Flue Gas Analysis as a Boiler Diagnostic Tool

Overview, and Traditional Application

Combustion flue gas analysis has been used by Power Plant 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, plant operators can operate at the best heat rate efficiency, lowest 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 O_2 is left over.

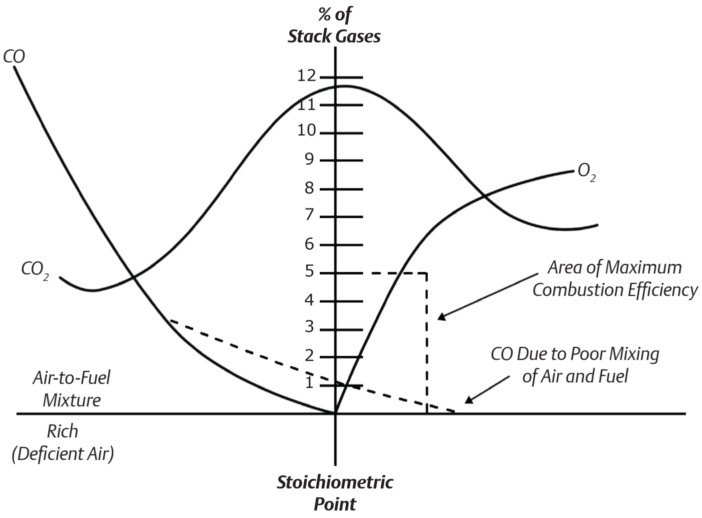

Figure 1 - Key flue gas measurements relating to ideal combustion stoichiometry.

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 boiler, 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 O_2 before unburned fuel (represented by CO) appears, or "breaks through".

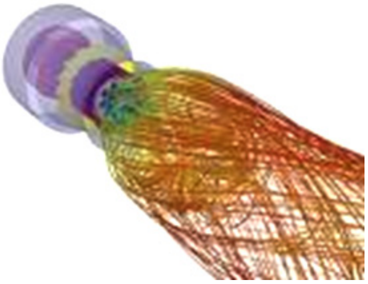

Figure 2 - CFD depiction of the turbulent mixing of fuel and air through a burner.

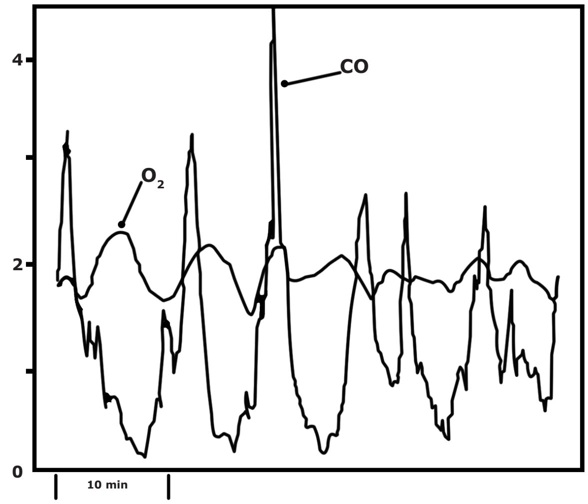

Figure 3 - DCS trend depicting the relationship of O_2 and CO indications at CO breakthrough point.

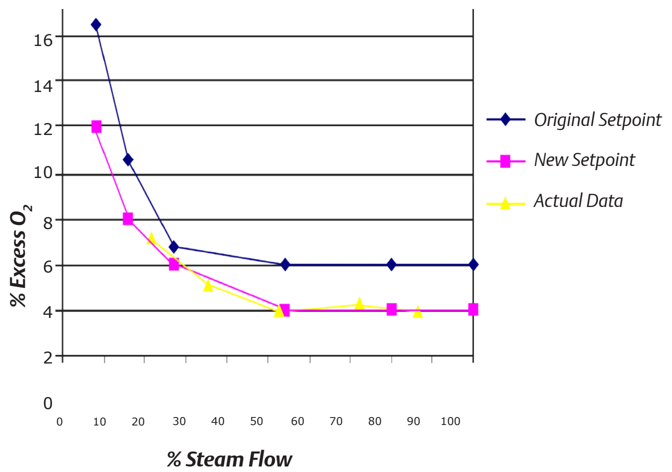

Figure 4 - a typical function generator depicting the optimum flue gas O_2 level at different steam flows (firing rates).

