Pressure Gain Combustion 101

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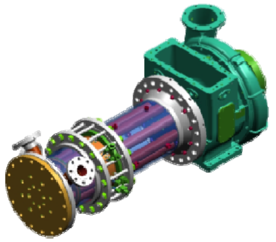
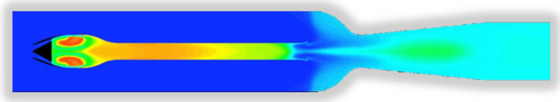
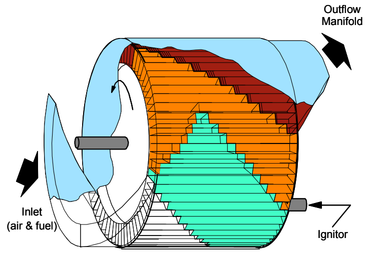
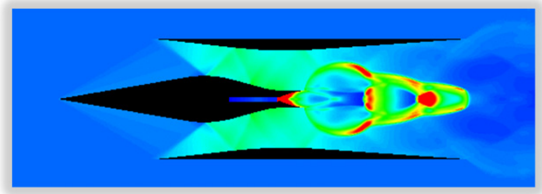
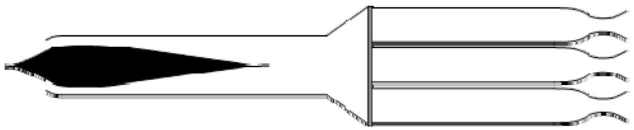








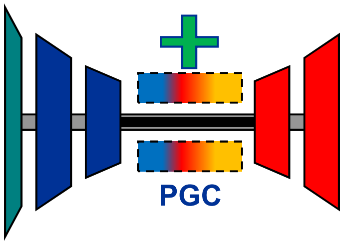


Pressure Gain Combustion Overview: Principles, Operation, and Applications

Propulsion and Energy 2018
Cincinnati, Ohio
July 9-11, 2018

Outline

- What is Pressure Gain Combustion (PGC)?
- Fundamental Thermodynamics
- Benefit Examples
- Implementation Strategies



What is Pressure Gain Combustion?

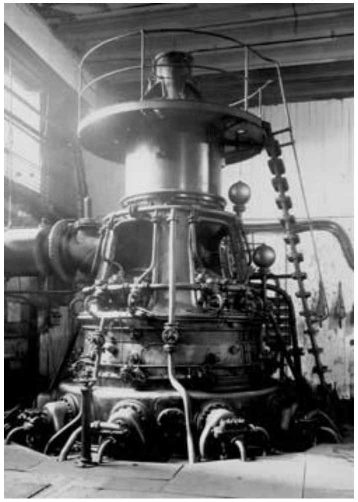
PGC[†]: A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure[*] and allowing work extraction by expansion to the initial pressure.

