Lecture Notes from the
AIAA Air Breathing Pulse Detonation Engine Technology Short Course
D.E. Paxson

Abstract

The following notes were prepared as part of an American Institute of Aeronautics and Astronautics (AIAA) sponsored short course entitled Air Breathing Pulse Detonation Engine (PDE) Technology. The course was presented in January of 2003, and again in July of 2004 at two different AIAA meetings. It was taught by seven instructors, each of whom provided information on particular areas of PDE research. These notes cover two areas. The first is titled Approaches to Cycle Analysis and Performance Metrics. Here, the various methods of cycle analysis are introduced. These range from algebraic, thermodynamic equations, to single and multi-dimensional Computational Fluid Dynamic (CFD) solutions. Also discussed are the various means by which performance is measured, and how these are applied in a device which is fundamentally unsteady. The second topic covered is titled PDE Hybrid Applications. Here the concept of coupling a PDE to a conventional turbomachinery based engine is explored. Motivation for such a configuration is provided in the form of potential thermodynamic benefits. This is accompanied by a discussion of challenges to the technology.

Approaches to Cycle Analysis

and

Performance Metrics

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AIAA Short Course

Air Breathing Pulse Detonation Engine Technology

Huntsville, Alabama, 2003

Glenn Research Center   at Lewis Field

Controls and Dynamics Technology Branch

Outline

- **Analysis is Difficult-Why?**

- **Approaches to Analysis-Pros and Cons**
  - 0-D (e.g. thermodynamic, lumped volume)
  - 1-D CFD
  - 2-D CFD
  - 3-D CFD

- **Performance Metrics**
  - Specific Impulse
  - Specific Thrust
  - Thrust-to-weight
  - Thrust per unit of cross section
  - Pressure ratio

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Analysis is Difficult-Why?

- Because it's unsteady
  - Not every particle entering the device goes through the same process.
  - Inlet and exit flows are highly non-uniform.
  - Cannot truly draw the process in any thermodynamic plane
  - Time scales vary immensely over a cycle.

- Understanding of Detonations is <u>Still</u> Limited.
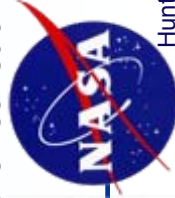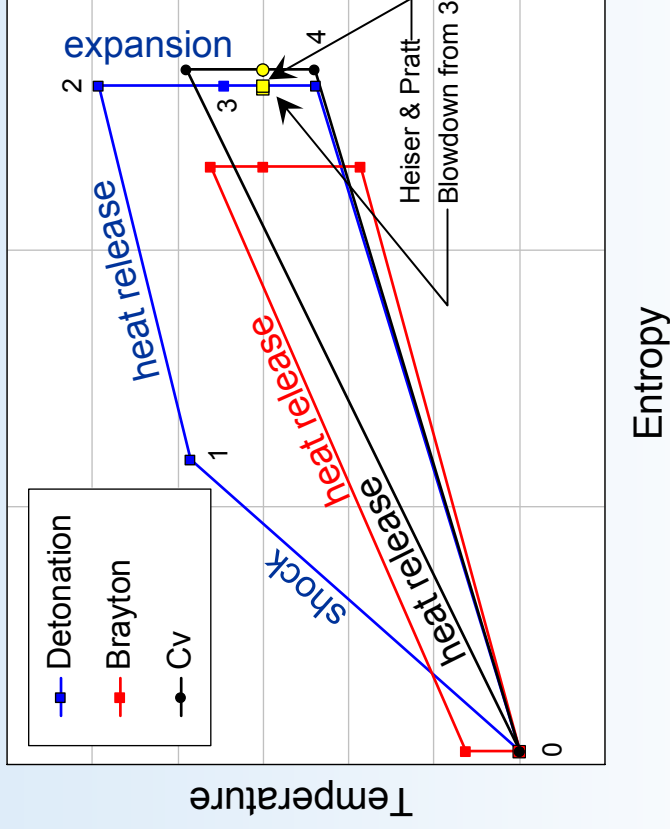- It's 'New'.

Approaches To Analysis: 0-D

Thermodynamic Cycles w/ Equal Heat Release
(overall equivalence ratio approximately 0.4 w/ air and generic hydrocarbon)

- Features
  - Thermodynamic, lumped volume.
  - All working fluid assumed to go through the same process.
  - Steady or quasi-steady.
  - Constant Volume, or ZND chemical reaction model.
  - Steady, isentropic expansion or lumped volume blowdown process*.
  - Basically a Humphrey Cycle.
  - Losses added as component efficiencies

- Examples
  - Kentfield, J.A.C, 2000
  - Heiser and Pratt, 2002
  - Dyer and Kaemming, 2002
  - Bussing and Pappas, 1994
  - Petters and Felder, 2002

*Note-blowdown models are time dependent (though not time accurate). They provide a more realistic representation of the expansion process.
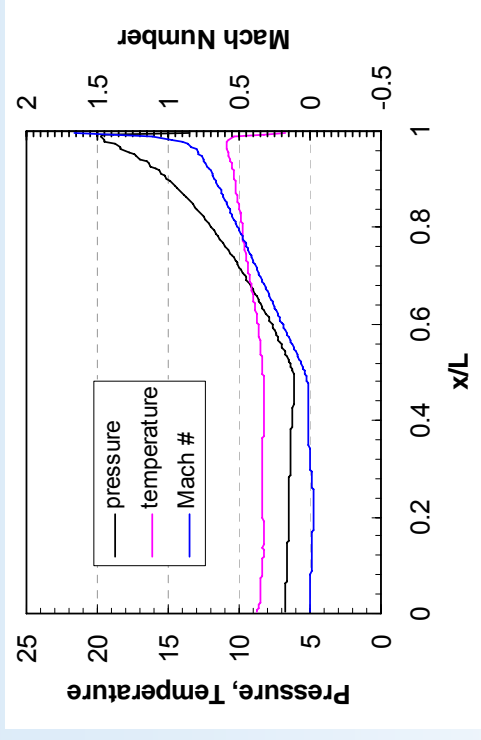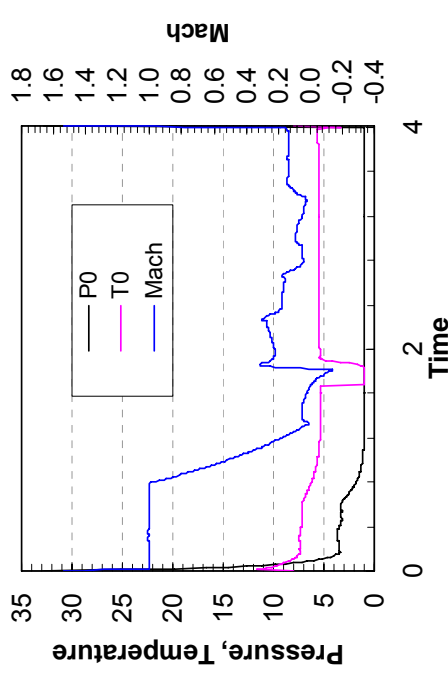
Approaches To Analysis: 0-D

Normalized state before expansion in a
PDE limit cycle: Stoichiometric Propane/Air

Normalized exhaust flow for a PDE limit cycle

- Pros
  - Rapid results (i.e. simple, answers on a spreadsheet).
  - Real gas, and real chemistry effects are relatively straightforward to implement.
  - Convenient for assessing PDE potential.

- Cons
  - Little design information (sizing, timing, heat loads, flow rates, etc.).
  - Often optimistic.
  - Can give a false sense of understanding.
  - Difficult to account for cycle modifications (e.g. partial filling, area variation, cooling flows).

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Approaches To Analysis: 1-D CFD

- Features
  - Time dependent
  - Time accurate
  - Assumes that axial flowfield dominates.
  - Chemical kinetics (usually one-step) computed or imposed as distributed source terms.
  - Detonation assumed (e.g. unconditional as long as reactants are present.)
  - Usually perfect gas.

