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PLANT OPERATIONS AND TECHNOLOGY I & II: REAL TIME FURNACE AIR IN- LEAKAGE MONITORING ON COAL, OIL AND/OR GAS FIRED BOILERS

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Abstract

As a furnace ages the small gaps that form between the tube penetrations, casing, soot blower openings, observation doors, and dead air spaces begin to contribute to the total air requirement for the furnace. However, when leakage occurs between the furnace exit and the boiler exit, this air does not contribute to the total air requirement. It simply dilutes the gas flow and artificially raises the excess oxygen indication. Most large utilities use oxygen probes at the economizer outlet for monitoring the furnace condition. A 3% reading at the economizer could represent 1% at the furnace exit if leakage is present in the penthouse or convection pass. This leakage can be measured by taking an in-furnace oxygen reading at the furnace exit and then comparing it to the readings at the economizer outlet. However, this cannot account for any air leakage that does contribute to the total air requirement or if combustion is delayed. If secondary combustion (combustion downstream of the furnace exit) is present, the oxygen reading will actually drop before it begins to increase due to leakage. In this case actual leakage would be higher than measured. In addition, air that infiltrates upstream of the furnace exit contributes to the total air requirement. This paper provides an overview of how using molar calculations and total airflow measurement into the furnace can be used to approximate total leakage rates between the furnace inlet and boiler outlet (from the burners to the economizer oxygen probes). If a reliable airflow indication is available, it can be compared to the total air requirement for a given fuel. As leakage increases, the percentage of the total air requirement that comes from the intentionally supplied air will decrease assuming a constant oxygen trim at the economizer outlet. This paper will review a case study of results and data collected from the Stanton Energy Center Units 1 and 2 as a documented level of online air in-leakage detection.

Key Points

I. Leakage within the envelope of the boiler is difficult to estimate.
II. Traditional methods of measuring oxygen at the furnace exit and economizer exit do not account for all types of leakage.
III. Total airflow (mass flow) can be used to estimate total air in-leakage in the boiler envelope.

Under normal operating conditions with properly calibrated and functioning equipment, the oxygen probes at the economizer outlet are sufficient for operating a furnace on a day to day basis. However, as leakage before the oxygen probes increases, their ability to give a good representation of furnace performance is decreased. The following summarizes the issues with a stand-alone oxygen probe grid at the economizer outlet and traditional methods for measuring leakage.

1. A stand alone oxygen probe grid at the economizer is subject to error when leakage is present upstream of the sampling location.
2. Oxygen probes cannot determine leakage upstream of the sampling location without a secondary measuring system to correlate values.
3. In-furnace measurements cannot account for oxygen contributions upstream (or midstream) of the combustion process.
4. In-furnace measurements are subject to error if secondary combustion exists or if the measurements are recorded before the completion of combustion

Typical leakage calculations across a system are based on the following equation:

$$\text{Percent Leakage} = \frac{\text{\% Oxygen Leaving - \% Oxygen Entering}}{\text{20.9 - Oxygen Leaving}} \times 90$$

Note: 20.9 is the normal percentage of oxygen in ambient air while 90 is a factor derived from empirical data and testing

Secondary combustion is the one factor that makes in furnace measurements suspect and the above equation inadequate. If secondary combustion is present with leakage, the measured leakage can be positive, neutral, or even negative even though a positive amount of air is leaking into the system. In other words, secondary combustion can hide leakage if the oxygen content reduced by secondary combustion is equal to or greater than the amount of oxygen increase due to leakage. Even some secondary combustion will reduce the amount of apparent leakage. Refer to figure 1 for an example. No current methods exist for accounting for this phenomenon other than the one described in this paper.

