Measurement and Verification of Hot Water Boiler Plant Thermal Efficiency in Real Operating Conditions

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Synopsis

This paper describes issues with continuous measurement and verification of the thermal efficiency of hot water boiler plants, in situ. Existing boiler rating systems use steady state laboratory conditions and do not properly relate to boiler efficiency under operating conditions. Currently, precise thermal efficiency ratings are typically not performed under field conditions because of the inability to control the required parameters that define efficiency and the high cost of performing such an analysis (ASHRAE 2008, 31.5). The paper presents methodologies for calculating boiler efficiencies, for calibrating metering sensors and for baselining boiler performance.

About the Authors

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Introduction

This paper describes the issues and challenges related to measuring and verifying boiler plant thermal efficiencies in real operating conditions. Boiler plant performance monitoring systems were implemented as part of a series of boiler plants retrofit projects for high-rise residential towers in Greater Vancouver, BC. The retrofit projects consisted of the replacement of the existing hot water boilers and domestic gas water heaters with high efficiency condensing boilers.

There is currently no standardized methodology for accurately measuring boiler plant thermal efficiency under actual operating conditions. The industry has recognized this problem and ASHRAE is attempting to establish a standard and guideline. Gas boiler combustion efficiencies tests are performed under fixed supply and return water temperature differences and steady state conditions in accordance with ANSI Z21.13. Efficiencies published under this procedure are generally not achieved in actual conditions.[1] This paper presents a possible process for commissioning and calibrating a system for monitoring and tracking boiler thermal efficiency under operating conditions. A key component of the system is a regression-based performance baseline of efficiency that validates fluctuations in efficiency that occur during normal boiler operation.

Measurement Phase

Boiler Plant and Monitoring Systems Description

A typical configuration of the new condensing boiler plants are installed as per arrangement shown in **Figure 1**.

The performance monitoring system includes permanent metering sensors, a data acquisition system (DAS) and an Energy Management Information System (EMIS). The projects metering sensors which are logged to calculate thermal efficiency include:

- 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.

The DAS collects and temporarily stores metered data from the building automation system (BAS) via Bacnet communication with a frequency of one minute for every sensor. The data is uploaded daily to the off-site database and energy application server. The EMIS application was used to calculate gas consumption, heating water and domestic hot water loads, and plant efficiencies, and to display key sensor trend logs.

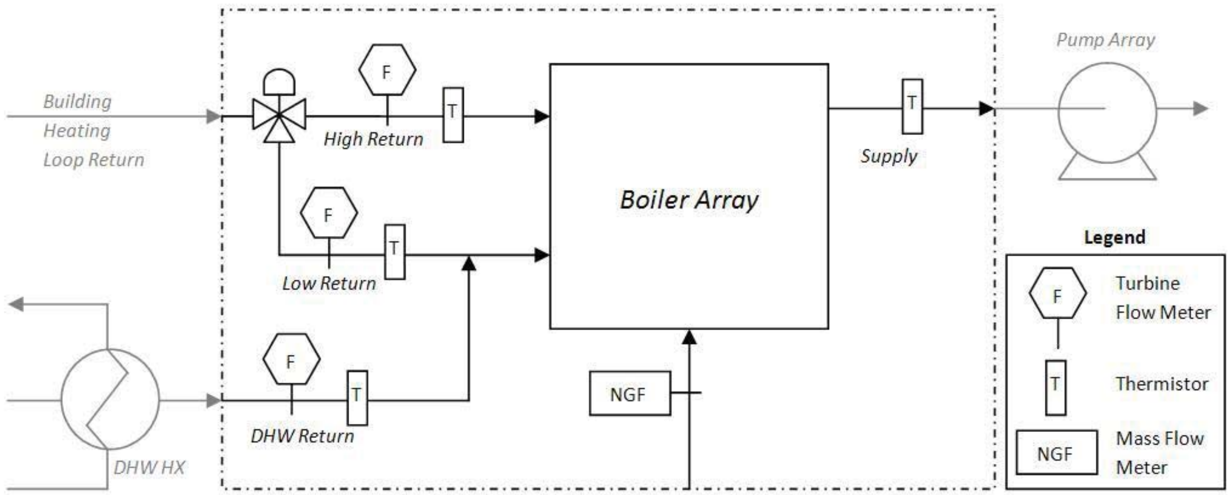

Figure 1. Typical Project Boiler Plant Configuration

Boiler Plant Efficiency Calculations

Thermal efficiency is typically calculated as a load-based instantaneous value,

$$\eta_{th} = \frac{\text{Boiler Load}\ (\frac{\text{Btu}}{\text{h}})}{\text{Gas Flow (scfh)} \times \text{Gas Constant}\ (\frac{\text{Btu}}{\text{scf}})} \quad \textbf{EQ1}$$

$$\text{Boiler Load}\ \left(\frac{\text{Btu}}{\text{h}}\right) = 500 \times \text{Hot Water Flow (gpm)} \times (\text{SWT} - \text{RWT})\ (°\text{F}) \quad \textbf{EQ2}$$

where,

Gas Constant = ~ 1025 – 1050;
SWT = boiler supply water temperature;
RWT = boiler return water temperature;

This method of calculating efficiency is **only accurate under perfectly steady conditions**. In reality, the boiler load and operating conditions are continuously varying, and due to delays between gas flow and heat output, thermal mass effects, and sensor inaccuracies, the efficiency calculated in **EQ1** can result in highly inaccurate results. The proper method of calculating thermal efficiency involves energy-based average value,

$$\eta_{th} = \frac{\sum_{i=0}^{n} \text{Boiler Output Energy (Btu)}}{\sum_{i=0}^{n} \text{Gas Input Energy (Btu)}} \quad \textbf{EQ3}$$

which is the average efficiency over a period of n samples. The standard output energy and input energy is calculated for every new time sample as,

$$\text{Boiler Output Energy Flux (Btu)} = \frac{\text{Boiler Load}_n\left(\frac{\text{Btu}}{\text{h}}\right) + \text{Boiler Load}_{n-1}\left(\frac{\text{Btu}}{\text{h}}\right)}{2} \times \frac{(\text{Time}_n - \text{Time}_{n-1})}{60} \qquad \textbf{EQ4}$$

$$\text{Gas Input Energy (Btu)} = \frac{\text{Gas Flow}_n\ (\text{scfh}) + \text{Gas Flow}_{n-1}\ (\text{scfh})}{2} \times \frac{(\text{Time}_n - \text{Time}_{n-1})}{60} \times \text{Gas Constant}\left(\frac{\text{Btu}}{\text{scf}}\right) \qquad \textbf{EQ5}$$

where **EQ4** and **EQ5** are trapezoidal numerical integrations.

