Natural Gas Engine Research at Colorado State University

Electrical Generating Systems Association (EGSA)
EGSA Fall Conference, September 14th, 2015

Daniel B. Olsen, Associate Professor
Mechanical Engineering Department
Colorado State University
Fort Collins, Colorado, USA
Presentation Outline

• Organizational Structure
• Research Overview and Capabilities
• Key Research Projects/Areas
Energy Institute at Colorado State University

Mission
Create innovative energy solutions through cross-disciplinary and entrepreneurial approaches

Key Strategies
• Provide opportunities and support to faculty members and students
• Foster linkages across University
• Provide a portal for external partners to connect with CSU expertise
• Facilitate large scale application of energy ideas and innovation
Energy Centers and Programs

Energy Centers

- Engines and Energy Conversion Laboratory
- Center for the New Energy Economy
- Center for Energy Development and Health
- Sustainable Biofuels Development Center
- Rural Energy Center
- Center for Energy and Behavior
- Industrial Assessment Center
- Institute for the Built Environment
- Center for Energy Water Sustainability
- Electric Power Systems Laboratory
- Center for Laser Sensing and Diagnostics
- Center for Next Generation Photovoltaics

Programs

- Research
- Technology to Market
- Education and Outreach
- Strategic Partnerships
The Powerhouse Energy Campus

- A facility of the Energy Institute at CSU
- 100,000 sq. ft. of project, office, and classroom space
- Facility includes Engines and Energy Conversion Laboratory, Electric Power Systems Laboratory, and Laser Sensing and Diagnostics Laboratory
- Fourth floor incubator, start-up, office space
The Engines and Energy Conversion Laboratory at the Powerhouse Energy Campus

• More than 2 decades of delivering solutions to meet the global energy challenges and opportunities of the 21st Century.

• Focus on market-driven solutions for industry: Engines, Fuels, Energy Conversion, Energy Distribution

• 24,000 sq.ft. world class facility: large-bore engine lab; diesel lab; grid-based renewable energy lab
Colorado State University
Mechanical Engineering Department

• 25 regular faculty
• 6 special faculty
• 18 research staff
• 5 administrative staff

• 859 ME undergraduates
• 157 Dual-degree ME/Biomed
• 1016 Total undergraduates
• 58 MS, 47 PHD
• 30 ME (Master of Engineering)
• 135 Total Graduate Students
Mechanical Engineering Department

• Bachelor of Science (B.S.) in Mechanical Engineering (M.E.)
• Dual degree: M.E./Biomedical Engineering
• Track III - Accelerated B.S./Master's Program*
• Graduate Program
  – Master of Engineering (M.E.)
  – Master of Science (M.S.)
  – Doctorate of Philosophy (Ph.D.)

* Track III will be changing names in the fall 2015 to IDP+ (Integrated Degree Programs Plus).
Graduate Research Areas

• Advanced Materials
• Biomechanics and Biomaterials
• Energy Conversion and Thermosciences
• Operations Research and Systems Engineering
• Motorsport Engineering
Presentation Outline

- Organizational Structure
- Research Overview and Capabilities
- Key Research Projects/Areas
Olsen: Engine Research Group

- 9 Graduate Students (1 PhD, 8 MS)
  - Chris Van Roekel, Jennifer Vaughn, Arunachalam Lakshminarayanan, Benjamin Neuner, Chris Page, John Ladd, Prerana Ghotge, Robbie Mitchel, Troy Nygren

- 5 Undergraduate Students (2 sophomores, 1 junior, 2 seniors)
  - Mary Stevens, Devin Link, John Finke, Brigid McCreery, Max Beard

- 1 visiting scholar (German Amador Diaz: Universidad del Norte, Columbia)
Research Focus: Industrial Engines

- Large industrial natural gas internal combustion engines
- Pollutant emissions reduction technologies – high energy ignition systems, fuel injection systems, exhaust aftertreatment, control systems
- Gaseous biofuels and fuel variability – combustion characterization, emissions impacts; producer gas, digester gas, shale gas
- Liquid biofuels – combustion characterization, emissions impacts, durability testing
Large Engines at the EECL

Engines outlined in blue are currently installed (Sept 2015).

