Common Boiler Excess Air Trends and Strategies to Optimize Efficiency

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ABSTRACT

Boilers are among the most common heating equipment in commercial facilities, often consuming the majority of a facility's fuel. The load on a boiler plant in a commercial facility constantly fluctuates depending on weather conditions, occupancy rate, and internal heat gains. Proper control of part-load operation can significantly affect energy use.

Most boilers in medium-to-large commercial facilities are equipped with a single-point positioning control that has a shaft mechanically linking the fuel control valve with the combustion air damper. With this control, the air-to-fuel ratio is typically calibrated at high fire, or near 100% capacity. However, as the load on the boiler decreases and the fuel valve begins to close, the combustion air flow is decreased at a lower rate due to the non-linearity of the linkage between the fuel valve and the combustion air damper. This results in increased excess air levels at medium and low fire, yielding poorer efficiencies. While boilers could potentially have higher efficiencies at reduced firing rates, high excess air levels trump the efficiency gains at part-load and significantly lower the efficiency.

Linkageless burner controls and O_2 trim controls are much more energy-efficient combustion control packages. Both of these packages allow the fuel valve and combustion air damper to operate independently of one another.

This paper presents case studies demonstrating trends in excess air over boilers' firing range in commercial space-heating applications. Case studies include boilers with single-point positioning control and boilers with linkageless controls. For single-point positioning controls, the quantity of excess air rises with decreased firing rate, and the difference in excess air between high and low fire is typically between 40 and 80 percentage points. For linkageless controls, excess air remains relatively low throughout a burner's firing rate.

Introduction

Boilers are widely used in commercial buildings for 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 provide significant fuel and cost savings.

A large percentage of 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 boilers. It also presents and describes alternative combustion control mechanisms that can greatly increase energy efficiency. Methods to calculate energy savings from improved combustion control 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:

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

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 lbm-air/lbm-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_a, and fuel mass flow rate, m_f.

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

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).

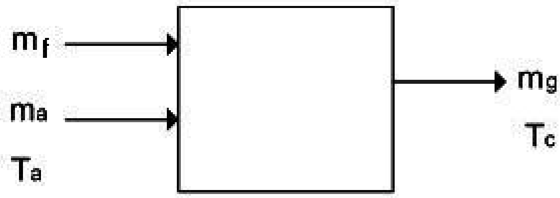
$$Q_{in} = m_f\ HHV \quad (3)$$

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

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

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% (DOE 2007). 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.

