Pressure-Gain Combustion for Gas Turbines

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Outline

• Motivation/Background
• Fundamental Thermodynamics of PGC (How It Works)
• Quantitative Benefit Examples
• Approaches to Implementation (How It’s Done)
• The Role of Modeling
• Technology Challenges
• Closing Remarks
Some Preliminary Facts

Sources: Bureau of Transportation Statistics, Department of Energy, Environmental Protection Agency

The U.S. Consumes (Converts) $97,400,000,000,000,000$ BTU of Energy Each Year

- $81\%$ from fossil fuels (petroleum, natural gas, coal)
- $66\%$ from petroleum and natural gas

Resulting Issues

- National & Economic security
- Pollution
- Climate Change

The Response

- Alternative fuels (biomass, etc.)
- Alternative conversion systems (wind, solar, hydro etc.)
- Conservation/ EFFICIENCY (use less)

Today’s Presentation Is All About This Response

Equivalent to 7.0 gallons of gasoline used by every U.S. citizen EVERY DAY!
Gas Turbines Constitute an Astonishing 14% of Energy Consumption
• 3.4% from aviation
• 10.5% from power generation (and growing if coal gasification and/or combined cycle plants are successful)

A mere 1% Improvement in Thermodynamic Efficiency is Equivalent to installing 17,300 commercial wind turbines, a 33% increase in the total number operating in 2016 on land.

Two Reasonable Conclusions:
Technologies to Improve Gas Turbine Performance Are Important
Those Applicable to Both Aviation and Ground Power are Critical
Pressure Gain Combustion is One Such Technology

PGC†: 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.

†The term “Pressure-Gain Combustion” is credited here to the late J.A.C. Kentfield
*Conventional combustion incurs a total pressure loss

The concept actually is old…

Holzwarth
Explosion Turbine
1914

The Implementation Approaches, Analysis Tools, and Design Capabilities Are New
Fundamental Thermodynamics

**Identical Mechanical Compression, & Heat Input**

- **Brayton**
  - 1-2: Isentropic (adiabatic) Compression
  - 2-3: Isobaric Heat Addition
  - 3-4: Isentropic Expansion
  - 4-1: Isobaric Heat Rejection

- **Atkinson**
  - 1-2: Isentropic (adiabatic) Compression
  - 2-3: Isochoric Heat Addition
  - 3-4: Isentropic Expansion
  - 4-1: Isobaric Heat Rejection

- $P_2/P_1=10$
- $\phi=0.3$

- PGC expands by gasdynamic conversion to kinetic energy (e.g. blowdown)
- Flow to turbine is fundamentally unsteady, and/or spatially non-uniform

\[ \gamma = 1.3 \]
Fundamental Thermodynamics

Animation of a Representative PGC Cycle

- Illustrates essential concepts
- Demonstrates the most basic acceptable level of modeling
- More quantitatively valuable than might be expected.
Quantitative Benefits

**Pressure Gain Combustion Theoretically:**

- Increases thermodynamic cycle efficiency
- Reduces SFC / fuel burn (NASA Objective)
- Reduces CO₂ gas emissions (NASA Objective)
- Competes with conventional cycle improvements

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**Constant Specific Thrust**

<table>
<thead>
<tr>
<th>Engine Parameter</th>
<th>Turbofan</th>
<th>Turbojet</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPR</td>
<td>30.00</td>
<td>8.00</td>
</tr>
<tr>
<td>ηₗ</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>ηₜ</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Mach Number</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Tₐmb (R)</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>Tₜ₄ (R)</td>
<td>2968</td>
<td>2400</td>
</tr>
<tr>
<td>Burner Pressure Ratio</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Tₚₙ (lb·s/lbm)</td>
<td>18.26</td>
<td>75.86</td>
</tr>
<tr>
<td>SFC (lb/hr/lbₗ)</td>
<td>0.585</td>
<td>1.109</td>
</tr>
</tbody>
</table>

Equation: \( \gamma = 1.35 \)

Equivalence:

- 6.0% increase in \( \etaₗ \)
- 2.5% increase in \( \etaₜ \)
- 1 compression stage

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Pressure Gain Combustion:

- Increases thermodynamic cycle efficiency
- Reduces SFC / fuel burn (NASA Objective)
- Reduces CO₂ gas emissions (NASA Objective)
- Competes with conventional cycle improvements

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Diagram:

- Fan: \( \Delta P > 0.0 \), \( P_4/P_3 > 1 \)
- Compressor
- Turbine
- PGC
More Quantitative Benefits

- PGC component modeled by various methods
  - Typically assumed detonative or constant volume combustion
  - Temperature ratio indicates fuel added
  - Pressure ratio represents performance
  - Varied loss assumptions

- Results With Engine Cycle Decks Show Promise:
  - Non-ideal turbomachinery
  - Turbomachinery cooling air boost pump added.

