Impact of Fuel Composition on Efficiency and Emissions of Prime Movers

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The National Energy Technology Laboratory

www.netl.doe.gov
The Future of Natural Gas
(Source: EIA Annual Energy Outlook 2007 – Early Release)

- **Demand for NG expected to grow**
  - Based on EIA long-term forecasts, U.S. natural gas consumption is projected to increase from 22.0 trillion cubic feet in 2005 to 26.1 trillion cubic feet in 2030

- **Supply can not keep pace**
  - Total domestic production, including supplemental natural gas supplies, increases from 18.3 trillion cubic feet in 2005 to 21.1 trillion cubic feet in 2022, before declining to 20.6 trillion cubic feet in 2030
The Growing Demand for Natural Gas
(International Energy Outlook 2006)

- **World Natural Gas Consumption**
  - Increased from 95 tcf in 2003 to 182 tcf in 2030.
  - Higher world oil prices increase the demand for natural gas.
  - By 2030 demand for natural gas in developing countries when more than double

![Graph showing projected natural gas consumption](image)

- **Iran – India Pipeline**
- By 2030 demand for natural gas in developing countries when more than double

- **Other Non-OECD**
- **Non-OECD Asia**
- **Non-OECD Europe and Eurasia**
- **OECD**

![Graph showing projected natural gas consumption](image)
What Are The Implications For Power Generation?

- Natural gas usage in the power generation sector continues to grow.

*Figure 71. Natural gas consumption by sector, 1990-2030 (trillion cubic feet)*
Looking at Alternatives: LNG
(Source: EIA Annual Energy Outlook 2006)

- Large natural gas reserves exist that must be liquefied to transport overseas.
- Growth in overseas imports (i.e., LNG)
  - Net U.S. LNG imports are expected to rise from 5 percent of net U.S. natural gas imports in 2002 to 39 percent in 2010
  - The United States imported 229 Bcf (4.8 million tons) of LNG in 2002 with more than half that volume originating in Trinidad and Tobago.
Differences Between LNG and NG

- **Transportation and storage**
- **Energy content**
  - LNG typically has a higher heat content per cubic foot.
- **Fuel Composition**
  - Low HC, water and CO2 content compared to domestic natural gas.
  - High cost of NG compared to NGL’s has lead to reduced extraction levels
    - Hydrocarbon Drop-out
    - Higher hydrocarbons may influence combustion and physical phenomena
What Are The Implications For Gas Turbine Power Plants?

- LNG fuel composition is different
  - Higher BTU value
  - Increase in heavier HC’s
  - Lower level of inerts

- Effects of sudden changes in gas composition
  - How will fuels mix in the pipeline?
  - How to sense changes in fuel composition?

- Gas turbine combustion sensitivity to fuel variations
  - Emissions
  - Dynamics
  - Auto-ignition
  - Flashback and LBO
DOE Research on Fuel Interchangeability

- FERC requests DOE’s help with a technical assessment of the effect of fuel variability on end-use equipment.
  - Database & Gap Analysis - gas fuel composition and effects on end-use equipment.
  - Pipeline Mixing - Steady-state and transient mixing behavior.
  - Reciprocating Engines - Effect of gas composition (literature review).
  - Stationary Gas Turbines – Literature and experimental analysis of fuel effects on stationary gas turbines.
  - Sensors for Gas Composition - Rapid gas composition measurement to assess equipment control options.
  - Hydrocarbon Dewpoint – Computational simulation could be used to improve dewpoint prediction (partnered with West Virginia University).
Fuel Interchangeability

- **Interchangeability** (NGC+, Feb 2005)
  - “The ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions”

- **Wobbe Index (Interchangeability Factor)**
  - Single index parameter to measure interchangeability
  - Relates the thermal input to a burner
  
  \[
  Wobbe = \frac{HHV}{\sqrt{SG}}
  \]
  - Does not capture the effects flame speed and combustion chemistry

- Narrower range may limit supply options
- Is blending inerts a viable option?

