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.

Stable combustion requires three inputs - fuel, oxygen and a source of ignition. If the combustibles can provide this third element as they burn, the source of ignition can be turned off.

In theory, there is a precise and predictable amount of oxygen needed to completely burn a given amount of fuel. This is called stoichiometric air. In practice, however, burning conditions are never ideal and more air must, therefore, be supplied to completely burn the fuel. The amount of air above the theoretical requirement is referred to as 'excess air'. If insufficient air is supplied to the burners, unburned fuel - soot and smoke, and carbon monoxide (the incomplete conversion to carbon dioxide) - appear in the exhaust from the boiler stack. These can result in:

- the heat transfer surface fouling;
- pollution;
- lower combustion efficiency;
- flame instability (i.e. the flame blows out); and
- the potential for an explosion.

An insufficient air- to - burner ratio can be dangerous. Operating boilers at excess air levels provides:

- protection from costly and potentially unsafe conditions;
- operating protection from an insufficient oxygen condition caused by variations in fuel composition.

On the other hand, air flows greater than those needed for stable flame propagation and complete fuel combustion needlessly increase flue gas flow and consequent heat losses, and thereby lower boiler efficiency. Flue gas loss is usually the largest factor in reducing a boiler's efficiency. Stack temperature and excess air level are the main factors that determine boiler efficiency. Most boilers lose between 15% and 20% of their fuel energy input up the stack.

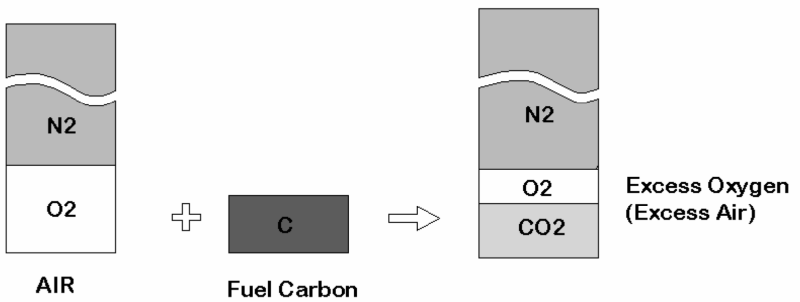
Flue gas measurements

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.

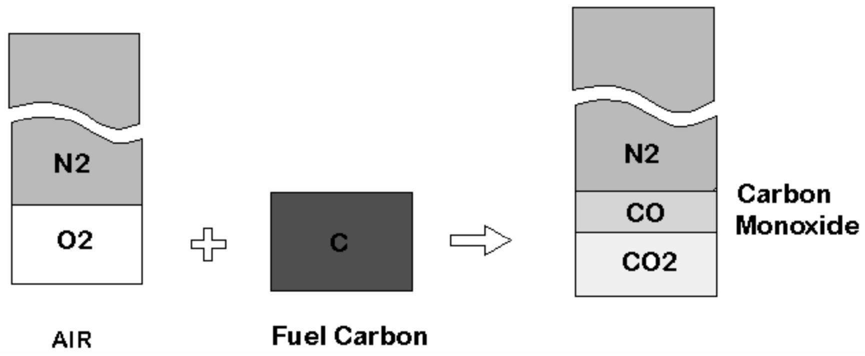
Once these measurements are made, the data is interpreted using calculated combustion parameters such as *combustion efficiency* and *excess air*. A more in depth analysis will examine the concentration of the undesirable products.

As described earlier, simple combustion of hydrocarbon fuel 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 where the bar on the right represents the exhaust gas composition.

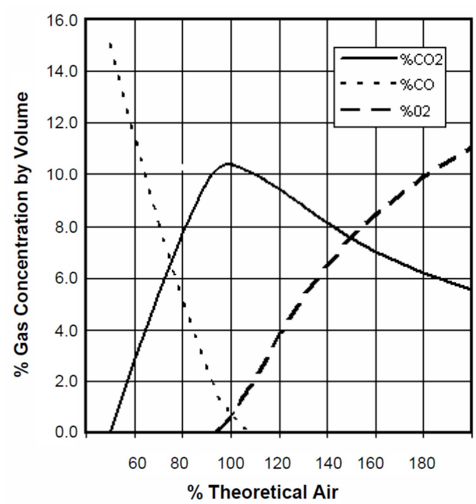


When too little air is supplied to the burner, there is not enough oxygen to completely form CO_2 with all the carbon in the fuel. Instead, some oxygen combines with carbon to form carbon monoxide (CO). CO is a highly toxic gas associated with incomplete combustion and efforts must be made to minimize 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.



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. kg per second, cubic meter per second, 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. 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 dependent on the type of fuel used.

In recent years, electronic flue gas analyzers 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.

