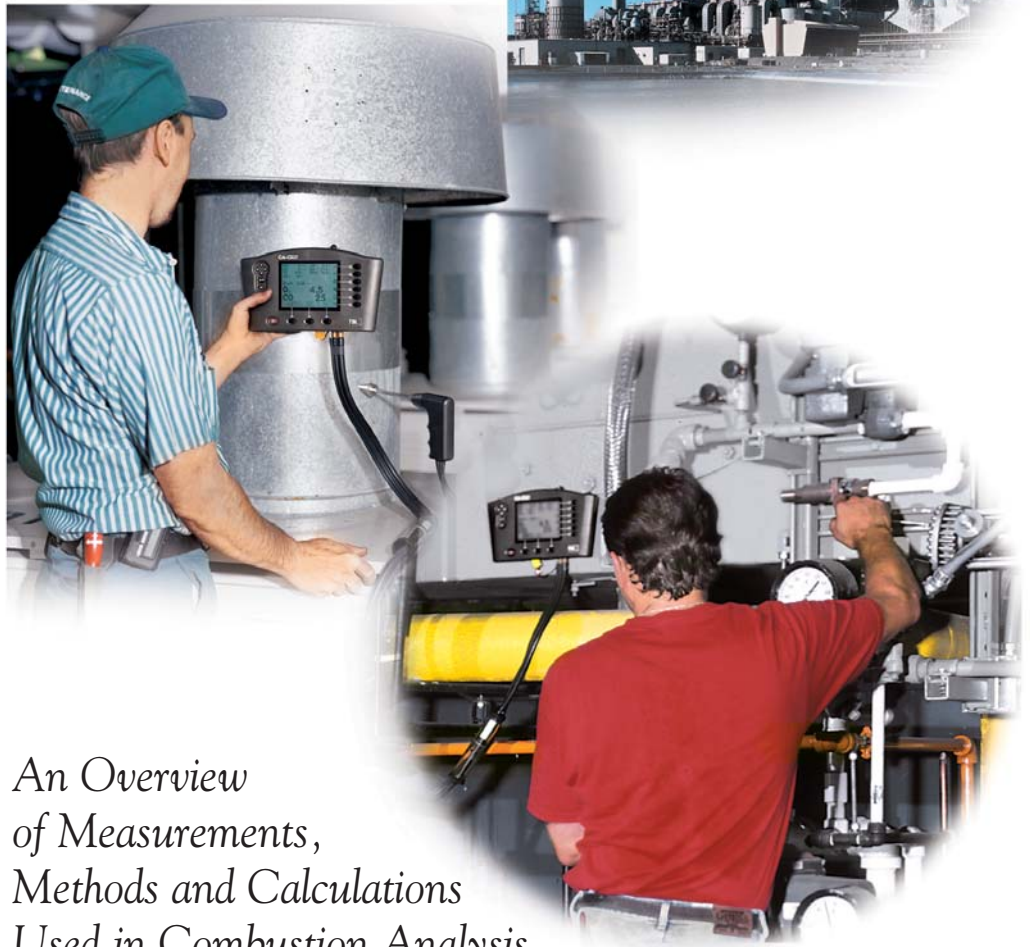# Combustion Analysis Basics

*An Overview
of Measurements,
Methods and Calculations
Used in Combustion Analysis*

TSI®

COMBUSTION ANALYSIS BASICS

An Overview of Measurements,
Methods and Calculations
Used in Combustion Analysis

# Contents

Introduction

Combustion

Combustion occurs when fossil fuels, such as natural gas, fuel oil, coal or gasoline, react with oxygen in the air to produce heat. The heat from burning fossil fuels is used for industrial processes, environmental heating or to expand gases in a cylinder and push a piston. Boilers, furnaces and engines are important users of fossil fuels.

Fossil fuels are hydrocarbons, meaning they are composed primarily of carbon and hydrogen. When fossil fuels are burned, carbon dioxide (CO_2) and water (H_2O) are the principle chemical products, formed from the reactants carbon and hydrogen in the fuel and oxygen (O_2) in the air.

The simplest example of hydrocarbon fuel combustion is the reaction of methane (CH_4), the largest component of natural gas, with O_2 in the air. When this reaction is balanced, or stoichiometric, each molecule of methane reacts with two molecules of O_2 producing one molecule of CO_2 and two molecules of H_2O. When this occurs, energy is released as heat.

$CH_4 + 2O_2 => CO_2 + 2H_2O$
Reactants => Products + Heat
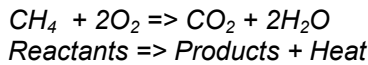
In actual combustion processes, other products are often formed. A typical example of an actual combustion process is shown in Figure 1. Fuel has reacted with air to produce the products shown on the right.
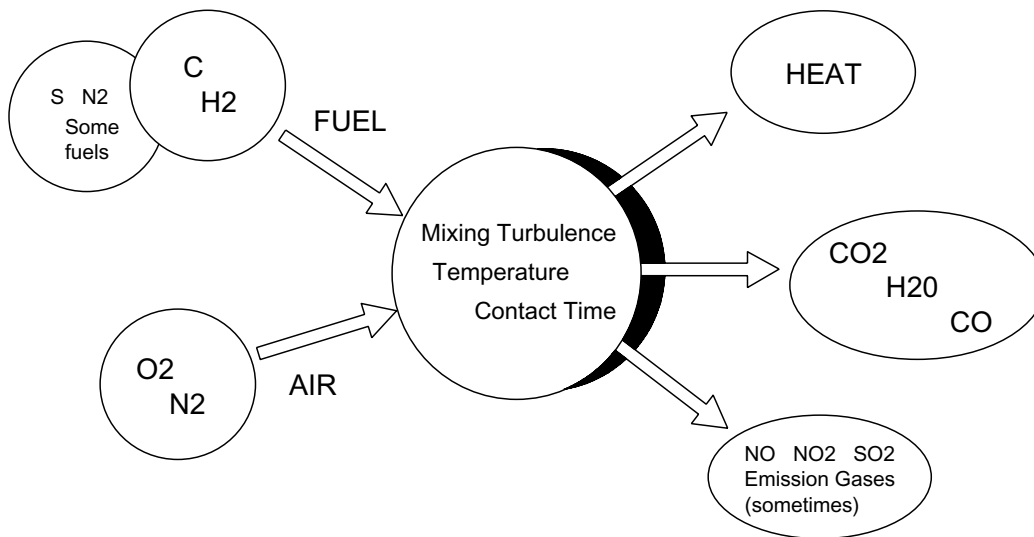
Figure 1. Combustion Diagram

The combining of oxygen in the air and carbon in the fuel to form carbon dioxide and generate heat is a complex process, requiring the right mixing *turbulence*, sufficient activation *temperature* and enough *time* for the reactants to come into contact and combine. Unless combustion is properly controlled, high concentrations of undesirable products can form. Carbon monoxide (CO) and soot, for example, result from poor fuel and air mixing or too little air. Other undesirable products, such as nitrogen oxides (NO, NO_2), form in excessive amounts when the burner flame temperature is too high. If a fuel contains

sulfur, sulfur dioxide (SO_2) gas is formed. For solid fuels such as coal and wood, ash forms from in-combustible materials in the fuel.

Combustion Analysis

Combustion analysis is part of a process intended to improve fuel economy, reduce undesirable exhaust emissions and improve the safety of fuel burning equipment. Combustion analysis begins with the measurement of flue gas concentrations and gas temperature, and may include the measurement of draft pressure and soot level.

To measure gas concentration, a probe is inserted into the exhaust flue and a gas sample drawn out. Exhaust gas temperature is measured using a thermocouple positioned to measure the highest exhaust gas temperature. Soot is measured from a gas sample drawn off the exhaust flue. Draft is the differential pressure between the inside and outside of the exhaust flue.

Once these measurements are made, the data is interpreted using calculated combustion parameters such as *combustion efficiency* and *excess air*. A more in depth analysis will examine the concentration of the undesirable products described earlier.

Why Perform Combustion Analysis?