<table>
<thead>
<tr>
<th>Country</th>
<th>Wobbe Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Average</td>
<td>1336</td>
</tr>
<tr>
<td>Trinidad</td>
<td>1372</td>
</tr>
<tr>
<td>Algeria</td>
<td>1398</td>
</tr>
<tr>
<td>Qatar</td>
<td>1417</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>1417</td>
</tr>
<tr>
<td>Malaysia</td>
<td>1434</td>
</tr>
<tr>
<td>Oman</td>
<td>1437</td>
</tr>
</tbody>
</table>
Typical LNG Compositions

**Average U.S. Composition**
- Methane: 92.30%
- Other: 1.50%
- Nitrogen: 1.80%
- Propane: 0.80%
- Ethane: 3.60%

**Very Low Btu Content**
- Methane: 96.18%
- Other: 0.08%
- Nitrogen: 0.01%
- Ethane: 3.39%

**Low Btu Content**
- Methane: 92.19%
- Other: 0.43%
- Nitrogen: 0.00%
- Ethane: 6.45%

**Moderate Btu Content**
- Methane: 87.14%
- Other: 1.84%
- Nitrogen: 0.49%
- Ethane: 10.74%

**High Btu Content**
- Methane: 88.77%
- Other: 0.29%
- Nitrogen: 0.03%
- Ethane: 7.38%

**Very High Btu Content**
- Methane: 85.98%
- Other: 1.21%
- Nitrogen: 0.02%
- Ethane: 8.69%

**Average U.S. Composition**
- Methane: 92.30%
- Other: 1.84%
- Nitrogen: 0.02%
- Ethane: 3.60%
Wobbe Number Control

- Reduce Wobbe number through the addition of inerts
  - Nitrogen
  - Air
  - Carbon Dioxide

<table>
<thead>
<tr>
<th></th>
<th>Very High BTU</th>
<th>Nitrogen Addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>85.98%</td>
<td>82.49%</td>
</tr>
<tr>
<td>Ethane</td>
<td>8.69%</td>
<td>8.34%</td>
</tr>
<tr>
<td>Propane</td>
<td>3.47%</td>
<td>3.33%</td>
</tr>
<tr>
<td>Butane</td>
<td>1.84%</td>
<td>1.77%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.02%</td>
<td>4.08%</td>
</tr>
<tr>
<td>Wobbe</td>
<td>1443</td>
<td>1400</td>
</tr>
</tbody>
</table>
Effects of Fuel Variability on Gas Turbine Combustion

• In-Use systems can be classified in two categories
  – Pre-mixed and Diffusion systems

• Lean pre-mixed, or DLN, systems account for > 85% of gas fired capacity built since 1995.¹

• Diffusion flame systems
  – Robust, can tolerate fuel variability
  – Small effect on older diffusion flame systems (+2ppm/100ppm)
    • Hung, 1976, 1977; Meier, 1998

\[
\frac{NO_x}{NO_{x_{CH4}}} = 1 + 10 \cdot \ln \left( \frac{T}{T_{CH4}} \right)
\]

• DLN systems are more susceptible to combustion related phenomena
  – Reduce NOx by lowering flame temperature
  – But…
    • Dynamics?
    • Flashback and LBO?

¹ Personal communications Chuck Linderman, Alliance of Energy Suppliers
Fuel Interchangeability Effects: Emissions

- **NOx Emissions: pathways**
  - Thermal NOx / Zeldovich
    - Primary NOx pathway with $T_f > 1800$ K.
  - Prompt (Fernimore) NOx
    - Hydrocarbon driven through oxidation of the HCN molecule
      $$\text{N}_2 + \text{CH} \rightarrow \text{HCN} + \text{N}$$
  - Nitrous Oxide ($\text{N}_2\text{O}$) Mechanism
    $$\text{N}_2\text{O} + \text{O} \rightarrow \text{NO} + \text{NO}$$
- **Fuel interchangeability concerns**
  - Changes in premixer performance
  - Changes in flame temperature
  - Presence of higher hydrocarbons
Fuel Interchangeability Effects: Flashback / Lean Blow-off

- **Flashback**
  - Flame propagates upstream to the premixer through a shear or boundary layer, or vortex core.
  - Flame speed exceeds local gas velocity. (primarily driven by flame speed)
  - Thermal damage to components.