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

[*] Conventional combustion incurs a total pressure loss

The concept actually is old…

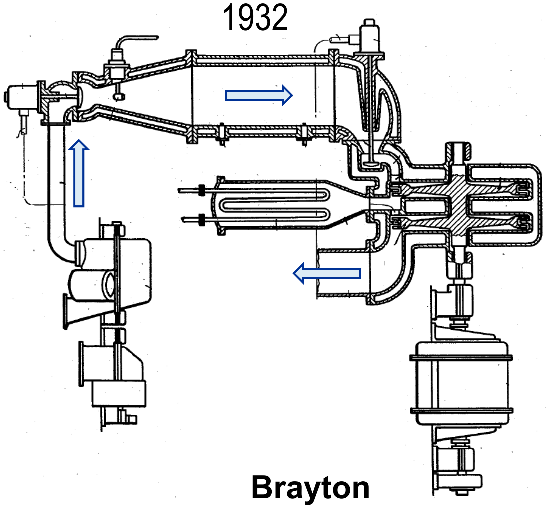
Holzwarth
Explosion Turbine
1914



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

Fundamental Thermodynamics

Explosion Turbine (Holzwarth)
1932



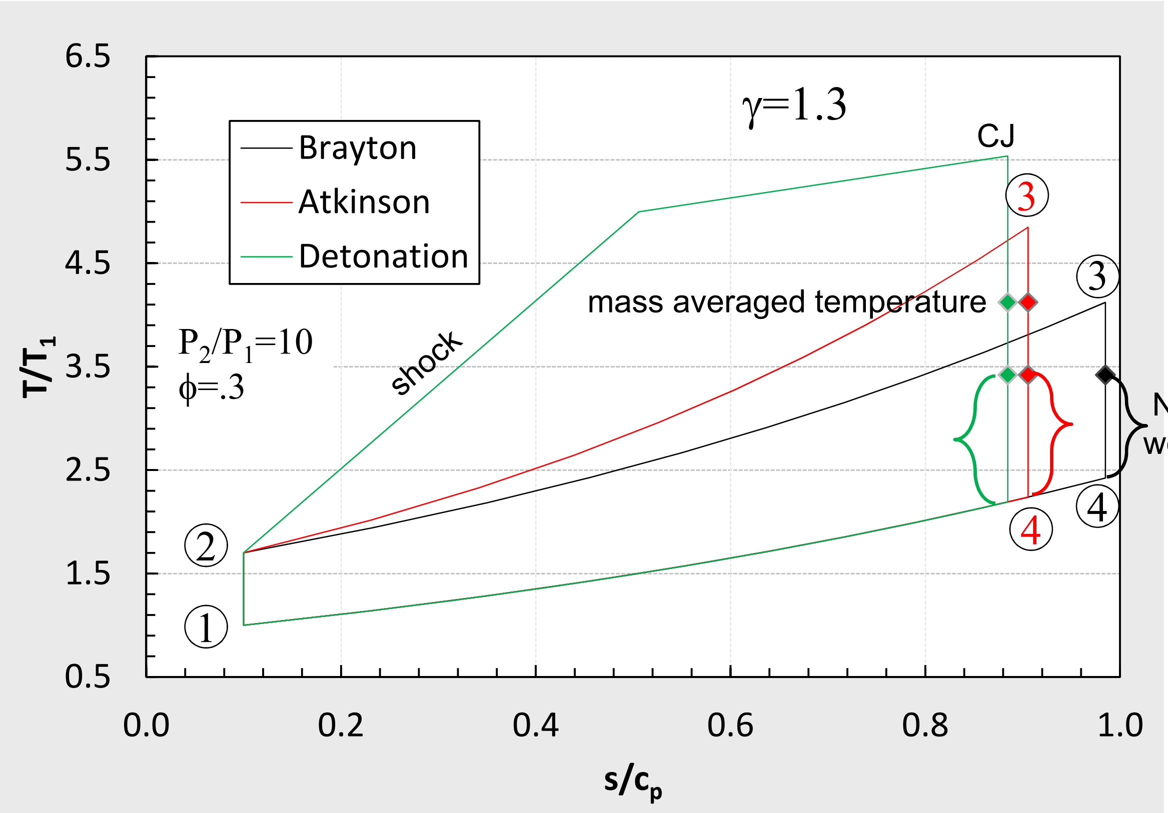
Brayton

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

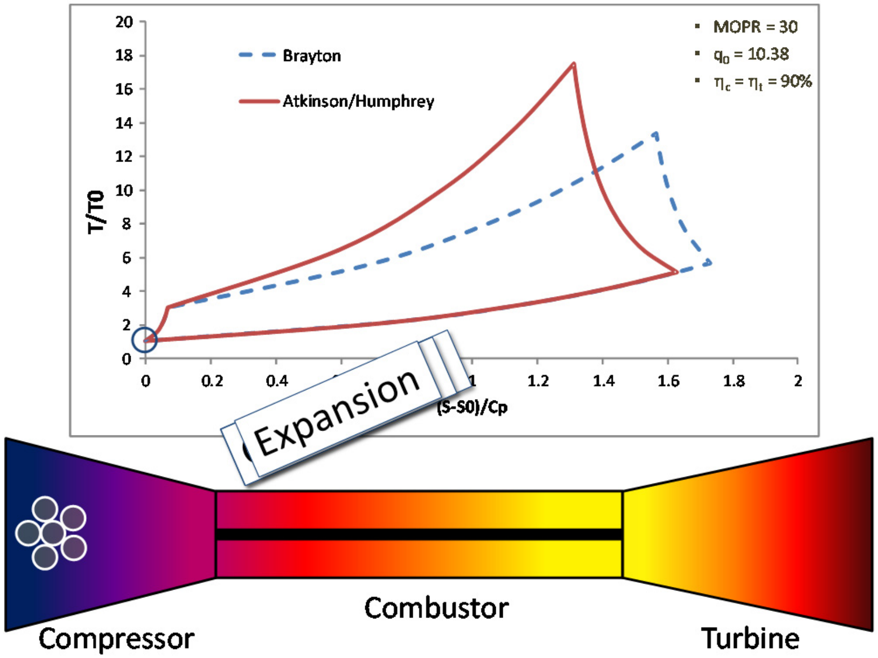


- PGC expands by gasdynamic conversion to kinetic energy (e.g. blowdown)
- Flow to turbine is fundamentally unsteady, and/or spatially non-uniform
- Peak Atkinson Temperature is only momentary

Fundamental Thermodynamics

Animation of a Representative PGC Cycle With Turbomachinery

- Illustrates essential concepts
- Demonstrates the most basic acceptable level of modeling
- More quantitatively valuable than might be expected.

