Numerical and Analytical Assessment of a Coupled Rotating Detonation Engine and Turbine Experiment

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SciTech 2017
55nd AIAA Aerospace Sciences Meeting
Grapevine, Texas
January 9-13, 2017

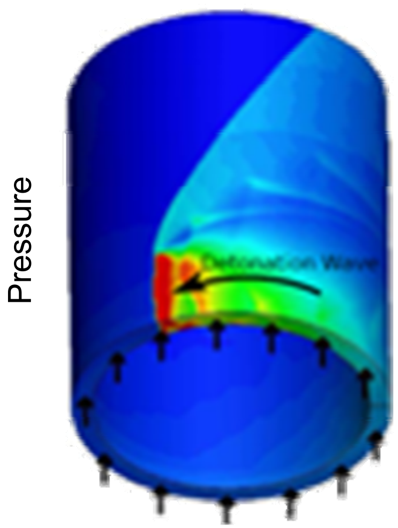
Outline

- Background/Motivation
- Experiment Description
- Model Approach
- Results
- Concluding Remarks

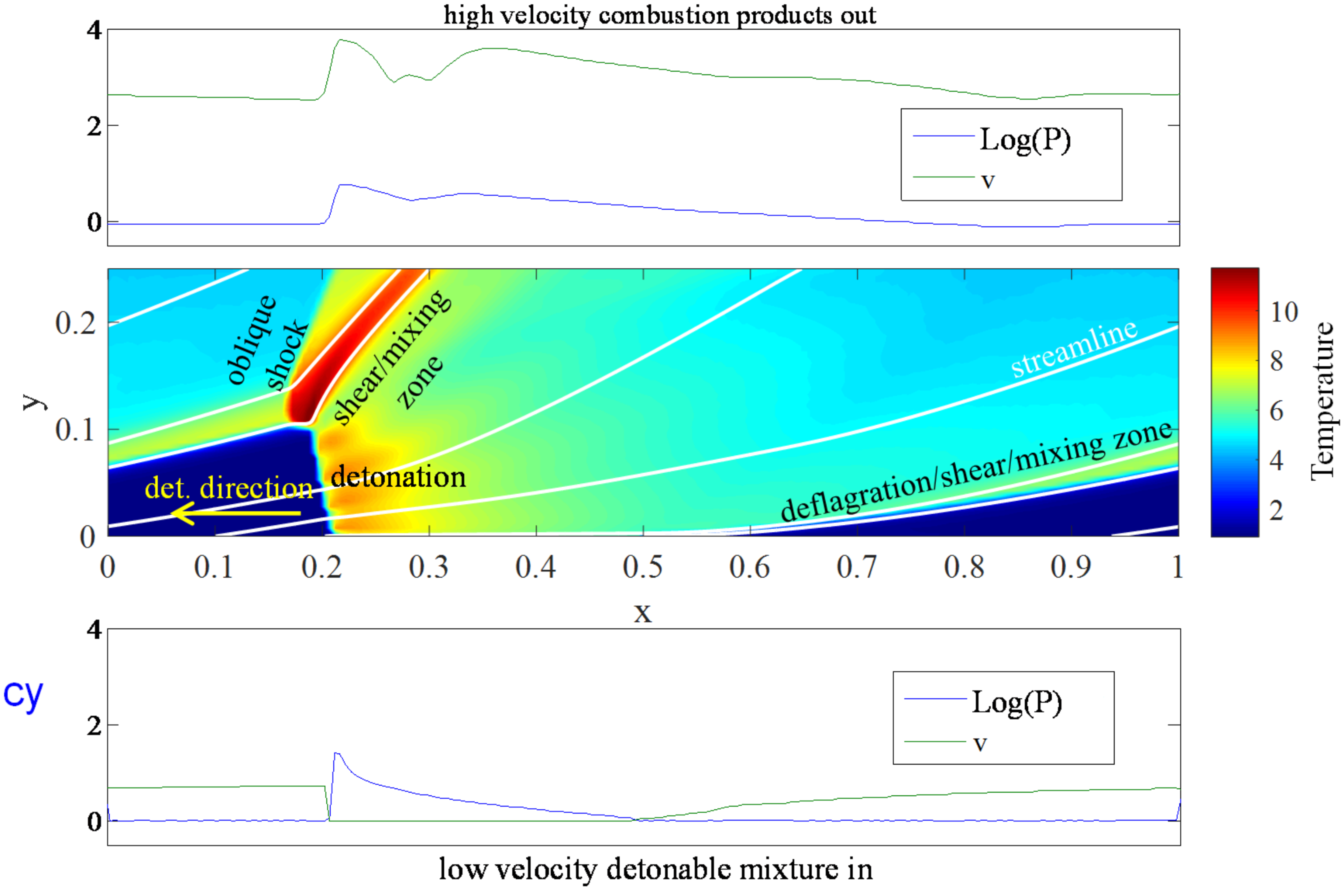
Background