- **Effects of fuel variability?**
  - Changes in flame speed
  - Lewis number effect (ratio of thermal diffusivity to mass diffusivity)

- **Lean Blow-off**
  - To maintain low flame temperatures, DLN combustor operate near the lean blow-out limit.
  - Flame becomes unanchored and can not be held in the combustor.
  - Correlated with characteristic combustor (flow) and chemical (flame speed) time scales.

- **Effects of fuel variability?**
  - Changes in flame speed
Fuel Interchangeability Effects: Dynamics

- **What are combustion dynamics**
  - Damaging pressure oscillations resulting from a coupling between acoustic pressure and heat release perturbations.

- **Mechanisms**
  - Equivalence ratio perturbations
  - Vortex shedding
  - Changes in the flame surface.

- **How fuel variability will effect**
  - Changes in chemical and physical time scales that affect phase relationship between heat release and acoustic pressure perturbations.
  - Changes in fluid medium (gas composition) alter acoustic properties.
NETL Investigation for Turbine Combustion

- **Paper results**
  - Literature, database
  - Discussion with OEMs, operators
  - Analytic models
  - CFD models

- **Experimental results**
  - Lab to full scale
  - Dynamics, blowout, emissions

- **Project start: October 2005**
High Pressure Propane Blending Facility

Meets Req'ts of NFPA-58

On-line Micro-GC

2x Fluid-bath, controlled-heat pressure vessels

165°F for propane

Metering runs
NOx Emissions

- Literature data (exp and predictions) suggests that NOx will be greater with higher HCs.
- NETL high-pressure tests in progress.

DLN Microturbine Correlation:

\[
\text{NOx [15\%O2] = 0.0351*C1+0.147*C2+0.225*C3}
\]


Table 6-2. Predicted NOx (ppmv @15\% O2) and \(\Delta\text{NOx} (%)\) relative to methane for the correlation of microturbine data from Equation 6-4. The correlation was not tested for pure propane fuel, column K, and does not account for butane.

Figure 6-5. Comparison of NOx emissions from jet-stirred reactor for three fuels (2.3ms residence time, 1790K temperature, 1 atm).\(^{20}\)

Figure 6-6. Replot of data presented by Klassen.\(^{22}\) Five natural gas compositions are considered, and an assumed baseline of 5 ppmv NOx is used to scale the normalized data sets; see the text – the actual NOx levels are not reported.

Physical Effects on Emissions
Simplified Analysis for Jet Penetration

- Premixing fuel uses jet penetration to mix fuel/air stream
- It is possible to relate the Wobbe index to jet penetration for comparing two fuel compositions
- Jet penetration is dependent upon the momentum ratio

\[ r = \frac{\rho_j u_j^2}{\rho_a u_a^2} \]

- Assuming a constant heat release independent of fuel composition \((Q_A = Q_B)\)
- Fluid mechanics tells us:

\[ \left( \frac{WIB}{WIA} \right)^2 = \left( \frac{\rho_A u_A^2}{\rho_B u_B^2} \right) = \left( \frac{\frac{Y_A}{d}}{\frac{Y_B}{d}} \right)^2 \]

- Jet penetration is inversely proportional to Wobbe index
CFD Analysis of Premixer Performance on Various Fuel Compositions

Two- and Three-Dimensional Analysis – agrees with analytical results

- Wobbe - 1360, Fuel Mass Fraction 100% CH4
- Wobbe - 1443, Fuel Mass Fraction 86% CH4, 8.7% C2H6, 3.5% C3H8, 1.8% C4H10, 0.02% N2

100% Methane
100% Propane
Experimental Results: NOx Emissions

- **NOx emissions**
  - Only measured in dynamically stable region due to pressure fluctuation bias.

