

madur

FOR OUR ENVIRONMENT AND OUR CUSTOMERS' MONEY

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COMBUSTION ANALYSIS

The environment has to deal with ever larger concentrations of pollutants due to the use of all types of combustion processes. Smog formation, acid rain and the constantly increasing number of allergies are a direct result of this development. The path to environmentally friendly energy production must therefore lead to a reduction in the emission of pollutants, which is only possible when the existing equipment is working correctly and defective equipment is taken off line. Flue gas analysis enables you to measure the concentrations of the pollutants present and to adjust your burners for optimal combustion.

1) What is combustion?

Combustion is the act or process of burning. For combustion to occur, fuel, oxygen (air), and heat must be present together.

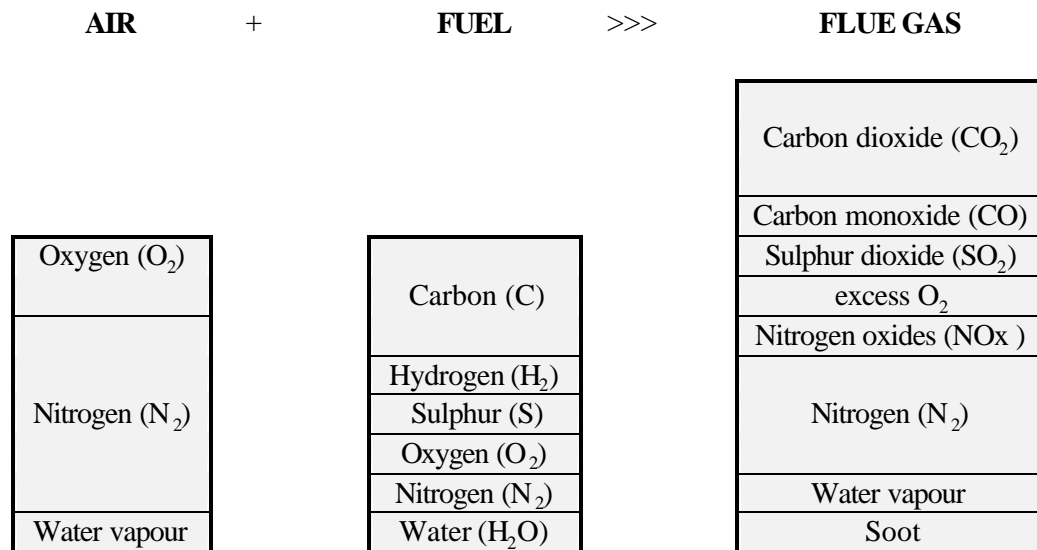
Per definition combustion is the chemical reaction of a particular substance with oxygen.

The combustion process is started by heating the fuel above its ignition temperature in the presence of oxygen. Under the influence of heat, the chemical bonds of the fuel are split. If complete combustion takes place, the elements carbon (C), hydrogen (H) and sulphur (S) react with the oxygen content of the air to form carbon dioxide CO_2 , water vapour H_2O and sulphur dioxide SO_2 and, to a lesser degree, sulphur trioxide SO_3 .

If not enough oxygen is present or the fuel / air mixture is insufficient then the burning gases are partially cooled below the ignition temperature (too much air or cold burner walls), and the combustion process stays incomplete. The flue gases then still contain burnable components, mainly carbon monoxide CO , carbon C (soot) and various hydrocarbons C_xH_y . Since these components are, along with NO_x , pollutants which harm our environment, measures have to be taken to prevent the formation of them.

To ensure complete combustion, it is essential to provide a certain amount of excess air.

The quality of a combustion system is determined by a maximum percentage of complete combustion, along with a minimum of excess air (commonly 5 to 20% above the necessary level for ideal combustion)



2) What is combustion efficiency?

Combustion efficiency is a calculation, of how well your equipment is burning a specific fuel, shown in percent. Complete combustion efficiency would extract all the energy available in the fuel. However 100% combustion efficiency is not realistically achievable. Common combustion processes produce efficiencies from 10% to 95%. Combustion efficiency calculations assume complete fuel combustion and are based on three factors:

1. The chemistry of the fuel.
2. The net temperature of the stack gases.
3. The percentage of oxygen or CO₂ by volume after combustion.

