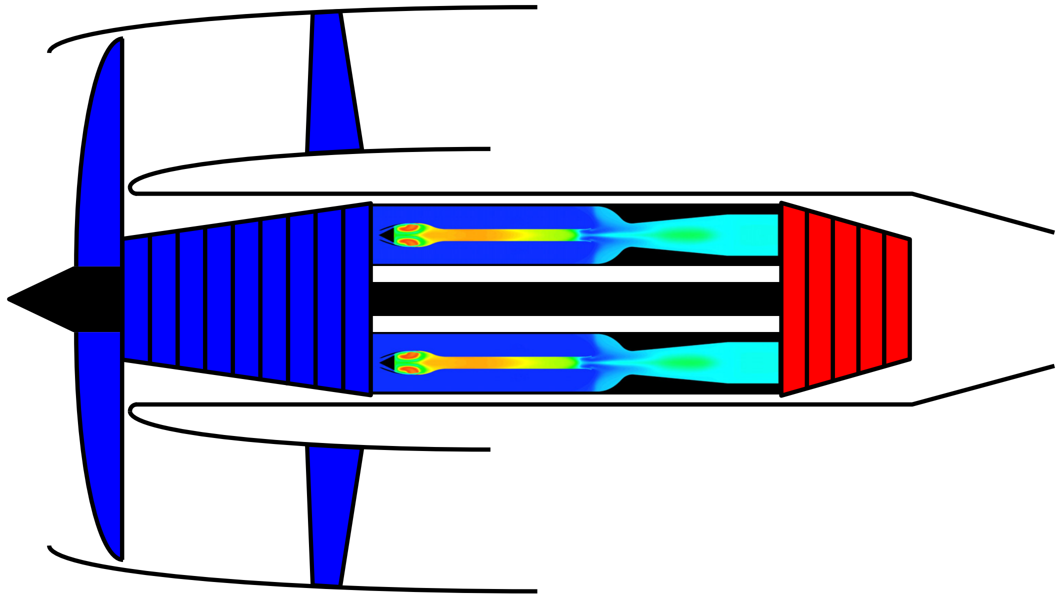

Defining and Measuring Pressure Gain

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For Any Pressure Gain Combustion (PGC) Device The Question Has Always Been The Same: *How Much Pressure Do You Get For The Energy You Put In?*

- P_{t4}/P_{t3} vs. T_{t4}/T_{t3} tells us both thrust potential and turbine work potential, that is, availability
- P_{t3}, T_{t3} are easy to measure
- P_{t4}, T_{t4} are harder to measure
- Measurement approaches should actually reflect fluid availability
- Measurement approaches should be experimentally practical
- Practical approaches differ between PGC device types
- Practical approaches should be used by both modelers and experimentalists.

Kentfield, J.A.C., J. Eng. Gas Turbines and Power, 1988

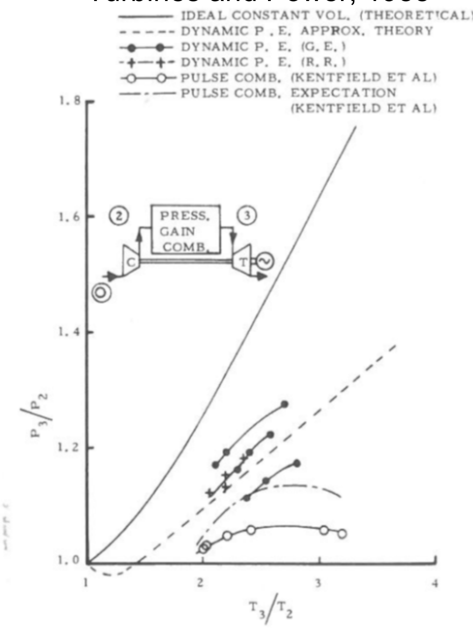
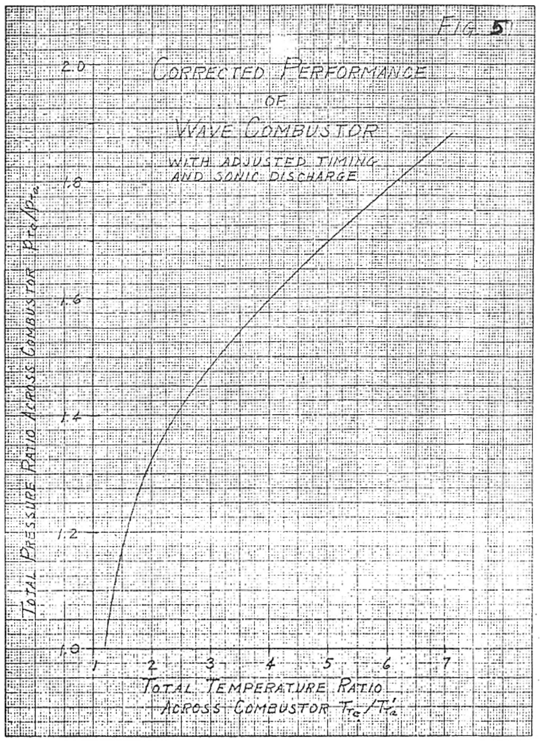