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.*



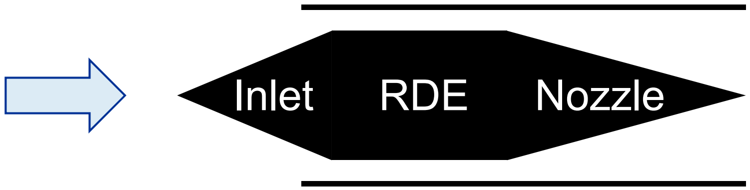
Source: Schwer, AIAA 2011-581



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

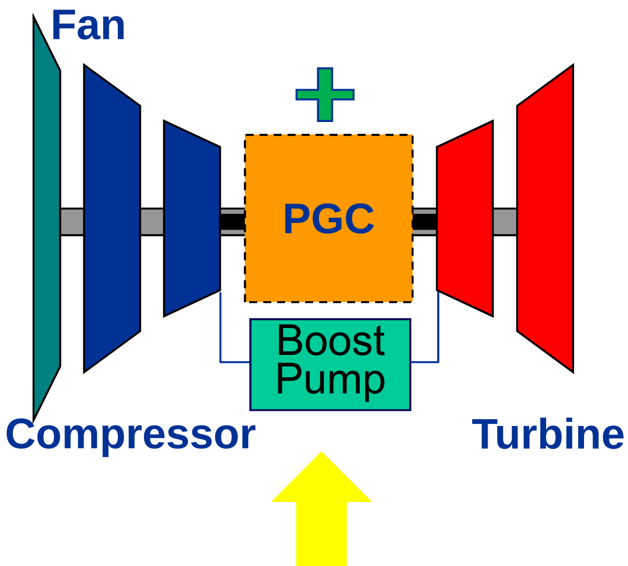
Background

RDE's may use the pressure gain for pure thrust



Or to provide more availability in a gas turbine

- Greater specific power
- Lower specific fuel consumption
- Same turbine inlet temperature



