A Case for Basic Rotating Detonation Engine Research

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Outline

- Basic Thermodynamics of Pressure Gain Combustion
- Benefits Thereof
- PGC Approaches
- The Rotating Detonation Approach
- Challenges

Why We Need Basic Research

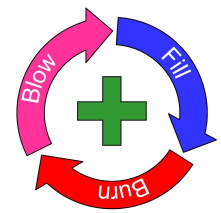
Basic Thermodynamics-RDE is PGC

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.

Practical PGC Devices for Propulsion and Power:

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



In a Nutshell:

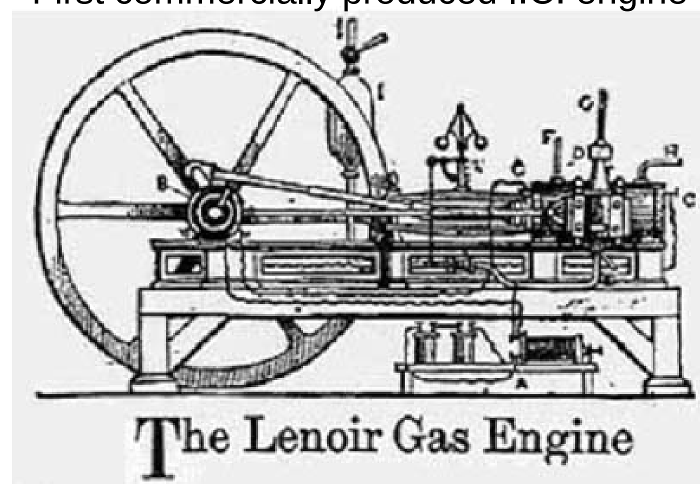
A Lenoir-like Cycle is Executed <u>Without Pistons</u>, (and with few moving parts)

Lenoir Cycle:

- Isochoric Heat Addition
- Isentropic Expansion
- Isobaric Heat Rejection

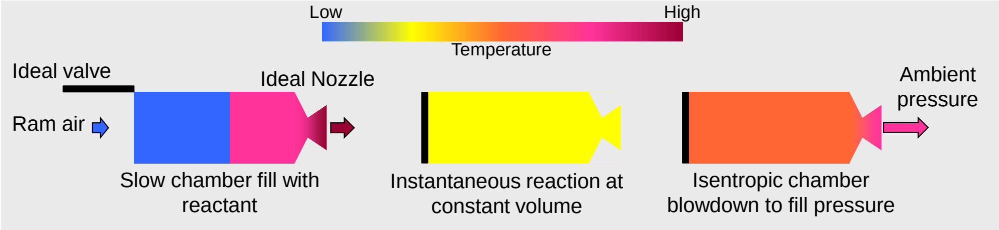
Patented 1860

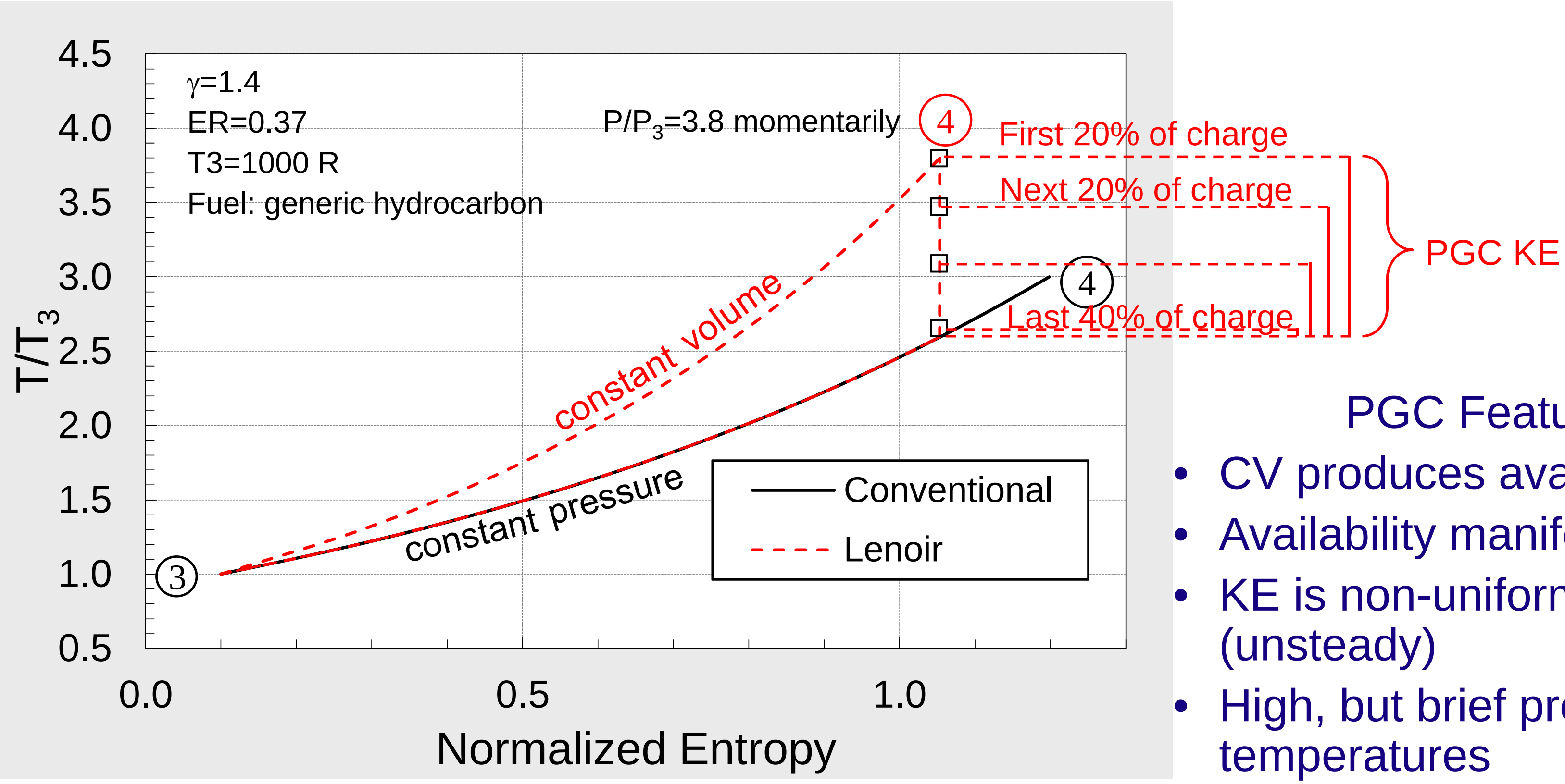
First commercially produced I.C. engine



Basic Thermodynamics-Lenoir Cycle

Notional PGC Device



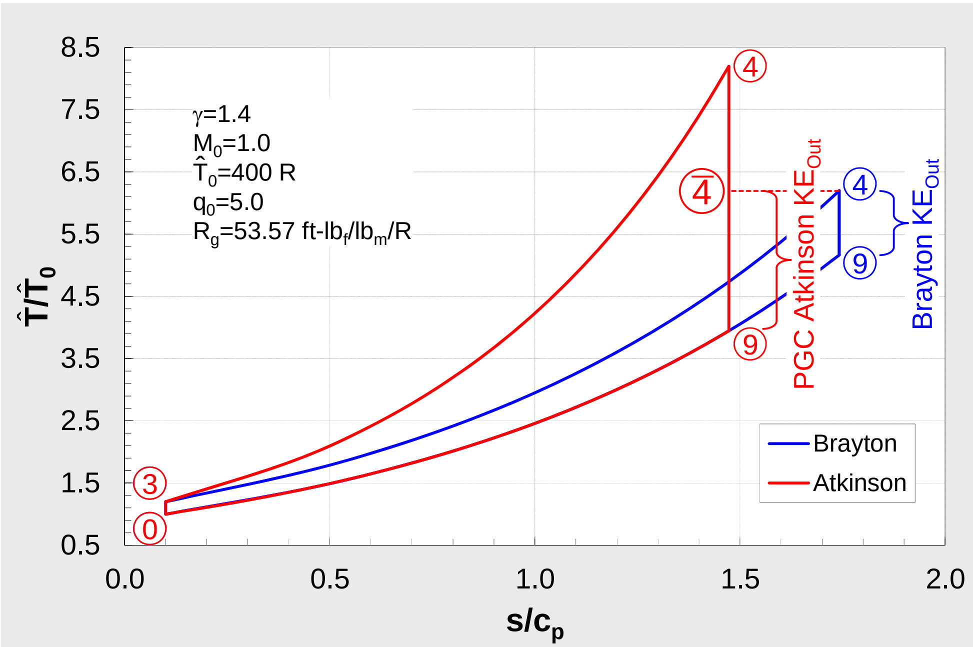


Confinement During Combustion Is Good

PGC Features

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

