Common Excess Air Trends in Industrial Boilers with Single-Point Positioning Control and Strategies to Optimize Efficiency

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ABSTRACT

Industrial boilers are among the most common pieces of energy-using equipment in industrial facilities, often representing the majority of energy use in those plants. Typically, process boilers operate at a large range of loading conditions depending on process loads, market conditions, and outdoor temperature. Proper handling of part-load operation can significantly affect energy use.

Most industrial boilers are equipped with single-point positioning control with a shaft mechanically linking the fuel valve and combustion air damper. To match combustion air flow with fuel input, inlet dampers are typically calibrated at high fire. At part-load, combustion air generally decreases at a lesser rate than fuel input due to the non-linearity between the fuel valve and the inlet damper. This results in higher excess air levels at medium and low fire, yielding poorer efficiencies. Although boilers are potentially more efficient at reduced firing rates, high excess air levels limit their part-load efficiency.

This paper presents case studies that demonstrate excess air level trends over the firing range of boilers. Excess air level rises with decreased firing rate, and the difference in excess air level between high and low fire is typically in the range of 30% to 80%. The paper also discusses methods to improve excess air control in boilers and methods to quantify both boiler efficiency as a function of excess air and savings from correcting air levels.

Introduction

Boilers are widely used throughout industry for purposes such as product heating, space heating, humidification, and power generation. One primary factor affecting a boiler's efficiency is excess air used in the fuel combustion. Boilers are most efficient when combustion air intake is only slightly higher than the minimum required for combustion. Maintaining low excess air levels at all firing rates ensures that boilers' fuel usage and operating costs remain reasonable.

A large percentage of industrial boilers use modulating burners with single-point positioning control consisting of a mechanically-linked fuel valve and a combustion air damper. Mechanical linkages seldom maintain a constant air/fuel ratio over a burner's entire firing range and often yield less-than-optimal efficiencies when not monitored and maintained. Boilers with single-point positioning control share a common trend: increased excess air levels with decreased firing rate. This paper demonstrates this trend by presenting measured data from various industrial boilers. It also identifies energy-savings opportunities. Methods to calculate energy savings are also presented.

Determining Combustion Efficiency

We define "combustion efficiency" as the ratio of heat transferred to boiler water/steam to the total fuel energy supplied. The following is a method for calculating combustion efficiency.

The minimum amount of air required for complete combustion is called the "stoichiometric" air. As an example, the equation for the stoichiometric combustion of natural gas (comprised mostly of methane, CH_4) with atmospheric air is:

$$CH_4 + 2\ (O_2 + 3.76\ N_2) \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2 \qquad (1)$$

The ratio of the mass of air required to completely combust a given mass of fuel is called the stoichiometric air/fuel ratio, AFs. For natural gas, AFs is about 17.2 kg-air/kg-ng. The quantity of air supplied in excess of stoichiometric air is called excess air, EA. Excess air can be written in terms of the stoichiometric air/fuel ratio, the combustion air mass flow rate, m_{ca}, and fuel mass flow rate, m_f.

$$EA = [(m_a / m_f) / AFs] - 1 \qquad (2)$$

Large quantities of excess air dilute combustion gas and lower its temperature, resulting in decreased efficiency.

The energy input, Q_{in}, to a combustion chamber is the product of fuel mass flow rate and higher heating value, HHV (about 23,900 Btu/lbm for natural gas).

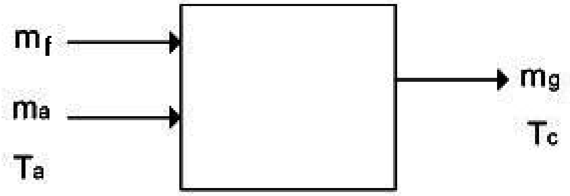
$$Q_{in} = m_f\ HHV \qquad (3)$$

The combustion gas mass flow rate, m_g, is the sum of the fuel mass flow rate and combustion air mass flow rate, m_a.

$$m_g = m_f + m_a \qquad (4)$$

The combustion temperature, T_c, can be calculated from an energy balance on the combustion chamber (figure 1), where the chemical energy released during combustion is converted into sensible energy gain of the gasses.