This curve should be reestablished from time to time as burners wear, and other furnace conditions change over time. The curve for burners using natural gas and light oil fuels will tend to remain valid for long periods of time (years). Burners firing solid fuels such as coal, petroleum coke, or pelletized biofuels will experience more frequent pluggage and other degradation in the burners and fuel delivery systems, and will benefit from more frequent reestablishment of this curve.

Large boiler operators will typically dynamically control oxygen to the optimal level via the distributed control system. Control of CO is more difficult, since target levels are usually in the PPM range, and making fan or damper adjustments small enough to control at these low levels is difficult. Many operators will make manual adjustments based upon the CO signal, or use the measurement as a feed forward signal to adjust the O_2 control setpoint upwards or downwards.

New Goals

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

1. Minimizing the thermal NO_x produced through the burner. O_2 levels and flame temperatures are key indicators to the production of NO_x.

   One operating strategy to produce less NO_x uses staged combustion, whereby a cooler fuel-rich combustion is established at the burner. Overfire air is then added higher in the furnace to complete the combustion. This results in less heat and oxygen passing through the burner, and less NO_x produced. Advanced control strategies utilizing neural nets are often implemented to find the optimum air settings to minimize thermal NO_x production.

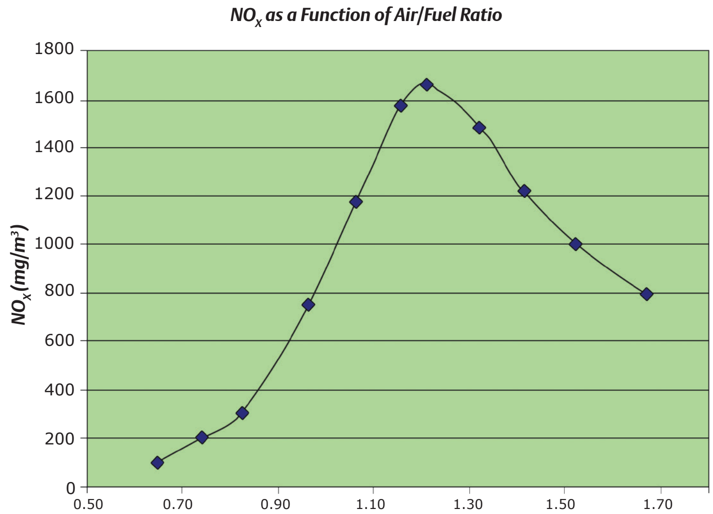

Figure 5 - NO_x as a function of flue gas excess O_2 Relationship of NO_x production.

   Another NO_x reduction strategy is flue gas recirculation, where a certain amount of flue gas is mixed with the normal air used for combustion. An O_2 probe mounted after this mixing valve can be used to control final O_2 going to the burner, resulting in a cooler flame that produces less NO_x.

2. Slag prevention- Flux sensors provide good information about soot and slag buildup, but close attention to combustion analyzers can provide another indication of slag formation. Fly ash fusion temperatures are usually affected by the amount of excess O_2 in the flue gases, and some operators run with an O_2 setpoint that has been established to prevent slag.