- Examples
  - Paxson, 2001
  - Cambier and Adelman, 1988
  - Bussing and Pappas, 1994

Q-1-D Euler Equations

$$\frac{\partial \overline{w}}{\partial t} + \frac{\partial \overline{F}(\overline{w})}{\partial x} = \overline{S}(\overline{w}, x)$$

$$\overline{w} = \begin{bmatrix} \rho A \\ \rho u A \\ \left(\dfrac{p}{\gamma(\gamma-1)} + \dfrac{\rho u^2}{2} + q_0 \rho z \right) A \\ \rho z A \end{bmatrix}$$
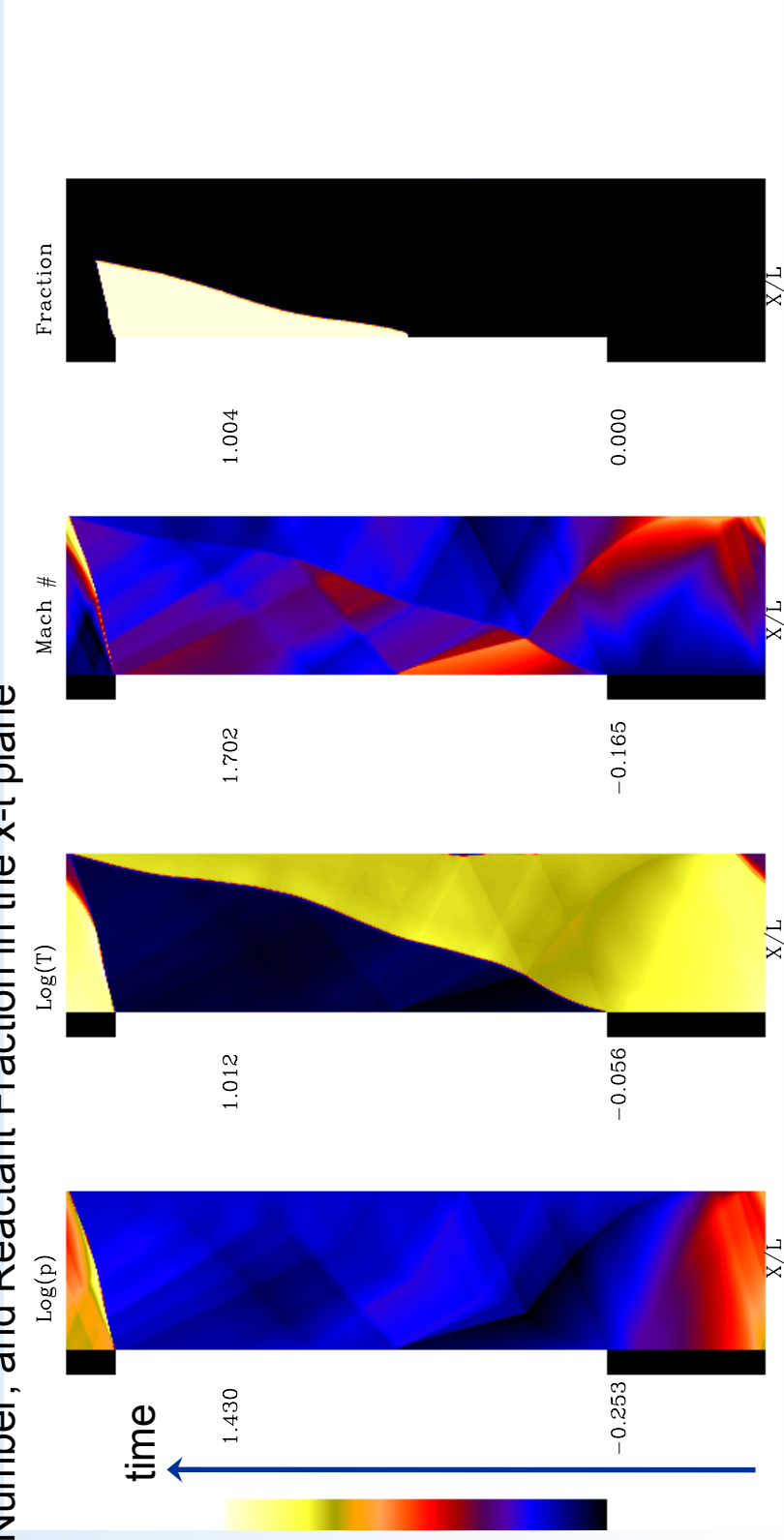
$$\overline{F} = \begin{bmatrix} \rho u A \\ \left(\dfrac{p}{\gamma} + \rho u^2 \right) A \\ u \left(\dfrac{p}{\gamma-1} + \dfrac{\rho u^2}{2} + q_0 \rho z \right) A \\ \rho u z A \end{bmatrix}$$

$$\overline{S}(\overline{w}, x) = \begin{bmatrix} 0 \\ \dfrac{p \; dA}{\gamma \; dx} \\ 0 \\ -RA \end{bmatrix}$$
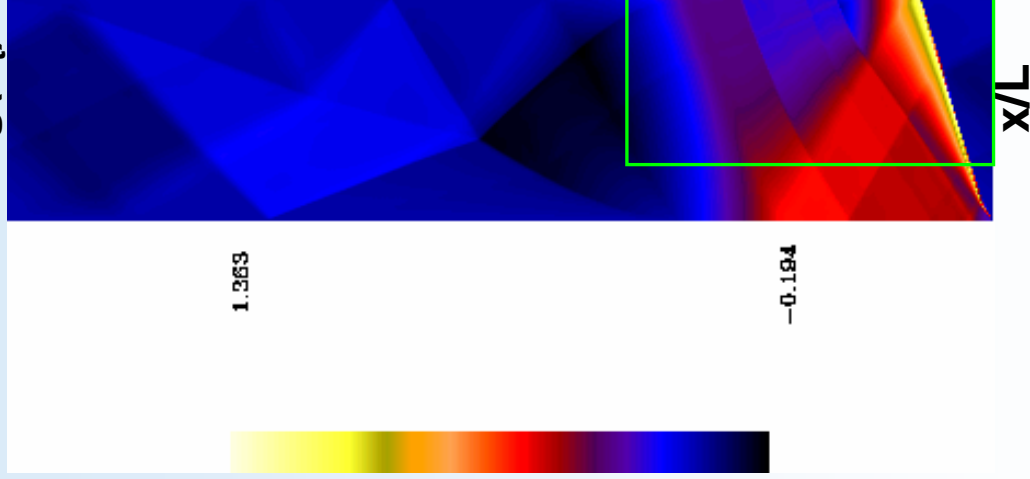
Approaches To Analysis: 1-D CFD

Example Result

Computed flowfield of an ideal, straight-tubed, partial fill, full purge PDE limit cycle shown as contours of normalized pressure temperature, Mach Number, and Reactant Fraction in the x-t plane
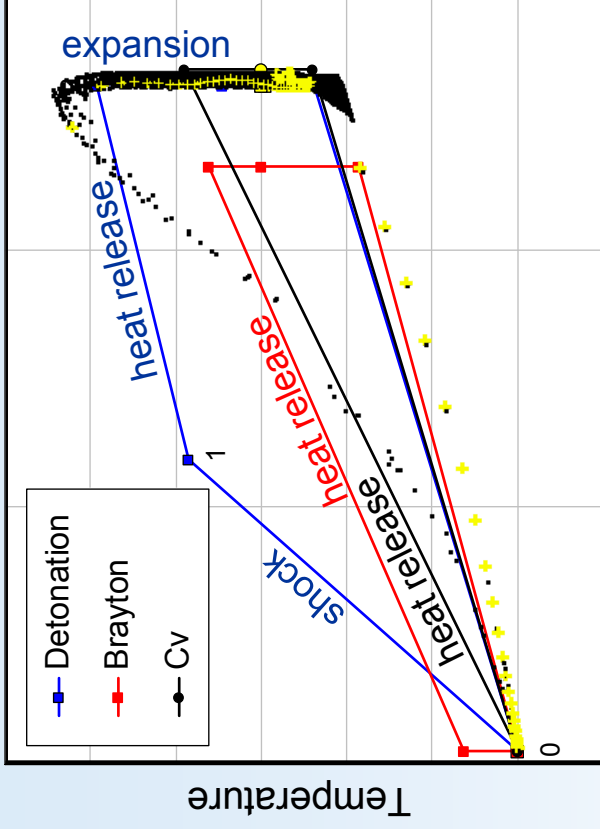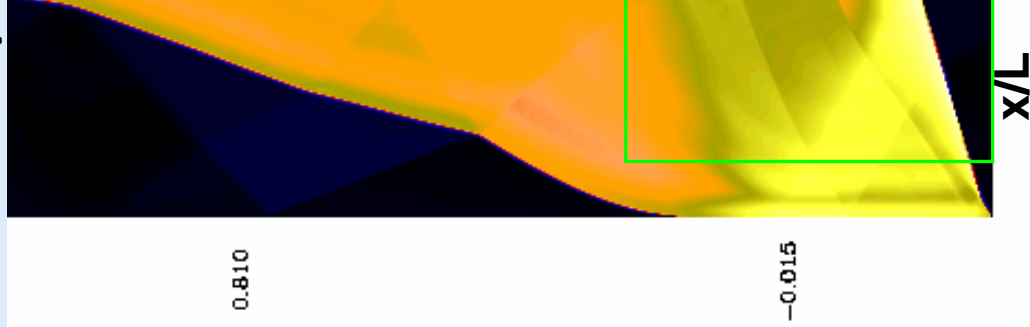
Log(p)

X/L

Log(T)

X/L

Mach #

X/L

Fraction

X/L

time

1.430

1.012

1.702

1.004

−0.253

−0.056

−0.165

0.000

Comparing 1-D & 0-D

Consider
- 1-D Limit cycle calculation.
- Identical heat release to 0-D.
- All points plotted in x-t region shown constituting 75% of per/cycle flow.
- Yellow points are exit plane only.
- Note that points end up all over the isentropic expansion line.