Figure 1. Mass Balance on Combustion Chamber



The energy balance reduces to the terms of inlet combustion air temperature, T_a, fuel lower heating value, LHV (about 21,500 Btu/lbm for natural gas), excess air, stoichiometric air fuel ratio, and combustion gas specific heat, Cp_g (about 0.26 Btu/lbm-F) (Carpenter and Kissock 2005). Equation 5 calculates combustion temperature in terms of these easily measured values.

$$T_c = T_a + LHV / [\{1 + (1 + EA)\ AFs\}\ Cp_g] \quad (5)$$

Combustion efficiency, η, is the ratio of energy transferred to boiler steam/water to the total fuel energy supplied. The energy transferred to steam/water is the energy loss of combustion gas as it travels through the boiler. On a per unit basis, its equation can be written as an enthalpy difference in terms of combustion temperature and exhaust temperature, T_{ex}. The total fuel energy supplied on a per unit basis is the fuel's higher heating value. Equation 6 calculates combustion efficiency in terms of easily measured values.

$$\eta = [\{1 + (1 + EA)\ AFs\}\ Cp_g\ (T_c - T_{ex})] / HHV \quad (6)$$

The variables in equations 5 and 6 that determine combustion efficiency are combustion air temperature, excess air, and exhaust temperature. Exhaust temperature and excess air, can be measured using a combustion analyzer. Combustion air temperature is typically the boiler room air temperature, and exhaust temperature depends largely on boiler steam pressure. The variable most subject to variance is excess air. The degree of excess air control is often the determining factor of a boiler's efficiency. The optimal quantity of excess air to guarantee complete combustion in most burners is about 10% (EPA 2001). This yields combustion gasses with about 1.7% O_2 content.

The useful heat output, Q_{out}, from a boiler is the heat input to the burner multiplied by combustion efficiency.

$$Q_{out} = Q_{in}\ \eta \quad (7)$$

Single-Point Positioning Control

In most boilers, a fuel valve regulates fuel to the burner and a combustion air damper regulates combustion air to the burner. The fuel valve is typically controlled by signals from the boiler's steam or hot water gauge and modulates based on heating demand. In single-point positioning control, the fuel valve is linked to the combustion air damper via a jackshaft mechanism to maintain correspondence between fuel and combustion air input.

Figure 2 shows an oil-fired burner with single-point positioning, and figure 3 displays the details of the burner's jackshaft mechanism. In figure 3, the electronic actuator, which receives signals from the boiler's pressure gauge, is linked to jackshafts that simultaneously move the oil valve and combustion air damper.

Figure 2. Burner with Single-Point Positioning

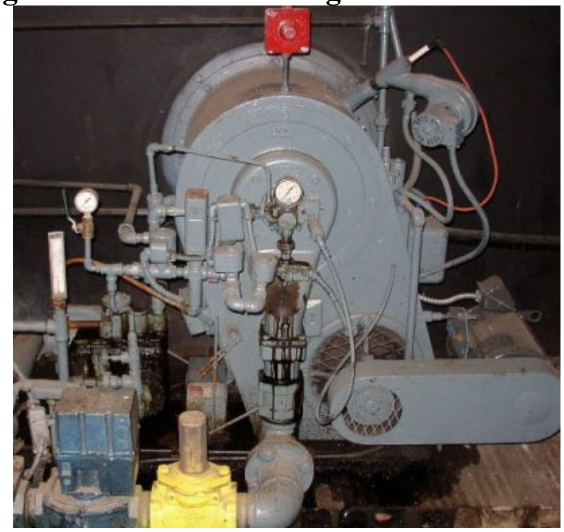
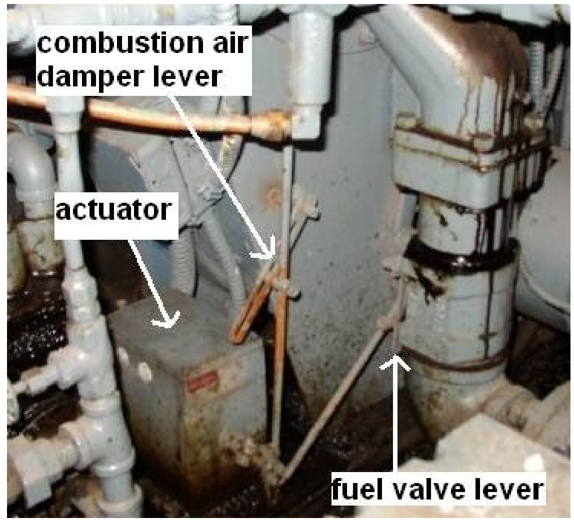


Figure 3. Burner's Linking Mechanism



The fuel valve, combustion air fan, and linking mechanism are usually calibrated by boiler service technicians at high fire. In an ideal scenario, excess air in a boiler would be maintained at 10% throughout the entire firing range. In reality, maintaining 10% excess air in a single-point positioning system is rather difficult. A well-calibrated and well-controlled single-point positioning system can maintain excess air levels between 10% and 30%. However, most systems do not maintain such levels.

