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

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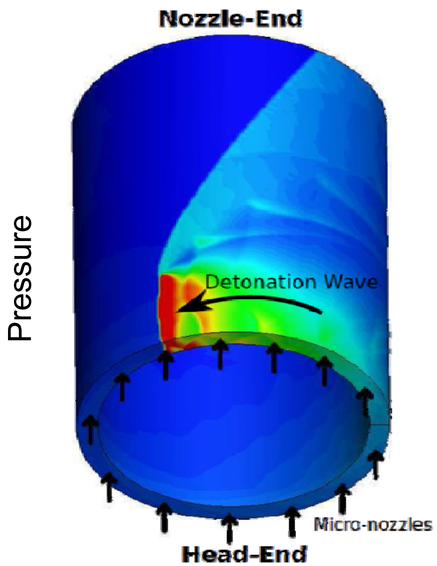
- Problem Analysis
- Accommodation Strategy
- Results
- Concluding Remarks

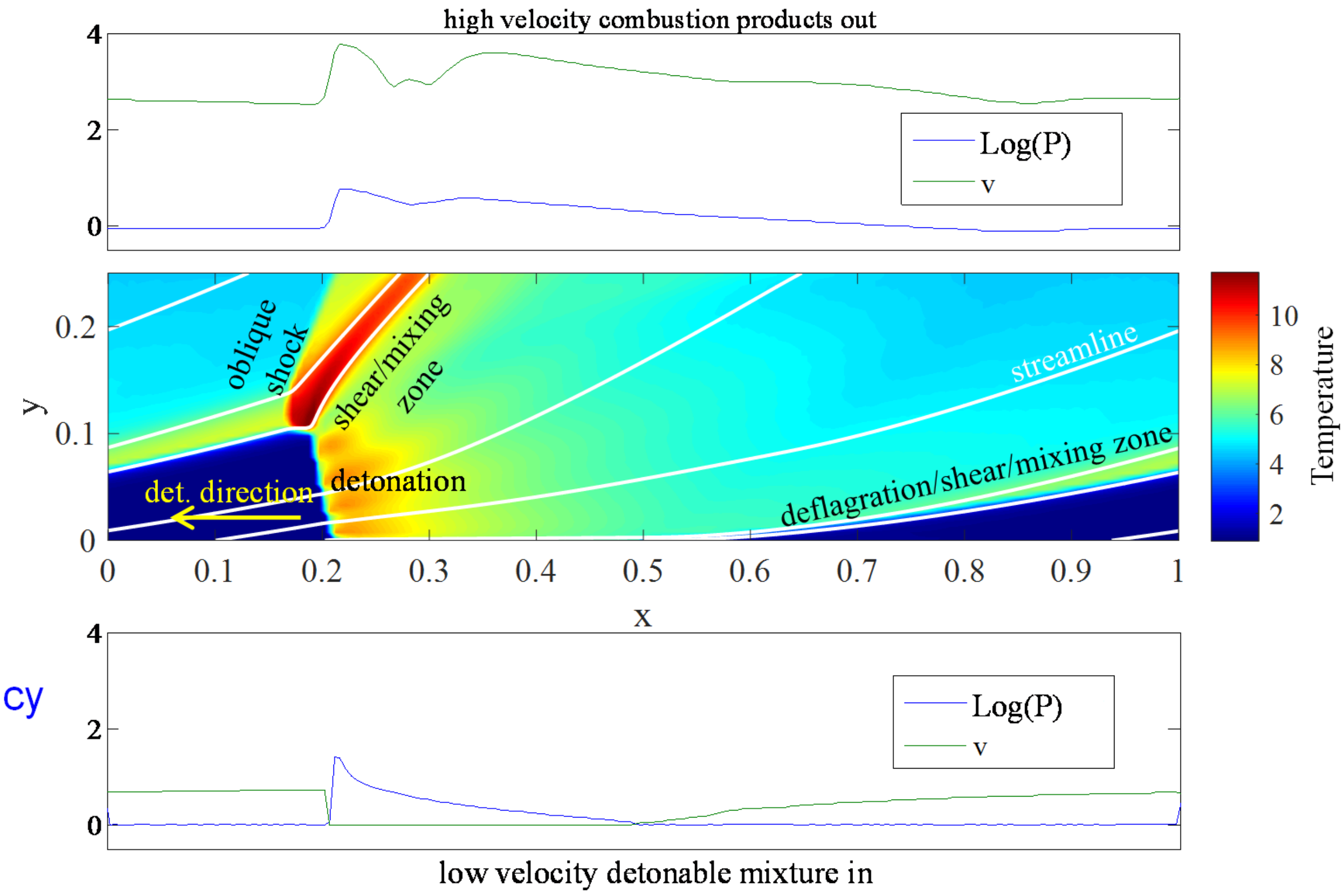
Background

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.*



Source: Schwer, AIAA 2011-581