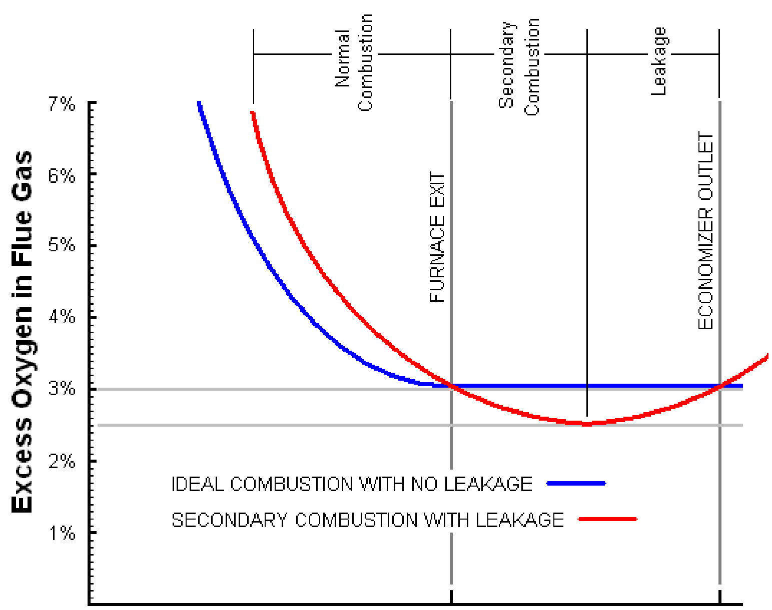

Figure 1 – Secondary combustion with post combustion leakage resulting in zero measured leakage via in-furnace and economizer measurements while actual leakage (and minimum oxygen level) is 2.5%.

Before the method for measuring is discussed, it is important to understand the basics of the combustion process. At its simplest form, a given amount of fuel requires a certain amount of air (oxygen) to combust fully. An additional amount of air is provided to ensure that the fuel combusts completely because in reality, the air and fuel mixing is not 100% perfect. The better the air and fuel can be mixed, the less margin is needed.

While a total mass flow measuring system would guarantee the proper ratio of air entering the furnace, there are no provisions for a deterioration in air fuel mixing. The degree at which air and fuel are mixed cannot be measured directly. Therefore instead of measuring the airflow into the furnace, the resulting level of oxygen is measured as an indicator of the mixing process and how much air is left over. While this solution is practical for new and good condition boilers, the drawbacks become apparent when the leakage upstream of the probes increases.

Because on balanced draft units the furnace is under a negative pressure (typically -0.5"w.c. at the furnace exit), the furnace is susceptible to ambient air entering the envelope of the furnace. For the purposes of this paper we will divide leakage into two categories: pre-combustion and post-combustion.

Pre-combustion leakage includes any ambient air that enters the furnace and theoretically participates in the combustion process. Sources of this type of leakage would include but are not limited to bottom ash hoppers, wall blower penetrations, gaps in tube membranes and access doors. While not directly harmful to the combustion process, this air takes the place of over-fire or secondary air (since primary air is usually controlled on a mass flow basis). Tuning for good combustion, low NO_X, fireside corrosion and slagging is heavily dependent on where and how air is introduced to the fuel. Leakage air is not introduced to the fuel in any particular manner. It more than likely leaks in and then follows up the walls due to the lack of penetration velocity. Therefore, typically leakage air will prove a hindrance for tuning and good combustion.

The other type of leakage is post-combustion leakage. As it sounds, this is any air that enters the furnace envelope and does not participate in the combustion process. Sources of this leakage could include soot blower penetrations, access doors, tube penetrations, gaps in the tube membranes, penthouse cracks and economizer hopper leakage. This leakage is particularly dangerous because it artificially raises the excess oxygen indication at the economizer outlet. Since most units are run on an automatic oxygen trim controller, the control system will see an increase in oxygen and reduce the air input into the furnace to maintain the oxygen set-point. Unless a large access door or other source of severe leakage is opened in the right place, this process will not be noticeable to even the most attentive operator. Air in-leakage is a problem that usually increases slowly over time.