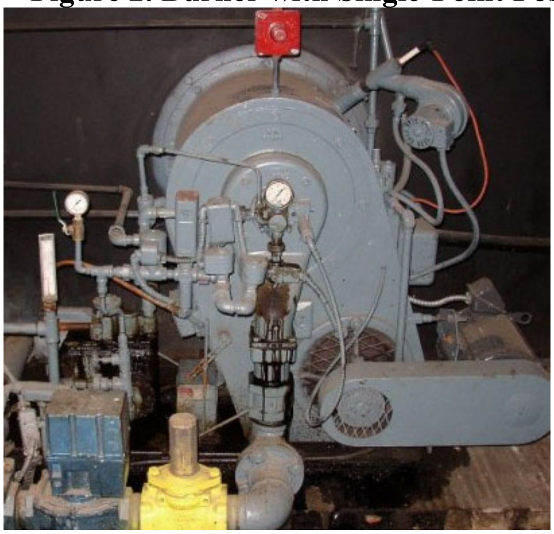
$$Q_{out} = Q_{in}\, \eta \quad (7)$$

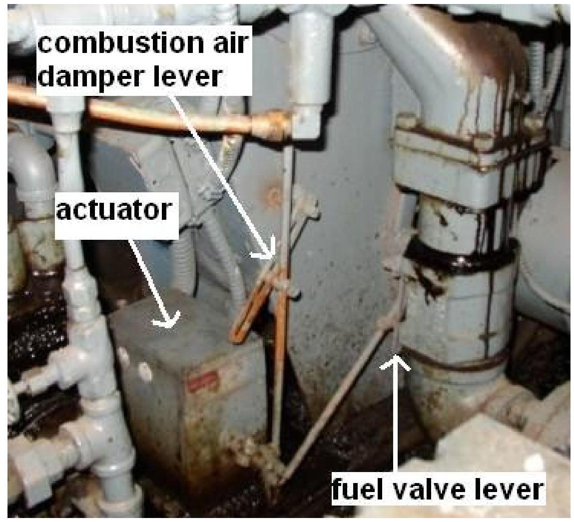
Single-Point Positioning Control

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.

Common Combustion Trends in Single-Point Positioning

Due to the non-linearity between the fuel valve and combustion air damper in single-point positioning control, the majority of single-point positioning boilers we have analyzed do not maintain low excess air levels over their firing range. Generally, boiler technicians calibrate single-point positioning burners at high fire. But as burners turn down to medium and low fire, excess air levels tend to dramatically increase. The following cases demonstrate typical performances in boilers with single-point positioning control.

Case 1: Piano Manufacturing Facility Boiler

Table 1 and Figure 4 present a case study of a boiler used for space heating and a small amount of process heating at a piano-manufacturing facility. It is apparent that exhaust temperature decreases at lower firing rates. This is due to combustion gases 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.

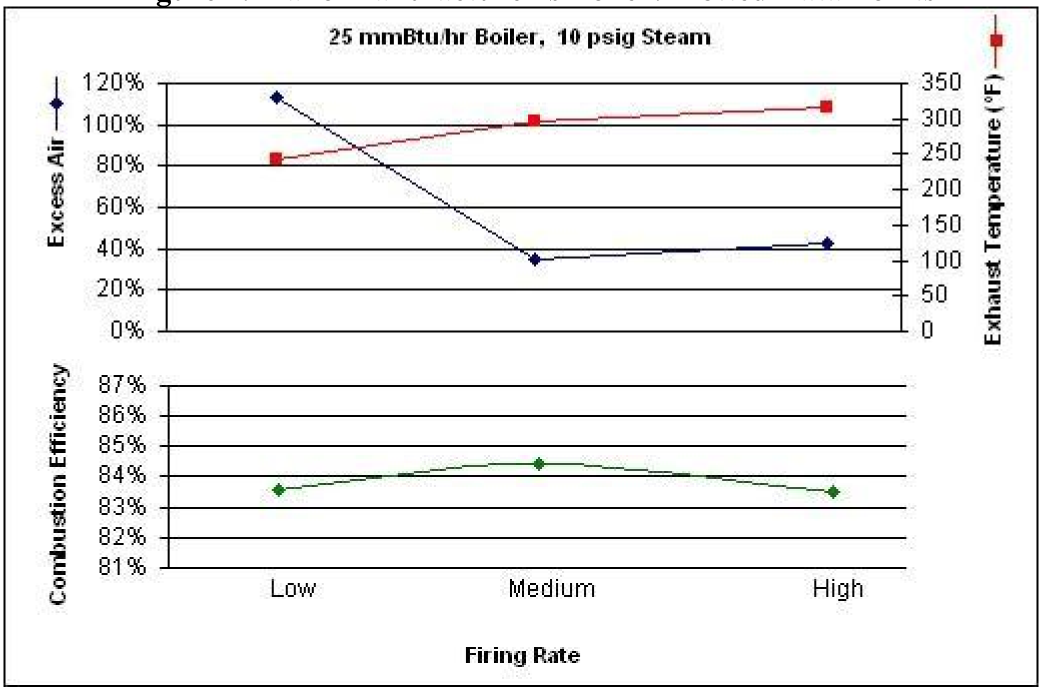
The boiler's excess air is at a relatively high 40% at high fire. This level slightly decreases at medium fire, but then significantly increases at low fire. Combustion efficiency is highest at medium fire and about equal between high and low fire.

