NOx Control for Reciprocating Engines

SEIMA Workshop
Air Quality in Saskatchewan
Friday, Jan 17, 2014
Presentation Overview

1. Introductions & Background
2. Background on NOx Emissions
3. Rich Burn Engine Control
4. Lean Burn Engine Control
5. Final Comments & Questions
Introductions

- Michael McMurray, P.Eng.
  - Environmental Systems Engineer from University of Regina
  - Started my career with the Ministry of Environment
  - Began with SaskEnergy/ TransGas in 2006 with Environment & Sustainability Dept.
  - Started developing a Greenhouse Gas / NOx emission control program in 2008
TransGas operates >50 reciprocating engines for gas compression in Saskatchewan.

- Slow speed Integral Compressors
  - Ingersoll Rand (KVS Model 36, 410, 412)
  - Cooper Bessemer (GMVC 6, GMVG10, GMVH12)

- High Speed Separable Units
  - Waukesha (L5790Gs, L5108GU)
  - White/ Superior (8GT, 8GTL, 16 SGT)
  - Caterpillar (L3606, G3512LE, 3516LE)
  - DeLaval (8-2C)
NOx Control for Reciprocating Engines

TransGas & NOx Reduction

- Significant effort invested already to reduce NOx.
  - REMVue AFRC packages
  - Guardian/ Woodward AFRC Packages
  - NSCR on Rich Burns

- Asset Retirement & Replacement Programs
  - Significant high emitting engines have been retired & replaced by engines < 2.0 gNOx/bhp-hr

- Engine Testing Program
  - Nearly all engines in the fleet have been tested multiple times since 2010.
What is NOx?

- NOx is a term used to describe the “Oxides of Nitrogen”, or NO (Nitrogen Oxide) or NO2 (Nitrogen Dioxide).
- It is formed due to the reaction between atmospheric nitrogen and un-combusted oxygen at the high temperature of combustion.
- It is predominantly of interest as a precursor to ground level ozone and photochemical smog.
Glossary of Useful Terms

- **Air/Fuel Ratio** is ratio between mass of air and mass of fuel in the fuel-air mix at any given moment.
- **Lambda (\( \lambda \)) = Actual air/fuel ratio** / Stoichiometric air/fuel ratio
- **Stoichiometric Combustion** refers to the perfect amount of oxygen needed to combust a volume of natural gas. \( (\lambda = 1.0) \) – Generally achieved with AFR at ~ 17:1
- **Rich Burn Engines** only use enough air in order to burn all of the air/fuel mixture in the cylinder during combustion \( (\lambda < 1.1) \)
- **Lean Burn Engines** operate with an excess amount of oxygen which absorbs heat and reduces the temperature and pressure of combustion \( (\lambda > 1.1) \)
Rich vs. Lean Burn
Rich Burn Emissions Control

- Rich-burn emissions controls are based on a principle of after-treatment.
- A 3-way catalyst is used to reduce emissions via Non-Selective Catalytic Reduction.
NOx Control for Reciprocating Engines

How an NSCR catalyst works?

- Given time NOx will break down to $N_2$ & $O_2$;
- Activation energy refers to the energy required to convert the reactant to products;
- A catalyst speeds up the reaction and lowers the activation energy, but is not used up in the process.

1. $NOx \rightarrow xO_2 + N_2$
2. $CO + \frac{1}{2} O_2 \rightarrow CO_2$
3. $CxHy + O_2 \rightarrow CO_2 + H_2O$
NOx Control for Reciprocating Engines

Sounds pretty easy... right?

Preventative Maintenance
- Catalyst wash every 8000 to 12000 hours
- Gasket Replacement
- Replace oxygen sensors every 6 months
- Inspect catalyst once a year

Operation
- Optimize the engine because the NSCR catalyst requires specific conditions to be effective.
  - 0.25-0.75% Oxygen
  - 750 to 1200°C
NOx Control for Reciprocating Engines

NSCR Air: Fuel Ratio Control Systems

Advanced NSCR

- Fuel Meter
- Upstream Fuel Pressure Sensor
- Safety shut off valve
- Fuel Pressure Regulator
- Altronic Fuel Control Valve
- Venturi Meter
- Throttle

INTAKE

EXHAUST

EXHAUST

INTAKE

- Wide Band Oxygen Sensor
- Temperature Thermocouple
- Pressure Sensors

NSCR Catalytic Converter

- Manifold Air Pressure Sensor
- Manifold Air Temp Sensor

CPM - Ion, LAMBDA, HEGO

Mapping System
Rich vs. Lean Burn

![Diagram showing emissions vs. air/fuel ratio for NOx, CO, and Total HC](image)

Date: January 17, 2014
A common strategy to reducing emissions on reciprocating engines is to “lean it out”.