The term energy ‘flux’ was used intentionally in **EQ4**, because the boiler load as typically calculated is the energy convected into and out of the boiler, and does not include the energy stored within the boiler mass. Including thermal mass is critical if short-term efficiency calculations are to be used (e.g. 1 hour averages vs. 1 day averages), because the change in the average system temperature over the short-term can constitute a significant portion of the boiler load. The thermal mass energy stored or released is calculated as,

$$\text{Boiler Output Thermal Mass Energy (Btu)} = (\text{System Temp}_n\ (°\text{F}) - \text{System Temp}_{n-1}\ (°\text{F})) \times \text{System Heat Cap (Btu/°F)} \qquad \textbf{EQ6}$$

where,

System Temp = Average temperature of the boiler mass between supply and return temperature sensors;
System Heat Cap = The estimated heat capacity of the boiler plant;

The equations presented above are written in a general way for a single boiler. For this specific boiler retrofit projects, each plant has multiple boilers and multiple hot water returns, as indicated in **Figure 1**. The boiler loads are calculated for each of the three return paths (high, low and domestic hot water), and the plant heat capacity varies depending on the number of boilers in operation in any given time.

The effect of modeling thermal mass with respect to efficiency calculations is shown below in **Figure 2**. This figure shows profile of thermal mass and flux energy compared to the gas input energy calculated for every 1 minute sample. Adding thermal mass to the boiler output energy calculation greatly improves the relationship between gas input energy and boiler output energy.

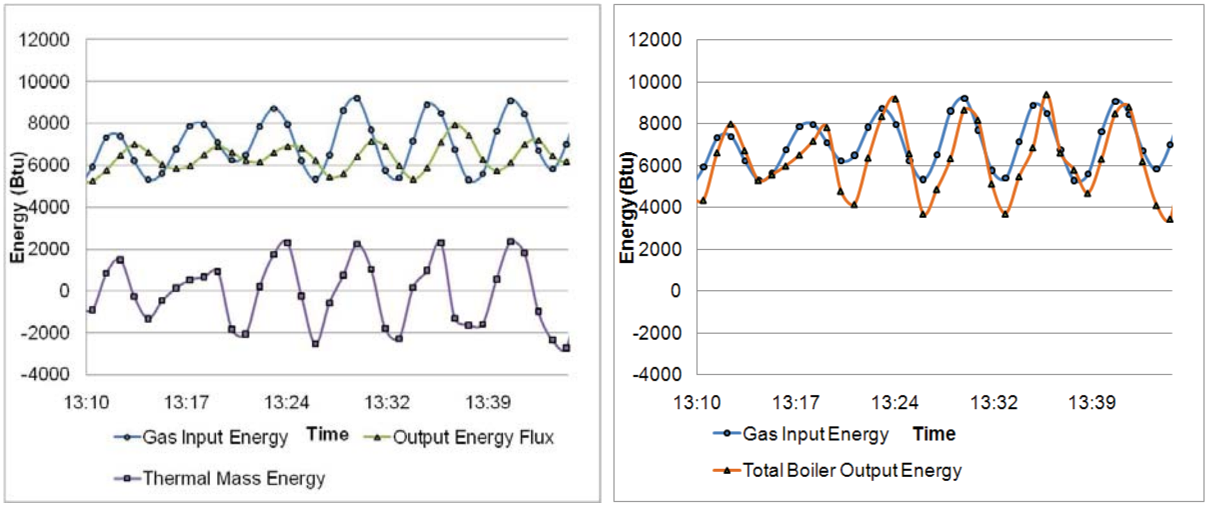

Figure 2. Sample of the Effect of Including Thermal Mass in Efficiency Calculations

Initial Data Analysis

The result of the first month of data collection and calculation of efficiency is shown in **Table 1**.

Table 1. December 2010 Monthly Average Efficiency

Building #1	Building #2	Building #3	Building #4
65%	68%	79%	85%

The initial results were not very encouraging. Thermal efficiencies in the range of 85-95% were expected, based on the manufacturer's published table of combustion efficiencies, shown in **Figure 3**, and accounting for losses.

Firing Rate %	Return Water Temperature F⁰ (C)						
	68 (20)	80 (27)	105 (38)	120 (49)	130 (55)	140 (60)	160 (72)
20	99	99	98.5	97	95.5	94.5	88.5
50	99	99	97.5	93.5	92	90.5	87.9
75	98	97	93	89	88	87.5	86.5
100	97.2	97	91.5	88.50	87.5	87	86.50

Figure 3. Boiler Combustion Efficiencies vs. Firing Rate and Return Water Temperature

Building #2 was selected for further investigation to determine the cause of the low average thermal efficiency measurement. Trend logs for Building #2 in December were examined and it was noticed that the boilers were cycling frequently (see **Figure 4**). Each cycle is accompanied by two purges of the boiler chamber for 15 seconds which wastes energy by removing stored heat from the mass of the boilers. There were approximately 3500 purges for the month of

