Application of Advanced 2-D TDLAS diagnostics for the Optimization of Combustion in Steam Methane Reformers

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We present results from two separate demonstration installations of the ZoloBOSS TDLAS sensor system on Steam Methane Reformers. The ZoloBOSS provides two-dimensional information on temperature and species concentration distributions (O_2, CO, and H_2O) inside the operating SMR furnace. This unique data set allows the operator to balance the temperature distribution in the furnace as well as insuring that the desired distribution of O_2 and fuel is realized. The value of such a system for operating SMRs includes contributions from improved efficiency, longer tube life, increased catalyst life, reduced emissions, remote monitoring, and safety. Results at both nominally well-run plants indicate that: 1) significant combustion profile imbalances were initially present in both furnaces upon installation, 2) the data provided by the ZoloBOSS can be used to improve balance by manually tuning burners, and 3) significant ROI will be realized as a result of long-term implementation and optimization.

Introduction

Combustion provides energy to drive many endothermic industrial processes. Industries as diverse as petroleum refining, cement, glass, aluminum, steel, and paper manufacturing as well as the production of chemicals such as hydrogen, ammonia, and ethylene rely on combustion. These processes have traditionally been run without much thought about combustion efficiency. However, competition, emissions regulations, higher fuel costs, and concern regarding global warming have conspired to cause manufacturers to focus attention on process efficiency. One of the largest cost inputs for any large-scale production facility is fuel. For instance, in the hydrogen production industry, a typical steam methane reformer (SMR) produces 100 mmscf/day (112 Nm^3/hr) hydrogen with a heat input of 15,000 mmBTUs. The fuel is typically natural gas (4.00 US$/mmBTU in the USA and 8.00 US$/mmBTU in Europe); in some other countries, fuels such as naphtha may be used at a cost of greater than 16 US$/mmBTU. A fuel savings of 0.5%, even in the United States where fuel is relatively inexpensive, is sufficient to spur interest in improving combustion efficiency. Along with reduced fuel consumption, optimized combustion can lead to higher process efficiency, increased tube life, reduced emissions and increased asset availability as well as improved safety.

In 2004, Zolo developed the ZoloBOSS, a laser-based combustion monitoring system that has the capability to measure temperature and species concentrations in the combustion environment, and so offers the possibility of optimization of the combustion process to improve efficiency. The ZoloBOSS architecture allows the user to monitor combustion parameters along multiple paths (currently up to 30) and this capability enables the calculation of two-dimensional (2D) species concentration and temperature profiles. The resulting 2D data provides the operator with the information required to homogenize combustion allowing reduced excess air and better optimized operating temperatures for better efficiency while maintaining required safety margins. Elimination of hot spots typically improves asset run time between unplanned outages.

Over 50 ZoloBOSS systems have been installed worldwide, primarily in coal-fired power plants. Efficiency improvements of up to 1% have been demonstrated straightforwardly leading to similar reductions in greenhouse gases such as CO_2 and often with concomitant reductions in NO_x (up to 30%). Recently, we have undertaken an initiative to apply the ZoloBOSS technology in other combustion-driven applications such as SMRs, electric arc furnaces (EAFs), steel reheat and glass furnaces. Here we talk about initial results from two SMR furnaces.

The ZoloBOSS for Steam Methane Reforming

The ZoloBOSS has been described in detail elsewhere.[1] Here we focus on aspects unique to installation in an SMR. SMRs produce hydrogen via a two-step process in which CH_4 reacts with steam over a catalyst at high temperature to produce a mixture of H_2, CO, and CO_2 along with some unreacted CH_4 and H_2O. The product H_2 is typically separated from this mixture using a pressure swing adsorber (PSA). The PSA off-gas contains a significant combustible content, including unreacted CH_4, CO, and some remaining H_2. The PSA off-gas typically provides about 80% of the energy content required to fire the furnace, so pure natural gas is added as a make-up fuel to provide the remaining energy required. However, the ratio of natural gas to PSA off-gas can change over time making optimization of the burners challenging without real time feedback control. In addition, the PSA off-gas pressure changes during its cycling causing the fuel flow to the burners to swing in a roughly periodic manner as a result. We shall see that this pressure oscillation is easily observed in the ZoloBOSS data.

Figure 1 shows an elevation schematic of the first SMR installation (Unit 1). The plane containing all 24 paths is located near the bottom of the down-fired furnace at the “end” of the active combustion region. Figure 2 shows a plan view schematic of Unit 1. It consists of rows of burners with rows of process tubes interspersed. In this SMR, gaps occur periodically in the process tubes allowing one to “thread” laser measurements paths through the tubes at an angle as shown. Angled paths are important for this application as they allow the reporting of the flue gas data in user –defined cells. In the best case, the cell resolution mimics the resolution of the available controls. In this case, manual adjustments are available on every burner, but it was determined that sufficient resolution would be obtained by changing groups of four burners together. The laser measurement paths shown allow us to calculate an average temperature and species concentration measurements for each cell using a Radon Transform. As with our coal boiler installations, the ZoloBOSS measures each path serially; however, in this application, the measurements can be quite fast since there is no fly ash to reduce laser power. It typically takes about 4 minutes to measure all 24 paths on Unit 1.