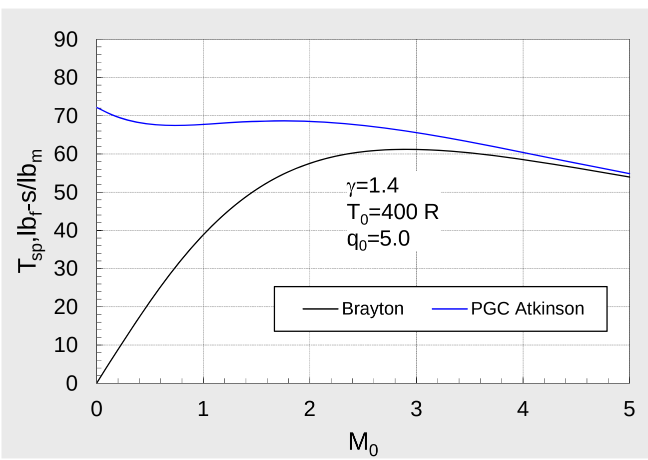
Benefits-Air Breather



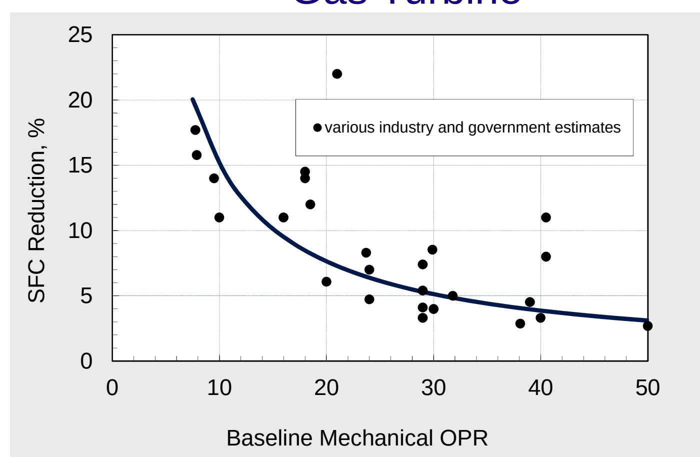
PGC Features

- Compression up front and additional expansion at the back yields Atkinson/Humphrey cycle.
- Significant decrease in SFC
- Significant increase in specific power or specific thrust
- May allow ‘effective’ OPR’s that are difficult to achieve with conventional means for a given engine class

