Cogeneration Performance Project
October 23, 2014

UTSR Fellow: Xan Cranney, Brigham Young University
Industrial Mentor: Jeff Armstrong, FlexEnergy

10/28/2014
Agenda

1. Who is FlexEnergy?

2. UTSR Fellowship Project: Cogeneration
Agenda

1. Who is FlexEnergy?

2. UTSR Fellowship Project: Cogeneration
OVERVIEW

- FlexEnergy produces 250 and 333 kW gas-fired turbines (over 3 million operating hours)
- Developed by Ingersoll Rand as a derivative of the Dresser-Rand KG2 (oilfield focused machine)
- Flex offers the only “micro” turbine built like larger, more robust turbine generators
- Flex turbines use synchronous generators, not high speed alternators, providing significantly more kVA & transient load capability than power electronics micro-turbines
Key Product Attributes...

- High availability in multiple applications
- Low annual maintenance time
- Ease of deployment
- Co & tri generation capabilities
- Utility power independence
- Compliance with emissions legislation

- Increased productivity – CHP generation
- Lower operating costs
- Environmentally Friendly
FLEXENERGY TURBINE CYCLE DIAGRAM

- 400/480 Volts
- 50/60 Hz
- 3 Phase

- 1500/1800 rpm
- 256°C/493°F Typical
- Up to 913°C/1675°F
- 45400 rpm
FLEX TURBINE™ MT250 & MT333

Rugged Turbine Engine
Back-to-back rotating components and proven oil-lubricated bearings with all bearings at cold end

Synchronous Generator
Same technology used by utilities delivering high starting kVA and clean three phase power

Durable Rolling Element Bearings
Same low maintenance, high reliability technology used for high performance engine and turbine systems

Patented Combustor
Dry low NOx easily meets and exceeds the most stringent regulations

Patented Recuperator
Critical to high efficiency and considered best-in-class

Planetary Gearbox
Rugged reduction gearbox with soft coupling drives generator at synchronous speed
FLEX TURBINE™ MT333

A 333kW gas turbine engine-driven power system

Key Features
- Uprated core engine derived from MT250
- High load starting capability up to 125 HP DOL

Inlet Guide Vanes
- Increases efficiency at part-load conditions
- Ideal for off-grid load and fuel following

- Integrated Controls
- Heat Recovery
- Recuperator
- Combustor
- Turbine Engine
- Synchronous Generator
- Inlet Guide Vanes

IGVs
- Actuator
What constitutes “Oil & Gas Ready”?

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Generation Technology</th>
<th>Speed reduction gearbox?</th>
<th>Bearings</th>
<th>Load management independent of battery?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolls Royce</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>GE</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>Seimens</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>Solar</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>Dresser Rand</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>Flex</td>
<td>SYNCHRONOUS</td>
<td>YES</td>
<td>OIL LUBRICATED</td>
<td>YES</td>
</tr>
<tr>
<td>Other Micros</td>
<td>HIGH SPEED ALTERNATOR</td>
<td>NO</td>
<td>AIR</td>
<td>NO</td>
</tr>
</tbody>
</table>

FlexEnergy is the ONLY ‘micro’ turbine generator that shares the same technology as larger gas turbine generators.
Turbine Electrical Performance

Note: Does not include fuel gas booster parasitic
Deduct 3.5% per 1000 ft (305 m)
COMBUSTOR OPTIONS BRING FUEL FLEXIBILITY

Fuel Lower Heating Value (Btu/ft³); dry basis at 14.7 psi (101 kPa) and 59F (15C)

H₂S Tolerance of up to 6,500 ppmv / CO₂ Content up to 70%

Requires N.G. to start

Associated gas with “Heavies”

Associated gas with Diluents

Digester Gases

Landfill Gases

Gaseous Fuels
1. Who is FlexEnergy?

2. UTSR Fellowship Project: Cogeneration
Motivation for Project

• New MT333 has higher mass flow:
  – Decrease DP of cogeneration heat exchanger
  – Maintain HX within turbine enclosure

• CHP Efficiency Incentives aggressive:
  – Public Utility Regulatory Policies Act (PURPA):
    • Requires 42.5% LHV combined efficiency with only ½ of
cogenerated heat
  – California SGIP:
    • Requires 60% HHV combined efficiency (~66% LHV)
  – Massachusetts’ CHP Program initiative:
    • Requires 60% HHV combined efficiency (~66% LHV)
    • Requires 75% LHV combined efficiency
Project Approach

- Calibrate model of existing cogen HX
- Identify Improved design
Project Overview

- Engineering Equation Solver (EES) heat exchanger model.