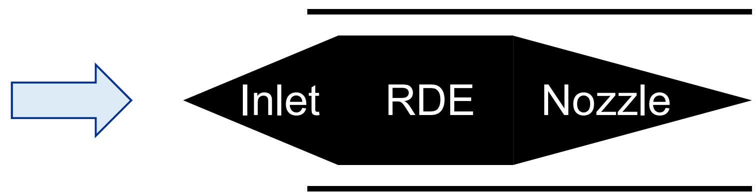


- 1000+ Hz. cycle frequency
- No 'spark' required
- No lossy DDT devices
- Compact

Problem Statement

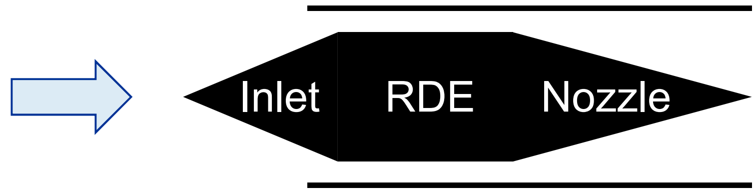
Consider a Semi-Ideal, Ram-Based, Stoichiometric Hydrogen Fueled RDE at 37,000 ft., Flying at Mach 1.37

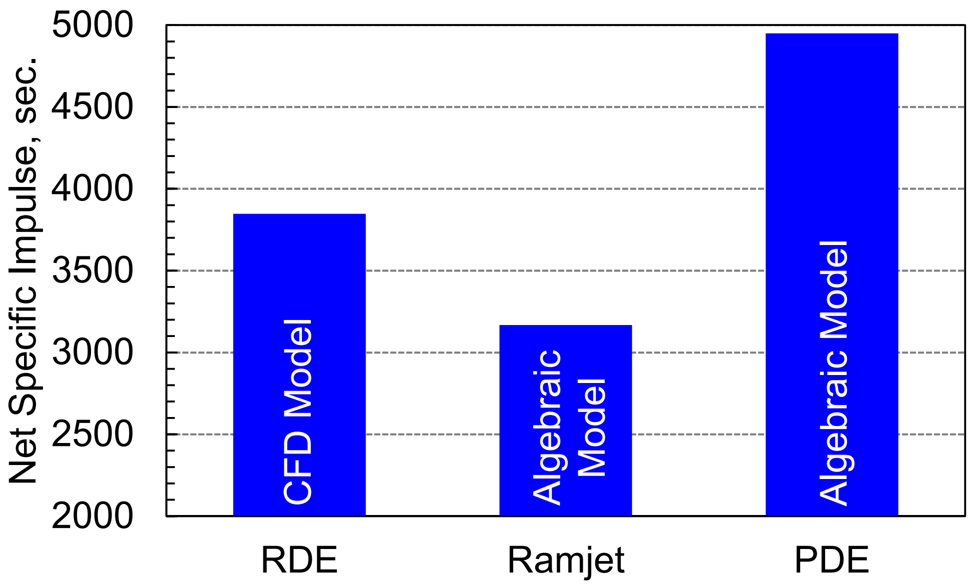
(Note-Flight conditions are illustrative only)