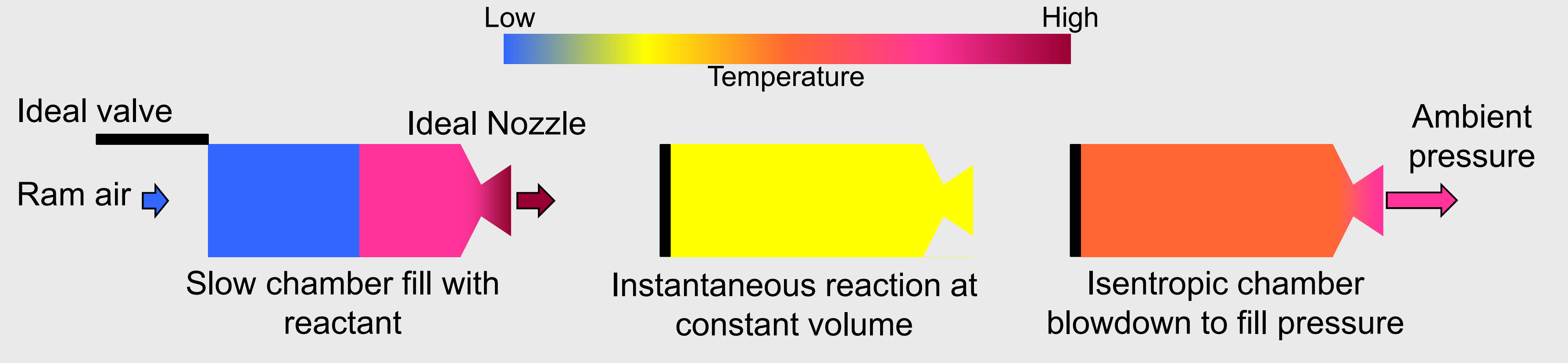


Fundamental Thermodynamics

PGC in Notional Ram Device

- High speed inlet compresses
- Mechanical combustor inlet valve envisioned
- Pressure gain converted to kinetic energy via unsteady nozzle