Improve Fuel Efficiency

The largest sources of boiler heat losses are shown Figure 2. Heat energy leaving the system exhaust flue (or stack) is often the largest single source of lost fuel energy and is made up of the Dry Gas loss and Latent Heat Loss. Although some flue loss is unavoidable, an equipment *tune-up* using combustion analysis data can often significantly reduce this source of heat loss and save fuel costs by improving fuel efficiency. Table 1 gives examples of yearly cost savings that can be realized by improving equipment efficiency by five percent.
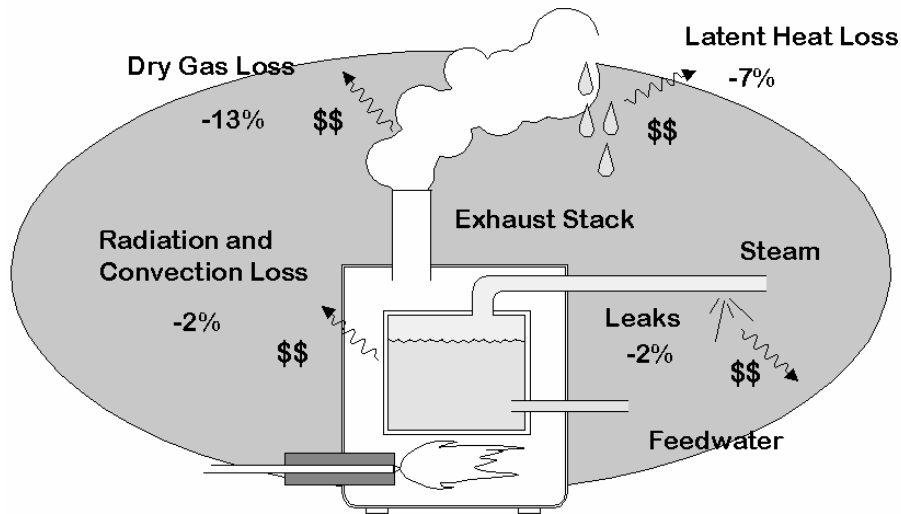
Figure 2. Boiler Heat Losses

Boiler HP	Fuel Cost			
	$0.75	$1.00	$1.50	$2.00
100	$3,635	$4,847	$7,271	$9,694
200	$7,271	$9,694	$14,541	$19,389
300	$10,906	$14,541	$21,812	$29,083
500	$18,177	$24,236	$36,354	$48,471
800	$29,083	$38,777	$58,166	$77,554

Table 1. Possible savings per year with a 5% improvement in boiler efficiency (based on 3000 hours per year of operation).

Reduce Emissions

Carbon monoxide, sulfur dioxide, nitrogen oxides and particles are undesirable *emissions* associated with burning fossil fuels. These compounds are toxic, contribute to acid rain and smog and can ultimately cause respiratory problems. Federal and state laws govern the permissible emission rates for these pollutants under the guidance of the Clean Air Act and oversight of the federal Environmental Protection Agency (EPA). State and local environmental agencies also exert authority in regulating the emissions of these pollutants. Combustion analysis is performed to monitor toxic and acid rain forming emissions in order to meet these federal, state and local regulations.

For specific information on emissions as they relate to a particular region, contact the local regulatory agency. For general information about U.S. regulations, refer to Appendix D, "Emissions."

Improve Safety

Good equipment maintenance practice, which includes combustion analysis, enables the boiler technician to fully verify and maintain the equipment operating specifications for safe and efficient operation. Many boiler manufacturers suggest that flue gas analysis be performed at least monthly. Boiler adjustments that affect combustion will tend to drift with time. Wind conditions and seasonal changes in temperature and barometric pressure can cause the excess air in a system to fluctuate several percent. A reduction in excess air can cause, in turn, a rapid increase of highly toxic carbon monoxide and explosive gases, resulting in rapid deterioration in system safety and efficiency. Low draft pressures in the flue can further result in these combustion gases building up in the combustion chamber or being vented indoors. Excessive draft pressures in the flue also can cause turbulence in the system. This can prevent complete combustion and pull explosive gases into the flue or cause flame impingement and damage in the combustion chamber and to the heat exchanger material.

What's Measured?

Combustion analysis involves the measurement of gas concentrations, temperatures and pressure for boiler tune-ups, emissions checks and safety improvements. Parameters that are commonly examined include:

- Oxygen (O_2)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)
- Exhaust gas temperature
- Supplied combustion air temperature
- Draft
- Nitric Oxide (NO)
- Nitrogen Dioxide (NO_2)
- Sulfur Dioxide (SO_2)

Oxygen, Carbon Monoxide and Carbon Dioxide

As described earlier, simple combustion involves the reaction of oxygen in the air with carbon and hydrogen in the fuel, to form carbon dioxide and water and produce heat. Under ideal conditions, the only gases in the exhaust flue are CO_2, water vapor and nitrogen from the combustion air.

When O_2 appears in the flue exhaust, it usually means that more air (20.9 percent of which is O_2) was supplied than was needed for complete combustion to occur. Some O_2 is left over. In other words, the measurement of O_2 gas in the flue indicates that extra combustion air, or *Excess Air,* was supplied to the combustion reaction. This is demonstrated in Figure 3 where the bar on the right represents the exhaust gas composition.
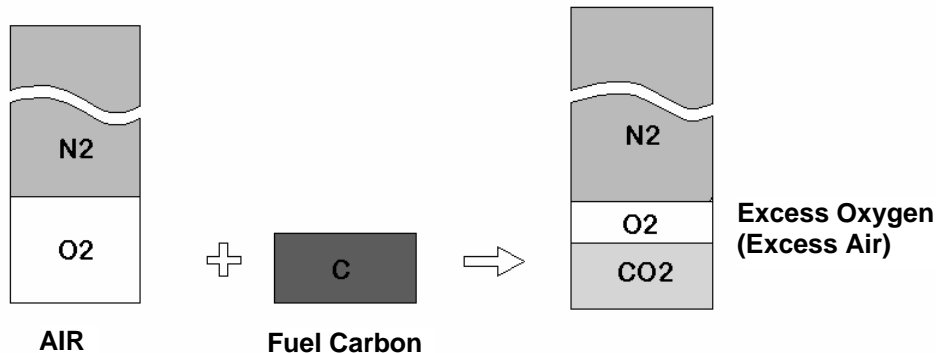
Figure 3. Excess Air Supplied

When too little air is supplied to the burner, there is not enough oxygen to completely form CO_2 with all the carbon in the fuel. Instead, some oxygen combines with carbon to form carbon monoxide (CO). CO is a highly toxic gas associated with incomplete combustion and efforts must be made to minimize its formation. This effort goes hand-in-hand with improving fuel efficiency and reducing soot generation. This formation of CO gas is illustrated in Figure 4.
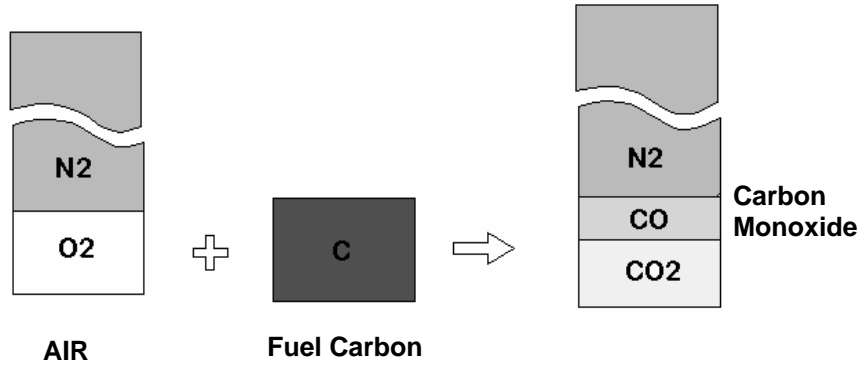
Figure 4. Too little combustion causes carbon monoxide to form.

As a rule, the most efficient and cost-effective use of fuel takes place when the CO_2 concentration in the exhaust is maximized. Theoretically, this occurs when there is just enough O_2 in the supplied air to react with all the carbon in the fuel supplied. This quantity of supplied air is often referred to as the *theoretical air.*

The theoretical air required for the combustion reaction depends on fuel composition and the rate at which the fuel is used (e.g. pounds per hour, cubic feet per minute, etc.). In real-world combustion, factors such as the condition of the burner and the burner design also influence the amount of air that is needed. The theoretical air is rarely enough.

The general relationship between the O_2 supplied and the concentration of CO_2 and CO in the exhaust is illustrated in Figure 5. As the air level is increased and approaches 100% of the theoretical air, the concentration of CO molecules decreases rapidly as they pick up additional oxygen atoms and form CO_2. Still more combustion air and CO_2 reaches a maximum value. After that, air begins to dilute the exhaust gases, causing the CO_2 concentration to drop. The maximum value of CO_2 is dependant on the type of fuel used.