- **Two-level factorial design**
  - Equivalence ratio
  - Propane level

- **Premixed system**
  - 5% pilot fuel
Preliminary NOx Data
(7.5 atm, 600F air preheat, RMS Pressure Levels < 1%)

Equivalence Ratio = 0.44-0.45

Equivalence Ratio = 0.50-0.51

Standard Deviation = 0.9 ppm
Preliminary NOx Levels Correlate With Flame Temperature

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Target Equiv. Ratio</th>
<th>Actual Equiv. Ratio</th>
<th>Target Propane Level</th>
<th>Actual Propane Level</th>
<th>Adiabatic Flame Temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.52</td>
<td>0.510 ± 0.005</td>
<td>5.0%</td>
<td>5.46 ± 0.002</td>
<td>1717</td>
</tr>
<tr>
<td>1</td>
<td>0.52</td>
<td>0.503 ± 0.004</td>
<td>0.0%</td>
<td>0.69 ± 0.095</td>
<td>1708</td>
</tr>
<tr>
<td>3</td>
<td>0.44</td>
<td>0.445 ± 0.004</td>
<td>5.0%</td>
<td>5.33 ± 0.029</td>
<td>1599</td>
</tr>
<tr>
<td>5</td>
<td>0.44</td>
<td>0.453 ± 0.005</td>
<td>0.0%</td>
<td>1.14 ± 0.016</td>
<td>1607</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>0.474 ± 0.005</td>
<td>3.5%</td>
<td>4.00 ± 0.018</td>
<td>1654</td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>0.479 ± 0.005</td>
<td>3.5%</td>
<td>4.19 ± 0.015</td>
<td>1660</td>
</tr>
<tr>
<td>7</td>
<td>0.48</td>
<td>0.478 ± 0.005</td>
<td>3.5%</td>
<td>4.08 ± 0.001</td>
<td>1659</td>
</tr>
<tr>
<td>8</td>
<td>0.44</td>
<td>0.453 ± 0.005</td>
<td>0.0%</td>
<td>1.00 ± 0.001</td>
<td>1608</td>
</tr>
</tbody>
</table>
Lean Blowout

- Premix combustors operate near lean blowout
- If the fuel variability changes the lean blowout, the engine fuel schedule will need to be changed
  - Possible emissions or stability compromise
  - Possible unexpected flameout
- Traditional blowout correlations based on laminar flame speed
  - Some difference for different hydrocarbons and methane is slower than propane
  - Note that the turbulent flame speed drops with propane (previous slide)
- Recent NETL studies on H2-CH4 blends:
  - Stirred reactor models better correlate the blowout data with wide fuel variability

Traditional correlations for “loading (L)” define when blowout occurs

\[
\tau_{\text{chem}} = \frac{\alpha}{S_L^2} \quad L = \frac{\tau_{\text{chem}}}{\tau_{\text{res}}} = \frac{\alpha U_{\text{ref}}}{S_L^2 d}
\]

From previous slide, turbulent Flame speed of CH4 –C3H8 mix

SimVal LBO Data (8 Aug 2005)
Tim=590K V=40 m/s
Effect of Pressure

Lean Blowout: Experimental Results

- Pure propane versus NG: big effect on blowout
  - Did not follow simple explanations from flame speeds
  - Did not follow stirred reactor model
  - Hypothesis is the flame anchor depends on the turbulent flame speed
  - More work needed to resolve details
- More realistic fuel blends (up to 10% propane in NG)
  - Blowout not significantly affected
Flashback

- **Flame speed is the key issue**
  - Flame speeds not very different among HCs
  - Very recent data: turbulent flame speeds change w/HCs
- **Lab tests so far do not reveal problems**
  - Not comprehensive
  - High pressure data still to come
  - Commercial associated gas applications operate w/o problems (not publicly documented).

