Rotating Detonation Combustion for Gas Turbines – Modeling and System Synthesis to Exceed 65% Efficiency Goal

DE-FE0023983

Edward D. Lynch
Fellow – Combustion CFD

Scott Claflin
Director – Power Innovations

Jeffrey Stout
Project Engineer – Combustion Devices

2015 University Turbine Systems Research Workshop
November 3 - 5, 2015
Atlanta, Georgia
Over 600 Hot Fire Tests to Date

Background: Aerojet Rocketdyne RDE Development Progress

2010 Proof of Concept

2010 Multiple Propellants

2011 Plasma System Integration

Efficient energy conversion and scaling

Initiating and maintaining continuous detonation across a range of effective operating conditions

Use of a plasma system to improve efficiency and allow air-breathing operation without supplemental oxygen

DARPA 2012 Code Anchoring Data

2015 NETL Gas Turbine Modelling

2014 ONR Low Loss Inlet

2014 ARPA-E Gas Turbine Environment

DARPA 2013 Liquid Fuel Demonstration

DARPA 2013 Vulcan Exhaust Probes

This document does not contain any ITAR or EAR technical information
Objective of Program

To advance combustion turbine technologies for combined cycle applications...

...by integrating a Rotating Detonation Engine (RDE), pressure gain combustion system with an air-breathing power-generating turbine system to achieve a combined cycle efficiency equal to or greater than 65%.
Five Major Program Steps

1. Develop a **power plant mass and energy balance system model** integrating an RDE with a gas turbine-based power generation system.

2. Define the RDE and the interaction of the RDE with the pieces of the gas turbine system through **component models** encapsulating the operation of these components with real, as opposed to ideal, performance in succinct fashion.

3. **Determine the efficiencies** defined in these component models through unsteady, multidimensional, Computational Fluid Dynamics (CFD).

4. **Validate the CFD models** feeding this system model with in-stream-probe pressure and flow angle measurements of an RDE operating under conditions traceable to gas turbine operation.

5. Employ this system model based on realistic performance for **product system trades** to define the path to an advanced combustion turbine in a combined cycle application capable of meeting or exceeding 65% combined cycle efficiency.
### Program Schedule

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems Requirements Definition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PGC Thermodynamic Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFD Model Development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Validation Hardware</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot Fire Testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Scale Design Study</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase II Program Planning</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Interdependencies require working systems, modeling, analysis and test in parallel
- Testing has been completed

This document does not contain any ITAR or EAR technical information
Task 2: Aspen model of combined cycle power plant developed including model for rotating detonation combustor subsystem.

Task 3: Fortran model of rotating detonation combustor subsystem developed for inclusion into Aspen plant model.

Task 4: CFD used to explore alternatives for managing rotating detonation flow field from discharge of compressor to turbine inlet. Results reflected in efficiencies used in Fortran model.

Work underway to confirm proposed performance goal

Example: CFD analysis on one candidate geometry downstream of rotating detonation combustor

This document does not contain any ITAR or EAR technical information
Task 3.0 – Thermal Models of Pressure Gain Combustion Components and Plant Systems
This document does not contain any ITAR or EAR technical information
RDE Model For Integration Into Plant System Model (Aspen)

1) Compressor
   J class

2) RDE Combustor Tap-off
   No loss

3) Isolator
   Friction
   Heat loss
   Shock isolation (cfd)

4) RDE Combustor
   Constant volume
   Deflagration bypass

5) Combustor Exit Choke

6) Ejector
   Shock primary to subsonic at Mach X
   Stream thrust averaged mixing

7) Bypass Duct

8) Turbine
   J class

This document does not contain any ITAR or EAR technical information
Baseline Assumptions for Plant Model

- 90% Combustion Efficiency (10% of fuel does not combust)
- Natural Gas Fuel (93.1% CH₄, 4.3% C₂H₆, 1.6% N₂, 1% CO₂)
- Turbine
  - Inlet Temperature 2,950 F, Pressure 350 psi
  - Isentropic Efficiency 87.5%
  - Exhaust to Hot Reheat Steam Generator (HRSG) 14 psi
- Compressor
  - Inlet 59 F, 15 psia
  - Outlet to RDE combustor, 180 psi and 683 F
  - Efficiency 85%
- Bypass Ratio = 0 (All air goes to RDE combustor)
- RDE Flow Equivalence Ratio = 0.45
- Steam Turbine & HRSG
  - 38% gross efficiency
  - Three Stage Turbine
  - Flue Gas exhaust 14 psi and 190 F
System Analysis Determines the Sensitivity of RDE-Specific Parameters on Plant Efficiency

- Δ Isolator mach
- Δ Combustion Efficiency
- Δ Equivalence Ratio (RDE)
- Δ Diffuser Mach #

This document does not contain any ITAR or EAR technical information
Task 4.0 – CFD Integrated Component Modeling
Integration Challenge Of RDE Combustion

• Non-uniform flow both temporally and spatially.
• Optimum turbine performance requires steady flow.
• Smoothing detonation pulse creates pressure loss.
• Challenge is balancing pressure loss of flow smoothing with turbine unsteady performance loss.
RDE Flow Path For Trade Study

Trade Study Parameters:
1. Isolator flow damping
2. Isolation shock strength
3. Equivalence ratio
4. Deflagration pre-burn
5. Detonation leak flow
6. Flow damping
7. Bypass mass flow
8. Bypass injection total pressure

CFD: Combustion can downstream of RD combustor

This document does not contain any ITAR or EAR technical information
To date, four broad classes of exhaust design configurations have been considered:

1) A configuration contracting then expanding the exhaust flow to the annulus axis.
2) Purely annular configurations.
3) Annular configurations with enhanced three-dimensional mixing.
4) Smoothing of the flow through magnetogasdynamics.