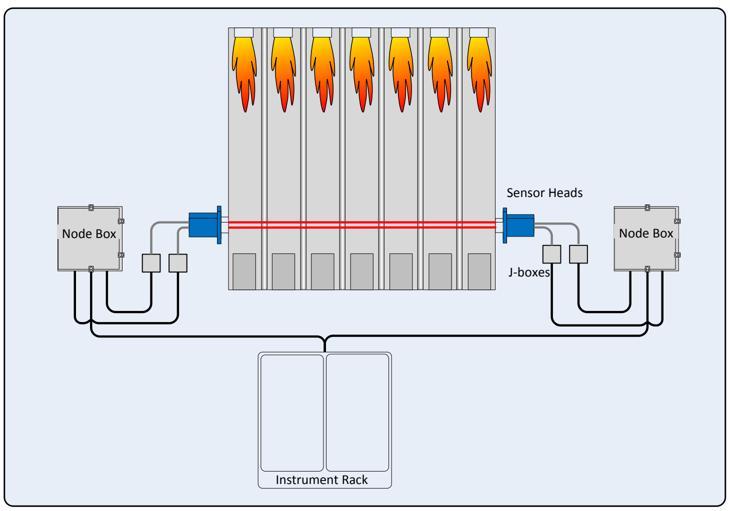


Figure 1: Elevation schematic of Unit 1. The plane containing all 24 measurement paths is located near the bottom of the down-fired furnace at the “end” of the active combustion region.

Figure 3 shows the SMR user interface. Twenty-one cells of temperature information are depicted and similar tabs are available for O_2, CO, and H_2O data. In the top and right margins is shown the path average temperature for that indicated row or column of burners. In addition to the 2D data, the system can focus on a single path to produce a time-series of temperature (T), O_2, CO, or H_2O data as shown in Figure 4.

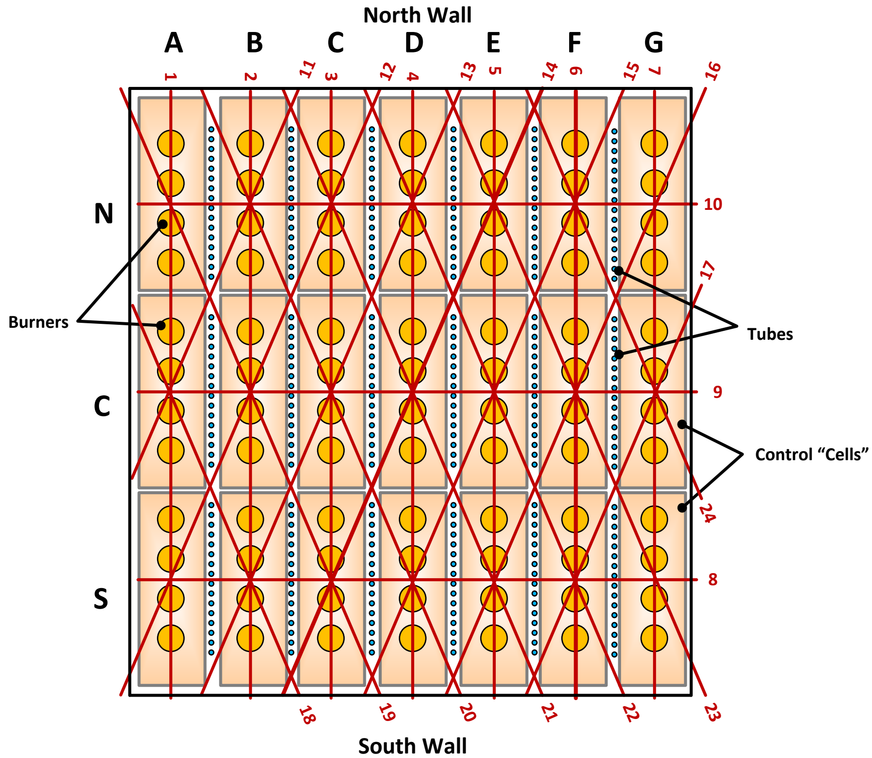


Figure 2: Plan view schematic of Unit 1 showing path layout. Temperature and concentration values are reported for each of the control 'cells', each consisting of four burners.