Figure 5. Combustion Gas Concentrations at Percent
of the Theoretical Combustion Air

Temperature and Draft

Exhaust Gas Temperature and Supplied Combustion Air Temperature

Heat leaving the exhaust flue with the hot gases is not transferred to do useful work, such as producing steam. This heat loss becomes a major cause of lower fuel efficiency. Because the heat content of the exhau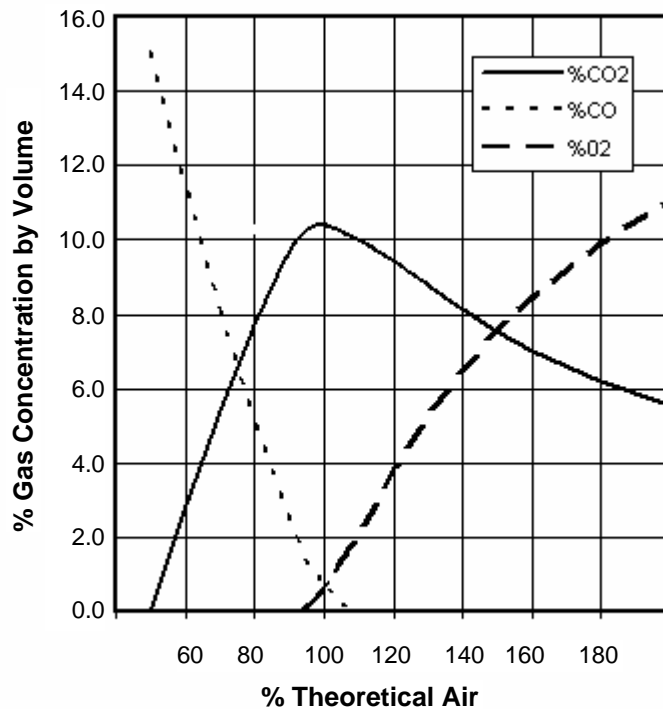st gas is proportional to its temperature, the fuel efficiency drops as the temperature increases. An example of efficiency loss due to the increase in stack gas temperature is shown in Figure 6.

When determining heat loss from the flue, the temperature of the supply air is subtracted from the flue gas temperature. This gives the *net* temperature and accounts for the heat supplied to the system by the supply air.

Some heat loss is unavoidable. The temperature in the flue needs to remain high enough to avoid condensation inside the stack. One process for recovering some of the heat loss in the exhaust is to use the hot flue gases to preheat the supply air before it is introduced into the combustion chamber.
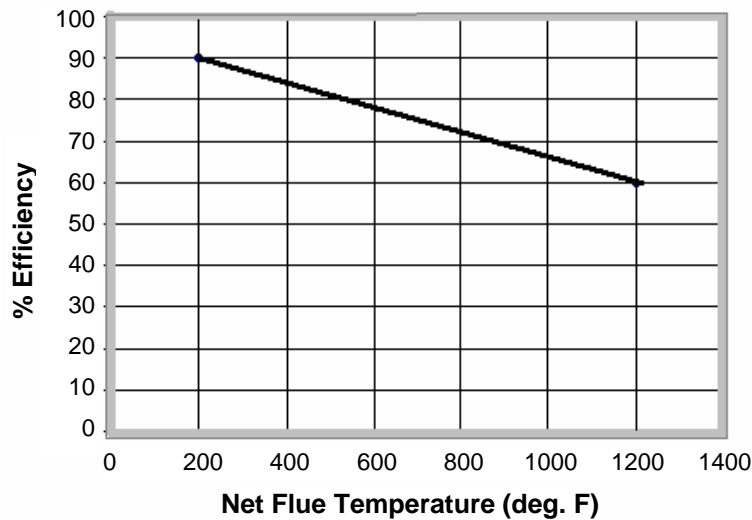
Figure 6. Flue Temperature vs. % Efficiency (fuel oil)

Draft

Draft refers to the flow of gases through the heat generating equipment, beginning with the introduction of air at the back of the burner. Once combustion occurs, the heated gas leaves the combustion chamber, passes heat exchangers and exits the exhaust stack. Depending upon the design of the equipment, draft is *natural*, meaning combustion air is pulled in by buoyant heated gases venting up the stack, or it is *mechanical*, meaning air is pushed or pulled through the system by a fan. Often, draft relies on a combination of both natural and mechanical means.

Adequate draft is typically verified by measuring the pressure in the exhaust stack. The manufacturer of the fuel burning equipment provides specifications for the required draft pressure and locations for making the draft measurement. Measurement is important since environmental influences such as changes in barometric pressure and ambient temperature can influence the flow. Typical draft pressures are in the range of –0.5 to 0.5 inches of water column.

Excessive draft can prevent heat transfer to the system and increase the flue temperature if the excess air percentage is not elevated. If the excess air increases from the high draft, the flue temperature will decrease. Low draft pressures can cause temperatures in the flue to decrease, allowing water vapor to condense in the flue, forming acid and damaging the system.

Nitrogen Oxides (NO$_x$)

Nitrogen oxides, principally nitric oxide (NO) and nitrogen dioxide (NO$_2$), are pollutant gases that contribute to the formation of acid rain, ozone and smog. Nitrogen oxides result when oxygen combines with nitrogen in the air or in the fuel. NO is generated first at high flame temperatures, then oxidizes further to form NO$_2$ at cooler temperatures in the stack or after being exhausted.

The NO concentration is often measured alone, and the NO$_2$ concentration is generally assumed to comprise an additional five percent of the total nitrogen oxides. The nitrogen oxide gas concentrations are sometimes combined and referred to as the *NO$_x$* concentration.

Sulfur Dioxide (SO$_2$)

Sulfur dioxide combines with water vapor in the exhaust to form a sulfuric acid mist. Airborne sulfuric acid is a pollutant in fog, smog, acid rain and snow, ending up in the soil and ground water. Sulfur dioxide itself is corrosive and harmful to the environment.

Sulfur dioxide occurs when the fuel contains sulfur and where the emission levels are directly related to the amount of sulfur in the fuel. The most cost-effective way to reduce sulfur emissions is to select a low-sulfur or de-sulfured fuel.

Hydrocarbons (HCs)/Volatile Organic Compounds (VOCs)

Organic compounds are sometimes present in the combustion exhaust products because of incomplete combustion. Hydrocarbons (HCs), or volatile organic compounds (VOCs), are best reduced through proper burner maintenance and by maintaining the proper air/fuel mixture.

Soot

Soot is the black smoke commonly seen in the exhaust of diesel trucks, and is present whenever fuel oils or solid fuels are burned. Excessive soot is undesirable because it indicates poor combustion and is responsible for coating internal heat transfer surfaces, preventing good thermal conductivity. Over time, serious damage to the heat exchanger can occur.

Soot is primarily unburned carbon, and is formed for the same reasons CO is formed—insufficient combustion air, poor mixing and low flame temperature. As with CO, it is usually impossible or impractical to entirely eliminate soot formation for some fuel types.

Measurement Tools

Manual Gas Measurements

The Orsat analyzer is a gas concentration analysis tool typically used to manually sample CO_2, O_2 and CO from the flue of a combustion system. The Orsat analyzer determines the gas concentrations from a sample of gas extracted from the flue and bubbled through solutions of reagents that selectively absorb each gas. By measuring the decrease in gas volume over the liquid reagents, the amount of gas absorbed is indicated. From this information, stack gas concentration is calculated. Manual gas measurements are time consuming and do not accurately reflect real-time adjustments made to a system.

Portable Electronic Instruments

In recent years, electronic instruments such as the CA-CALC™ Combustion Analyzer from TSI Incorporated (see Figure 7) have been developed to analyze combustion routinely for tune-ups, maintenance and emissions monitoring. These instruments are extractive. They remove a sample from the stack or flue with a vacuum pump and then analyze the sample using *electrochemical* gas sensors. Thermocouples are used for stack and combustion air temperature measurements, and a pressure transducer is used for the draft measurement. An on-board computer performs the common combustion calculations, eliminating the need to use tables or perform tedious calculations. Electronic instruments show the results of boiler adjustments in real-time and give more accurate information to help ensure that a system has been tuned properly.

Figure 7. Portable Combustion Monitor

Continuous Emission Monitors

Continuous emission monitors, or CEMS, are a class of electronic instruments designed to measure exhaust stack gases and temperature continuously. CEMs are sometimes used for combustion control, but typically are used for monitoring pollutant gas emissions as required by government regulations. CEMs can use both extractive and *in-situ* (sensors in the stack) sampling methods, and employ a variety of electronic sensor technologies for gas detection. CEMs are used most often on larger installations or when required by regulatory agencies.