Fig. 13 Pressure-gain performances of pressure exchangers and valveless pulse combustors

G.E. Wave Engine Project
First Quarterly Report
April 18, 1960



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At A Minimum The Measurement Method Should Be Described

What Have We Seen To Date?

- For PDE's & RDE's: gross thrust, specific thrust, or fuel specific impulse
  - This performance metric has little meaning on its own (*Give me a K-bottle of air, a regulator, and a nozzle and I'll give you any gross specific thrust you want*)
  - For PDE's, an inlet supply pressure has never been published
  - For RDE's, inlet supply pressure is occasionally published; however, it is never related back to the typical published gross thrust measurement in any meaningful way
  - Both PDE and RDE results have been published where only dubious static pressure measurements have been made, along with equally dubious claims of pressure gain
- For ICWR's, pressure ratio results have been published, but not how they were obtained (*recent LibertyWorks/IUPUI results are a <u>notable</u> exception*)
- For RPC's, pressure ratios have often been published without associated temperature ratio

NOTE-
- *PDE= Pulse Detonation Engine*
- *RDE=Rotating Detonation Engine*
- *ICWR=Internal Combustion Wave Rotor*
- *RPC= Resonant Pulse Combustor*

Without Meaningful Performance Metrics Could We Be Drawing False Conclusions?

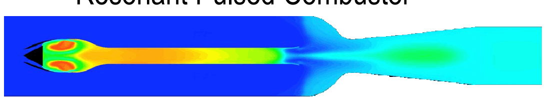
Possible Examples

- Should high combustion efficiency be noted if the unreported pressure gain is -15%?
- Should high mass flux rates be a noted feature if the unreported pressure gain is negative?
- Should the claim be made that the number of waves in an RDE is unimportant without demonstrating pressure gain?
- Do heat flux measurements have meaning in a device if the pressure gain is unknown, but likely negative?
- Should reliable DDT obstacles be reported if they lead to unreported negative pressure gain?

The Following Slides Describe Pressure Gain Measurement Techniques Applicable to Each of the Devices Currently Under Investigation for PGC

- Useful for both experiments and CFD
- Not definitive
  - Though they do have some analysis to support them
- Intended to foster discussion
- Put forth without consideration of cost of implementation