Log(T_t) $Log(T_t)$

0.810

−0.015

x/L

Log(P_t) $Log(P_t)$

1.363

−0.194

x/L

Legend:
- Detonation
- Brayton
- Cv

expansion

heat release

heat release

heat release

shock

1

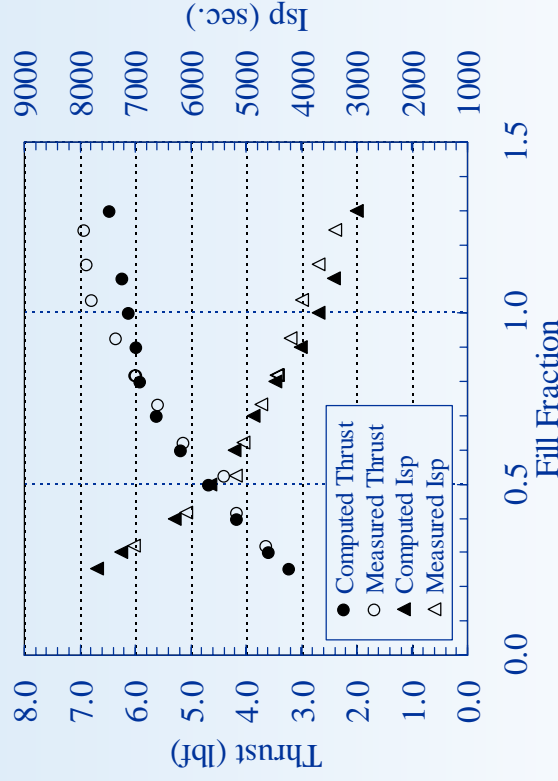Temperature

Entropy

Approaches To Analysis: 1-D CFD

● Pros

– Moderately fast results (i.e. minutes).

– Realistic flowfield results.

– Can be used for preliminary design.

– Remarkably accurate.

– Loss modeling is straightforward (e.g. valves, heat transfer, friction).

– Many cycle modifications are easily addressed such as partial filling, area variation, and nozzles.

– Operational performance maps possible for a particular design.

● Cons

– Much more input information required.

– Limit cycle operation must be achieved.

– No information beyond the tube.

– Initiation, DDT and detonability not considered.

– Boundary conditions are difficult.

Comparison of computed and experimentally measured thrust and Isp for a range of fill fractions in a 16 hz. H2/Air PDE

Legend:
● Computed Thrust
○ Measured Thrust
▲ Computed Isp
△ Measured Isp

X-axis: Fill Fraction (0.0, 0.5, 1.0, 1.5)
Left Y-axis: Thrust (lbf) (0.0–8.0)
Right Y-axis: Isp (sec.) (1000–9000)

Approaches To Analysis : 2-D CFD

Detonation development and propagation in a tube with a wavy wall .
(courtesy Sheng-Tao Yu)

Pressure
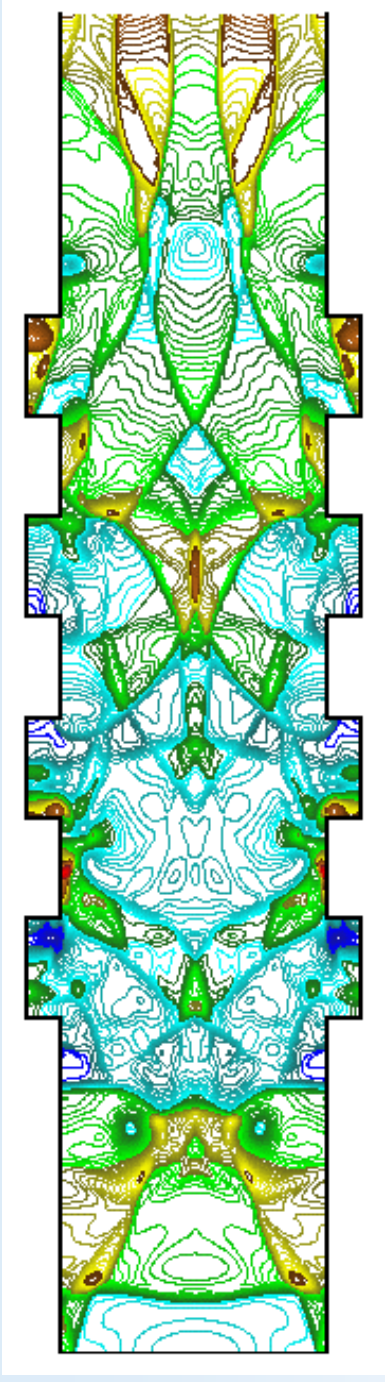
- Features
  - Time accurate
  - Flowfield is assumed symmetric or dominated by two space dimensions
  - Real gas
  - Can use full NS or Euler equations
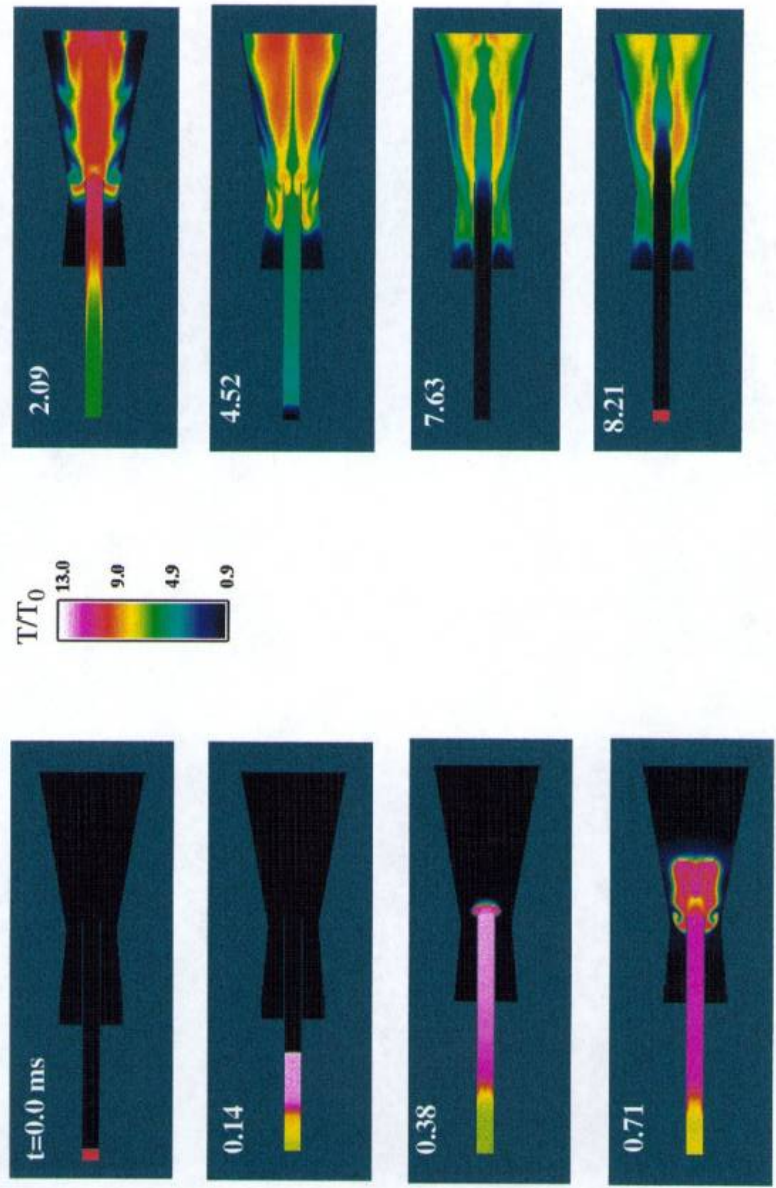 - Multi-species, multi-step chemical kinetics, or Simple one-step.
- Examples
  - Yungster, S., 2003
  - Ebrahimi, H., et. al., 2000

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Approaches To Analysis : 2-D CFD

Axis-symmetric simulation of a PDE with an ejector. (courtesy Yungster)
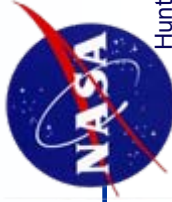

- Pros
  - Useful flow details.
  - Can tell us about what's going on outside the tube.
  - Good for DDT studies and fundamental examination of detonation structure.
 - Can captures boundary layer and turbulence effects.

