Reduced Turbine Emissions Using Hydrogen-Enriched Fuels

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Relevance to DOE, FreedomCAR, and Hydrogen Technical Barriers and Targets

• Use of hydrogen in gas turbines provides a driver for increased hydrogen production and infrastructure development
  – Mechanism for near-term utilization of hydrogen
  – Relaxes more stringent and costly requirements of feed stock purity for fuel cell utilization
  – Field testing of emerging production technologies (approached by a major oil company to use H₂-enriched turbines as market pull for their developing H₂ production hardware)

• Added Environmental Benefits
  – Hydrogen-burning gas turbines enable optimal use of fuel lean combustion for NOₓ control
  – Replaces hydrocarbon fuels for reduced CO₂ emissions

• Aids in the attainment of energy independence from foreign sources
  – Low-heating and medium-heating value fuels containing H₂ can provide significant source of cost-effective fuels for gas turbines
  – Enables use of domestically-produced H₂
U.S. CO₂ Emissions

- Gas turbines are the fastest growing power production technology
- Passenger cars account for only a small fraction of total CO₂ emissions

Source: Analysis of Strategies for Reducing Multiple Emissions from Power Plants: Sulfur Dioxide, Nitrogen Oxides, and Carbon Dioxide, EIA, Dec 2000
Trade-offs Associated with Lean Premixed Combustion Systems

- Lean Premixed Combustion (LPC) is method of choice for NO\textsubscript{x} control in Gas Turbines

At ultra lean conditions a tradeoff exists between NO\textsubscript{x} and CO emissions

Ultimately, lean operation is limited by the onset of flame instability and blowout

- Hydrogen-enrichment extends the lean flammability limit and reduces CO emissions
Approach

Lean Premixed Swirl Burner Experiments
• Establish scientific data base for lean premixed swirl burners typical of Dry Low NOx gas turbine burners
• Emphasize H2-enriched fuels over wide range of pressures
• Design and fabricate a lean premixed swirl burner with well-characterized boundary and flow conditions
• Quantify effects of H2 addition on flame stability and emissions
• Leverage existing Sandia expertise in experimental diagnostics development

Large Eddy Simulation Model Development
• Parallel development of next generation simulation capability based on Large Eddy Simulation (LES)
• Detailed model development and validation at atmospheric pressure
• Extended validation at realistic operating pressures and temperatures
• Bridge gap between laboratory and gas turbine environment through collaborations with industry
## Project Timeline

<table>
<thead>
<tr>
<th>Task Name / Milestone</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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<tbody>
<tr>
<td><strong>Lean Premixed Swirl Burner</strong></td>
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<td>Fabricate &amp; characterize CFB burner operation</td>
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<td>Obtain nonreacting &amp; reacting flow databases</td>
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<td>LES model development &amp; validation</td>
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<td>Obtain low-pressure database in SimVal burner</td>
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<td>Obtain high-pressure database in SimVal burner</td>
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<td><strong>Hydrogen Burner Collaboration (NASA)</strong></td>
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<td>Characterize burner operation</td>
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<td>Identify design improvements &amp; implement</td>
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<td><strong>Industrial Collaboration</strong></td>
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<td>Implement hardware &amp; develop test matrix</td>
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<td>Identify problem areas for potential H₂ use</td>
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<td>Demonstrate merits of H₂ addition</td>
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<td><strong>Economic Analysis</strong></td>
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<td>Establish base case cost &amp; emissions</td>
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<td>Evaluate economics of H₂ addition for NOₓ control</td>
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<td>Extend cost analysis to include carbon credits</td>
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<td><strong>International Collaborations</strong></td>
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<tr>
<td>Parse off program areas &amp; solicit funding</td>
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<td>Develop hierarchy of test burners</td>
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<td>Obtain experimental databases for chosen flames</td>
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<tr>
<td>Collaborative model validation and development</td>
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</table>
Current Status

• Comprehensive experimental-computational program focused on hydrogen-enriched lean premixed gas turbines established
  – Detailed diagnostics being applied in swirling-flow dump-combustor configurations
  – Benchmark experimental databases under development

• Comprehensive simulation capability based on the Large Eddy Simulation (LES) technique in place
  – Massively-parallel high-fidelity simulations of key target flames being performed
  – Device relevant issues related to transient combustion being systematically treated

• Hierarchy of laboratory-scale burners and target flames identified and at various stages of development
  – Emphasis placed on complex phenomena associated with hydrogen-enriched lean premixed combustion
  – Detailed subgrid-scale model development and collaborative model comparisons underway
CRF Confined Flow Burner