Figure 6-2. **Laminar** flame speeds of several natural gas blends and methane. The x-axis is the equivalence ratio (normalized fuel/air ratio).

Figure 6-3. **Turbulent** flame speeds (Kido et al.10) of methane/propane mixtures having the same *laminar* flame speed.
Potential Effects of Fuel Variability on Combustion Instabilities (Dynamics)

- **Chemical Effects**
  - Changes in chemical time scales
  - Changes in the turbulent flame speeds

- **Physical Effects**
  - Changes in the acoustic characteristics of the medium
Chemical Effects of Fuel Variability on Dynamic Response

- **Effect on dynamic flame response**
  - Changes in chemical time scales
    - Damköhler Number
      - $Da \gg 1$ chemical reactions are fast in comparison to fluid mixing rates.
      - Alters the phase difference between heat release and acoustic pressure
  - Changes in the turbulent flame speeds
    - Changes flame surface area

\[
Da = \frac{\tau_{flow}}{\tau_{chemical}} = \frac{1/\delta_L}{u'/S_L}
\]
Potential Physical Effects of Fuel Variability on Dynamic Response

- **Changes in fuel system impedance**
  - Measure of the fluids resistance to propagating acoustic waves
  - Speed of sound changes with medium (gas properties).
    - Alters phase-gain between components.
  - Transmission from one fluid into another
    - Alters characteristics of reflected waves.

\[
\begin{align*}
  c_{\text{O-air}} &= 343 \text{ m/sec} \\
  c_{\text{O-meth}} &= 450 \text{ m/sec} \\
  c_{\text{O-prop}} &= 252 \text{ m/sec}
\end{align*}
\]
Lab Burner Tests (14,000 BTUH)

- Tests used to determine any fundamental differences in flame dynamics versus fuel composition?
- Fuel and air fully premixed (no fuel injector impedance effects)
- Most fuels fall within NGC+ Recommended limits
- Nitrogen blending used to reduce Wobbe back to Methane levels

<table>
<thead>
<tr>
<th></th>
<th>Fuel A</th>
<th>Fuel B</th>
<th>Fuel C</th>
<th>Fuel D</th>
<th>Fuel E</th>
<th>Fuel F</th>
<th>Fuel G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (%)</td>
<td>100</td>
<td>75</td>
<td>70</td>
<td>90</td>
<td>88.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethane (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Propane (%)</td>
<td>0</td>
<td>25</td>
<td>20</td>
<td>10</td>
<td>8.25</td>
<td>100</td>
<td>62.3</td>
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<tr>
<td>Nitrogen %</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>3.5</td>
<td>0</td>
<td>37.7</td>
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<tr>
<td>HHV (BTU/scf)</td>
<td>1012</td>
<td>1389</td>
<td>1213</td>
<td>1163</td>
<td>1101</td>
<td>2523</td>
<td>1572</td>
</tr>
<tr>
<td>Wobbe (BTU/scf)</td>
<td>1360</td>
<td>1554</td>
<td>1363</td>
<td>1439</td>
<td>1365</td>
<td>2041</td>
<td>1369</td>
</tr>
<tr>
<td>Wobbe % Diff</td>
<td>0%</td>
<td>14%</td>
<td>0.2%</td>
<td>6%</td>
<td>0.4%</td>
<td>50%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Lab Burner Results (14,000 BTUH)

- Fuel D and E most realistic “LNG like” fuel
  - Comparable to methane response (no change from baseline)
  - Additional tests not shown that included ethane produced similar response

- High levels of propane produced a significant change in response.