If the boiler's excess air had remained constant throughout its firing range, combustion efficiency would have been highest at low fire when stack temperature is lowest.

Table 1. Piano Manufacturer's Boiler: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Exhaust Temp. (^oF)	Combustion Efficiency
High	43%	316	83.5%
Medium	35%	297	84.4%
Low	113%	243	83.6%

Figure 4. Piano Manufacturer's Boiler: Plotted Data Points



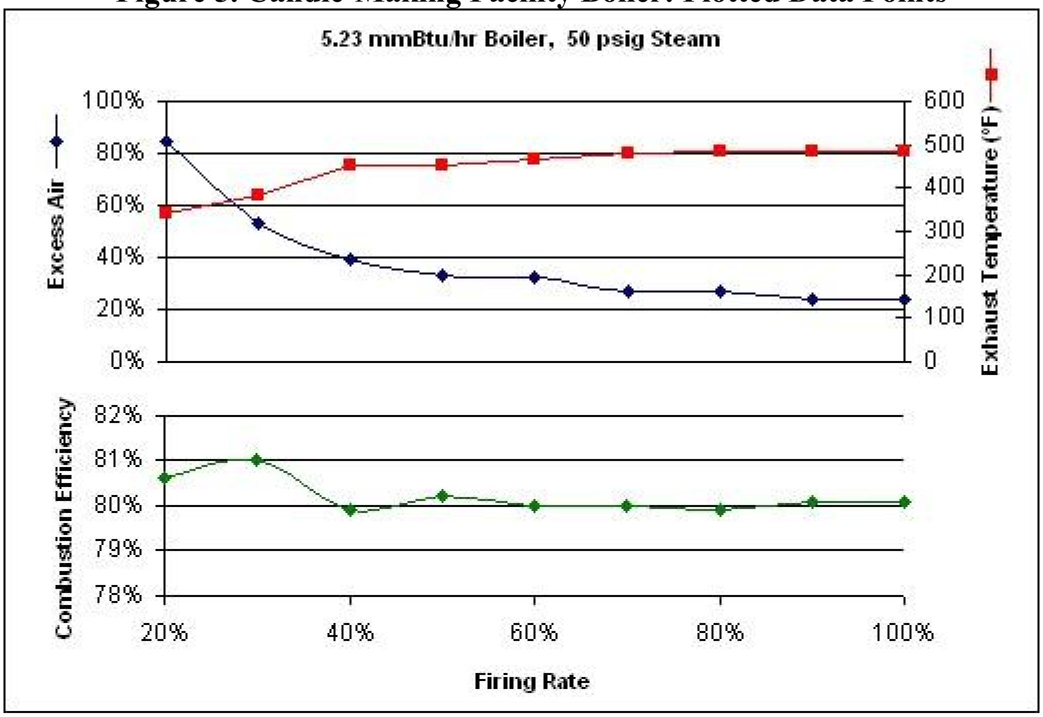
Case 2: Candle-Making Facility Boiler

Table 2 and Figure 5 present a case study of a boiler used for space heating and process heating at a candle-making facility. 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. Exhaust temperature also decreases in this example as firing rate decreases. Combustion efficiency is slightly higher at low fire than at high fire, but not nearly as high as it could potentially be.