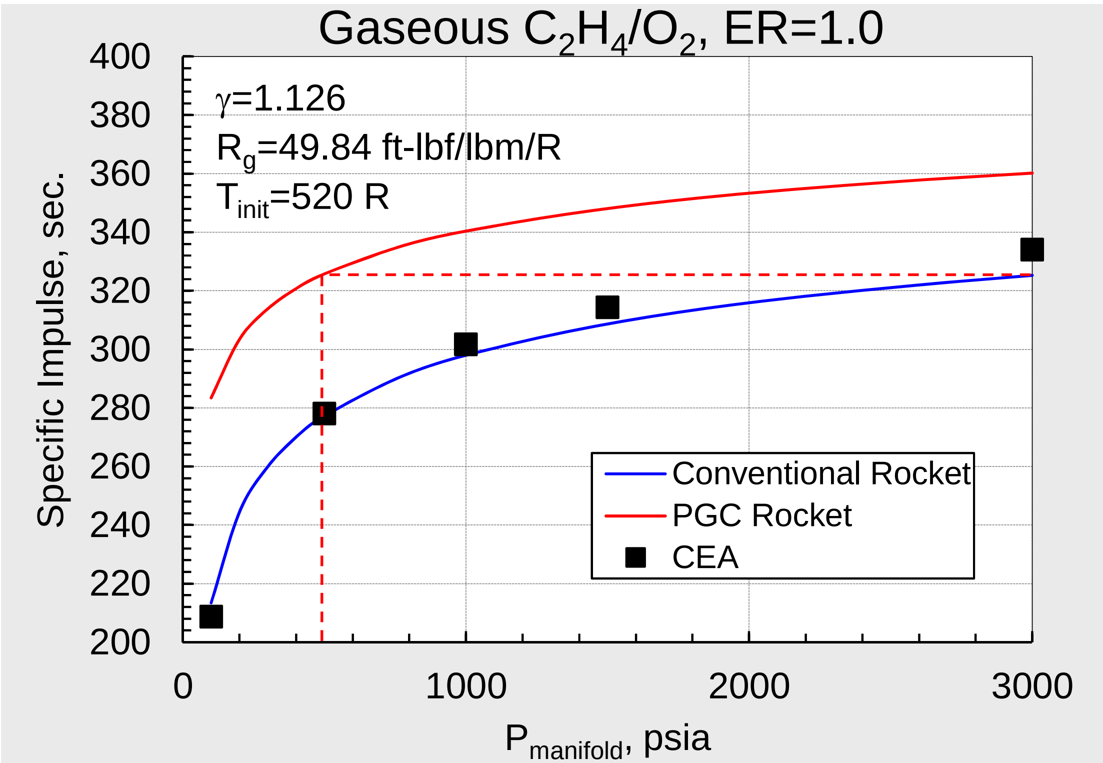
Ram



Gas Turbine

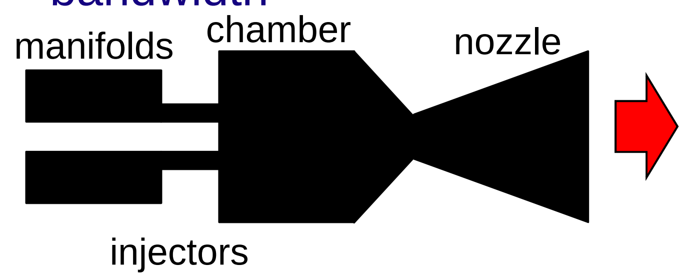


Benefits-Rocket



Assumptions:

- Calorically perfect gas (excluding CEA)
- Adiabatic
- Ideal Nozzle
- Sea level exhaust pressure
- Lossless injectors w/ infinite bandwidth



PGC Rocket at $P_{manifold}$ of 488 psia Delivers Same I_{sp} as Conventional Rocket at $P_{manifold}$ of 3000 psia

Smaller or Even No Pumps → Better T/W

Tyranny of the Rocket Equation

"When making a rocket that is near 90% propellant, small gains through engineering are literally worth more than their weight in gold."