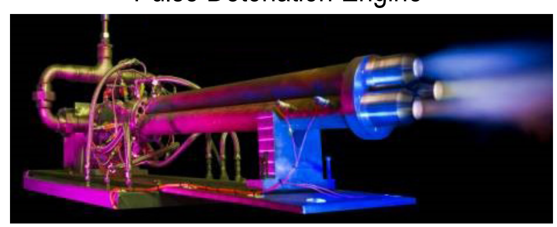
Resonant Pulsed Combustor



Internal Combustion Wave Rotor

IUPUI/Purdue/LibertyWorks

Pulse Detonation Engine

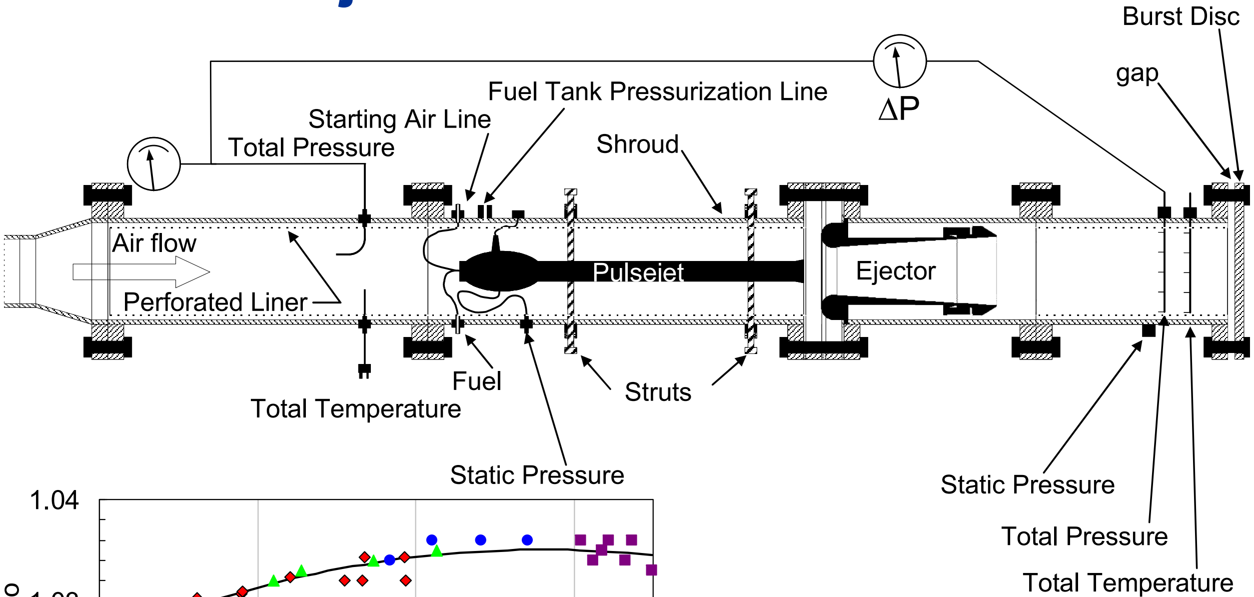


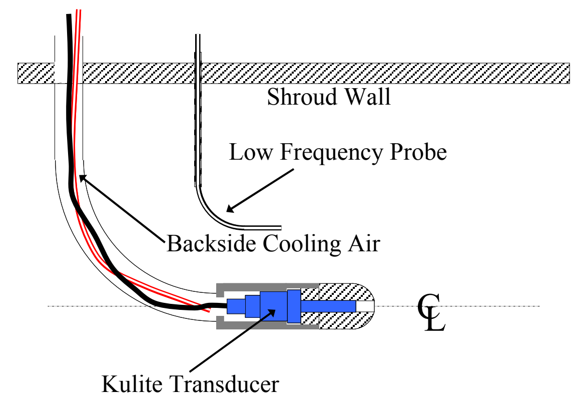
G.E. Global Research Center

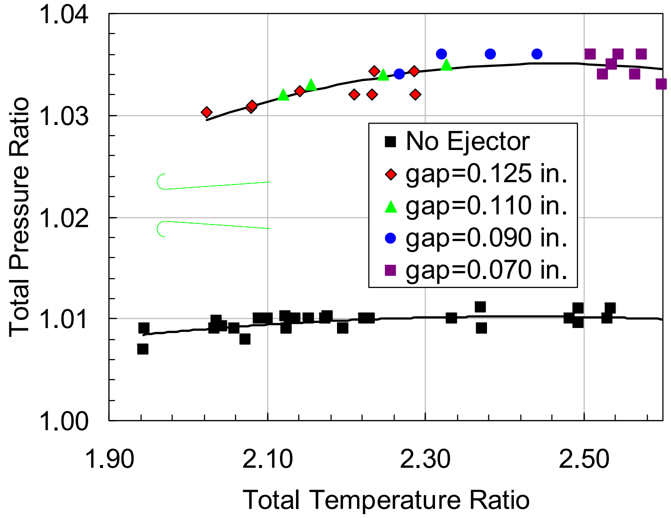
Rotating Detonation Engine

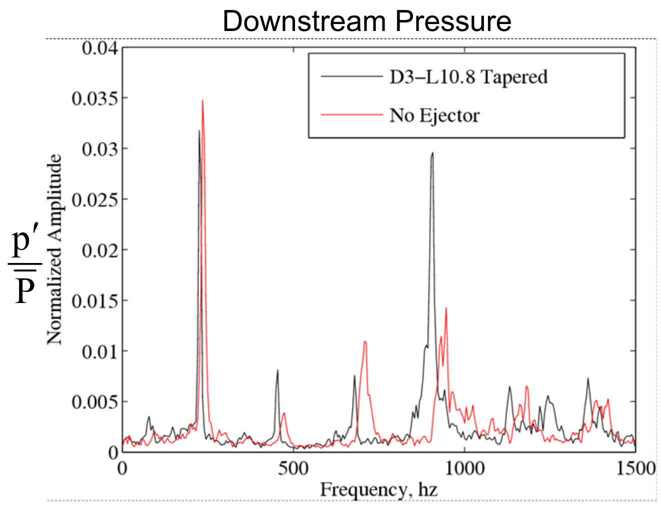
Air Force Research Laboratory

Ejector Enhanced Resonant Pulse Combustor





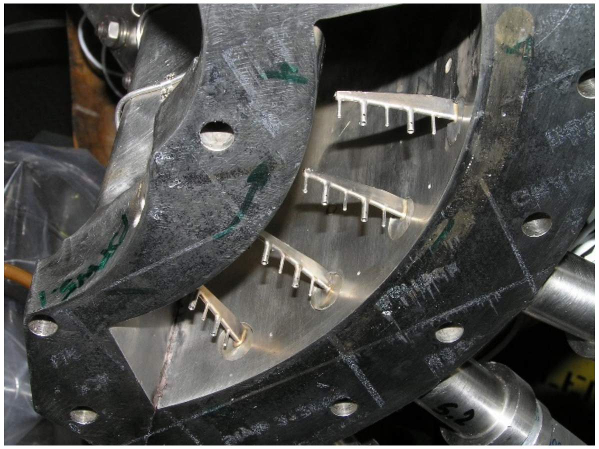


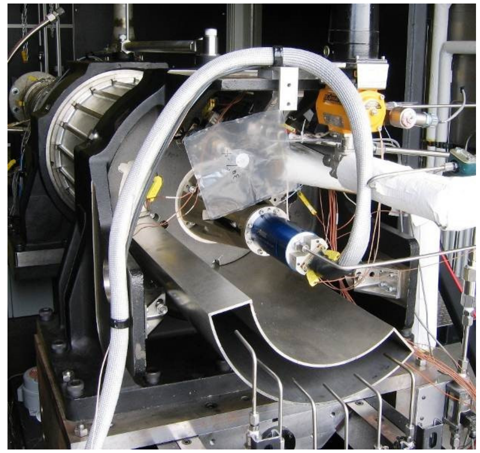


- Directly measured time averages are appropriate because:
  - Fluctuations are small
  - Flow is well-mixed
- Capillary Tube Averaged Pressure (CTAP) appropriate because:
  - Mach numbers are small
- Spatial variation accomodated with CTAPs on a bus