Notional Ram PGC Device



Pressure Rise Provides Increased Availability to Nozzle

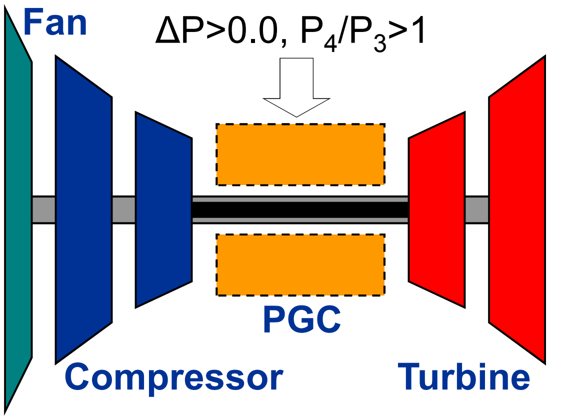
Example Benefits

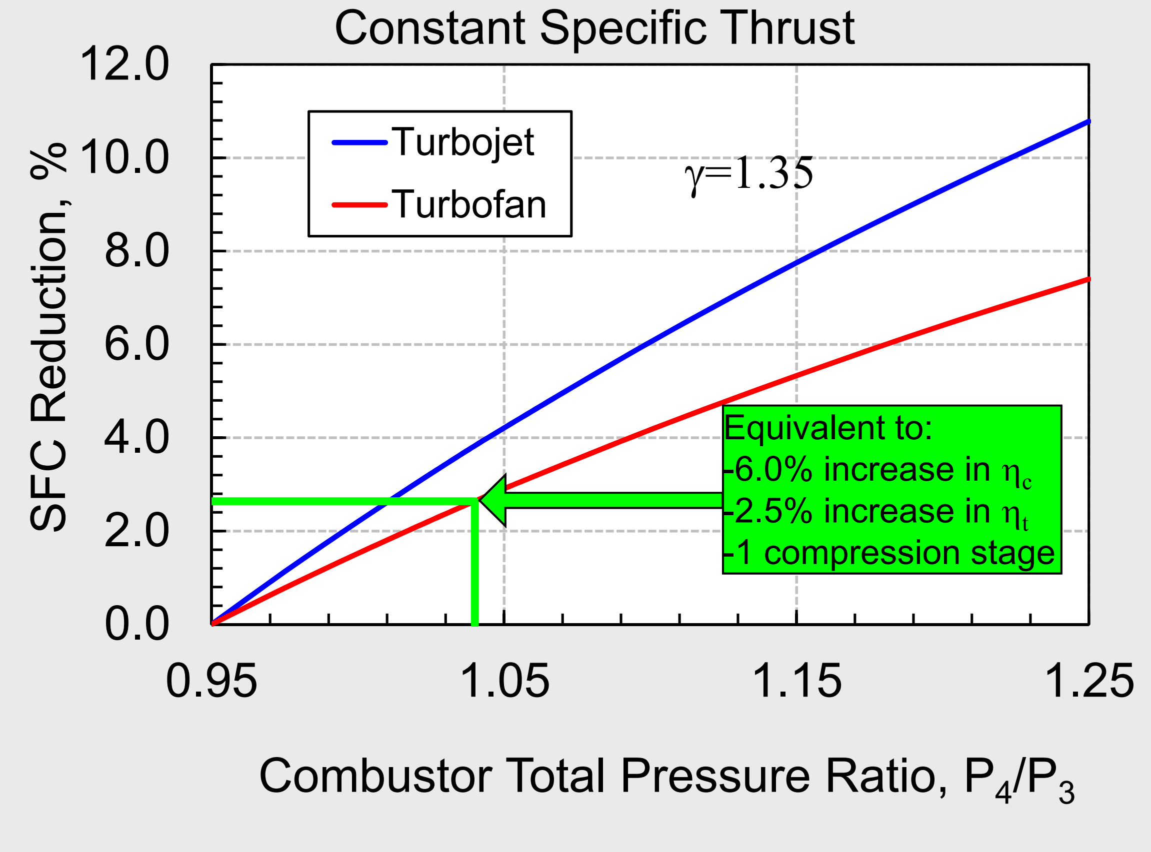
PGC for Gas Turbines

Two specific engines considered

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

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



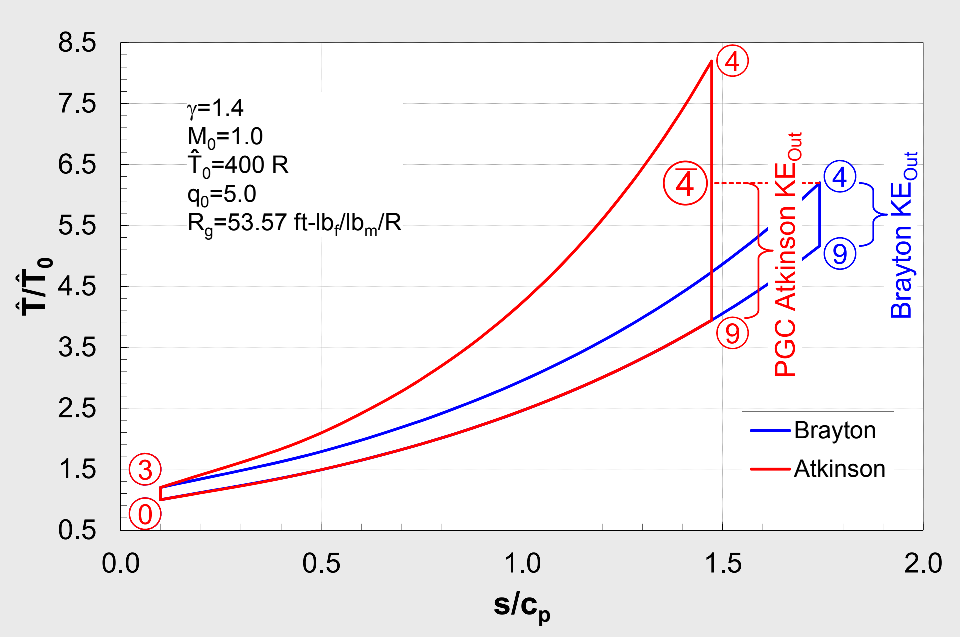


Equivalent to:
- 6.0% increase in η_c
- 2.5% increase in η_t
- 1 compression stage

