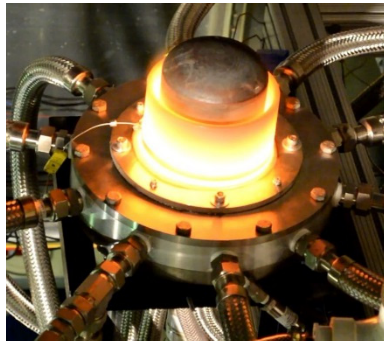
Contours of properties in over the course of one cycle



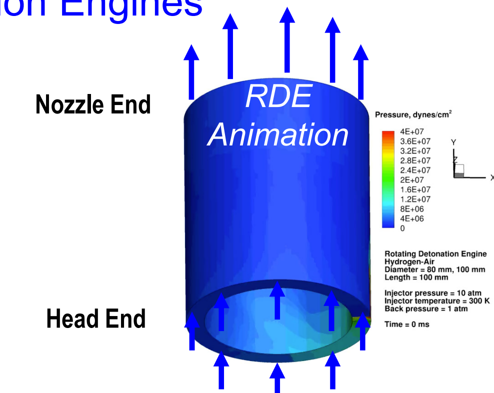
How is PGC Done in the Real World?

Rotating Detonation Engines

Courtesy AFRL



Courtesy AFRL

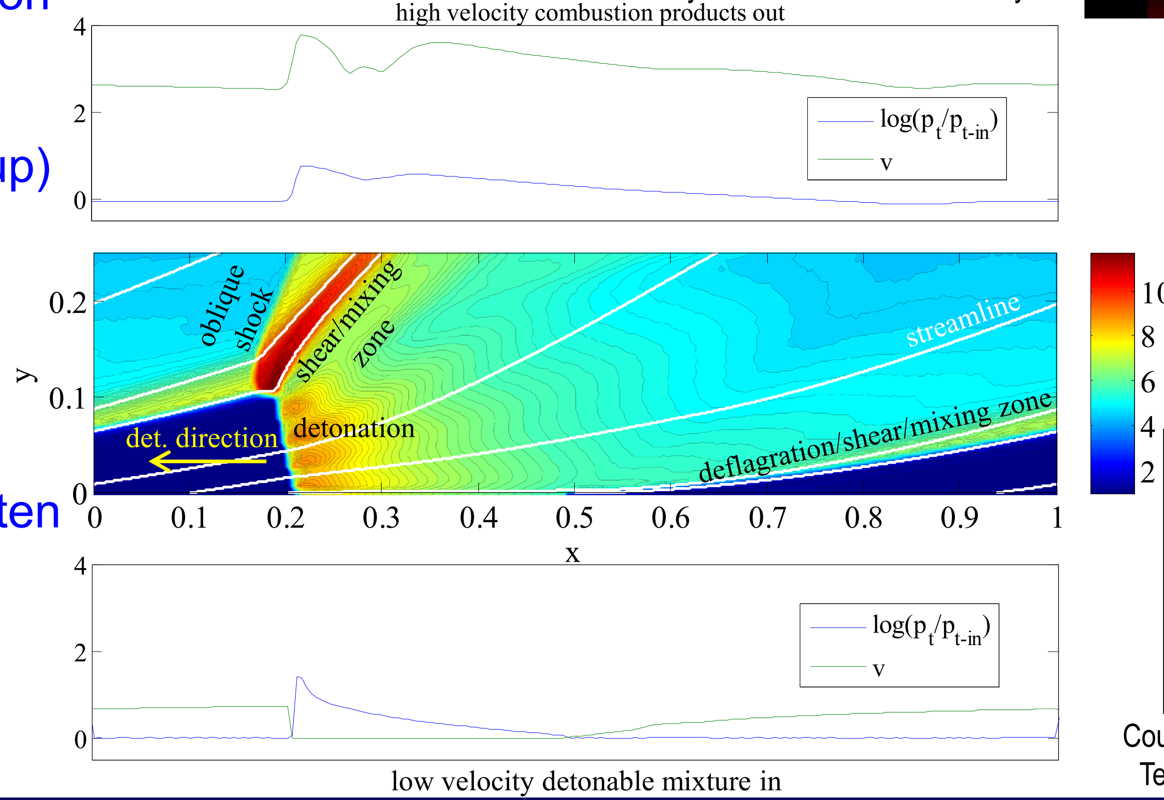


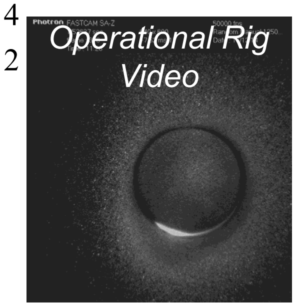
Courtesy Naval Research Laboratory

Courtesy AFRL

Characteristics

- Supersonic detonation approximates CV
- No ignition source required (after startup)
- No DDT obstacles required
- High performance potential
- Very high frequency operation (kHz) – often aero valved
- Highly non-uniform effluent (but less so than PDE)





Courtesy National Energy Technology Laboratory

…And PGC Someday?

