Design and Field Test of a Full Scale Performance Augmentation Network (PAN)
2014 GMRC Research Project

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Glen F. Chatfield & Dale K. Wells, OPTIMUM Pumping Technology
Scott Schubring, Williams
End User Interest and Objectives

- Support advancement of new technology
- Significant commercial benefit from
  - More flow from compressors for given driver size & rating
  - Higher efficiency reduces fuel cost & specific exhaust emissions
  - Reduce no. & size of multiple parallel drivers at a station
- Such advancements may become mandatory in future
  - Recently announced DOE efficiency initiative
  - EPA GHG reduction initiatives
### PAN & Bottle Systems Are Fundamentally Different

<table>
<thead>
<tr>
<th></th>
<th>Bottle Systems</th>
<th>PAN Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsation energy</td>
<td>95% dissipated</td>
<td>95% recovered</td>
</tr>
<tr>
<td>Throw phasing</td>
<td>Individually</td>
<td>all throws Interleaved</td>
</tr>
<tr>
<td>Pressure &amp; HP losses</td>
<td>can be large</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Components</td>
<td>expansion bottles</td>
<td>tuned pipe lengths</td>
</tr>
<tr>
<td></td>
<td>baffles</td>
<td>tuned pipe diameters</td>
</tr>
<tr>
<td></td>
<td>choke tubes</td>
<td>primary Y or W junctions</td>
</tr>
<tr>
<td></td>
<td>orifice plates</td>
<td>secondary Y junctions</td>
</tr>
</tbody>
</table>
Design and Field Test of a Full Scale PAN

Brief PAN Technology Development History

• 1994 engine technology development begins with Univ. of Belfast
• 2006 modeled 1st compressor cylinder
• 2007 GMC paper on 1st PAN compressor model
• 2008 GMC paper on lab air compressor PAN testing
• 2009 GMC paper on TGT Ellisburg station PAN field test
• 2010 El Paso sta. 96 PAN conversion designed; project suspended
• 2011 GMRC project - PAN conversion at El Paso Batesville station
• 2011 GMC paper on efficiency increase with PAN tuning
• 2012 El Paso sale cancelled Batesville host & GMRC project on hold
• 2013 GMRC project - PAN conversion at Williams sta. 85; withdrawn
• 2014 GMRC project – Williams Zick station (this paper!)
Design and Field Test of a Full Scale PAN

Project Objectives

Primary
• Cover operating range from 450-900 suction & 1000-1200 discharge
• Maximize capacity at all conditions at rated power & speed
• Total system (line to line) pressure drop <2.0 psig at all conditions
• Control pulsations to <1.5% of line pressure level at all conditions
• Control mechanical vibrations and stress levels to API 618 M5
• 10% reduction in BHP/MMSCFD at the high flow condition (compared to existing bottle unit)

Secondary
• Validate predictive accuracy of OPT VPS software
• Demonstrate ability to create optimal PAN that simultaneously achieves all objectives
• Achieve performance with unloading limited to HE VVCPs
• Fit factory-built PAN entirely onto the compressor package skid
• Dependable operation over 1300 to 1400 rpm speed range
Compressor Package Specifications

• Caterpillar G3516 gas engine driver
• 1380 BHP @ 1400 rpm
• Ariel JGT/4 4.5” stroke compressor
• (4) 6.75” cylinders with HE VVCP
• Single stage
• Suction pressure 450 to 900 psig
• Discharge pressure 1000 to 1200 psig
• Separate motor-driven cooler
• Single suction scrubber
### Specified PAN System Design Points

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Suction Pressure (psig)</th>
<th>Discharge Pressure (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low suct; Low disch. (low flow)</td>
<td>450</td>
<td>1000</td>
</tr>
<tr>
<td>Low suct; high disch. (high ratio)</td>
<td>450</td>
<td>1200</td>
</tr>
<tr>
<td>Center of operating map (design pt.)</td>
<td>675</td>
<td>1100</td>
</tr>
<tr>
<td>High suct; low disch. (low ratio/high flow)</td>
<td>900</td>
<td>1000</td>
</tr>
<tr>
<td>High suct; high disch.</td>
<td>900</td>
<td>1200</td>
</tr>
</tbody>
</table>
Predicted PAN Performance