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

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

Example Benefits



PGC for Ram Devices

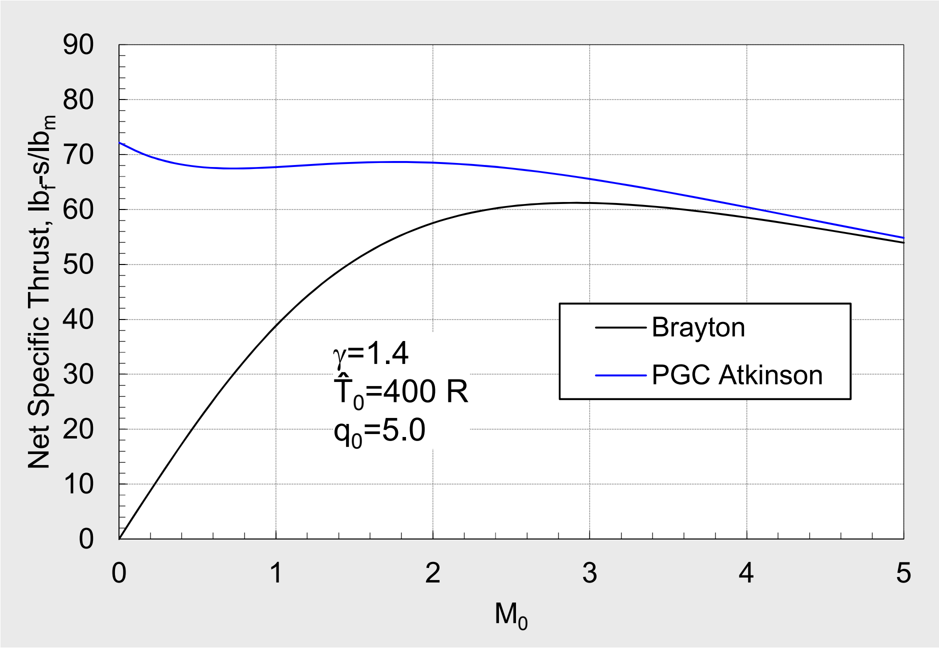
Ideal inlet

Ideal nozzle

Brayton P_{t4}/P_{t3}=1.0

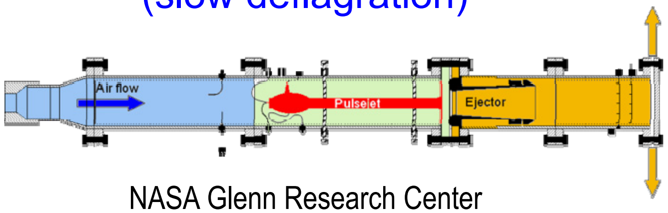
For the Same Heat Addition:

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



Implementation Strategies

Resonant Pulse Combustor (slow deflagration)



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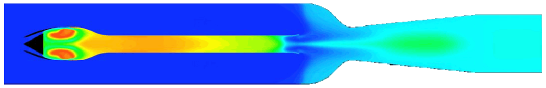
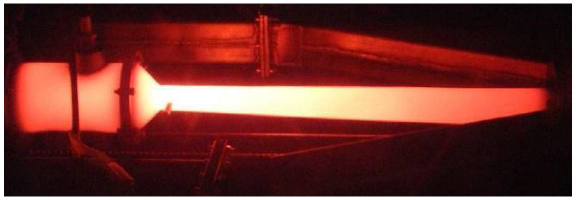


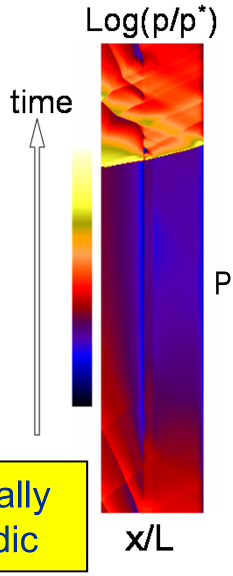


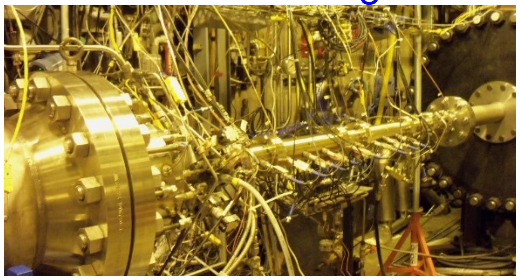
University of Cambridge

All Are Fundamentally Unsteady & Periodic

Fill →Burn →Blowdown →Repeat

Pulsed Detonation Engines

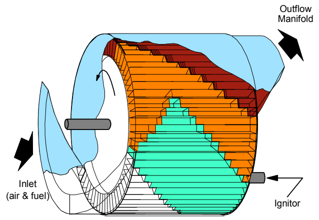




Pratt & Whitney/United Technologies Research Center

G.E. Global Research Center

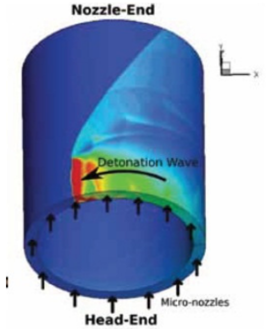
Internal Combustion Wave Rotor ('Fast' Deflagration)



