FIRED HEATER OPTIMIZATION

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ABSTRACT

Process heaters, furnaces and fired heaters account for most of the energy costs associated with running hydrocarbon processing and chemical plants. Continuous measurement of both oxygen (O_2) and combustibles in the radiant section of the heater provides the information needed for effective heater operation with significant benefits in energy savings, NOx (oxides of nitrogen) reduction, product quality, product throughput, heater and tube life, as well as safety. Widely varying fuel values, high temperatures, multiple burners and multiple cells provide special challenges to combustion optimization in fired heaters. This paper will discuss how reliable, properly located high-temperature oxygen and combustibles analyzers help meet heater performance objectives with minimal investment cost. A practical approach to setting up a heater will be outlined, along with examples of energy savings and NOx reduction.

INTRODUCTION

A fired heater is a direct-fired heat exchanger that uses the hot gases of combustion to raise the temperature of a feed flowing through coils of tubes aligned throughout the heater. Depending on the use, these are also called furnaces or process heaters. Some heaters simply deliver the feed at a predetermined temperature to the next stage of the reaction process; others perform reactions on the feed while it travels through the tubes.

Fired heaters are used throughout hydrocarbon and chemical processing industries such as refineries, gas plants, petrochemicals, chemicals and synthetics, olefins, ammonia and fertilizer plants. Most of the unit operations require one or more fired heaters as start-up heater, fired reboiler, cracking furnace, process heater, process heater vaporizer, crude oil heater or reformer furnace.

Heater fuels include light ends (e.g. refinery gas) from the crude units and reformers as well as waste gases blended with natural gas. Residual fuels such as tar, pitch, and Bunker C (heavy oil) are also used. Figure 1 shows a natural draft process heater with inspiration type burners. Combustion air flow is regulated by positioning the stack damper. Fuel to the burners is regulated from exit feed temperature and firing rate is determined by the level of production desired.