December. To verify the purge energy loss, a manual calculation was done to estimate the maximum possible heat loss through purging,

$$\text{Max Purge Heat Loss (Btu)} = \text{Air Specific Heat Cap}\left(\frac{\text{Btu}}{\text{lb}\cdot{}^{\circ}\text{F}}\right) \times \left(\text{Stack Temp }({}^{\circ}\text{F}) - \text{ Ave OAT }({}^{\circ}\text{F})\right) \times 100\%\ \text{Air Flow Rate}\left(\frac{\text{ft}^3}{\text{min}}\right) \times \text{Air Density}\left(\frac{\text{lb}}{\text{ft}^3}\right) \times \frac{15(\text{sec})}{60\ (\text{sec})} \quad \textbf{EQ7}$$

The calculation showed an average purge loss of 840 Btu, which results in 2.94 MBtu of energy lost through purging in the month of December. However this loss was only 0.6% of the total gas energy of 480 Mbtu for December, and was not enough to explain the unusually low average thermal efficiency.

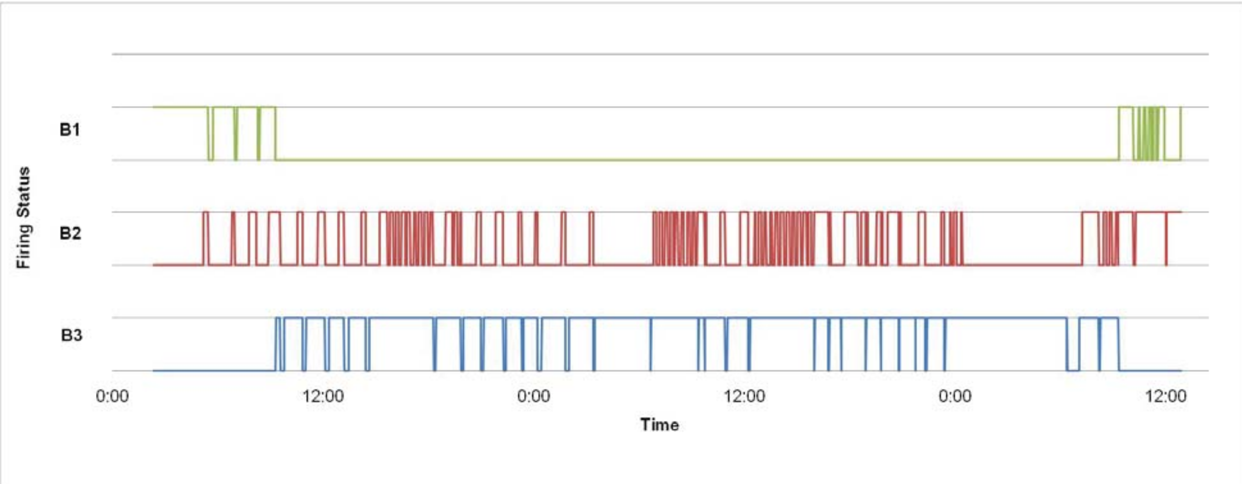

Figure 4. Sample Logs of Boiler Status Showing Boiler Short-Cycling

Verification Phase

Boiler Combustion Efficiency Tests

The commissioning team had access to a boiler combustion efficiency gas analyzer, which was then used to confirm that the boilers combustion efficiencies were in line with manufacturer published performances and that the measured low thermal efficiency was a result of other factors. The combustion gas analyzer was installed and data was logged for a period of four hours for a single boiler. The results of the test are shown in **Table 2**.

Table 2. 4-hour Combustion Efficiency Test Results

Average Measured Combustion Efficiency	Manufacturer Published Efficiency at Same Average Conditions	Calculated Thermal Efficiency
89.1%	87.7%	64.3%

As a result of this test, it was suspected that the primary reason for measured low thermal efficiency was due to inaccuracy of the temperature and flow sensors. Theoretically, boiler jacket heat losses associated with radiation and convection are about 2.5-4%[2], so thermal efficiencies should be roughly in the 84-86% range.

Sensor Calibration Tests

Measuring reasonable thermal efficiencies requires accurate measurements of flow and temperature. For Building #2 in the month of December, a **difference of 1°F** in the supply water temperature sensor will result in a **change in thermal efficiency measurement of over 5%**. The thermistors for these projects are rated to an accuracy of 1.5°F. Most sensors are not calibrated by the manufacturer and therefore do not have the required accuracy for this application. Therefore, sensor calibration and adjustment is a crucial part of the monitoring system commissioning process.[3]

Despite the inaccuracy in the sensor readings, the readings were discovered to be consistent over time. In other words, the sensors are reasonably precise but not accurate. This was confirmed by comparing relative readings of sensors installed in the boiler plant, selecting the data during times when the sensors should be reading the same temperature. The results of the sensor comparison tests are shown in **Table 3**.

Table 3. Temperature Comparisons of Sensors over 4 Months

		Dec-10	Jan-11	Feb-11	Mar-11
Common High Return vs. Boiler 1 High Return	Average Difference	-4.19	-4.13	-4.14	-4.18
	Standard Deviation	0.35	0.81	0.39	0.32
Common Low Return vs. Boiler 1 Low Return	Average Difference	-9.30	-9.16	-9.32	-9.27
	Standard Deviation	0.43	0.47	0.42	0.41

Each average difference in **Table 3** is calculated for the entire month and consists of thousands of temperature comparisons. The standard deviation shown is the standard deviation of the difference between sensor readings for that month.

The gas flow sensor readings were compared with the utility gas meter readings for the same period and it was found that there was less than 1% error between the two instruments. As a result, the gas flow meter readings were not adjusted in the efficiency calculation.