Using The Measurements

Once flue gas and temperature measurements are made, *combustion parameters* are calculated to help evaluate the operating performance of the furnace or boiler. Typical combustion parameters include:

- Excess Air
- Carbon Dioxide
- Combustion Efficiency
- O_2 Reference
- Emissions Conversions

Excess Air

Insufficient combustion air causes a reduction in fuel efficiency, creates highly toxic carbon monoxide gas and produces soot. To ensure there is enough oxygen to completely react with the fuel, extra combustion air is usually supplied. This extra air, called "Excess Air," is expressed as the *percent air above the amount theoretically needed for complete combustion.* In real-world combustion, the excess air required for gaseous fuels is typically about 15 percent. Significantly more may be needed for liquid and solid fuels.

A good estimate of excess air can be determined using the following formula. This calculation uses the oxygen concentration measured in the exhaust. If the CO concentration is very high, it may also be included in the excess air calculation. This is shown in Appendix C, "Calculations."

$$\% \, Excess \, Air = \frac{\%O_2 \; measured}{20.9 - \%O_2 \; measured} \; x \; 100$$

Although required, higher excess air comes with a price—it wastes fuel. There are a number of reasons why this occurs but, stated simply, supply air cools the combustion system by absorbing heat and transporting it out the exhaust flue. The more air, the more the cooling. Consider, too, that nitrogen, which makes up about eighty percent of the air, plays no role chemically to produce heat. It does, however, add significantly to the weight of gas that absorbs heat energy. Figure 8 illustrates how increasing excess air reduces combustion efficiency.
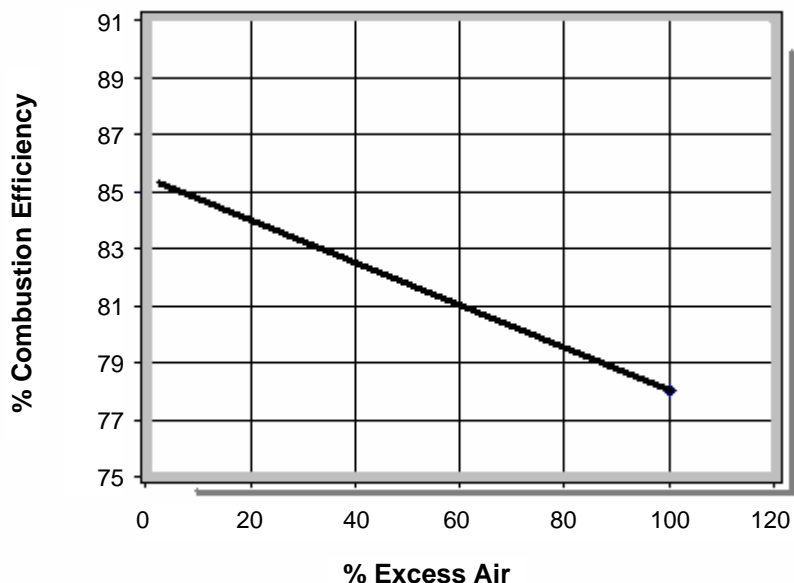
Figure 8. % Combustion Efficiency vs. % Excess Air (fuel oil)

Using too much excess air is one of the principal causes of poor fuel economy. For this reason, optimizing excess air usage can be one of the simplest ways to achieve significant fuel savings.

NOTE: *Excess Air and Fuel/Air Mixing*
Adding additional excess air is often done to reduce the CO concentration. Too much excess air can actually have the reverse effect of increasing CO. This results when fuel and air no longer mix properly in the burner, reducing the time of contact between oxygen and fuel and inhibiting a complete reaction.

Calculating the Carbon Dioxide Concentration

Carbon dioxide (CO_2) forms when carbon in the fuel combines with O_2 in the combustion air. When there is just enough O_2 supplied to react with the carbon in the fuel, the CO_2 concentration in the stack exhaust is at its highest level. This is generally at or close to the ideal operating condition for the heat generating equipment. This was shown in Figure 5.

The maximum possible CO_2 exhaust concentration depends ultimately on the carbon content of the fuel being burned. This number, the CO_2 maximum, appears often in combustion calculations, such as the one below for determining the percent of CO_2 in the exhaust. Maximum CO_2 concentrations for a variety of fuels are presented in Appendix D, "Fuel Specifications."

$$\% \ CO_2 \ \text{(by volume)} = CO_2 \ \text{(maximum)} \ x \ \frac{(20.9 - \%O_2 \ measured)}{20.9}$$

NOTE: *Using Measured O_2 to Determine CO_2*
Using the O_2 concentration to determine the concentration of CO_2 has advantages compared to measuring CO_2 directly. As indicated in Figure 5, the same CO_2 concentration is possible when there is too little air supplied (less than 100% theoretical air) or too much air (greater than 100% theoretical air). When CO_2 is measured alone, it is not possible to tell if the mix of exhaust gases is represented by those to the left of the CO_2 peak or those to the right of the CO_2 peak. When to the left of the peak, high levels of toxic CO are present, resulting in a potentially dangerous operating condition. By detecting sufficient O_2 in the exhaust, the combustion reaction stays on the right side of the CO_2 peak, minimizing the formation of CO.

Determining Combustion Efficiency

Combustion efficiency is a measure of how effectively energy from the fuel is converted into useful energy (e.g. to create steam). Combustion efficiency is determined by subtracting the heat content of the exhaust gases, expressed as a percentage of the fuel's heating value, from the total fuel-heat potential, or 100%, as shown in the formula below.

$$\% \text{ Combustion Efficiency} = 100\% - \left(\frac{\text{stack heat losses}}{\text{fuel heating value}} \times 100 \right)$$

Stack *heat losses* are calculated using gas concentration and temperature measurements from combustion analysis, and using the fuel's specifications for chemical composition and heat content. These *fuel specifications* are unique properties of the fuel, determined from chemical analysis by the fuel supplier. Typical fuel specifications for some common fuels are presented in Appendix B, "Fuel Specifications."

Stack heat losses are primarily from the heated dry exhaust gases (CO_2, N_2, O_2) and from water vapor formed from the reaction of hydrogen in the fuel with O_2 in the air (refer to Figure 2). When water goes through a phase change from liquid to vapor, it absorbs a tremendous amount of heat energy in the process. This "heat of vaporization," or *latent heat*, is usually not recovered. The white cloud seen exiting a stack on a cold day is mostly condensing water vapor giving up its latent heat to the atmosphere.

The calculations used to determine heat losses and combustion efficiency are presented in Appendix C, "Calculations." Fortunately, modern portable analyzers, like TSI's CA-CALC Combustion Analyzers, automatically perform combustion efficiency calculations, typically with better accuracy than manual calculations or charts. Table 2 below shows the combustion efficiency for fuel oil under various conditions.

Net Temperature (stack temperature – supply temperature) degrees F.

%CO2	%O$_2$	300	320	340	360	380	400	420	440	460	480	500	550	600
15.6	0.0	88.0	87.6	87.2	86.8	86.4	86.0	85.6	85.2	84.8	84.4	84.0	83.0	82.1
14.1	2.0	87.5	87.1	86.6	86.2	85.8	85.3	84.9	84.5	84.0	83.6	83.2	82.1	81.0
13.4	3.0	87.2	86.8	86.3	85.9	85.4	85.0	84.5	84.1	83.6	83.2	82.7	81.6	80.5
12.6	4.0	86.9	86.4	85.9	85.4	85.0	84.5	84.0	83.5	83.1	82.6	82.1	80.9	79.7
11.9	5.0	86.5	86.0	85.5	85.0	84.5	84.0	83.5	83.0	82.5	82.0	81.5	80.3	79.0
11.1	6.0	86.0	85.5	85.0	84.5	83.9	83.4	82.9	82.3	81.8	81.3	80.7	79.4	78.1
10.4	7.0	85.6	85.0	84.5	83.9	83.3	82.8	82.2	81.7	81.1	80.5	80.0	78.6	77.2
9.6	8.0	85.0	84.4	83.8	83.2	82.6	82.0	81.4	80.8	80.2	79.6	79.0	77.5	76.0

Table 2. Combustion Efficiency % (fuel oil)

NOTE*: Other Definitions of Efficiency*
It is important to recognize that other definitions of efficiency are often used to describe furnace or boiler performance in addition to combustion efficiency. Thermal efficiency or boiler efficiency are examples. These may include or exclude sources of heat loss as part of their calculation. Combustion efficiency, for example, does not include losses from radiation or steam leaks. Sometimes the latent heat of water formation is not included. There are also fundamental differences between calculations performed in the U.S. and those performed in some European countries. Appendix B, "Fuel Specifications," touches on this briefly in the discussion of heating values used in the efficiency calculation. When comparing the performance of equipment from different manufacturers, it is important to know how an efficiency number is calculated.