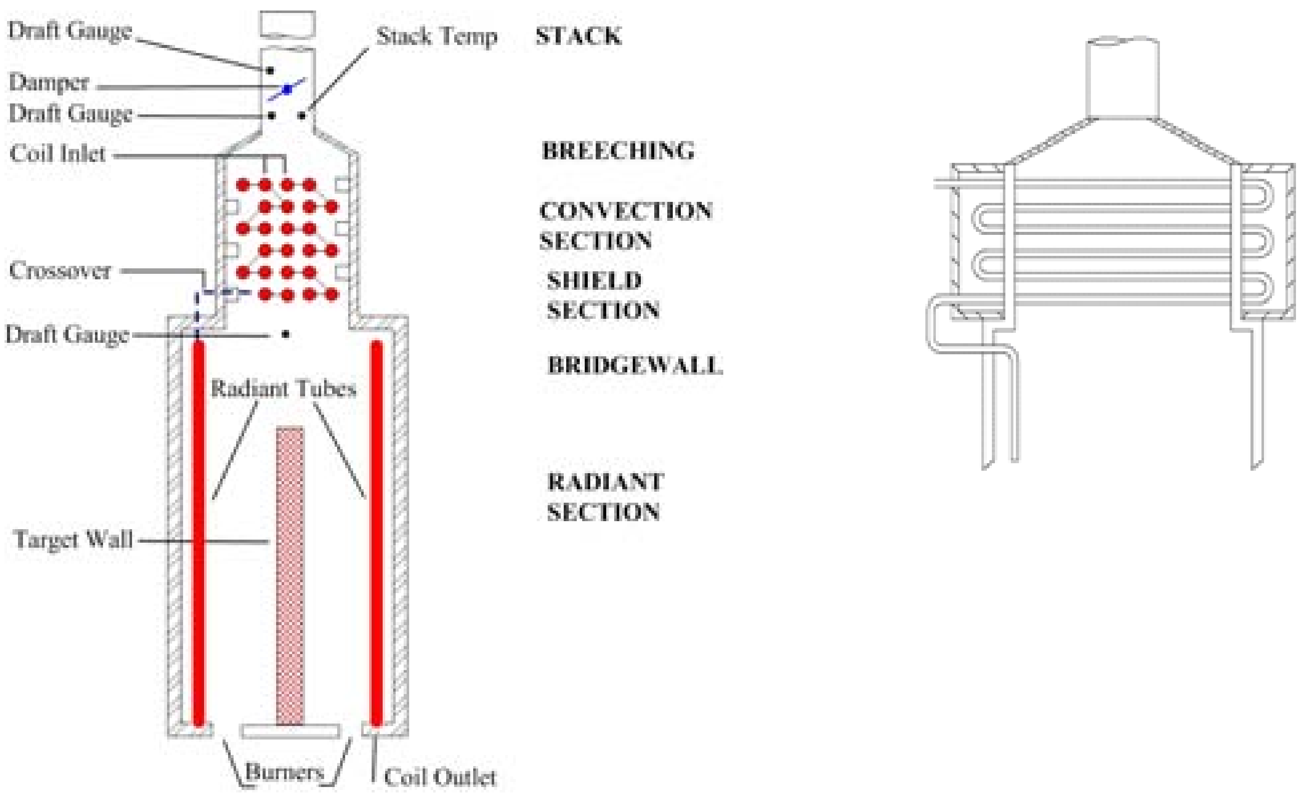


FIGURE 1 – ILLUSTRATION OF FIRED HEATER WITH SIDE VIEW OF TOP SECTION

Radiant Section: The radiant tubes, either horizontal or vertical, are located along the walls in the radiant section of the heater and receive radiant heat directly from the burners or target wall. The radiant zone with its refractory lining is the costliest part of the heater and most of the heat is gained there[1]. This is also called the firebox.

Convection Section: The feed charge enters the coil inlet in the convection section where it is preheated before transferring to the radiant tubes. The convection section removes heat from the flue gas to preheat the contents of the tubes and significantly reduces the temperature of the flue gas exiting the stack. Too much heat picked up in the convection section is a sign of too much draft. Tube temperature is taken in both convection and radiant sections.

Shield Section: Just below the convection section is the shield (or shocktube) section, containing rows of tubing which shield the convection tubes from the direct radiant heat. Several important measurements are normally made just below the shield section. The bridgewall or breakwall temperature is the temperature of the flue gas after the radiant heat is removed by the radiant tubes and before it hits the convection section. Measurement of the draft at this point is also very important since this determines how well the heater is set up. This is also the ideal place for flue gas oxygen and ppm (parts per million) combustibles measurement.

Stack and Breeching: The transition from the convection section to the stack is called the breeching. By the time the flue gas exits the stack, most of the heat should be recovered and the temperature is much less. From a measurement point of view, this location places fewer demands on the analyzer but is much less desirable for the ability to control the process. Measurement of stack emissions for compliance purposes is normally made here.

MEETING PERFORMANCE OBJECTIVES

The performance objectives of process heaters are to maximize heat delivery of the process-side feed while minimizing fuel consumption, maximize heat delivery with varying fuel quality, minimize heater structural wear, minimize stack emissions and maximize safety integrity levels. Proper monitoring and control brings benefits and avoids problems in the following areas of heater operation:

ENERGY SAVINGS

Energy costs represent up to 65% of the cost of running a chemical/petrochemical/refining complex[2]. Furnace and heater fuel is the largest component of this cost. Correct use and placement of gas analyzers can conserve the amount of fuel used and maximize heater efficiency. When waste fuel was cheap, the excess was often flared with little reason to seek efficiency improvements. Today many refinery processes require hydrogen (H_2), and a lot of the hydrogen-rich off-gases, which were previously used as heater fuel, are needed to meet this demand. Natural gas, which is now very expensive, is used to make up shortfalls. The more energy that can be squeezed from existing plant fuels, the less supplementary natural gas is required.

NOx REDUCTION

Stringent emission limits require greater control of NOx and other stack components. Operating the heater at optimum efficiency, with low excess air firing is the simplest and least expensive way to reduce NOx emissions[3].

PRODUCT QUALITY AND THROUGHPUT

Gases with widely varying calorific content are now widely used as fuel for heaters. This can produce large variations in heat delivered in the radiant section, and therefore, to greater demands on control of combustion to maintain the product or feed temperature. Localized heating can lead to coking and a drop in capacity. Temperature control of the process tubes and reactions is critical in reforming and cracking operations.

SAFETY

No information or incorrect information from a poorly placed analyzer can lead to unsafe operation of heaters from air leaks, tube leaks, and fuel or burner problems. Most furnace incidents occur during startup[4]. Purgedown and lightoff cycles require special care and warrant consideration of methane monitoring in addition to oxygen and ppm combustibles.