Temperature Calibration Tests

The first temperature calibration tests involved using two reference temperature sensors, the ‘Taylor’, a thermocouple probe-type temperature sensor, and the ‘Fluke’, a multimeter with a wire-type thermistor, to validate the installed thermistor BAS readings. These calibration sensors were temporarily installed at the each of the key plant temperature sensors and their values and the plant sensor BAS readings were manually recorded and compared. The recorded temperatures of all three devices were plotted and the average differences between temperature readings were calculated. A sample of the plotted temperatures is shown in **Figure 5**, and the test summary for Building #2 is shown in **Table 4**.

Adjusting the values of the temperature sensor readings with constant offset adjustments from **Table 4** (the same adjustment applied for all temperatures) resulted in a further reduction in the calculated efficiency. The test indicated that the supply water temperature sensor reading should be adjusted down more than all of the return water temperatures, which reduces the calculated output of the boiler according to **EQ4**.

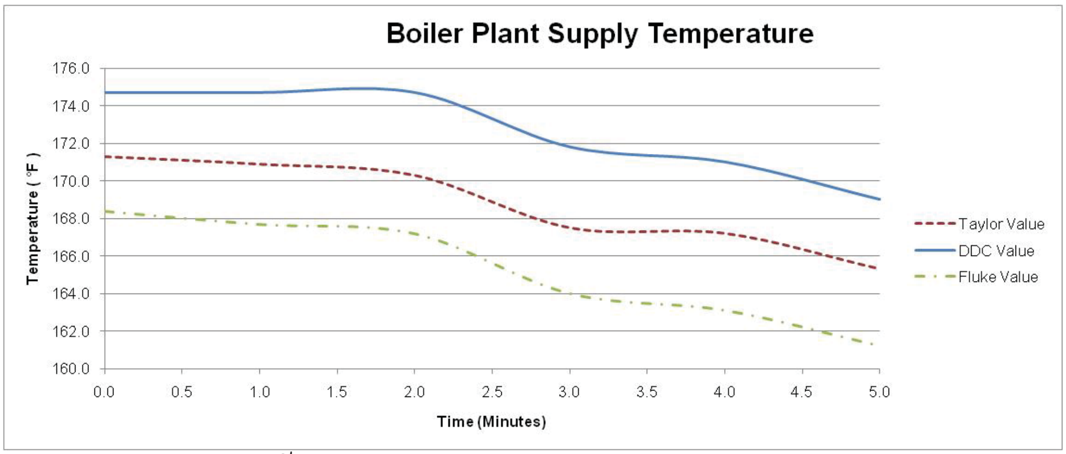

Figure 5. Sample 1st Temperature Sensor Calibration Method Test Results

Table 4. Summary of 1st Temperature Sensor Calibration Method Results

	Supply Temperature	**High-Return Temperature**	**Low-Return Temperature**	**Domestic Hot Water Return Temperature**
Average BAS Temperature During Test (°F)	172.7	129.5	136.9	152.1
Taylor Sensor vs. Boiler Plant Sensor (°F)	-7.4	-1	-3.2	-4
Fluke Sensor vs. Boiler Plant Sensor (°F)	-3.9	1.3	-2.6	-3.8

The team then devised another method of testing temperature sensors – inserting the sensors into a kettle of boiling water, which is at a known temperature of 212°F at sea level. The temperature sensors were removed from their casings and held in a kettle of boiling water until the BAS temperature readings stabilized; the result of the test is shown in

Table 5.

Using the test results as constant sensor offset adjustments from the boiling hot water test results in an increase the difference between supply water and return water temperatures, and a calculated efficiency of **80%** for the month of December.

Table 5. Summary of Temperature Sensor Boiling Hot Water Test for Building #2

	Supply Temperature	High-Return Temperature	Low-Return Temperature	Domestic Hot Water Return Temperature
Temperature at Boiling, 212°F (°F)	216.5	218.3	217.8	219.4
Sensor Offset Adjustment (°F)	-4.5	-6.3	-5.8	-7.4

Flow Calibration Tests

To confirm the flow sensor accuracy, the commissioning team conducted tests to compare the turbine flow sensor readings with flow-rates calculated from pump differential pressure measurements at known speeds, using the pump manufacturer's pump curves. Differential pressures were determined from standard diaphragm pressure gauges located at the pumps suction and discharge. Pump speeds were manually set to 30%, 50% and 100%, the pump differential pressures and the BAS flows were manually read, and a total of 12 tests were conducted. Plots of pump curve estimated flows vs. BAS flows were created to compare the results and to create possible equations for adjusting the BAS flows; these plots are shown in **Figure 6** and **Figure 7**. These figures contain the same data but with different trend-lines.