- Established as test bed for all working groups

- Design provides well-defined non-ambiguous boundary conditions for LES

- Makes optimal use of advanced laboratory and diagnostic capabilities at CRF

- **Injector Section** (Note \(D_h = D_o - D_i\))
  - \(D_i = 20\) mm (centerbody diameter)
  - \(D_o/D_i = 1.4\)
  - \(L = 320\) mm (16 \(D_i\))
  - Choked at inlet, houses premixing-, swirler-, and wake-mixing sections

- **Burner Section**
  - \(D_b = 115\) mm (5.75 \(D_i\))
  - \(L_b = 485\) mm (24.25 \(D_i\))
  - Ceramic face plate, quartz outer wall

- **Nozzle Section**
  - \(D_e = 50\) mm (2.5 \(D_i\))
  - \(L_n = 230\) mm (11.5 \(D_i\))
  - High Mach number flow at exit

\[U_{ref,m}/s\]

\[\text{Re}_{ref} = U_{ref} \delta / \nu\]

\[\text{Re}_d = U_{ref} D_h / \nu\]

\[\text{Combustion Chamber}\]

\[\text{Annular Injector Duct}\]

\[U_{m}, m/s\]

\[Q, slm\]
Complimentary to NETL SimVal Burner

- CRF burner will be used to provide complete high-fidelity validation datasets at 1 atmosphere.
- NETL burner will facilitate investigations at device relevant pressures.
- NETL has delivered SimVal hardware to CRF.
## Experimental Capabilities

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Quantity</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Particle Image Velocimetry</td>
<td>Instantaneous velocity field</td>
<td>Velocity, vorticity and strain fields.</td>
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<tr>
<td>OH and CH PLIF</td>
<td>Instantaneous OH/CH distributions</td>
<td>Flame zone structure and characteristics (thickness, local extinction).</td>
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<tr>
<td>Simultaneous OH &amp; CH PLIF/PIV</td>
<td>Simultaneous velocity/OH/CH fields</td>
<td>Turbulence/flame interactions. Flame stability/extinction.</td>
</tr>
<tr>
<td>Simultaneous OH and CO PLIF</td>
<td>Forward reaction rate of CO+OH=CO2+H</td>
<td>Characterize CO production and burnout</td>
</tr>
<tr>
<td>Simultaneous Raman/Rayleigh/LIF</td>
<td>N2, O2, CH4, H2, H2O, CO2, CO, OH, NO and Temperature</td>
<td>Turbulent mixing, flame structure and chemistry. Validation of flame chemistry models.</td>
</tr>
</tbody>
</table>
LES Capabilities

• Theoretical Framework
  – Fully-coupled compressible conservation equations of mass, momentum, total energy, species (multicomponent, mixture-average)
  – Generalized treatment of equation of state, thermodynamics and transport (high-pressure, real-gas, liquid, cryogenic fluids …)
  – Dynamic modeling for treatment of subgrid-scale turbulence and scalar mixing
  – Full treatment of multiple-scalar mixing, finite-rate chemical kinetics
  – Full treatment of multiphase phenomena, particulates, sprays

• Numerical Framework
  – Implicit multistage scheme using dual-time stepping with generalized all-Mach-number preconditioning (Eulerian-Lagrangian formulation)
  – Fully-conservative, staggered, finite-volume differencing in generalized curvilinear coordinates, time-varying mesh capability
  – Highly scalable, massively parallel with general distributed multi-block domain decomposition
Validation Sequence for Target Flames

- **Cold-flow PIV, LDV measurements**
  - Time-averaged characterization of burner inlet conditions
  - Instantaneous, time-averaged structure of planar velocity field
  - Time-averaged profiles of mean, rms, cross-stress terms

- **Reacting PIV, LDV, PLIF measurements**
  - Companion datasets analogous to cold-flow measurements above
  - Instantaneous, time-averaged characterization of minor species fields
  - Time-averaged profiles of simultaneous velocity-scalar correlations
  - Instantaneous, time-averaged flame zone structure

- **Raman-Rayleigh-LIF point/line measurements**
  - Instantaneous, time-averaged characterization major species, temperature
  - Instantaneous reaction-rate imaging
CRF Burner: Experimental Progress

- Burner operation characterized over a range of conditions
- Quantified effect of H₂ addition on lean flame stability
- Flame structure characterized using OH imaging
- Velocity field characterized in nonreacting flow

Particle Image Velocimetry

OH PLIF Image

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CRF Burner: *Model Progress*

