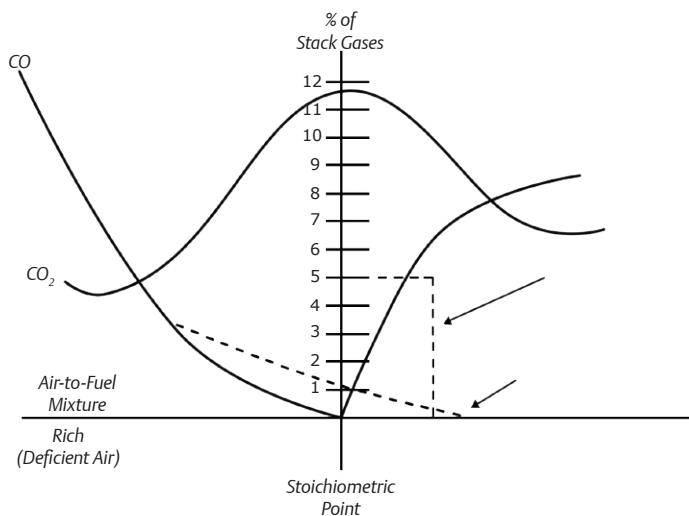


# Flue Gas Analysis as a Diagnostic Tool for Fired Process Heater Furnaces

## Overview, and Traditional Application

Combustion flue gas analysis has been used by process heater operators for decades as a method of optimizing fuel/air ratio. By measuring the amount of excess oxygen and/or CO in the flue gases resulting from combustion, furnace operators can operate at optimum efficiency and lowest  $\text{NO}_x$ , and also generate the least amount of greenhouse gas. The theoretical ideal, or the stoichiometric point is where all fuel is reacted with available oxygen in the combustion air and no fuel or  $\text{O}_2$  is left over.

**Figure 1 - Key Flue Gas Measurements Relating to Ideal Combustion Stoichiometry**



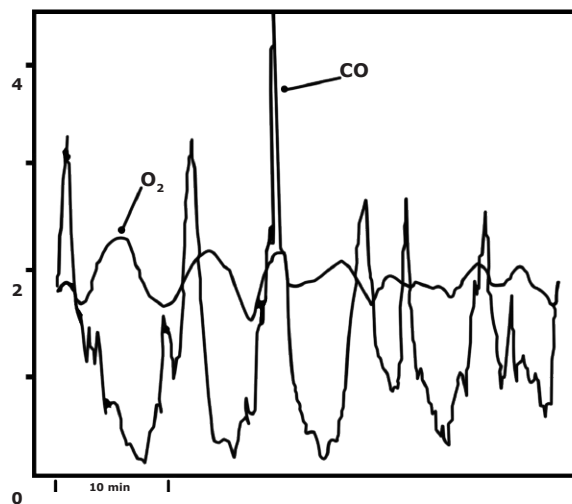
Operating furnaces never attain this ideal, however, and the best operating point usually will result in 1–3 % excess air and 0–200 PPM of CO. This optimum operating point is different for every furnace and also varies for differing loads, or firing rates. A higher firing rate induces greater turbulence through the burner(s), providing better mixing of fuel and air, and enabling operation with a lower excess  $\text{O}_2$  before unburned fuel (represented by CO) appears, or “breaks through”. For most furnaces, this point of CO breakthrough is fairly repeatable, and reduces the need for a separate CO or combustibles sensor.

**Figure 2 - CFD Depiction of the Turbulent Mixing of Fuel and Air Through a Burner**



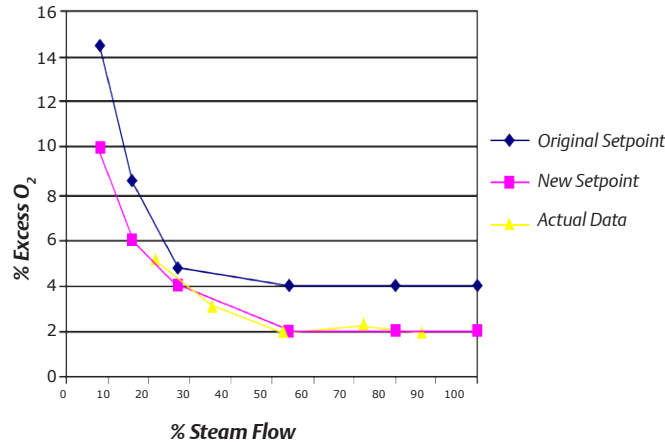
*The "combustion process" is the burner.*

**Figure 3 - DCS Trend Depicting the Relationship of  $\text{O}_2$  and CO Indications at CO Breakthrough Point**



This ideal O<sub>2</sub> operating point will vary with firing rate, so a *function generator* is usually developed from test data using a portable analyzer to assign the ideal O<sub>2</sub> control point based upon an index of firing rate, such as fuel flow or charge flow.