- Cooper-Bessemer GMV
- Cummins QSK19G
- Caterpillar 3508
- Cummins QSK19
- Caterpillar 3516C
- Cummins QSK19
- Caterpillar 3412
- Cummins QSK50
- Waukesha VHP
- Waukesha VGF
- Superior 6G-825
Some Key Measurement Capabilities

Nicolet 6700 FTIR

Partial Dilution Tunnel

5-Gas Analyzer Rack

Varian CP-4900 MicroGC

ECM AF Recorder

HP 5890 Series II GC
Currently Funded Research Projects

- Investigation of Dual Fuel and Its Effects on Lubricant Performance, Chevron Oronite.
- Evaluation of Ethanol Substitution in Diesel Engines, Colorado Corn.
- Field Evaluation of Timed Power Cylinder Lube Oil Injection, Pipeline Research Council International.
- Variable Fuel Composition Air Fuel Ratio Control of Lean Burn Engines, Pipeline Research Council International.
- NSCR Catalyst Testing in Support of KSU Modeling Effort, PRCI.
- Field Evaluation of Oxidation Catalyst Degradation on a 2-Stroke Lean-Burn NG Engine, Pipeline Research Council International.
- Impact of H2-NG Blending on Lambda Sensor NSCR Control and Lean Burn Emissions, Southern California Gas.
Major Natural Gas Compressor Stations, 2008, Interstate + Intrastate
Typical Field Engines Used for Gas Compression in Compressor Stations

12 Cylinder Cooper GMV

8 Cylinder Cooper V-275

35 - 56 cm bore

Click for animation
Clark TLA-6
US Legislation Trend

Emissions Level (g/bhp-hr)

Uncontrolled Levels: 15 – 25 g/bhp-hr

Driving Legislation

- '95 CAA 3.0 state standards
- Continual reduction of permit levels
- Typical 2001 1.0 permit
- Houston 0.17 standard
## Legislation Example: US Stationary, New SI Engines

**Table 4.** NO\(_x\), CO, and VOC Emission Standards for Stationary SI Engines ≥100 HP (Except Gasoline and Rich Burn LPG), Stationary SI Landfill/Digester Gas Engines, and Stationary Emergency Engines >25 HP

<table>
<thead>
<tr>
<th>Engine type and fuel</th>
<th>Maximum engine power</th>
<th>Manufacture date</th>
<th>Emission standards^a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/HP-hr</td>
<td>ppmv at 15% O(_2)</td>
<td>NO(_x)</td>
</tr>
<tr>
<td>Non-Emergency SI Natural Gas and Non-Emergency SI Lean Burn LPG.</td>
<td>100≤HP≤500</td>
<td>7/1/2008</td>
<td>2.0</td>
</tr>
<tr>
<td>Non-Emergency SI Lean Burn Natural Gas and LPG.</td>
<td>500≥HP≤1,350</td>
<td>1/1/2011</td>
<td>1.0</td>
</tr>
<tr>
<td>Non-Emergency SI Natural Gas and Non-Emergency SI Lean Burn LPG (except lean burn 500≥HP≤1,350).</td>
<td>7/1/2010</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Non-Emergency SI Natural Gas and Non-Emergency SI Lean Burn LPG (except lean burn 500≥HP≤1,350).</td>
<td>7/1/2007</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>Landfill/Digester Gas (except lean burn 500≥HP≤1,350).</td>
<td>HP≥500</td>
<td>7/1/2010</td>
<td>1.0</td>
</tr>
<tr>
<td>Landfill/Digester Gas (except lean burn 500≥HP≤1,350).</td>
<td>HP&lt;500</td>
<td>7/1/2008</td>
<td>3.0</td>
</tr>
<tr>
<td>Landfill/Digester Gas lean burn</td>
<td>HP≥500</td>
<td>1/1/2011</td>
<td>2.0</td>
</tr>
<tr>
<td>Landfill/Digester Gas lean burn</td>
<td>500≥HP≤1,350</td>
<td>7/1/2010</td>
<td>3.0</td>
</tr>
<tr>
<td>Emergency</td>
<td>25&gt;HP&lt;130</td>
<td>7/1/2009</td>
<td><strong>10</strong></td>
</tr>
<tr>
<td>Emergency</td>
<td>HP≥130</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

^a Emission standards are in grams per horsepower-hour (g/HP-hr) and ppmv at 15% O\(_2\).