- Baseline operating conditions, target cases, and corresponding grid configuration established ✔
- Grid resolution requirements for high-fidelity (wall-resolved) simulations of target cases established ✔
- First high-fidelity simulations for validation with Particle-Image-Velocimetry (PIV) measurements in progress
- Development of multiple-scalar combustion closure based on approximate deconvolution methodology in progress

- Generalized multi-block decomposition
  - 96 blocks ($32^3$ cells per block)
  - 3.1 million cells total
**Instantaneous and Mean Flow Characteristics Established**

**Flame structure:**
- Premixed flame fronts
- Local quenching.
- Extinction, re-ignition
- Strained and freely propagating

**Flow structure:**
- Primary toroidal recirculation zone
- Unsteady stagnation point
- Flow separation and reattachment
- Secondary, tertiary recirculation zones

- Turbulent combustion involves strong interaction between flow and chemistry
- Plots left show turbulent velocity field obtained using LES
- Plots above show corresponding OH PLIF image and flame luminosity

OH measurements highlight local flame characteristics
LES calculations highlight complex fluid dynamic interactions
Local Flame Characteristics Established

Instantaneous OH Field

Flame structure changes locally with mixture properties and fluid dynamics
Ideal Flame Structure With Detailed Chemical Kinetics Analyzed

- Solid lines represent pure CH₄-Air flame ($\Phi_{\text{Global}} = 0.6$)
- Dashed lines represent CH₄-Air flame enriched with 10 % H₂
Current Collaborations

**University**
- Vanderbilt (Diagnostics)
- Heidelberg (Kinetics)
- Darmstadt (LES Development)
- Lund Technical (Diagnostics)
- Cranfield (Diagnostics)
- U. Oklahoma (LES Validation)
- Cornell (Diagnostics)
- U. London (LES Validation)
- Toronto (Diagnostics)

**Government**
- Sandia (LES Development & Validation, Diagnostics)
- NETL (LES Validation, Diagnostics)
- WPAFB (LES Validation, Diagnostics)
- AFOSR (LES Validation, Diagnostics)
- NASA (Diagnostics, LES Validation)

**Industrial**
- General Electric (LES Development)
- Pratt & Whitney (LES Development)
- Rolls Royce (LES Development)
- Praxair (H₂ Utilization)
- Pinnacle West (H₂ Utilization)
NETL Collaboration: Approach & Progress

**Approach**

- Extend data base for lean premixed swirl burners to realistic pressures and temperature. Emphasis on H₂-enriched fuels
- Atmospheric-pressure tests in SimVal burner at Sandia; high-pressure tests at NETL
- Utilize Sandia’s diagnostic expertise for the development of high pressure diagnostics in realistic gas turbine environments

**Progress**

**Sandia Burner Completed ✓**

- Atmospheric pressure operation
- Design optimized for Sandia CRF laboratory facilities
- Full optical access for optimal use
- Of advanced diagnostics

**NETL Burner Completed ✓**

- Operation to 30 atmospheres
- Inlet temperature to 800 K
- Optical access
- Limited datasets at elevated pressure
**NASA Collaboration: Approach & Progress**

**Approach**
- Program focuses on the development of H₂-fueled burner for aircraft application
- Atmospheric-pressure testing at Sandia
- High-pressure tests at NASA GRC

**Quantified effect of H₂ addition on lean flame stability**

- Burner operation characterized ✓
- Flame structure characterized using OH imaging ✓

- Acetone PLIF used to quantify fuel/air mixing ✓
GEAE Collaboration: **Approach & Progress**

**Approach**
- Select fuel injector for lean premixed operation
- Apply advanced diagnostics and LES to understand problematic areas related to industrial gas turbines
- Identify problem areas where hydrogen addition could be beneficial and demonstrate merits of H₂ enrichment

**Design issues identified ✓**
- Lean blowout limits
- Lean emissions (NOₓ, CO)
- Fuel-air mixing
- Combustion instabilities

**Completed hardware for swirlcup installation in Confined Flow Burner ✓**

**Diagnostics implemented ✓**
- PIV, OH and CO PLIF
- Raman Scattering

**GEAE Swirlcup Injector**

**Sandia National Laboratories Combustion Research Facility**
International Efforts

**IEA Technical Working Group on Modeling**
- Develop an international effort to address fundamental and applied aspects of H₂-enriched fuels for lean premixed gas turbine combustion
- Define program research areas
- Establish a validated simulation capability based on the LES technique
- Establish a complementary experimental capability for database acquisition