- 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

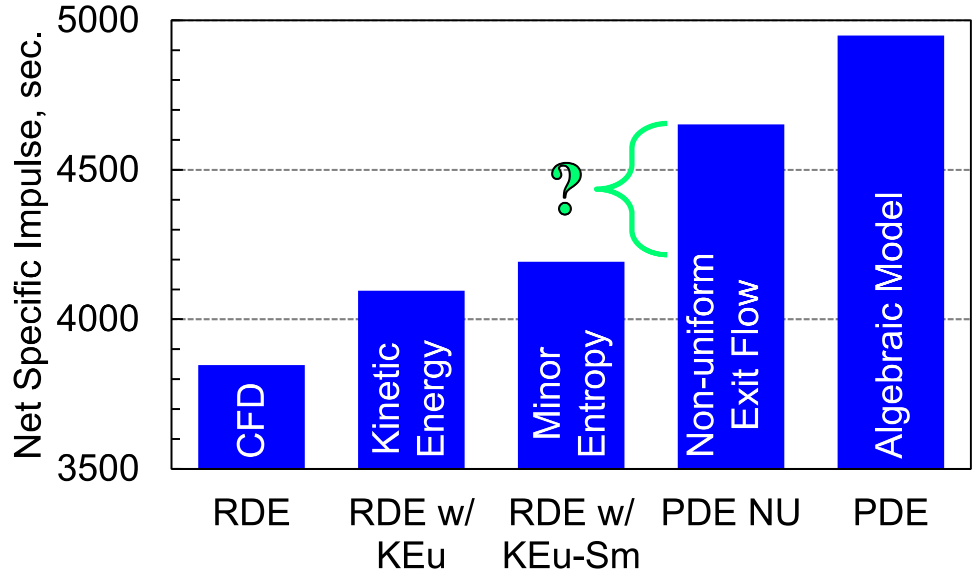
Problem Statement

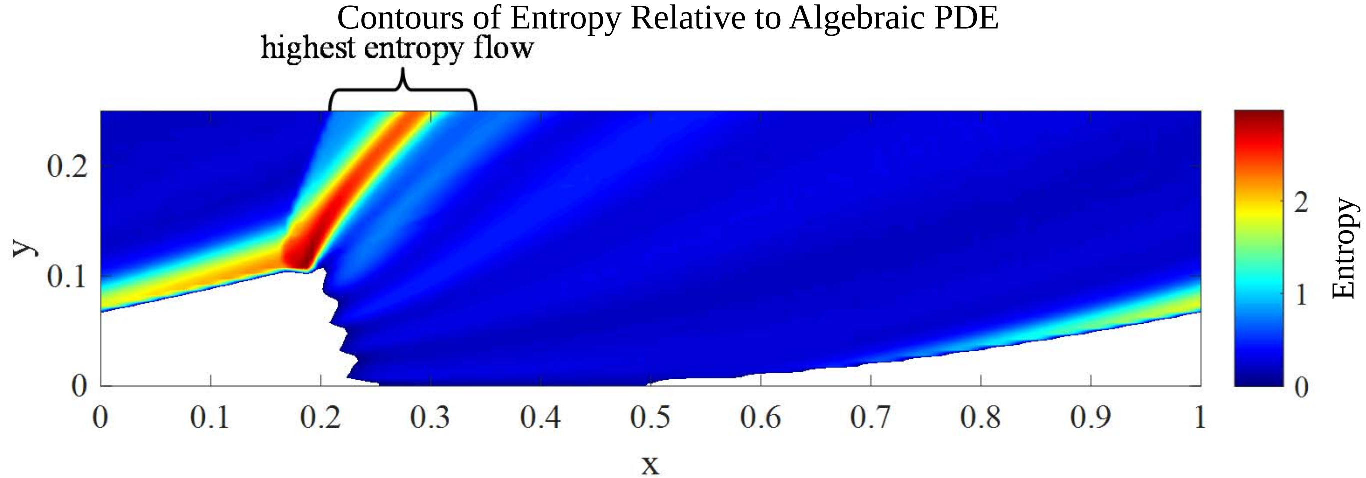




- RDE 21% above RJ
- RDE 22% below PDE ?