---

Engine Operating Regimes

- **Detonation**
  - Uncontrolled combustion, rich air/fuel advanced ignition timing
- **Rich-Burn Operation**
  - Flexibility for fuel fluctuation, changes in site conditions, changes in speed/load
- **Lean-Burn Operation**
  - Not enough fuel to burn, lean air/fuel, retarded ignition timing

- **Lean Misfire**
  - Not enough fuel to burn, lean air/fuel, retarded ignition timing

**High engine-out NOx and CO emissions. 3-way catalyst required.**

**Highest efficiency, BMEP. Low emissions without catalyst. Engine must be controlled between detonation and misfire limits.**
Efficiency Trends

- Higher power density (bmep) results in higher efficiency
- Higher compression ratio yields higher efficiency

- Knock (detonation) limits compression ratio and bmep of engine
- Fuel quality determines knock limit

Engine Knock in GMV Engine

10 cycles of each together

Cylinder Pressure [psia]

Crankangle [deg]

High Knock

No Knock
Combustion Stability

PV Diagrams Stable Combustion

PV Diagrams Near Lean Limit

IMEP Stable Combustion

IMEP Near Lean Limit
Presentation Outline

• Organizational Structure
• Research Overview and Capabilities
• Key Research Projects/Areas
PRECOMBUSTION CHAMBERS
Precombustion Chamber (PCC) Characterization

PCCs extend the lean limit and accelerate and stabilize combustion.

Diesel Supply Co. Screw-in-Prechamber

Effect of PCC on Combustion

- Precombustion chamber (PCC) ignition stabilizes combustion and reduces variability
- Extends lean limit by allowing operation at higher boost at constant load

Precombustion Chamber Jet Visualization

Optical access in head in bored out air start port

Fused silica window

High speed photography equipment

Camera view angle

Optimal PCC Fueling ($\approx 20\text{psi, } 8\text{SLPM}$)
Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Point 4

Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Point 9

Optimal PCC Fueling ($\approx 20\text{psi}, 8\text{SLPM}$)
Optimal PCC Fueling (≈20psi, 8SLPM)
Optimal PCC Fueling (∼20psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)

Point 12
Optimal PCC Fueling ($\approx 20$psi, 8SLPM)
Optimal PCC Fueling ($\approx 20$psi, 8SLPM)
Optimal PCC Fueling ($\approx 20$psi, 8SLPM)
Optimal PCC Fueling (≈20psi, 8SLPM)
Estimating jet penetration

Enables quantification of flame development
PCC Design Study

Note: 54 cc = 1.6% of Clearance Vol.; 8.6 cc = 0.25% of Clearance Vol.
Results: NOx vs. CO

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Multiple nozzle</th>
<th>Fueled MPCC</th>
<th>ePCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum $\Phi_{PCC}$</td>
<td>1.09</td>
<td>1.01</td>
<td>1.20</td>
<td>1.16</td>
</tr>
<tr>
<td>COVPP$_{MC}$ (%)</td>
<td>10.7</td>
<td>6.8</td>
<td>5.4</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Graph: Scatter plot showing NOx ppm at 15% O2 vs. CO ppm at 15% O2 with different symbols and lines for Baseline, Multiple nozzle, Fueled Micro, and ePCC cases.
PCC Development: Optimal Design

Baseline Design

New Design – Fueled Micro PCC

Checkvalve
Sparkplug
PCC Volume
PCC Nozzle

Sparkplug
Checkvalve
PCC Volume
PCC Nozzles
HIGH PRESSURE FUEL INJECTION
“Low Pressure” Gas Admission
Fuel Injection

- At time of spark (end of simulation), fuel and air are not fully mixed.
- Improved fuel injection technique is needed.
Dresser-Rand / Woodward
HPFi System

Also commercialized by Hoerbiger Corp.
High Pressure Fuel Injection

Performance Benefits

![Graphs showing performance benefits of different fuel injection systems.](image-url)
GASEOUS FUEL CHARACTERIZATION
CFR Engine – MN Measurement

<table>
<thead>
<tr>
<th>#</th>
<th>Test Gas</th>
<th>%CH₄</th>
<th>%H₂</th>
<th>%N₂</th>
<th>%CO</th>
<th>%CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reformed Natural Gas</td>
<td>39.7</td>
<td>46.7</td>
<td>0.8</td>
<td>0.9</td>
<td>11.9</td>
</tr>
<tr>
<td>2</td>
<td>Coal Gas</td>
<td>*</td>
<td>24.8</td>
<td>16.3</td>
<td>58</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Wood Gas</td>
<td>10</td>
<td>40</td>
<td>3</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>Wood Gas</td>
<td>1</td>
<td>31</td>
<td>35</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Digester Gas</td>
<td>60</td>
<td>*</td>
<td>2</td>
<td>*</td>
<td>38</td>
</tr>
<tr>
<td>6</td>
<td>Landfill Gas</td>
<td>60</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>Reformed Natural Gas</td>
<td>1.2</td>
<td>30.8</td>
<td>49.0</td>
<td>15.6</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>Coal Gas</td>
<td>7</td>
<td>44</td>
<td>*</td>
<td>43</td>
<td>6</td>
</tr>
</tbody>
</table>

