Computational Assessment of Inlet Backflow Effects on Rotating Detonation Engine Performance and Operability

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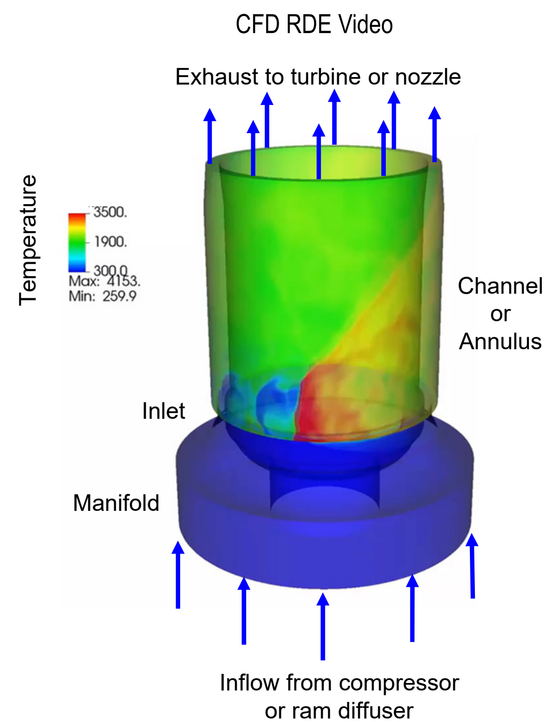
Motivation

- Rotating Detonation Engines (RDE’s) are a promising approach to Pressure Gain Combustion (PGC) for airbreathing propulsion applications
  - High pressure gain potential
  - Compact
  - Low emissions
  - No moving parts
- Successful development requires overcoming several critical challenges
- Inlet design is one such challenge
  - Must provide low total pressure loss to fluid entering the channel
  - Must provide a thrust surface in the high-pressure region behind the detonation
  - Must prevent backflow into the inlet manifold in the high-pressure region behind the detonation
- Competing objectives make optimal design difficult
- Losses associated with forward flow and backflow are not well understood
- RDE mission and benefits studies are difficult without a reasonable assessment of inlet effects on performance



This Paper Describes a Computational Assessment of These Losses for a Basic Inlet Design Using Idealizations That Isolate the Inlet From Other Loss Sources

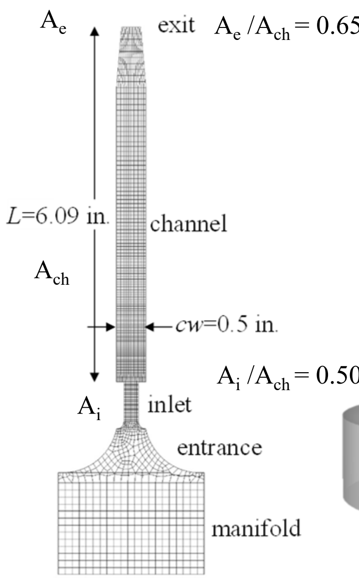
In-House Codes and Configuration

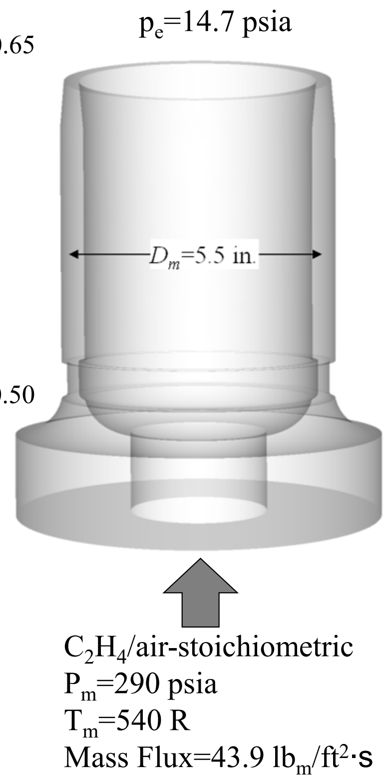
Adiabatic, inviscid, premixed

(Run as Euler Solvers)