-Don Pettit

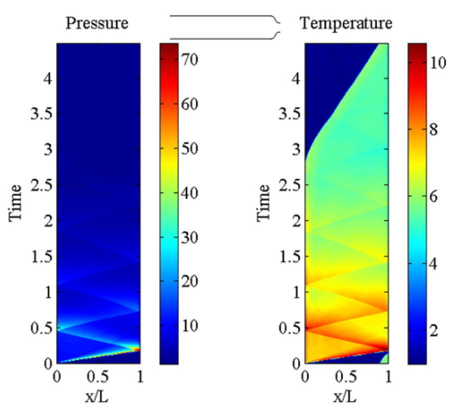
PGC Approaches

Pulse Detonation

- Axially propagating detonation wave replaces CV process
- Typically mechanically valved at inlet
- Usually envisioned as a cluster of regularly firing tubes
- Per tube frequencies on order of 100 Hz.
- Substantial history of efforts
- Current efforts exist

PDC

G.E. Global Research Center 2005

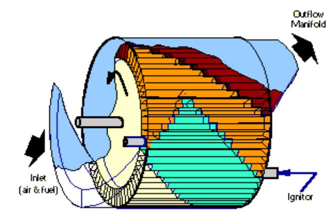


Rotating Detonation is Not the Only Game in Town

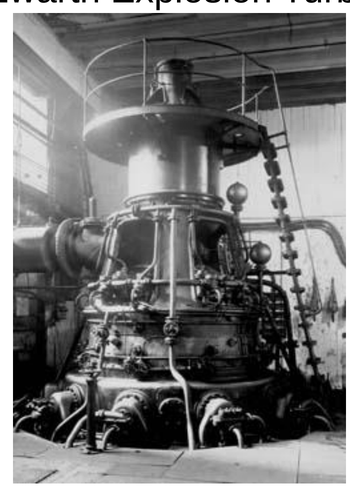
True Constant Volume

- Confinement provided by valves at both ends
- Operational versions exist

IC Wave Rotor



Holzwarth Explosion Turbine

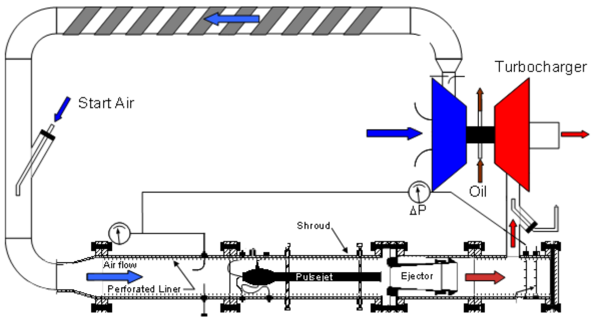


PGC Approaches

Other

- Resonant Pulse Combustion
- See Kan, Heister, et. al.

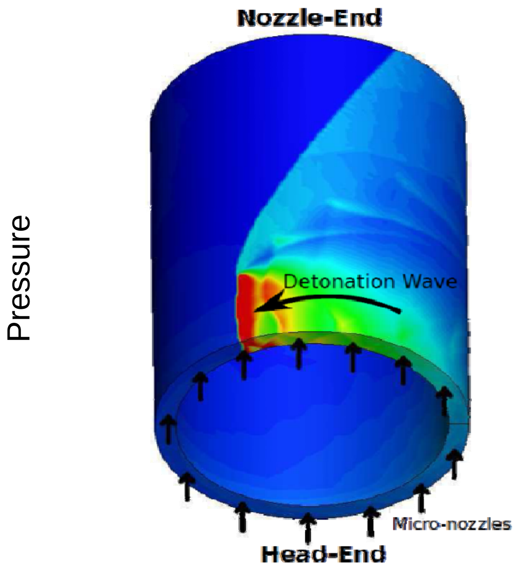
Resonant Pulse Combustor



Demonstrated pressure gain during closed loop operation in gas turbines using liquid fuels