NOTE*: Why use Combustion Efficiency?*
Combustion efficiency, determined from combustion analysis, is a cost-effective way to improve equipment operation and reduce fuel expense. The stack losses used in combustion efficiency calculations are simple to determine using combustion analysis. Other losses, such as those from steam leaks, radiation or boiler blow-down, are much more difficult to assess. Stack losses are typically the largest source of energy waste. If the equipment is properly maintained, losses such as those from steam leaks are minimal. Convection and radiation losses are often small also, and usually unavoidable.

The O$_2$ Reference

As discussed earlier, excess air is supplied to the combustion process to ensure that there is enough oxygen to completely react with the fuel. Excess air is measured in the flue as a percentage of O$_2$. This excess air dilutes the concentration of other gases measured.

Local regulatory agencies have guidelines for monitoring NO, NO$_2$, CO, and SO$_2$ gases. Generally, it is required that the concentration of these gases be corrected for the diluting effects of excess air. The amount of excess air is determined from the O$_2$ concentration measured in the flue. The measured O$_2$ concentration, together with the *O$_2$ reference* value is used in the equation below to obtain the corrected gas concentration. O$_2$ reference values of 3 and 6 percent are often used, giving a corrected gas concentration equivalent to that at oxygen concentrations of 3 or 6 percent. When an O$_2$ reference of zero is used, the gas concentration is referred to as *undiluted* or *air free.*

To obtain the O$_2$ referenced concentration of gasses in the flue, the following equation is used:

$$\text{Corrected PPM} = \text{measured PPM} \times \frac{20.9 - O_2 \ \textit{reference}}{20.9 - O_2 \ \textit{measured}}$$

Emission Conversions

A measure of the toxic gas concentration in parts per million (PPM) or percent does not indicate the actual weight of pollutant entering the atmosphere. The EPA requires the conversion of pollutant concentrations to pounds per million Btu of fuel consumed (lb/MBtu). This is done so the weight of pollutants can be readily determined from the pollutant concentration and the rate of fuel usage. EPA Method 19 has equations for performing the conversions and presents fuel-specific conversion factors for use in performing the calculations. Emission conversion procedures are described in greater detail in Appendix C, "Calculations," along with factors derived from EPA Method 19.

Making Measurements

Taking Gas Samples

Extracting flue gases to measure their concentration is done using a stainless sampling probe inserted through a small hole in the exhaust flue. Probe placement is important, and several factors must be considered when choosing a sampling location.

To get the most accurate measurement, the gas sampling probe must be placed prior to any draft damper or diverter, so that the gases are not diluted, and as close to the equipment breach as possible so the gases have not cooled in the flue. If there is a stack economizer or similar device, the measurement should be taken just downstream of the installed device.

Figures 9 and 10 show two examples of recommended insertion points for gas sampling probes.
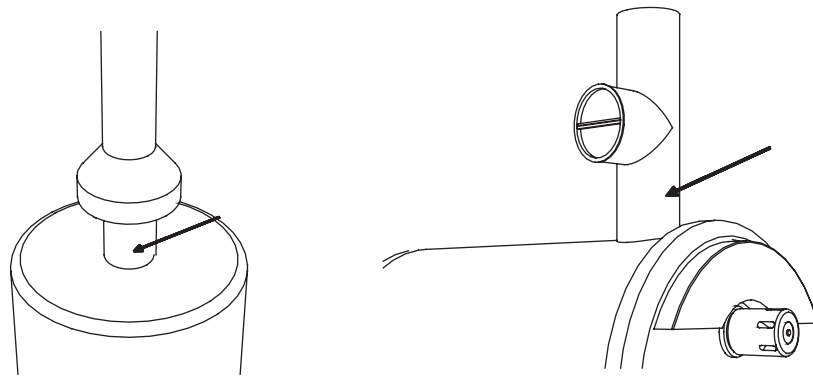

Figure 9. Flue Gas Sampling Locations

NOTE: Special Care for Emission Gas Measurements
For emission gas measurements, consideration must be given to the fact that as water vapor cools and condenses in the stack, highly soluble NO_2 and SO_2 gases may be s*crubbed* out by dissolving in the water droplets. Sampling must be done before condensation begins.

Condensation is a problem in the gas sample line as well as in the flue, causing a loss of NO_2 and SO_2. Measurement errors due to the loss of SO_2 and NO_2 are lessened by reducing the time water and gases are in contact, and by reducing the contact surface area between the water and gases. This is achieved by quickly removing moisture from the gas sample. If necessary, the use of an ice bath or Peltier cooler, followed by immediate collection of the condensed water in a reservoir away from the gas stream, is beneficial. In addition, when sampling SO_2 and NO_2, use of a non-reactive, non-wetting material such as Teflon for the sample tubing is essential. Wetting of the interior surfaces, associated with other tubing materials, significantly increases the contact surface area between gas and water, resulting in gas loss from absorption. When a SO_2 or NO_2 gas sample must be transported more than a few feet before the water is removed, the sample lines are usually heated (250–300°F) to keep water in a vapor state.

Making Temperature and Draft Measurements

As described earlier, measurements of the stack gas temperature and the combustion air temperature are required to establish the heat loss from the exhaust gases and determine combustion efficiency. Since stack temperatures can exceed 1,000 degrees Fahrenheit, a bimetallic thermocouple probe is typically used to measure the stack temperature. This thermocouple probe is placed at the point of highest exhaust gas temperature at the base of the flue and toward the center for small ducts. If the stack gas temperature is underestimated, the operating efficiency will be overstated. When an econo-

mizer or air heater is used, stack temperature is measured after these devices. Figure 10 shows locations for measuring both stack and combustion air temperatures. Combustion air temperature is measured outside the equipment in these examples.

Draft is a measurement to ensure the combustion gases are being properly exhausted. Draft is measured using a manometer or electronic pressure transducer. The equipment manufacturer can provide the recommended draft pressure for specific equipment and where to take the measurement. Draft is usually measured in the same location as the stack temperature relative to the ambient space. When a draft diverter or draft hood is in the stack, a second measurement should be taken downstream of the device.
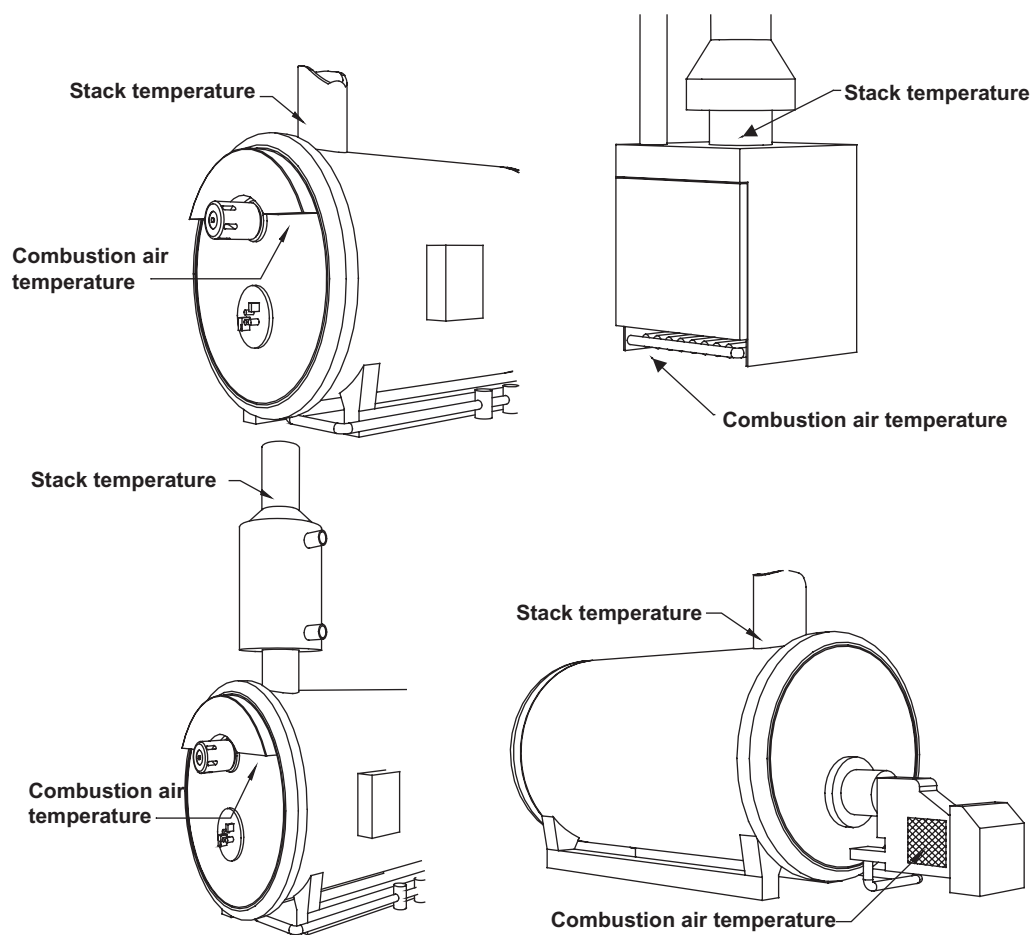
Figure 10. Stack Temperature and Combustion Air Temperature Sampling Locations