Quasi-Two-Dimensional (Q2D)

- Detonation frame of reference
- Single calorically perfect gas
- Single step, 2 species, ultra-simplified reaction with limited deflagration
- 200 azimuthal X 70 axial grid
- Inlet modeled in boundary conditions
  - Forward flow loss = f(A_i/A_{ch}, mass flow rate)
  - Backflow = f(A_i/A_{ch}, pressure, diodicity)
  - Diodicity, $\delta=(1-A_{i,\ backflow}/A_{i,\ forward})$
- No manifold, prescribed P_m, T_m
- Prescribed axial reaction delay
  - No combustion allowed upstream of a prescribed axial distance
  - Ensures that backflow won't be combustion products
  - Crudely simulates a non-premixed RDE
- Seconds per wave revolution on PC



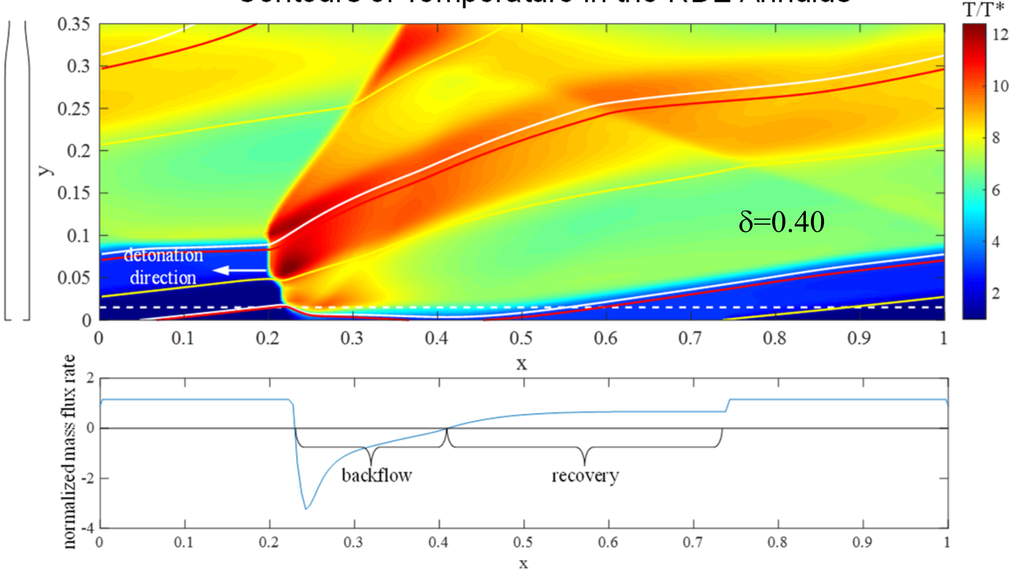


Three-Dimensional (3D): OpenNCC

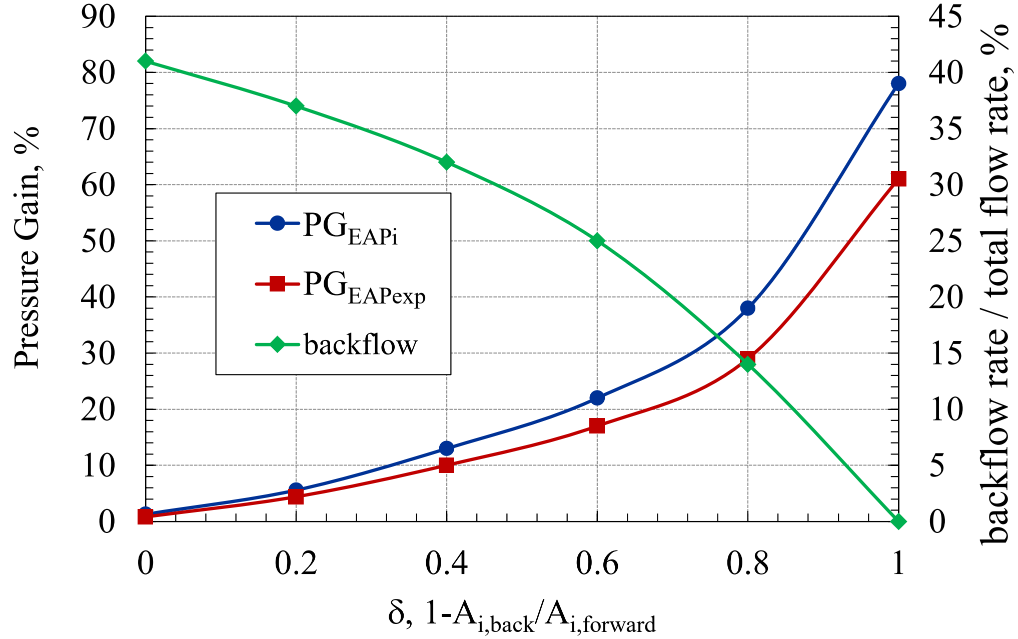
- Laboratory frame of reference
- Mixed thermally perfect gas
- Two step, 6 species, Arrhenius reaction with limited deflagration