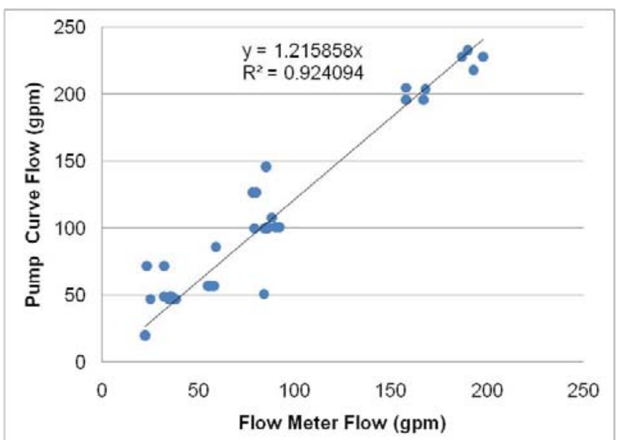

Figure 6. Flow Adjustment 1 - Linear

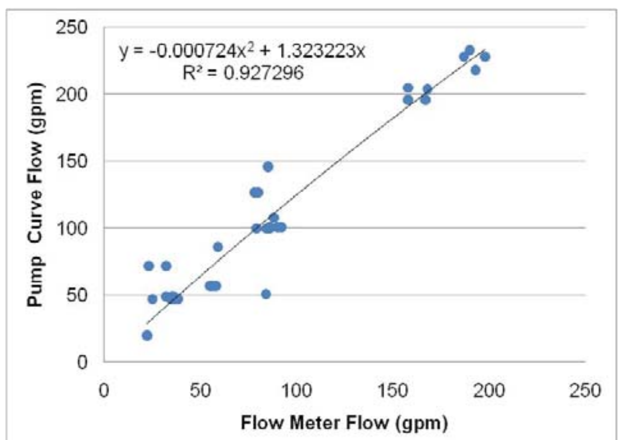

Figure 7. Flow Adjustment 2 - Quadratic

The trend-lines are curves of 'best fit' calculated from single variable parametric regression. **Figure 6** uses a linear equation and **Figure 7** uses a quadratic equation. The flows estimated from the manufacturer pump curves are on average significantly higher than the monitored flow, which can be seen most easily in **Figure 6 –** based on the regression-calculated linear equation, the BAS flows have to be increased by 21% on average to match the flows estimated from the manufacturer pump curves.

Applying these adjustments to the December Building #2 average thermal efficiency calculation yields the results shown in **Table 6**.

Table 6. Building #2 Flow Sensor Calibration Adjusted Efficiencies

Unadjusted December 2010 Efficiency	Flow Adjustment 1 Efficiency	Flow Adjustment 2 Efficiency
68%	83%	87%

Flow Adjustment 2 appears to provide a reasonable average efficiency, but since the temperature sensors are clearly inaccurate is desirable to adjust both flow and temperature to achieve a reasonable average thermal efficiency. Determining the proper adjustments ultimately required analyzing efficiencies on an hourly basis, creating baselines of these efficiencies, and creating criteria for the acceptability of sensor adjustments.

Performance Baselining

One of the team's main goals was to develop a mathematical expression that characterized the boiler efficiency based on key variables, to be used as a baseline of the system performance under future operating conditions. A baseline of boiler efficiency can be used to diagnose boiler operational issues such as heat exchanger fouling or improper combustion due to combustion airflow and gas flow control issues, indicating a need for servicing. An equipment performance baseline can also be used to calibrate energy models for M&V purposes.

Baselining boiler efficiency requires comparing efficiencies to the operating conditions that affect boiler efficiency, similar to how a boiler manufacturer will document efficiencies over a range of operating conditions (see **Figure 3**). Performance baselining goes step further and attempts to derive a mathematical equation through regression analysis that best represents efficiency, based on the relevent operating conditions that influence efficiency. Typical manufacturer rating conditions used to document boiler efficiencies are boiler firing rates or part-load-ratios (the boiler output divided by the boiler capacity), and RWT. Energy modeling programs also use performance equations based on part-load-ratio (PLR) and RWT or supply water temperatures (SWT).

To develop the boiler performance equations, 1 hour averages of the boiler plant thermal efficiencies were calculated, along with the corresponding averages of PLRs and RWTs. A comparison of thermal efficiency vs. RWT is shown in **Figure 8**. It is desirable to use the minimum averaging period possible to improve the accuracy of the baseline calculation, but there are practical limitations to the minimum due to the calculation errors described above under

Boiler Plant Efficiency Calculations. Using 1 hour averages turned out to be a reasonable balance between these calculation errors and an accurate baseline efficiency calculation.

To calculate the baseline equation, the range of data was extended to the end of February 2011 to provide more data points for a more robust calculation. With the 1 hour thermal efficiencies and average PLRs and RWTs calculated for the three months, a multi-variable regression calculation was conducted that used a standard polynomial equation form used in energy modeling software programs.[4] A sample of the 1 hour unadjusted efficiencies and the baseline equation efficiency is shown in **Figure 9**.

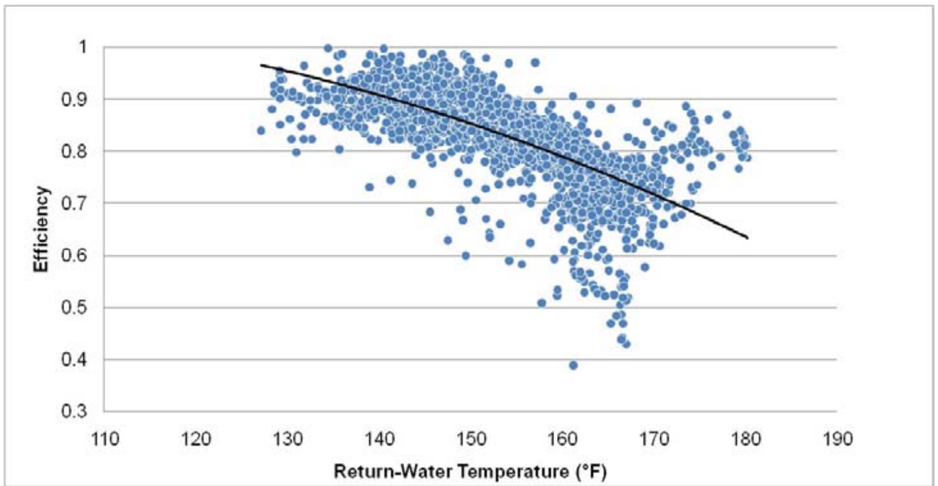

Figure 8. Adjusted 1-Hour Average Efficiency vs. Return Water Temperature – Dec 2010 to Feb 2011