HEATER AND TUBE LIFE

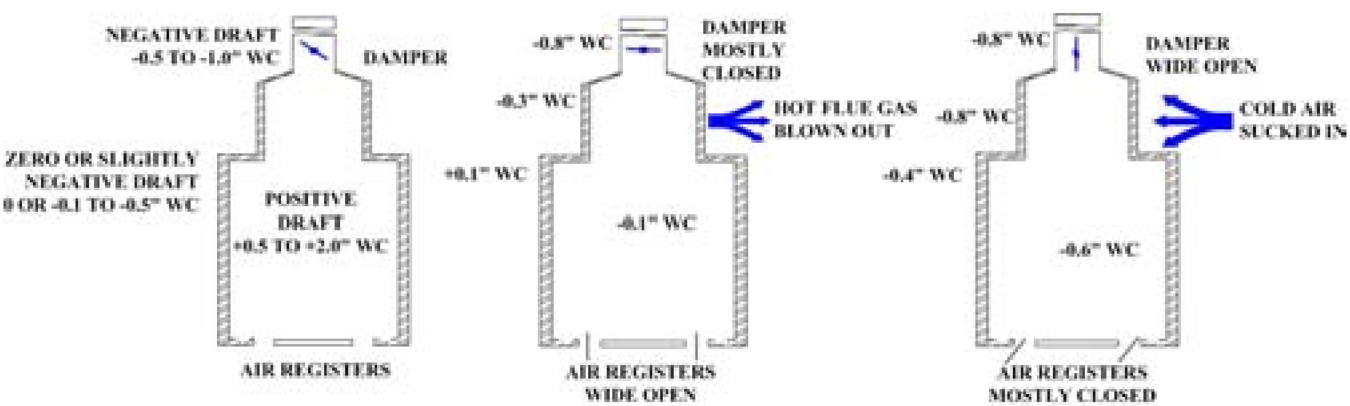
Incorrect operation leads to premature failure, structural damage or tube leaks due to flame impingement, secondary combustion and flue gas leaks[5].

FACTORS AFFECTING PROCESS HEATER OPERATION

Process heaters offer particular challenges for measurement and control due to high temperature in the radiant zone, multiple burners, multiple cells, widely varying fuel calorific value, low investment in heater optimization and the difficulties associated with low NOx burner operation. Factors affecting safe and efficient process heater performance include draft, burner operation, and NOx production.

DRAFT

Optimum operation requires that excess air in the flue gas entering the convection section be minimized and there should be a very small negative pressure at the convection section inlet.



2a **2b** **2c**

FIGURE 2 – ILLUSTRATION OF CORRECT AND INCORRECT DRAFT

Excessive draft, either positive pressure or negative pressure, can lead to severe problems.

CORRECT DRAFT

Figure 2a shows a process heater operating with correct draft. Stack dampers and secondary air registers affect the draft and both adjustments are related. The hot gas pushes so that the pressure is always greatest at the firewall. The stack draft pulls and when correctly balanced the pressure at the bridgewall should be close to zero or very slightly negative. A process heater operating properly will have a zero, or slightly negative draft, at the shield section of zero to -0.5" wc (water column). The firebox will be slightly positive (+0.5 to +2.0 " wc) and the stack will have a range of -0.5 to -1.0" wc.

EXCESSIVE DRAFT - POSITIVE PRESSURE CREATED

The pressure is always greatest at the firewall. In Figure 2b, the air registers are wide open and the damper mostly closed. This generates a positive pressure which forces flue gases outward through leaks in the convection section leading to serious structure damage, as well as heat loss.

EXCESSIVE DRAFT - NEGATIVE PRESSURE CREATED

The air registers are mostly closed and the stack damper is wide open (Figure 2c) leading to a high negative pressure in the convection section. Cold ambient air is sucked in through leaks in the convection section leading to erroneous oxygen readings, as well as heat loss; excessive draft causes tall flames that can reach the tubes resulting in serious damage.

BURNER OPERATION

Traditional premix burners on a process heater premix the fuel with the primary air which is inspired to the burner by the fuel gas flow The pressure of the fuel gas supply is important since low gas pressure degrades performance. The primary air flow should be maximized without lifting the flame off the burner. Most of the air (as primary air) is delivered to the burner along with the fuel. Secondary air is introduced and adjusted with the registers.