Well-Controlled Combustion Air Case

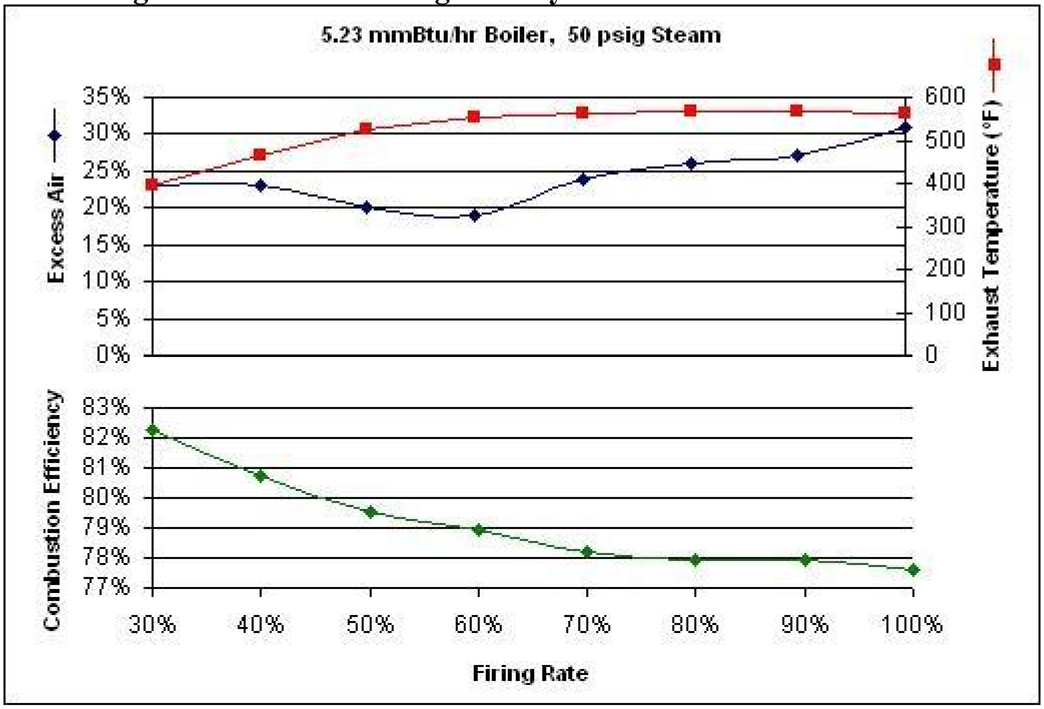
Table 1 and figure 4 present a case study of a process boiler at a candle-making factory with well-controlled excess air. This boiler is an unusual case in which the fuel valve and combustion air damper act almost linearly. No particular care was given to this boiler, though the linkages allow for nearly constant excess air over the firing range.

Excess air and exhaust temperature were measured with a combustion analyzer, and combustion efficiency was calculated using equations 5 and 6.

Table 1. Candle-Making Factory Boiler: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Exhaust Temp. (^oF)	Combustion Efficiency
100%	31%	562	77.6%
90%	27%	567	77.9%
80%	26%	567	77.9%
70%	24%	563	78.2%
60%	19%	553	78.9%
50%	20%	526	79.5%
40%	23%	465	80.7%
30%	23%	397	82.3%

Figure 4. Candle-Making Factory Boiler: Plotted Data Points



Note that exhaust temperature decreases at lower firing rates. This is due to combustion gasses moving more slowly through the boiler at lower firing rates, causing gas residence time within the boiler to increase. Increased residence time facilitates heat transfer, allowing each gas volume to exchange more heat and therefore exhaust at a lower temperature. In a well-controlled combustion air scenario, a boiler's combustion efficiency significantly rises at decreased firing rates.

Manufacturer's Data

Table 2 shows manufacturer's specifications for boiler combustion efficiency over its firing range. Although the efficiency increase is not as significant as the example presented in table 1, the manufacturer's specifications follow the consensus that combustion efficiency increases as firing rate decreases. Boiler manufacturers throughout the industry generally follow this consensus.