- Cons
  - Large amount of input information required.
  - Slow turnaround times.
  - Not well validated on some flows to which it is applied.
  - Difficult boundary conditions.

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Approaches To Analysis : 3-D CFD

Six million node computation of a detonation wave traveling in a square channel. (courtesy Sheng-Tao Yu)

propagation direction

- Features
  - Time accurate
  - Real gas
  - Can use full NS equations
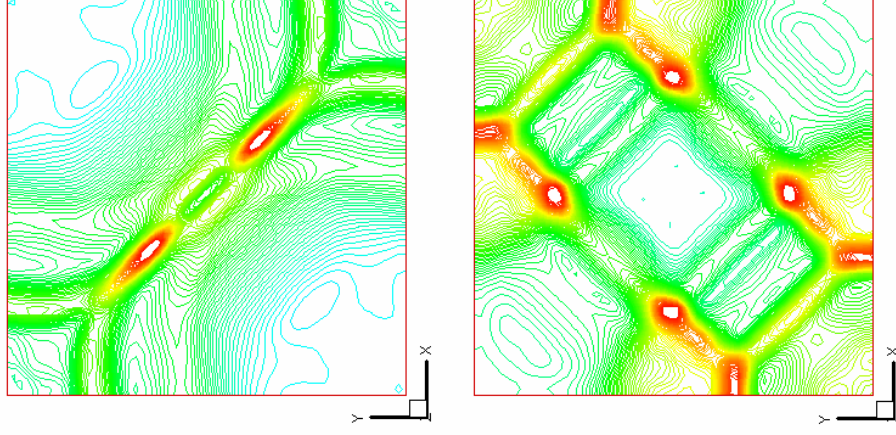 - Multi-species, multi-step chemical kinetics, or ZND
- Example
  - Yu, S., 2003
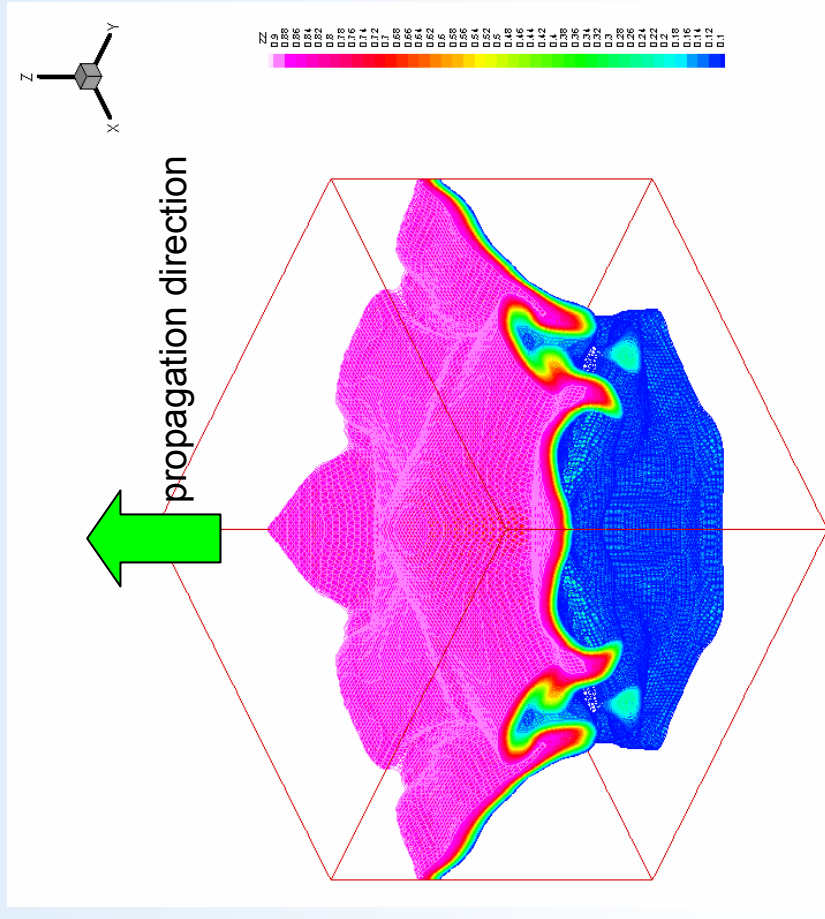
Approaches To Analysis : 3-D CFD

Contours of pressure at different moments of time, in a plane traveling with the detonation showing transverse waves.

(courtesy Sheng-Tao Yu)

- Pros
  - Everything you ever wanted to see, and then some.
  - Good for DDT studies and fundamental examination of detonation structure.
  - Captures boundary layer and turbulence effects.
  - Few assumptions about flowfield required

- Cons
  - Vast input information required.
  - Very long turnaround time.
  - Not practical for parametric analyses.
  - Not practical for limit cycle analysis
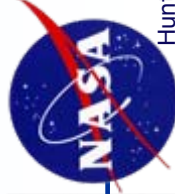
Performance Metrics

Few propulsion systems are developed based on only one metric. Most represent a compromise between...
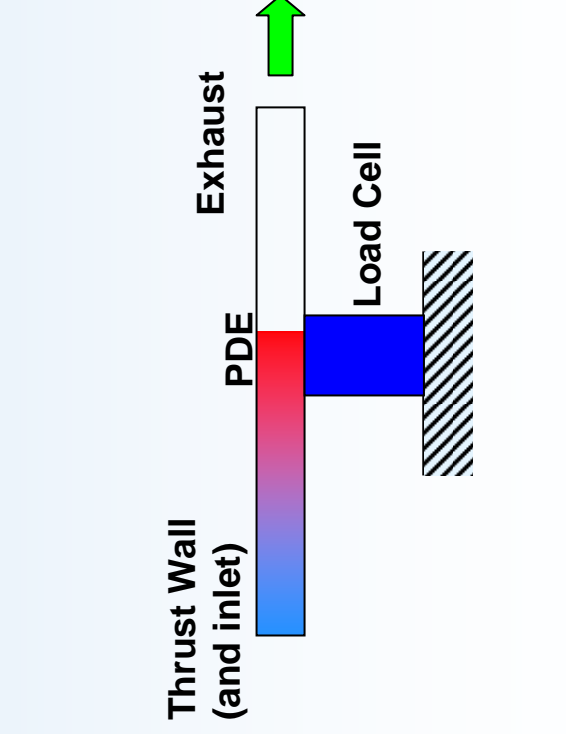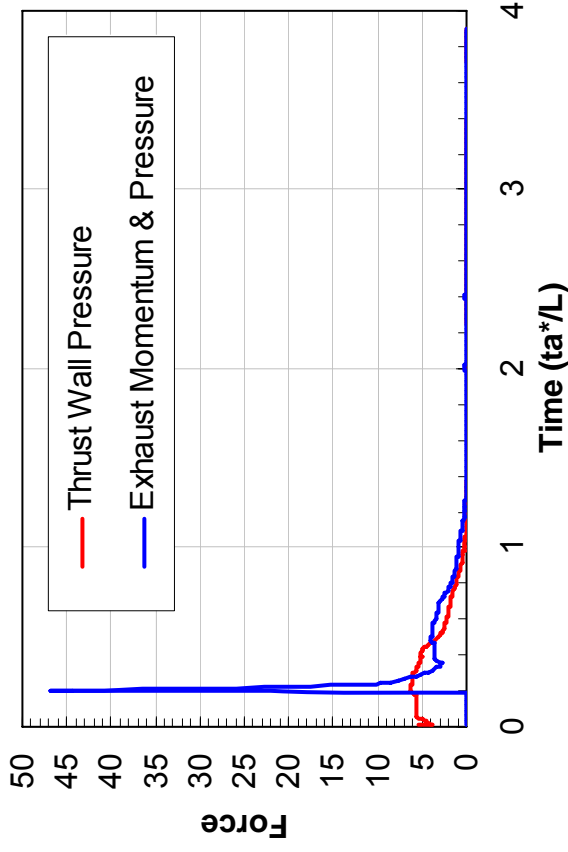
- Specific Impulse
  - Essentially the inverse of SFC
- Specific Thrust
  - Straightforward for fully fueled tubes. Trickier for partial fuelling.
- Thrust per unit of cross section
- Thrust-to-weight
  - Currently difficult to assess, but essential.
- Pressure ratio
  - A derived metric. Useful for some applications.