IUPUI/Purdue/LibertyWorks

Rotating Detonation Engines

Air Force Research Laboratory

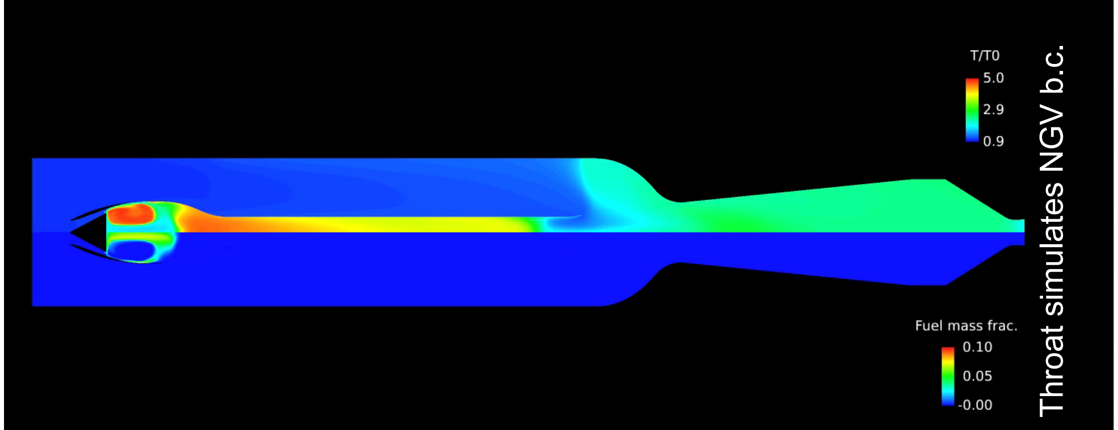


Naval Research Laboratory

Implementation Strategies

Resonant Pulse Combustion

Envisioned As One of Many For Gas Turbine Application



CFD Shrouded Pulse Combustor Video

Unshrouded Operational Video

Characteristics

- Self-sustaining (no spark required)
- Self-aspirating (i.e. operates statically) thus unequivocally demonstrates pressure gain
- Readily operates on liquid fuels
- Few or no moving parts
- Relatively low mechanical/thermal stress
- Relatively benign effluent
- Limited performance potential (confined, not constant volume combustion)

Implementation Strategies

Internal Combustion Wave Rotor (ICWR)

('Fast' Deflagration)

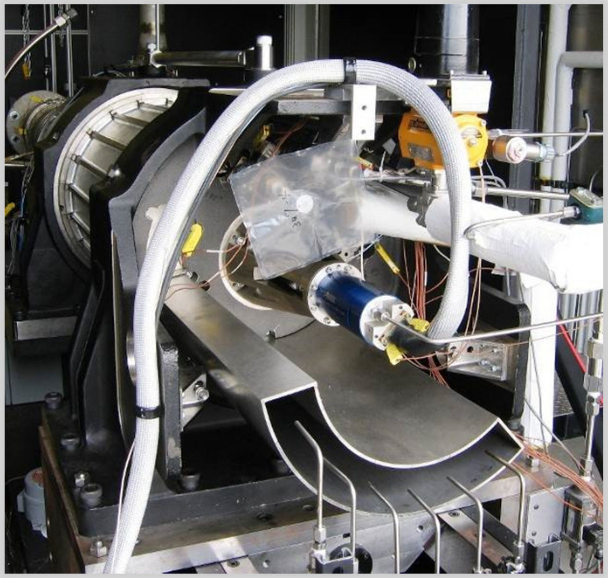
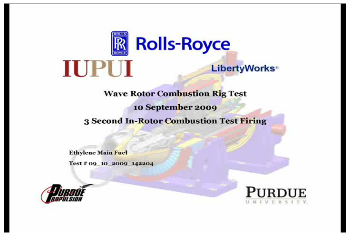


Photo and video courtesy IUPUI and LibertyWorks



Rolls-Royce

IUPUI

LibertyWorks

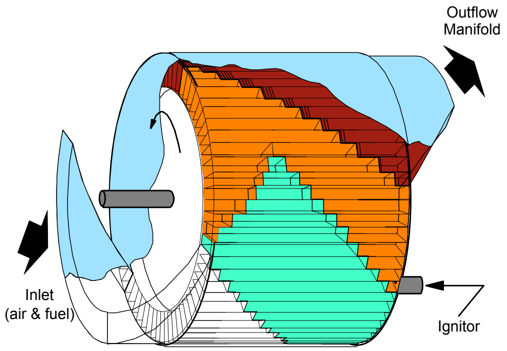
Wave Rotor Combustion Rig Test
10 September 2009
3 Second In-Rotor Combustion Test Firing