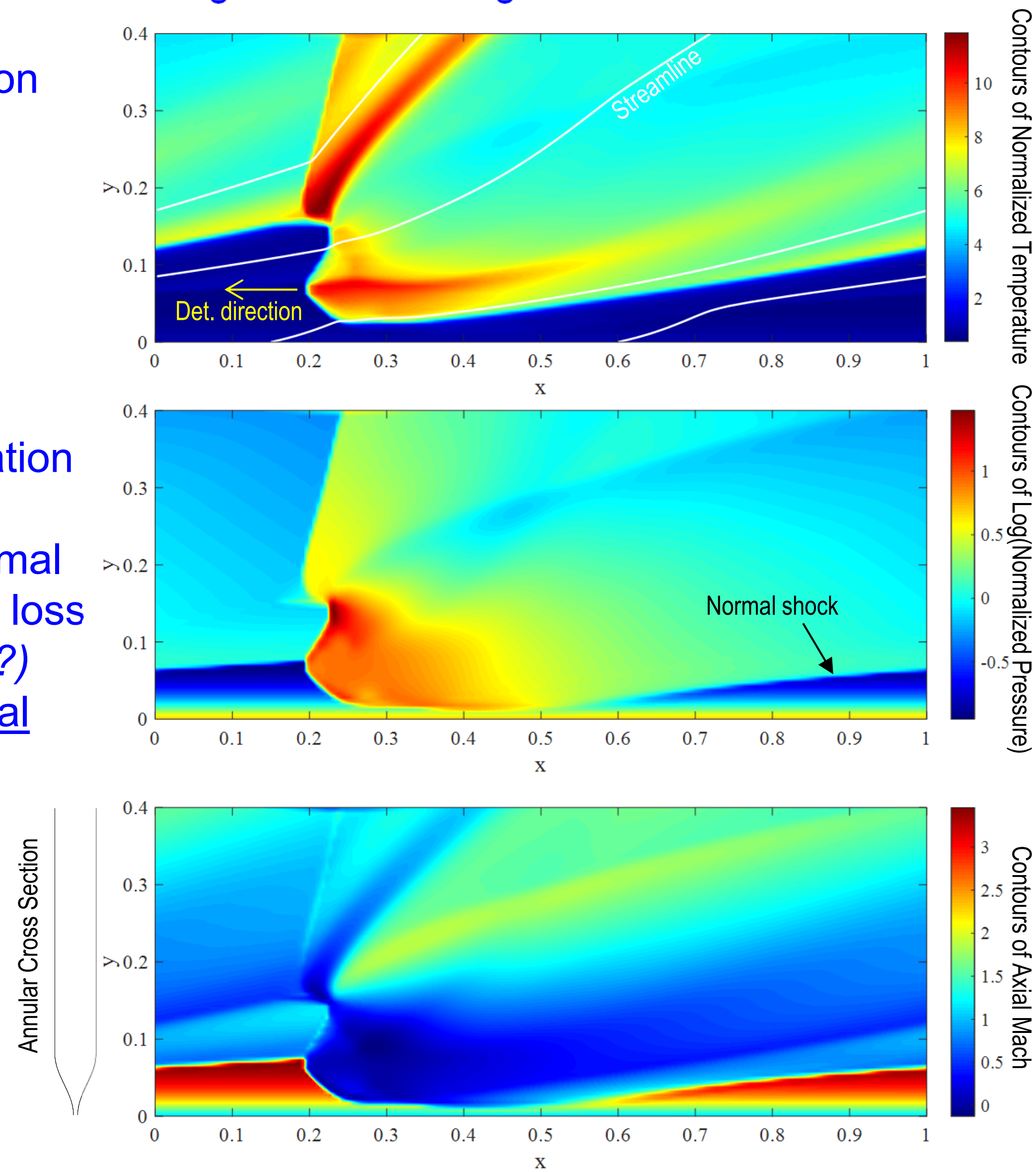
Supersonic Throughflow Rotating Detonation Engines

Setup

- Isentropic inlet
- Inviscid
- Adiabatic
- Premixed
- Guaranteed detonation
- Stoichiometric H_2/Air
- $P_{t3}/p_9=10$
- $T_{t3}=540$ R

