Pressure Gain Combustion for Land Based Power Generation

NETL – Office of Research and Development (ORD) and Advanced Energy Systems Program (AES)
Providing Clean Energy Technology Through Innovative Ideas

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Cost of Carbon Capture


- Comparative analysis of the increased Cost of Electricity with 90% capture
  - PC and NGCC with post-combustion MEA capture
  - IGCC with pre-combustion absorption

- Analysis considers the sensitivity of COE to changes in parameters such as Heat Rate (fuel consumed)
  - For a 10% decrease in fuel consumed (Heat Rate) for NGCC with CC, estimated COE would decrease by 13%

- Subsequent benefit of reducing the size of the CC with a reduction in fuel consumed

<table>
<thead>
<tr>
<th>Difference from Ref with no capture.</th>
<th>PC</th>
<th>NGCC</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Therm Efficiency (%Change)</td>
<td>-6.3%</td>
<td>-6.0%</td>
<td>-4.3%</td>
</tr>
<tr>
<td>COE (% Change)</td>
<td>+53%</td>
<td>+40%</td>
<td>+25%</td>
</tr>
</tbody>
</table>

Decrease in COE with 10% decrease in parameter. A 10% decrease in HR could have a 13% decrease in COE for NGCC.
DOE/NETL Turbines Program

- Manages a research, development, and demonstration (RD&D) portfolio of projects designed to remove environmental concerns about the future use of fossil fuels through development of revolutionary, near-zero-emission advanced turbine technologies.

Advanced combined cycle turbine
- Applicable to natural gas and H₂
- T3 of 1900 K
- Adv. components: pressure gain combustion, advanced transition, air foils w/ decoupled thermal & mechanical stresses
- Delivers another $20/T reduction in CO₂ capture cost
- NG CC (LHV) efficiency approaching 65%
Gas Turbine Technology Development

*Evolution to Revolution*

- Recent technology advancements have resulted in incremental improvements in efficiency. For example consider the GE F class engine.

<table>
<thead>
<tr>
<th>Model</th>
<th>Year</th>
<th>CC Eff</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>7FA.01</td>
<td>1992</td>
<td>54%</td>
<td>Combined cycle advancement</td>
</tr>
<tr>
<td>7FA.02</td>
<td>1995</td>
<td>55.5%</td>
<td>DLN Combustion</td>
</tr>
<tr>
<td>7FA.03</td>
<td>1997</td>
<td>56.6%</td>
<td>Materials and Coatings (&gt; $T_3$)</td>
</tr>
<tr>
<td>7FA.04</td>
<td>2010</td>
<td>57.8%</td>
<td>Hot gas path, single crystal blades</td>
</tr>
<tr>
<td>7FA.05</td>
<td>2012</td>
<td>57.9%</td>
<td>Compressor improvements</td>
</tr>
</tbody>
</table>

- The need for transformational technology!!
  - Combustion
• Convention gas turbines rely on Constant Pressure Combustion (Brayton cycle)
  – Utilizes Deflagration (slow combustion – subsonic)
  – Actually results in a pressure loss across the combustor due to viscous effects

Constant volume combustion through detonation offers a pathway to improved efficiency compared to deflagration
# Current Technology Trends in PGC

<table>
<thead>
<tr>
<th></th>
<th>Pulse Combustion</th>
<th>Wave Rotor Engine</th>
<th>Pulse Detonation Engine</th>
<th>Rotating Detonation Engine</th>
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<tr>
<td><strong>System Analysis</strong></td>
<td>- Lower pressure gain potential</td>
<td>Large tube numbers reduce provide nearly steady flow</td>
<td>- Detonation offers greatest PG potential</td>
<td>Benefits of PDE with near steady flow and hot gas ignition.</td>
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<td></td>
<td>- Eliminates complexities of detonation waves</td>
<td></td>
<td>- 10% improvement in thermal efficiency</td>
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<td><strong>System Integration</strong></td>
<td>- Few/no moving parts</td>
<td>- Availability as a topping cycle</td>
<td>- Cycle timing dictates hardware.</td>
<td>- Small package with big impact</td>
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<td>- Impact of ejector on unsteady flow?</td>
<td>- Complex flow path</td>
<td>- Turbine interactions need quantified</td>
<td>- Start-up and wave travel issues</td>
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<tr>
<td><strong>Components / Materials</strong></td>
<td>Heat transfer/cooling concerns</td>
<td>- Sealing issues</td>
<td>- Injectors</td>
<td>- Thermal Management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Bearings</td>
<td>- Thermal management</td>
<td>- Turbomachinery</td>
</tr>
<tr>
<td><strong>Basic Physics and Chemistry</strong></td>
<td>Basic physics are understood although difficult to predict amplitudes of pulses</td>
<td>Basic physics of detonation or fast deflagration</td>
<td>- DDT challenges</td>
<td>- Similar to physics of PDE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Ionized flow behind shock</td>
<td>- Complex flow field</td>
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- Resonant Pulse Combustor (NASA-Glenn)
- Wave Rotor Engine (IUPUI)
- Multi-Tube PDE G.E. Global Research Center 2005
- RDE Simulation Naval Research Laboratory - 2011

- System Analysis - Lower pressure gain potential - Eliminates complexities of detonation waves
- Wave Rotor Engine - Large tube numbers reduce provide nearly steady flow
- Pulse Detonation Engine - Detonation offers greatest PG potential - 10% improvement in thermal efficiency
- Rotating Detonation Engine - Benefits of PDE with near steady flow and hot gas ignition.