This is the focus application of the present work

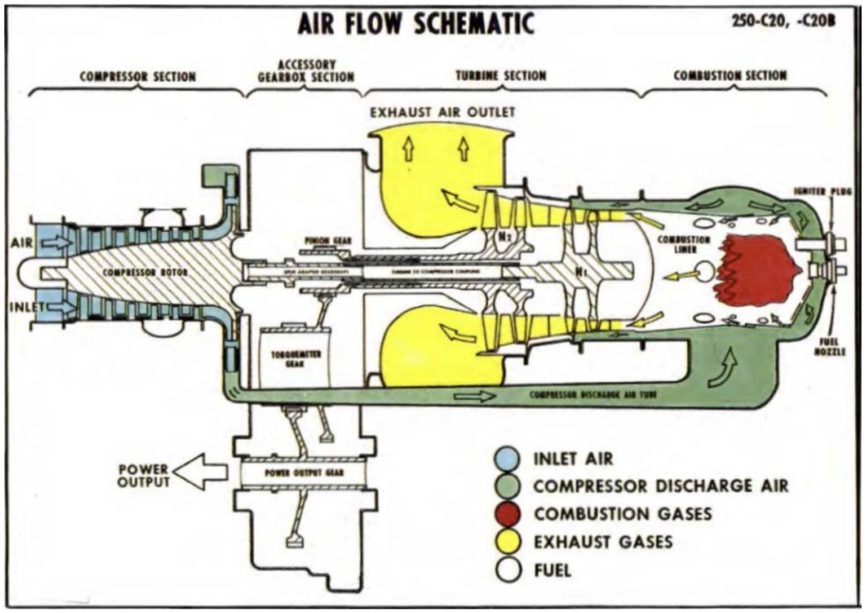
Background

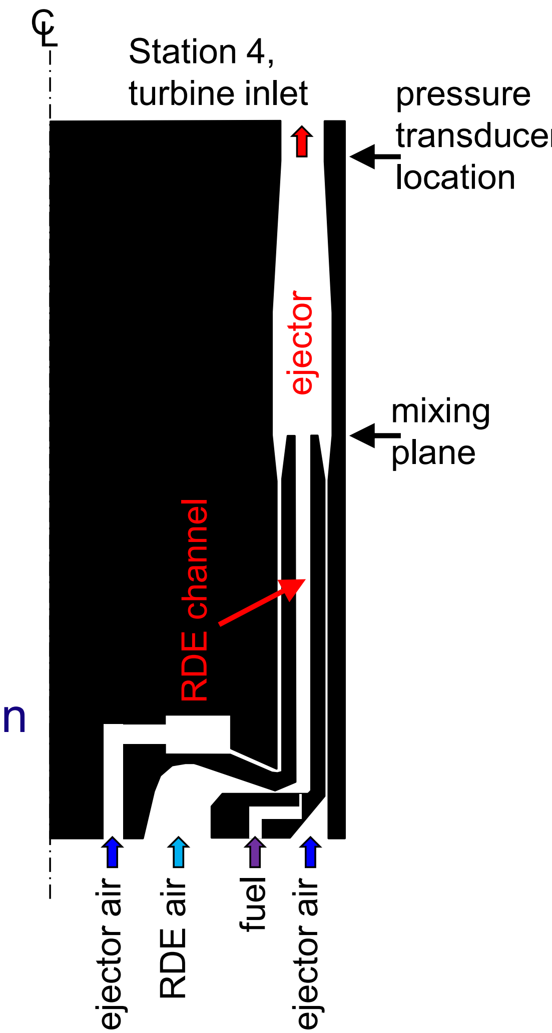
- There are many questions about the interaction of a conventional turbine with the temporally and spatially non-uniform RDE effluent.
  - An experiment was designed at the Air Force Research Laboratory (AFRL) to investigate this at a preliminary level
  - There is a companion presentation detailing the experiment
- There are many questions about the performance of an RDE in general, and in the gas turbine environment in particular
  - These were not the focus of the experimental effort
  - But they are always a focus of modeling efforts
- This presentation is mostly about modeling
  - Can this setup be modeled?
  - Will the model work?
  - Can the model be validated?
  - Can the model be guide to a better RDE?

Yes, Yes, Define Validated, Yes

Experiment Description

- Start with a small gas turbine
  - T-63 (~3 lbm/s; ~6 OPR)