- 800 azimuthal X 200 axial X 15 radial grid
- Inlet in computational domain
  - Basic annular slit
  - Aerodynamic leading edge
  - Sharp trailing edge
- Manifold in computational domain, prescribed head end mass flux, T_m
- No combustion allowed upstream of inlet trailing edge
- Hours per wave revolution on supercomputer (360 cores)

Preliminary Q2D Performance A_i/A_{ch}=0.5

Contours of Temperature in the RDE Annulus



Equivalent Available Pressure (EAP) Gain vs. Diodicity (δ)



- Backflow affects performance by:
  - Being heated and returning to channel
  - Creating blockage
  - Reducing high pressure region

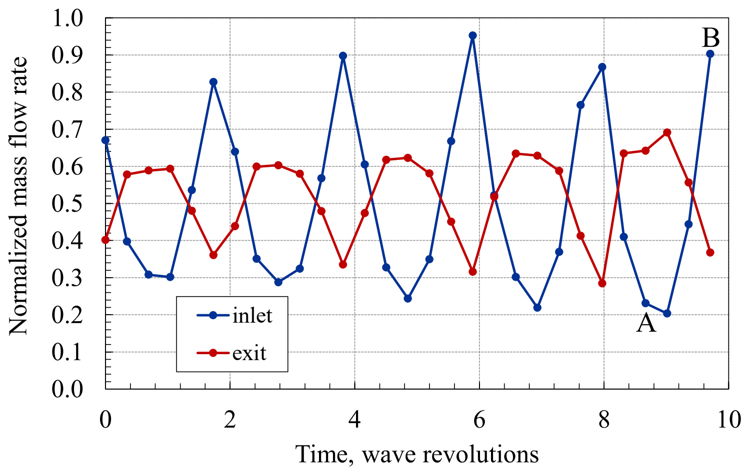
EAP≡An Averaged Total Exit Pressure Based on Ideal Specific Thrust

$$PG = \frac{EAP}{P_m} - 1$$

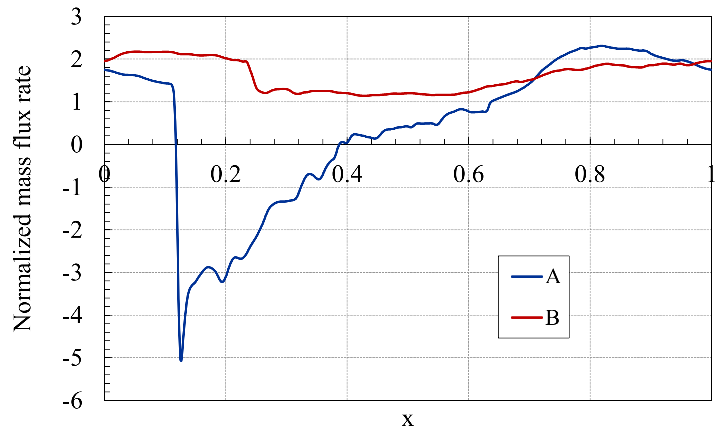
Backflow Can Profoundly Affect RDE Performance
3D Code Should Provide δ Estimate