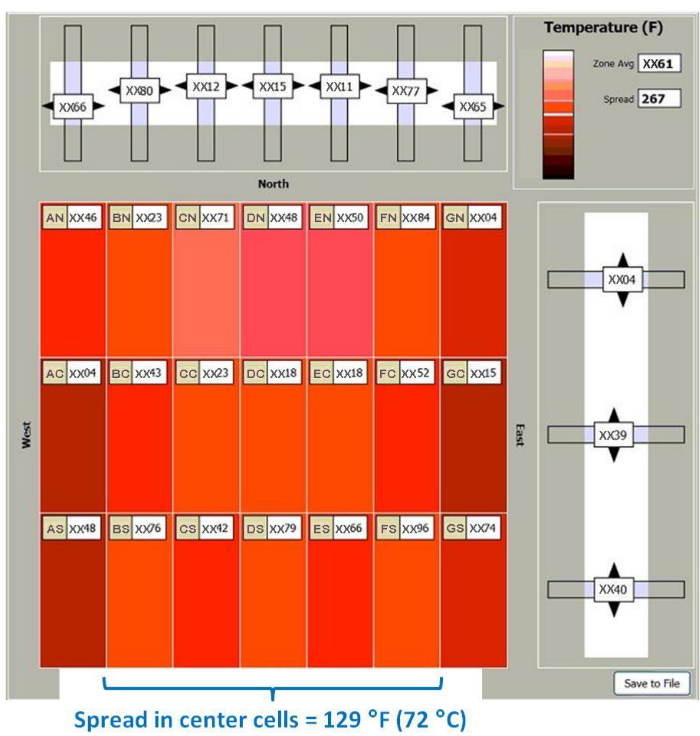


Figure 3: Example of the temperature screen of the SMR user interface. Similar screens are available for H2O, O2, and CO concentrations.

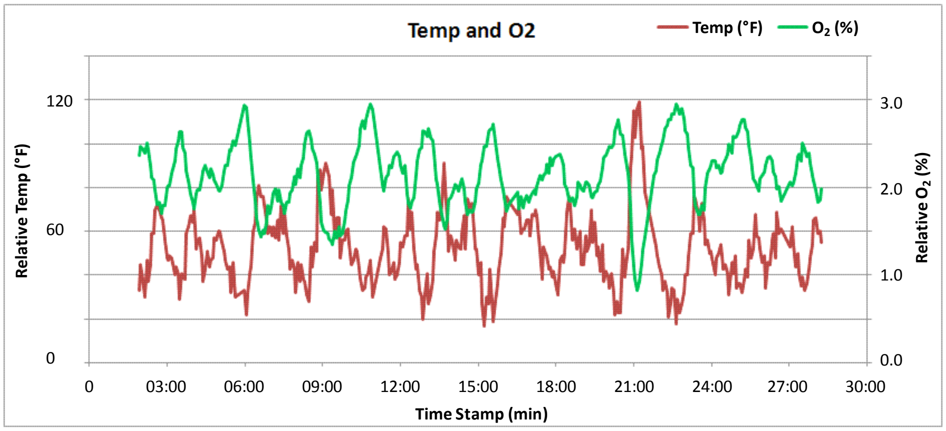


Figure 4: Times series data for temperature and species concentrations along a single path are available from the ZoloBOSS as well.

Results – Unit 1

Figure 4 shows O_2 and T time series data for path 4, which runs down the center of the furnace. Significant variations are seen in both signals due to variations in the fuel flow resulting from the cycling action of the PSA method used to separate the H_2 product from CO, CO_2, and CH_4 – the byproducts of the reaction as described above. The period of the oscillation (~ 1 minute) and its amplitude are approximately as expected. Note that the T and O_2 signals are highly (anti) correlated. This is because, while the fuel flow varies due to the PSA action, the combustion air flow is nominally constant. Since the ZoloBOSS paths are located in a region in which combustion is largely complete, it is measuring the excess O_2. When the fuel flow increases, the excess air decreases in a correlated fashion and vice-versa.

Figure 3 shows the 'as found' temperature distribution in Unit 1. As can be seen, the temperature spread among the cells is very large (~270°F or 150°C). Typically, the outer rows are purposefully operated at a lower firing rate since only one row of tubes is being heated. However, even ignoring the outer cells (A row and G row), temperature variation in the remaining cells is 129°F (72 °C), much larger than the desired spread. After balancing the combustion by adjusting fuel valves manually to move fuel from the hotter cells to the cooler cells, the temperature distribution is much more uniform as shown in Figure 5. Here the spread in the center rows has been reduced to 32°F (18°C). The resulting homogenization of the combustion field reduces the spread in the process tube temperatures. With the tube spread reduced, the operator can increase the process temperature to improve efficiency without risking tube life. In this case we expect the operator should be able to increase the process temperature by 15-25°F (8-14°C). This would be expected to increase process efficiency by 0.4%-0.7%. In addition, elimination of hot spots increases the likelihood that the process tubes will survive for their design lifetime, thereby lowering operating costs. Process tube lifetime versus operating temperature is described by the Larsen-Miller equation. It is generally accepted that an increase in temperature of only 10°C can decrease the tube lifetime by a factor of two. Thus optimizing overall SMR operation is a careful balance between increasing temperature to improve efficiency and maintaining sufficient safety margin for the process tubes. The data provided by the ZoloBOSS can play a unique and valuable role in achieving this balance.