These Are Large Reductions!
Detonative PGC component model implemented in NPSS
- Numerous known loss mechanisms incorporated
PGC component integrated with other turbomachinery components
Performance changes of gas turbine propagated through steam cycle.

Power Plant Efficiency: +1.86%
Power Plant Power: +2.97%
Recent Implementation Approaches

Resonant Pulse Combustor
(slow deflagration)

NASA Glenn Research Center

Pulsed Detonation Engines

Pratt & Whitney/United Technologies Research Center

G.E. Global Research Center

All Are Fundamentally Unsteady & Periodic

University of Cambridge

Internal Combustion Wave Rotor
('Fast' Deflagration)

IUPUI/Purdue/LibertyWorks

Air Force Research Laboratory

Rotating Detonation Engines

Naval Research Laboratory
Recent Implementation Approaches

Resonant Pulse Combustor (RPC)

Successful cycles balance:
- Gasdynamic waves
- Large vortex dynamic
- Chemical kinetics
- Helmholtz phenomena
Recent Implementation Approaches

RPC as Gas Turbine Combustor

Effluent is too hot and impulsive for direct turbine coupling:
  - Add optimized unsteady ejector
  - Entrain bypass flow
  - Mix efficiently
  - Pump

PIV Measured Ejector Flowfield Video

Ejector Enhanced Resonant Pulse Combustor

- 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
Recent Implementation Approaches

**RPC as Gas Turbine Combustor**

Lab Demo Results:
- True closed loop operation @ SLS
  - All air supplied by compressor
- \((P_4/P_3 - 1)=3.5\% @ T_4/T_3=2.2\)
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine stops with conventional combustor at same \(T_4/T_3\)
- -20 dB noise reduction across Turbine
- 4\% rms \(P'/P_4\) at turbine inlet

**It Works!**
Recent Implementation Approaches

**RPC as Gas Turbine Combustor**

High $P_3$, $T_3$ Operation and Optimization Through Simulation

- **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

- **Emission Index $< 10 \text{ g}_{\text{NOX}}/\text{kg}_{\text{fuel}}$**
  - Lower pressure gain configurations showed values below 1.0!
  - $(P_t4/P_t3 - 1)=3.3\% \text{ at } T_{t4}/T_{t3}=2.4$
  - A large improvement considering $T_{t3}=990 \text{ R}$

- **Relatively benign station 4 conditions**
  - 7\% rms $p'/P_{t4}$
  - 23\% rms $u'/u_{t4}$
  - 1.7\% rms $T'/T_{t4}$

**Validated Models Are Essential For Design, Performance Assessment, and Diagnostics**

- **Combustion Chamber:** Length, Diameter, Contour
- **Ejector:** Length, Throat Diameter, Contour
- **Fuel injection:** Placement, Timing
- **CFD Shrouded Pulse Combustor Video**

ASME TE 2018
Recent Implementation Approaches

**RPC as Gas Turbine Combustor**
Images Courtesy of King Abdullah University of Science and Technology, Prof. William Roberts

Active Air Valve System
- Successful self-sustained, self-aspirated operation
- Successful operation for long periods

Shrouded High Pressure Test Bed
- Heated air
- Extensive diagnostics

Images Courtesy of King Abdullah University of Science and Technology, Prof. William Roberts
Recent Implementation Approaches

RPC as Gas Turbine Combustor

Images Courtesy of Whittle Laboratory and Rolls-Royce, Prof. Robert Miller

Aerovalved Configurations

- **Engine integration**
- **Defining and optimizing pressure gain**
- **Optimizing combustor/turbine interaction**
Recent Implementation Approaches

*Internal Combustion Wave Rotor (ICWR)*

('Fast' Deflagration)

**Characteristics**

- Flow in ports is nominally steady, though spatially non-uniform
- Rotor is self-cooled
- Rotation provides valving not power extraction
- Valves implemented at both ends
- Closest to true constant volume combustion

*5%-17% Pressure Gain Measured on a 1st Generation, Concept Demonstrator Rig*
Recent Implementation Approaches

Internal Combustion Wave Rotor
('Fast' Deflagration)

Pressure trace 5” from intake end

Contours of fluid properties in single passage illustrate cycle

Temperature

Log(pressure)