Soot Measurements

Soot is most commonly measured during equipment tune-up and maintenance by extracting a sample of the exhaust gases using a manual sampling pump. The sample is taken from the same location as the stack temperature measurements shown in Figure 10. A specific number of strokes on the pump (recommended by the pump manufacturer) is required to draw a known gas volume through a glass fiber filter. Once complete, the filter color is compared to a scale displaying shades of gray corresponding to known soot concentrations.

Sample Boiler Tune-Up Procedure

NOTE: These abbreviated procedures are presented here for illustration purposes only and are not meant to substitute for the actual procedures. When performing tuning or other equipment maintenance, always follow the equipment manufacturer's recommendations first. Maintenance, including tune-ups, must always be performed by a qualified technician or engineer.

Tune-up Procedure—Using an Electronic Combustion Analyzer

1. Insert the combustion analyzer gas sampling probe into the flue. The probe should be as close to the equipment breach as possible, upstream of any diverter or draft damper and downstream of the last heat exchanger or heat recovery coil.

2. If ambient air is used as the combustion air, an additional temperature probe is not required. An ambient temperature probe is located inside the combustion analyzer.

3. If the combustion air is ducted directly to the combustion chamber or preheated, place a combustion supply air temperature probe into the ductwork just prior to the combustion chamber inlet.

4. Without the gas sampling probe connected to the instrument, turn on the combustion analyzer. Follow the steps on the analyzer to determine if a baseline calibration is required to zero out any sensors that may have drifted too far off zero. If you are using TSI's CA-CALC Combustion Analyzer, it will give you an alarm message when a baseline calibration is recommended. Caution— baseline calibration requires ambient air to be fresh air.

5. After you have passed or completed a required baseline calibration and there were no errors, the gas sampling probe can be connected to the instrument.

6. Be sure the gas sampling pump is on and all temperature probes are attached. The electronic analyzer is now ready for use to tune the system to optimize combustion efficiency and to monitor any emission gases for which the appropriate sensor is installed in the combustion analyzer.

7. Combustion analysis should be performed on a warmed up unit at firing rates typical of normal operation. For systems with high, low and additional firing rates, adjustments should be made at all firing rates whenever possible.

8. Place the combustion analyzer in a location where the screen is easy to view, free from the modulation controller or linkages to be adjusted.

9. Put the burner control system into manual mode and test several firing rates for combustion efficiency and emission gas concentrations.

    a. Observe the values on the combustion analyzer. If the percentage of O_2 in the stack is at the lower end of the expected minimum values (as specified by equipment manufacturer) and the CO emissions are low with no smoke being generated, the burner is probably tuned at or near optimum efficiency at this firing rate.

    b. Observe the values on the combustion analyzer. If the combustion equipment has been tuned previously, compare the previous combustion efficiency to the combustion efficiency of the current measurement. A significant difference indicates burner adjustments or repair might be appropriate to improve combustion efficiency.

10. If tuning the equipment is required, adjust the mechanical linkages to decrease the excess air until CO is about 400 PPM or to the maximum allowable concentration stated in the local code. If a bad flame develops or significant smoking occurs prior to reaching 400 PPM CO, stop making adjustments at this point. This will verify that too much excess air is not lowering efficiency.

11. Observe the O_2 level on the combustion analyzer at these settings. Add oxygen sufficient to satisfy local codes to the observed oxygen level and reset the burner to operate automatically at this higher stack gas oxygen level.

12. Compare the measured value of oxygen at this burner setting to the minimum value of excess oxygen recommended by the local authority. If the minimum value measured is significantly higher than the minimum value recommended by the local authority, then the burner may need additional maintenance or replacement.

13. When an adjustment has been completed, verify the new adjustment has not had an adverse effect on the other firing rates that have already been adjusted. If it has, settings should optimize conditions at the predominant firing rate and the combustion controls need to be readjusted at the affected firing rates.

14. After adjustments have been completed at all firing rates, the controls should be modulated or staged through all combustion firing rates to ensure proper operation. The control settings at firing rates most typical of operation should be recorded. The measurements by the combustion analyzer should be data logged into memory for future reference and for generating printouts and reports.

Additional adjustments may be needed to balance the emissions with the combustion efficiency.

Appendices

Appendix A. Energy Units

The common unit of heat measure in the U.S. is the British thermal unit or Btu. One Btu is defined as the amount of heat required to raise one pound of liquid water one degree Fahrenheit, specifically from a temperature of 59 degrees to 60 degrees.

The energy content of a fuel is typically given in Btus per pound of fuel. Fuel oil, for example, has an energy content of roughly 18,500 Btu/lb. For gaseous fuels, such as natural gas or propane, energy content is also expressed in Btus per cubic foot (Btu/ft^3). For liquid fuels, such as fuel oil, Btus per gallon (Btu/gal) is commonly used.

When measuring the rate of fuel energy used, the input power or the rate of heat produced, the output power BTUs are given per unit time (e.g. Btu/hour). To convert from the rate of fuel used to power, the consumption rate is multiplied by the energy content of the fuel. This calculation is shown in the example below, where ten pounds of fuel with an energy content of 20,000 Btu/lb is burned per hour. The resulting energy consumed is 200,000 Btu per hour.

200,000 Btu/hr = 10 pound/hr x 20,000 Btu/pound

Boilers are often rated in "Boiler Horsepower" (BHP) rather than Btus per hour. One boiler horsepower is defined as the amount of energy it takes to convert 34.5 pounds of water to steam in one hour at 212 degrees Fahrenheit. A boiler HP equals 33,472 Btu/hour.

Metric Equivalents
Although common in the United States, the British thermal unit is not used universally. The metric units corresponding to Btus and pounds are kilo-Joules (kJ) and kilograms (kg). The relationships between these measures are:

1 kJ = .948 Btu
1 kg = 2.204 pounds
1 kJ/kg = .429 Btu/pound

Appendix B. Fuel Specifications

Every fuel has a unique composition and energy content described by its fuel specifications. Knowing the fuel specifications is essential for determining combustion parameters such as combustion efficiency, minimum air requirements, CO_2 concentration and emissions factors.

Table 3 presents fuel specification values for a number of common fossil fuels used in commercial and industrial process boilers and heaters. For some electronic analyzers, like TSI's CA-CALC Combustion Analyzer, these values are pre-programmed into the instrument for easy analysis. The fuel specifications are typical fuel values, and may not accurately represent the makeup of the fuel you are presently using. When available, fuel specifications supplied by the fuel vendor should be used.

Specifications	Nat. Gas	Propane	Oil #2	Oil #6	Coal	Wood (dry)	Bagasse	Coke
%Carbon	70.93	81.82	85.84	87.49	94.5	51.8	17.8	98.2
%Hydrogen	23.47	18.18	12.46	9.92	5.2	6.3	2.13	1.5
BTU/lb HHV	21869	21669	19512	18300	13388	9130	4500	16532
BTU/lb LHV	19693	19937	18357	17381	12903	8546	4303	16393
CO₂max	11.8	13.8	15.6	16.5	17	19.1	20.6	20.1
%Sulfur	0	0	1.6	1.40	0.034	0	0	0
Moisture	0	0	0	0	0.12	0	63.790	0.5

Table 3. Fuel Specifications for Selected Fuels

NOTE*: High and low heating values of fuel?*
When a hydrocarbon fuel is burned, water is formed from the reaction of oxygen and hydrogen in the fuel. In most cases, this water is in the vapor phase at high temperature and exhausted with the other products of combustion. When exhausted, the heat of vaporization (latent heat) of the water is lost.