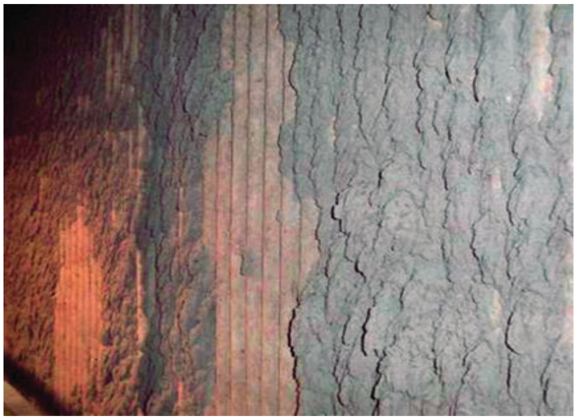

Figure 6 - Slag formation on boiler tubes.

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 1 970s, but the technology has transferred to use for any combustion process. All automobiles now use one or more of these sensors for controlling fuel-air ratios, and small engines for lawn mowers, chain saws, etc. will soon be using them.

Much has been written about the details of how the Nernstian phenomenon operates[1], and this paper will not review this information.

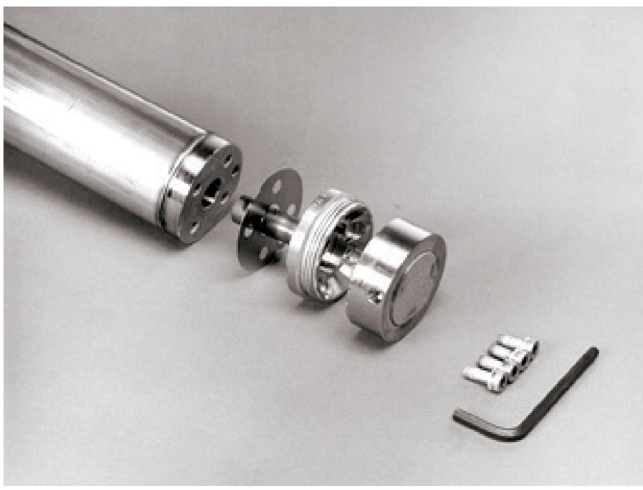

Figure 7 - Z_rO_2 sensing cell mounted to the end of a probe (.5–6 M long).

The Z_rO_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 way 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 700–750 °C, so operation in hot combustion flue gases does not present a problem.
- The sensor is robust, and can withstand the sulfur components found in many fuels.
- No sampling system is required. The sensor can be placed directly into the flue gas stream on the end of probe that can be from .5 M to 6 M 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.

The in situ Z_rO_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 infra-red spectroscopy is well suited to measuring at these low levels.2 Repeatabilities of better than +/-5 PPM are possible, with low interference from H_2O and CO_2. Instrument configurations include:

- Extractive systems where the flue gases are removed from the duct and cleaned before being placed into a rack-mounted analyzer.
- 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.

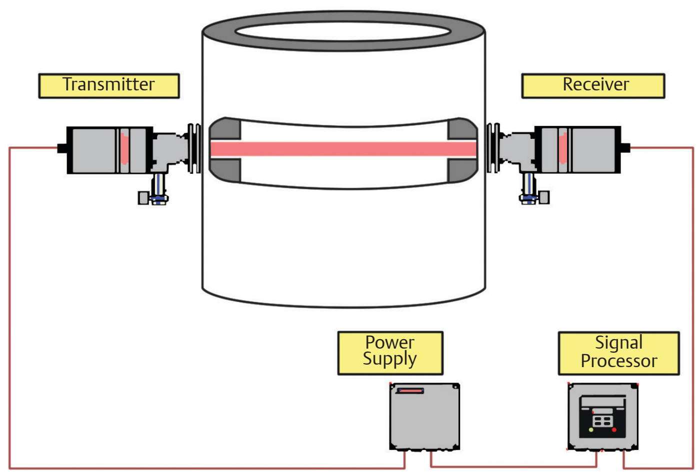

Figure 8 - Typical across-duct infra-red measuring arrangement.

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_2 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 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. It is possible to conduct an on-line calibration by filling the optical path inside the pipe with calibration gases.