Table 2. Candle-Making Facility Boiler: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Exhaust Temp. (°F)	Combustion Efficiency
100%	24%	485	80.1%
90%	24%	486	80.1%
80%	27%	485	79.9%
70%	27%	482	80.0%
60%	32%	467	80.0%
50%	33%	454	80.2%
40%	39%	451	79.9%
30%	53%	381	81.0%
20%	85%	341	80.6%

Figure 5. Candle-Making Facility Boiler: Plotted Data Points



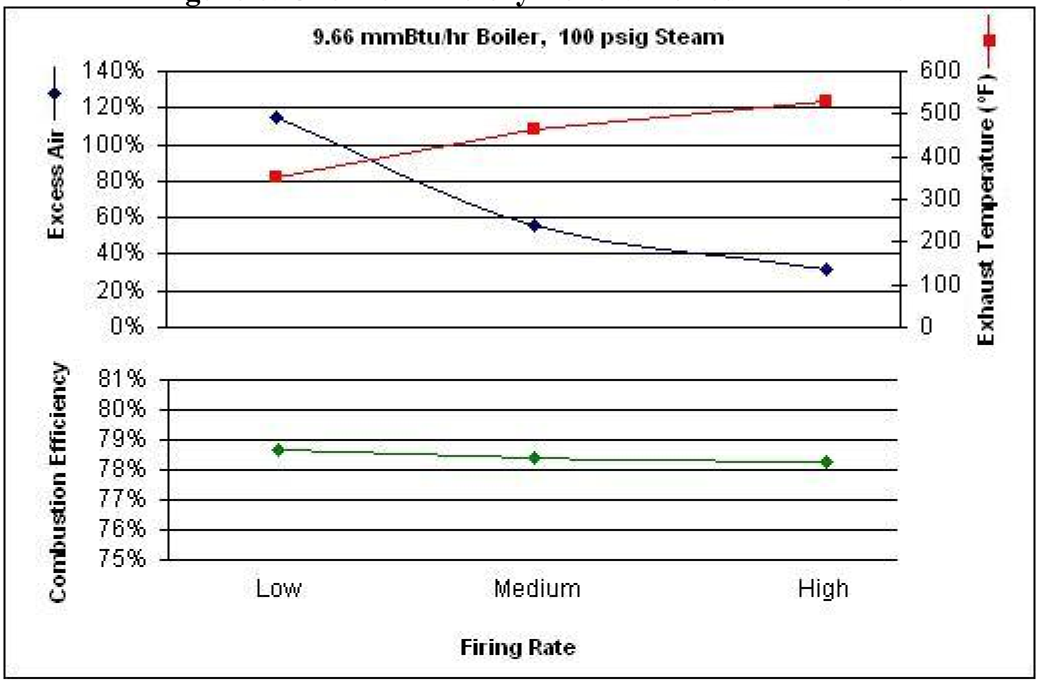
Case 3: Chemical Factory Boiler

Table 3 and Figure 6 present a case study of a process boiler at a chemical factory. Although it is an industrial process boiler, it operates the same as any commercial-facility boiler. 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: 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 6. Chemical Factory Boiler: Plotted Data Points



Summary of Cases

It is clear from these three cases 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 in Case 1 between high and medium fire, the general trend is upward as low fire is approached. The difference in excess air levels between high fire and low fire ranges from 61 to 83 percentage points in these three cases. In general, this difference between high and low fire ranges from 40 to 80 percentage points in most boilers. 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.

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. For example, the piano manufacturer's boiler (Case 1) and the candle-making facility boiler (Case 2) provide winter space heating in addition to process heating and therefore operate at lower firing rates during non-winter months. The chemical factory boiler (Case 3) supplies steam to outdoor processes whose load varies with outdoor temperature.

One method of maintaining low excess air levels throughout the year is to frequently monitor and calibrate excess air levels. Another method is to replace the single-point positioning controls with linkageless controls or 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 weather-dependent loads, 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.

Linkageless Burner Controls

For better-controlled combustion air intake, linkageless burner controls could be installed as an alternative to single-point positioning controls. In a linkageless control system, the fuel valve and combustion air damper are each powered by a separate actuator. This allows the combustion air damper position to be adjusted and set for optimal efficiency at several firing rates (usually at 10% increments) throughout the burner's range and maintain a consistent excess air level. The control system's memory allows the damper actuator to return the damper to every pre-set position for all firing rates. Figures 7 and 8 present photos of the primary components of a linkageless system, and Figure 9 presents a complete photo of a burner equipped with linkageless controls.