Table 2. Combustion Efficiency from Manufacturer's Specifications

Firing Rate	25%	50%	75%	100%
Combustion Efficiency	84%	84%	83%	82%

Source: Clayton 2007

Typical Cases and the Common Trend

The level of control by the combustion system presented in table 1 is very uncommon. The majority of industrial boilers we have analyzed do not have linear-acting fuel valves and combustion air dampers and do not maintain low excess air levels over their firing range. Due to the fact that boiler technicians usually calibrate single-point positioning burners at high fire, excess air levels can dramatically increase as burners turn down to medium and low fire. The following cases demonstrate typical performances in boilers with single-point positioning control.

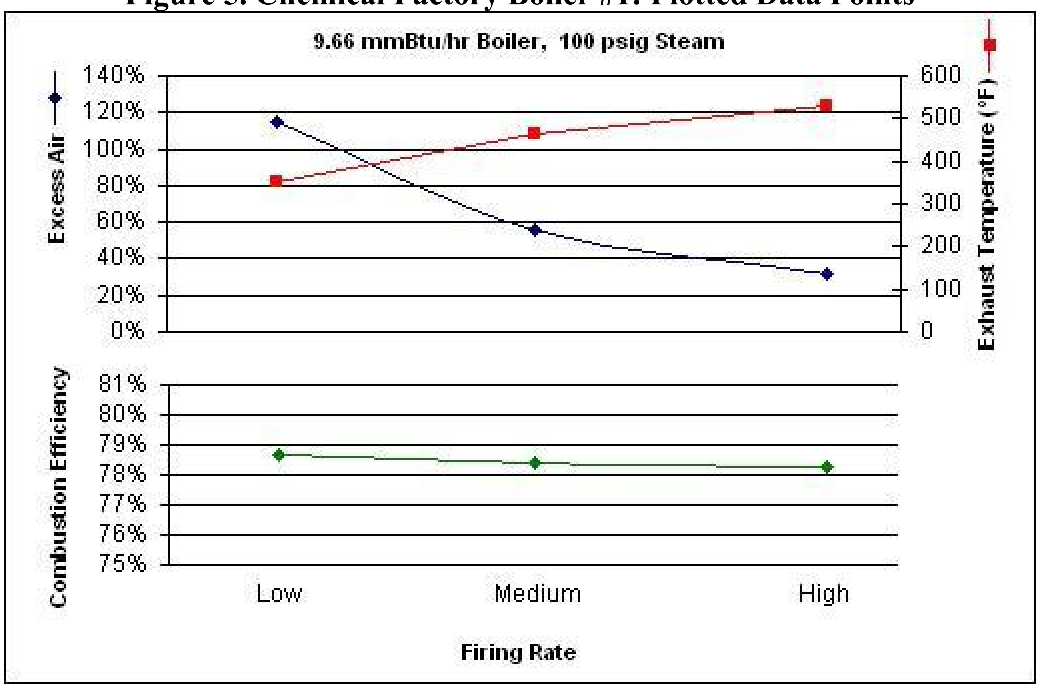
Case 1: Chemical Factory Boiler (9.66 mmBtu/hr)

Table 3 and figure 5 present a case study of a process boiler at a chemical factory. This boiler shows relatively low excess air levels at high fire, but those levels gradually increase as firing rate decreases. As a result, combustion efficiency shows virtually no increase at low fire from high fire despite a significantly lower exhaust temperature.

Table 3. Chemical Factory Boiler #1: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Exhaust Temp. (°F)	Combustion Efficiency
High	32%	531	78.3%
Medium	56%	463	78.4%
Low	115%	352	78.7%

