THE IMPACT OF CHANGING PIPELINE CONDITIONS ON COMPRESSOR EFFICIENCY

BRANDON RIDENS - SOUTHWEST RESEARCH INSTITUTE (SWRI)

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OVERVIEW

• Shale Gas Deposits and Production
• Gas Compositions and Comparison
• Centrifugal Compressor Performance
• Simulations with Varying Gas Compositions
• Performance and Efficiency Impacts
• Reciprocating Compressor and Piping System Impacts
• Pulsation and Vibration Case Study
• Summary
**SHALE GAS DEPOSITS**

- US and Canada largest producers of shale gas
- Predicted 46% of US NG supply will come from shale by 2035
- Hydraulic fracturing and horizontal drilling increasing production

*Not All Shale Gas Is Equal*

*Source: Energy Information Administration*
## Shale Gas Compositions Around the United States

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Well 1</td>
<td>Well 2</td>
<td>Well 3</td>
<td>Well 4</td>
<td>Well 1</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>7.9</td>
<td>1.5</td>
<td>1.1</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>CO2</td>
<td>1.4</td>
<td>0.3</td>
<td>2.3</td>
<td>2.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Methane</td>
<td>80.3</td>
<td>81.2</td>
<td>91.8</td>
<td>93.7</td>
<td>79.4</td>
</tr>
<tr>
<td>Ethane</td>
<td>8.1</td>
<td>11.8</td>
<td>4.4</td>
<td>2.6</td>
<td>16.1</td>
</tr>
<tr>
<td>Propane</td>
<td>2.3</td>
<td>5.2</td>
<td>0.4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Relative Density (SG)</td>
<td>0.66</td>
<td>0.67</td>
<td>0.61</td>
<td>0.60</td>
<td>0.67</td>
</tr>
</tbody>
</table>

SHALE GAS DEPOSITS (TEXAS)

Source: Ed Bowles – Natural Gas Composition in the U.S. and Impact of Shale Gas (2014)
# Shale Gas Compositions at the Same Location

<table>
<thead>
<tr>
<th></th>
<th>Station 1</th>
<th>Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Well 1</td>
<td>Well 2</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.1191</td>
<td>0.1571</td>
</tr>
<tr>
<td>CO2</td>
<td>1.7376</td>
<td>1.726</td>
</tr>
<tr>
<td>Methane</td>
<td>79.9909</td>
<td>78.8998</td>
</tr>
<tr>
<td>Isobutane</td>
<td>1.2568</td>
<td>0.8767</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.7993</td>
<td>1.3513</td>
</tr>
<tr>
<td>i-Pentane</td>
<td>0.3373</td>
<td>0.3575</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.2766</td>
<td>0.278</td>
</tr>
<tr>
<td>Hexanes</td>
<td>0.2341</td>
<td>0.248</td>
</tr>
</tbody>
</table>

|          |          |          |          |          |          |          |          |          |          |
| Relative Density (SG) | 0.72 | 0.72 | 0.71 | 0.69 | 0.65 | 0.76 | 0.76 | 0.75 | 0.75 | 0.67 |

Source: Ed Bowles – Natural Gas Composition in the U.S. and Impact of Shale Gas (2014)
COMPRESSOR PERFORMANCE

- Performance and efficiency are significantly tied to suction and discharge conditions
  - Suction and Discharge pressure/temperature
  - Head
  - Molecular Weight (molar mass)
  - Density and Compressibility
  - Ratio of Specific Heats
- Common conditions to change
  - Suction and Discharge pressure/temperature
  - Head
COMPRESSOR MAPS

Head, H (m)

Flow, Q (m³/h)

Isentropic Head [ft-lbf/lbm]

Actual Flow [cfm]

Compressor Map with Performance Data

- Base Case
- Case 2
- Case 3
- Case 4B
- Case 4
- Case 5
- Case 5B

Theoretical Surge Line

19800 RPM Test
17800 RPM Test
19800 RPM Prediction
17800 RPM Prediction
MEASURED SURGE LINE
• Stoner (Synergi) Pipeline Simulator (SPS)
  • Transient fluid flow simulator of natural gas pipeline networks
  • Types of analyses
    • Control systems
    • Equipment (compressor/pump) performance analysis
    • Pressure-Flow capacity
  • Equations of State (EOS): BWRS, CNGA, AGA-8, and specify unique gas properties
• Model Conditions
  • Gas Composition (SG)
  • Pressure Ratio and Temperature
  • Compressor Speed
  • Gas Flow Rate
  • Compressor map and polytrophic efficiency
  • Gas turbine power, heat rate, and speed
COMPRRESSOR MODEL