Tunable diode lasers (TDL) have recently come onto the scene, again using spectroscopy, but with a laser source and a diode sensing array. These systems typically use the line-of-sight arrangement across the duct, or a dual pass probe method. This technology is also capable of measuring O_2 in the overtone range, and NO_x.
Again, much has been written about the underlying technology[3], 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. Analyzers cannot be challenged with known calibration gases.

New Applications in Large Power Boilers

Each of the 20 or more burners in a large boiler can be considered as separate processes, each producing its own flue gases. The flue gases in furnaces utilizing burners in a single or opposed-wall firing configuration tend to form up into "columns" that often tend to stay stratified throughout the furnace.

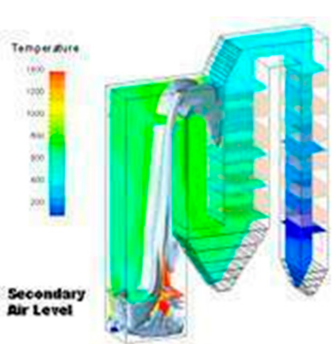

Figure 9 - CFD depiction of the flue gases passing through a wall-fired furnace.

Combustion analyzers are typically mounted in the "back pass" of the furnace, after the economizer, and it is common for operators to see this stratification when using multiple O_2 probes in these large ducts. It's not uncommon to see differences of one percent or more across a large furnace. To accommodate this, an arithmetic average of multiple probes is often calculated in the DCS, and used as input to the O_2 control loop.

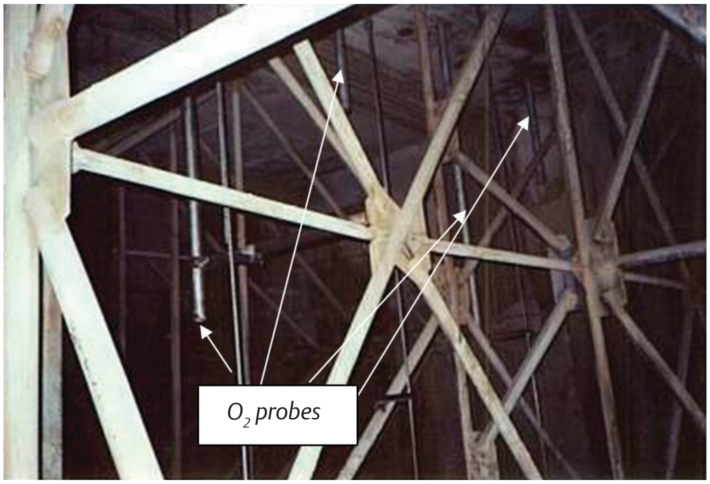

Figure 10 - An n array of oxygen probes mounted vertically downstream of an economizer.

Flue Gas Stratification Tells A Story

Forward-thinking operators will use these varying O_2 indications as a diagnostic tool to look for problems in the furnace, such as:

- Fouled burners
- Sticking sleeve dampers
- ID fan imbalances
- Roping in coal pipes
- Classifier pluggage/coal finess problems
- Coal mill imbalances

The flue gases passing through a tangential-fired boiler do not experience as much stratification of the flue gases, and burner to burner variations are harder to differentiate. Some operators claim to be able to detect corner to corner variations with the O_2 probes in tangential furnaces, however.

Abrasion-resistance

Furnaces firing solid fuels (particularly coal) can have high levels of fly ash carried with the combustion flue gases. Separate schedule 40 pipes are often used as "abrasive shields" to protect in situ oxygen probes from fly ash erosion. Some operations have discovered, however, that fly ash is often much less abrasive in the hotter zones of the furnace (500-700 °C), above the economizer. As the combustion flue gases are cooled through the economizer and air heater, the ash often agglomerates into larger particles that are far more abrasive. A location higher in the furnace can not only minimize abrasion, but also detect stratification better. Rosemount Analytical has developed a heavy-wall probe body that is more cost-effective than traditional abrasion shields, yet endures fly ash erosion well in high areas of coal-fired boilers.