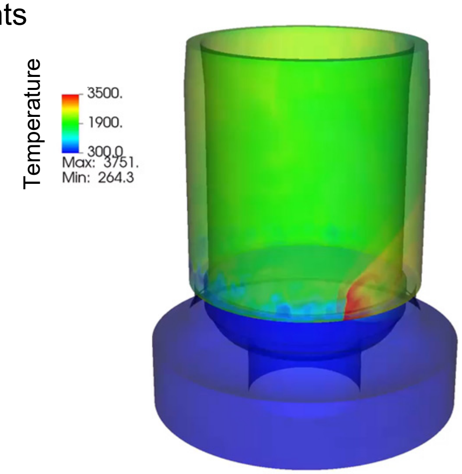
3D Instability A_i/A_{ch}=0.5

Mass Flow Rate at Inlet Leading Edge and Exit Plane



Inlet Leading Edge Mass Flux Distributions at Two Instants





CFD Video During Early Instability Development Showing Detonation Height Variation

Characteristics:

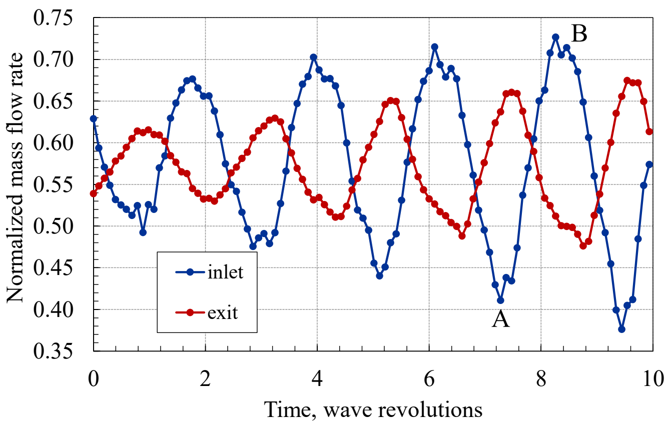
- Commences approximately 20 wave revolutions after simulation initiation
- Grows to detonation failure approximately 25 wave revolutions after detection
- Periodic fluctuations in inlet mass flow caused by periodic fluctuations in backflow
- Periodic fluctuations in detonation height
- Period is 2 wave revolutions

Instability is Self-Exciting and Grows Continuously Until Detonation Failure
Is This Peculiar to the 3D Code, or Real Physics?