Rotating Detonation

- Circumferentially propagating detonation wave replaces CV process
- Typically aero-valved at inlet
- Basically an annulus with a nozzle
- Operating frequencies on order of 1000 Hz.
- Smaller history of efforts



Source: Schwer, AIAA 2011-581

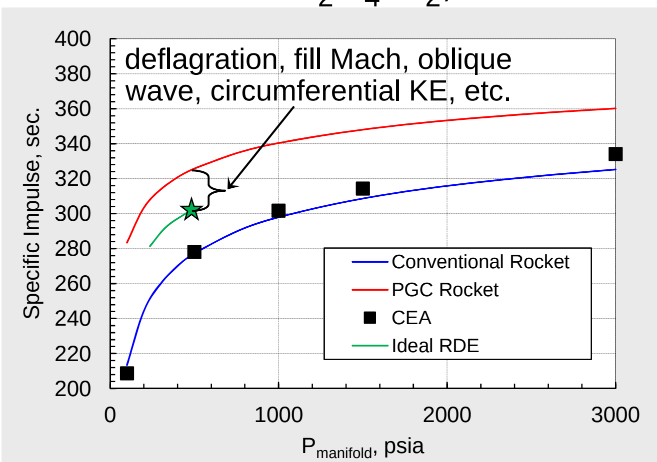
All Do The Same Basic Thing; All Have Pros and Cons

Why the Rotating Detonation Approach?

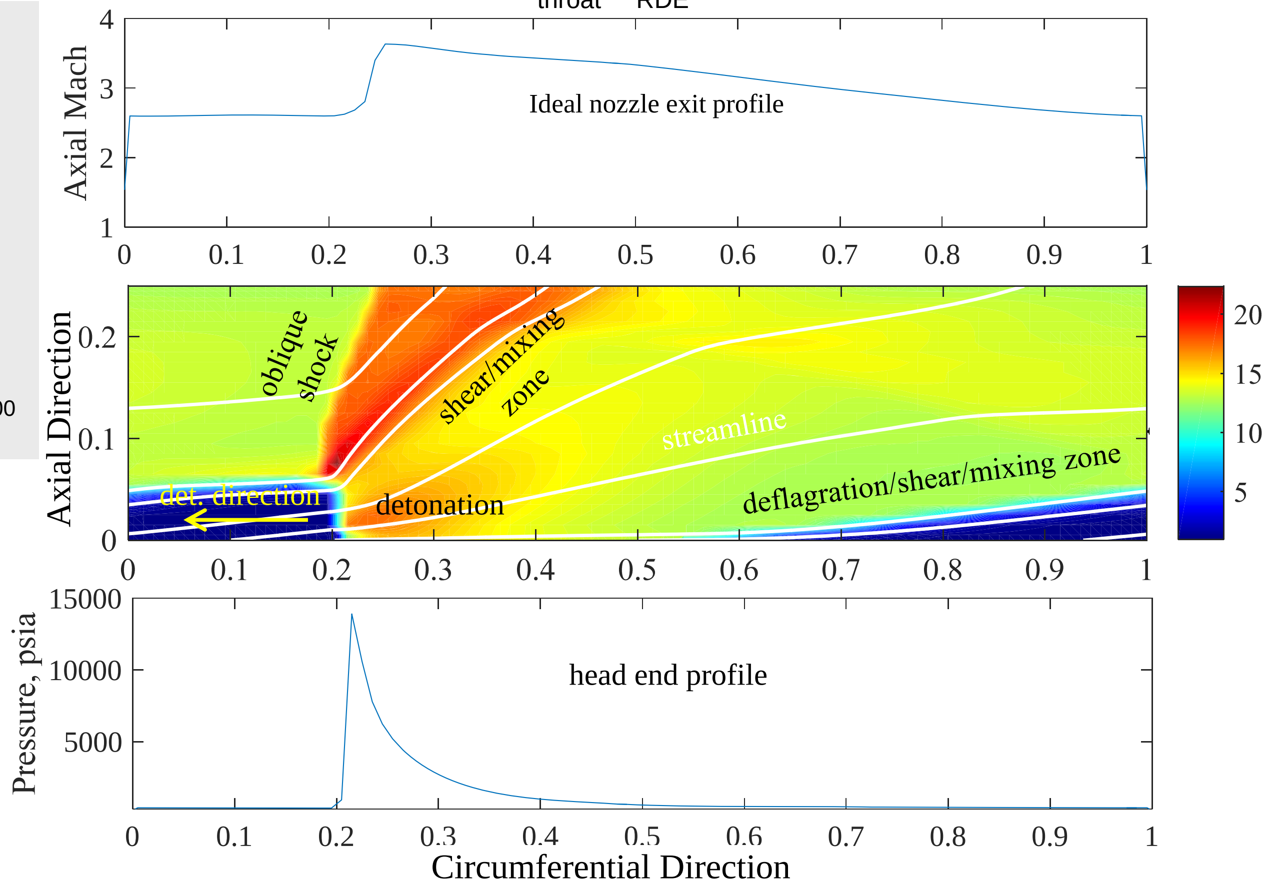
A Closer Look at an Example Rocket Cycle