Figure 5. Chemical Factory Boiler #1: Plotted Data Points



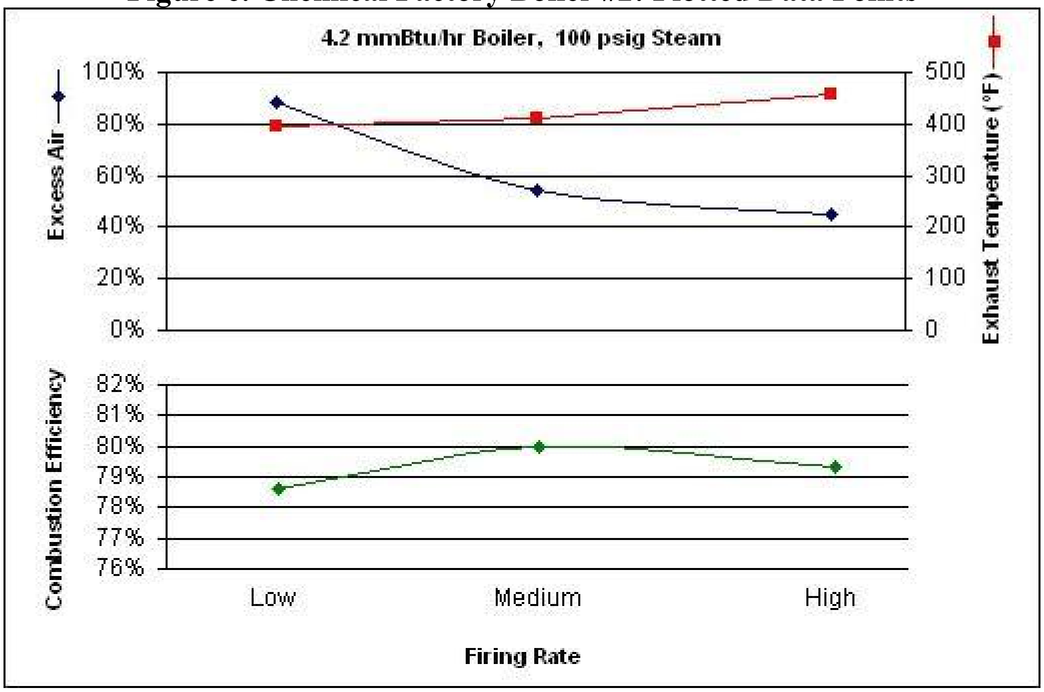
Case 2: Chemical Factory Boiler (4.2 mmBtu/hr)

Table 4 and figure 6 present a case study of another process boiler at the same chemical factory. This boiler shows a similar upward excess air trend from high fire to low fire, however it is not as dramatic as the previous example. In this case, combustion efficiency is lower at low fire than at high fire.

Table 4. Chemical Factory Boiler #2: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Ex. Temp. (°F)	Combustion Efficiency
High	45%	457	79.3%
Medium	54%	412	80.0%
Low	88%	394	78.6%

Figure 6. Chemical Factory Boiler #2: Plotted Data Points



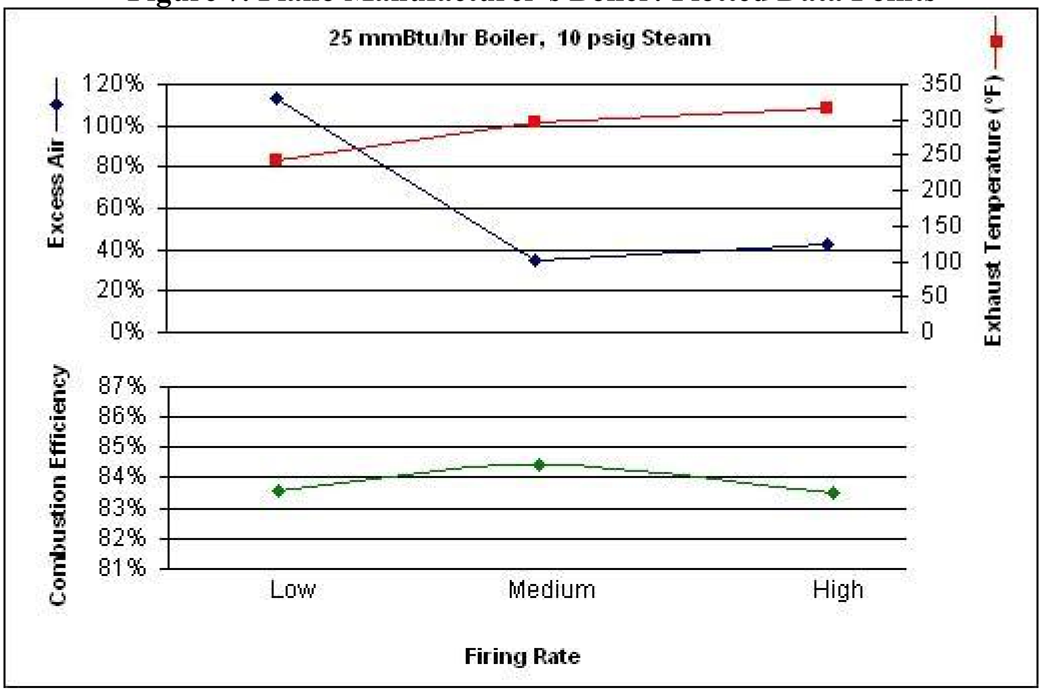
Case 3: Piano Manufacturing Facility Boiler

Table 5 and figure 7 present a case study of a boiler used for both process heat and space heat at a piano-manufacturing facility. Although excess air is relatively high at high fire, its level slightly decreases at medium fire, but then significantly increases at low fire. Combustion efficiency is highest at medium fire and about equal between high and low fire. Facility management stated that the boiler is calibrated at high fire. However, it is possible that the boiler service technician appropriately calibrated the boiler at medium fire, which may explain its relatively low medium-fire excess air.