Alternative Approach Required Without Ejector

Internal Combustion Wave Rotor





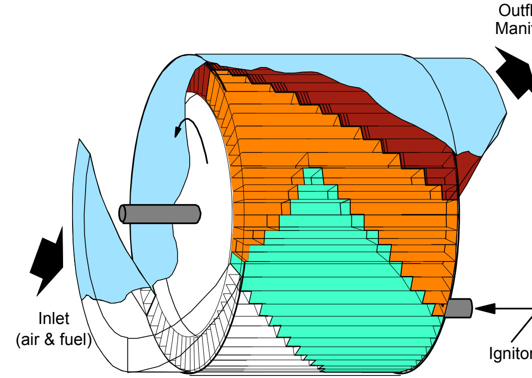


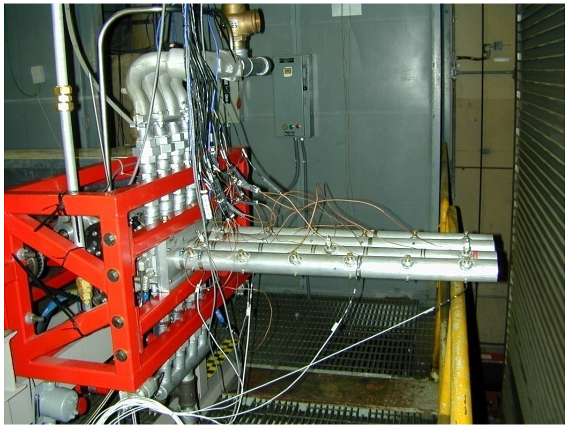
Photo courtesy IUPUI and LibertyWorks

- Constant area mixing (CAM) calculations[*,+] are appropriate because:
  - Port flows are nominally steady
  - Port flows are spatially non-uniform
  - CAM calculations account for Foa's "efficiency of non-uniformity"
  - CAM calculations allow multi-point measurements to be represented by a single value
- Appropriate instrumentation for CAM is resource intensive (i.e. $$$), but not exotic
- CAM avoids the problem of designing an aerodynamic duct to diffuse non-uniform port flow
- Can be problematic with high heat transfer, heat soak experiments