Pressure Drop

Total PAN Suction plus Discharge Pressure Loss
GOAL < 2 psi
@ 1300 bhp, 1400 rpm

Limit
Predicted PAN Performance

Suction Pulsation

PAN Suction Pulsation as % of Suction Pressure
Goal < 1.5%
@ 1300 bhp, 1400 rpm
Predicted PAN Performance

Discharge Pulsation

PAN Discharge Pulsation as a % of Discharge Pressure

Goal < 1.5%

@ 1300 bhp, 1400 rpm
Predicted Pressure Drop Reduction
PAN Unit vs. Baseline Bottle Unit
1300 BHP @1400 rpm

<table>
<thead>
<tr>
<th>Unit #8 (PAN) vs. Unit #1 pressure drop reduction</th>
<th>1000</th>
<th>1050</th>
<th>1100</th>
<th>1150</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>92.8%</td>
<td>93.1%</td>
<td>92.9%</td>
<td>96.0%</td>
<td>93.7%</td>
</tr>
<tr>
<td>495</td>
<td>98.3%</td>
<td>90.5%</td>
<td>96.1%</td>
<td>93.1%</td>
<td>96.2%</td>
</tr>
<tr>
<td>540</td>
<td>91.6%</td>
<td>92.9%</td>
<td>92.6%</td>
<td>88.4%</td>
<td>93.1%</td>
</tr>
<tr>
<td>585</td>
<td>90.9%</td>
<td>91.2%</td>
<td>88.8%</td>
<td>92.4%</td>
<td>88.8%</td>
</tr>
<tr>
<td>630</td>
<td>93.6%</td>
<td>91.8%</td>
<td>87.6%</td>
<td>89.6%</td>
<td>91.7%</td>
</tr>
<tr>
<td>675</td>
<td>89.4%</td>
<td>93.7%</td>
<td>90.5%</td>
<td>89.6%</td>
<td>91.7%</td>
</tr>
<tr>
<td>720</td>
<td>88.8%</td>
<td>86.3%</td>
<td>91.5%</td>
<td>89.6%</td>
<td>91.7%</td>
</tr>
<tr>
<td>765</td>
<td>90.6%</td>
<td>91.6%</td>
<td>91.1%</td>
<td>89.6%</td>
<td>91.7%</td>
</tr>
<tr>
<td>810</td>
<td>92.7%</td>
<td>93.3%</td>
<td>91.8%</td>
<td>90.8%</td>
<td>91.7%</td>
</tr>
<tr>
<td>855</td>
<td>92.8%</td>
<td>93.0%</td>
<td>89.3%</td>
<td>92.0%</td>
<td>91.7%</td>
</tr>
<tr>
<td>900</td>
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<td>92.5%</td>
<td>85.2%</td>
<td>90.6%</td>
<td>88.0%</td>
</tr>
</tbody>
</table>

Table Average – 91.5%
# Predicted Flow Increase (MMSCFD)

## PAN Unit vs. Baseline Bottle Unit

1300 BHP @1400 rpm

<table>
<thead>
<tr>
<th>Unit #8 (PAN) vs. Unit #1 flow improvement (MMSCFD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>450</td>
</tr>
<tr>
<td>495</td>
</tr>
<tr>
<td>540</td>
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<tr>
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<tr>
<td>810</td>
</tr>
<tr>
<td>855</td>
</tr>
<tr>
<td>900</td>
</tr>
</tbody>
</table>

Table Average – 8.0
Predicted Flow Increase (MMSCFD)
PAN Unit vs. Baseline Bottle Unit

Incremental Unit #8 Flow in MMSCFD
@ 1300 bhp, 1400 rpm
### Predicted % Improvement in BHP/MMSCFD