**Figure 4 - A Typical Function Generator Depicting the Optimum Flue Gas O<sub>2</sub> Level at Different Steam Flows (Firing Rates)**



This curve should be reestablished from time to time as burners wear, and other furnace conditions change over time.

If the furnace utilizes forced draft fans, operators may dynamically control oxygen to the optimal level via the distributed control system, or they may make manual adjustments to establish the optimum O<sub>2</sub> and/or CO levels. Natural draft furnaces may not offer control of the inlet air to the burners, so the the outlet stack damper can be adjusted to change the draft, and the air flow coming through the burners. The stack outlet damper also controls furnace pressure, which becomes a constraint. Manual adjustments to the inlet vanes at natural draft burners are sometimes made by operators.

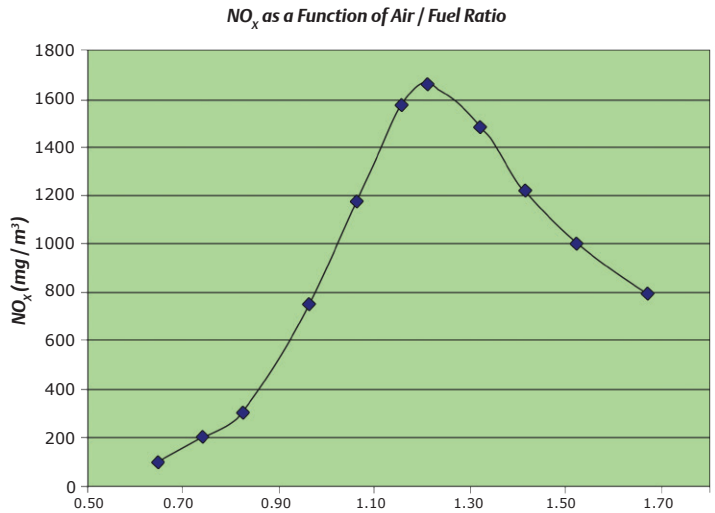
Direct control of CO is sometimes done, typically with a line-of-sight infra-red analyzer, or more recently the tunable diode laser analyzers. Since target CO levels are usually in the low PPM range, making fan or damper adjustments small enough to control at these low levels can be challenging.

## New EPA Regulations

The traditional goal of achieving best combustion efficiency is often being modified to accommodate two other goals:

1. Minimizing the thermal NO<sub>x</sub> produced through the burner. O<sub>2</sub> levels and flame temperatures are key indicators to the production of NO<sub>x</sub>.

**Figure 5 - NO<sub>x</sub> as a function of flue gas excess O<sub>2</sub> Relationship of NO<sub>x</sub> production**



Low NO<sub>x</sub> burners use internal flue gas recirculation, which results in less heat intensity in the burner, producing less thermal NO<sub>x</sub>

Lower greenhouse gas production - carbon dioxide (CO<sub>2</sub>) is a natural byproduct of combustion. but the US EPA has been given authority to regulate its production as with more toxic flue gas emissions like SO<sub>2</sub> and NO<sub>x</sub>. Indeed, the refining industry has been singled out for enforcement under the EPA's "National Petroleum Refinery Initiative". The Greenhouse Gas Mandatory Reporting Rule (GHG MRR) requires most refinery sources to measure either the carbon content of the fuel under Tier III rules, or to measure the actual CO<sub>2</sub> exiting the stack as part of a CEMS system.

Operating a furnace or boiler at its optimum efficiency minimizes the production of CO<sub>2</sub>. This is counter-intuitive, since, as Figure 1 indicates, CO<sub>2</sub> production actually peaks out around the stoichiometric fuel-air ratio. While one might be tempted to operate a bit lean of stoichiometry (with extra air), this extra air would have a quenching effect on the flame, and less energy would be produced. The furnace would have to run longer to make up for the losses, and more CO<sub>2</sub> would be produced in the end.

## Technologies for Measuring Combustion Flue Gases

### Oxygen

The most ubiquitous technology for measuring combustion flue gases has been the zirconium oxide fuel cell oxygen analyzer. This analyzer technology was first used in the power generation industry in the early 1970s, but the technology has transferred to use for any combustion process. Much has been written about the details of how the Nernstian sensor operates, and this paper will not review this information.