Fuel Concentration

Pressure trace and contour plot courtesy IUPUI and LibertyWorks

Again, Validated Models Are Essential for Design, Performance Assessment, and Diagnostics
Recent Implementation Approaches

Pulsed Detonation Engines (PDE)

A Detonation:
- Provides confinement by coupling shock wave with supersonic combustion wave
- Has a very thin reaction front
- Creates a supersonic wave front with subsonic fluid velocities
- Creates a large local pressure spike which is immediately reduced by a following Taylor wave that spreads in time
- Results in a fluid state in the tube that is similar to constant volume combustion
Recent Implementation Approaches

PDE’s

Reliable PDE operation requires:

- Active valves
- Ignition source
- Deflagration to Detonation (DDT) mechanism
- Rapid fuel and air mixing
- Repeatability

Details

- Rotary air valve
- Schelkin type spiral for DDT
- Exit nozzles for back pressure
- 20 Hz per tube operation
- Stoichiometric C₂H₄-Air
- Pressure gain demonstrated

Numerous Research Efforts Have Yielded Significant Progress

“A pulse detonation engine developed by the Pratt & Whitney/United Technologies Research Center demonstrates pressure gain at turbine conditions.”

– AIAA 2014 Year In Review
Recent Implementation Approaches

**PDE’s**

**Details**
- Premix H$_2$/Air PDE
- Automotive valve system
- 1D CFD Model
  - Valve Sub-Model
  - Heat transfer sub-model
  - Viscous sub-model

**Did I Mention:** Validated Models Are Essential for Design, Performance Assessment, and Diagnostics
Recent Implementation Approaches

PDE’s As Gas Turbine Combustors

Details

- Goal was to study turbine/PDE interactions, not PDE performance
- 8 tube “can-annular” configuration
- 1000 hp, 25000 RPM single stage axial turbine
- Airflow ≈ 10 lbm/s (50% secondary flow)
- Constant air flow, fuel is valved
- C2H4 – Air, stoichiometric conditions
- Detonations verified at 10 Hz and 20 Hz
- Long duration operation to thermal steady state
- 10 dB broadband acoustic noise reduction

“The turbine component efficiency was indistinguishable under steady and PDC fired operation with the present measurement resolution.” – AIAA JPP V.27, 2011
Recent Implementation Approaches

PDE’s As Gas Turbine Combustors

Details
• 6 tube linear PDE array
• Single stage axial turbine
• Airflow ≈ 1.5 lbm/s
• H₂/Air
• 10 Hz. per tube operation
• Similar turbine efficiencies measured for steady and PDC fired operation

While It Is Understood That:
• There are many caveats to these and other investigations (some to be discussed later)
  - How are requisite P₄, T₄, etc. measured in an unsteady environment?
  - What does the partial admission nature of PDE tubes do to a turbine that wasn’t built for it?
  - Etc.
• These were not high performance turbines to begin with
• The results seem to contradict much of what we expect in terms of the impact of unsteadiness

These Preliminary Investigations Indicate That PDE Combustors for Gas Turbines Are Feasible
Recent Implementation Approaches

**Rotating Detonation Engines (RDE)**

Rotating Detonations:
- Supersonic detonation propagates circumferentially
- Fluid travels axially
- No ignition source required (after startup)
- No DDT obstacles required
- Very high frequency operation (kHz)
- Inlet often aero-valved to reduce/prevent backflow

Contours of Temperature in the Detonation Frame of Reference, H₂/Air

Low velocity detonable mixture in...
Recent Implementation Approaches

RDE’s

Upper images and videos courtesy Air Force Research Laboratory (AFRL)

Details

• All operation shown H₂/Air
• Audible screech is operational frequency
• No premix
• Throttling demonstrated

Exhaust End Operational Video

RDE Run to Thermal Steady State

Exhaust End Operational Video

Significant Progress Since First Widely Reported Operations in 2012

Looking Upstream from Exhaust End Operational Video

Courtesy Department of Energy/National Energy Technology Laboratory
Recent Implementation Approaches

RDE’s As Gas Turbine Combustors

Images and details courtesy Air Force Research Laboratory

Details
• T-63 engine selected
• Operated in open-loop mode
• RDE combustor run stoichiometrically with bypass air to achieve $T_4$

Non-Optimized Laboratory RDE Used
This Was A Turbine Performance Test NOT A Pressure Gain Test
Recent Implementation Approaches

RDE’s As Gas Turbine Combustors

Images, video, and details courtesy Air Force Research Laboratory

Details

• H2/air
• 3/6 kHz detonation frequency
• Operation from light-off to Rated Power
• Each operating point at thermal steady state
• Compressor discharge always matched core flow
• Combustor efficiency 97-100%
• NOx emissions very low
• **Turbine efficiency unaffected**