Ideal Probe Placement

Oxygen probes are provided in a wide range of lengths, from .5 M to 6 M, but plant engineers often wonder if a given placement is the optimum. A variable insertion capability has been developed that permits the Instrument Engineer to find the best possible mounting location for a given probe.

Figure 11 - Variable insertion O_2 probes in horizontal and vertical orientations.

Air Heater and Other Duct Seal Leaks

Some air heater styles rotate like a revolving door in order to exchange remaining heat from the flue gases to the fresh air being fed to the burners. As the seals in these large rotating structures wear, air will typically migrate over to the flue gas side, elevating the O_2 levels on the flue gas side of the air heater.

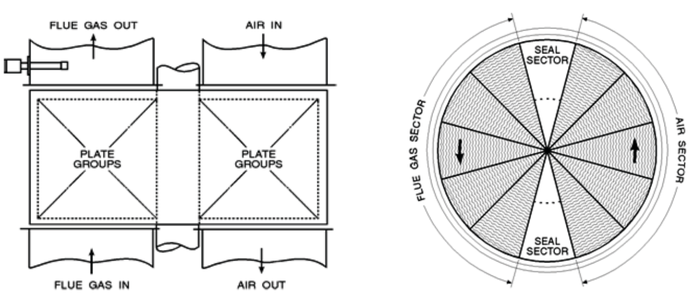

Figure 12 - Rotating air heater.

Any air leak into a furnace negatively affects heat rate efficiency, and also reduces fan capacity used for combustion, limiting boiler capacity.

New Applications in Gas Turbines

Gas turbines tend to run with around 15 % excess O_2 in order to keep the turbine sections from experiencing heat stress. If a heat recovery steam generator (HRSG) is used, duct burners are often added after the turbine in order to increase the amount of steam generated inside the HRSG, but this secondary combustion also results in a more efficient total combustion, with final O_2 values in the 2–4 % range. An O_2 probe placed after the duct burner can control the amount of fuel being added.

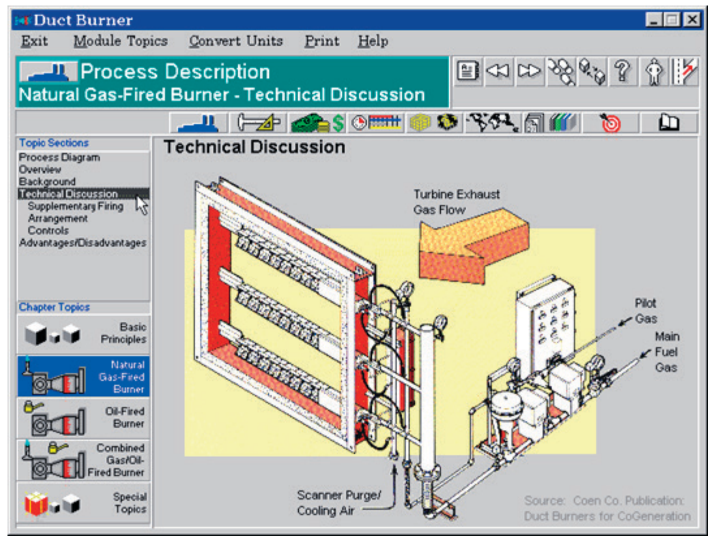

Figure 13 - Duct burner for gas turbine (courtesy of Coen Co.).

New Sensor Developments

Continued research into the Z_rO_2 fuel cell technology is yielding new capabilities. It was previously mentioned that the millivolt output of these sensing cells is inverse and logarithmic, so lower levels of oxygen results in higher levels of signal. A sensing cell has been developed that will continue outputting increasing voltage as flue gas O_2 levels pass through zero and into reducing conditions.