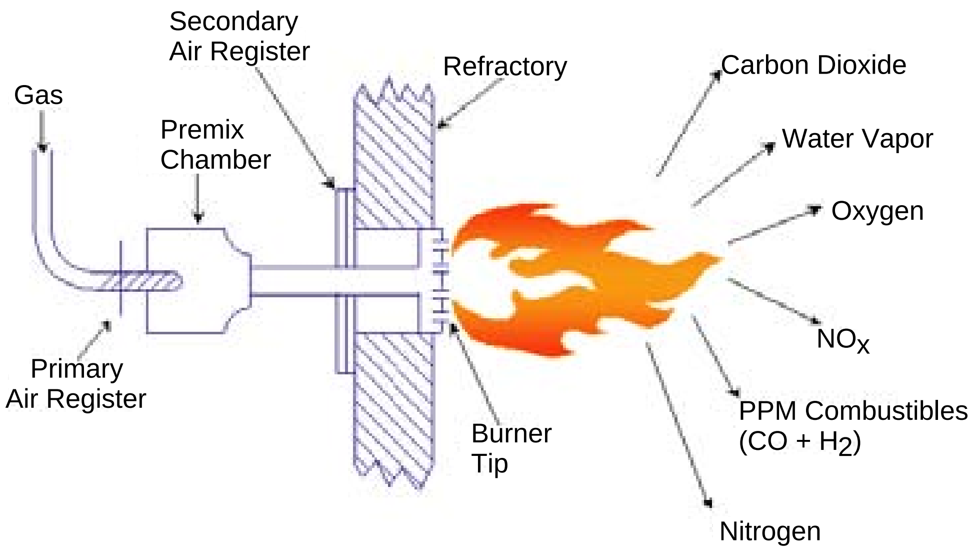


FIGURE 3 – PREMIX BURNER WITH PRODUCTS OF COMBUSTION

Normally, six to ten thermocouples report the temperature stratification across the radiant section and this temperature profile of the radiant zone is used to determine the burner air/fuel ratio and to balance multiple burners. A visual on the flame is used to adjust the flame color and flame height based on the fuel pressure. The temperature pattern generated at the bridgewall will determine how to adjust the burners. Once the flame is set correctly, the damper is adjusted for the correct draft and the secondary air supply is adjusted to give the desired O_2 setpoint. A correctly set burner, with good air-fuel mixing, produces the maximum flame temperature in a compact conical flame (see Figure 3). The flue gas contains a minimum of oxygen together with levels of combustibles (CO and H_2) in the 100 to 200 ppm range and a minimum of NOx. Equation 1 shows the combustion of methane (CH_4) with 20% excess air.

$$CH_4 + 2.4O_2 + 3.73N_2 = CO_2 + 2H_2O + 0.4\ O_2 + 3.73N_2 + \text{ppm CO} + \text{ppm } H_2 + \text{ppm NOx} \qquad \text{Equation 1}$$

Too much or too little secondary air gives poor combustion. A minimum excess air level is required for complete combustion but too much excess air reduces flame temperature and drops efficiency.

Incomplete combustion results when not enough excess air is supplied to burn all the fuel completely. The large amount of CO and H_2 formed as a result of the incomplete combustion makes the burner extremely inefficient and is potentially dangerous. This reduces the flame temperature and might encourage the operator to increase fuel flow thus making matters worse. The condition may not be noticed because leakage in the convection section can hide insufficient air getting to the burner. Completion of combustion in the convection section results in heater damage.

NO_X PRODUCTION

The high temperature in the flame and radiant section, together with combustion turbulence at the burners, causes reaction of oxygen with nitrogen forming NO (nitric oxide) and NO_2 (nitrogen dioxide). Low excess air firing (LEA) is the simplest way to reduce NOx formation and improve efficiency. The more excess air, the more oxygen is available to produce NOx. Low NOx burners stage the combustion reducing the available oxygen, temperature or residence time to limit the formation of NOx.

WHAT IS THE CORRECT O_2 SETPOINT?

Reducing excess air to the minimum safe level is the most important step in reducing energy consumption, but there is no single O_2 level that is right for all heaters. The optimum flue gas oxygen concentration depends on the load (duty), burner design, type of fuel and burner performance. Reducing oxygen while measuring ppm combustibles allows the correct operating point to be determined (see Figure 4). The combustibles detector allows the oxygen level to be reduced safely until the combustibles starts to increase. This is the correct value for that heater. The term “combustibles” here refers to the products of incomplete combustion in the flue gas, primarily carbon monoxide, hydrogen, and trace hydrocarbons, not to the raw fuel. Percent level combustibles measurements can be used to detect serious process upsets or for precipitator protection but play no part in combustion optimization. A ppm combustibles measurement should be taken from the same location as the oxygen.

It was difficult in the past to obtain a reliable ppm combustibles measurement. Today's ppm catalytic 'hot wire" combustibles detectors offer reliable measurement even on difficult fuels.