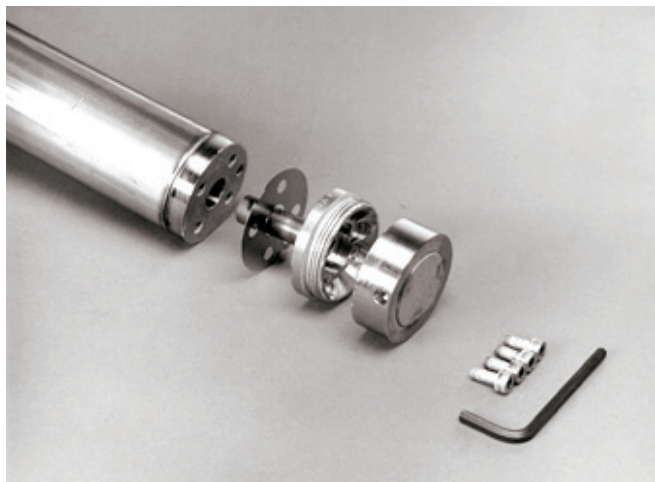


Figure 6 -  $ZrO_2$  sensing cell mounted to the end of a probe (.5–6 M long)

The  $ZrO_2$  sensing technology is ideally suited for measuring combustion flue gases for the following reasons:

- The sensing cell generates its own millivolt signal, similar to the a thermocouple works.
- This raw millivolt signal is inverse and logarithmic, i.e. increasing greatly with the low percent  $O_2$  readings typically found in combustion processes. Accuracy actually improves as  $O_2$  levels decrease.
- The sensor is typically heated to  $700\text{ }^\circ\text{C}$ – $750\text{ }^\circ\text{C}$ , making it suitable for operation in hot combustion flue gases.
- The sensor is robust, and can withstand the sulfur components found in many waste fuel gases.
- No sampling system is required. The sensor can be placed directly into the flue gas stream on the end of the probe that can be from 18 inches to 12 feet long. Since the flue gases enter the sensor via passive diffusion, even applications with heavy particulate content are possible with a low rate of filter pluggage.
- Sensors can be calibrated on-line and in-place. Automated calibration is also available.
- Hazardous area approvals are available to Class I Zone 1 Gr. B, C, D, and also the European ATEX equivalent.

The in situ  $ZrO_2$  probe results in a point measurement within the flue gas duct, however, and several probes of different lengths may be required in order to get a representative average across large flue gas ducts.

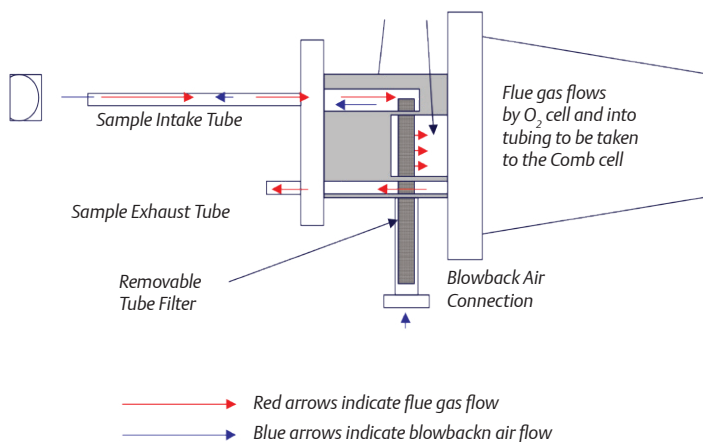
### Carbon Monoxide

CO is usually the first combustible gas component to appear when combustion fuel/air ratios start becoming too rich. Desired CO levels in combustion flue gases are typically less than 200 PPM, and several technologies are used to measure carbon monoxide.

- Extractive systems where the flue gases are removed from the duct and cleaned, and moisture removed before being placed into a rack-mounted analyzer. Infra-red spectroscopy is usually used in these systems, and is well suited to measuring at these low levels. Repeatability of better than  $\pm 5$  PPM are possible, with low interference from  $H_2O$  and  $CO_2$ .
- Close-coupled extractive systems which filter out particulate, but do not remove moisture from the flue gases. A  $ZrO_2$  sensor is typically used, along with a calorimetric combustibles sensor (sometimes termed CO equivalent or COe).



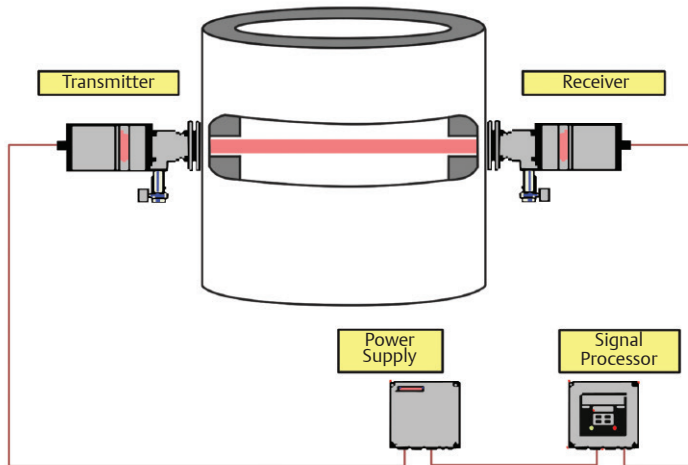
Figure 7 - Close-coupled Analyzer for Measuring Oxygen and or Combustibles.