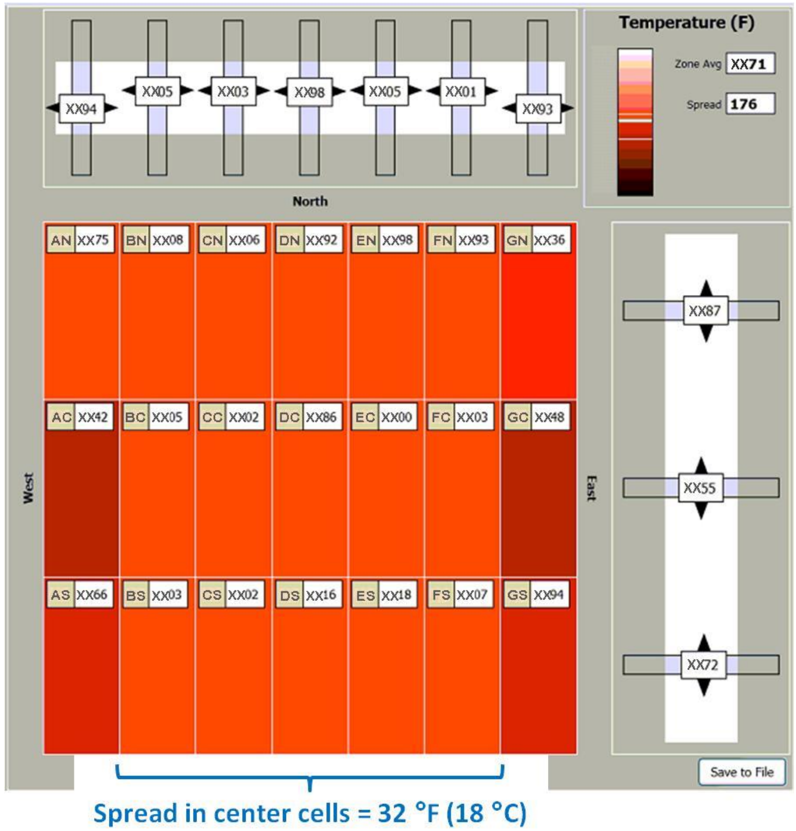
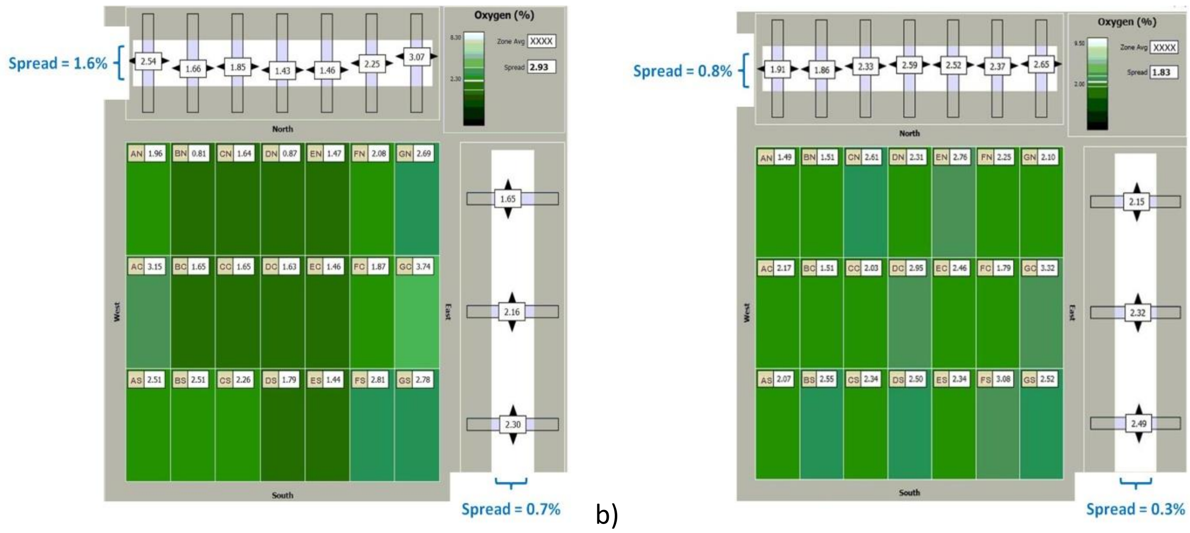


Figure 5: Improved temperature distribution after balancing Unit 1.

Figure 6a shows the O_2 distribution in the furnace in the "as-found" configuration. Note that the outer rows, which are known to be cooler, also show the highest levels of excess O_2. (The high levels of excess O_2 are actually cooling the outer rows – a very inefficient practice, whether intentional or not). Typically, the target for excess O_2 is around 2%, so there is room for improvement in the O_2 distribution and for lowering the overall level of excess O_2. Such a change would improve combustion efficiency and simultaneously reduce the emission of NO_x which either is or soon will be coming under regulation for SMRs depending on what part of the country the installation exists. We did not spend much time trying to balance and reduce excess O_2 for this first demonstration. However, as shown in Figure 6b, we did demonstrate measurement of O_2 and control over its distribution. In Figure 6b, O_2 has been reduced to the outer rows lowering both the O_2 levels and increasing the temperature slightly (not shown). In addition, it was observed that balancing the temperature distribution by redistributing the fuel also improved the O_2 balance. This effect is also included in the improved profile in Figure 6b. This behavior is certainly as expected and indicates that it will be important to alter fuel and air to achieve a completely balanced furnace operating at the correct temperature.



a) b)

Figure 6: a) Furnace O2 distribution in "as-found" state, and b) after decreasing air flow to the outer rows and balancing the fuel distribution.