- Singular variable speed centrifugal compressor with defined suction and discharge conditions
- No suction/discharge piping or equipment
- Nuovo Pignone Compressor with GE Frame 3 Gas Turbine
- Case Studies:
  - Process and pipeline applications

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Fixed Pressure Ratio</th>
<th>Fixed Compressor Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2</td>
<td>Fixed Pressure Ratio</td>
<td>Fixed Flow Output</td>
</tr>
<tr>
<td>Case 3</td>
<td>Fixed Suction Pressure</td>
<td>Fixed Compressor Speed</td>
</tr>
</tbody>
</table>
FIXED SPEED CASE STUDY

- Set (constant) conditions:
  - Suction and Discharge Pressure
  - Suction Temperature
  - Compressor Speed

<table>
<thead>
<tr>
<th>Suction Pressure (psig)</th>
<th>Discharge Pressure (psig)</th>
<th>Suction Temperature (F)</th>
<th>Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>580.2</td>
<td>855.7</td>
<td>63.8</td>
<td>5200</td>
</tr>
</tbody>
</table>
FIXED SPEED CASE (EFFICIENCY)

- Decrease in efficiency as specific gravity increases
  - SG change of 0.23 ~ 10% change in Efficiency
FIXED SPEED CASE (HEAD & FLOW)

- A decrease in initial Head as SG increases (38%)
- An increase in flow as head decreases (32%)
FIXED SPEED CASE (POWER & FUEL CONSUMPTION)

- Increase of power utilization as SG increases
- Fuel is the same as the process gas

**Rated Compressor Power Utilized versus Specific Gravity**

- Iso Power of 13751 HP

**Fuel Consumption versus Specific Gravity**

- Fuel Flow Rate (SCFM)
VARIABLE SPEED CASE STUDY

- Set (constant) conditions:
  - Suction and Discharge Pressure
  - Suction Temperature
  - Flow Output

<table>
<thead>
<tr>
<th>Suction Pressure (psig)</th>
<th>Discharge Pressure (psig)</th>
<th>Suction Temperature (F)</th>
<th>Flow (MMSCFD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>580.2</td>
<td>855.7</td>
<td>63.8</td>
<td>423.8</td>
</tr>
</tbody>
</table>
VARIABLE SPEED CASE (EFFICIENCY)

• Decrease in efficiency as specific gravity increases
  • SG change of 0.23 ~ 2% change in Efficiency
VARIABLE SPEED CASE (HEAD)

- Decrease in initial Head as specific gravity increases
  - 38% decrease in head with a fixed flow rate
VARIABLE SPEED CASE (POWER & FUEL CONSUMPTION)

- Very little change in power utilized
- Decrease in fuel consumption as SG increases (28%)

**Rated Compressor Power Utilized versus Specific Gravity**

*Iso Power of 13751 HP*

**Fuel Consumption versus Specific Gravity**

![Graphs showing relationship between power utilization and specific gravity, and fuel consumption and specific gravity.](chart)
FIXED SPEED/FLOW CASE STUDY

- Set (constant) conditions:
  - Suction Pressure
  - Suction Temperature
  - Compressor Speed
  - Flow Output

<table>
<thead>
<tr>
<th>Suction Pressure (psig)</th>
<th>Suction Temperature (F)</th>
<th>Flow (MMSCFD)</th>
<th>Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>580.2</td>
<td>63.8</td>
<td>398.4</td>
<td>5200</td>
</tr>
</tbody>
</table>
FIXED SPEED/FLOW CASE (EFFICIENCY)

- Increase in efficiency as specific gravity increases
  - SG change of 0.23 ~ 3% change in Efficiency
FIXED SPEED/FLOW CASE (HEAD)

- Increase in initial head as specific gravity increases
  - 21% increase in head with a fixed speed and flow rate

![Head versus Specific Gravity Graph](chart.png)
FIXED SPEED/FLOW CASE (POWER & FUEL CONSUMPTION)

- Increase of power utilization (38%) and fuel consumption (20%) as SG increases
- Approaching surge conditions
PULSATION AND VIBRATION ISSUES