- Computational Fluid Dynamics
NTU-ε Model

\[
NTU = \frac{UA}{C_{\text{min}}}
\]

\[
C_{\text{min}} = \dot{m} \times C_p
\]

\[
UA = \frac{1}{R_{eq}}
\]

Thermal circuit, \( R_{\text{unit}} \)

\[
R_{eq} = \frac{R_{\text{unit}}}{N_{\text{fins}} \times N_{\text{tubes}} \times N_{\text{rows}}}
\]
Improving the Thermal Circuit - Candidates

- Flat plate correlation
- Single tube correlation
- Circuit in parallel with itself
Modified Thermal Circuit

- Tube correlation changed to Chilton-Colburn analogy of finned banks of tubes.
- No suitable replacements were found for flat plate correlation.
Modeling the Leak

- Model continued to over-predict empirical data by 4%, on average.
- To compensate, air leaking past the heat exchanger was modeled using the correlation:

\[ m_{\text{leak}} = A_{\text{effective}} \times \sqrt{\Delta P / P_{\text{amb}}}/1.991 \]

- \( A_{\text{effective}} \) was chosen such that the models predictions were reduced by 4%, to more closely match the empirical data.
Empirical and Modeled Values

\[ \dot{Q} = \dot{m} \times C_p \times \Delta T_{\text{water}} \]
ΔT_{water} \rightarrow ΔT_{air}

Predicted $Q$ (Btu/hr) vs Measured $Q$ (Btu/hr)

- Perfect Correlation
- + or - 10%

10/28/2014
Energy Balance – A New Approach

\[ \dot{Q} = \dot{m} \cdot C_p \cdot \Delta T_{water} \, , \quad \dot{Q} = -\dot{m} \cdot C_p \cdot \Delta T_{air} \, , \quad \dot{Q} = \frac{T_{air} - T_{water}}{R_{row}} \]

\[ R_{row} = \frac{R_{unit}}{N_{fins} \cdot N_{tubes}} \]

6 row, 2 pass
Empirical and Modeled Values

Predicted $Q^\prime$ (Btu/hr)

Measured $Q$ (Btu/hr)

Perfect Correlation

+ or - 10%
Project Overview

- Engineering Equation Solver (EES) heat exchanger model.

- Computational Fluid Dynamics
CFD Modeling

- Realizable k-Epsilon
- Mass flow Inlet
- Pressure Outlet
- HX — Porous, Laminar Zone
- HX — Negative Heat “Source”
- Color/arrow length depicts velocity
- Over 50 Geometries tested
Pressure Drop (ΔP) Calculations

- ΔP data is proprietary
- All ΔP data in this report are relative. They are based off of the current cogen configuration
- ΔP refers to total pressure
- ΔP refers to ΔP across the entire geometry, excluding the HX.

\[ \Delta P_{\text{relative}} = \frac{\Delta P}{\Delta P_{\text{current}}} \times 100 \]
Grid Independence Study

- CFD models are not grid independent.
- This table refers to percentage change of values resulting from doubling the previous density.

<table>
<thead>
<tr>
<th></th>
<th>2x</th>
<th>4x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet ΔP</td>
<td>-45%</td>
<td>29%</td>
</tr>
<tr>
<td>Outlet ΔP</td>
<td>32%</td>
<td>50%</td>
</tr>
<tr>
<td>Total non-HX ΔP</td>
<td>-5%</td>
<td>42%</td>
</tr>
</tbody>
</table>

- Most models in this report are “4x” grid density.

10/28/2014
• The back/front pivot designs were rejected for two reasons:
  1. High damper door torque
  2. Undesired heat transfer when in “closed” position.
New Considerations

- At this point in the design stage, it was determined that a deeper HX would be required.
- Decided to quantify the independent effect of a flow-tripping “lip”.

Center Pivot with thick HX, $\Delta P = 52$

Added lip, $\Delta P = 91$
Final Design

Other designs had better $\Delta P$. However, this geometry was superior because of other considerations:

- Small damper torque
- Fits desired size of HX
- Damper closes completely
- Accommodates the geometric constraints of the remainder of the MT333.

Final Design, $\Delta P = 95$
Conclusion

As a result of the UTSR fellowship, a number of objectives were achieved:

- The HX model was refined and calibrated
- $\Delta P$ was predicted for various geometries
- A final HX size was selected
- A final cogen geometry was designed
Acknowledgements

- FlexEnergy, Inc.
- UTSR Fellowship Program
- Special Thanks to
  - Jeffrey Armstrong, Chris Bolin, John Alday, Nikolai Kozulin, Corey Bergeron, Mike Carney, Tom Hackett, Bob Megee, Brian Finstad, and Greg Arbo, all of FlexEnergy.
  - Dr. Steven Gorrell, Brigham Young University
Questions?

- If I don’t know the answer, then I reserve the right to pretend that it’s proprietary information.