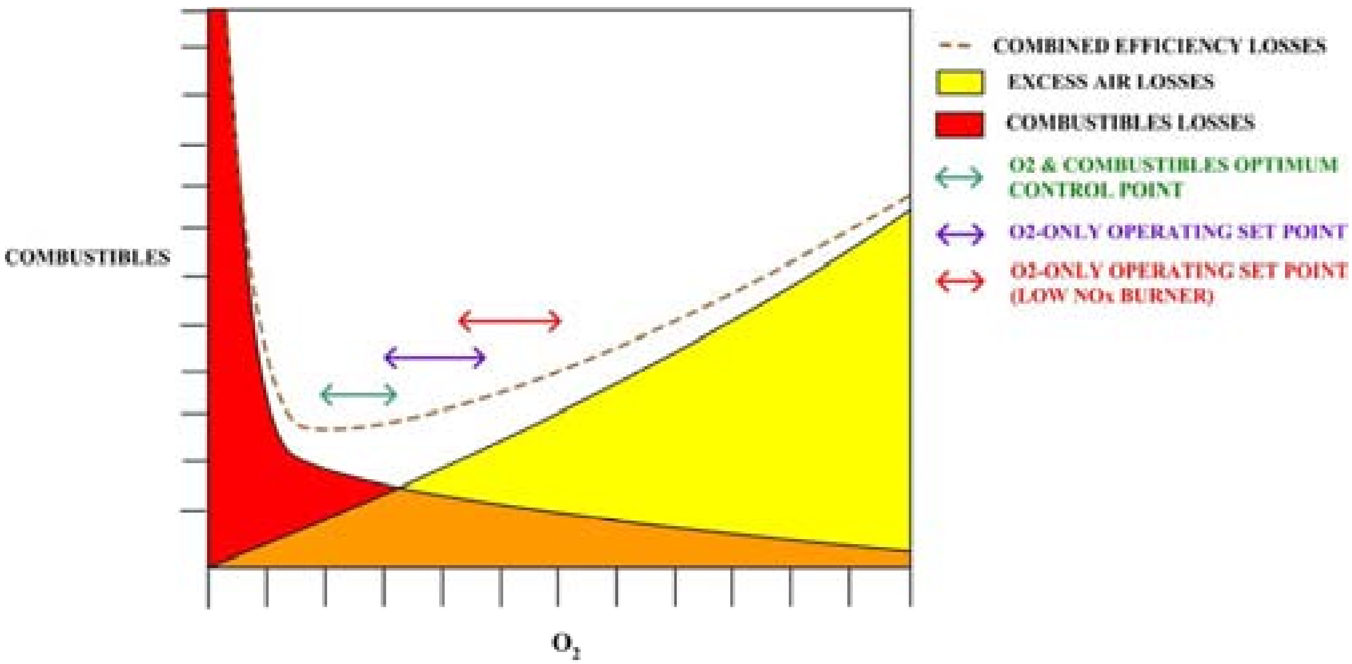


FIGURE 4 – DETERMINATION OF OPTIMUM OXYGEN VALUE

Low NOx burners provide special challenges. The flame parameters which are favorable to reducing NO_X tend to enhance CO production. Combustion volume increases significantly leaving less space for the complete oxidation of CO and other combustibles and hence the levels of combustibles can be higher than on traditional burners for the same excess air level. The complex flame patterns of low NOx burners add a degree of sensitivity to changing combustion parameters. This has caused a shift to the right in the oxygen versus combustibles curve and to some unusual oxygen and combustibles combinations. Newer low NOx burner designs aim to reduce the overall size of the flame to maintain the combustion volume. It is a lot riskier to reduce the excess air without the added information provided by combustibles measurement.

ANALYZER CONSIDERATIONS

LOCATION

A process heater is a complex combustion device with many variables to take into consideration. Control of the temperature of the feed or reactants inside the tubes relies greatly on precise control of the combustion process. Many heaters, reformers, and furnaces have multiple burners with two, three or more radiant sections (or cells). Proper control of the heater requires knowledge of the oxygen and combustibles levels of the flue gas as well as draft and temperature data. However, location of the oxygen analyzer greatly affects the validity of the measurement for control. Figure 5 shows a cabin furnace with three separate radiant zones, but many configurations of fired heater exist.