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

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 which is valid for complete combustion. This calculation uses the oxygen concentration in % measured in the exhaust.

$$\lambda = \frac{21}{21 - O_2}$$

If the CO concentration or unburned carbon in ash is very high, it must also be included in the excess air calculation.

Boiler Efficiency

In the boiler the heat energy resulting from the combustion of fuel is transferred to the working medium (hot water or steam). During this process, part of the energy contained in fuel is lost. The total losses from the generation of hot water or steam depend on many parameters e.g. the fuel (ash and water content, calorific value); the capacity and operation of the steam generator; the air-fuel mix; the final temperature of the flue gas; and the mode of operation. The operation of the boiler requires continuous surveillance.

Losses in Boiler Systems

The heat losses from the steam generator can be categorised as:

- Losses via the off-gas (stack losses). These depend on the flue-gas temperature and air excess in outgoing flue gas. Flue-gas temperature depends on fuel quality and the level of fouling of the boiler.
- Losses through unburnt gases, the chemical energy of which is not converted. Incomplete combustion causes CO and hydrocarbons to occur in the flue-gas.
- Losses through unburnt material in the residues, such as carbon in bottom and fly ash.
- Losses via the bottom and fly ash from a dry bottom boilers and the slag and fly ash from a wet bottom boilers.
- Losses through conduction and radiation. These mainly depend on the quality of insulation of the boiler walls.

In addition to the heat losses, the energy consumption needed for the **operation of auxiliary** machinery (fuel transport equipment, coal mills, pumps and fans, ash removal systems, cleaning of the heating surfaces, etc.) also has to be taken into consideration.

Stack Losses

The largest energy loss in most boiler systems is the energy that is lost through the flue gases, out the stack. Gaseous products of combustion, that is CO_2, O_2, N_2, SO_2, Ar and vapor carry a considerable amount of sensible heat up the stack. The extent of the losses is mainly dependent on the temperature and volume of the stack gases. It is practically impossible to completely eliminate stack losses since that would require the stack temperature to be reduced to the ambient temperature. The flue-gas temperature leaving the boiler (depends on the fuel type) is traditionally between 120 and 170 °C, kept high enough to minimize risks of acid corrosion by the condensation of sulphuric acid. The losses can, however, be minimized by several techniques, such as ensuring that heat transfer surfaces in the boiler are clean and in good condition. By minimizing the amount of excess air the amount of flue gas losses can also be kept at a minimum. The amount of excess air used depends on the type of boiler and on the nature of the fuel. Typically, 12 – 20 % excess air is used for a pulverised coal-fired boiler with a dry bottom. For reasons of combustion quality (related to CO and unburnt carbon formation), and for corrosion and safety reasons (e.g. risk of explosion in the boiler), it is often not possible to reduce the excess air levels further.

Unburned Carbon

Some energy may be lost through unburned carbon due to incomplete combustion. This is often the second largest heat loss in boiler systems. In stoker fired boilers the losses can be considerably higher. If the stoker is improperly controlled a large amount of unburned carbon can end up in the bottom ash.
Optimization of the combustion leads to less unburnt carbon-in-ash. It should be noted that NO_X abatement technologies using combustion modification (primary measures) show a tendency of increased unburnt carbon. Increased unburnt carbon could also worsen and harm the quality of the coal fly ash and make it difficult, or even prevent, their utilisation for certain applications, with the risk that they may not comply with the specifications and requirements laid down in relevant national standards.

Unburned CO

In all types of boilers, combustible gases can enter the stack as a result of incomplete combustion. The losses are not usually significant due to strict emission limits which have to be reached.

Convection and Radiation Losses

Some of the heat from the combustion escapes from the external surface of the boiler. For a boiler at operating temperature the loss is constant. Expressed as a percentage of the boiler output, the loss increases as the output is reduced so it is at a minimum when the boiler operates at full load. The relative loss is greater for smaller boilers than larger ones. Some of this loss is unavoidable but it can be controlled to some extent by proper insulation techniques.

Efficiency Definitions

Efficiency is parameter commonly used for evaluation of boiler fuel utilization. There are several efficiency definitions that are commonly used when discussing boiler systems. In some cases these definitions can differ slightly between literature sources. The efficiency definitions are therefore explained below in order to prevent any misunderstanding or confusion.

Combustion Efficiency

Combustion efficiency indicates a burner's ability to burn fuels. The combustion efficiency can be assessed by measuring the amount of unburnt fuel and excess air in the exhaust. When the fuel and oxygen are in perfect balance the combustion is said to be stoichiometric. The combustion efficiency is fuel dependent and generally, gaseous and liquid fuels burn more efficiently than solid fuels.