Problem Statement





- 7-10% Disparity?

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

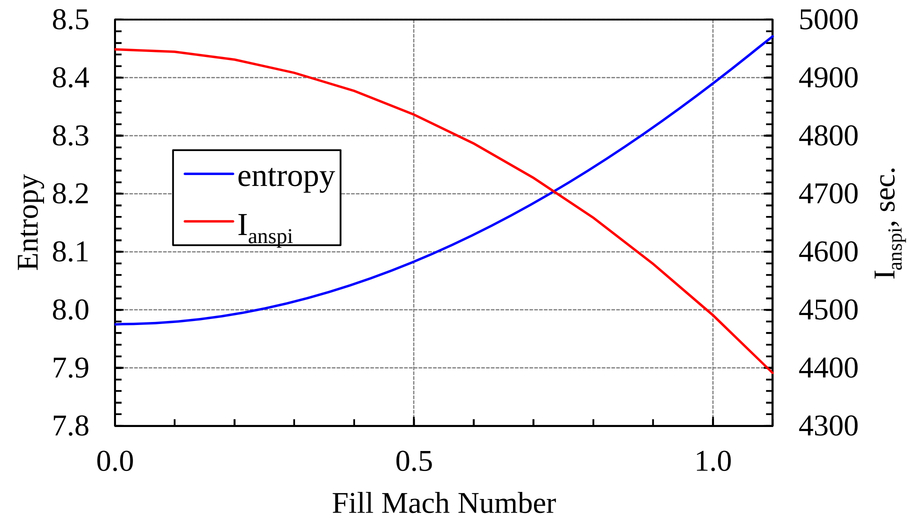
Problem Analysis
Primary Analysis Tool

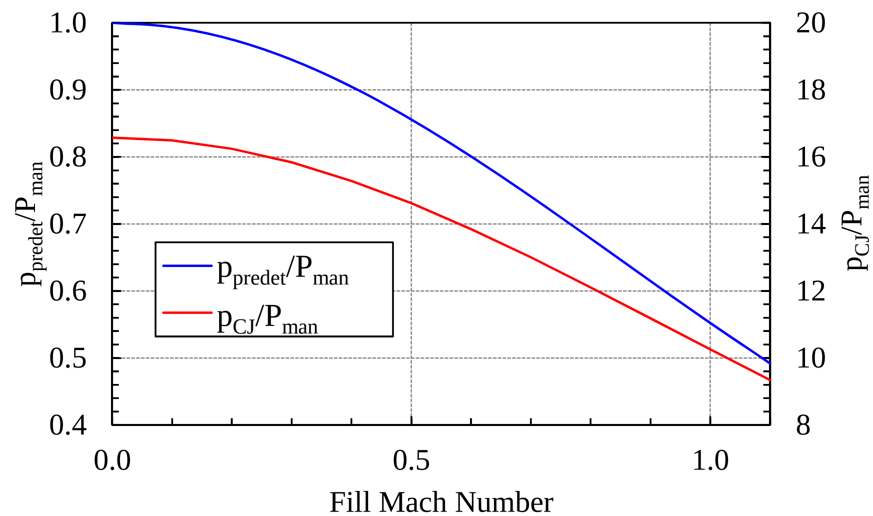
Quasi-2-Dimensional Euler Solver With Sources