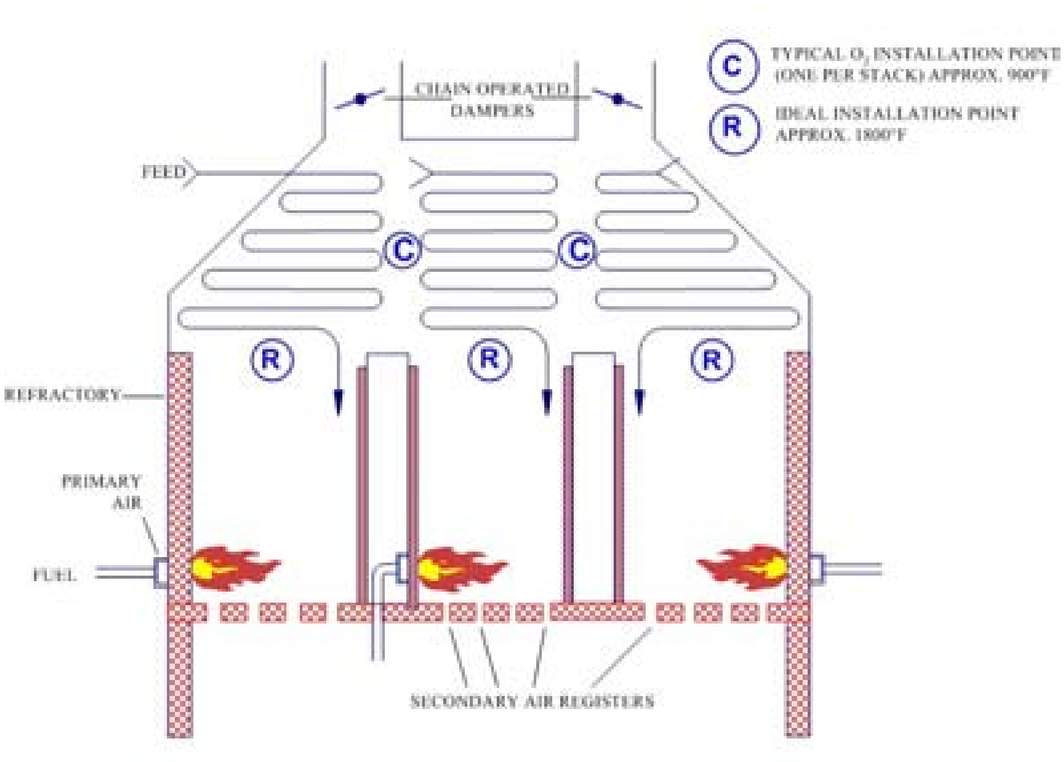


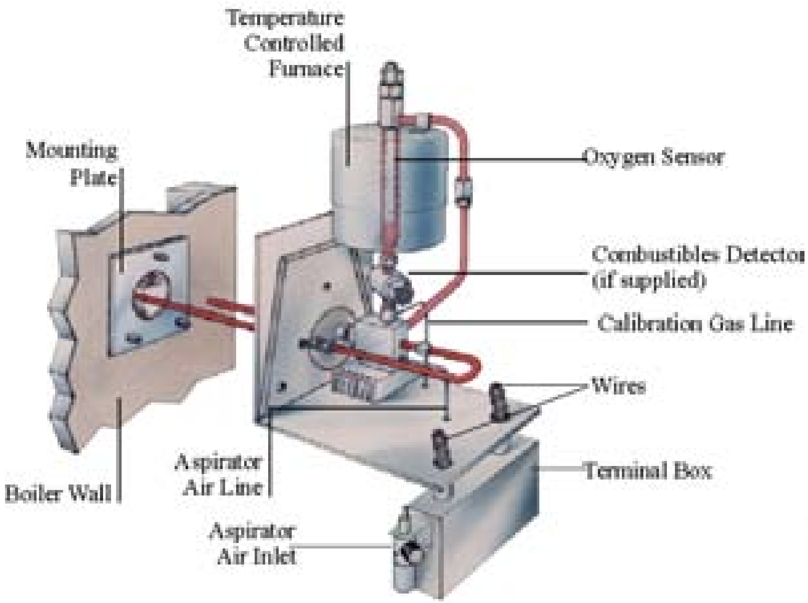
FIGURE 5 – PLACEMENT OF ANALYZERS

Analyzers are often placed in the convection section due to favorable temperatures and easier access. Ideally oxygen and combustibles should be measured directly in the firebox for the following reasons:

1. Air leakage in the convection section will give erroneous oxygen readings and can mask problems in the burner zone.
2. Combustibles in the flue gas will continue to burn on the hot tubes of the convective section and will not show the correct values at this location.
3. An oxygen measurement taken from the convection section cannot be related to what is happening in the burner zones. It is quite common for one or more burners to be operating with high combustibles levels. One sure sign of insufficient combustion air is that increasing fuel gas flow results in a decrease of process side temperature.
4. Measurement of oxygen alone in the firebox cannot indicate burner or process problems. It is often thought that the oxygen measurement from a zirconia probe will also indicate when there is insufficient excess air. This is because any combustibles present will burn on the cell and reduce the displayed oxygen accordingly. Although correct in principle, the drop in oxygen becomes significant only when a major upset occurs. A 2000 ppm (0.2%) level of combustibles (CO or H_2) in the flue gas will reduce the O_2 value by only 0.1%. A decrease in oxygen from 3.0 to 2.9% will not be treated by an operator as an indication of burner problems, but a reading of 2000 ppm on the combustibles detector would certainly be noticed and acted upon.