Thermal Efficiency

Thermal efficiency measures the effectiveness of the boiler's heat exchanger, i.e. the heat exchanger's ability to transfer heat from the combustion process to the water in the boiler. The thermal efficiency does not take radiation or convection losses into account and does therefore not provide a true indication of the boiler's fuel usage and should therefore not be used for the purpose of economic evaluation.

Fuel-to-Steam Efficiency

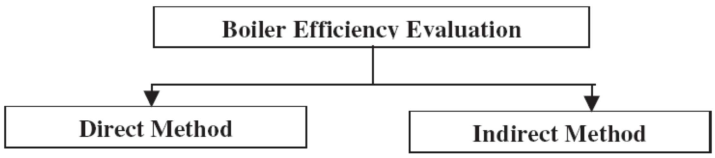
The fuel-to-steam efficiency is a measurement of the overall efficiency of a boiler. It accounts for the effectiveness of both the combustion process and the heat exchanger as well as the losses due to radiation and convection. The fuel-to-steam efficiency is a true indicator and is the measurement that should be used for economic evaluation.

Evaluation of Boiler Efficiency

It is defined as the percentage of heat input that is effectively utilized to generate hot water or steam. There are two methods of assessing boiler efficiency:

1) **The Direct Method** where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) **The Indirect Method w**here the efficiency is the difference between the losses and the energy input.



The direct method is based on the output-to-input of the boiler. The input and output, both expressed in kW (MW), are determined through instrumentation and the resulting data is used in calculations that determine the fuel-to-steam efficiency.

The indirect method is based on accounting for all heat losses of a boiler. The total stack, radiation and convection losses in percents are subtracted from 100 % and the resulting value is the fuel-to-steam efficiency of the boiler.

Determination of boiler efficiency

Standards

There are two main standards used for definition of boiler efficiency. Of those, the German DIN 1942 standard employs the lower heating value (LHV) of a fuel and is widely used in Europe. The American ASME standard is based on higher heating value (HHV). However, this chapter calculates the efficiency according to the DIN 1942 standard. It should be marked that with the DIN standard it is possible to reach boiler efficiencies over 100 %, if the condensation heat of the flue gases is recovered.

Major heat losses

Heat loss with unburned combustible gases

The typical unburned combustible gases are carbon monoxide (CO) and hydrogen (H_2). In largeboilers usually only carbon monoxide can be found in significant amounts in flue gases.

Assuming that flue gases contain only these two gases, the losses [kW]can be calculated as:

$$\phi_{L1} = \dot{m}_{CO} \cdot H_{l,CO} + \dot{m}_{H_2} \cdot H_{l,H_2}$$

where is $\dot{m}_{CO}$ the mass flow of carbon monoxide [kg/s], $\dot{m}_{H2}$ the mass flow of hydrogen, $H_{l,CO}$ the lower heating value (LHV) of carbon monoxide (10,12 MJ/kg), and $H_{l,H2}$ the lower heating value (LHV) of hydrogen (119,5 MJ/kg). If a relevant amount of some other flue gas compound can be found in the flue gases, it should be added to the equation.

Heat loss due to unburned solid fuel

Unburned fuel can exit the furnace as well as bottom ash or fly ash. The heating value of ashes can be measured in a specific laboratory test. The losses [kW] of unburned solid fuels can be calculated as:

$$\phi_{L2} = \dot{m}_{ubs} \cdot H_{l,ubs}$$

where is $\dot{m}_{ubs}$the total mass flow of unburned solid fuel (bottom ash and fly ash in total) [kg/s], and $H_{l,ubs}$ the lower heating value (LHV) of unburned solid fuel (fly ash and bottom ash in total) [kJ/kg]. Some estimates of the losses with unburned solid fuels are presented in table

Boiler type	Heat loss per heat input of fuel
Oil fired boiler	0,2 - 0,5 %
Coal fired boiler, dry ash removal	0,7 - 2 %
Coal fired boiler, molten ash removal	about 2 %
Grate boiler	2 - 4 %

Heat loss due to wasted heat in flue gases

Flue gases leave the furnace in high temperature and thus they carry significant amount of energy away from boiler process. To decrease flue gas losses, flue gas exit temperature should be decreased. However, the acid dew point of flue gases restricts the flue gas temperature to about 150-170 °C for sulphur containing fuels. The losses caused by the sensible heat of flue gases can be calculated as:

$$\emptyset_{L3} = \dot{m}_{fuel} \sum_i V_i \cdot (h_{i,t_{stack}} - h_{i,t_{ref}})$$

where is $\dot{m}_{fuel}$ the fuel mass flow [kg/s], is V_i the volume of a flue gas component (e.g. CO_2) from combustion of 1 kg of fuel obtained from stoichiometric calculation, $h_{i,t_{stack}}$ the specific enthalpy of a flue gas component [kJ/Nm^3] for stack temperature and $h_{i,t_{surr}}$ the specific enthalpy of a flue gas component [kJ/Nm^3] for reference (surrounding) temperature. Values of specific enthalpies of flue gas components are in following table.