**PAN Unit vs. Baseline Bottle Unit**

1300 BHP @1400 rpm

<table>
<thead>
<tr>
<th></th>
<th>1000</th>
<th>1050</th>
<th>1100</th>
<th>1150</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit #8 (PAN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>5.7%</td>
<td>4.5%</td>
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<td>3.3%</td>
<td>2.5%</td>
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<td>495</td>
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<td>4.8%</td>
<td>3.8%</td>
<td>3.0%</td>
</tr>
<tr>
<td>540</td>
<td>8.0%</td>
<td>6.6%</td>
<td>5.5%</td>
<td>4.4%</td>
<td>4.9%</td>
</tr>
<tr>
<td>585</td>
<td>9.9%</td>
<td>8.1%</td>
<td>6.9%</td>
<td>5.5%</td>
<td>14.4%</td>
</tr>
<tr>
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<td>10.9%</td>
<td>9.6%</td>
<td>7.9%</td>
<td>16.4%</td>
<td>23.7%</td>
</tr>
<tr>
<td>675</td>
<td>13.3%</td>
<td>11.4%</td>
<td>9.3%</td>
<td>16.4%</td>
<td>23.7%</td>
</tr>
<tr>
<td>720</td>
<td>15.8%</td>
<td>13.8%</td>
<td>11.0%</td>
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<td>765</td>
<td>18.5%</td>
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<td>810</td>
<td>21.5%</td>
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</tr>
<tr>
<td>855</td>
<td>25.5%</td>
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<td>18.6%</td>
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</tr>
<tr>
<td>900</td>
<td>30.5%</td>
<td>25.3%</td>
<td>21.5%</td>
<td>18.8%</td>
<td>15.4%</td>
</tr>
</tbody>
</table>

Table Average – 13.5%
Predicted % Improvement in BHP/MMSCFD
PAN Unit vs. Baseline Bottle Unit

Improved Unit #8 Efficiency - Reduced bhp/MMSCFD
@ 1300 bhp, 1400 rpm

Goal
@ 1000 PD
Existing Bottle Unit

- G3516 gas engine
- JGT/4 compressor
- 6.0” cylinders
- Engine driven cooler
- 1300 BHP @ 1400 rpm
PAN Mechanical Design
3-D CAD Model

• PAN includes (6) TST-collectors
• 12”, 8” & 6” standard pipe & elbows
• 1440 psig MAWP design rating

• PAN entirely on skid
• Robust supports and attachments
• Off-mounted scrubber (best practice)
• Maintenance access considered
PAN Mechanical Design
3-D CAD Model

Suction PAN designed for 45° Phase Delay

Discharge PAN designed for 135° Phase Delay
PAN Mechanical Design
Completed Package
PAN Mechanical Design
Completed Package
PAN Mechanical Design
TST-Collectors

- (4) 8x6x6 Y-collectors
- (2) 12x8x8 Y-collectors
- ASTM A395 Cast DI
- 1500 psig MAWP
- Serialized Items
PAN Mechanical Analysis
FEA Model

Rear
Front
Frame
Dynamic Loads

- Compressor reciprocating and rotating inertia
- Cylinder gas force (stretch force)
- Crosshead guide force
- Pressure pulsations
Design and Field Test of a Full Scale PAN

PAN Mechanical Analysis
Pulsation Model

Suction

Discharge
PAN Mechanical Analysis
Maximum Shaking Forces - Suction

Resonance at 4x Compressor Speed

Guideline
PAN Mechanical Analysis
Maximum Shaking Forces - Discharge

Resonance 4x Compressor Speed

Guideline
PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Result at 81 Hz

Maximum vibration
= 4.2 ips peak
PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Result at 81 Hz – Cyl. 1 & 3 Side View

Maximum vibration
= 4.2 ips peak
PAN Modal Analysis & Mechanical Forces Response Analysis
Dynamic Stress at 81 Hz

Maximum dynamic stress = 3,460 psi peak

Stress per mil = 422.02 psi/mil (SEQV)
Allowable Deflection = 7 mil peak-to-peak
Allowable Velocity (MNF=81.01 Hz) = 1.81 in/s peak (32 mn/s rms)
(Assumes 3000 psi peak-to-peak maximum stress)
Load Case # 36 (81.01 Hz)
Max Disp. (inch peak) = .00829
Max Vel. (inch/sec peak) = 4.221
208471 r58, ACI, Williams, Zick, Skid, 1170-1540 rpm
Preliminary Results