- Current work with Caterpillar
- Measure MN for syngas blends
- Examine other metrics
  - Boost requirements
  - De-rating
  - Critical compression ratio
  - Combustion statistics
  - Knock statistics
MN Measurement for Producer Gas Blends

Ordered by Measured MN - AVL Predicted MN

- Measured MN
- AVL Predicted MN

Methane Number

Plasma, Choren (O2), Dil Gap C, S4 Example, Blend #1, Blend #4, S4 Avg, Blend #8, Blend #4, VT4/7/08, VT4/9/08, CPC, Blend #5, Blend #4, W1G, AF Gap A, Report, Dil Gap D, TEMCO, Cranfield, AF Gap E, Meadow Tate, Hyde, Guising, Villing, AF Gap D, Victoria 1, Harbord, Dil Gap F, Blend #2, Banham, AF Gap C, I12C, City Energy, AF Gap A, AF Gap B
ENGINE CONTROL WITH NOX SENSORS
Broad perspective and Overall Project Goals:

- Smaller (1500 hp and lower) natural gas engines used for power generation, water pumping, and gas compression are often stoichiometric engines.
- These engines have high utilization factors, often running 24/7 through most of the year.
- They use a 3-way, or NSCR, catalyst similar to what is used in most US automobiles.
- The objectives of this work are:
  - Determine the feasibility of using a minimization algorithm with a NOx sensor to control Non-Selective Catalytic Reduction (NSCR) catalyst systems
  - Demonstrate that we can achieve strict CARB 2007 fossil fuel emissions levels.
Engine Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore and Stroke size</td>
<td>4.36”x3.85” (110.744x97.79mm)</td>
</tr>
<tr>
<td>Displacement</td>
<td>7.5 liters (460 CID)</td>
</tr>
<tr>
<td>Engine Type</td>
<td>90° valve-in-head</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>8.0:1</td>
</tr>
<tr>
<td>Connecting rod Length</td>
<td>60.604” (167.729mm)</td>
</tr>
<tr>
<td>Piston Length</td>
<td>3.74” (95mm)</td>
</tr>
</tbody>
</table>
Continental NOx Sensor Behavior

![Graph showing the behavior of Continental NOx Sensor with Lambda on the x-axis and Concentration (ppm) on the y-axis. The graph displays a peak around Lambda 0.97.](image-url)
Final Algorithm Implementation will provide feedback from the NOx sensor directly to catalyst monitor.

\[ LM = \text{Lean Multiplier} \]
\[ RM = \text{Rich Multiplier} \]
NOx Sensor Feedback AFR Control

NOx sensor closed loop operation turned on at rich starting point

NOx sensor closed loop operation turned on at lean starting point
DUAL FUEL ENGINE RESEARCH
Dual Fuel Engine Setup: John Deer 6.8 liter T2

Natural gas metered into air intake between air filter and turbocharger compressor inlet.
Natural Gas Substitution

\[
\%\text{NG Substitution} = \frac{m(\text{Diesel Baseline}) - m(\text{Diesel, I})}{m(\text{Diesel Baseline})} \times 100
\]
CO, NOx Comparison

![Graph showing comparisons of CO and NOx emissions across different power levels. The graph plots brake specific emissions in g/bkW-hr against power in kW. The data points are color-coded to represent diesel CO, dual fuel CO, diesel NOx, and dual fuel NOx.](image-url)
ISO Weighted Emissions

![Graph showing weighted emissions for THC, NOx, CH4, CH2O, and VOCs for Diesel and Dual Fuel.]
ISO Weighted Emissions

Regulated Emissions

Tier 2 Limits
Optimized %NG Substitution

![Graph showing NG Substitution (%) for different loads with baseline and optimized results.](image)
Oxidation Catalysts: NG Engine Testing

To meet T2 CO limit, ~ 70% CO reduction is required.

Oxidation Catalysts: NG Engine Testing

Approximate Diesel Engine Exhaust Temperature Range 400-1200°F

To meet T2 (NOx+NMHC) limit, ~75% NMHC reduction is required.
The Powerhouse Energy Campus

Contact: Daniel B. Olsen
Associate Professor
Mechanical Engineering Department
(970) 491-3580
daniel.olsen@colostate.edu

http://www.energy.colostate.edu/p/powerhouse-energy-campus