Q2D Instability A_i/A_{ch}=0.5; δ=0.50

Channel Length Shortened by 7%

Mass Flow Rate at Inlet and Exit Planes



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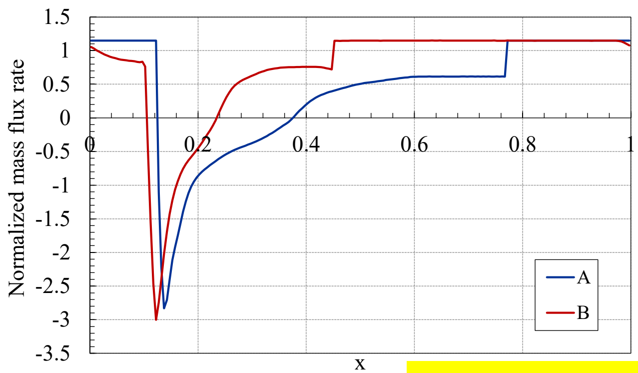
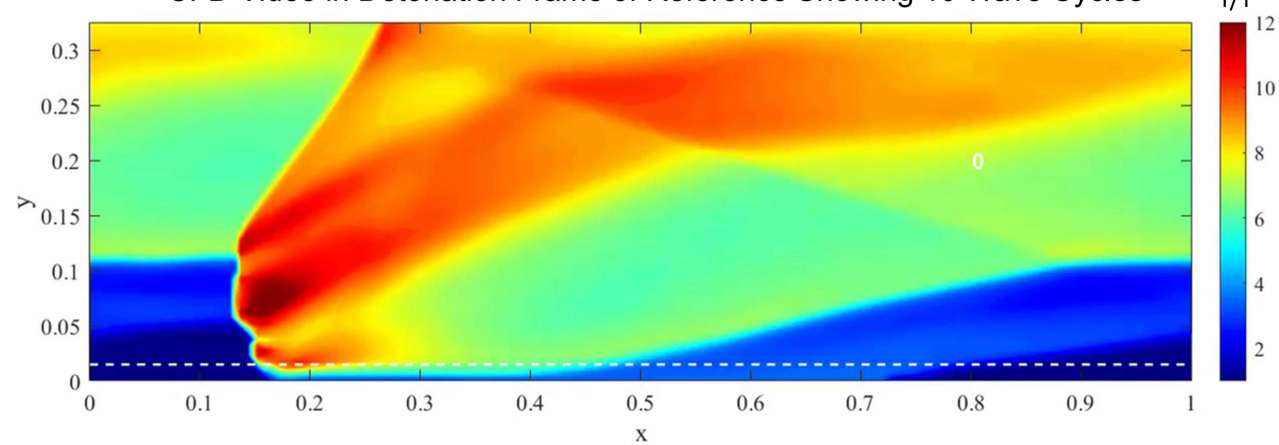


CFD Video in Detonation Frame of Reference Showing 10 Wave Cycles



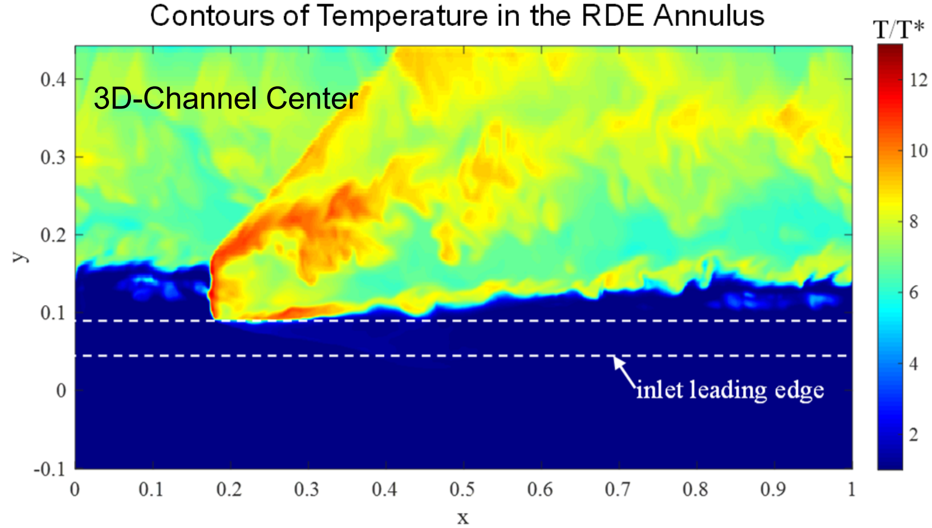
Characteristics:

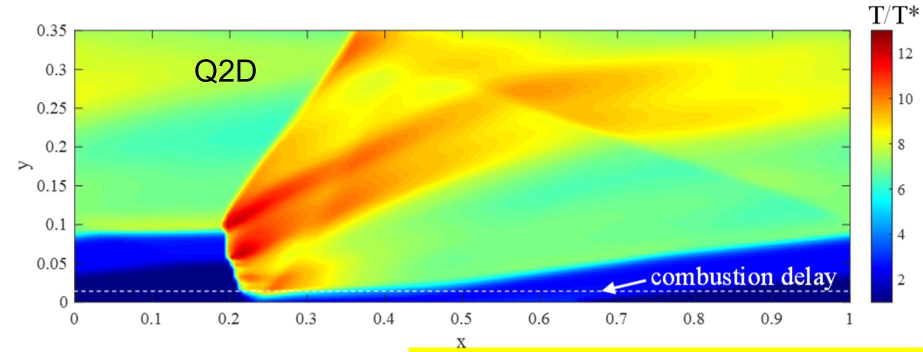
- Commences immediately after configuration change
- Grows to simulation failure approximately 35 wave revolutions after configuration change
- Periodic fluctuations in inlet mass flow caused by periodic fluctuations in backflow
- Periodic fluctuations in detonation height
- Period is 2 wave revolutions

Small Configuration Modification Shows Same Instability in Q2D Apparently, It's Physics!