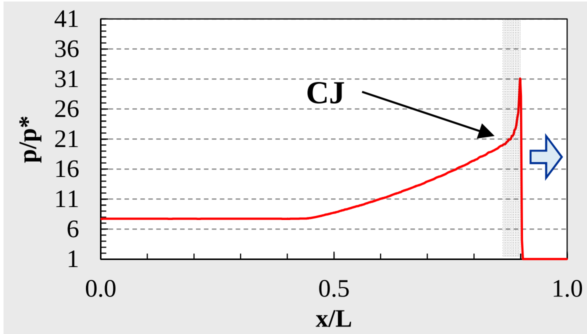
- Source Terms Model:
  - Chemical Reaction
  - Friction *(not used here)*
  - Heat Transfer *(not used here)*
- 2 Species Reaction (reactant or product)
- Simplified Finite Rate Reaction
- High Resolution Numerical Scheme
- Coarse Numerical Grid (< 10,000 cells)
- Adopts Detonation Frame of Reference
  - 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



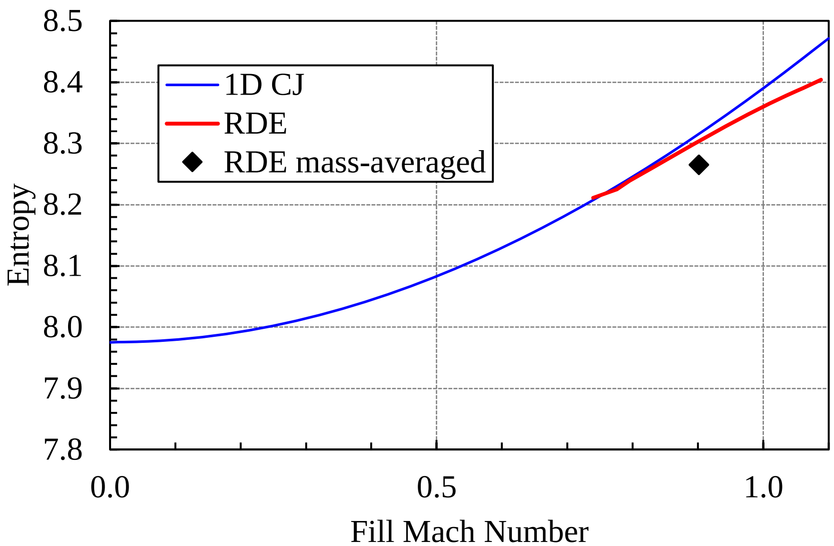


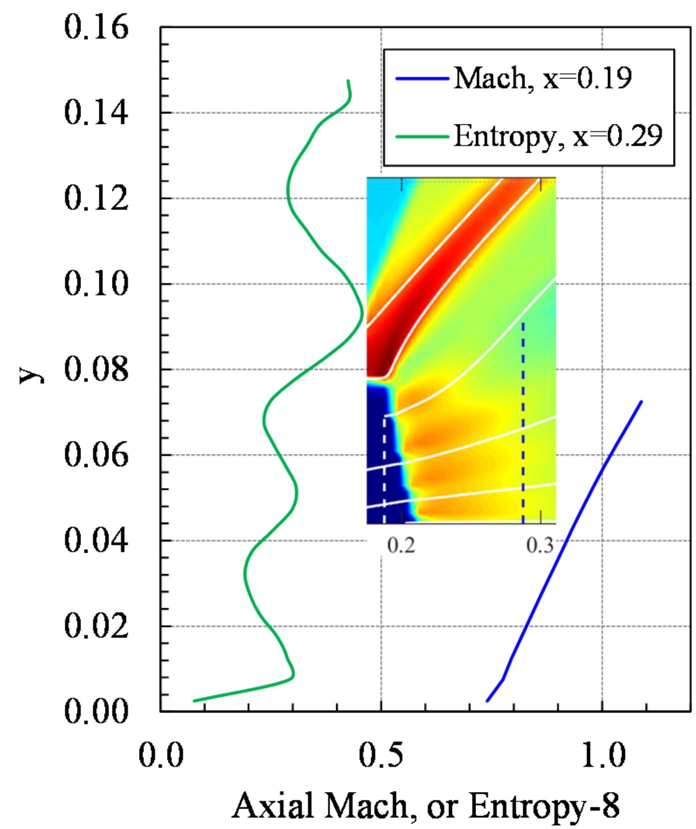


Analytical Results for 1D PDE's Say Fill Mach is the Culprit

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