RESPONSE TIME

The response time of an analyzer is measured, not by the time it takes to react to calibration gas, but rather by its reaction to a process step change. Calibration gas is forced into the analyzer under pressure and reaches the measuring cell very quickly so that all analyzers appear to be fast during calibration. The time it takes for the flue gas to get to the cell depends upon the design of the system. "Process response" not response to calibration gas is the important factor. The close-coupled extractive style analyzer mounts directly to the process flange and is heated to maintain all sample wetted components above the acid dew point. An air-operated aspirator draws a sample into the analyzer and returns it to the process. A portion of this sample rises into the convection loop past the combustibles and oxygen cells and then back to process. This design (see Figure 6) gives a true fast response to a process step change and is suitable for process temperatures up to 3000ºF (1649ºC).



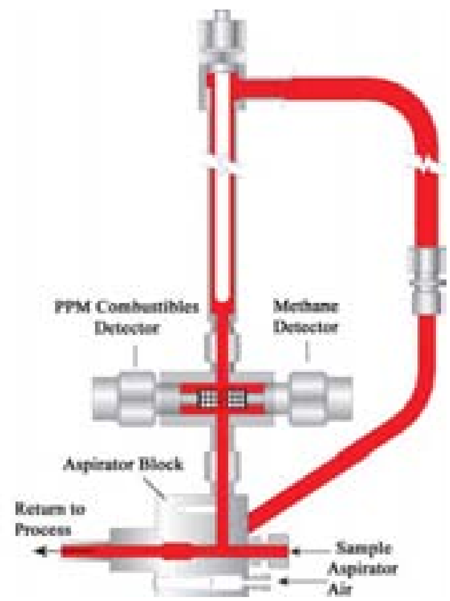


FIGURE 6 – CLOSE-COUPLED EXTRACTIVE   FIGURE 7 – O2, COMB. and METHANE

The broad definition of the term "insitu" refers to an analyzer directly mounted to the process flange, rather than a remote location with sample conditioning system. "Insitu" can also refer to the distinction of whether the zirconia cell is located inside or outside of the flue gas duct. This type of analyzer has a slower response since it depends on diffusion of the flue gas to the cell, rather than on induced flow.

A by-pass or cooling extension tube is often used for installation of insitu analyzers at higher temperature locations because of the probe temperature limit. Here it acts as a close-coupled extractive analyzer but with a slower response time. High temperature insitu analyzers, heated by the process and requiring a minimum process operating temperature of 1200°F (648°C), are available from some manufacturers. These have a slightly faster response time than standard insitus but tend to break more easily and cannot generate any process information during heater start-up. Both process-heated and self-heated insitus can measure only oxygen.

LIMITATIONS OF INFRARED CO MEASUREMENT

A CO specific measurement, while useful, is not sufficient for process heaters for a number of reasons.
1. The temperature limitations on infrared (IR) CO analyzers require installation after the convection section or in the stack. Improper burning or poor fuel quality can cause afterburning in the convection section which leads to convection tube bundle plugging and tube overheating. CO measurement after the convection section will not pick this up.
2. The response time of a CO analyzer on a sampling system is too slow.
3. Refinery fuel gases and other fuels used for process heaters have a highly variable composition. Products of incomplete combustion of these fuels include components other than CO, such as aldehydes and hydrocarbons, which are not detected by CO specific devices[6].

FUEL GAS DETECTION AND BURNER MONITORING DURING START-UP

An integral methane detector will detect any natural gas or other fuels which have leaked into the firebox and could cause an explosion during the purge and lightoff cycle. The catalytic methane detector runs hot enough to oxidize CH_4, which does not react on a standard combustible detector, but cannot measure at ppm levels. The methane detector gives additional peace of mind when heaters or boilers are frequently started up, but is of limited use in situations where the heater runs continuously. The methane output from a combination O_2, combustibles and methane analyzer is used only during the purge and lightoff cycle (see Figure 7). Once the burner is lit, the oxygen and ppm combustibles measurements provide the information needed during completion of safe start up and for efficient operation.