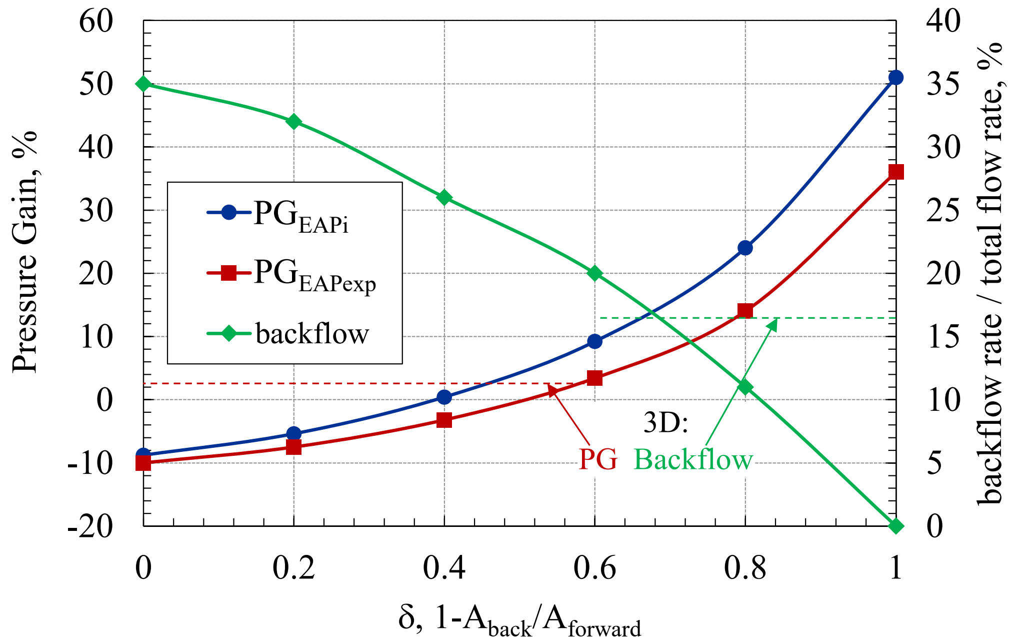
Stable Limit Cycle 3D & Q2D Performance A_i/A_{ch}=0.4

Contours of Temperature in the RDE Annulus





Equivalent Available Pressure (EAP) Gain vs. Diodicity (δ)



- At diodicity value δ=0.6, Q2D and 3D:
  - Channel flowfields are similar
  - Backflow rates agree within 3.5%
  - Pressure gains are the same

Simplified Q2D With Inlet Sub-Models Can Reasonably Match 3D

Summary

- The impact of flow reversal, or backflow at the inlet of an airbreathing RDE was investigated using Q2D and 3D CFD simulations.
- The simulations were idealized to isolate the effects of backflow from other loss-inducing RDE phenomena.
- The results showed that RDE inlets allowing significant backflow suffer substantial performance loss.
- Both simulations also exhibited a novel instability that developed in certain RDE configurations with large backflows
  - The instability appears to be physical (under the idealizations) rather than due to numerical anomaly and may be relevant to real-world RDE's
- Comparison of the Q2D and 3D results established a reasonable value for the Q2D diodicity parameter
  - Provides confidence in the Q2D output
  - Q2D is far less resource intense than 3D
  - Readily used for parametric optimization and mission analysis
- All results highlight need for sophisticated RDE inlets designs that provide low loss when flow is inward, and high resistance during backflow

Thank You for Viewing