This Preliminary Investigation Indicates That RDE Combustors for Gas Turbines Are Feasible
The Role of Models
Using RDE’s to Illustrate

In PGC Devices:
• Flowfields are extraordinarily complex
• Instrumentation is difficult
  • Harsh environment
  • Orders of magnitude variations
  • Very high frequency
  • Average flow rates, pressures, thrust, are typically all that’s available in the lab
• Highly coupled processes
• No conventional ‘stations’ (i.e. locations fixed in time and space)

Models Serve To:
• Interpret typically averaged readings
• ‘Measure’ where instruments can’t
• Literally allow us to see what’s going on
• Guide optimization in experiments

PGC System Development Requires Strong Model, Experiment, Measurement Collaboration
Example Effort
Using RDE’s to Illustrate
Images and details courtesy Aerojet Rocketdyne

• Phase II National Energy Technology Laboratory funded, multi-team research effort characterizing and optimizing the fluid and mechanical interface between the RDE and a turbine cascade.
  –Aerojet Rocketdyne lead and integrator

University of Alabama
• Testing 10-cm RDE with optical diagnostics for combustor & diffuser exhaust flow characterization.

University of Michigan
• Lab-scale testing and CFD modeling of RDE for injector & combustion physics

Purdue University
• Flow effects on turbine efficiency
• 21-cm and 31-cm RDE testing with air/natural gas.

Southwest Research Institute
• Testing 10-cm RDE and various diffuser geometries with optical diagnostics

University of Central Florida
• High fidelity TDLAS optical diagnostic for composition & unsteady flow analysis

Duke Energy
• NGCC integrated plant study support and funding partner
Technology Challenges
(aka What Makes it Fun!)

• Turbine/PGC Component Interactions
  − How is turbine performance quantitatively affected by non-uniformity?
  − Can unsteadiness-tolerant turbines be designed?
  − Is efficient bypass mixing (with associated entropy) viable?
  − Where does turbine cooling flow come from?

2D CFD Video Courtesy G.E. Global Research Center

3D CFD Video
Technology Challenges
(aka What Makes it Fun!)

• Inlet Valves
  – All PGC methods require robust mechanical or aero-valve systems which:
    1. Prevent backflow into inlet and/or seal
    2. Have low loss to forward flow
    3. Operate at high frequency
    4. Don’t fail
    5. Tolerate high thermal and stress loads (though they are at least intermittent)
Technology Challenges
(aka What Makes it Fun!)

• Thermal Management
  – PGC devices have very high associated thermal loads
  – They are intermittent, but still require attention

• Instrumentation and Measurement
  – High frequency, large amplitude range, harsh environment tolerant capabilities required
  – Methodologies for assessing meaningful averages for $P_{t4}$, $T_{t4}$
    *(Hint: time-average won’t work)*

• Controls and Actuation
  – Many PGC devices do not operate (well) passively

• Modeling and Validation
  – PGC environment is computationally challenging (fundamentally unsteady, multiple time scales, chemical kinetics uncertain, turbulence models uncertain)
  – Validation is difficult due to instrumentation limits and lack of canonical flows

• Emissions?
  – Some approaches are problematic due to near stoichiometric operation, exceptionally high temperatures, and long residence time.
  – Several approaches have shown competitive levels due to rapid expansion following reaction

Recent Research Efforts Have Yielded Substantial Progress in All Areas
No Show Stoppers Identified to Date
Concluding Remarks

Pressure Gain Combustion is a promising technology area for improving gas turbine performance

• Competitive with conventional improvement strategies
• Targets improvement at the major source of entropy generation

There are numerous promising implementation strategies under investigation

• Resonant Pulsed Combustion
• Internal Combustion Wave Rotor
• Pulse Detonation Engine
• Rotating Detonation Engine
• Aero or mechanical valves
• Valves fore and aft, or just fore
• Mixing, bypass, lean, etc. operational modes to achieve acceptable TR

There are technology challenges however:

• None have yet been identified as insurmountable
• Analysis tools have advanced significantly
• Understanding has increased dramatically

"Great things are done by a series of small things brought together.”
- Vincent Van Gogh
QUESTIONS?

“Nothing in this world can take the place of persistence. Talent will not: nothing is more common than unsuccessful men with talent. Genius will not: unrewarded genius is almost a proverb. Education will not: the world is full of educated derelicts. Persistence and determination alone are omnipotent.”

-Calvin Coolidge