USING OXYGEN AND PPM COMBUSTIBLES

SUGGESTED MANUAL TRIM OF A FIRED HEATER

1. Adjust primary air on the burner for proper flame height and color at the operating fuel gas pressure.
2. Adjust the stack damper to the recommended - 0.1" wc draft at the entrance to the convection section, with secondary air registers open.
3. Trim the secondary air registers to the lowest excess oxygen level up to, but not exceeding, the PPM combustibles operational limit as dictated by plant personnel or experience.
4. Readjust stack damper and secondary air registers as necessary to maintain convection section draft and minimal radiant section oxygen with a safe level of combustibles.
5. Set up the heater using oxygen and combustibles. The heater is now controlled on oxygen, and the combustibles detector is used to watch for process upsets and burner performance over time. This is the window into the process.
6. A 100 ppm combustibles level can achieve maximum fuel efficiency as well as minimizing emissions, without sacrificing safety.

A series of tests were performed on several heaters in a refinery in 2000 to determine the optimum set point and the cost savings that can be achieved by monitoring O_2 and combustibles. The following parameters were monitored during the air-to-fuel ratio step testing exercise for each heater: Excess Oxygen (O_2), Carbon Monoxide (CO), Nitric Oxide (NO), Excess Air, Process Heater Duty (firing rate) and Stack Temperature

The refinery provided the following economic data concerning fuel cost used in the calculations.

- Refinery Fuel Gas Lower Heating Value (Lhv) = 900BTU/million standard cubic feet (Mscf)
- Refinery Fuel Gas cost = $2.25/ Million BTU ($2.025/Mscf)

TESTING PROCEDURE

The air-to-fuel ratio step testing was carried out in the following manner:
1. The as found values for the process heater duty, stack temperature and normal %O_2 set point were recorded from the DCS. The maximum heater duty was also obtained from the control room operator.
2. For balanced draft heaters, the air supplied to the process heater burners was reduced by either dropping the O_2 set point for the forced draft damper controller in small increments or by placing the FD fan controller in manual and reducing the output to the FD fan damper in small increments. This was performed while maintaining a constant firing rate (heater duty). For natural draft heaters, closing the burner registers in small increments reduced the air supplied to the process heater while maintaining constant firing rate.
3.The O_2, CO and NO (nitric oxide) levels were monitored to record the optimum control point that would safely provide the maximum efficiency gain
4.The stack temperature was recorded, and the heater duty and product temperature were also monitored to make sure that they did not change by an appreciable amount during the testing.

EXAMPLE OF SITE TEST RESULTS (May 2000)

Balanced Draft Cylindrical Process Heater (Crude Heater)

	As found values	Optimum achieved
Time	09:00:00 5/10/2000	09:44:10 5/10/2000
Excess O_2	2.8% O_2	2.00% O_2
CO	0 PPM CO	13 PPM CO
NO	50 PPM NO	41 PPM NO
Stack Temperature (after air heater)	316 ºF (XXX ºC)	310 ºF (XXX ºC)
Efficiency[6] (Based on Natural Gas)	84.4%	84.8%
Maximum Duty	250 MMBTU/HR	250 MMBTU/HR
Duty	216 MMBTU/HR	216 MMBTU/HR
Firing rate	86.4%	86.4%
Fuel Cost	$2.025/Mscf	$2.025/Mscf
Operation (Availability)	24 hours per day, 365 days/year	
Annual Fuel (refinery fuel gas)	2,102,400,000 ft^3	2,093,990,400 ft^3
Annual Fuel Cost (refinery fuel gas)	$4,257,360	$4,240,330
NO Reduction	9 PPM = [1-(41 PPM/50 PPM)]*100% = 18%	
Annual refinery fuel gas cost savings	$17,029 (calculated on 2000 prices)	

CONCLUSION

Operators often feel that it is sufficient to maintain thermal objectives and this can be done by controlling the excess air from an oxygen analyzer. Even the smallest heater benefits from fast response O_2 and ppm combustibles because slugs of waste gas with poor BTU value can hit the burners at any time causing major and rapid changes to the combustion parameters. Oxygen and combustibles analyzers can help meet heater performance objectives with minimal investment cost. Benefits include improved efficiency, reduced emissions, increased heater and tube life, consistent product quality and optimum throughput.

The analyzer provides the information needed for proper control during start-up and operation. It is a window into the process to monitor burner performance and avoid problems due to air and tube leaks. Low NOx burners are sensitive to changing combustion parameters and benefit from increased flue gas information. Even older heaters with manual secondary air adjustments can benefit from optimization made possible by reliable oxygen and combustibles measurements from the correct location.

ACKNOWLEDGEMENTS

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