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 Without Pistons, (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

Notional PGC Device

1. CV produces availability
2. Availability manifested as KE
3. KE is non-uniform (unsteady)
4. High, but brief pressures & temperatures
5. 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

\[ \gamma = 1.4 \]
\[ M_0 = 1.0 \]
\[ T_0 = 400 \text{ R} \]
\[ q_0 = 5.0 \]
\[ R_g = 53.57 \text{ ft-lb/lbm/R} \]
Assumptions:

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

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

Smaller or Even No Pumps $\rightarrow$ 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

True Constant Volume

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

IC Wave Rotor

Holzwarth Explosion Turbine

Rotating Detonation is Not the Only Game in Town
PGC Approaches

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

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

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

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 $\text{C}_2\text{H}_4/\text{O}_2$, ER=1.0

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
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

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 practical 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% Δp/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