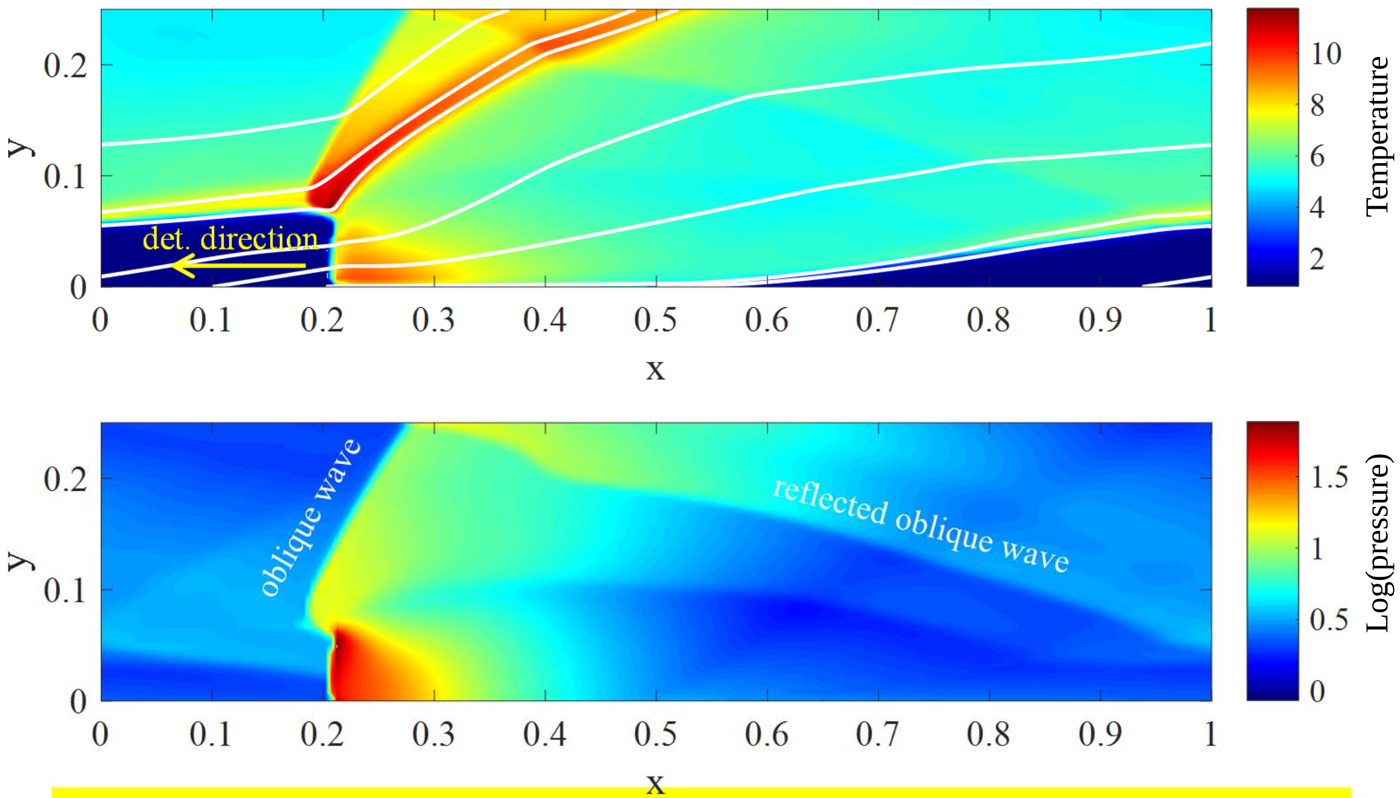


CFD Results for RDE's Suggest Fill Mach is Indeed the Culprit

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

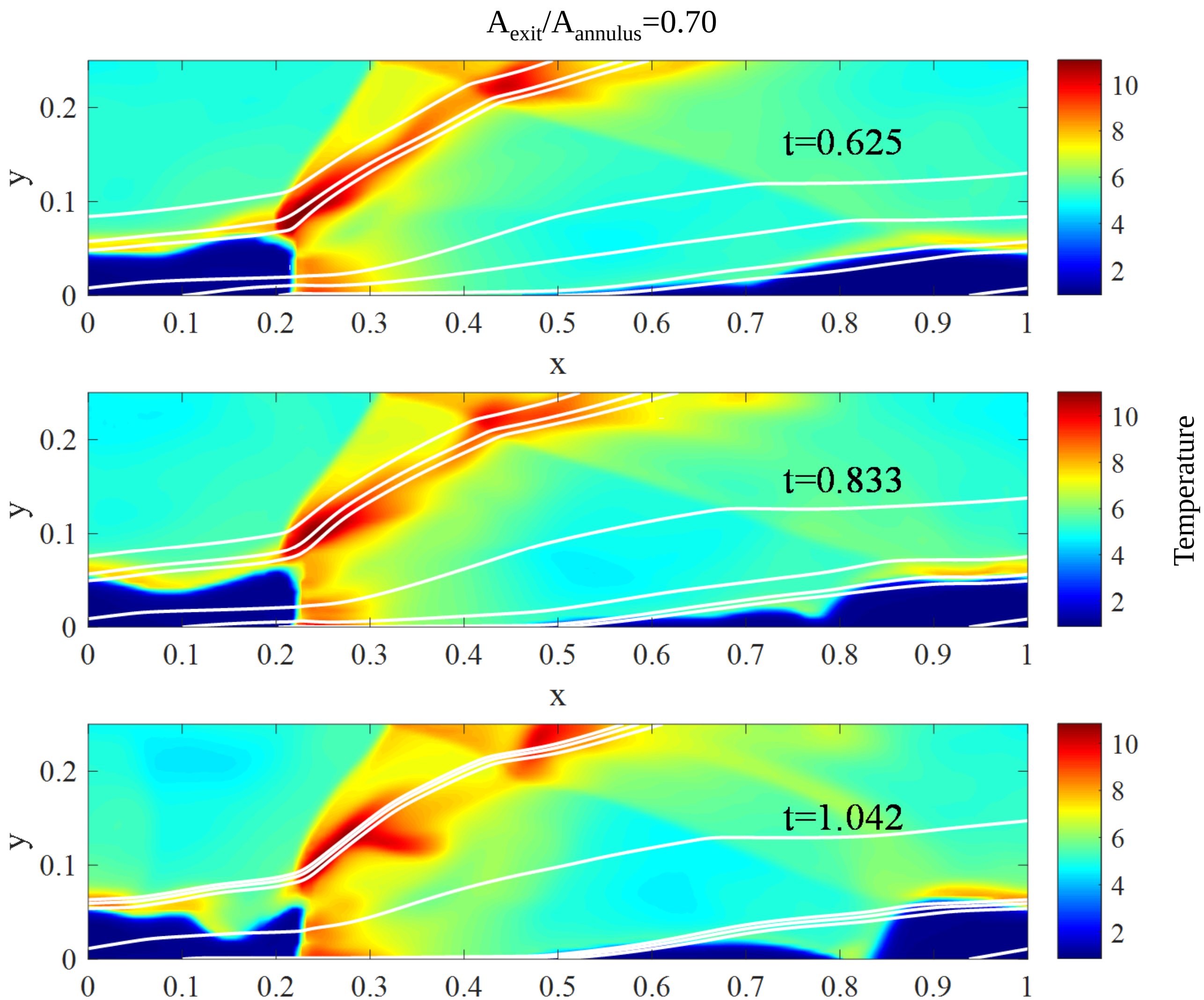
$A_{exit}/A_{annulus}=0.75$



It Works! 9.4% Specific Impulse Increase

Accommodation Strategy
More Restriction!