The combustibles sensor burns any combustible gases, which results in a temperature increase in a sensing RTD or other element. Sensitivity and repeatability are not as good as with an infra-red analyzer, but is suitable as a safety indication.

- Across duct line-of-sight configurations whereby an infra-red source is mounted on one side of the duct, and a receiver or detector is mounted to the opposite side.

**Figure 8 - Typical Across-Duct Infra-Red Measuring Arrangement**



- This line-of-sight method results in an inherent average across the entire duct, so multiple instruments are less likely required to cover a large duct. Conversely, one does not get the granularity of information that an array of point measurement O<sub>2</sub> probes provides.
- Dual-pass probe - A modification to the across stack line-of sight method, this arrangement is a dual pass probe where the infra red energy is sent out to a mirror at the end of a hollow pipe, and then reflected back to the source end for analysis. The flue gases are permitted to fill the probe tube through holes or filters.

Any optical technology presents application challenges that need to be considered:

- An extractive system involves transporting and filtering the sample flue gases removing the moisture, and returning the sample to the process or to a safe vent. This adds considerable cost to the system and will require significant maintenance attention if there is a particulate in the flue gases.
- An across duct line-of-sight system cannot be placed where temperatures are much above 600 °C, nor endure high levels of particulate. Thermal growth of the ductwork and vibration can negatively impact the alignment of the source and receiver sides. Also, this type of arrangement cannot undergo a true calibration, since this would involve filling the entire duct with calibration gases.
- A dual-pass probe system has to contend with soiling of the reflecting mirror at the end of the probe.

Tunable diode lasers (TDL) have recently come onto the scene, again using IR spectroscopy, and again usually using an averaging line-of-sight arrangement. This technology is also capable of measuring O<sub>2</sub> in the overtone range, and NO<sub>x</sub>. Again, much has been written about the underlying technology, so we will not cover this in this paper.

As with the traditional IR systems, a TDL in an across stack line-of-sight arrangement will inherently average across the entire furnace volume, requiring fewer instruments to cover a large duct, but also providing less granularity of the flue gases within the duct. Line-of-sight analyzers cannot be challenged with known calibration gases, and, according to the US EPA, are not acceptable for use as continuous emissions monitors (CEMS).

### New Applications in Large Furnaces

Historically, combustion analyzers have been placed above the convective zone, or into the smokestack. Large furnaces may have several combustion zones, however, and there has been a trend to place the analyzers into the top of each radiant zone.



*Figure 9 - Four O<sub>2</sub> analyzers placed zone by zone, at the top of the radiant sections.*

### Flue Gas Stratification Tells A Story

Forward-thinking operators will use these varying O<sub>2</sub> indications as a diagnostic tool to look for problems in the furnace, such as:

- **Fuel Gas BTU variation** - will be indicated by both O<sub>2</sub> and CO variation.
- **Fouled burners** - depending on the consistency and quality of waste fuel gas burned in a furnace, a burner will change over time. Low NO<sub>x</sub> burners can be particularly sensitive.
- **Flame carryover** - combustion sometimes progresses well into and beyond the convective zone, and is indicated by lower O<sub>2</sub> readings, higher CO readings, or both, along with rising outlet temperatures.
- **Tube leaks** - an unbalanced furnace can cause flame impingement and associated tube wastage. A tube leak will typically show up as a lower O<sub>2</sub> reading, and spiking CO readings.



New installation locations are being attempted, with hotter radiant zones gaining favor. Variable insertion probe mounts afford the ability to find the ideal location within a flue gas duct. Continued research into fuel cell sensing technology has yielded a new sensor that measures oxygen deficiency during upset reducing conditions. The addition of a combustibles sensor is becoming more common in close-coupled extractive systems, yielding a "CO equivalent" measurement that is not as sensitive as an infra-red measurement, but is suitable for use as a safety indication of fuel/air ratio.

The measurement of CO is most commonly made with infra red technology in either an extractive configuration, across duct line-of-sight configuration, or dual pass probe configuration. CO is typically found in low PPM levels, so automatic control on CO is more difficult.

New tunable diode laser technology has the capability of measuring O<sub>2</sub>, CO and NO<sub>x</sub>. As with the traditional Infra-red technology, across-duct line-of-sight configurations inherently average across a flue gas duct, minimizing the need for multiple instruments, but affording poor granularity within a given optical path. It is not possible to calibrate a line-of-sight instrument inside the process with calibration gas.

Maximum benefit from the use of flue gas analyzers results from close collaboration between instrument suppliers, plant instrument engineers who implement them, and operations personnel that use them on a daily basis.

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## Notes

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