COMBUSTION PROCESSES AND THEIR COMBUSTION EFFICIENCY RANGES	
PROCESS	TYPICAL COMBUSTION EFFICIENCY RANGE
HOME FIREPLACE	10-30 %
SPACE HEATER	50-80 %
COMMERCIAL GAS BOILER	70-82 %
RESIDENTIAL GAS BOILER WITH ATMOSPHERIC BURNER "LOW EFFICIENCY"	70-82 %
OIL BURNER HEATING SYSTEM	73-85 %
INDUCED DRAFT FURNACE "MEDIUM EFFICIENCY"	74-80 %

BOILER WITH GAS BURNER	75-85 %
CONDENSING FURNACE (GAS & OIL) "HIGH EFFICIENCY"	85-93 %

If your calculation shows that your equipment is losing 20 % of the heating energy of the fuel through stack losses, your equipment is running at 80 % efficiency.

3) What needs to be measured for combustion efficiency?

Assuming that the fuel parameters are known, only the oxygen or carbon dioxide concentration and temperature have to be determined. Since that does not give a 100% certain reading (see chart chapter 8 & 9), it is really necessary to measure CO as well.

4) What is flue gas?

When fuels are burned there remains, besides ash, a certain number of gas components. If these still contain combustion heat, they are called heating gases. As soon as they have conveyed their energy to the absorbing surfaces of a heat exchanger, they are called flue or stack gases.

The various common flue gas contents were already mentioned in chapter 1.

4.1) Which units are commonly used ?

The presence of pollutants in a flue gas stream can be expressed in terms of the concentrations of the individual gas components.

The following units are the most common:

ppm (parts per million)

Like the reading "percent (%) ", ppm expresses a ratio. If there is a concentration of 333 ppm CO in a cylinder and you take one million particles out of that cylinder, 333 particles would be carbon monoxide particles.

For convenience, higher concentrations are generally expressed as a percentage (%). The conversion is as follows:

$$\begin{aligned} 10\ 000\ \text{ppm} &= 1\ \% \\ 1\ 000\ \text{ppm} &= 0.1\ \% \\ 100\ \text{ppm} &= 0.01\ \% \\ 10\ \text{ppm} &= 0.001\ \% \\ 1\ \text{ppm} &= 0.0001\ \% \end{aligned}$$

An oxygen concentration of 21.95 vol.% would equal 219 500 ppm O₂,

and 10% CO is identical with 100 000ppm CO.

mg/Nm³ or mg/m³ (milligram per cubic meter)

When using the unit mg/Nm³, the standard volume (standard cubic meter, Nm³) is used as a reference and the mass concentration of the flue gas is given in milligrams (mg). Since this unit is pressure and temperature dependent, the volume is expressed at standard conditions. There are different sets of standard conditions used for different purposes. Flue gas analysis commonly uses the following standard conditions:

Temperature: 0°C
Pressure: 1013 mbar (hPa)

The quantity of oxygen present in the flue gas is the last criteria necessary to define the mass concentration of the gas components, since these will change according to the volume of the flue gas stream. The concentrations are converted to concentrations relative to a particular oxygen concentration, the reference oxygen concentration. The actual oxygen concentration is also needed for the conversion from ppm to mg/m³.

Conversion to mg/Nm³

$$\text{CO (mg/m}^3\text{)} = (21 - \text{O}_2 \text{ ref} / 21 - \text{O}_2) \times \text{CO (ppm)} \times 1.25$$

$$\text{NO}_x \text{ (mg/m}^3\text{)} = (21 - \text{O}_2 \text{ ref} / 21 - \text{O}_2) \times (\text{NO} + \text{NO}_2 \text{ in ppm)} \times 2.05$$

$$\text{SO}_2 \text{ (mg/m}^3\text{)} = (21 - \text{O}_2 \text{ ref} / 21 - \text{O}_2) \times \text{SO}_2 \text{ (ppm)} \times 2.86$$

The conversion factors used in the formula come from the density of the gas components at standard conditions.

For more detailed explanations about the calculations performed in madur instruments read the user's manual of one of the analysers, Chapter 3 http://www.madur.at/mdcom/Sites_GB/support/manuals/Gmanu.html.

5) Why is it important to do combustion testing ?

By using gas analysers you can make sure that your equipment is operating safely and at maximum efficiency, and that it fulfils environmental legislations.

6) What is the difference between traditional (mechanical) instruments and continuous sampling flue gas analysers?

The information traditional instruments will give you is comparable in accuracy to electronic instruments, though electronic instruments have very important advantages.

The expression "traditional" is perhaps now misleading, since the electronic instruments have now more or less become the standard for use in most countries. The chemical and mechanical analysers have, fortunately, become the exception to the rule.