- This means that we are increasing the amount of air in the cylinder, without increasing the fuel.
- This reduces engine temperature; which is a critical component of NOx formation.
- This yields a lot of changes to the overall control system.
Lean Burn Emissions Reductions

<table>
<thead>
<tr>
<th>NOx Level</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 g/bhp-hr</td>
<td>Reduced Load, Retarded Ignition</td>
</tr>
<tr>
<td>5 g/bhp-hr</td>
<td>Turbocharger Upgrade (“More Air”)</td>
</tr>
<tr>
<td>3 g/bhp-hr</td>
<td>Port Fuel Electronic Fuel Injection (EFI)</td>
</tr>
<tr>
<td>1 g/bhp-hr</td>
<td>Advanced Ignition System</td>
</tr>
<tr>
<td>0.5 g/bhp-hr</td>
<td>Prechamber (PCC)</td>
</tr>
<tr>
<td></td>
<td>$ePCC$ closed loop $ePCC$</td>
</tr>
<tr>
<td></td>
<td>Balancing &amp; Diagnostics</td>
</tr>
<tr>
<td></td>
<td>A/F Control Advanced TER Control</td>
</tr>
</tbody>
</table>
Port Fuel Injection (PFI)

- Fast response speed governing
- Precise control of engine fueling rate throughout start-up and load ranges
- Reduced fuel consumption up to 9% in part load
- Better combustion stability
- Significantly reduced maintenance requirements
- (no carburetor, no governor, no throttle)
- Advanced air-fuel-ratio controller
Pre-Combustion Chambers

➢ Improves the ability to ignite lean mixtures.
➢ Can increase air fuel ratio from 17:1 to 25:1.
➢ Reduces Combustion Temperature
➢ Reduces NOx
➢ Reduces Fuel Gas Usage.
   ✷ 9000 BTU/bhp-hr to 7900 BTU/bhp-hr
Aftermarket OEM PCC Retrofit
BSFC ~7,900

NO\textsubscript{x} vs Trapped Equivalence Ratio
NOx Control for Reciprocating Engines

Classification of Combustion Cycles

- Normal Combustion (Group 1)
- Complete Misfires (Group 2)
- Late Burning Cycles (Group 3)
  - Comb. peak < cold compr. pressure
- Slow Burning Cycles (Group 4)
  - CA of 50% mass fraction burned exceeds 20 deg after TDC
- Fast combustion (Group 5)
  High combustion peak pressure

Date: January 17, 2014
Cylinder Instability - Where we are:

- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
NOx Control for Reciprocating Engines

Cylinder Instability - Where we want to be:

- To achieve this, we need Electronic Fuel Injection, and advanced sensors.
- Real-time Balancing & Engine Diagnostics
Real-time Balancing
Engine Balancing & Diagnostics

- Average peak combustion pressure (PP)
- Average location of peak pressure (LOPP)
- Cold compression pressure (CCP)
- Indicated mean effective pressure (IMEP)*
- Indicated power (IP)*
- Historical combustion integrity
- Percentage of cycles with poor combustion (misfire) detected
- Percentage of cycles where the early combustion or pre-ignition was detected
- Percentage of cycles where the over-pressure threshold was exceeded
- Percentage of cycles where detonation or “knock” was detected*
Developing an emissions management plan is a key first step prior to taking any actions. To be considered are things like:

- Age & life expectancy of existing infrastructure
- Cost of replacement infrastructure
- Cost of integrating new components into the existing system
- Regulatory requirements
- Emissions testing & reporting requirements
- Resources to execute projects & maintain equipment
NOx Control for Reciprocating Engines

Thank you!

Questions?