Figure 7. Fuel Valve in Linkageless Control System

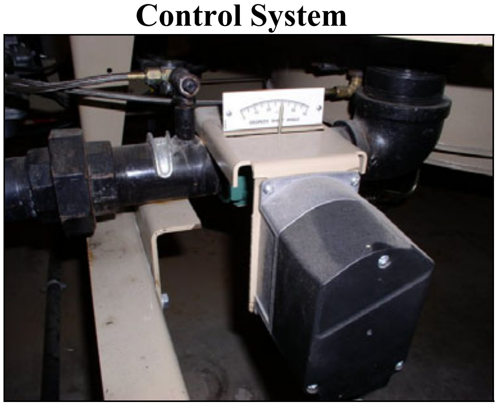
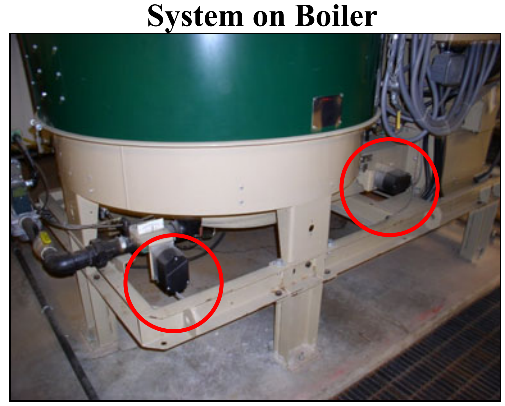


Figure 8. Combustion Air Damper in Linkageless Control System

Figure 9. Linkageless Control System on Boiler



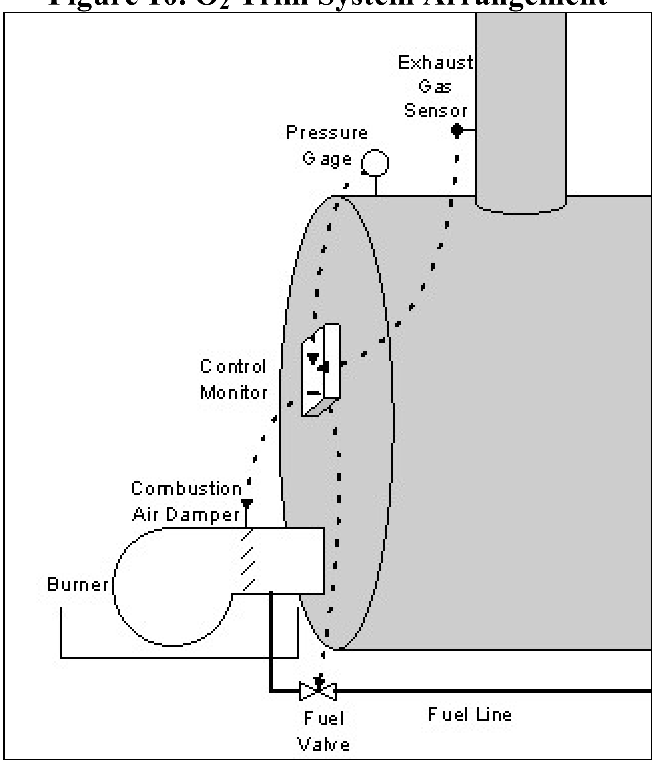
Because a linkageless control system involves fewer mechanisms than a single-point positioning system, it is less prone to falling out of tune. Thus, it decreases the safety need to calibrate excess air slightly higher than desired. The three cases presented above demonstrate excess air levels greater than 20% at high fire; perhaps intentionally calibrated high to ensure a safety factor in the case that controls falling out of tune.