ZoloBOSS accuracy

Zolo takes great care to insure that the ZoloBOSS measurements are accurate, and performs laboratory testing using carefully controlled facilities to mimic combustion conditions that we measure in the field. We compare our lab results with known methods of measurement such as thermocouples for temperature and traditional gas analyzers for CO, H_2O, and O2. However, quite often we are making measurements in regions of the furnace where other technologies will not survive, so there is no direct in-situ comparison to other types of measurements possible. In this case, we attempt to correlate our measurements with existing plant sensors that measure in cooler regions of the furnace. Figure 7 shows such a comparison. There exists a strong correlation between the excess O_2 measured by the average of all of the ZoloBOSS paths and the two Zirconium Oxide sensors that the plant currently uses to monitor excess O2 levels in the cooler crossover region. The offsets between these sensors arise partly from the fact that the ZoloBOSS data is an average over the entire furnace, whereas the ZrO_2 readings are single point measurements of a varying O_2 profile. However, this data also points out the problems with sensors such as ZrO_2 that exhibit drift. The plant sensor that provides a dry O_2 measurement is about 0.8% higher than the ZoloBOSS, which is roughly as expected since the ZoloBOSS measures in-situ in the presence of H_2O. The other plant ZrO_2 sensor, however, consistently reads nearly 1% higher than the dry sensor, suggesting a calibration issue.

Similarly, Figure 8 shows the average of all of the ZoloBOSS paths compared to the two flue gas temperature sensors (thermocouples) previously installed on the furnace. The offset between each of these sensors is due to their location in the furnace. The ZoloBOSS is mounted approximately 6 feet (1.8 m) above the top of the flue gas tunnels, and the two plant sensors are located inside one of the tunnels and in the crossover region, at which point additional heat has been transferred to the process.

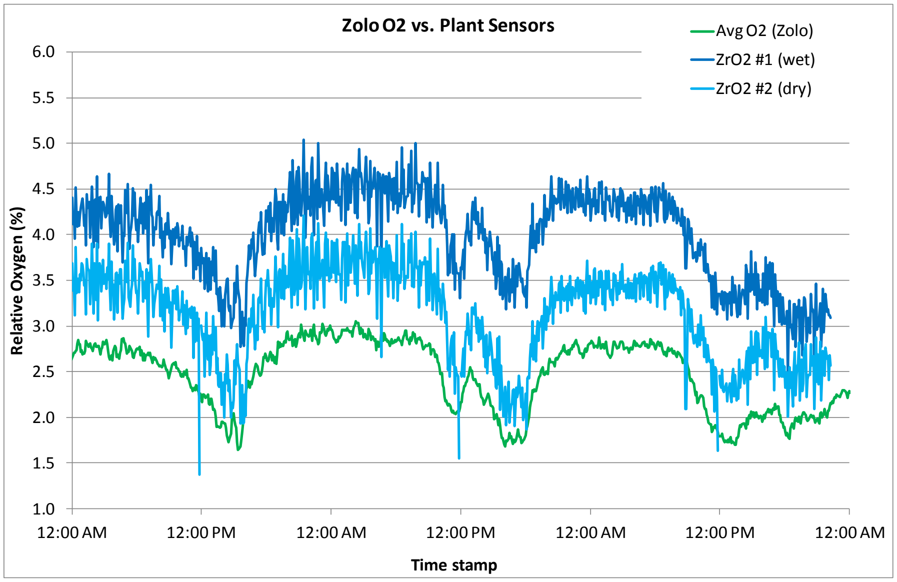


Figure 7: Graph of the excess O2 measured by the ZoloBOSS compared to the two plant oxygen sensors, located in the crossover region.

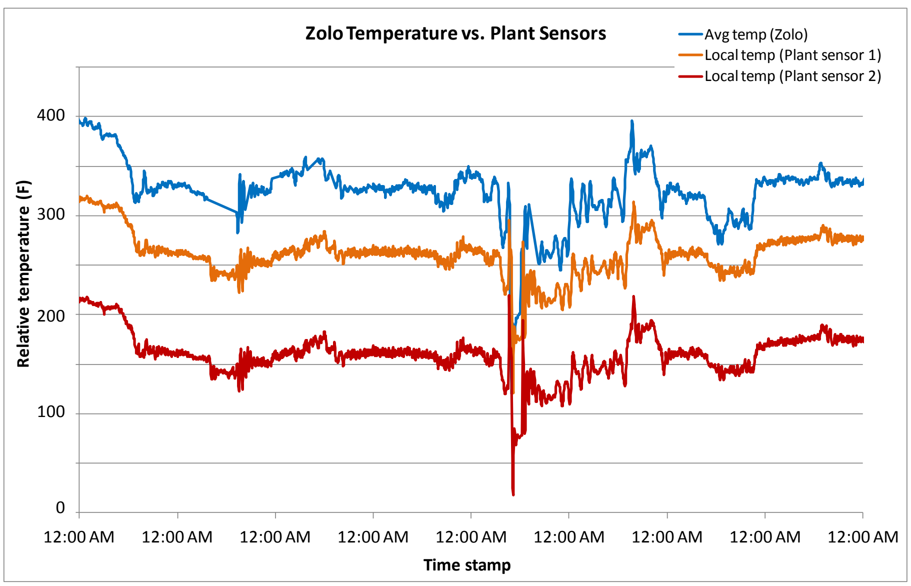


Figure 8: Graph of the average temperature measured by the ZoloBOSS compared to the two existing flue gas temperature sensors, located inside one of the flue gas tunnels and in the crossover section.