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Performance Metrics

•Specific Impulse
  – Mean thrust per unit rate of fuel used.
    or
  – Impulse per unit mass of fuel used.
  – Requires thrust which may be measured at thrust wall or via exhaust flow (if a limit cycle exists).

Thrust Wall (and inlet) | **PDE** | **Exhaust**

Load Cell

Load Cell

Non-dimensional force from a 1- D CFD calculation of a full purge, 0.7 fuel fill limit cycle

Legend: Thrust Wall Pressure; Exhaust Momentum & Pressure

Axis: Force (0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50); Time (ta*/L) (0, 1, 2, 3, 4)

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Performance Metrics

- Specific Impulse
  - Often computed using so-called one-shot calculation
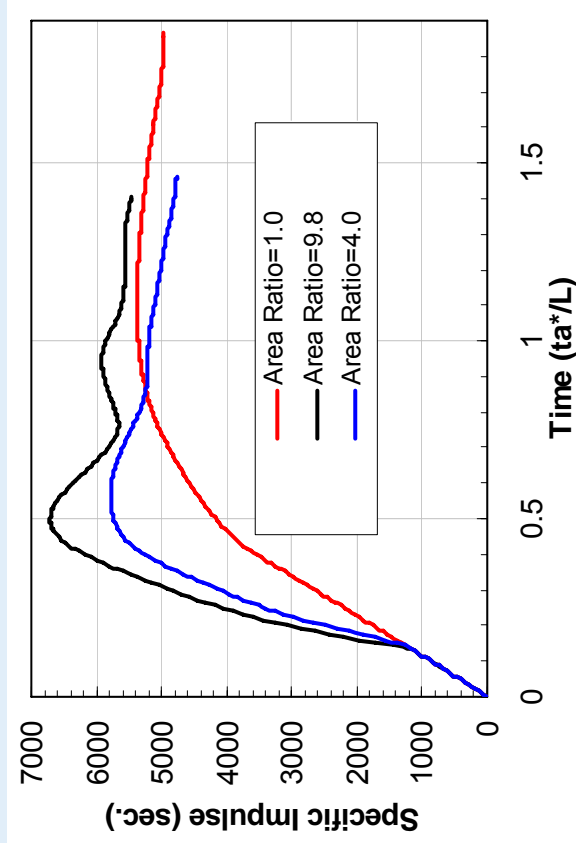 - This is not always correct.
  - Consider...
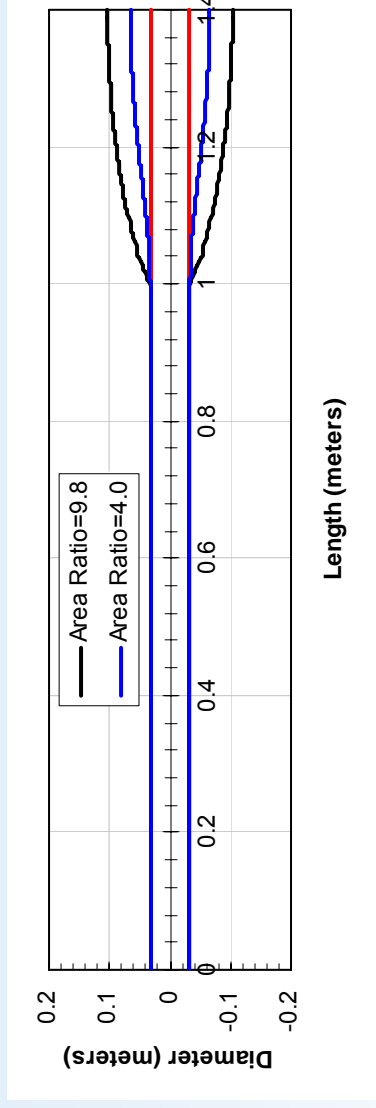
THREE IDEAL PDE GEOMETRIES

- Each tube initially filled w/ detonable, stoichiometric H_2/Air mixture to a length of 1.0 meter.
- All gases at rest at sea-level conditions.
- A wall is placed at the left end (no inlet).
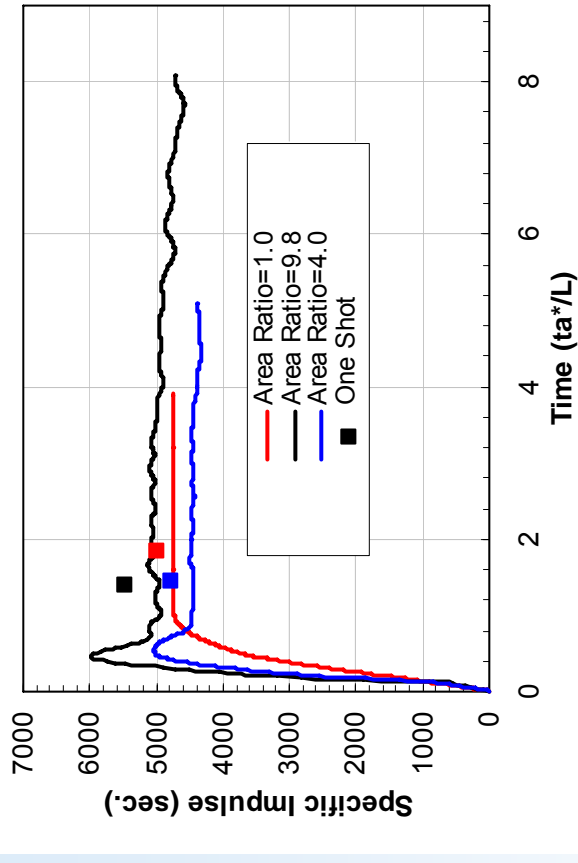
Performance Metrics

- Specific Impulse
  - Often computed using so-called one-shot calculation
 - This is not always correct.
  - Consider…

LIMIT-CYCLE RESULTS

- Computations run until cycle repeats.
- Tubes completely purged and refilled with air and detonable mixture to a length of 1 m.
- Inlet opened when thrust wall pressure matches ambient.
- Specific impulse at AR=9.8 the same as AR=1.0, but average thrust much lower.

ONE-SHOT RESULTS

- Computations run until pressure at thrust wall matched ambient.
- Specific impulse at AR=9.8 10% above straight tube.

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Performance Metrics

- Specific Thrust
  - Thrust per unit of total mass flow rate (air and fuel).
  - Determines engine size.
  - Often at odds with Specific Impulse.
  - Straightforward for fully fueled tubes. Trickier for partial fuelling.
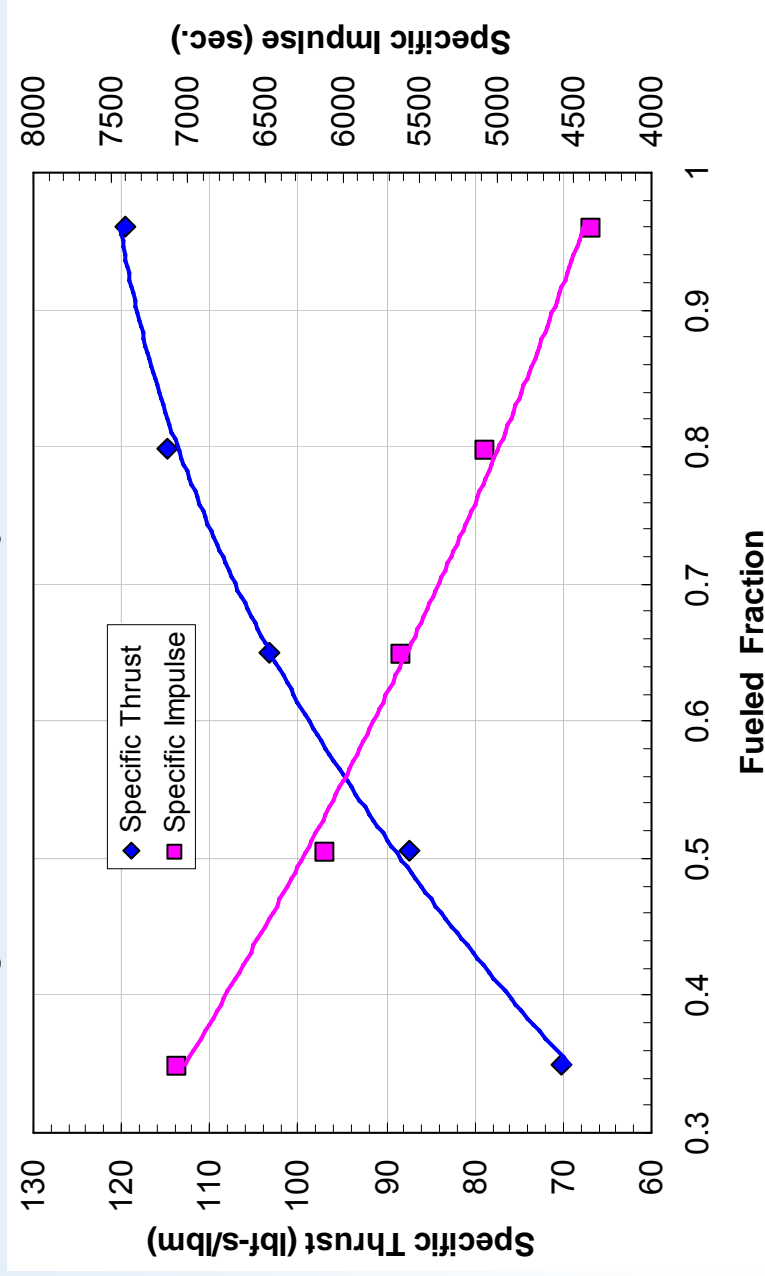
1-D, IDEAL LIMIT-CYCLE RESULTS