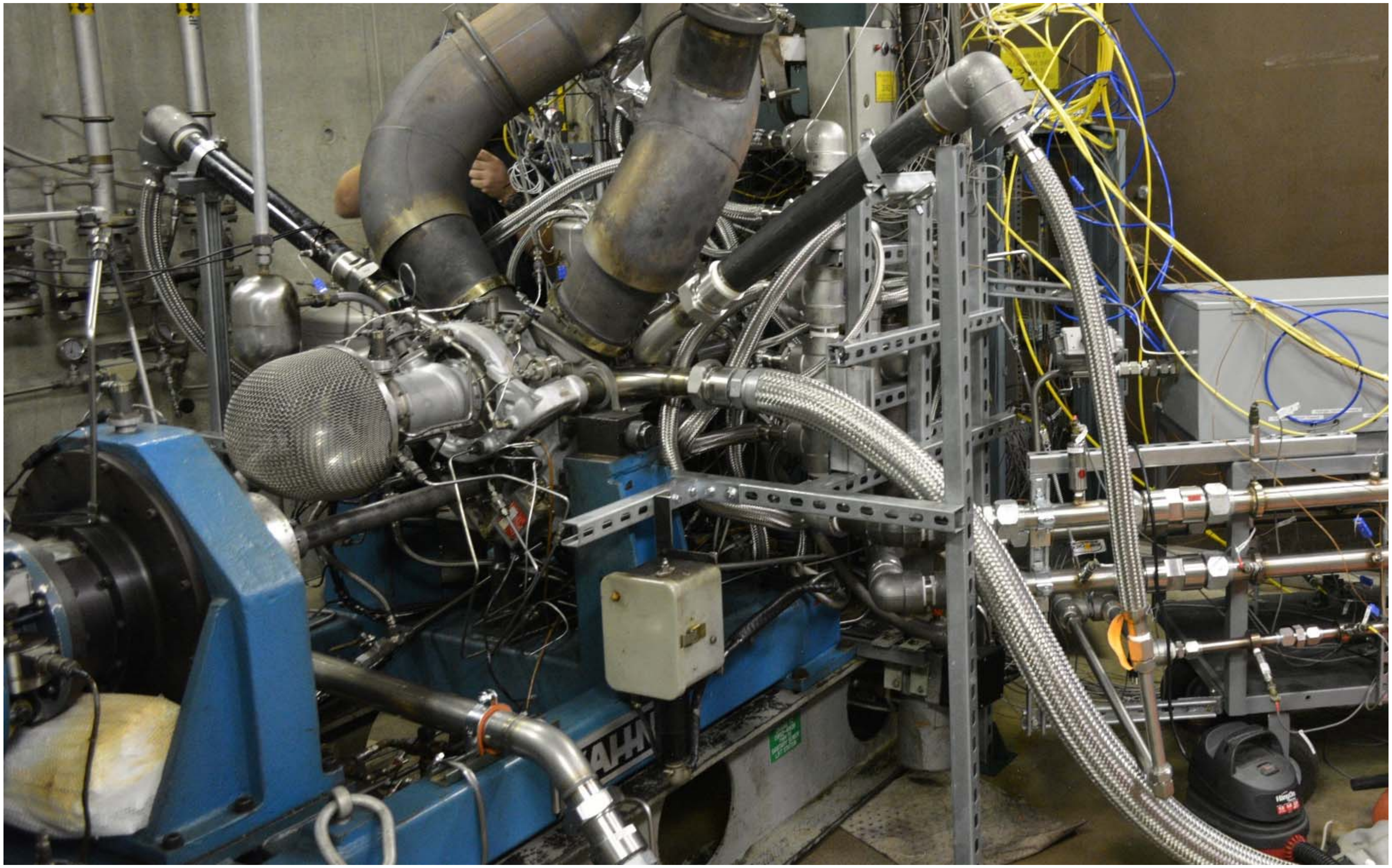
- Replace combustor with RDE & Ejector/ Bypass Configuration

- Vent compressor output
  - Compressor becomes HPT dynamometer
- Facility supply RDE & bypass
- Add dynamometer to LPT

And the Result is…

Experiment Description

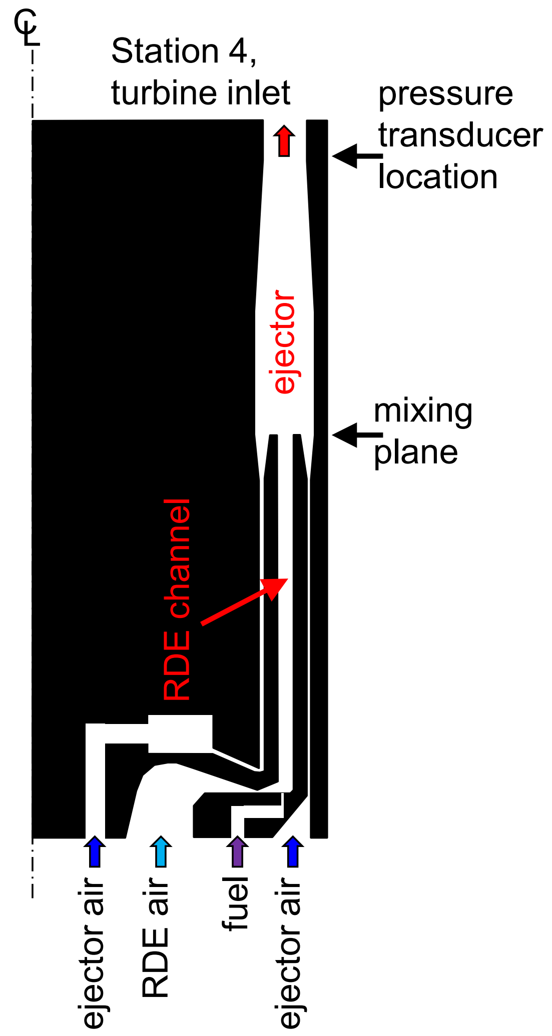
… a masterpiece, albeit a pretty crowded one