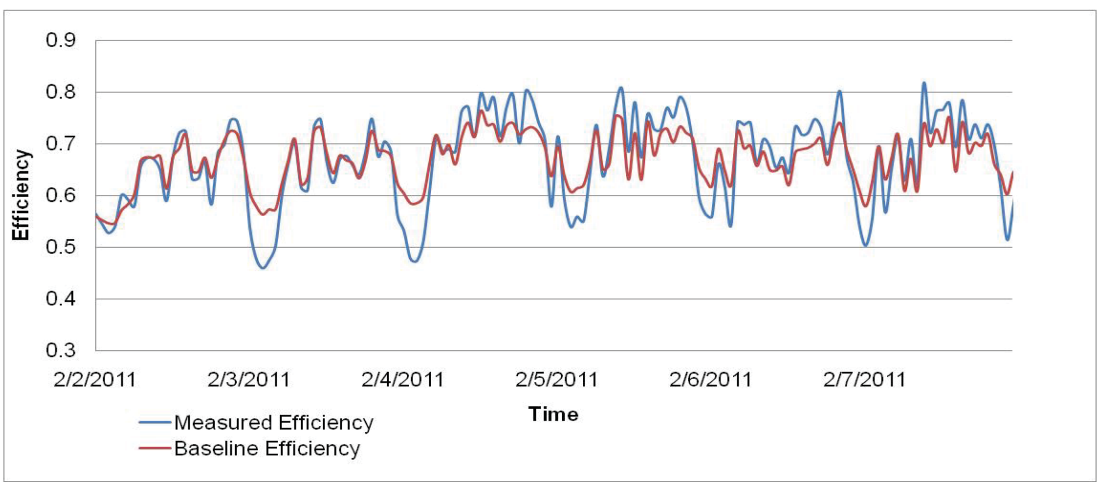

Figure 9. Sample of 1 hour Unadjusted Efficiencies and Baseline Predicted Efficiencies

The short-term efficiency calculations and multi-variable regression calculations were initially performed with Microsoft Excel, but it was found that due to the nature of the program that the calculations were extremely slow. The calculations consist of using over 100,000 data points in a series of calculations for efficiency averaging, sensor adjustments and regression. It is recommended that advanced mathematical modeling tools such as Matlab®, Mathematica® and Statistica® be used because they are much faster at doing these calculations, perhaps on the order of 100 times faster.

Selecting Metering Sensors Adjustments

After creating a performance baseline, the effect of adjusting metering sensors values could be further analyzed. The temperature adjustments presented in **Table 5** were seen to cause a number of efficiencies to increase well over 100%. After some experimentation, it was determined that the only plausible explanation was that proper temperature adjustments are non-linear, so while the boiling hot water test indicated a certain temperature offset at boiling point, the sensor offsets decrease as the measured temperature decreases. This effect can also be observed in **Table 4**: the lower the measured temperature, the smaller the temperature offset.

The relationship between thermistor output voltage and measured temperature is shown in **Figure 10**. This equation is nearly linear between 0°F and 100°F and becomes exponential beyond these limits. The slope of the curve follows qualitatively with the observations of the scale of adjustment required at varying temperatures – that at higher temperatures greater adjustments are required than at lower temperatures. Using a 'voltage offset adjustment' instead of a temperature offset adjustment (whereby a sensor voltage is calculated at each measured temperature and then adjusted by the values determined from the calibration test results in **Table 5)** has the effect causing a larger temperature adjustment at higher temperatures and a lower adjustment at lower temperatures. Using this type of adjustment resolved the issue of the unusually high efficiencies seen with the constant offset adjustments from the boiling hot water test, but is still a rough estimate of the proper temperature adjustment. An ideal calibration method would involve testing the BAS sensors against a calibrated reference sensor over a range of temperatures and creating a mathematical expression to convert the BAS sensor readings, similar to the pump flow tests discussed above.

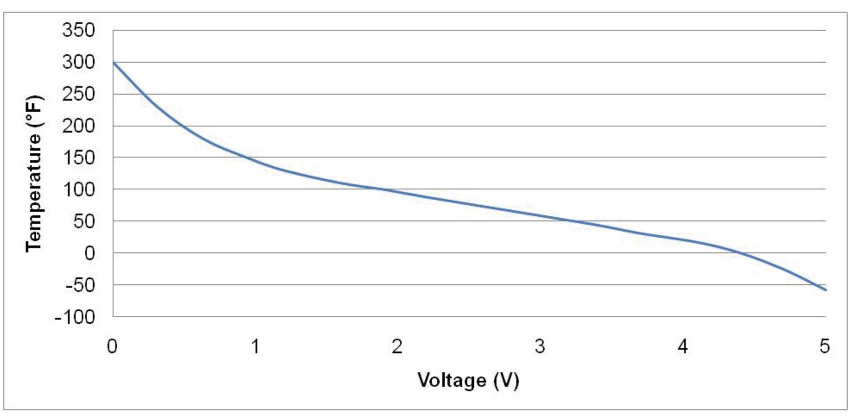

Figure 10. Typical Thermistor Measured Temperature vs. Output Voltage Curve

It was hypothesized that since the sensor readings were inaccurate, that as the sensor readings are adjusted toward the true values the error between predicted efficiency and measured efficiency should decrease, since the sensor error could be creating error in the relationship between efficiency and the operating conditions. It was verified that as the sensor adjustments described herein were applied, that the hypothesis was true. Occasionally, and due to sampling and/or calculation errors, efficiencies of over 100% were calculated, which are physically impossible efficiencies. It is desirable to minimize these unrealistic efficiencies for the sake of accurate M&V. The criteria for the sensor adjustments can then be summarized as follows:

1. Average efficiency that makes sense based on manufacturer's published data;
2. Decrease in the error of the regression calculated baseline efficiency;
3. Minimum thermal efficiencies over 100%;

The boiling hot water test sensor adjustments, converted to a voltage offset adjustment, combined with Flow Adjustment 1 resulted in an average efficiency for Building #2 for the month of December of 86.5%. Flow Adjustment 2 results in an average efficiency of 87.5%. Both of these average efficiencies appear to be reasonable. We can also use an approximate temperature-only adjustment that results in a similar average efficiency. The flow sensors are factory-calibrated, so a temperature-only adjustment can be used to verify whether a flow adjustment is necessary.