Two heating values are typically assigned to fossil fuels depending upon whether the latent heat of the water formed during combustion is included, or excluded. If the latent heat of water formation is included, the heating value is referred to as the fuel's *high heating value* or HHV. This is the total fuel energy determined using a *calorimeter*. If the latent heat energy is not included, the fuel's heating value is referred to its *low heating value* or LHV. High and low heating values are both used for calculations of combustion efficiency. Because these heating values can be significantly different, especially for fuels that have a high hydrogen content, it is important to know which heating value is used. Generally, in the United States, the HHV is used whenever efficiency calculations are performed. In Europe, the LHV is often used. Contact your local regulatory agency to determine which value to use.

Appendix C. Calculations

List of Calculations described in this section:

1. Determining CO_2 using the O_2 concentration
2. Excess air calculation
3. Combustion efficiency calculation
4. Combustion calculations using the Siegert formula
5. O_2 reference concentration calculation
6. Emission Rate calculations using dry gas factors
7. A general equation for the combustion of a simple hydrocarbon in air
8. Calculating CO_2 max from the carbon content
9. Combustion air calculation

1. Determining CO_2 using the O_2 concentration

Instruments using electronic sensors determine the CO_2 concentration in real time by measuring the O_2 concentration in the flue exhaust and calculating CO_2.

The CO_2 concentration is determined using the following equation.

$$\% \ CO_2 \ \text{(by volume)} = \ CO_2 \ \text{(max)} \ x \ \frac{(20.9 - \%O_2 \ measured)}{20.9}$$

CO_2 (max) is the theoretical maximum concentration produced for the fuel used.

2. Excess air calculation

Excess air is determined by measuring the concentration of non-reacted O_2 in the flue gas.

A good approximation for excess air, expressed as a percent, can be calculated from the equation below. This calculation is often used to automatically calculate % Excess Air in electronic combustion analyzers, like TSI's CA-CALC Combustion Analyzer. O_2 and CO concentrations are obtained from sampling the stack gas constituents.

$$\% \ Excess \ Air = \frac{\%O_2 - \dfrac{\%CO}{2}}{20.9 - \left(\%O_2 - \dfrac{\%CO}{2}\right)} \ x \ 100$$

An expression of excess air referred to as Lambda (λ) is also used. The relationship between % Excess Air and Lambda is shown below:

$$\lambda = \frac{\% \ Excess \ Air}{100} + 1$$

3. Combustion efficiency calculation

Combustion efficiency is expressed as a percent and determined by subtracting individual stack heat losses, as percents of the fuel's heating value, from the total heating value of the fuel (100%). Dry gas loss and latent heat loss due to H_2 in the fuel are typically the largest sources of stack loss. Others can be included, such as heat loss from moisture in the air and fuel and losses from the formation of CO rather than CO_2. This basic form for calculating efficiency is described in the ASME Power test code 4.1 and is applicable for losses other than flue losses when determining total system efficiency by the *Heat-Loss* method.

$$\% \text{ Net Combustion Efficiency } = 100 - \frac{\text{flue heat losses/lb fuel}}{\text{fuel heating value/lb fuel}} \times 100$$

flue heat losses = *Lg* + *Lh* + *Lm* + *Lco* (Individual heat losses are described in this section.)

Where: *Lg* = heat loss due to dry gas
Lh = heat loss due to moisture from burning hydrogen
Lm = heat loss due to moisture in fuel
Lco = heat loss from the formation of CO

fuel heating value: HHV or LHV (see notes in Appendix B)

NOTE: In Europe, combustion efficiency is often calculated without the latent heat loss from the formation of water. The dry gas alone is subtracted from 100 percent, and sometimes referred to as the gross efficiency. In addition, flue gas loss is commonly calculated using the Siegert forumula. Also refer to the following discussion in "*4. Combustion calculations using the Siegert formula*" on the following page.

$$\% \text{ Gross Combustion Efficiency (dry)} = 100 - \frac{\text{dry losses/lb fuel}}{\text{fuel heating value/lb fuel}} \times 100$$

Heat loss due to dry gas (Lg)

Lg = Wg x Cp x (T_{flue} − T_{supply}) (The CA-CALC displays Loss as the dry gas loss.)

Where: *Wg*   = the weight of the flue gases per pound of as-fired fuel.
Cp   = specific heat of the exhaust gas mix.
T_{flue} = flue temperature
T_{supply} = combustion supply air temperature

$$Wg = \frac{(44 \; CO_2 + 32 \; O_2 + 28 \; N_2 + 28 \; CO)}{12 \; x \; (CO_2 + CO)} \; x \left(Cb + \frac{12 \; x \; S}{32} \right)$$

NOTE:
The coefficients 44, 32, 28 are the molecular weights of the constituents.
CO_2, O_2, CO, N_2 are gas concentrations expressed as percent.
N_2 is determined by subtracting *CO_2, CO, O_2* from 100%.
Cb is the carbon content, specific to the fuel.
S is the sulfur content of the fuel.
Cp is the specific heat that varies with temperature. Values are charted in the ASME PTC 4.1 document for different fuels. It is apparent that fuel type has very little influence on the ultimate *Cp* of the exhaust gas mix. A good estimate for the *Cp*, regardless of the fuel, is determined from this simple equation: $Cp = .240 + .000038 \; x \; (T_{flue} − 200)$.

Heat loss due to H₂O from combustion of hydrogen (Lh)

Where the fuel has a high hydrogen content, latent heat loss from the water formation can be very significant.

Lh = 8.936 x H x (hl – hrw)

Where: 8.936 = weight of water formed for each hydrogen atom
   H   = fractional hydrogen content of the fuel
   hl   = enthalpy of water at the exhaust temperature and pressure
   hrw = enthalpy of water as a saturated liquid at fuel supply temperature

Heat loss due to moisture in fuel (Lm)

Moisture in the fuel is determined from lab analysis of the fuel and can be obtained from the fuel supplier.

Lm = fraction fuel moisture *x (hl – hrw)*

Where: *hl* = enthalpy of water at exit gas temperature and pressure
   hrw = enthalpy of water at fuel supply temperature

Heat loss due from the formation of carbon monoxide (Lco)

Carbon in the fuel reacts with oxygen to form CO first, then CO_2, generating a total of 14,540 Btus of heat per pound of carbon. If the reaction stops at CO because of insufficient O_2 or poor mixing of fuel and air, 10,160 Btus of energy are lost.

$$Lco = \frac{\%CO}{\%CO2 + \%CO} \ x \ 10,160 \ x \ Cb$$

Where: *Cb* = fractional carbon content

4. Combustion calculations using the Siegert formula

The Siegert formula is widely used in Europe to determine flue losses (qA) and efficiency.

$$qA = (Ts - Ta) \ x \ \left(\frac{A2}{(21 - O_2)} + B \right)$$

Efficiency = 100 – qA

Where: *qA*   = flue loss
   Ts   = flue temperature
   Ta   = supply air temperature
   O_2   = measured volumetric oxygen concentration expressed as a percent
   A2, B = fuel dependent constants

The constants *A2* and *B* are derived from the fuel composition. In Germany, the following values are prescribed for some common fuels:

Fuel Type	A2	B
Natural gas	.66	.009
Fuel oil	.68	.007
Town gas	.63	.011
Coking oven gas	.60	.011
LPG (propane)	.63	.008

Table 4. Siegert Constants

5. O_2 reference concentration calculation

$$\text{Corrected Gas Concentration (ppm)} = \text{gas conc. Meas.} \times \frac{20.9 - O_2 \text{ reference}}{20.9 - O_2 \text{ measured}}$$

6. Emission Rate calculations using dry gas factors

The emission rate calculation presented below is described in EPA Method 19. This uses the dry gas factor *Fd*. Dry factors are incorporated into the values found in Table 5 below. The table values (*Ft*), convert the measured concentrations of emission gases CO, NOx, and SO_2 from PPM to pounds per million Btu of fuel.

$$E = Cg \times Ft \times \left(\frac{20.9}{20.9 - O_2 \text{ measured}} \right)$$

Where: *E* = Emission rate (pounds/MBtu of fuel)*
  Cg = Gas concentration (PPM)
  Ft = Emission rate conversion factor from Table 5 (below)
  O_2 measured = Oxygen concentration from flue measurement (%)

*To convert emission rate to metric equivalent units, kg/kJ, multiply *E* in the equation above by 2.236.