Little Room for Model Validating Instrumentation

Model Approach

- Solve RDE flowfield with 2-D CFD
- Combine RDE exit flow with ejector/bypass flow using constant area mixing equations
- Accelerate flow to Station 4 using isentropic area change relations
  - Static pressure at Station 4 is the only local measurement



Model Approach

2-Dimensional CFD

Euler Solver With Source Terms

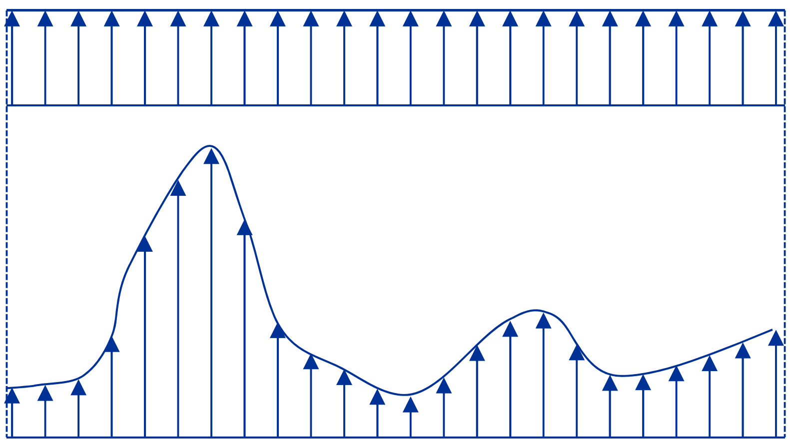
- Calorically Perfect Gas
- Source Terms Model:
  - Chemical Reaction
  - Friction
  - Heat Transfer
- 2 Species Reaction (reactant or product)
- Simplified Finite Rate Reaction
- High Resolution Numerical Scheme
- Coarse Numerical Grid (< 10,000 cells)
- Adopts Detonation Frame of Reference
  - Time 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
  - Physics based inlet loss model from typical restriction
- Runs on a laptop
  - Approximately 20 sec. per wave revolution

Validated: Compares Well With Instrumented RDE Experiments
(Thrust, Mass Flow Rate, Pressures)

Model Approach

Mixing Calculation

- Sums all flows (RDE and bypass/ejector) into hypothetical mixing plane over one detonation wave cycle
  - Mass
  - Momentum
  - Energy
- Mixes to a uniform conserved state
- Generates entropy which essentially scales with levels of non-uniformity



Involves About Two Pages of Algebra That You Don't Want to See in a Presentation

Closure

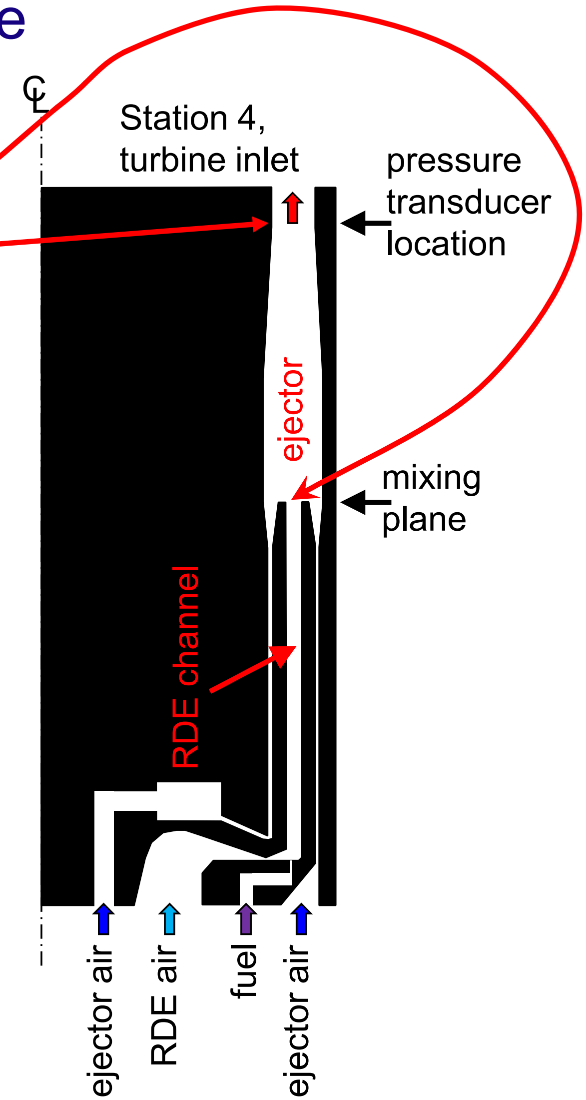
- Both RDE solver and mixing calculation require a specified pressure here – p_{exit}
- We only know pressure here – p_4