• Vibration = 4.1 ips peak at 81 Hz
  o Guideline is 1 ips peak
• Dynamic stress = 3,460 psi peak at 81 Hz
  o Guideline is 1,500 psi peak
• Assumptions
  o 81 Hz resonance occurs (81 Hz at 4x = 1215 rpm). Normal operating speed is 1300-1400 rpm.
  o Damping ratio is 1%. Typical damping ratio for this mode is 2% to 4%.
• Vibration and dynamic stress will be lower at normal operating speed and higher damping
Design and Field Test of a Full Scale PAN

PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Summary for Condition 4 Assuming 2% Damping

![Graph showing vibration summary for PAN
Condition 4 with 2% damping. The graph includes data points
for Cylinder, Pipe/Vessel, Compressor Frame, and Structure.
The speed ranges are 1170-1250 rpm and 1300-1400 rpm.]

Vibration (% Guideline) vs. Frequency (Hz)
PAN Modal Analysis & Mechanical Forces Response Analysis
Dynamic Stress Summary for Condition 4 Assuming 2% Damping

- Speed Range 1170-1250 rpm
- Speed Range 1300-1400 rpm
Recently scrubber inlet piping design was finalized. Potential scrubber resonance.

Proposed Solution: Skirt Cut-out
PAN Modal Analysis & Mechanical Forces Response Analysis
Mechanical Recommendations

• Design & assembly care to avoid pipe strain
• Small bore piping natural frequency testing
• Shop bump testing to verify model MNF predictions
• Shop bump testing to verify damping ratio assumptions
• Field bump testing to verify MNF placement & response
• Running test to verify acceptable vibration limits at first start-up
• Inspect pipe clamps, flange studs & other critical fasteners at regular intervals to ensure there is no vibratory loosening.
Field Performance Testing

• Steady state tests at 5 specified points – 1300 BHP @ 1400 rpm
• Data also recorded during speed and pressure transient sweeps
• Multiple pressure points on both PAN & existing bottle unit
• Both units will be tested simultaneously at each operating point
• Enthalpy rise measured between system suction & discharge
• AGA flow meters on each unit suction
• Laboratory grade instrumentation and (3) data acquisition systems
• All cylinder ends indicated with (3) Windrock analyzers
• Valve losses indicated
• Crosshead ODC measured for accurate phasing
• Engine & panel data recorded for reference only
• Pulsations measured throughout both systems (full port valves)
• All recording systems time synched
• Gas sample at each suction each day
• Downstream gas chromatograph log obtained for each day
Field Performance Testing
PAN System Test Points

LEFT SIDE

45 PRESSURE TAPS TOTAL FOR UNIT 8

RIGHT SIDE
Field Performance Testing
Bottle System Test Points

LEFT SIDE
46 PRESSURE TAPS TOTAL FOR UNIT 1

RIGHT SIDE
Field Performance Testing

- Test team of 13-14 people with detailed protocol established.
- Calculation methods pre-established.
- VMG and NIST gas data.
- Data adjusted for differences in cylinders (based on predictions).
- Comparison of measured and predicted results for both units.
- Unfortunately, construction delays prevented test data for paper.
- Mechanical testing this week.
- Performance testing late October awaiting higher gas flows to reach high end of suction pressure required for test points.
Conclusions

• Simulations confirm optimized PAN can cover large range of operating conditions (to be verified by field test).
• Higher PAN efficiency mandated choice of larger cylinders to load unit and maximize flow (conflicting end user requirement that complicates the pure research comparison with bottle unit).
• Predicted system pressure drop less than 1.0 psig over most of operating range.
• Predicted pulsation less than 0.3% of line pressure at all conditions.
• -30.5% BHP/MMSCFD predicted improvement at high flow point.
• Control of pulsation induced forces within the PAN is challenging.
• PAN structural design to avoid MNFs is challenging, but doable.
• Fixed speed applications much easier to design.
• More to follow in report and paper after field tests are complete.

Testing currently planned for wk. of Oct. 27
Thanks for your attention.

Questions???