**Group Members**
- Sandia
- University of Heidelberg
- Darmstadt University
- Lund University
- Cranfield University
- National Energy Technology Laboratory
- University of Toronto
- NASA Glenn

**Progress**
- Primary program focus is the use of gas turbines in “zero-emission” H₂ applications
- Administrative framework established. Technical and Strategy Committee members selected with Sandia co-chairs on each
- Technical and Strategy groups met in Fall, 2002 to discuss procedures related to multi-nation tasks and to review technical progress
- Working group meeting was held in Spring, 2003
Related Efforts

**International Workshop on Modeling and Validation of Combustion in Gas Turbines**

- Objective is to establish a collaborative validation capability based on the LES technique
- Focused on turbulent, swirl-stabilized flames and the complex flow dynamics in gas turbine combustors
- Construct database repository on Web for selected flames to be used for model validation

**Economic Analysis**

- Energetics Inc. performed technical cost analysis
- Cost comparisons with Dry Low NO\(_x\) combustors and Selective Catalytic Reduction showed 20% H\(_2\) addition is cost competitive
- H\(_2\) addition up to 20% offers NO\(_x\) levels below 1 ppm and reduced CO\(_2\) emissions
- Extended analysis showed up to 60% H\(_2\) addition is cost competitive when carbon credits are included

Workshop home page: [www.ca.sandia.gov/CGT](http://www.ca.sandia.gov/CGT)
Working Groups

IEA Technical Working Group on Modeling
• Primary program focus is the use of gas turbines in “zero-emission” H₂ applications.
• An administrative framework has been established. Technical and Strategy Committee members were selected with Sandia co-chairs on each.
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<tr>
<td>H₂ Enrichment / Diagnostics</td>
<td>Sandia</td>
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<td>LES Development</td>
<td>Sandia</td>
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<td>Cranfield</td>
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<td>High Pressure Experiments</td>
<td>NETL</td>
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<td>Diagnostics</td>
<td>Toronto</td>
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AIAA Fluid Dynamics Technical LES Working Group
• Goal is development of predictive design tools for next generation aerospace and industrial applications.
• Group focus is joint LES/laboratory investigations on prototypical configurations with industrial impact.
• Participants are NRL, GEAE, Pratt & Whitney, WPAFB, U. Cincinnati, FOI-Stockholm, NCSU, Rolls-Royce, Alstom, SNL, U. Poitiers & CNRS, CTR and GATECH.
New Collaborations

Pratt and Whitney

- P & W will supply fuel injector to emphasize different aspects of practical gas turbine combustors (flow and flame dynamics)
- Fundamental data needed for LES model development
- Sandia will apply advanced diagnostics and LES to characterize combustion process and obtain detailed datasets
- Identify problem areas where hydrogen addition could be beneficial

Wright Patterson Air Force Base (emerging)

- WPAFB has extensive high-pressure diagnostic capabilities that complement Sandia capabilities
- Available high-pressure test facilities for realistic combustion pressures and temperatures
Proposed Future Work and Milestones

• Obtain detailed measurements of the velocity, temperature and species concentration fields in atmospheric pressure burner at Sandia (swirl burner)
• Establish LES model validity through comparisons with experimental database (swirl burner)
• Develop laser diagnostics for high pressure application (NETL)
• Complete evaluation of fuel/air mixing and implement improvements in hydrogen burner (NASA)
• Obtain NO\textsubscript{x} and CO emissions data in hydrogen burner (NASA)
• Explore issues surrounding the use of H\textsubscript{2} as an alternative gas turbine fuel (NASA)
• Complete experimental measurements in production injector (GEAE)
• Identify areas where H\textsubscript{2} addition could prove beneficial and demonstrate potential merits of H\textsubscript{2}-enrichment in these areas (GEAE)
• Explore potential use of H\textsubscript{2} addition as a “control knob” to eliminate instabilities related to fuel lean operation in practical gas turbines (GEAE)
Responses From 2002 Review Panel

• Panel strongly endorsed continuation of this project
  – No criticisms or questions, continued funding recommended
  – Score 95 (rank 2 in session, highest score was 96)

• Goals and objectives being addressed properly
  – Cost competitive even at 15% H₂ due to avoided cost of NOₓ removal
  – Goal to use hydrogen to reduce NOₓ emissions deemed solid

• Approach viable and project well planned and on track
  – Strong project management and research tools
  – Good use of laboratory resources and capability

• Significant progress being made with reasonable milestones
  – All milestones met or exceeded, significant results produced
  – Strong commercial collaboration in place and growing

● Excellent communication, collaborations and publication record
Publications