Procedure

1. Guess p_{exit}
2. Adjust RDE inlet area until mass flow rate matches experiment
    - Measured inlet manifold P, and T imposed
3. Mix RDE and ejector flows
4. Accelerate Mixed flow through area change
5. Compare computed p_4 with measured value
6. Repeat steps 1-5 until a match is found

Validation

- Compare calculated and measured inlet areas



A_{calc}/A_{meas}≈0.71 for 2 Operating Points-Reasonable Considering Actual Flowpath and Model Simplicity

Results

$$\eta_t = \frac{\dot{W}_t}{(\dot{m}_{ejector} + \dot{m}_{RDE}) c_{p\_mix} T_{t\_mix} \left(1 - \left[\frac{p_{amb}}{p_{t\_mix}} \right]^{\frac{\gamma_{mix}-1}{\gamma_{mix}}} \right)}$$

- Calculated Turbine Efficiency:
  - η_t=0.83
- NPSS says
  - η_t=0.86-0.90
- No manufacturer value available

Caveats

- Relatively high turbine efficiency may be partly due to unsteadiness mitigation from mixing

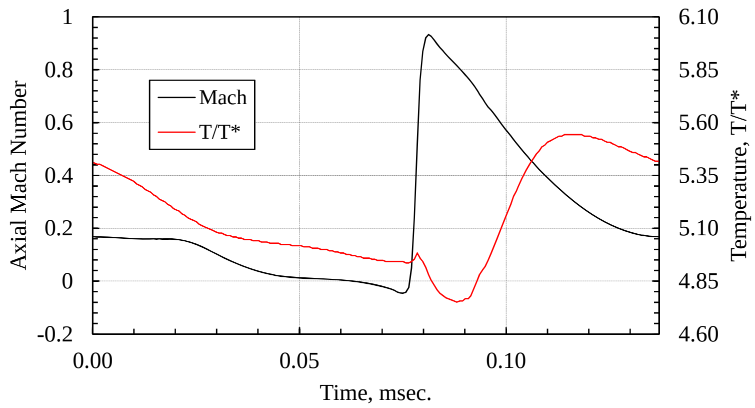
  Turbine is not directly behind RDE
- Relatively high turbine efficiency may be partly because loss is already accounted for with mixing

One Operating Point Examined

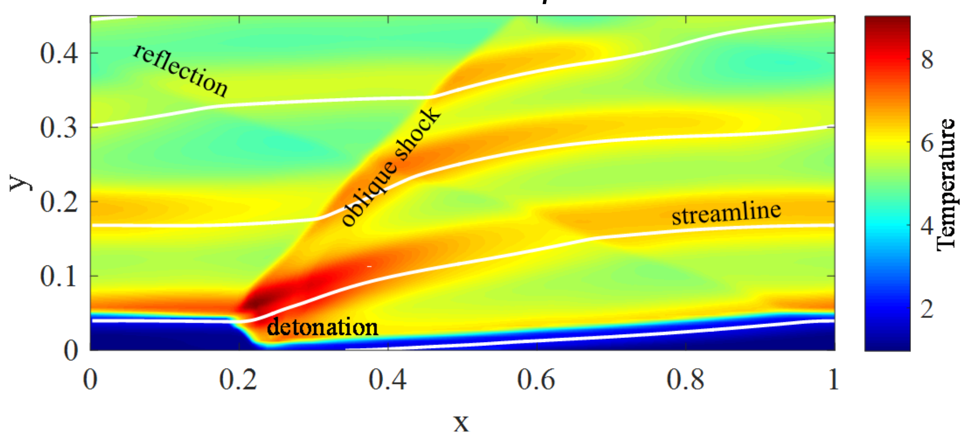
Approximate % Design Speed	90
Ejector Air Flow Rate (lbm/s)	1.81
RDE Air Flow Rate (lbm/s)	0.66
Compressor Air Flow Rate (lbm/s)	2.68
RDE Equivalence Ratio	0.98
Overall Equivalence Ratio	0.24
RDE Inlet Manifold Air Pressure (psia)	86.2
Power Turbine Power (hp)	168
Supply Air Temperature (R)	460
Compressor Inlet Pressure (psia)	14.7
Compressor Inlet Temperature (R)	527
Compressor Discharge Pressure (psia)	57.3
Compressor Discharge Temperature (R)	877
Turbine Inlet Average Static Pressure (psia)	64.9
Computed RDE exit plane pressure (psia)	63.1
Calculated Turbine Inlet Temperature (R)	1790
Calculated Turbine Inlet Pressure (psia)	67.0