t [°C]	CO_2	SO_2	N_2	Ar	H_2O	dry air	CO	O_2	fly ash [kJ/kg]
0	0	0	0	0	0	0	0	0	0
25	41,62	46,81	32,53	23,32	39,10	32,57	32,49	32,78	20,20
100	170,0	191,2	129,5	93,07	150,6	132,3	132,3	131,7	80,4
200	357,5	394,1	259,9	186,0	304,5	266,2	261,4	267,0	170,0
300	558,8	610,4	392,1	278,8	462,8	402,5	395,0	406,8	264,6
400	771,9	836,5	526,7	371,7	625,9	541,7	531,7	550,9	361,6
500	994,4	1070	664,0	464,7	794,5	684,1	671,6	698,7	459,5
600	1225	1310	804,3	557,3	968,8	829,6	814,3	849,9	558,0
700	1462	1554	947,3	650,2	1149	978,1	960,4	1003	658,3
800	1705	1801	1093	743,1	1335	1129	1109	1159	760,8
900	1952	2052	1241	835,7	1526	1283	1260	1318	868,4
1000	2203	2304	1392	928,2	1723	1439	1413	1477	982,8
1100	2458	2540	1544	1020	1925	1597	1567	1638	1106
1200	2716	2803	1698	1114	2132	1756	1723	1802	1240
1300	2976	3063	1853	1207	2344	1916	1881	1965	1386
1400	3239	3323	2009	1300	2559	2077	2040	2129	1543
1500	3503	3587	2166	1393	2779	2240	2199	2293	1710
1600	3769	3838	2325	1577	3002	2403	2359	2465	2061
1800	4305	4363	2643	1742	3458	2732	2682	2804	2381
2000	4844	4890	2965	1857	3925	3065	3008	3138	2500
2500	6204	6205	3778	2321	5132	3909	3830	4006	-

Heat loss due to wasted heat in ashes

Ash can exit the furnace either as bottom ash from bottom of the furnace or as fly ash with flue gases. The losses related to the sensible heat of ash can be calculated as:

$$\phi_{L4} = \dot{m}_{ba} \cdot c_{p,ba} \cdot \Delta T_{ba} + \dot{m}_{fa} \cdot c_{p,fa} \cdot \Delta T_{fa}$$

where is $\dot{m}_{ba}$the mass flow of the bottom ash [kg/s], $c_{p,ba}$ the specific heat of the bottom ash [kJ/(kgK)], ΔT_{ba} the temperature difference between the bottom ash temperature and the reference temperature [°C], $\dot{m}_{fa}$the mass flow of fly ash, $c_{p,fa}$, the specific heat of fly ash, ΔT_{fa} the temperature difference between the fly ash temperature and the reference temperature [°C]. Usually the reference temperature is 25 °C. In wet bottom boilers the bottom ash is removed as molten sludge in temperature of about 700-800 °C. In addition, the amount of bottom ash divided by the amount of fuel is about 60 % in stocker boilers and 15 % in pulverized coal fired boilers. In some cases sensible heat in fly ash is involved in heat of gaseous flue gas and is added to stack losses.

Losses due to heat transfer (radiation) to the environment

The main form of heat transfer from boiler to boiler room is radiation. It is proportional to the outer surface area of the boiler and is usually 200-300 W/(m^{2}K) for a well-insulated boiler having its outer surface temperature below 55 °C. Another possibility to determine the heat transfer losses to the environment is to use a table from the DIN 1942 standard, presented in table.

	Combustion method	Mass flow rate of steam [t/h]									
		10	20	40	60	80	100	200	400	600	800
Loss [%]	Pulverized firing	-	1,3	1,0	0,9	0,75	0,7	0,55	0,4	0,35	0,3
	Grate	1,5	1,1	0,9	0,7	-	-	-	-	-	-
	Oil/gas fired boiler	1,3	0,9	0,7	0,6	0,55	0,4	0,3	0,25	0,2	0,2

Calculating boiler efficiency

Direct method

In the direct method, the boiler efficiency is directly defined by the exploitable heat output from the boiler and by the fuel power of the boiler:

$$\eta = \frac{\phi_{output}}{\phi_{input}}$$

where ϕ_{output} is the exploitable heat output from boiler, and ϕ_{input} the fuel power of the boiler.

Indirect method

Indirect method determines the efficiency of a boiler by the sum of the major losses and by the fuel power of the boiler:

$$\eta = 1 - \frac{\phi_{losses}}{\phi_{input}}$$

where ϕ_{losses} is the sum of the major losses within the boiler, and ϕ_{input} is the fuel power of the boiler. The indirect method provides a better understanding