Ethylene Main Fuel
Test # 09_10_2009_142204

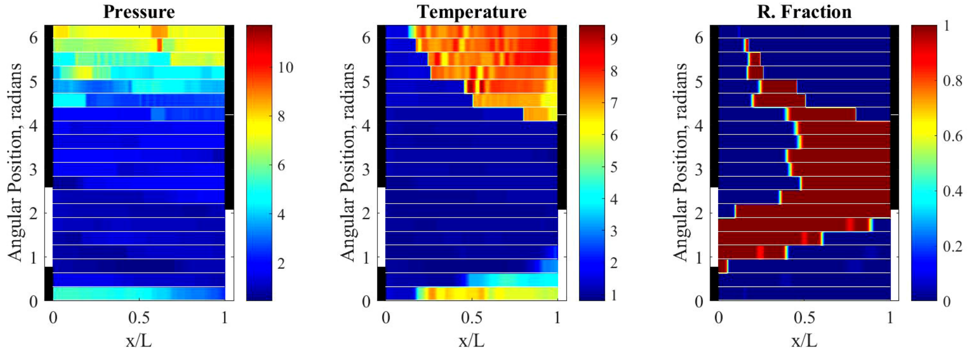
Purdue Propulsion

Purdue University

Operational Rig Video



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



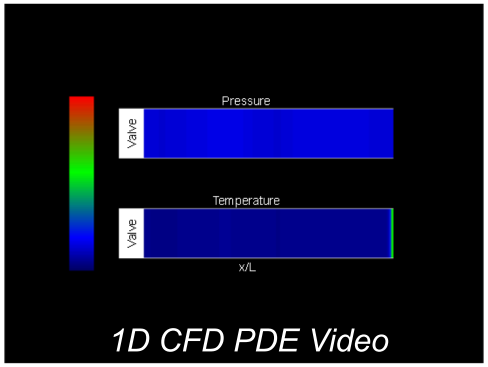
1D CFD Wave Rotor Video

Characteristics

- Flow in ports is nominally steady, though spatially non-uniform
- Rotor is self-cooling is possible
- Very high frequency ignition source req
- Rotation provides valving not power extraction
- Valves implemented at both ends (closest to true constant volume combustion
- Requires sealing between rotor and endwall
- High performance potential
- Measured pressure gain

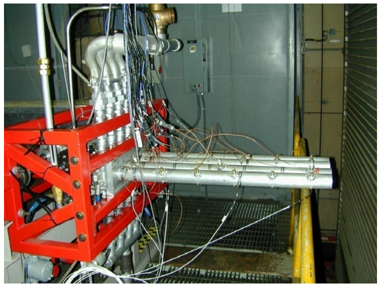
Implementation Strategies

Pulsed Detonation Engines (PDE)