- Stoichiometric H_2/Air.
- Sea Level Conditions.
- Tubes completely purged and refilled with air or detonable mixture.
- Inlet opened when thrust wall pressure matches ambient.
- Very similar result for fully fueled lean mixtures.
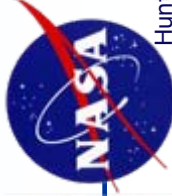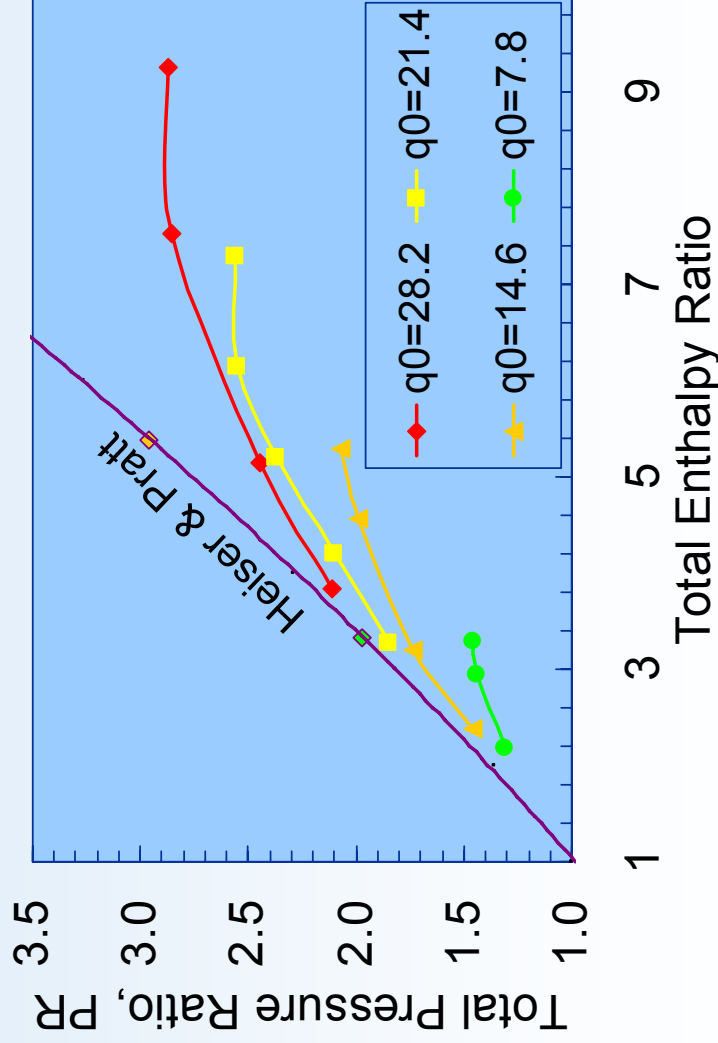- 'Looks-like' by-pass in gas turbines.

Performance Metrics

- **Pressure Ratio**
  - What if PDE is coupled to something else (e.g. multiple tubes w/ plenum and common nozzle, turbomachinery, etc.)?
  - Need a steady or averaged metric that can be used with other components.
    ONE POSSIBLE ANSWER
    (applicable to computed results)
    - Mass-average the total exhaust enthalpy and ratio to inlet enthalpy.
    - This becomes a measure of heat added to the working fluid.
    - Calculate thrust.
    - Find the total pressure that, when ideally expanded from the same averaged total enthalpy, at the same averaged flow rate, to the ambient static pressure would yield the same thrust.
    - Use this as the available total pressure.
    - Limited to a particular type of cycle, and back-pressure.

Chart — Total Pressure Ratio, PR (y-axis: 1.0 to 3.5) vs Total Enthalpy Ratio (x-axis: 1, 3, 5, 7, 9)

Heiser & Pratt

Legend: q0=28.2, q0=21.4, q0=14.6, q0=7.8

PDE Hybrid Applications

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Huntsville, Alabama, 2003

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Outline

- What is a Hybrid PDE?
- Why Look at Them?
- Potential Configurations
- Potential Implementations
- Considerations/Challenges

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What is a Hybrid PDE?

- Pulse Detonation technology combined with gas turbine technology.

Ha Ha….You're kidding right? You're not really going to bolt one of those things to a gas turbine are you? You'd blow it to smithereens! Why, we can't even handle resonant combustors, let alone this!

- The concept is not without precedent, but must be considered carefully.

- There may be advantages.
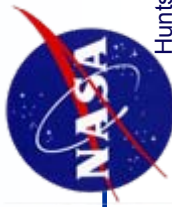
Why Look at Them?

- Because PDE's 'look like' Pressure-Gain Combustors.

  – Pressure-gain is better than pressure-loss.

- Because they may lower manufacturing and service costs by reducing complexity, and part counts.

- Because they may circumvent current material limits.

- There are related precedents.

  – The first working gas turbines used valved, CV combustors w/o compressors.

  – Small gas turbines have been operated with unsteady, pulsejet-driven combustors.

  – Wave Rotors (unsteady, gasdynamic pressure-exchange devices) coupled to conventional turbomachinery have been investigated.

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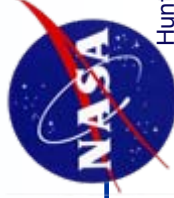
Why Look at Them?

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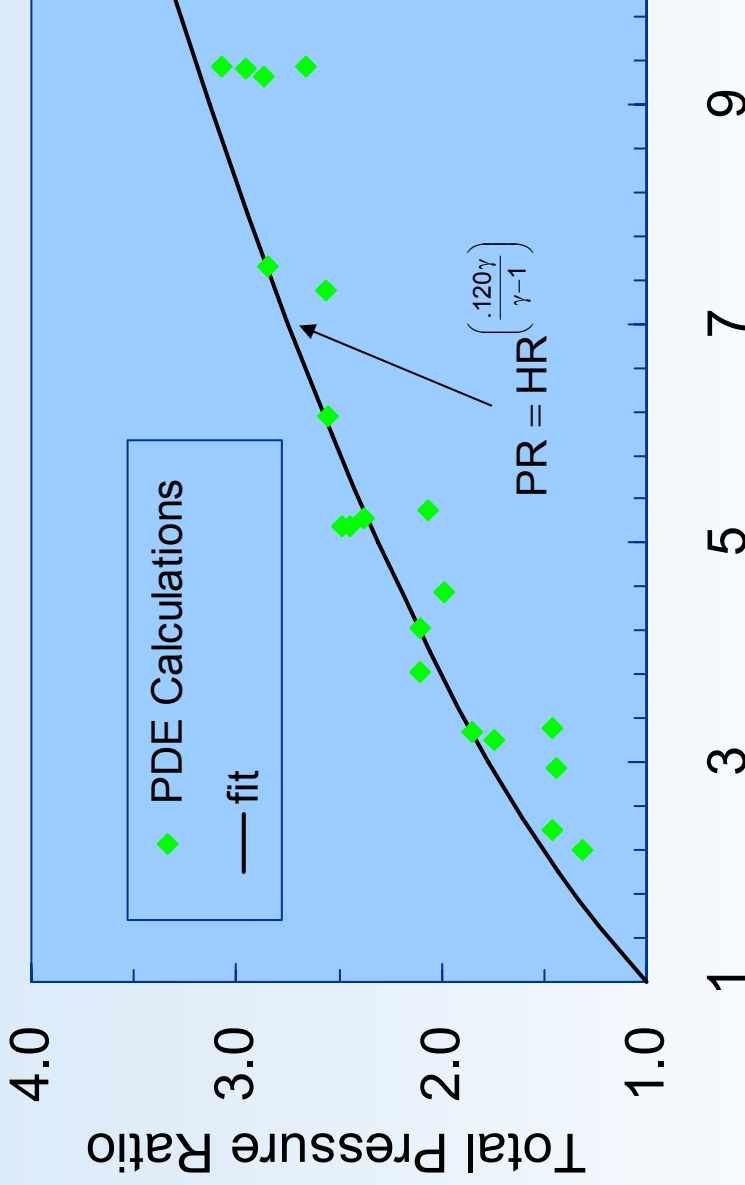
PERFORMANCE POTENTIAL OF IDEAL PDE