(using a 'validated' code)

Gaseous C_2H_4/O_2, ER=1.0



RDE with A_{throat}/A_{RDE}=0.8 at Exit



Features

- Impressive performance
- Compact combustor L/D near 1 (and possibly << less!)
- Continuous operation – no sparking or crossover tubes, no DDT devices

Potential Exist for Very Compact, High Efficiency, High T/W Engines, With Fewer Parts

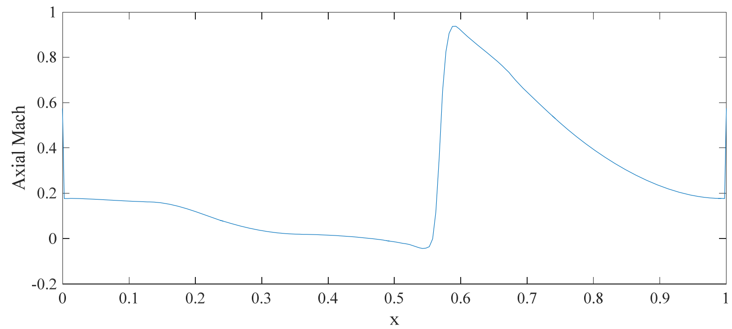
Challenges

The 'Real' World

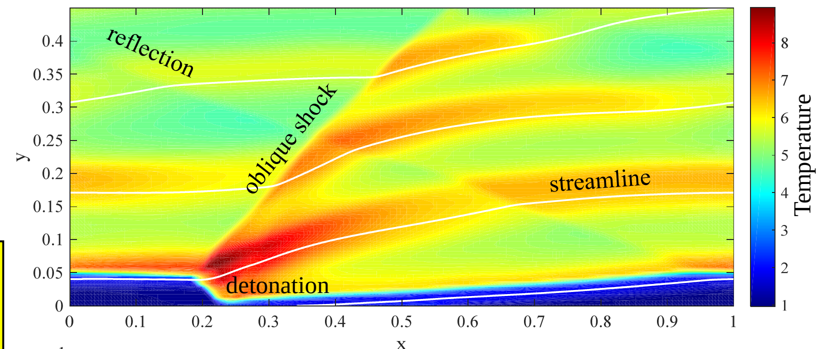
Simulated RDE in a T-63

- Non-optimized, laboratory RDE
- Intended as a turbine interaction test, not a RDE performance test
- Unusual high back pressure scenario
- Used here because it is illustrative