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RDC Potential Advantages

• Benefits are in addition to other gas turbine improvements

• Unlike related pressure gain combustion technology, RDE offer continuous flow eliminating the need to Purge and Fill events and complicated valving.

• Once initiated, detonation wave is self-sustaining (limited DDT)

• High frequency detonation results in quasi-steady flow through combustor exhaust.

• Scalable and good turn-down performance
Physical Characteristics of RDE Combustion

• Complex fluid and thermodynamic feature occur throughout the flow field (Nordeen, 2013)

Temperature with Density shading highlights complexity (Induction Parameter Model)

Different regions of the flow experiences different thermodynamic cycles
Thermodynamic Analysis of RDE

- Individual streamlines exhibit unique thermodynamic cycles.

One approach is to model flow along streamlines as individual thermodynamic cycles (Nordeen, 2013). But over-simplifies the chemistry.
Chemical Reactor Network Approach (NETL) Thermodynamic Model
Comparison of CRN with CFD

Reactor zone properties

<table>
<thead>
<tr>
<th>Zone</th>
<th>T(avg) [K]</th>
<th>P(avg) [Pa]</th>
<th>Reactor Volume /Total Volume</th>
<th>Fraction mass flow (Fig. 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR_DW</td>
<td>2585</td>
<td>7.0948E+05</td>
<td>0.05638</td>
<td>x1 = 0.95</td>
</tr>
<tr>
<td>PSR_DW_up</td>
<td>1935.4</td>
<td>1.658E+05</td>
<td>0.48411</td>
<td></td>
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<tr>
<td>PSR_DW_low</td>
<td>1686.2</td>
<td>1.0758E+05</td>
<td>0.20616</td>
<td></td>
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<tr>
<td>PSR_Flame</td>
<td>1144.6</td>
<td>1.135E+05</td>
<td>0.01403</td>
<td></td>
</tr>
<tr>
<td>PSR_Post_flame</td>
<td>1816.4</td>
<td>1.0108E+05</td>
<td>0.07777</td>
<td>y1 = 1-x1</td>
</tr>
<tr>
<td>PSR_Obq_1</td>
<td>2682.2</td>
<td>3.5188E+05</td>
<td>0.0164</td>
<td></td>
</tr>
<tr>
<td>PSR_Obq_2</td>
<td>2778.29</td>
<td>2.77029E+05</td>
<td>0.04614</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of CRN predicted mass fractions with 2-D CFD results at RDE outlet

Reactor wise product mass fraction comparison with CFD
Rotating Detonation, Continuous Wave, Combustion offers a set of unique challenges

- Combustor
  - Inlet/Injector design
    - Low-loss injectors
  - Combustion stability / Efficiency
    - Mixing
    - Limiting deflagration
    - Wave bifurcation
    - Directionality
- Exhaust Transition
  - Maintain pressure gain
  - Sub-Sonic vs Super-Sonic
- Unsteady Heat transfer
- Emissions
  - High or low NOx
Rotating Detonation, Continuous Wave, Combustion offers a set of unique challenges

- Compressor (unsteady flow or backflow from combustor) – could this induce surge / stall on the compressor

- Turbine
  - Turbine blade film cooling with PGC
  - Integration of Combustor to Turbine to minimize pressure loss.

- Cycle benefit from pressure gain
  - Hybrid cycles
  - Coupled with reciprocating engine for turbo-compounding in a PDE arrangement taking advantage intermittent flow from cylinders.
NETL-ORD Program Objectives

• Identify and address knowledge gaps relative to detonation and shock wave management for sustained combustion in land based power generation applications.

• Define a realistic pathway for implementing pressure gain combustion in a gas turbine engine for land based power generation.

• Provide experimental data for model validation
NETL Bench-Scale Experimental Research

- **Hardware / Facilities**
  - AFRL 6” RDE, H2-Air
  - Facility capabilities
    - 30 bar (30 atm)
    - 800 K (1000 F) preheat
    - 2100 K (3100 F) combustion temperatures
    - 1.5 kg/sec (3.2lb/sec) combustion air
    - H2, NG, Propane, Ethane

- **Objectives**
  - Influence of pressure on RDE
  - Low loss inlet and wave directionality
  - Exhaust flow transition for turbine
  - Heat transfer
  - NOx Emissions
  - Generate validation data for models
Preliminary Data Analysis

- Dynamic Pressure measurements using fast response transducers in ITP (Infinite Tube Pressure) and flush mounted configuration