Linkageless burner systems typically cost between $12,000 and $14,000 per system. These systems can be factory installed or installed as a retrofit. Many new boilers on the current market offer a linkageless system as the standard option. Boiler suppliers and technicians generally recommend that a linkageless control system be calibrated three to four times per year (Oliver 2008). This could result in an annual maintenance cost of between $1,500 and $2,000.

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. Similar to linkageless controls, the fuel valve and combustion air damper are controlled independently. Figure 10 displays the arrangement of a boiler O_2 trim system.

Figure 10. O_2 Trim System Arrangement



Perhaps to a higher extent than linkageless controls, O_2 trim reduces or eliminates the general safety protocol to calibrate excess air slightly higher than desired.

O_2 trim controls 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).

Calculating Energy Savings from Reduced Excess Air

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 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 from a boiler remains the same, but energy input reduces from Q_{in} to $Q_{in,n}$. Thus,

$$Q_{in} / \eta = Q_{in,n} / \eta_n \tag{8}$$

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

$$Q_{sav} = Q_{in} - Q_{in,n} \tag{9}$$

Combining Equation 8 with Equation 9 gives:

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

Case Study of Facility with Linkageless Burner Controls

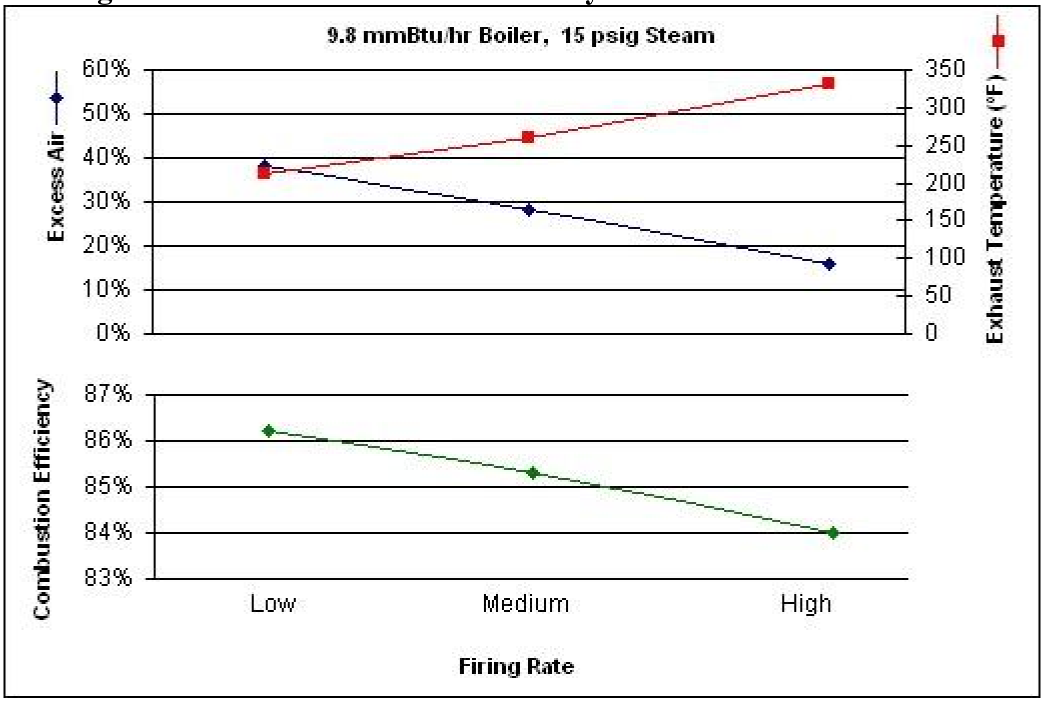
A 2 million square-foot commercial facility that houses subdivided tenant space recently installed four 9.8 mmBtu natural gas-fired boilers for facility space heating. Each boiler is a Clayton steam generator with a linkageless burner control system that was factory installed as the standard option. Typically, three of the four boilers operate during the heating season and modulate to meet the facility's heating demand.