For example, contrary to traditional instruments, flue gas analysers monitor on a continuous basis. That ensures you that you will not oversee the most important value, because you can follow the changes automatically and rapidly, and provide a printout of the measured and stored data, and furthermore you have the opportunity to transfer the data to a computer.

Overall, electronic analysers have many important advantages, such as ease of use and speed, automatic sampling, calculations and report generation.

7) What is the best place to take a sample?

The measurement for gases and (gas) temperature should be taken at the same point. The sample point should be before draft diverters and barometric dampers so that the gases are not diluted and the temperature has not been decreased by the addition of outside air.

Use the following guidelines for residential or light commercial/industrial equipment.

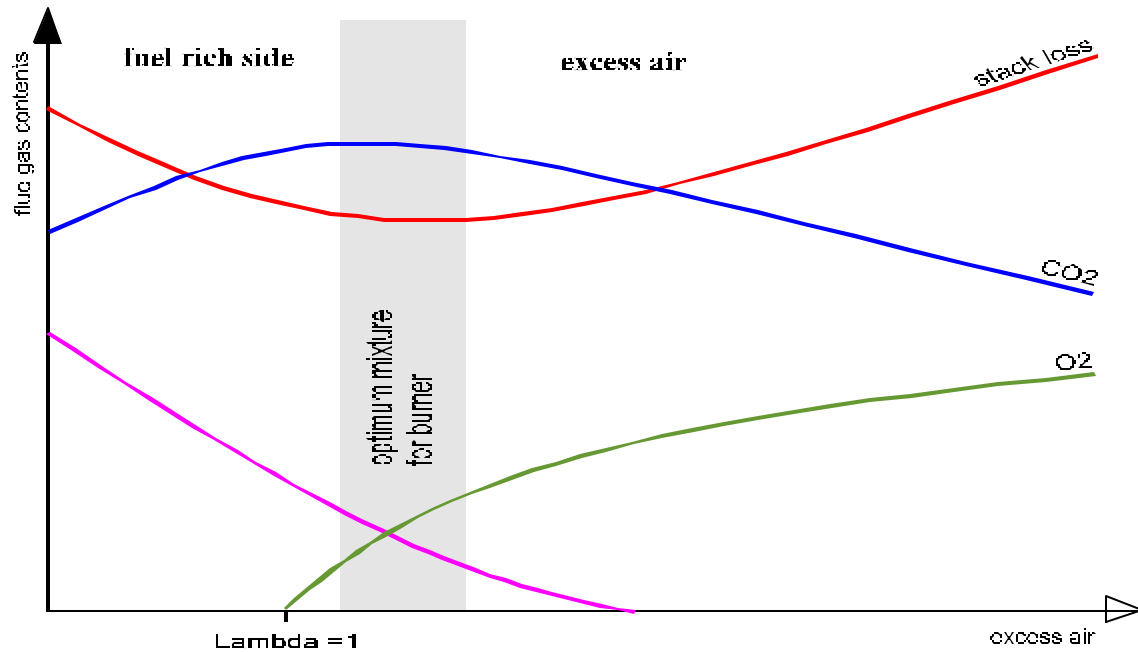
Oil Burners / Gas Burners - at least 15cm upstream from the furnace side of the draft regulator (diverter), and as close to the furnace breeching as possible.

For larger Equipment - downstream from, and as close as possible to, the last heat exchange device. This insures that the net temperature change (flue gas temperature minus ambient air temperature) will provide an accurate indication of the efficiency of the heat exchangers.

8) How important is it to measure CO ?

The concentration of carbon monoxide is an essential part of determining optimum boiler efficiency. An operation near trace levels about 100ppm and a slight amount of excess air indicates conditions near optimum. No burner is able to mix fuel and air perfectly. The consequence is that there will be products of incomplete combustion present. Where CO begins to be produced in volume, maximum efficiency is achieved. By providing continuous monitoring of CO and O₂, **madur** analysers make it easy to determine maximum efficiency and optimum boiler operation.

9) How do relevant combustion parameters like O₂, CO, CO₂, temperature, and smoke (soot) relate to efficiency?



If it were possible to have perfect combustion, CO₂ would be maximised and O₂ would be at, or close to, zero in the flue gas stream. Since perfect combustion is not practically possible due, in part, to incomplete mixing of the fuel and air, most combustion equipment is set up to have a small percentage of excess oxygen present. The lower the temperature for a given O₂ or CO₂ value the higher is the combustion efficiency. This is because less heat is carried up the stack by the combustion gases.