Ft**	Nat. Gas	Propane	Oil #2	Oil #6	Coal	Wood (dry)	Bagasse	Coke
SO₂	.00145	.00145	.00153	.00153	.00164	.00153	0.0016	0.00164
NOx	.00104	.00104	.00110	.00110	.00118	.00110	0.001	0.00118
CO	.00063	.00063	.00067	.00067	.00072	.00067	0.00067	0.00072

**Ft units are lb/MBtu PPM.

Table 5. Emission rate conversion factors to convert from ppm to pounds per million btu of fuel for selected gases.

For those familiar with Method 19, *Ft* is related to *Fd* in the following way:
Ft is in units lbs/(MBtu ppm)
Fd is in units scf/MBtu
Ft = *Fd* x lb/(scf ppm)

7. A general equation for the combustion of a simple hydrocarbon in air

$$CxHy + \frac{(4x + y)O_2}{4} => xCO_2 + (y/2)H_2O$$
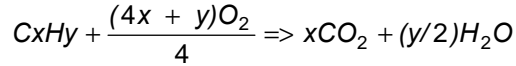
Where: x and y are the number of atoms of carbon and hydrogen in the fuel.

8. Calculating CO_2 max from the carbon content

Complete combustion of a simple hydrocarbon CxHy produces a fixed amount of carbon dioxide. If the theoretical air is used (i.e. excess air is zero) the concentration of CO_2 in the exhaust is at the maximum concentration. To calculate the maximum CO_2 concentration we assume water condenses out leaving only CO_2 and N_2 (from the air) as gases in the exhaust stream. Using the equation above for a simple hydrocarbon, we get.

$$\%CO_2 \ max = \frac{moles \ CO_2}{(moles \ CO_2 + moles \ N_2)} \ x \ 100$$

$moles \ CO_2 = x \ moles$

$$moles \ N_2 = \frac{(4x + y) \ x \ 3.76}{4}$$

This is for a simple hydrocarbon fuel, but the approach is the same for any fuel. Where fuels are mixtures of compounds, the determination of CO_2 max is more difficult, often requiring the assumption that the fuel is a single compound.

9. Combustion air calculation

It is possible to predict the amount of air needed to completely burn one pound of fuel using the equation below. This calculates the theoretical air requirement.

Pounds Air/Pound Fuel = 11.53C + 34.34(H_2 – O_2/8) + 4.29S

C, H_2, O_2 and S are the fractions, by weight, of each chemical constituent of the fuel.

Appendix D. Emissions

Clean Air Act

The Clean Air Act was first enacted in 1963 for monitoring and controlling environmental air pollution. This Act directly impacts facilities using fossil fuels. Since 1963, Clean Air Act Amendments (CAAA) in 1970, 1977 and particularly 1990 have greatly expanded the government's role. The CAAA of 1990 is considered the most complex and comprehensive of the amendments. With eleven titles, it gives the EPA more administrative enforcement capability and sets up a massive permitting program for pollutant sources.

Title 1

One of the most important 1990 CAAA titles, Title 1 deals with attainment and maintenance of the National Ambient Air Quality Standards (NAAQS). The NAAQS focus on six "criteria" pollutants: ozone (O_3), carbon monoxide, nitrogen dioxide, sulfur dioxide, particulates and lead. Monitoring stations throughout the country have been set up to determine locations exceeding the maximum concentration limits for these pollutants and designate them as "nonattainment" areas. If a location exceeds none of the NAAQS pollutant levels, it is designated an "attainment" area.

Of the criteria pollutants, O_3 is the most common and CO is second. Unlike CO, O_3 is not produced from combustion directly but forms from combustion products as a result of the reaction between nitrogen oxides and volatile organic compounds (VOCs) in sunlight (ultraviolet wavelength).

SIP

An important part of the Clean Air Act (Title V), is the establishment of the State Implementation Plan (SIP) program. This gives the states the responsibility for developing their own strategies to reduce ambient air pollution to meet the NAAQS. The SIPs can be significantly different from state-to-state due to differences in weather, demographics and geography. The federal government has specifically avoided imposing uniform regulations for all the states, citing these differences.

Implementation of a SIP requires a state to submit a plan to EPA with specified deadlines for achieving emission reductions, monitoring provisions, and permitting of individual source polluters. After public comment, the EPA reviews and accepts the state's plan or returns it for revision. It is important that operators of equipment producing criteria pollutants are familiar with the unique requirements for their state and area. Ignorance of specific regulations can result in stiff fines.

NSPS

In contrast to the non-uniform regulations created as part of the SIP program, the *New Source Performance Standards* (NSPS) are national minimal standards for ambient pollutant emissions. The NSPS differ depending on the size of the emission source and fuel type being used. For example, boilers are classified in three size ranges: boilers consuming more than 250 million Btu per hour of fuel energy, those consuming between 100 and 250 million Btu per hour, and those classified as small *boilers,* consuming between 10 and 100 million Btu per hour. All small boilers built after June 9, 1989 must meet the NSPS.

Nonattainment Areas

An area that does not meet the NAAQS is considered a nonattainment area. A state identifies and defines a nonattainment area after performing ambient monitoring of all the criteria pollutants. A nonattainment area is further classified using a system based upon the ambient pollutant levels. This classification scheme identifies an area using a range of designations from "marginal" to "extreme," best to worst, respectively.

The nonattainment designation level is very important to the source polluter since it ultimately determines if a source is considered a "major" source. A facility considered a major source might be required to implement costly pollutant control technologies. Major polluters may be required to follow regulations based upon the Best Available Control Technology (BACT), the Lowest Achievable Emission Rate (LAER) or the Reasonably Available Control Technology (RACT). BACT and RACT are written to be sympathetic to the economic impact that implementing the controls will have on the source polluter. When the LAER regulation is implemented, the facility must use the most effective emission technology available, regardless of cost.

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CA-CALC™ Combustion Test Instruments For Industrial, Commercial and Residential Systems

Model	Carbon Monoxide (CO)	Oxygen (O_2)	Nitric Oxide (NO)	Nitrogen Dioxide (NO_2)	NO_x	Sulfur Dioxide (SO_2)	Carbon Dioxide* (CO_2)	Ambient and Stack Temperatures	Draft Pressure	Efficiency (Loss) (qA)	Excess Air (λ)	Emission Rates/O_2 Reference**	CO/CO_2 Index & CO Air Free	Battery Life (hrs)	AC Power	Pre-Calibrated Replacement Sensors	Water Trap with Rinseable Filter	Water-Stop Filter	Data Storage/Review/Print (Qty)	Factory-Default Fuels	User-Defined Fuels	Sample Conditioning Dryer	Printer	Built-in Compliance Protocol	Automatic Data Logging	Carrying Case
CA-6010	●													12		●	○	●								○
CA-6020		●												12		●	○	●								○
CA-6030			●											12		●	○	●								○
CA-6040				●										12		●	○	●								○
CA-6050						●								12		●	○	●								○
CA-6060	C													12		●	○	●								○
CA-6070	XC													12		●	○	●								○
CA-6110	●								●					12	○	●	●	●	20				○			○
CA-6120		●					●	●		●	●			12	○	●	●	●	20	7	1		○			○
CA-6120-OH		●					●	●		●	●			12	○	●	●	●	20	7	1		○			●
CA-6130	●	●					●	●		●	●	●	●	12	○	●	●	●	20	7	1		○			●
CA-6140	●	●					●	●		●	●	●	●	12	○	●	●	●	20	7	1		○			●
CA-6203	H	●	●		●		●	●	●	●	●	●	●	24	●	●	●	●	100	7	1		○			●
CA-6210S	H	●					●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6211S	H	●	●		●		●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6212	H,C	●					●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6213E	H	●	●	●		●	●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6214	H,C	●	●		●		●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6215E	H	●	●	●	●		●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6216	H	●			●	●	●	●	●	●	●	●	●	24	●	●	●	●	680	8	5		○			●
CA-6315D	H	●	●	●	●		●	●	●	●	●	●	●	24	●	●	●	●	680	8	5	●	●	●	●	●
CA-6316D	H	●			●	●	●	●	●	●	●	●	●	24	●	●	●	●	680	8	5	●	●	●	●	●

Series CA-6000 · Series CA-6100 · Series CA-6200 · Series CA-6300

* Calculated from fuel type and O_2
** O_2 reference = 0 for Series CA-6100 and CA-6203,
O_2 reference is adjustable for Series CA-6200, CA-6300
Custom length probe/hose assemblies available.

C High concentration, 2%
H Hydrogen compensated
XC High concentration, 8%
○ = Optional

Series CA-6000 **Series CA-6100** **Series CA-6200**

TSI