Technologies for Gaseous Fueled Advanced Reciprocating Engine Systems

DE-AC02-06CH 11357
Argonne National Laboratory/ ARES team
FY2011

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U.S. DOE Industrial Distributed Energy Portfolio Review Meeting
Washington, D.C.
June 1-2, 2011
Develop technologies to improve efficiency and reduce emissions of reciprocating engines that use natural gas/ opportunity fuels.

1 Distributed Energy Research Center (DERC):
   • A user facility to develop/test technologies to improve DE performance.

2 Advanced Laser Ignition System (ALIS):
   • Laser ignition was shown to extend lean ignitability of methane-air mixtures up to $\phi = 0.5$.
   • Besides improving ignition probability, laser ignition enabled efficiency improvements up to 3% points, and/or NO$_x$ emissions reductions up to 70%.
   • Developed a prototype laser ignition system for a 6-cyl engine; demonstration pending completion of engine test cell.

3 Nitrogen Enriched Air (NEA):
   • NEA is a clean alternative to Exhaust Gas Recirculation; hardware durability is improved as obnoxious particulate and acidic species are avoided.
   • NO$_x$ emissions reduced up to 50% with modest efficiency penalty.

4 Diagnostics for engine metrics:
   • Developed advanced diagnostics for in-cylinder temperature, rate of heat release, local equivalence ratio and in-cylinder EGR fraction.
Project objectives

- Develop in-cylinder technologies for emissions and performance improvement of natural gas fueled engines.
- Aim to improve performance of both existing as well as newer engines.
- Develop prototypes for high-risk high-return concepts for both lean-burn as well as rich-burn engines.
- Develop advanced diagnostics for combustion assessment in production engines.
- Research use of opportunity fuels – syngas, digester gas, landfill gas, etc.

Leaner Operation

\[ \phi = 1.0 \]
\[ \phi \approx 0.65 \text{ to } 0.7 \]

Rich-burn

\[ \eta \approx 36\% \]

Lean-burn

\[ \eta \approx 42\% \]

High EGR

Turbo-charged

3-way catalyst

No aftertreatment
1 Distributed Energy Research Center

- A user facility for advanced DE technologies
DERC: A user facility for industry/ universities/ national labs to test/develop advanced DE technologies

Nov. 2010
2 Advanced Laser Ignition System
Current spark ignition systems cannot meet the demands of stationary natural gas engines

- Capacitance Discharge Ignition (CDI) Systems cannot generate the needed voltage across the spark gap

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<tbody>
<tr>
<td>Lean operation ($\phi &lt; 0.65$)</td>
<td>High in-cylinder densities require ignition voltages &gt; 40 kV</td>
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<tr>
<td>High boost pressures</td>
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<td>High BMEP levels</td>
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- Though noble metal (Platinum & Iridium) electrodes are used, durability of spark plugs is still a concern

Spark gap adjustment interval

**Benefits/ Technical approach**

- **Ignition of mixtures at higher pressures**
  - Higher BMEPs → Higher engine efficiencies

- **Ignition of leaner mixtures**
  - Lower NO\_x emissions

- **Ignition kernel away from walls**
  - Less heat transfer losses

- **Ignition of lower quality fuel-air mixtures**
  - Syn gas, sewer gas, landfill gas, (CO\_2: 20-50%)
  - High levels of EGR

- **Multi-point ignition possible**
  - higher burn rates

- **No aftertreatment**
  - could displace expensive SCR systems
Technical accomplishments

- 70% reduction in NOx emissions, and/or efficiency gains up to 3% points

- Significant improvement in combustion stability.
Technical accomplishments

Pulsed output of a single laser multiplexed to different cylinders. Developed a prototype system - free space delivery had to be used as fiber transmission proved difficult

- Limited engine tests at Cummins Technical Center
- Improvements made in the system for heat and vibration insensitivity
- Further tests pending completion of DERC test cell#3
Partial view of Argonne’s laser ignition system installed on 6-cylinder engine
Commercialization approach

- Two patents
- US gas engine manufacturers and ignition system suppliers updated through timely reports/meetings

Future Plans

- Demonstrate on Argonne’s Cummins 6-cyl engine
- Also, evaluate Takunori Taira’s (Japan) micro-laser system
3 Nitrogen Enriched Air (NEA)
Exhaust gas recirculation leads to increased maintenance costs

Average of all customer engines 1993-2005; sum 1 Mil running hours

- Additional oil costs (low ash type)
- Spare parts (liner, cylinder head, oxygen sensor, spark plugs, ...)
- Personal costs (catalyst cleaning)