- Transient Heat Flux estimate

Simplification: 1-D Semi-infinite Transient Conduction

- Transient heat flux \( q_{1,2} \) @ \( x = 0 \)

\[
q(t_N) = 2\sqrt{\rho C_k} \left[ \sum_{i=1}^{N} \frac{T_s^*(t_i) - T_s^*(t_{i-1})}{(t_N - t_i)^{1/2} - (t_N - t_{i-1})^{1/2}} \right]
\]

\( q_{12} \rightarrow \) Heat flux using TC2-TC1

\(^1\) Dennis E. Lilelkis, AFRL, MS thesis, 1986
\(^2\) Cook and Felderman, AIAA, 1966
NETL RDE Inlet Experiments

• Linear RDE apparatus designed and fabricated to facilitate development of improved inlets
  - Inlet and plenum optically accessible from multiple sides
  - Detonation pressure wave created by accompanying H₂/air detonation tube
  - 3D printed inlet geometries for rapid evaluation of designs

• Scaling and similitude used to maintain relevance to full-scale, fired RDE at NETL MGN
Linear RDE Apparatus

• Non-reacting gases within inlet passages (He/air)
  – H₂/air detonation tube connected to end of linear RDE channel
  – 3D printed inlet geometry mimics RDE cross section at 1:1 scale
  – Optical accessibility permits non-intrusive data collection

• Rapidly propagating pressure wave creates characteristic backflow and recovery behavior seen in full-scale, fired RDE
  – Diagnostics include dynamic pressure measurements and high-speed Schlieren imaging to evaluate inlet dynamics, acetone PLIF for fuel/air mixing within channel
Synchronized Measurements

![Graph showing normalized dynamic pressure over time for different channels: RDE Air Side Inlet, Linear RDE Channel, Detonation Tube.](image)
CFD Modeling of NETL RDE

- Fluent being used to simulate RDE operation.
  - 3D grid (~1.8M cells) includes discreet fuel injection and air slot with partial manifolding.
  - 1 step H2/Air mechanism, no combustion model.
  - k-e turbulence model.
  - Characterizing overall thermal efficiency, pressure gain/loss, potential turbine work, etc...

Simulation shows significant interface burning (~40% of fuel). Turbulence chemistry interaction models are not valid for both deflagration and detonation zones.

- Includes Air and Fuel Injectors and Partial Manifolding
• Combustion gasses and shock waves propagate back into manifolding.
CFD Modeling of NETL RDE

Simulations to evaluate turbine integration, effect of pressurized operation (S. Escobar, I. Celik, West Virginia University).

Mach number contours for Pout=0.11atm (top) and Pout=2atm (bottom)

Parametric study to define loss mechanisms

Baseline case, steady, premixed combustion at 6 bar: $\eta = 33\%$

No inlet, premixed, no heat loss

$\eta = 37.6\% 
\Delta\eta = +4.6$ pts

With inlet, no heat loss

$\eta = 30.6\% 
\Delta\eta = -2.4$ pts

Schematic of simulation of interaction of RDE and integrated turbine exit.
DOE / NETL PGC Funded Activities

• Aerojet Rocketdyne (FY15-16)
  – Develop, validate, and integrate a systems model for a rotating detonation combustor into an overall systems model of a power plant and define the path to configurations that exceed 65 percent combined-cycle efficiency.

• UTRC (FY15-16)
  – Assess the potential benefit of PGC system technology for combined-cycle gas turbines and compare it to the DOE goals.

• Penn State University (FY15-17) - UTSR
  – Impact of fuel-oxidizer mixture concentration inhomogeneity on detonation wave quality and stability in a hydrogen and hydrogen/natural gas with air fueled RDE.
  – Parametric study to better understand relationship between combustor geometries and injector performance.
DOE / NETL PGC Funded Activities

• **University of Michigan (FY15-17) - UTSR**
  – Explore fundamental physics governing non-idealities and impacted performance in a linear RDE analogue.
  – Develop detailed computational tools (DNS & LES) for studying detonation wave propagation processes in RDEs.

• **Purdue University (FY15-17) – UTSR**
  – Characterize the performance of RDE injection/mixing systems using an optically-accessible, linear platform with actual injector geometry.
  – Evaluate the operability of an RDE combustion chamber relative to installation in a gas turbine system

• **Oregon State University (FY15 – FY 17)**
  – Evaluate the performance of a Pulse Detonation Engine for an application in a MHD System.
Cathode Recycle Configuration with Ejector

Pressure Gain provides flexibility in hybrid cycles
Making Oxy-fuel an **Advantage**

Direct Power Extraction (via MHD)

- **Magnetohydrodynamic (MHD) Power Generator**: Use a strong magnet and convert kinetic energy of conductive gases directly to electric power.

- **Higher plant efficiency – works at higher temperature**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS
    - oxy-coal COE much higher than baseline COE primarily due to ASU
    - Legacy: MHD-steam coal has ASU (to combust to higher T) but COE lower than baseline COE →

MHD cycle turns having an oxygen production from efficiency disadvantage to efficiency advantage!

Plot from Okuno et. al. 2007
Questions??