Results – Unit 2

The second SMR installation (Unit 2) was less oriented towards operational benefit and more focused on research and development interests and characterizing the furnace profile. As a result, and because the configuration of the SMR prevented installation of angled paths, 2D resolution at the level shown above was not feasible. Even so, results were obtained that indicate that significant savings from correct balancing are possible. Another major difference is that tube temperature data is available from the second test, and this data clearly shows that balancing the temperature profile of the flue gas in the furnace leads to more uniform tube wall temperatures. Physics certainly dictates that this must be the case, but it is nevertheless comforting to see that this is observed empirically as well. More uniform tube temperatures reduce failures and enable higher operating outlet temperatures leading to higher process efficiency.

Figure 9 shows the path layout for the Unit 2 installation, and Figure 10 shows a plan view detail of the two rectilinear grids comprising the upper and lower zones. The layout consists of two grids displaced vertically from each other. Each grid comprises a rectilinear system of 7 paths. As mentioned above, without the additional angled paths, measurements are limited to averages along each path. Even with this limitation, balancing the furnace temperature distribution was accomplished leading to a flatter distribution and more uniform tube temperatures, as corroborated by independent tube temperature measurements. The upper level grid is located 11 feet (3.3 m) below the burners in the down-fired furnace and the lower level grid is located 27 feet (8.2 m) below the burners, i.e. the grids are spaced by 16 feet (4.9 m). Four additional, individual paths are located throughout the furnace and crossover region. These are single paths located in order to track the progress of the combustion process as the gas exits the burners and traverses the furnace. We focus here on the data obtained from the two grids.