We can hold these adjustments up to the adjustment criteria to determine which is more appropriate, as shown in **Table 7**. The average prediction error is calculated as the average absolute % difference between predicted and actual efficiency for every hour. Since Overall Adjustment 3 resulted in the least error and the least efficiencies over 100%, it was selected as the overall adjustment method. Adjusting temperature only was observed to be highly unrealistic no matter what combination of temperature sensor adjustments.

Table 7. Final Overall Adjustment Selection Summary

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

Refining the Baseline and Predicting Performance

A scatter-plot of measured efficiency vs. the regression calculated baseline efficiency for the months of December 2010 to February 2011 is shown in **Figure 11**, compared to a perfect baseline. A surface plot of the same data set is shown in **Figure** 12.
Figure 12

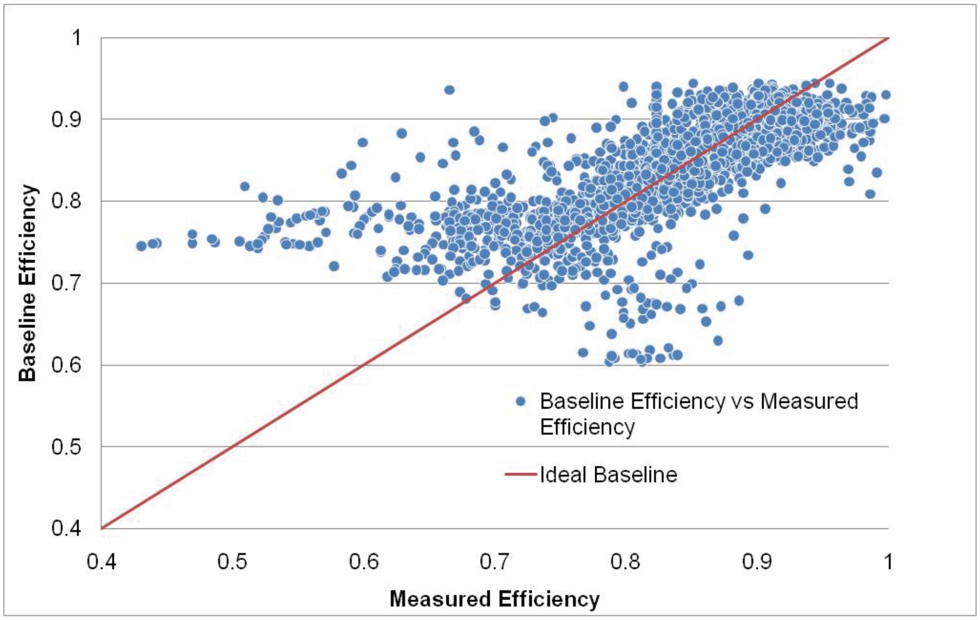

Figure 11. Dec 2010 – Feb 2011 Baseline Prediction Scatter Plot

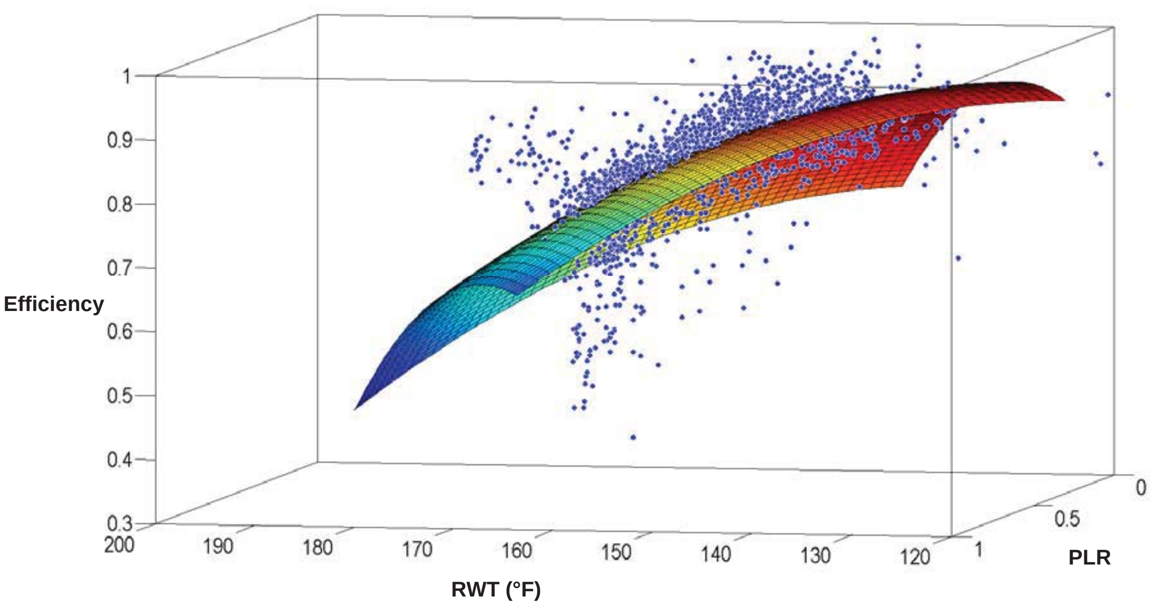

Figure 12. Surface plot of 2-Variable Baseline Efficiency Equation

Figure 12 and **Figure 13** indicate that the standard performance variables of PLR and RWT, used by manufacturer's to rate boilers and used in energy modeling programs may not be sufficient to fully describe boiler efficiency. To test this hypothesis a 4-variable regression baseline was calculated, including average boiler SWT and average flow per boiler in the baseline equation. Sample plots of the 2-variable and 4-variable prediction are shown in **Figure 13** and **Figure 14**, and a comparison of the errors of regression and prediction are shown in

Table 8.