- Enthalpy Ratio is mass-averaged over a cycle.
- Enthalpy ratio achieved via partial filling and/or changes in fuel equivalence ratio.
- Pressure ratio is an average based on equivalent steady thrust.

Chart axes: Total Pressure Ratio (1.0, 2.0, 3.0, 4.0) vs Total Enthalpy Ratio (1, 3, 5, 7, 9)

Legend: ◆ PDE Calculations — fit

$$PR = HR^{\left(\frac{.120\gamma}{\gamma-1}\right)}$$

– Combustors and afterburners have enthalpy ratios near 2.0 (determined by material limits).

– For combustors, a rough "rule of thumb" states that SFC reduction and specific power increase follow pressure ratio.

– SFC REDUCTIONS OF 15-30% APPEAR POSSIBLE!

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Potential Configurations

PDE replaces conventional combustor
(and possible stages of compression)

PDE as duct afterburner
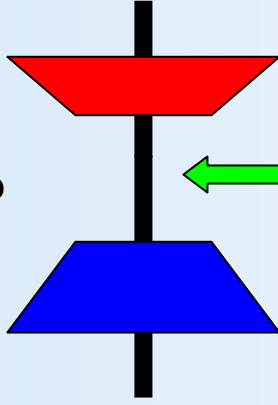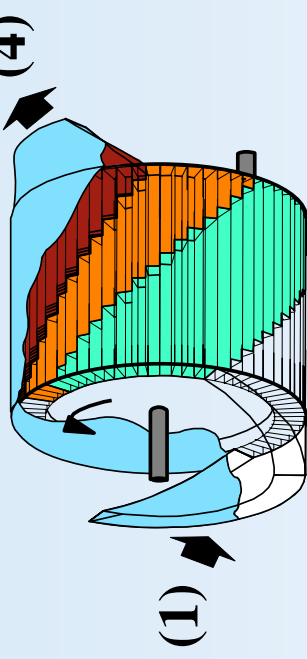
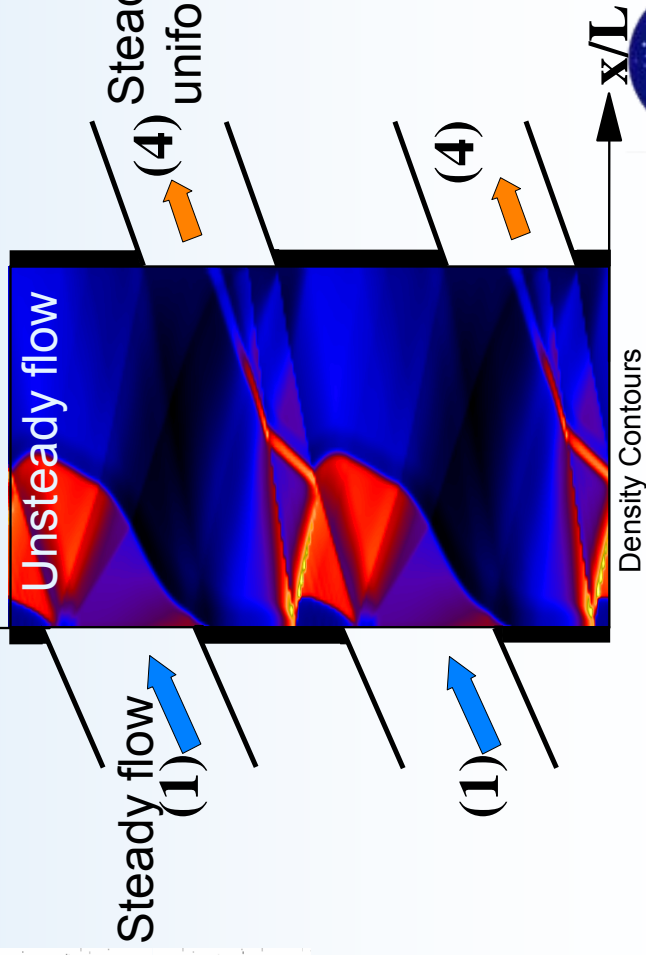PDE replaces mixed flow afterburner
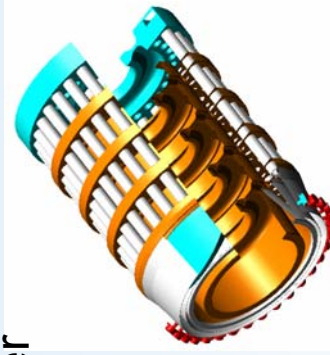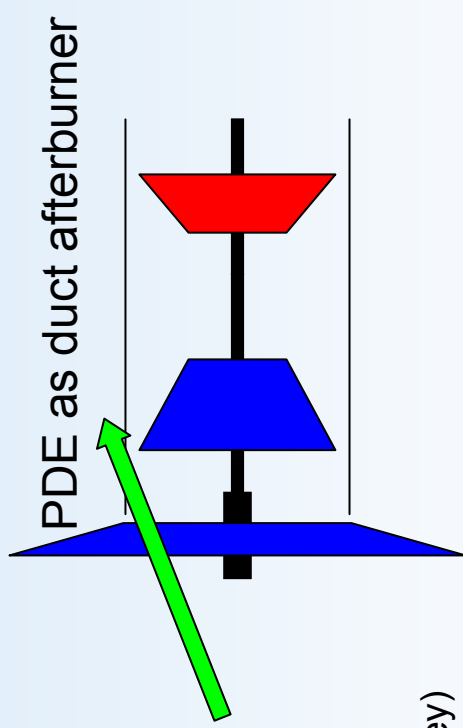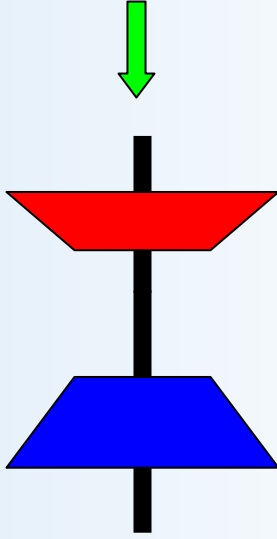
(courtesy Pratt & Whitney)

PDE

All possibilities envision multiple tubes operating in a phased fashion to mitigate unsteadiness

Potential Implementations

Spin the tubes (Wave Rotor) **(4)**

(1)

2-Port

Spin the valves

Fig. 10-5. Pressure exchanger proposed by Darrieus (Ref. 20).

Steady flow   Unsteady flow

Detonative Combustion-On-Rotor **circumferential position**

Steady, non-uniform flow

x/L

(4)

(4)

Unsteady flow

Steady flow **(1)**

(1)

Density Contours
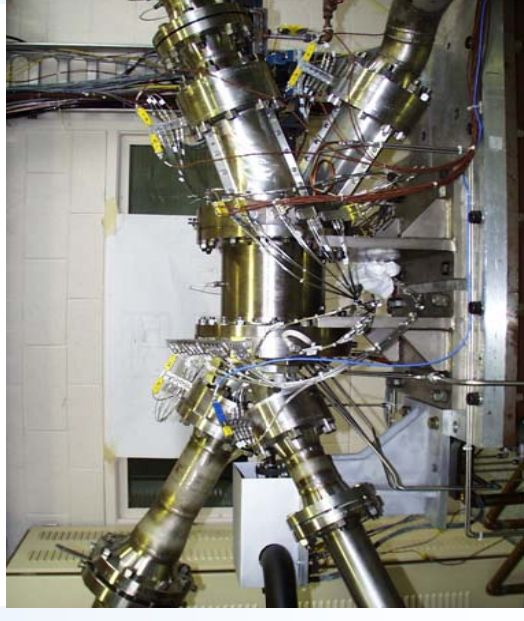
Potential Implementations

Wave Rotor

- Wave Rotors are under investigation as topping cycles.