- Nitrogen dilution to reduce Wobbe did not influence dynamic response.
Atmospheric Pressure Development Combustor (100,000 BTUH)

Dynamic pressure for various fuel blends

- Natural Gas
  - Wobbe = 1360
  - Hollow Symbols Represent Data from Original N.G. Tests in Jan '06
  - Solid Symbols Represent July '06 Repeats

- 100% Propane
  - Wobbe = 2041

- NG/Propane (90/10%)
  - Wobbe = 1439

- Propane/Nitrogen
  - Wobbe = 1369

Reference Velocity

- 20.0 m/sec
- 22.5 m/sec
- 25.0 m/sec
- 27.5 m/sec
- 30.0 m/sec
Dynamic Gas Turbine Combustor
(5 million BTUH, up to 10atm)

- Evaluate change in stability boundary versus fuel
  - Nominal +4.6% propane to site NG

- Slight change – wider replicate range – minor
  - Hysteresis loop is larger than fuel effect (component heating)

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane (%)</td>
<td>0.5</td>
<td>0.5</td>
<td>4.6</td>
<td>4.6</td>
</tr>
<tr>
<td>HHV (mBTU/scf)</td>
<td>1.036</td>
<td>1.029</td>
<td>1.094</td>
<td>1.094</td>
</tr>
<tr>
<td>WOBBE MJ/m³</td>
<td>50.7</td>
<td>50.7</td>
<td>51.9</td>
<td>51.9</td>
</tr>
<tr>
<td>WOBBE BTU/scf</td>
<td>1360</td>
<td>1356</td>
<td>1394</td>
<td>1393</td>
</tr>
</tbody>
</table>

- Pressure vessel for combustor
- ~2.5-inches
- Fuel injector (looking upstream)
- Holes are centerbody pilot flow
Summary for Combustion Dynamics

• From lab scale to full scale…..
  – Modest additions (5-10%) of propane to natural gas didn’t produce a significant change in dynamics amplitude or stability boundary.

• Fuel composition does matter
  – Pure propane is significantly different than natural gas.
  – Nitrogen blending for constant Wobbe does not compensate.
    • Wobbe does not account for changes in flame speed and combustion chemistry
  – Changes in acoustic impedance in fuel injectors and modest changes in flame shape could contribute to changing in the dynamic response in marginally stable combustors.
Overview Summary Turbines (1/2)

- **Fuel effects on gas turbines**
  - Limited literature, public data available.
  - Effects on dry-low NOx system not well-understood.

- **Emissions**
  - **Uncontrolled NOx emissions will rise with hydrocarbons**
    - Literature: small effect on older, diffusion flame systems (e.g., $+2ppm/100ppm$ base?)
    - Literature: small *absolute* effect in DLN, but may be significant for machines near permit levels (e.g., $+2ppm/4ppm$ base?)
    - NETL analysis: effect not likely due to premixer deterioration
    - NETL experimental data shows only a small effect – inconclusive?
  - SCR control may be able to accommodate
  - Did not obtain public report of “brown-plume” exacerbation by HCs
    - Link between fuel and brown plume plausible at part-load
Overview Summary (2/2)

- **Operational issues (DLN systems)**
  - Autoignition
    - Actual data on autoignition time scale is NOT in the literature
    - Experience with premixers in service suggest (but don’t prove) no problems
  - Blowout
    - Literature correlations: expect little change among HCs
    - Lab data: noticeable shift in blowout for extreme fuel change
  - Flashback
    - Literature correlations: expect little change among HCs
    - Lab data did not identify any problems
  - Dynamics
    - Literature: uncertain effects, and physics
    - NETL analysis: likely effect of fuel impedance + composition on some engines
    - Lab data: minor effect for modest fuel change, but significant effect for extreme fuel change
  - Key point:
    - Wobbe is not a useful parameter to quantify the behavior observed in lab tests (flame speed and combustion chemistry).
    - Dilution or fuel heating (to maintain Wobbe) will not negate fuel composition effects.
Questions?

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