Impact of an Exhaust Throat on Semi-Idealized Rotating Detonation Engine Performance

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SciTech 2016
54th AIAA Aerospace Sciences Meeting
San Diego, CA
January 4-8, 2016
Outline

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Background

Rotating Detonation Engines (RDE’s) represent an Intriguing Approach to Detonative Pressure Gain Combustion (PGC)

PGC: A periodic process, in a fixed volume, whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure.

- 1000+ Hz. cycle frequency
- No ‘spark’ required
- No lossy DDT devices
- Compact

Source: Schwer, AIAA 2011-581
Problem Statement

Consider a Semi-Ideal, Ram-Based, Stoichiometric Hydrogen Fueled RDE at 37,000 ft., Flying at Mach 1.37
(Note-Flight conditions are illustrative only)

- Semi-Ideal Means
  - Mil. Spec. engine inlet
  - Combustor (RDE) inlet is lossless
  - Combustor inlet has no reverse flow (i.e. perfect valve)
  - Engine exit nozzle is lossless (i.e. perfectly expanded)
  - Adiabatic
  - Inviscid
  - Premixed
  - Retains fundamental entropy sources associated with RDE’s
Problem Statement

- RDE 21% above RJ
- RDE 22% below PDE
Problem Statement

Contours of Entropy Relative to Algebraic PDE

highest entropy flow

- 7-10% Disparity?

Where's All This Blue Coming From and What Can Be Done About it?
Problem Analysis

Primary Analysis Tool

Quasi-2-Dimensional Euler Solver With Sources

- Source Terms Model:
  - Chemical Reaction
  - Friction (*not used here*)
  - Heat Transfer (*not used here*)
- 2 Species Reaction (reactant or product)
- Simplified Finite Rate Reaction
- High Resolution Numerical Scheme
- Coarse Numerical Grid (< 10,000 cells)
- Adopts Detonation Frame of Reference
  - Time derivatives ultimately vanish and solution is steady
- Robust Boundary Conditions
  - Sub or supersonic exhaust flow
  - Optional isentropic exhaust throat
  - Forward or reverse inlet flow with choking possible (*not used here*)
  - Physics based inlet loss model from typical restriction (*mostly not used here*)
- Runs on a laptop
  - Approximately 20 sec. per wave revolution
- Validated
  - Compares well with other semi-idealized numerical results
  - Compares well with experimental results
Problem Analysis

Effects of Fill Mach Number On 1D PDE

- Algebraic 1D PDE Results Assumed Low Fill Mach Number
- As Fill Mach Increases Post Detonation Entropy Increases and Specific Impulse Decreases
- As Fill Mach Increases Predetonation Pressure Drops
- Detonation Does Not Recover Pressure
- So Post-Detonation CJ Pressure Drops
- Less Availability for Thrust Production

Analytical Results for 1D PDE’s Say Fill Mach is the Culprit
Problem Analysis
Effects of Fill Mach Number On RDE

- Fill Mach Number Tricky to Define
  - Using axial Mach number just prior to detonation
- Axial Mach Number Is High
- Post-Detonation Entropy Is High
- Fill Mach and Entropy Follow Same Relationship as 1D PDE

CFD Results for RDE’s Suggest Fill Mach is Indeed the Culprit
Accommodation Strategy

Add an Exit Throat

• Rate of Exhaust Affects Rate of Fill
  • Well established from PDE efforts
• Lower Rate of Fill Yields Higher Pre-detonation Pressure, Higher Post-Detonation Pressure, Lower Entropy, Higher Specific Impulse

It Works! 9.4% Specific Impulse Increase
Accommodation Strategy
More Restriction!

- Throat Sends Strong Waves Upstream
- Waves Affect Inflow
- Inflow Changes Affect Detonation Structure
- Detonation Changes Generate Additional Spurious Waves
- Waves Get Reflected
- Cascade Established

Unstable Behavior Results
Accommodation Strategy

Inlet Restriction With Loss

- Inlet Restriction Creates Total Pressure Loss…
- But Damps Unstable Behavior Allowing Smaller Exit Restrictions…
- Ultimately Yielding Net Gain

\[ \frac{A_{\text{exit}}}{A_{\text{annulus}}} = 0.70; \frac{A_{\text{in}}}{A_{\text{annulus}}} = 0.75 \]

10.3% Specific Impulse Increase
Concluding Remarks

• For an idealized, basic RDE configuration, the fill Mach number can be quite high under representative boundary conditions.
• Through the same basic mechanism as the PDE, the high fill Mach limits performance as measured by net specific impulse.
• The fill Mach can be reduced by adding a throat to the exit, thereby gaining as much as 9% net specific impulse.
• Too much exit restriction yields unstable operation.
• Adding a ‘lossy’ inlet restriction adds stability and allows for a 10% specific impulse improvement.
• Experimental validation (or refutation) is justified.
END