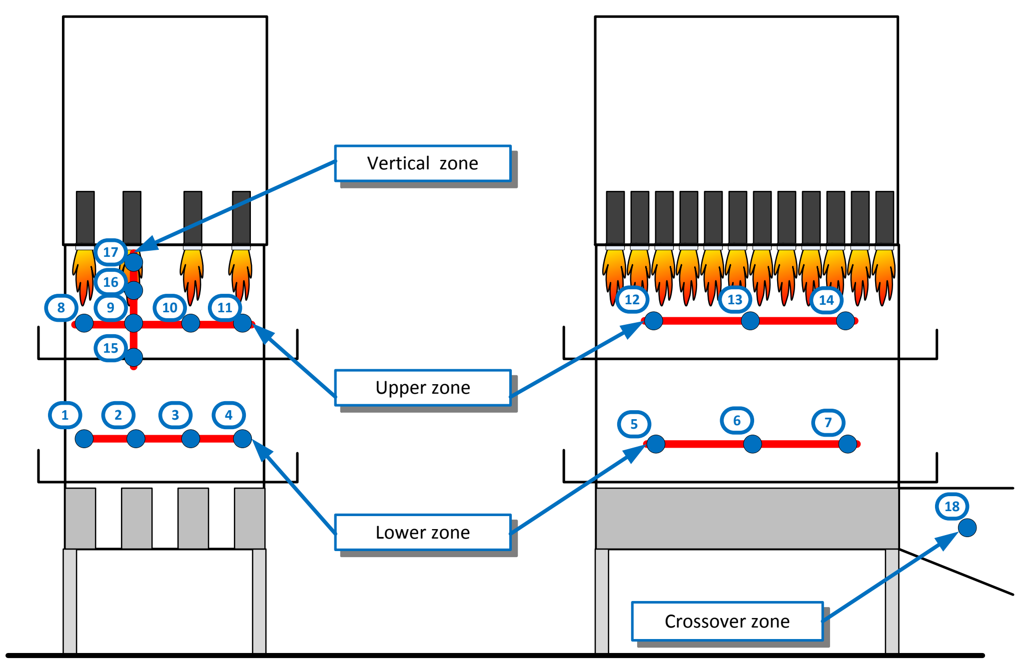


Figure 9: Schematic of Unit 2 showing location of the ZoloBOSS paths

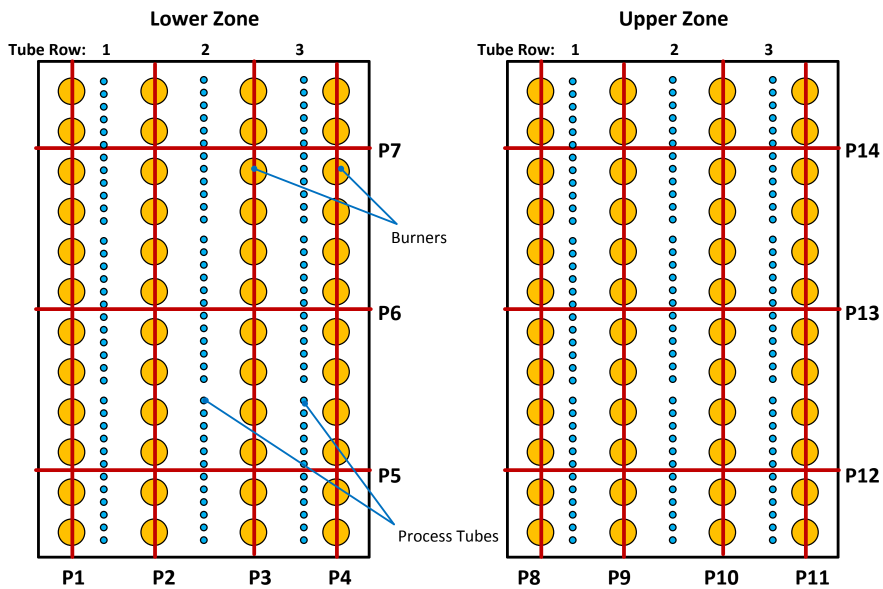


Figure 10: Rectilinear grid configuration for the upper and lower measurement zones installed in Unit 2. The upper zone is 11 feet (3.3 m) below the burners and the lower zone is 27 feet (8.2 m) below the burners.

Controlling the flue gas temperature by changing the burner fuel valves was straightforward and predictable. With a series of balancing steps, it was possible to significantly alter the flue gas temperature profile. Figure 11 shows the measured path-averaged temperatures before and after balancing. As can be seen, the initial spread in the East-West (92°F/51°C) and North-South (132°F/73 °C) directions was reduced substantially (16°F/9°C) and (7°F/4°C).

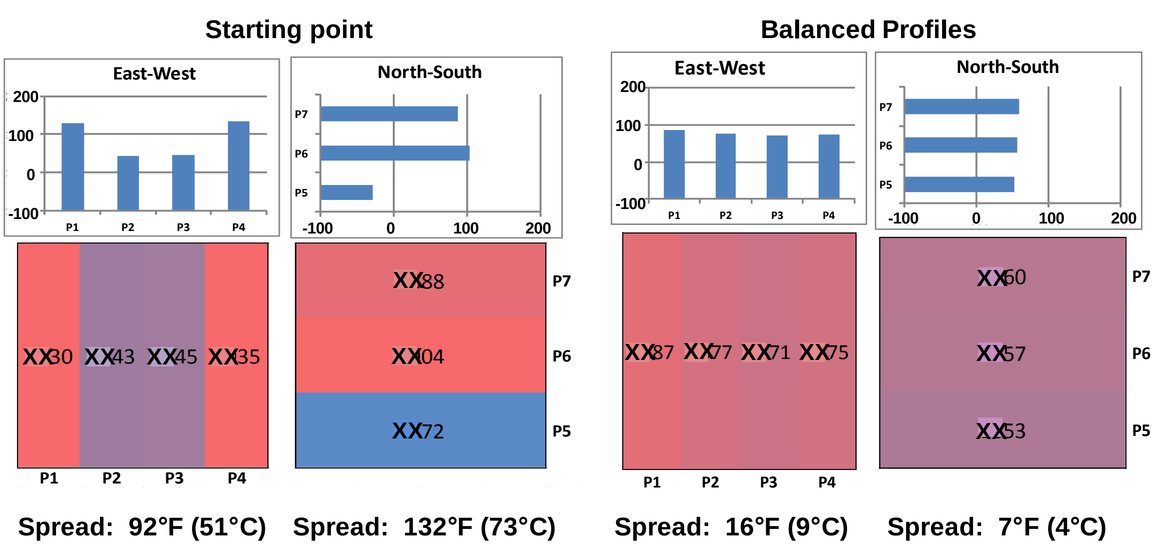
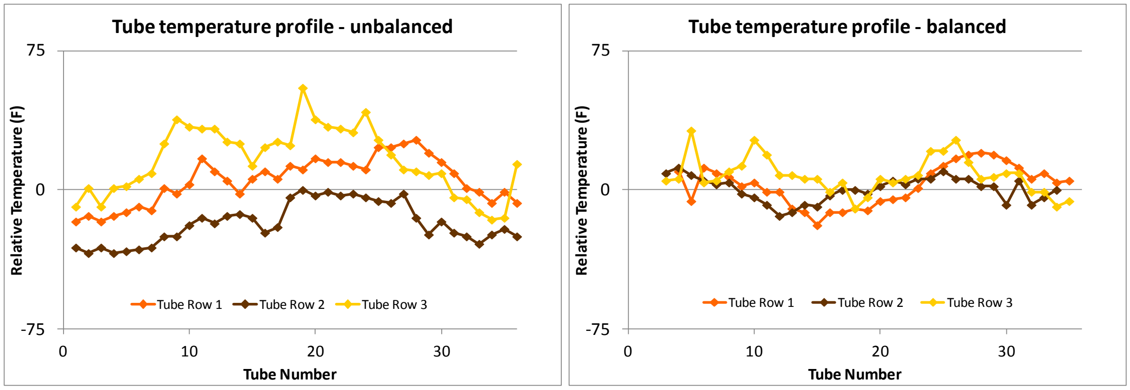


Figure 11: Path-averaged temperatures before and after balancing at the lower level. Significant improvements in the gas temperature distribution are observed.