Table 5. Piano Manufacturer's Boiler: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Ex. Temp. (°F)	Combustion Efficiency
High	43%	316	83.5%
Medium	35%	297	84.4%
Low	113%	243	83.6%

Figure 7. Piano Manufacturer's Boiler: Plotted Data Points



Summary of Cases

It is clear from these three examples that boilers with single-point positioning share a common trend of increased excess air levels at decreased firing rates. Although excess air may decrease slightly at some point of lower firing rate, as seen in case 3 between high and medium fire, the general trend is upward as low fire is approached. The difference in excess air level between high and low fire is typically between 30% and 80%. Although boilers should ideally be most efficient at low fire due to improved heat transfer and lower exhaust temperatures, the high excess air levels limit boilers' ability to reach their optimal efficiency. The examples demonstrate that the boilers' low-fire efficiency is either just slightly greater or even less than high-fire efficiency despite lower exhaust temperatures at low fire.

Addressing the Issue: Methods to Improve Efficiency

Because most boilers typically operate throughout their entire firing range, opportunities exist to address the issue of low- and medium-fire inefficiency. The chemical factory boilers (cases 1 and 2), for example, supply steam to outdoor processes whose load varies with outdoor temperature. The piano manufacturer's boiler (case 3) provides winter space heating in addition to process heating and therefore operates at low fire during summer months. Two methods of maintaining low excess air levels throughout the year are (1) frequently monitoring and calibrating excess air levels or (2) installing digital monitoring controls.

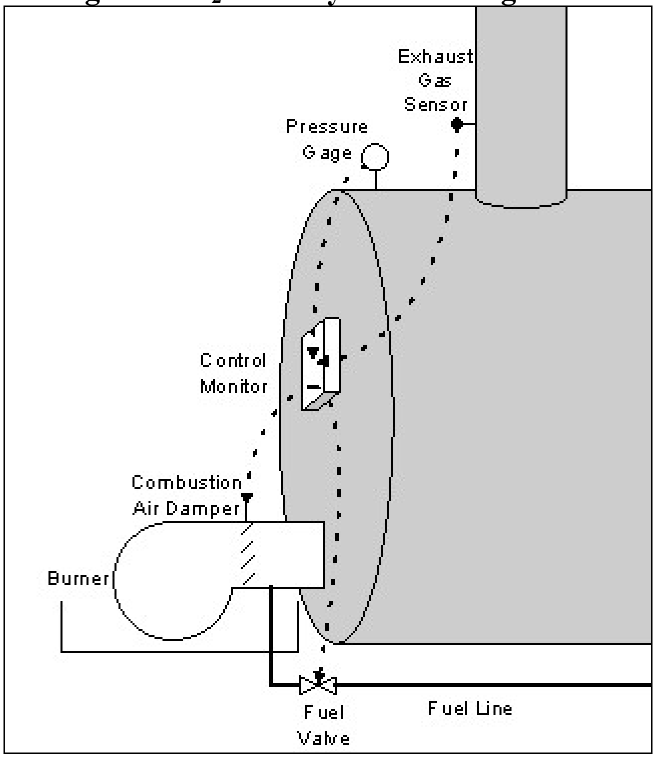
Monitoring and Calibrating Excess Air Levels

As stated earlier, boiler air/fuel ratio is typically calibrated at high fire. Often, boilers are only calibrated once or twice per year. To compensate for changing loads throughout the year, particularly if loads are weather-dependent, boilers could be calibrated more frequently and be calibrated for their current load. For example, a boiler that serves space heating equipment could be calibrated at high fire during winter and be calibrated at medium or low fire during warmer periods. To achieve best results, calibration should occur frequently—at least once a month. A combustion analyzer is needed to monitor excess air levels during calibration. The person performing calibration should be fully aware of the boiler's firing rate and range during the calibration period.

