M&V of Hot Water
Boiler Plant

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Learning Objectives

1. Case study examples of procedures and obstacles in measuring and verifying equipment efficiencies
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Project Description

• High-rise residential boiler plant retrofit projects
  ○ Existing non-condensing boilers replaced with condensing boilers
    - Performance monitoring system included within projects work scope
      » Data acquisition system integrated with BMS system
      » Metered data uploaded to EMIS for energy calculations, display and trendlogging
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Typical Project Boiler Plant Configuration
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Measurement Process

- Metering sensors
  - A natural gas mass-flow-meter installed at the gas pipe header serving all boilers
  - A supply water temperature sensor at the common supply header served by all boilers
  - Return water temperature sensors and flow sensors for the common boiler high-return, common low-return, and common domestic hot water return.
  - Boiler units start/stop signal, boiler isolation valve positions, circulation pumps start/stop signals and power consumptions.
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Initial Data Analysis

Table 1. December 2010 Monthly Average Measured Efficiency

<table>
<thead>
<tr>
<th>Building #1</th>
<th>Building #2</th>
<th>Building #3</th>
<th>Building #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>65%</td>
<td>68%</td>
<td>79%</td>
<td>85%</td>
</tr>
</tbody>
</table>

Table 2. Manufacturer Published Efficiencies

<table>
<thead>
<tr>
<th>Firing Rate %</th>
<th>Return Water Temperature F°C (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68 (20)</td>
</tr>
<tr>
<td>20</td>
<td>99</td>
</tr>
<tr>
<td>50</td>
<td>99</td>
</tr>
<tr>
<td>75</td>
<td>98</td>
</tr>
<tr>
<td>100</td>
<td>97.2</td>
</tr>
</tbody>
</table>

85%
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So where is the problem??
What are we measuring?

- Boiler units are rated and tested primarily for combustion efficiencies.
- We are measuring thermal efficiency
- The combustion efficiencies do not account for the effectiveness of the boiler unit heat exchanger as well as radiation and convection losses.
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Operational problems?

Boilers short cycling
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Purge Losses

\[
\text{Max Purge Heat Loss (Btu)} = \text{Air Specific Heat Capacity} \left(\frac{\text{Btu}}{\text{lb} \cdot \text{°F}}\right) \times \left(\text{Stack Temp (°F)} - \text{Ave OAT (°F)}\right) \\
\times 100\% \times \text{Air Flow Rate} \left(\frac{\text{ft}^3}{\text{min}}\right) \times \text{Air Density} \left(\frac{\text{lb}}{\text{ft}^3}\right) \times \frac{15 \text{ (sec)}}{60 \text{ (sec)}}
\]

- 3500 purges in December
- Average purge loss 840BTU.
- Purge losses only 0.6% of the total gas energy for December
Heat Transfer Modeling Accuracy

- Approximation in modeling energy balance and heat losses under boiler operating condition.

- The exact energy model formula describing boiler performance using physical operating parameters does not exist.
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Boiler Plant Efficiency Calculations

Load based instantaneous value

\[
\eta_{th} = \frac{\text{Boiler Load} \left( \frac{\text{Btu}}{\text{h}} \right)}{\text{Gas Flow} \times \text{Gas Constant} \left( \frac{\text{Btu}}{\text{scf}} \right)}
\]

• Only accurate under perfectly steady condition

Energy based average value

\[
\eta_{th} = \frac{\sum_{i=0}^{n} \text{Boiler Output Energy} \left( \text{Btu} \right)}{\sum_{i=0}^{n} \text{Gas Input Energy} \left( \text{Btu} \right)}
\]

• Proper method of calculating thermal efficiency
Boiler Plant Efficiency Calculations

