Resonant Pulse Combustors: A Reliable Route to Practical Pressure Gain Combustion

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Acknowledgements

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• Shaye Yungster - CFD
• Doug Perkins - Analysis
• Scott Jones - Analysis
• Kevin Dougherty - Experiments
• Robert Pelaez - Experiments
• Paul Litke - Experiments
• Andy Naples - Experiments
• Mark Wernet - PIV
• Trevor John - PIV
Pressure Gain Combustion (PGC) Defined:
A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure.

Context:
Our Focus Is Not the Promotion of Any One PGC Mode
It Is the Practical Utilization of Confinement
**Motivation**

**Pressure Gain Combustion Theoretically:**
- Increases thermodynamic cycle efficiency
- Reduces SFC / fuel burn (NASA Objective)
- Reduces greenhouse gas emissions (NASA Objective)
- Competes with conventional cycle improvements

### Engine Parameter Comparison

<table>
<thead>
<tr>
<th>Engine Parameter</th>
<th>Turbofan</th>
<th>Turbojet</th>
</tr>
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<tbody>
<tr>
<td>OPR</td>
<td>30.00</td>
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</tr>
<tr>
<td>$\eta_c$</td>
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<td>Mach Number</td>
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<tr>
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<tr>
<td>$T_{combustor exit}$ (R)</td>
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<tr>
<td>Burner Pressure Ratio</td>
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<tr>
<td>$T_{sp}$ (lb$_f$-s/lb$_m$)</td>
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<td>SFC (lb$_m$/hr/lb$_f$)</td>
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**Low NOX Constraint on All Concepts**

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**Turbine Compressor**

$\Delta P > 0.0$, $P_4/P_3 > 1$

*Equivalence:*

- 6.0% increase in $\eta_c$
- 2.5% increase in $\eta_t$
- 1 compression stage

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**INNOVATION**

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Motivation

Resonant Pulse Combustor-RPC
(aka ‘Confined’ Volume Deflagration)

FEATURES:
• Self-sustained operation
  • No spark plugs
• Only one moving part
• Relatively low unsteadiness amplitudes
  • Lower thermal and mechanical stresses
  • Effluent easier to smooth
  • Fewer potential issues for downstream turbomachinery
• Readily operates with liquid fuels (gasoline, ethylene, kerosene)
• Effective lean operation (low $T_{t4}$’s) with bypass ejectors
• Unequivocally a pressure gain device
  • Only known PGC system to operate under static conditions

DRAWBACK
• Only Modest Pressure Gain is Possible
  • Confined (not constant) volume combustion

Practically: Features May Outweigh Drawback – Even Compared to Other PGC Approaches
Motivation

Resonant Pulse Combustion Basic Cycle
Experimental Investigations

Ejector Mixing and Pumping Optimization

Pressure Gain in a Shrouded Configuration

Closed Loop Operation in a Gas Turbine

• PR=1.037 @ TR=2.2
• rms p’/P=4.5% in the shroud
• Successful operation at 2 Atm. inlet pressure

All Work Done With COTS Hobby Scale Pulse Combustor (Pulsejet)
Experimental Investigations

Results:

- True closed loop operation @ SLS
  - All air supplied by compressor
- \((P_{\text{in}}/P_{\text{out}} - 1) = 3.5\% \at \frac{T_{\text{in}}}{T_{\text{out}}} = 2.2\)
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine slows and stops with conventional combustor at same \(\frac{T_{\text{in}}}{T_{\text{out}}}\)
- -20 dB noise reduction across Turbine
- 4% rms \(p'/P_{\text{out}}\) at turbine inlet

Without Qualification…It Works!
Numerical Investigations
What Happens to RPC at Representative $P_3$, $T_3$?

Approach:
• Use in-house 2D axisymmetric CFD code
  • Turbulent
  • Contains detailed chemical kinetics
  • Adiabatic
  • Gaseous Jet-A fueled
  • Successfully applied to PDE, RDE, and SCRAM combustion
  • Pressure actuated, prescribed motion slide valve simulates reed
• Validate on atmospheric tests of experimental RPC
  • Compare thrust, mass flow rate, pressure traces, frequency
• Run at 10 Atm., 990 $R$ inlet conditions
• Optimize for maximum pressure gain at $T_{t4}/T_{t3}$≈2.0
  • Fuel injector location
  • Inlet geometry
  • Combustion chamber size
  • Combustor length
  • Ejector/mixer parameters (length, position, diameter)
• Monitor emissions
  • Seek lowest index with largest pressure gain
• Seek minimum size

CFD as Predictive Design Tool
Numerical Investigations
Results To Date

- Emission Index < 10 g\textsubscript{NOX}/kg\textsubscript{fuel}
  - Lower pressure gain configurations showed values below 1.0!
- \( (P_4/P_3 - 1) = 3.3\% @ T_4/T_3 = 2.4 \)
  - A large improvement considering \( T_3 = 990 \) R
- Relatively benign station 4 conditions
  - 7\% rms \( p'/P_4 \)
  - 23\% rms \( u'/u_4 \)
  - 1.7\% rms \( T'/T_4 \)

Inflow Vortex Motion is Key
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (\( \phi = 0.72 \)).

- Self-ignition via residual hot gas
- Rapid confined combustion
- Expansion/acceleration
- Refill
Ongoing and Future Directions

Alternative Valve Concepts

• Minimum length and diameter configuration
  • Computational
• Turbine interaction studies
  • Computational
• Active air valves
  • Still in planning stages
• High $P_3$, $T_3$ testing facilities
  • Still in planning stages

Life Extending Techniques for Existing Reed Valves

Active Fuel Modulation

AFRL/NASA - 2009
Concluding Remarks

Resonant Pulse Combustion (RPC):
• Represents a promising approach for achieving practical Pressure Gain Combustion (PGC)
• Has features which are well suited for gas turbine applications
  • Relatively low unsteadiness
  • Demonstrated approaches to achieving requisite overall lean operation
  • Few moving parts
  • Relatively low thermal and mechanical stresses
  • Self-sustaining
  • Low emissions potential
• Is a remarkably well developed concept
  • Liquid fueled operation
  • Demonstrated pressure gain
  • Demonstrated benefit to gas turbines
• Has potential for high $P_3$, $T_3$ operation
• Presents multiple opportunities for improvement and optimization that are achievable with current technology

RPC Could Be the Gateway to Making PGC Mainstream
END