- They have been built and operated over the course of several research efforts
  - NASA Glenn
  - G.E.
  - Power Jets Corp.
  - Brown-Boveri
  - Calspan
  - Mathematical Sciences

- Though their current target application is not PDE's, their inlet and exhaust flows are similar. That is to say, <u>Highly Non-uniform</u> (though steady).

- Preliminary investigations of low-loss transition ducting from rotor-to-turbine have been conducted.
  - Rolls Royce Corp.

Diffuser with baseline nozzle ring (courtesy Rolls Royce Corp.)
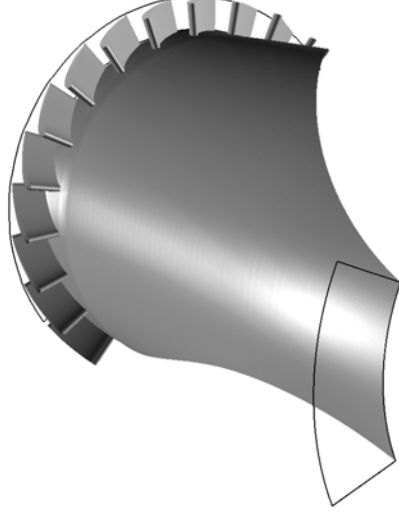
Wave Rotor rig at Glenn

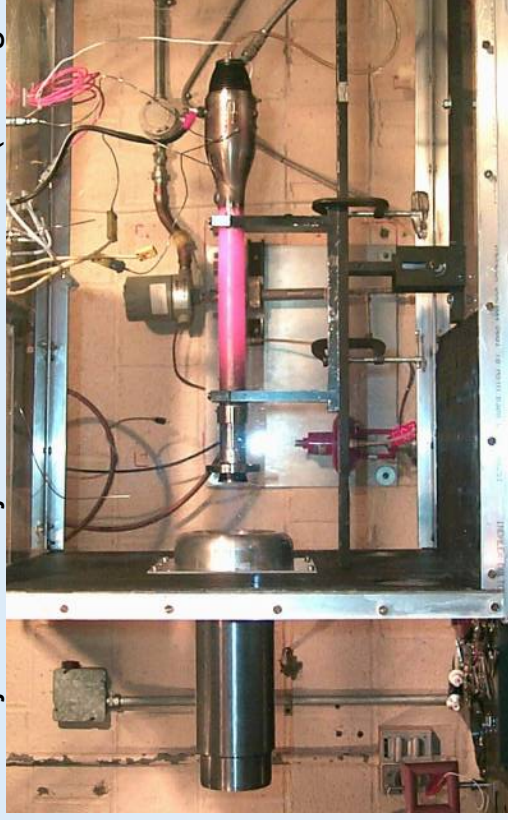<u>Glenn Research Center</u>   at Lewis Field
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Potential Implementations

Ejectors
(Taking Advantage of Unsteadiness)

- Thrust Augmentation of 1.8 obtained. This is very high compared to equivalent steady ejectors.
- Entrainment Ratio of 18 obtained
- Velocity fluctuations reduced by factor of 5.
- Entire unit may be shrouded.

CAN THRUST AUGMENTATION BE TURNED INTO PRESSURE-GAIN?

Pulsejet Driven Ejector

PDE Driven Ejector

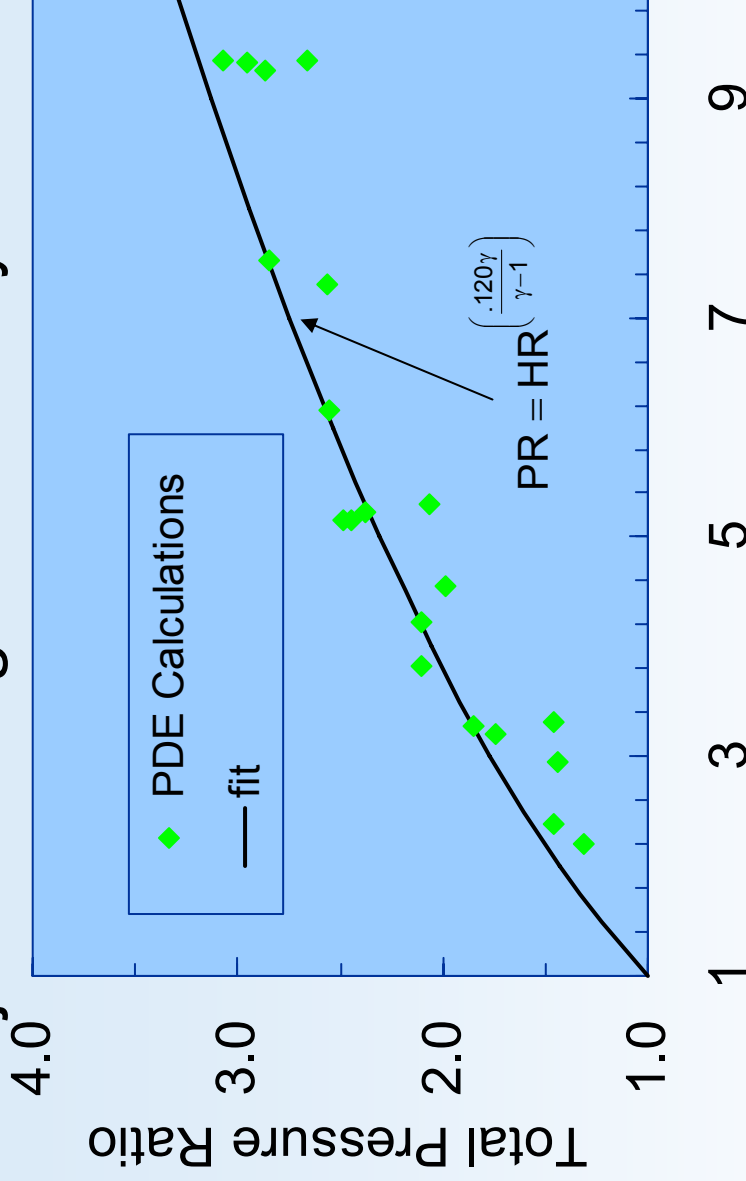- Thrust Augmentation of 1.6 obtained

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Potential Implementations

- Ejector configurations may be necessary.

Chart: Total Pressure Ratio (y-axis, 1.0 to 4.0) vs Total Enthalpy Ratio (x-axis, 1 to 9)

Legend:
- ◆ PDE Calculations
- — fit

$$PR = HR^{\left(\frac{.120\gamma}{\gamma-1}\right)}$$

CONSIDER AN 8:1 OPR GAS TURBINE WITH ENTHALPY RATIO OF 2.2

– Requires either a fill fraction of 33% or equivalence ratio of 0.3.
– This is probably an unrealistic equivalence ratio.
– Partial filling results in highly stratified flow (temporally and/or spatially)
– Thus, fill fraction may be impractical, or present the turbine with an unacceptable temperature gradient.

Considerations/Challenges

DISCLAIMER

- PDE's are a technology in infancy.
- Hybrid PDE's are even more so.
- Many issues remain unresolved and even undiscovered.

HAVING SAID THAT......

Considerations/Challenges

AN UNORDERED LIST TO PONDER

- Initiation
  - Many tubes, each firing at <u>hundreds</u> of hz.
- Transition (DDT)
- Fuel distribution
- Emissions
- Sealing
- System Integration
- Valving
  - A self-aspirated PDE has not yet run.
- Heat Transfer/Cooling
  - PDE & Turbomachinery

Glenn Research Center   at Lewis Field
Controls and Dynamics Technology Branch
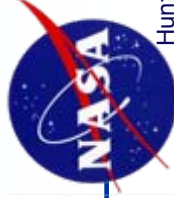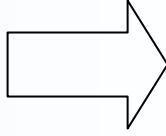
Considerations/Challenges

...MORE

- Optimization
  - Cycle timing.
  - Tube shaping
- Noise
- Vibration
- Sizing
- Starting
- Ducting
- Operational Envelope
- Performance
  - This does the same thing as adding a spool.
  - Is it competitive with turbomachinery?
  - Are there advantages over turbomachinery?