Digital Monitoring Controls

For best excess air control, a digital monitoring control system, often called an "O_2 trim" system, can be installed on a boiler. An O_2 trim system consists of an exhaust-gas monitoring probe that communicates with the combustion air inlet damper via a central digital controller. Based on the O_2 level detected in the exhaust gas, the combustion air damper automatically adjusts to achieve a user-defined excess air setpoint. To optimize combustion efficiency over a boiler's firing range, the O_2 setpoint should be set to 1.7%, which corresponds to 10% excess air. Rather than be linked by a jackshaft as in single-point positioning, the fuel valve and combustion air damper are controlled independently in O_2 trim control. Figure 8 displays the arrangement of a boiler O_2 trim system.

Figure 8. O_2 Trim System Arrangement



In addition to maintaining excess air at desired levels, O_2 trim eliminates the general safety protocol to calibrate excess air slightly higher than desired. For example, case 1 presented above showed low excess air at high fire, however excess air was still above the desired 10%. Excess air in the well-controlled case presented above, although low throughout the firing range, was also still above 10%. O_2 trim would allow for 10% excess air throughout the firing range.

O_2 trim controls are commercially available and typically cost between \$20,000 and \$30,000 per system. Boiler suppliers and technicians generally recommend that an O_2 trim system be calibrated three to four times per year, which results in an annual maintenance cost of between \$1,500 and \$2,000 (Turton 2005).

Energy-Savings Potential

Methodology for Calculating Savings

To calculate energy savings from reducing excess air to a lower level (i.e. 10%), equations 5 and 6 can be used to calculate combustion efficiency, η, with current excess air quantity, and new combustion efficiency, η_n, with reduced excess air. Exhaust temperature, T_{ex}, in equation 6 may change slightly as excess air changes. However, the change is typically small and can be neglected (Carpenter and Kissock 2005). When an energy-savings measure is implemented to improve combustion efficiency from η to η_n, the useful energy output, Q_{out}, from a boiler remains the same, but energy input reduces from Q_{in} to $Q_{in,n}$. Thus,

$$Q_{in} / \eta = Q_{in,n} / \eta_n \qquad (8)$$

Energy savings, Q_{sav} is the difference between Q_{in} and $Q_{in,n}$.

$$Q_{sav} = Q_{in} - Q_{in,n} \qquad (9)$$

Combining equation 8 with equation 9 gives:

$$Q_{sav} = Q_{in} (1 - \eta / \eta_n) \qquad (10)$$

Case Study

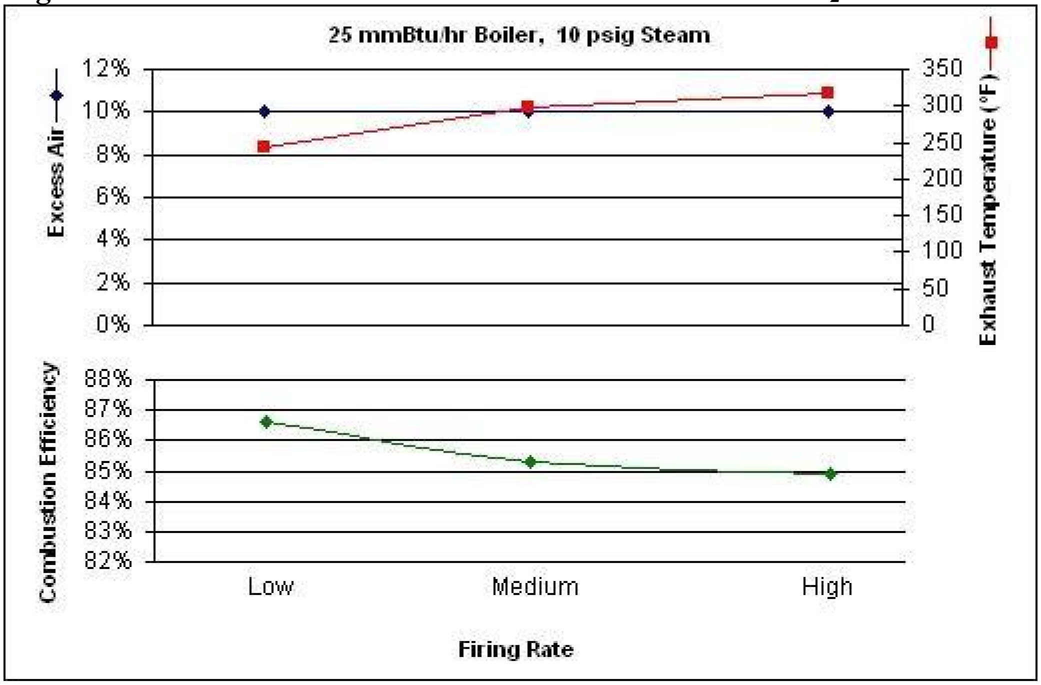
The boiler in the piano manufacturing facility from case 3 above is used for heat in the plant's board-pressing process and is also used for winter space heating. The boiler's capacity is so large that it is approximately only half loaded during the coldest winter period. During all of summer and much of spring and fall, the boiler operates at its lowest setting to support the process heating load. As shown in table 5, low fire operation constitutes the highest excess air level. To improve efficiency, plant management recently proposed installing an O_2 trim system.