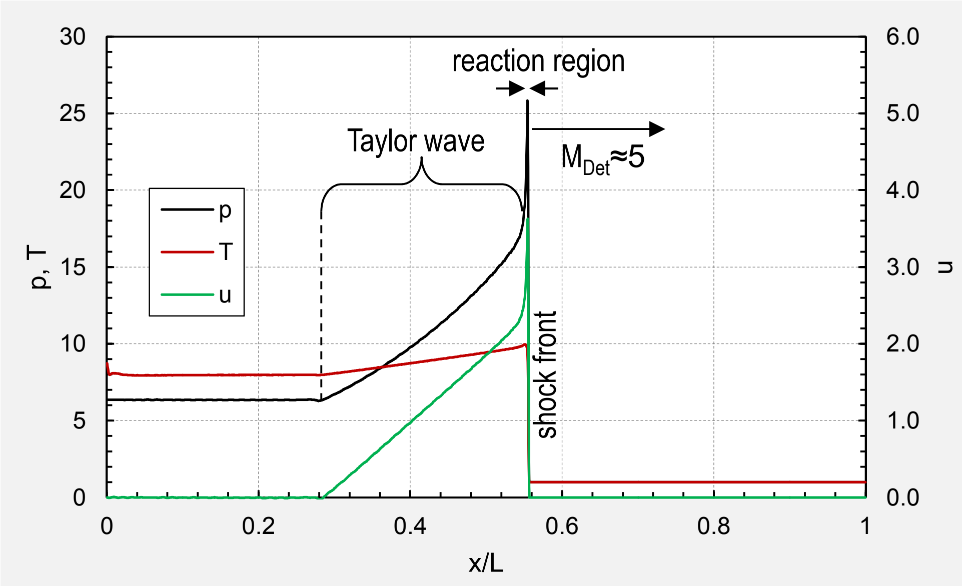


1D CFD PDE Video

Courtesy Naval Postgraduate School



Courtesy Air Force Research Laboratory

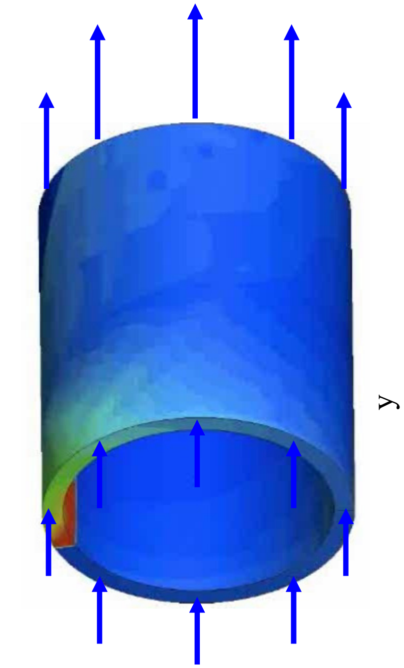


Characteristics

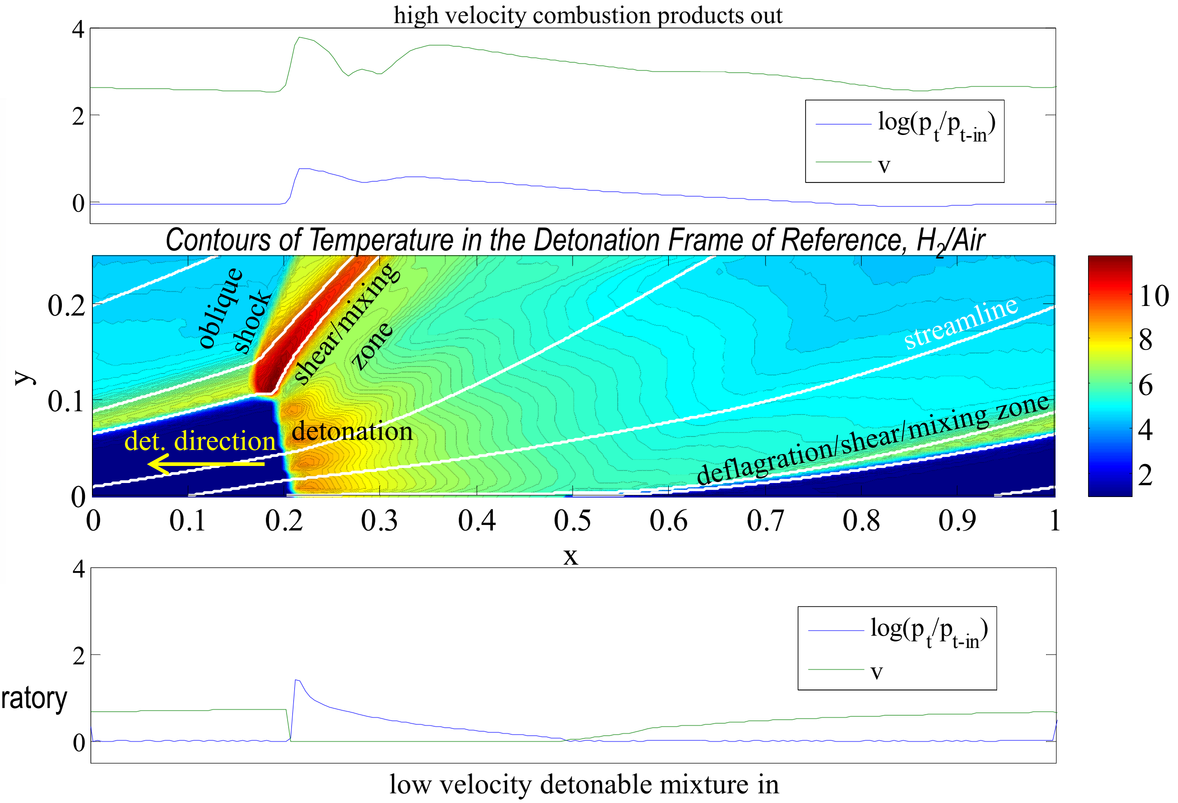
- Supersonic detonation approximates CV
- Ignition source required
- Deflagration-to-detonation transition obstacles required
- High frequency valves required
- Highly non-uniform effluent
- High performance potential
- Pressure gain measured

Recent Implementation Approaches

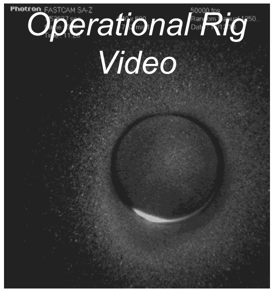
Rotating Detonation Engines (RDE)



CFD RDE Video
Courtesy Naval Research Laboratory



Courtesy AFRL



Courtesy National Energy Technology Laboratory

Characteristics

- Supersonic detonation (approximating CV) travels circumferentially
- Fluid travels (predominantly) axially
- No ignition source, or DDT obstacles required
- High performance potential
- Very high frequency operation (kHz) – typically mandating aero valve
- Highly non-uniform effluent (but less so than PDE)

Conclusion

- Pressure Gain Combustion offers the possibility of substantial performance enhancement in propulsion and power applications
- The concept can be thought of as transforming the basic propulsion cycle from Brayton to Atkinson/Humphrey
- Targets improvement at the major source of entropy generation
- There are numerous ways to implement PGC: All are fundamentally unsteady

END