Maintenance costs [%]

Leann Engine: 100
Stoic. Engine (TC+EGR): 142

Courtesy: GE Jenbacher
NEA is a clean alternative to EGR

- Ideal for stationary engines
- Unlike EGR, engine reliability is not compromised
- Relatively inexpensive
- 3x-4x longer lifetime compared to aftertreatment devices
- Small foot print

2 NEA bundles
18in dia. x 24 in.
Tests were performed in Argonne’s single-cylinder engine

<table>
<thead>
<tr>
<th>Engine Specifications</th>
<th>Single-Cylinder, 4-Stroke, SI</th>
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<tbody>
<tr>
<td>Bore (mm)</td>
<td>130</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>140</td>
</tr>
<tr>
<td>Comp. Ratio</td>
<td>11:1</td>
</tr>
<tr>
<td>Displacement (L)</td>
<td>1.857</td>
</tr>
<tr>
<td>Power (kW/hp)</td>
<td>33/45</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1800</td>
</tr>
<tr>
<td>Ignition System</td>
<td>CDI (Altronic, Inc.)</td>
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</table>

Knobs: Equivalence ratio, ignition timing, % NEA
Nitrogen Enriched Air

Exhaust Gas Recirculation
NEA offers promise for NO\textsubscript{x} reduction

- 50% NOx reduction with modest efficiency loss under lean conditions
- Further gains possible with improved ignition
(Laser ignition +NEA) showed 67% NO\textsubscript{x} reduction with a modest efficiency penalty.
Within auxiliary power uncertainty, NEA and EGR are of comparable performance

\[ \phi' = 0.62 \]
Summary

Commercialization Approach

- One patent
- Work with industries for manufacturing the needed NEA bundles
  - Medarray
  - Compact Membrane Systems
  - Airproducts

Transition and Deployment

- Retrofit technology for engines existing in the field
- Clean alternative to EGR in future engines

Future Plans

- Demonstrate on Argonne’s Cummins 6-cylinder engine
4 Diagnostics for Combustion Metrics
Motivation

- To address the lack of spectral information for natural gas combustion in reciprocating engines (pressures up to 120 bar) - A request from Cummins

- To develop advanced diagnostics that are enablers for low-polluting combustion strategies

![Diagram showing traditional and advanced diagnostics]

**Traditional**
- Misfire detection
- Knock detection

**Advanced**
- Rate of Heat Release
- Combustion Temperature
- Equivalence Ratio
- EGR rate

**Spectroscopy**

**LIBS**
Test setup

Test Matrix: Equivalence ratio (0.6 to 1.0); EGR (up to 19%)
Time evolution of combustion spectra
272 - 534 nm

- One spectra obtained per DEG CA from Start of ignition
- Contribution from CH* (431.4 nm) and C2* (473 & 516 nm) species is insignificant
Peak $\text{CO}_2^*$ signals correlated with peak cycle temperatures and with peak Heat Release Rates.

- Potential use of flame emission to monitor Heat Release Rate & Peak cycle temperature in natural gas engines.
Laser Induced Breakdown Spectroscopy (LIBS) enables measurement of In-cylinder equivalence ratio

- EGR rate can be calculated with the knowledge of global equivalence ratio

\[
\psi = \frac{(mf/mO_2)}{(mf/mO_2)_{st,EGR=0}}
\]
Notable milestones in DERC’s progress

Patents

Invention Disclosures

Significant Publications (out of 30+)
- Air Separation Membranes: An Alternative to EGR in Large Bore Natural Gas Engines, Journal of Engineering for Gas Turbines and Power (Vol.132, Iss.8), August. 2010.
- Low Temperature Combustion Using Nitrogen Enrichment to Mitigate NOx From Large Bore Natural Gas Fueled Engines, Journal of Engineering for Gas Turbines and Power (Vol.132, Iss.1), Jan. 2010
Project status

1. Laser Ignition on multi-cyl. engine (In Progress)
2. NEA tests on single-cylinder engine (Completed)
3. Diagnostics development (LIBS, CO2*, OH*) (Completed)
4. DERC Multi-Cylinder Engine Test Cell (TC#3) (In Progress)
5. Opportunity fuels research (Future)
Future plans

Future efforts will address

- Opportunity fuel research
  - Digester gas, landfill gas, syngas, woodgas etc.
  - Infrastructure to be established soon.
- Advanced ignition systems
- Diesel micro-pilot ignition
- Reformer gas enrichment
Questions?