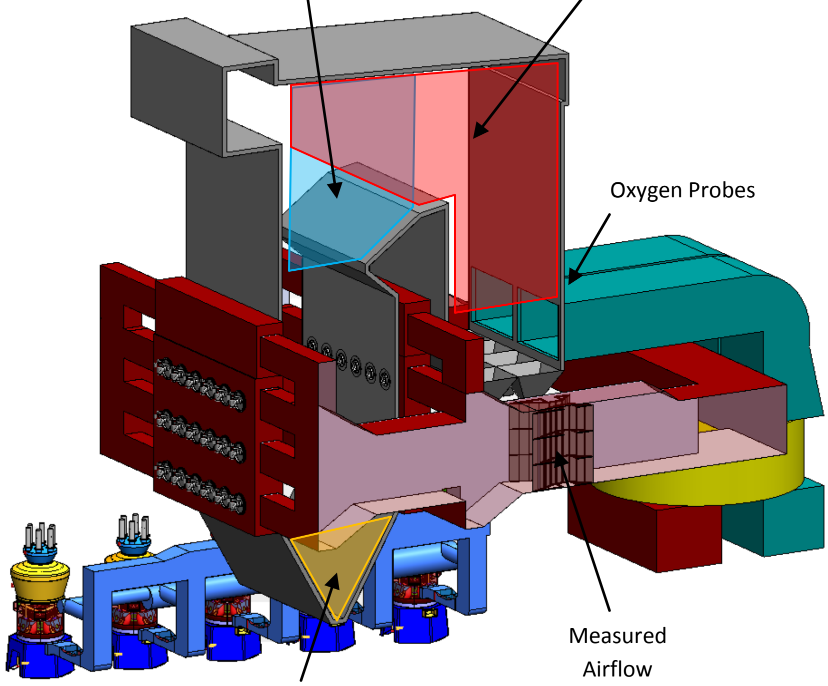

Figure 2 – Typical Zones for Leakage

As stated earlier, the oxygen measurement is just an indirect measurement of the relative amount of margin air. This system would work absolutely if it were not for the abundance of oxygen in the surrounding ambient air.

<u>Mass Flow Only Indication</u>

Pros: - Precisely metered for proper air to fuel ratios

Cons: - Does not measure leakage air
- Cannot indicate a level of air fuel mixing

<u>Oxygen Only Indication</u>

Pros: - Measurement includes leakage air
- Shows a relative indication of air fuel mixing assuming good furnace conditions

Cons: - Cannot distinguish between leakage air and actual margin
- Susceptible to stratifications in the measurement grid due to combustion related issues or leakage

By evaluating the pros and cons of each method, it is apparent that each system's pros can compensate for the cons of the other method.

Prerequisites

The system is easily implemented given the following criteria is met:

1. Total combustion airflow is accurately measured on a mass flow basis.

   Secondary air and primary air can be measured separately or together. However, the system will not be accurate if some of the air is not measured or poorly assumed. The most common methods for measuring airflow are venturis, airfoils, and averaging pitot arrays. Storm Technologies recommends venturis for their simplicity and the fact that the calibration is relatively stable compared to other systems that lose accuracy when they become plugged with ash carryover (which could be concern with long term monitoring). Total airflow needs to be measured within an accuracy of 3-5%. This also needs to include any seal air fan systems prior to the combustion process. If these flows are not measured, reasonable assumptions can be made due to the low percentage of total airflow contribution they represent.

2. Furnace exit oxygen is accurate and representative

   The leakage indication will determine the total leakage between the furnace inlet and the oxygen probes. This calculation it directly derived from the indicated oxygen levels measured by the oxygen probes. Therefore it is imperative that wherever the probes are located, they need to be accurately **calibrated and representative** of the entire duct. An error here is a direct error in the leakage calculation.

3. Total fuel consumption measured accurately within 5-10%

   The calculations are based on air to fuel ratios. Therefore the more accurate the fuel feed rates, the more accurate the leakage indication. Individual coal feeders can be less accurate (~10%) as long as the total fuel indication is around 5%. For oil or gas units, fuel flow will need to be converted into a mass flow basis instead of a volumetric basis.

4. Fuel quality and composition are relatively constant on a long term basis

   Daily variations in fuel quality are expected and will create "noise" in the leakage indication when looking at a historian. However, long term trends need to be based on a relatively constant fuel composition. If a fuel change occurs, the calculations need to be updated to reflect changes in moisture, carbon and hydrogen content. Alternatively, online coal analysis with a belt analyzer could be used to accommodate for changing fuel specifications.

5. Fly ash carbon content is kept reasonably low.

   The effects of unburned carbon content (UBC or LOI) will vary heavily on the fuel type. 2% LOI on an eastern fuel with 5% ash means that roughly 0.15% of the carbon is unburned. This equates to approximately a 0.1% reduction in leakage. Oxygen that would have oxidized the carbon shows up as excess O_2. High LOI levels will artificially raise the leakage indication. In reality, leakage can increase LOI. As air is pulled out of the burner belt (and introduced as leakage elsewhere), the potential for high LOI is increased. This effect will raise the excess oxygen even more, which can cause the unit to pull out even more oxygen.