The linkageless burner controls allow the boilers to be set to a low excess air level at high fire. Measurements indicate that excess air increases slightly as firing rate decreases; however, the increase is much less dramatic than the previous three examples. Table 4 and Figure 11 present the performance of one of the four facility boilers. Excess air increases by only 22 percentage points between high and low fire. Combustion efficiency is over two percentage points higher at low fire than at high fire. The remaining two operating boilers perform similarly.

Table 4. Commercial Tenant Facility Boiler: Measured Values and Calculated Combustion Efficiency

Firing Rate	Excess Air	Exhaust Temp. (^{o}F)	Combustion Efficiency
High	16%	332	84.0%
Medium	28%	260	85.3%
Low	38%	212	86.2%

Figure 11. Commercial Tenant Facility Boiler: Plotted Data Points



To calculate natural gas savings resulting from the linkageless system, we consider the boilers' current efficiency compared to the efficiency that would result from having the same excess air profile as a typical boiler with single-point positioning controls. In the following analysis, we use the piano manufacturer's excess air profile that is presented in Figure 4 as the typical, or baseline, profile. Based on the facility's 2007 natural gas consumption and its improved combustion efficiency, Table 5 presents the annual natural gas savings per boiler resulting from linkageless burner controls. The facility's heating load was assumed to be shared equally among its three operating boilers. Equation 10 was used to calculate natural gas savings.

Table 5. Commercial Tenant Facility: Natural Gas Savings per Boiler from Linkageless Burner Controls

Month	Monthly Facility Natural Gas Use (mmBtu/mo)*	Average Hourly Usage per Boiler (mmBtu/hr)	Firing Rate	Single-Point Control		Linkageless Control		Natural Gas Savings per Boiler (mmBtu/mo)
				Excess Air	Combustion Efficiency	Excess Air	Combustion Efficiency	
January	12,652	5.67	Medium	35%	85.0%	28%	85.3%	44
February	12,735	6.32	Med/High	39%	83.9%	22%	84.7%	120
March	10,954	4.91	Medium	35%	85.0%	28%	85.3%	39
April	8,694	4.02	Med/Low	74%	84.6%	33%	85.8%	122
May	6,121	2.74	Low	113%	84.2%	38%	86.2%	142
June	1,809	0.84	Low	113%	84.2%	38%	86.2%	42
July	0	0.00	Off	-	-	-	-	0
August	0	0.00	Off	-	-	-	-	0
September	0	0.00	Off	-	-	-	-	0
October	4,346	1.95	Low	113%	84.2%	38%	86.2%	101
November	8,331	3.86	Med/Low	74%	84.6%	33%	85.8%	117
December	11,505	5.15	Medium	35%	85.0%	38%	85.3%	40
Total	**77,145**							**767**

*From 2007 facility natural gas bills. This is the total consumption of three 9.8 mmBtu/hr operating boilers.

The calculated savings is 767 mmBtu per boiler, or 2,301 mmBtu for all three boilers. At an average annual cost of \$11.63 per mmBtu that the facility pays, an annual savings of 2,301 mmBtu equates to \$26,760 per year. Although the linkageless control system came factory installed as the standard option, a system typically costs between \$12,000 and \$14,000 (Oliver 2008). Assuming such a system added \$13,000 to each boiler's purchase cost, the total cost of four systems is approximately \$52,000. The resulting simple payback is approximately 2 years.

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.

Three case studies were presented of boilers exhibiting an increase in excess air levels with decreased firing rate. This is the common trend for boilers with single-point positioning control serving commercial facilities. The difference in excess air level between high and low fire is typically between 40 and 80 percentage points.

The paper described three 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 a linkageless control system that can be pre-set to maintain desirable excess air levels throughout a burner's firing range. The third 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 large commercial facility that recently installed new boilers with linkageless burner controls. The resulting annual savings from this system relative to a standard single-point positioning control system is approximately \$26,760 with a 2-year payback.

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