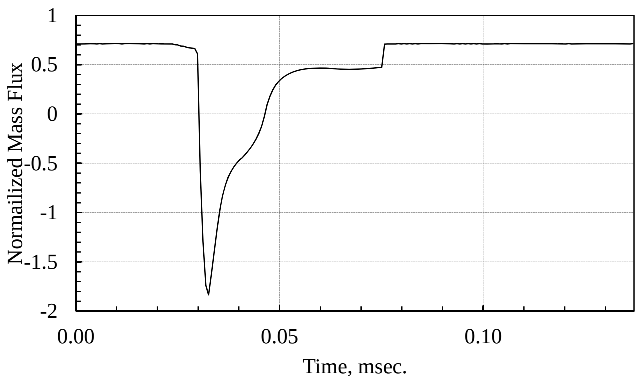
Caveats and All, This is Encouraging

Results



Contours of Temperature





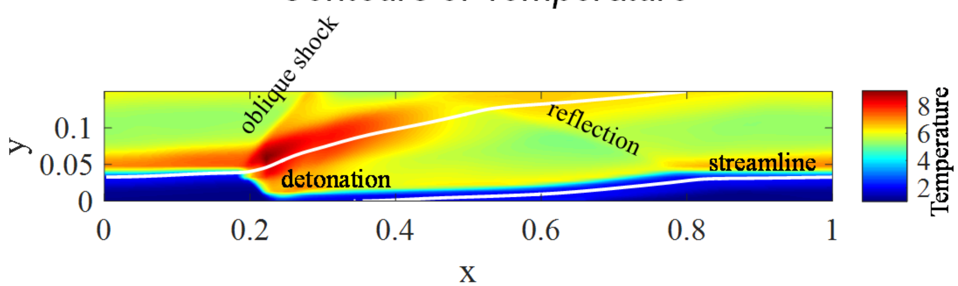
Observations

- RDE is longer than necessary
  - Adds to viscous losses
  - 28% of chemical energy sent to walls
- Exit flow is entirely subsonic and has inflow
- Inlet shows a relatively low backflow of 18% of total, but a large total pressure loss of 43% relative to manifold.
- Overall RDE pressure ratio=0.83
  - Not a pressure gain device
  - Though detonation itself has PR=1.46

Perhaps We Can Do Better

Optimization

Contours of Temperature



Actions

- RDE is shortened by 67%
  - No more exit inflow
  - Only 14% chemical energy to walls
- Inlet area increased by 49%
  - Backflow increases to 25% throughflow
  - Pressure loss now only 25%
- Overall RDE pressure ratio=1.11
- Mixed total pressure unchanged
  - Higher performing RDE also yields larger gradients at exit. Leading to larger mixing losses.

Rather Substantial RDE Performance May Be Possible With Modest Configuration Changes

Conclusion

- Results from an experimental rig consisting of a rotating detonation engine (RDE) with bypass ejector flow coupled to a downstream turbine were analyzed using a validated computational fluid dynamics RDE simulation combined with an algebraic mixing model of the ejector.
- The analysis agreed reasonably well with limited available data.
- The analysis indicated only modest loss of turbine efficiency compared to that under steady loading
- The examination indicated that the RDE operated in an unusual fashion, with subsonic flow throughout the exhaust plane.
- The rotating detonation produced a total pressure rise relative to the pre-detonative pressure; however, the length of the device and the substantial flow restriction at the inlet yielded an overall pressure loss.
- It was shown that with changes to the RDE length and inlet area the RDE could produce an overall pressure rise.

Acknowledgment

NASA's contribution to this work was done under a cooperative Reimbursable Space Act Agreement with the Air Force Research Laboratory in Dayton, Ohio.

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