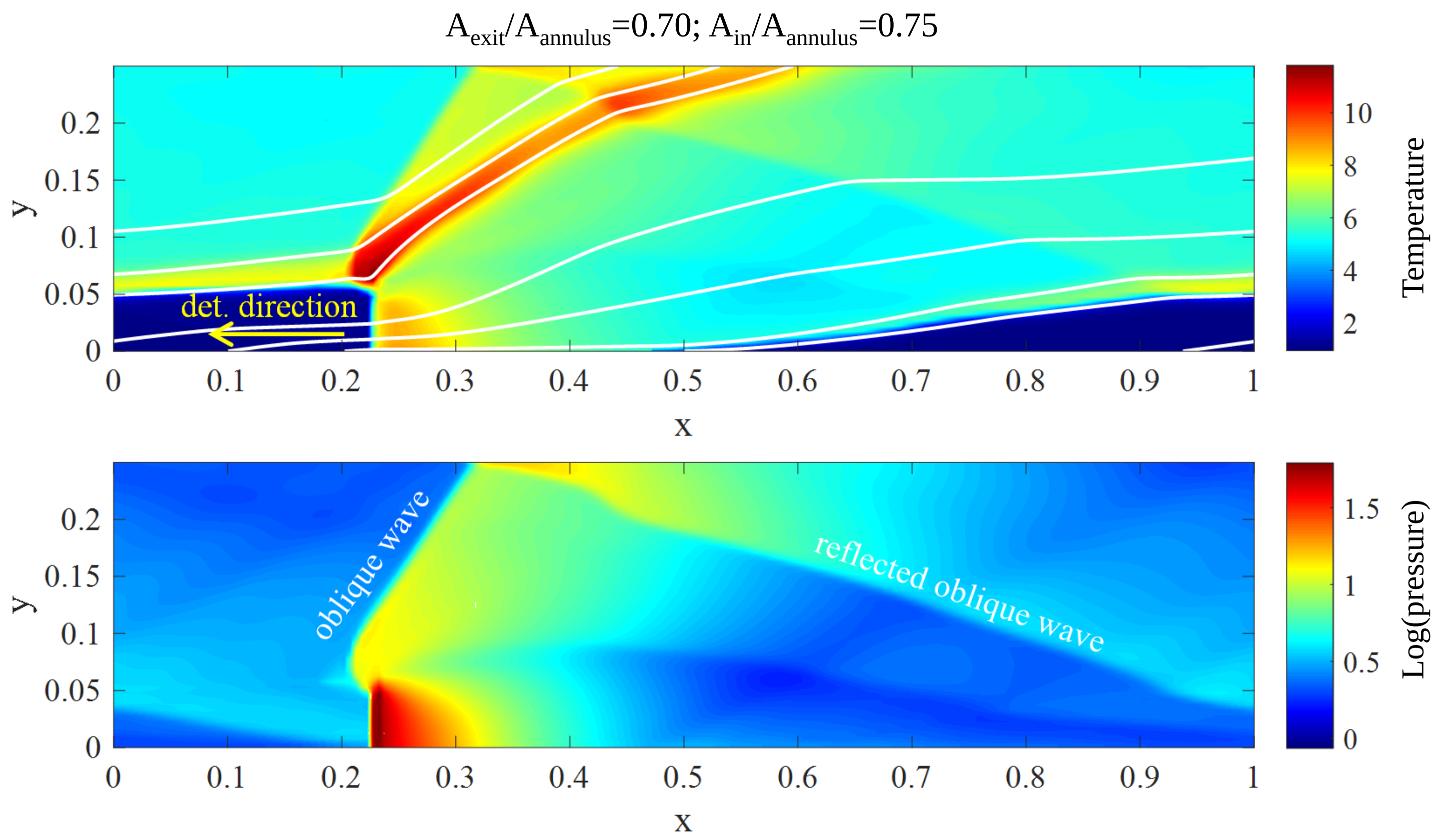
- Throat Sends Strong Waves Upstream
- Waves Affect Inflow
- Inflow Changes Affect Detonation Structure
- Detonation Changes Generate Additional Spurious Waves
- Waves Get Reflected
- Cascade Established



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



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