- Changes in gas compositions can cause harmful resonances from reciprocating compressors
  - Pulsations caused by periodic pulsations (pressure & velocity)
  - High amplitude pulsations (resonance) caused when frequencies of pulsations coincide with acoustic natural frequencies
- Horsepower losses and increases with pressure drop associated with pulsation mitigations (increase fuel consumption)
  - Pulsation bottle
  - Orifices

\[ f = \frac{\text{rpm}}{60} \text{ where } n = 1, 2, 3, \ldots \]
VIBRATION SAFETY & RELIABILITY CONCERNS

- Vibration ➔ Stress ➔ Failure
- Noise ➔ Operation/Environmental Safety Issues

- Cracks and fatigue failures
- Insulation deterioration
- Compressor cylinder vibration and nozzle failures
- Valve failures
- Loosening or breaking of piping clamps
- Foundation damage or failure
- Elevated noise
- Flow measurement inaccuracies
- Overall reduction of compressor performance
PULSATION ANALYSIS CASE STUDY

- Existing reciprocating compressor station operating with new shale gas using initial pulsation mitigations for older gas composition
- Operating with the same conditions (compressor speed)

<table>
<thead>
<tr>
<th></th>
<th>Existing % mol</th>
<th>Future % mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>0.958</td>
<td>1.761</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.347</td>
<td>0.081</td>
</tr>
<tr>
<td>Methane</td>
<td>97.909</td>
<td>77.947</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.494</td>
<td>11.782</td>
</tr>
<tr>
<td>Propane</td>
<td>0.19</td>
<td>4.718</td>
</tr>
<tr>
<td>Iso-Butane</td>
<td>0.036</td>
<td>1.167</td>
</tr>
<tr>
<td>N-Butane</td>
<td>0.042</td>
<td>1.35</td>
</tr>
<tr>
<td>Iso-Pentane</td>
<td>0.01</td>
<td>0.523</td>
</tr>
<tr>
<td>N-Pentane</td>
<td>0.007</td>
<td>0.34</td>
</tr>
<tr>
<td>N-Hexane</td>
<td>0.007</td>
<td>0.248</td>
</tr>
<tr>
<td>N-HEPTANE</td>
<td>0</td>
<td>0.052</td>
</tr>
<tr>
<td>N-OCTANE</td>
<td>0</td>
<td>0.011</td>
</tr>
<tr>
<td>N-NONANE</td>
<td>0</td>
<td>0.001</td>
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<tr>
<td>BENZENE</td>
<td>0</td>
<td>0.002</td>
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<tr>
<td>METHYLBENZENE</td>
<td>0</td>
<td>0.002</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td>16.511</td>
<td>21.288</td>
</tr>
</tbody>
</table>
COMPARISON OF SPEED OF SOUND

Decrease in the SOS of 17 to 21% depending on the operating conditions.
RESPONSE SHIFTING

- All acoustic natural frequency responses shift down
- 6.5 Hz response (Helmholtz or piping length response)
- 17 Hz response (lateral length or other piping response)
- 35 Hz response (cylinder nozzle or piping length response)

- Issues seen in field
  - Floor vibrations
  - Pulsation on Discharge
  - Pulsation on Suction (potential baffle failures)
SUGGESTED MODIFICATIONS

• Option 1
  • Orifice installation in discharge cylinder nozzle
  • Rerouting of discharge piping
  • Implementation of more rigid piping restraints
  • De-coupling of cylinder supports

• Option 2
  • Combined with Option 1
  • Modify internal and external components of the existing pulsation bottles
    • Suction and discharge internal and external choke tubes
    • Suction and discharge baffles

• Option 3
  • Combined with Option 1
  • Fabricate and install new pulsation bottles
SUMMARY

- Notable impact on efficiency and performance
  - Efficiency change upwards of 10%
  - Head change upwards of 40%
  - Power utilized change upwards of 38%
  - Fuel consumption change upwards of 28%
- Possibility of reaching surge under certain conditions
- Pulsation and vibration issues may be experienced causing potential damage, loss of performance, and/or need for modifications
THANK YOU

• Brandon Ridens
  • Brandon.ridens@swri.org
  • 210-522-3459

• Adrian Alvarado
  • Adrian.alvarado@swri.org

• Augusto Garcia Hernandez
  • Augusto.garciahernandez@swri.org

• Eugene (Buddy) Broerman III
  • Eugene.broerman@swri.org