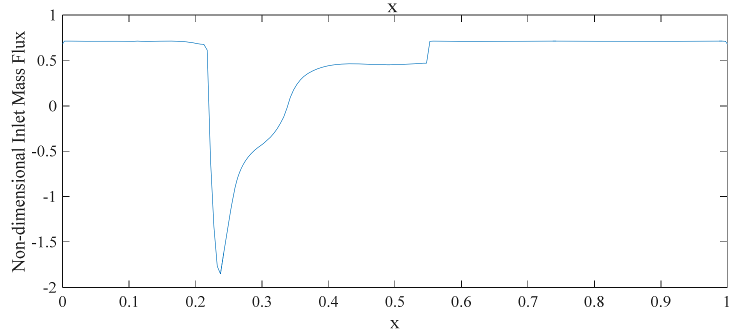
REMEMBER: RDE's Have Only Been Truly Operational for 4-5 Years



- RDE exit flow is all subsonic with some inlfow



- RDE length→long residence time, excess heat transfer, dissipation of KE

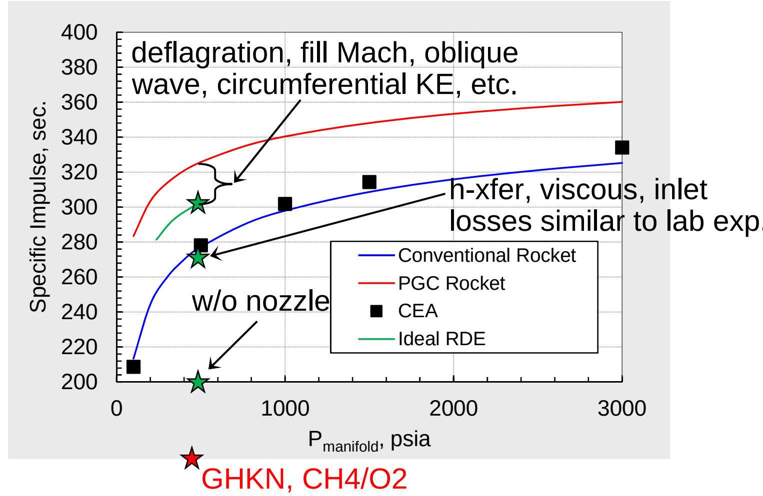


- 45% RDE inlet total pressure drop
- 18% RDE inlet backflow

Current RDE Simulation Shows PR<1.0; Configuration Changes Could Yield PR>1.2

Challenges

Why We Need Basic Research



- RDE's are difficult to analyze
  - Highly coupled
  - Hard to know what causes what
- Conventional measurements are tough to make
- Validated codes are few and often unavailable
  - And murderously hard to validate (see above)
  - Need parametric variation capability
- Significant improvement requires <u>practical</u> understanding of underlying processes
  - Processing liquid fuels
  - Throttling
  - Geometric effects *(min. length, min. diameters, max. annulus width, annular vs. axisymmetric, etc.)*
  - Wave number control *(small effect now, but possibly critical with optimized designs)*
  - Unsteady injection and mixing *(rapid mixing may not be the ultimate goal)*
  - Unsteady nozzle design *(many modeled operating points show mixed sub- & supersonic flow)*
  - Heat transfer *(high temp., density, & velocity →multi-megawatt heat flux & associated lost performance)*
  - Low loss/High diodicity inlets *(models of some current designs indicate >20% backflow and 50% $\Delta p/p$)*
- More minds are needed
  - Understanding these devices enough to be useful takes time, not just $
- Practical application studies are essential
  - What is the best way to utilize the technology, and who should determine this?

Challenges Are Real, Typical for TRL, And Tractable

Concluding Remarks

- Pressure Gain Combustion (PGC) can significantly enhance propulsion and power system performance.
- Rotating Detonation Engine (RDE) technology may be a particularly effective way to affect PGC.
- Significant strides have been made with relatively limited resources, but a sustained effort at basic practical process understanding is needed in order to fully exploit RDE technology.
- Coordination and cooperation between organizations is key, as is growing the community.

END