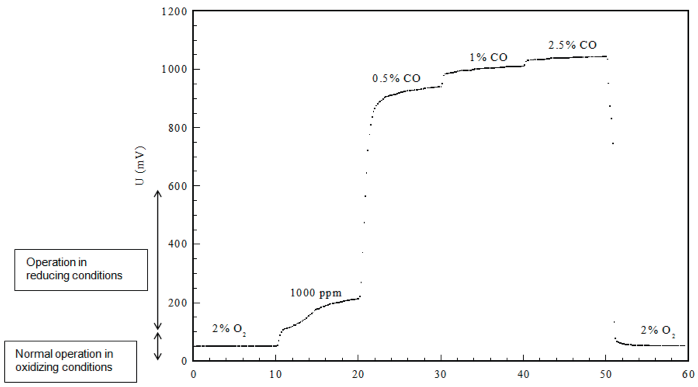

Figure 14 - Millivolt signal output from a new Z_rO_2 sensing cell in Oxidizing and Reducing conditions.

This has become a tool for processes that periodically pass into reducing conditions, providing an indication of the level of oxygen deficiency during these events, and informing the operator if recovery measures being taken are being effective.

Continued research into the Z_rO_2 fuel cell technology is yielding new capabilities including a Z_rO_2 cell that measures CO. Eight test sites have been established at N. American power plants with promising results.

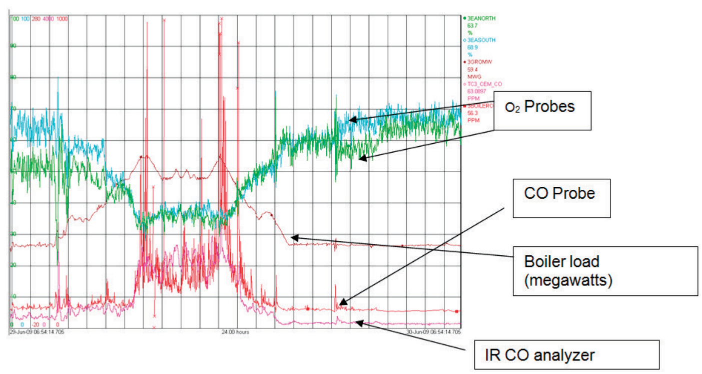

Figure 15 - DCS trace depicting PPM reading from Alpha CO probe.

Summary

Combustion flue gas analysis has long been a key tool for optimizing the combustion of large power generation boilers. Innovative customers have exploited reliable analyzers to achieve new goals, such as NO_x reduction, and slag prevention.

The measurement of Oxygen has been dominated by the in situ Z_rO_2 probe, which provides a point measurement requiring an array of probes across a flue gas duct in order to arrive at a good average reading. Good granularity is afforded by this array, opening a boiler diagnostic capability to detect burner and coal mill problems.

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_2, CO and NO_x. 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. New installation locations are being attempted, with hotter zones ahead of the economizer producing less abrasive fly ash. Variable insertion probe mounts afford the ability to find the ideal location within a flue gas duct.

Innovative customers use flue gas analyzer to detect leaks in air heaters or duct transitions, and also modify heat rate calculations of in-leakage.

Gas turbines do not use flue gas analysis internally, but are increasingly using them to measure the final oxygen from a duct burner ahead of a heat recovery steam generator.

Continued research into fuel cell sensing technology has yielded a new sensor for the measurement of CO in PPM levels.

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.

References:

1) Z_rO_2 measuring technology:
P. Shuk: Process Zirconia Oxygen Analyzer: State of Art, Technisches Messen, N 1, 19–23 (2010).

2) Infra-red spectroscopy:
Michael B. Esler, David W. T. Griffith, Stephen R. Wilson, and L. Paul Steele: Precision Trace Gas Analysis by FT-IR Spectroscopy. Simultaneous Analysis of CO2, CH4, N2O, and CO in Air, Anal. Chem., 72 (1), pp 206–215 (2000).

3) Tunable diode laser:
Maximilian Lackner, (Ed): Gas sensing in industry by tunable diode laser spectroscopy (TDLS). Review on state-of-the-art metrology for demanding species concentration, temperature and pressure measurement tasks, Verlag ProcessEng Engineering, 115 pp (2009).

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