Concessions

The system described within this paper is designed to be implemented with very little effort given the five prerequisites are met. However, there are some aspects that are not addressed in the system. The chemical equations assume that all of the carbon in the fuel is converted to a gas (carbon dioxide or carbon monoxide). If CO is not measured or measured a significant distance away from the oxygen probes, 0.0ppm can be assumed. However, accuracy is sacrificed. Every 350ppm CO represents roughly 0.1% less leakage. Any carbon left in the fly ash is ignored. Severe amounts of UBC (unburned carbon) should be resolved regardless of leakage. Likewise it is assumed that all of the fuel and atmospheric nitrogen leaves in the flue gas as diatomic nitrogen (N_2). In reality, small amounts of NO and NO_2 are created during the combustion process. However, both quantities (UBC and NO_X) are considered negligible on a mass flow or volumetric flow basis.

Basic Process Theory

The system works by assuming the following chemical equation:

$$C_XH_YO_ZS_V(H_2O)_W + A(O_2 + 3.76N_2) + A'(H_2O)$$
$$= X_1CO_2 + X_2CO + (0.5 + W + A')H_2O + VSO_2 + KO_2 + 3.76N_2$$

Where:

- X, Y, Z, V & W are all molar percentages based on the ultimate analysis of the fuel
- (A) is the molar amount of air required
- (A') is the molar amount of moisture in the air
- (K) is the molar oxygen remaining from combustion

Note: to compensate X for LOI, it will need to multiplied by the fraction of carbon actually burned.

More simply:

$$Fuel + Air + Moisture\ in\ Air$$
$$= Carbon\ Dioxide + Carbon\ Monoxide + Water + Sulfur\ Dioxide + Oxygen + Nitrogen$$

Using this equation, a certain indicated oxygen percentage remaining, K, should correspond to a given theoretical airflow provided to the system. If leakage is present, the airflow corresponding to the indicated oxygen level (theoretical airflow) will be higher than the measured airflow. The difference in the two values is the amount of air in leakage.

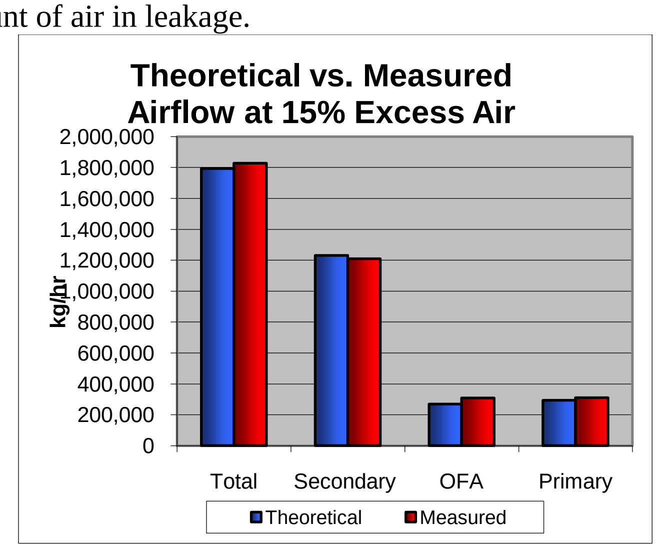

Figure 3 – Correlation between theoretical molar calculations and measured values

For example, Assume 1,000,000 lb/hr airflow is measured. Through the calculations it is found that the excess oxygen should indicate 2.7%. If the O_2 trim is still reading 3%, then the additional 0.3% oxygen by volume is from air in-leakage.

This does not determine the source of the leakage or whether it is pre or post combustion. However, if secondary combustion is not an issue, in-furnace measurements could be used to determine the split between pre and post combustion leakage.

Practical Application

Orlando Utilities Commission created a control screen and set up a historian to monitor the leakage on both of their 450MW B&W boilers. However, leakage is a slow progressing problem. Since neither unit has been through an outage to address leakage issues the leakage indication has not changed significantly. Therefore the leakage system was tested by artificially introducing leakage to the system. Observation doors on the 8-12 floors were opened to simulate leakage through normal means.