The O_2 trim system would not only dramatically reduce low fire excess air, but would also reduce high and medium fire excess air, thus improving efficiency at every firing rate. Table 6 and figure 9 present the boiler's performance when equipped with an O_2 trim system with a 10% excess air setpoint.

Table 6. Piano-Manufacturer's Boiler: Operating Parameters with O_2 Trim Control

Firing Rate	Excess Air	Exhaust Temp. (°F)	Combustion Efficiency
High	10%	316	84.9%
Medium	10%	297	85.3%
Low	10%	243	86.6%

Figure 9. Piano Manufacturer's Boiler: Performance with O_2 Trim Control



Based on the boiler's 2005 natural gas consumption and its improved combustion efficiency at low and medium fire, table 7 presents the annual natural gas savings from installing O_2 trim. Equation 10 was used to calculate natural gas savings.

Table 7. Piano-Manufacturer's Boiler: Operating Parameters with O_2 Trim Control

Month	Number of Days	Monthly Natural Gas Use (mmBtu/mo)	Average Hourly Usage (mmBtu/hr)	Firing Rate	Baseline		Proposed		Natural Gas Savings (mmBtu/mo)
					Excess Air	Combustion Efficiency	Excess Air	Combustion Efficiency	
January	31	7,864	10.57	Medium	35%	84.4%	10%	86.6%	83
February	28	8,301	12.35	Medium	35%	84.4%	10%	86.6%	88
March	31	9,417	12.66	Medium	35%	84.4%	10%	86.6%	99
April	30	4,818	6.69	Low	113%	83.6%	10%	85.3%	167
May	31	3,809	5.12	Low	113%	83.6%	10%	85.3%	132
June	30	2,628	3.65	Low	113%	83.6%	10%	85.3%	91
July	31	2,521	3.39	Low	113%	83.6%	10%	85.3%	87
August	31	2,549	3.43	Low	113%	83.6%	10%	85.3%	88
September	30	2,567	3.57	Low	113%	83.6%	10%	85.3%	89
October	31	4,142	5.57	Low	113%	83.6%	10%	85.3%	144
November	30	6,797	9.44	Medium	35%	84.4%	10%	86.6%	72
December	31	8,244	11.08	Medium	35%	84.4%	10%	86.6%	87
Total		**63,656**							**1,227**

Based on 2005 natural gas consumption data

At an average cost of $12 per mmBtu, an annual savings of 1,227 mmBtu equates to $14,724 per year. Assuming $2,000 per year is required for system calibration and maintenance, the net annual savings would be approximately $12,724. The O_2 trim system costs about $30,000, resulting in about a 28-month payback.

Summary and Conclusions

This paper described a method to determine combustion efficiency based on three easily measured parameters: combustion air temperature, excess air, and exhaust temperature. Of the three, the one most subject to variance and most difficult to control in boilers is excess air. This is especially the case in boilers with single-point positioning control consisting of a mechanically linked fuel valve and combustion air damper.

A case study was presented of a boiler with single-point positioning control that exhibited well-controlled combustion air levels over its firing range. Subsequently, three case studies were presented of boilers exhibiting poorer-controlled combustion air levels over their firing range. These three cases show trends much more common in industry. In general, the common trend in boilers with single-point positioning control is an increase in excess air levels with decreased firing rate. The difference in excess air level between high and low fire is typically between 30% and 80%.

The paper described two methods to address the problem of high excess air levels at low fire. The first method is to frequently monitor and calibrate excess air levels, which is a relatively inexpensive method but requires persistent maintenance. The second method is to install digital monitoring (O_2 trim) controls, which is the state-of-the-art for excess air control, but involves a significant capital investment.

Finally, the paper presented a case study of a manufacturing company who has proposed to install an O_2 trim system on its boiler that operates at low fire for much of the year. The annual savings would result in an approximate 28-month payback on the O_2 trim system.

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