Energy based average value

\[
\text{Boiler Output Energy Flux (Btu)} = \frac{\text{Boiler Load}_n \left(\frac{\text{Btu}}{\text{h}}\right) + \text{Boiler Load}_{n-1} \left(\frac{\text{Btu}}{\text{h}}\right)}{2} \times \frac{(\text{Time}_n - \text{Time}_{n-1})}{60}
\]

\[
\text{Boiler Output Thermal Mass Energy (Btu)} = (\text{System Temp}_n \, (^{\circ}\text{F}) - \text{System Temp}_{n-1} \, (^{\circ}\text{F})) \times \text{System Heat Cap} \, (\text{Btu/}^{\circ}\text{F})
\]

\[
\text{Gas Input Energy (Btu)} = \frac{\text{Gas Flow}_n \, (\text{scfh}) + \text{Gas Flow}_{n-1} \, (\text{scfh})}{2} \times \frac{(\text{Time}_n - \text{Time}_{n-1})}{60} \times \text{Gas Constant} \left(\frac{\text{Btu}}{\text{scf}}\right)
\]
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Gas Input Energy
Output Flux Energy
Thermal Mass Energy

Gas Input Energy
Total Boiler Output Energy
Metering Accuracy

- The accuracy of metered data is dependant on the sensors physical characteristics, sources of error and field calibration methods.
- Physical sensors bring in fixed errors for the sensor part and associated transducer instruments or transmitters.
- Fixed and random errors are introduced by data acquisition systems infrastructure, missing and duplicated data samples, etc.
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Verification Phase

- Boiler Combustion Efficiency Test

<table>
<thead>
<tr>
<th>Average Measured Combustion Efficiency</th>
<th>Manufacturer Published Efficiency at Same Average Conditions</th>
<th>Calculated Thermal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.1%</td>
<td>87.7%</td>
<td>64.3%</td>
</tr>
</tbody>
</table>

Table 3. 4 hour Combustion Efficiency Test Results
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Sensors Calibration Tests

- Difference of 1 °F in the supply water temperature sensor will result in a change in thermal efficiency measurement of over 5%.
- No sensors drifting confirmed

<table>
<thead>
<tr>
<th></th>
<th>Dec-10</th>
<th>Jan-11</th>
<th>Feb-11</th>
<th>Mar-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common High Return vs. Boiler 1 High Return</td>
<td>Average Difference</td>
<td>-4.19</td>
<td>-4.13</td>
<td>-4.14</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.35</td>
<td>0.81</td>
<td>0.39</td>
</tr>
<tr>
<td>Common Low Return vs. Boiler 1 Low Return</td>
<td>Average Difference</td>
<td>-9.30</td>
<td>-9.16</td>
<td>-9.32</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.43</td>
<td>0.47</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 4 Temperature Comparison of Sensors over 4 Months
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Temperature Calibration Tests

Boiler plant supply temperature measured with 3 different temperature sensors

<table>
<thead>
<tr>
<th></th>
<th>Supply Temperature</th>
<th>High-Return Temperature</th>
<th>Low-Return Temperature</th>
<th>Domestic Hot Water Return Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average BAS Temperature During Test (°F)</td>
<td>172.7</td>
<td>129.5</td>
<td>136.9</td>
<td>152.1</td>
</tr>
<tr>
<td>Taylor Sensor vs. Boiler Plant Sensor (°F)</td>
<td>-7.4</td>
<td>-1</td>
<td>-3.2</td>
<td>-4</td>
</tr>
<tr>
<td>Fluke Sensor vs. Boiler Plant Sensor (°F)</td>
<td>-3.9</td>
<td>1.3</td>
<td>-2.6</td>
<td>-3.8</td>
</tr>
</tbody>
</table>
Temperature Calibration Tests

- Kettle of boiling water test (212°F)

<table>
<thead>
<tr>
<th></th>
<th>Supply Temperature</th>
<th>High-Return Temperature</th>
<th>Low-Return Temperature</th>
<th>Domestic Hot Water Return Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature at Boiling, 212°F (°F)</td>
<td>216.5</td>
<td>218.3</td>
<td>217.8</td>
<td>219.4</td>
</tr>
<tr>
<td>Sensor Offset Adjustment (°F)</td>
<td>-4.5</td>
<td>-6.3</td>
<td>-5.8</td>
<td>-7.4</td>
</tr>
</tbody>
</table>