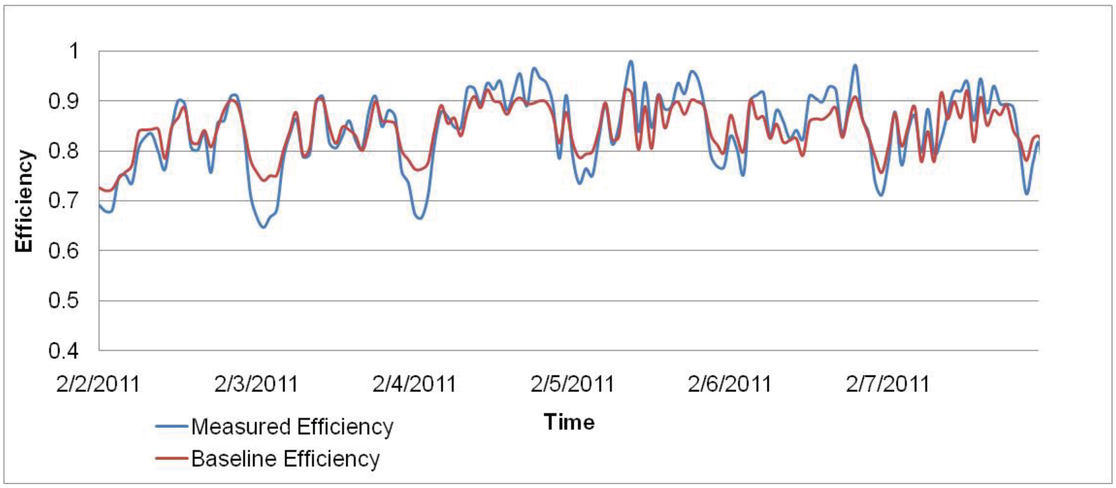

Figure 13. Sample of 1 Hour Adjusted Efficiencies and 2-Variable Baseline Efficiencies

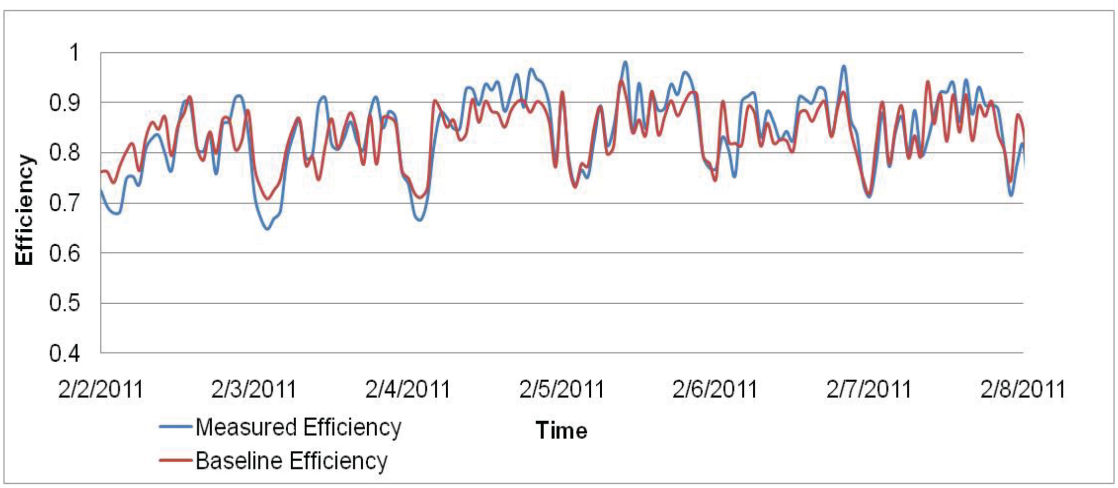

Figure 14. Sample of 1 Hour Adjusted Efficiencies and 4-Variable Baseline Efficiencies

Table 8. Error Summary of Baseline and Prediction for 2 and 4 Variable Efficiency Models

	2 Variable Regression, PLR, RWT - Dec to Feb Baseline	**4 Variable Regression, PLR, RWT, SWT, Ave Flow -** Dec to Feb Baseline	**2 Variable Regression, PLR, RWT -** Mar to May Prediction	**4 Variable Regression, PLR, RWT, SWT, Ave Flow -** Mar to May Prediction
Mar-May 2011 Ave Prediction Error	-1.6%	-1.3%	2.3%	2.0%
Mar-May 2011 Standard Deviation of Error	9.9%	9.6%	9.1%	8.4%

The regression and prediction error decreased when using a 4-variable efficiency model. Other parameters could theoretically be included in the efficiency model such as number of boiler purges and % time using high return flow vs. low return flow (which changes the amount of active boiler heat exchange area). Other uncertainties in the efficiency and baseline calculations include – estimation of the heat capacity for thermal mass calculations, differences between individual boiler flow-rates and loads when operating at the same time, and sampling errors such the BAS repeating identical readings for many samples. The average prediction error can be used to calibrate performance alarms. A performance alarm can be issued when the predicted efficiency exceeds the measured efficiency by an average error (taken from a number of average efficiency samples, perhaps 6-12 hours using 1 hour efficiencies) greater than the typical error of the prediction.

Conclusions

There is still much research to be done on the performance of boilers under real operating conditions and on the most practical and effective methods of calibrating sensors, but this paper presents a process for calibrating an efficiency monitoring system to provide reasonable and consistent values of thermal efficiencies that can be used to track plant performance, issue alarms to notify building operators of poor performance so that corrective action can be taken, and to provide valuable information for optimizing plant performance.

It was clearly seen how the boiler retrofits plants operating almost constantly in the non-condensing temperature range are not utilizing their full efficiency potential. The boilers were also seen to be cycling excessively, even under peak cooling demand. While this cycling may cause minimal energy losses in the short term, it is likely that boiler performance will degrade more quickly over time due to increased wear from cycling thermal expansion and contraction. Without a monitoring system in place, this degraded performance could persist for years without being noticed.

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