[*] *Cumpsty, N.A., Horlock, J.H., "Averaging Nonuniform Flow for a Purpose," J. Turbomachinery, v. 128, Feb. 2005*

[+] *Oates, G.C., Aerothermodynamics of Gas Turbine and Rocket Propulsion*

Pulse Detonation Engine



Courtesy Air Force Research Laboratory

- Equivalent Available Pressure (EAP) appropriate because:
  - Other approaches produce ambiguous results
  - If pressure gain is measured, it is undoubtedly ‘real’
- EAP is very conservative
  - Uses fuel heating value to estimate mass flux averaged exhaust temperature
  - Includes nozzle performance in calculation
- EAP works for RPC’s without bypass ejectors and even ICWR’s

Measuring EAP

1. Measure gross specific thrust, T_{spg}
2. Calculate mass flux averaged exhaust total temperature, $\bar{T}_{t4}$ using *a/f* , T_{t3}, and fuel heating value
3. Calculate the steady total pressure which, when ideally expanded to the ambient pressure at the exhaust total temperature yields the measured gross specific thrust

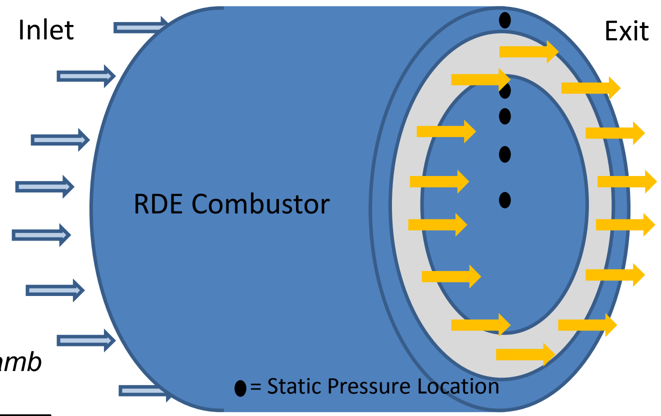
$$p_{tEAP} = \frac{p_{amb}}{\left(1 - \frac{\gamma - 1}{2}\left[\frac{T_{spg}^2 g_c}{\gamma R_g \bar{T}_{t4}}\right]\right)^{\frac{\gamma}{\gamma-1}}}$$

See:
AIAA-2012-0770 (NASA TM-2012-217443)
AIAA-2018-4567

Rotating Detonation Engine

Courtesy Air Force Research Laboratory

- Equivalent Available Pressure (EAP) appropriate because:
  - See PDE justification
- Ideal EAP, or EAP_i is also an option
  - Repesents the steady total pressure which, when ideally expanded to the ambient pressure at the exhaust total temperature yields the ideal gross specific thrust resulting from isentropic expansion of each fluid particle leaving the RDE
  - Requires choked exhaust flow with no internal divergence
  - Requires an instrumented bluff body in the exhaust plane
  - Uncouples nozzle performance



Measuring EAPi

1. Calculate augmented gross thrust, T_{ga} by subtracting measured drag, D from measured gross thrust, T_g
2. Calculate effective static pressure based on choked (Mach=1.0) exit assumption➔ $\tilde{p}_4 = \dfrac{\dfrac{T_{ga}}{A_{exit}} + p_{amb}}{1+\gamma}$
3. Calculate total from static pressure based on choked (Mach=1.0) exit assumption➔ $p_{EAPi} = \tilde{p}_4 \left(\dfrac{\gamma+1}{2}\right)^{\left(\frac{\gamma}{\gamma-1}\right)}$

See:

AIAA-2012-0770 (NASA TM-2012-217443)

AIAA-2018-4567

Additional Approaches

- Find a simple measurement, or a derived metric based on a simple measurement that empirically correlates with one of the previously described approaches
  - Generally limited to specific configurations
- Match numerical models to available measurements and then use model to calculate pressure gain using one of previously described approaches
  - Nobody believes these results except the modeler :-)

Concluding Remarks

- The PGC community needs to demonstrate that devices can actually achieve PG
  - And ultimately do so without excessive energy input (PR vs. TR ➔ efficiency)
- The PGC community needs an accepted means for measuring PG
  - Then they have to convince everyone else of its validity
- The measurement methods outlined here may get us started
- Even small laboratories need an awareness of rig performance to insure sure that they are investigating a relevant configuration.
  - The highly coupled nature of PGC devices means that there's no such thing as a component test
- Simpler performance measurements that can be theoretically or empirically tied to established approaches are worthwhile; however:
  - Be aware of the limitations

END