Since hot spots in the flue gas cause overheated process tubes, and regions of cooler flue gas lead to reduced process conversion and high methane slip, balancing the flue gas can lead to significant improvements in both reliability and efficiency. The tube temperature profiles in Figure 12 demonstrate the significant improvement in tube temperature profile that can be achieved by adjusting the flue gas profile.



Spread: 89°F (49°C) **Spread: 51°F (28°C)**

Figure 12: Typical measured tube temperature profiles with unbalanced flue gas and balanced flue gas, showing that a significant reduction in tube spread can be achieved by balancing the flue gas temperature profile.

Value

The ability to control and improve the flue gas temperature distribution can provide value to SMR operation in a number of areas:

- **Improved Efficiency:** Balancing the flue gas temperature profile will reduce the spread of tube wall temperatures, allowing the overall process temperature to be increased without pushing some tubes above the desired maximum operating temperature. This allows an improvement in the process efficiency without a decrease in reliability. In addition, for plants that do not produce large amounts of steam, combustion efficiency improvements can be obtained by reducing excess oxygen to the desired optimal levels. The Zolo***BOSS*** allows operators to bring the entire furnace into the optimal excess oxygen range, rather than simply the limited regions measured by the conventional plant sensors, leaving the risk that other regions are operating either above or below the optimal range.

  Based on industry standards, a 30-50°F (16-28°C) reduction in the tube temperature spread through better balance can allow the plant to operate at a 15-25°F (8-14°C) increase in reformer outlet temperature (ROT) without damaging tube life or impacting reliability. Additional improvements in combustion efficiency may be obtained by balancing and reducing excess O2. As a result, a process efficiency gain of 1.5-2.5 btu/scf can be achieved, which provides US$200,000 to US$350,000 per year in savings for a 100 mmscf/day (112 Nm^3/hr) reformer, based on a natural gas price of 4.00 US$/mmBTU.

- **Longer Tube Life:** The high performance process tubes installed in SMRs have a lifetime that is highly temperature dependent, as described by the Larson-Miller relationship. It is generally accepted that a 10°C increase in the operating temperature can reduce the tube life up to 50%.

Therefore, reducing the tube wall temperature spread by balancing the flue gas temperature can eliminate the need to inspect and replace individual tubes that are prematurely approaching their design life. Eliminating the high temperatures on only 10-15% of the tubes can reduce maintenance costs (i.e. tube replacement) by over US$100,000 per year on a 100 mmscf/day reformer. Additional value will be realized from the significantly reduced risk of a premature tube failure.

- **Increased Catalyst Life:** Narrowing the spread in tube temperatures has an added benefit in that it reduces premature catalyst degradation that results from overheating. Reducing the temperature spread for catalyst in different tubes will produce more consistent utilization and increase the overall catalyst life. Savings of up to US$50,000 per year may be achieved by less frequent catalyst changes.

- **Remote Monitoring:** Typical steam methane reformers have a wide array of sensors for measuring fuel and air/flue gas properties before and after the combustion region, but there are very few sensors available for directly inside the furnace. The Zolo***BOSS*** combustion sensor provides the first quantitative sensor that measures real-time and directly in the furnace, where the process is taking place. This compliments operator observations and pyrometer measurements of tube temperatures. As an example, a sudden increase in the Temperature and H_2O as measured by the Zolo***BOSS*** can provide an early warning of a tube leak and prevent further damage to adjacent tubes.

- **Safety:** The real-time measurement capability of the Zolo***BOSS*** provides real-time status of the furnace so operators can identify poor combustion conditions or dangerous situations in the safety of the control room. For example, excessive CO levels measured in-situ by the Zolo***BOSS*** can be a signal of a dangerous combustion condition. Quantitative measurements can be configured to trigger alarms if certain limits are exceeded.

Summary

We have installed the ZoloBOSS on two SMRs and demonstrated the straightforward balancing of the temperature and air distributions in the furnace. The results demonstrated here should lead to large improvements in furnace efficiency as well as tube and catalyst lifetime. This leads to significant savings, as summarized in Table 1:

Value	Annual savings		
	4.00 US$/mmBTU	8.00 US$/mmBTU	16.00 US$/mmBTU
Efficiency	$200k to $350k	$400k to $700k	$800k to $1.4M
Tube Life	$100k	$100k	$100k
Catalyst Life	$50k	$50k	$50k
Remote Monitoring	$TBD	$TBD	$TBD
Safety	$TBD	$TBD	$TBD
Net:	$350k to $500k	$550k to $850k	$950k to $1.55M

Table 1: Summary of the value that can be achieved on a 100 mmscf/day reformer by balancing combustion with the ZoloBOSS.

In addition, the measurements provide a window into the safe operation of a very valuable and expensive asset where none existed before.

References:

1. Andrew D. Sappey, Pat Masterson, Eric Huelson, Jim Howell, Mike Estes, Henrik Hofvander and Atilio Jobson "Results of Closed-Loop Coal-Fired Boiler Operation Using a TDLAS Sensor and Smart Process Control Software" Combustion Science and Technology, Vol. 183, Issue 11, pages 1282-1295 (2011).