Table 5. Summary of Temperature Sensors
Boiling Hot Water Test
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Flow Calibration Tests

• Difference between pump curve estimated flows and BMS reported flow from turbine flow meter

<table>
<thead>
<tr>
<th>Unadjusted December 2010 Efficiency</th>
<th>Flow Adjustment 1 Efficiency</th>
<th>Flow Adjustment 2 Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>68%</td>
<td>83%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Flow Adjustment 1  Flow Adjustment 2
Linear Equation   Quadratic Equation
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Performance Baselining

• Mathematical expressions that characterizes the boiler efficiency based on key operation variables (RWT, SWT, Part Load, Water Flow, Boiler Cycling, etc).

1-Hour Average Efficiency versus Return Water Temperature

1-Hour Unadjusted Efficiencies and Baseline Predicted Efficiencies
Selecting Metering Sensors Adjustments

- Suggested criteria for sensors adjustments
  - Average efficiency shall be comparable to manufacturer’s published data for properly commissioned systems
  - Error of regression calculated efficiency shall decrease with adjustments
  - Number of short term efficiencies calculated beyond 100% shall decrease with adjustment
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### Selecting Metering Sensors Adjustments

<table>
<thead>
<tr>
<th></th>
<th>Unadjusted Data</th>
<th>Overall Adj 1</th>
<th>Overall Adj 2</th>
<th>Overall Adj 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Temperature Only</td>
<td>Flow Adj 2</td>
<td>Flow Adj 1 + Boiling Hot Water Voltage Offset</td>
</tr>
<tr>
<td>Dec 2010 Ave Thermal Efficiency (%)</td>
<td>68.3</td>
<td>87.7</td>
<td>87.5</td>
<td>86.5</td>
</tr>
<tr>
<td>Dec 2010 Ave Prediction Absolute Value Error (%)</td>
<td>2.5%</td>
<td>3.0%</td>
<td>2.4%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Dec 2010 Std Deviation of Absolute Value Error (%)</td>
<td>2.4%</td>
<td>2.8%</td>
<td>2.3%</td>
<td>2.1%</td>
</tr>
<tr>
<td># of Efficiencies over 100%</td>
<td>0</td>
<td>203</td>
<td>23</td>
<td>3</td>
</tr>
</tbody>
</table>

Final Overall Adjustment Selection for Building #2
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Refining the Baseline and Predicting Performance

Dec 2010 – Feb 2011 Baseline Prediction Scatter Plot

Surface Plot of 2-Variable Baseline Efficiency Equation
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Baseline and Predictions

Sample of 1 Hour Adjusted Efficiencies and 2-Variable Baseline Efficiencies

Sample of 1 Hour Adjusted Efficiencies and 4-Variable Baseline Efficiencies
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Baseline and Predictions

<table>
<thead>
<tr>
<th>Mar-May 2011 Ave Prediction Error</th>
<th>2 Variable Regression, PLR, RWT - Dec to Feb Baseline</th>
<th>4 Variable Regression, PLR, RWT, SWT, Ave Flow - Dec to Feb Baseline</th>
<th>2 Variable Regression, PLR, RWT - Mar to May Prediction</th>
<th>4 Variable Regression, PLR, RWT, SWT, Ave Flow - Mar to May Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.6%</td>
<td>-1.3%</td>
<td>2.3%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Mar-May 2011 Standard Deviation of Error</td>
<td>9.9%</td>
<td>9.6%</td>
<td>9.1%</td>
<td>8.4%</td>
</tr>
</tbody>
</table>

Table 6. Error Summary of Baseline and Prediction for 2 and 4 Variable Efficiency Models
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Baseline and Predictions

Predicted Gas Consumption versus Measured Gas Consumption
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Sample of Performance Monitoring Dashboard
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Sample of Performance Monitoring Dashboard
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Sample of Performance Monitoring Dashboard
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