Characteristics

- Supersonic axial flow upstream of detonation throughout annulus
- Pressure gain of detonation offset by normal shock loss yielding system total pressure loss *(but doesn't all scram lose total pressure?)*
- Reaction completes over a <u>very short axial distance</u>
- Intended to demonstrate theoretically possible flow field scenario only
- Implies an annular propulsion system



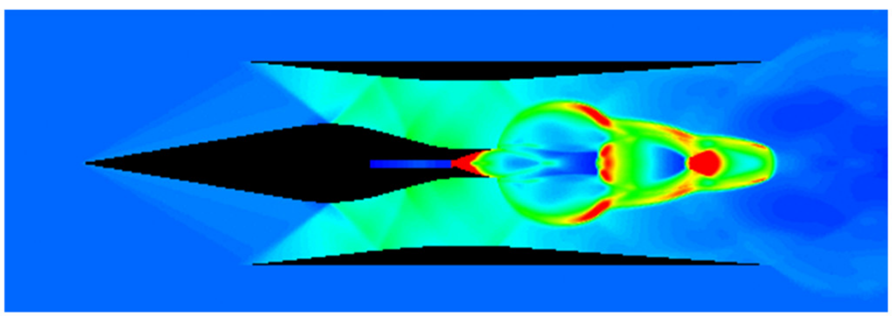
…And PGC Someday?

Pulse Detonation Combined-Cycle Propulsion (PDCC)

The Concept: Take advantage of improved thermodynamic efficiency and ejector performance of pulse detonation to enable a family of high performance combined-cycle propulsion options for access to space.

<u>Advantages for initial application study (Pulse Detonation RBCC):</u>

- Increased rocket cycle efficiency for a given propellant supply pressure
- Improved energy transfer to the secondary stream - gasdynamic waves instead of viscous shear – for Modes 1 & 4 (ducted rocket)
- Valved combustor provides increased rocket throttle ratio, leading to improved trajectory optimization
- Fast deflagration/detonation in secondary stream can improve thermodynamic efficiency further in Modes 1 & 4



Axi-symmetric Model of PDRBCC Engine with Pressure Contours

<u>PDRBCC Operating Modes</u>

- Mode 1 – Ejector Ramjet
- Mode 2 – Ramjet
- Mode 3 – Scramjet
- Mode 4 – Rocket

See Yungster, S., Perkins, H., "COMPUTATIONAL STUDY OF THE AIR-AUGMENTED PULSE DETONATION ROCKET ENGINE," JANNAF Meeting, May, 2007

Challenges

(We're Engineers-This is What We Live For!)

(Hey, if it were easy, it would have been done years ago)

- Fundamental Unsteadiness
  - Manifests as loss when developed momentum is considered
  - Components to which PGC device couple (inlets, nozzles, turbomachinery) are often designed/optimized for steady flow
  - Component aerodynamic response unquantified, unsteady-tolerant design approaches unclear
- Valves
  - All PGC methods require robust valve systems (mechanical or aero) which: prevent backflow; have low loss on forward flow; operate at high frequency; don't fail, tolerate high heat loads (though they are at least intermittent); are lightweight.
- Thermal Management
  - PGC methods have very high associated temperatures and heat transfer coefficients. They are intermittent, but still require attention.
- Instrumentation and Measurement
  - Harsh, high frequency, large amplitude range environment of PGC devices makes most conventional measurements very difficult
- Controls and Actuation
  - Most PGC devices do not operate (well) passively
- Modeling
  - Methods for PGC are fluidically complex
  - **Validated** models are essential to development and optimization

Recent Research Efforts Have Yielded Substantial Progress in All Areas: No Show Stoppers

Community (U.S. Only)

Government

- Defense Advanced Research Projects Agency
- Air Force Research Laboratory
- Air Force Office of Scientific Research
- National Aeronautics and Space Administration – Glenn Research Center
- Naval Research Laboratory
- Department of Energy – National Energy Technology Laboratory

Industry (incomplete)

- GE
- UTRC
- Aerojet
- Rolls/Royce
- LibertyWorks

University (U.S. incomplete)

- Purdue
- IUPUI
- U. Cincinnati
- Penn. State
- Naval Postgraduate School
- University of Connecticut
- U.T. Arlington
- U. Central Florida
- U. Michigan
- U. Maryland
- U. Florida

These and Many Other Organizations Are Represented in the
AIAA Pressure Gain Combustion Technical Committee

Conclusion

- Pressure Gain Combustion offers the possibility of substantial performance enhancement in high speed propulsion
- The concept can be thought of as transforming the basic propulsion cycle from Brayton to Atkinson/Humphrey
- There are numerous ways to implement PGC: All are fundamentally unsteady
- There are numerous challenges to successful implementation, but progress is ongoing and no show stoppers have been identified
- This is really exciting stuff!

END