Preexisting RDE exit flow solution with ethylene and air propellants was used as an entrance boundary condition.
Contours for an Attenuator with a 15 degree Cone, Three Pulses, and Six Atmosphere Back Pressure

This document does not contain any ITAR or EAR technical information
Contours for Initial RDE Plus Constant Area Ejector

This document does not contain any ITAR or EAR technical information
Parameter Profiles for Annular Attenuator

Straight Annulus Swirl Number

- Max. Swirl = 85.63 deg.
- Min. Swirl = -50.2 deg.

- Max. Swirl = 40.0 deg.
- Min. Swirl = -17.5 deg.

“Zig-Zag” Annulus Mach and Pressure

This document does not contain any ITAR or EAR technical information
Profiles for Magnetohydrodynamic (MHD) Attenuator

Entrance (Inside) and Exit (Outside) Planes

The MHD system was successful in reducing the variation in the total pressure, bringing the Mach number down to subsonic, and reducing the swirl variation.

Retarding or Accelerating force depending on the swirl direction (JxB).
Task 5.0 – Test Data Validation Hardware Development
Validation Testing Used 24 cm ARPA-E Hardware

Test Objective: Obtain RDE exhaust dynamic pressure measurements that can be used to validate component thermodynamic models.

Approach: Use angle-of-attack “cobra” pressure probe with high frequency sensors to measure per-pulse time-resolved exhaust flow angle.

This document does not contain any ITAR or EAR technical information
Instrumentation (in Addition to the Cobra Probe) for the Hot-fire Test Program

81 channels, low speed, 1kHz

7Ch High Frequency Data: 1.25 MS/s
PCB pressure at P3, P3.2
+3 more PCB for cobra probe
2 ion gauges

<table>
<thead>
<tr>
<th>Chamber Static Pressure</th>
<th>Air Venturi U/S Pressure</th>
<th>Air Venturi Throat Pressure</th>
<th>Air T/A Feed Pressure</th>
<th>Air Inlet (outer) CTAP Pressure</th>
<th>Fuel Venturi U/S Pressure</th>
<th>Fuel Inlet Pressure #1</th>
<th>Fuel Inlet Pressure #2</th>
<th>Contraction Section Pressure</th>
<th>Air Venturi U/S Temperature</th>
<th>Air T/A Feed Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT111</td>
<td>PT 201</td>
<td>PT 202</td>
<td>PT 204</td>
<td>PT 254</td>
<td>PT 303</td>
<td>PT 304</td>
<td>PT 305</td>
<td>PT 902</td>
<td>TC 201</td>
<td>TC 204</td>
</tr>
<tr>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIA</td>
<td>PSIG</td>
<td>deg_F</td>
<td>deg_F</td>
</tr>
</tbody>
</table>

High Speed Video:
67,000 fps 256x256
Cobra Probe Design Took Advantage of Additive Manufacturing

- Obtained time-resolved per pulse flow angle of attack with high frequency pressure sensors.
- Also can extract time resolved total pressure.

PROBE HAS FACETED TIP TO MEASURE AoA
Orientation of the Cobra Probe in the Combustion Chamber
24 cm RDE Hot-Fire Test Results

- 66 Hot-fire Tests
- Three different fuels tested
  - Methane (41 tests)
  - 35/65 hydrogen/methane mixture (9 tests)
  - 70/30 hydrogen/methane mixture (16 tests)
- Equivalence ratio from 0.75 to 1.05
- Inlet air temperature from 310 to 764 degrees F
- Back pressure from 50 to 246 psia
- Air flow rate from 6.1 to 8.7 lbs/sec
- Detonation wave velocities > 3,300 feet/sec

Analysis of the test data is in progress

High magnitude pressure spikes indicate efficient detonation.

This document does not contain any ITAR or EAR technical information
Summary and Next Steps

- Under the NETL “Rotating Detonation Combustion for Gas Turbines” contract, Aerojet Rocketdyne is assessing the potential of incorporating a rotating detonation engine into a Natural Gas Combined Cycle power plant.
  - AspenPlus cycle analysis of RDE-based power plants is on-going.
  - RDE potential performance gains can be achieved but system interfaces must be carefully engineered to minimize losses.
  - CFD modelling is being used to assess methods for interfacing the unsteady exhaust of an RDE with a conventional turbine.
  - Hot-fire testing of a 24 cm air/methane RDE at gas turbine conditions has been completed.
  - Analyses are on-going.

- Synthesis of the analysis and hot-fire results into a full scale system design study has been initiated.

- Final results will be reported in early 2016.