A few notes on the implementation of this system:

- CO is not measured and thus not accounted for
- LOI (UBC) is assumed to be 0%

Another issue discovered while testing the system is that the oxygen probes installed are not perfectly sensitive to air in-leakage. This is due to the fact that the oxygen probes are not perfectly representative of the true oxygen content of the flue gas. Any oxygen that is not read by the probes diminishes the leakage indication. Therefore, once the system is implemented on a furnace, a "reality check" using traditional methods should be performed. Figure 4 shows how the system performed on Unit 2.

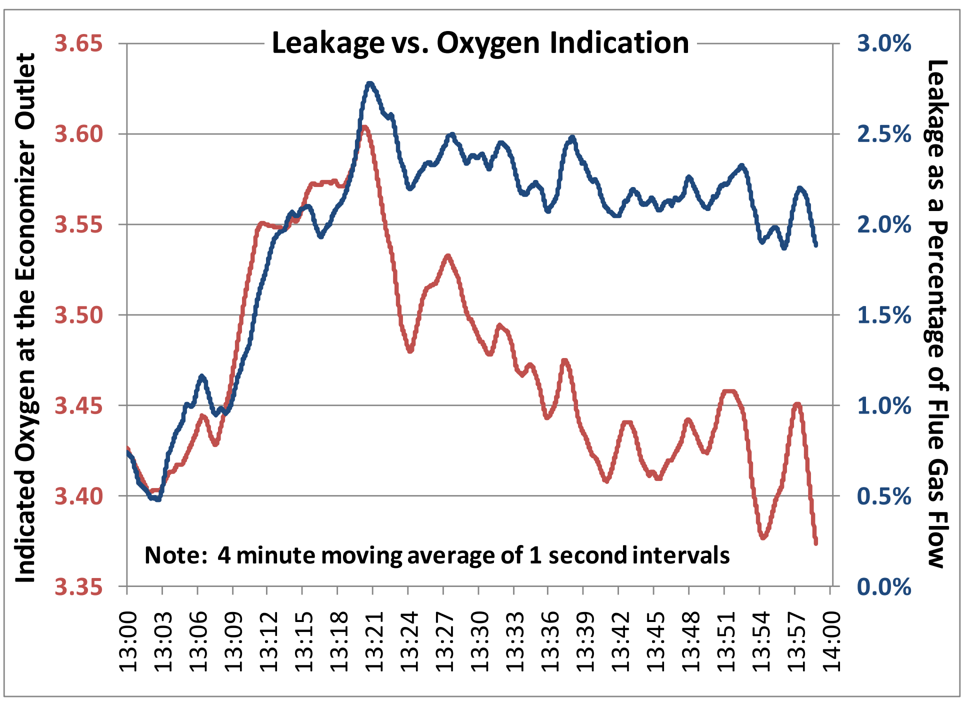

Figure 4 - Data from a functional test of the online-leakage monitor

As oxygen is introduced to the system (in this case over the span of a few minutes instead of the typical months and years) the leakage indication spikes to show the influx of air. However, as the O_2 trim begins to pull air out of the furnace to return the excess oxygen indication to that of the set-point, the leakage indication remains elevated. Once the doors were shut the leakage indication settled back to approximately 0% as air is automatically added to the secondary airflow. This is relatively consistent with historical physical data taken from the furnace exit at the nose arch elevation and economizer outlet.

Closing Comments

It is important to note that this is not a perfect system. The calculations are capable of giving leakage rates as a mass flow down to the lb/hr rate. However, the oxygen indication is always going to lag behind the fuel and airflow indication as well as being susceptible to un-representativeness. The fuel and air indications are also susceptible to inaccuracies. Steps can be taken to ensure the data is as accurate as possible by adding in online coal analyzers, including CO indications, adding in provisions for LOI and doing practical testing to verify and calibrate indications. Keep in mind though, that the ultimate goal of this system is to give the operator a tool for diagnosing potential problems and to keep an eye on leakage rates that may become an issue. Regardless of precision, the system can be used as a relative indication for the progression of air in-leakage.

Acknowledgements

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References

[1] ***"The Extreme Importance of Total Air & Fuel Flow Measurement on a 450MW B&W Wall Fired Unit firing high sulfur fuels***" Stephen Storm (Storm Technologies, Inc.); Jack Lyons (Orlando Utilities); PWR2008-68024, Electric Power 2008