Smoke is the usual indicator of incomplete combustion in oil burners. In addition to indicating poor combustion, smoke can deposit soot on the heat exchangers, further reducing fuel efficiency as well.

10) Why measure draft?

This is important because draft measurement shows how rapidly the gases pass through the furnace or boiler. Draft measurements ensure that there is continuous negative pressure (systems without forced ventilation) in the combustion system. Excessive draft increases stack temperature and therefore decreases combustion efficiency.

It is important to measure draft on the chimney side, well downstream from a draft diverter. This measurement will inform you whether there is enough draft to move the flue gases up the chimney and vent them to the outside air.

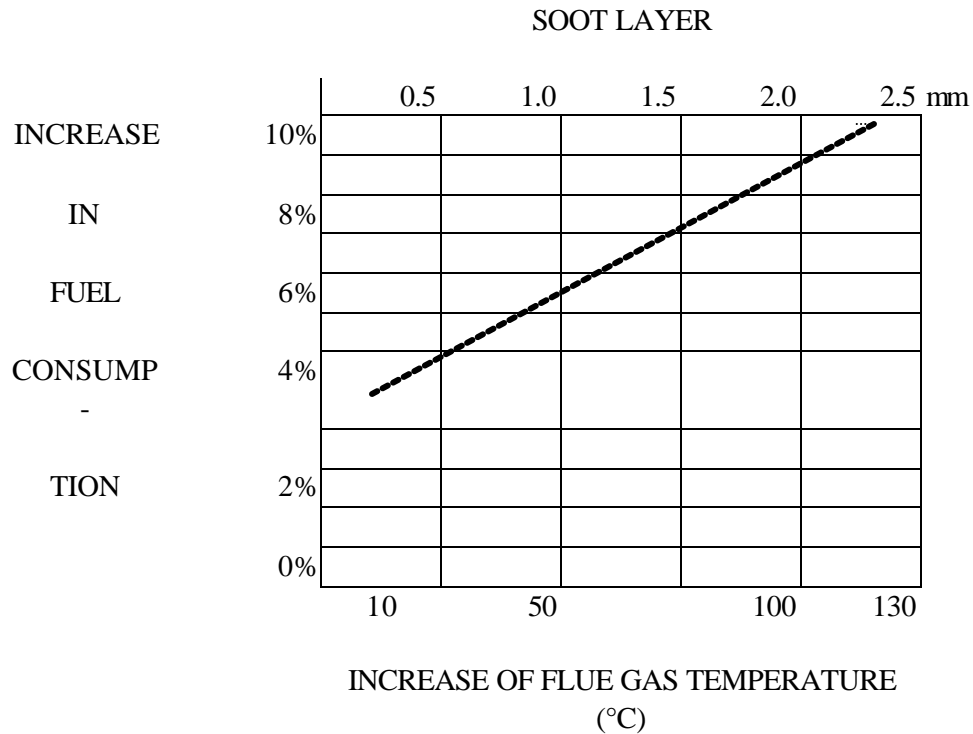
Typical values for draft:

Burner with fan 0.12...0.20 hPa (mbar)
 Oil burner and
 gas burner without fan - 0.04...- 0.10 hPa (mbar)

11) Is it important to measure smoke in oil-fired furnaces?

As already mentioned, smoke is a primary sign of incomplete combustion since it is basically composed of very small unburnt carbon particles, therefore it is important to determine the smoke (soot) content of the flue gas. Using madur portable flue gas analysers gives you the opportunity to perform a soot test and determine oil burner condition and operating efficiency and safety. However, smoke spot testing will not indicate the presence of CO. Since smoke and CO will almost certainly coexist, both tests are necessary.

EFFECT OF SOOT ON FUEL CONSUMPTION



Smoke Scale Reading	Burner Performance
1	Excellent - Little, if any, sooting of furnace or boiler surfaces
2	Good - May be slight sooting with some types of furnace or boiler but little increase in flue gas temperature or consumption
3	Fair - Substantial sooting with some types of furnace or boiler and will require cleaning more than once a year on most types of furnace or boiler.
4	Poor - This is a borderline smoke reading, some units may soot only moderately, others may soot rapidly.
5	Very Poor - Heavy sooting in all cases - may require cleaning several times during the season.
6	Extremely Poor - Severe and rapid sooting may result in damage to stack control and reduce overfire draft to danger point.

12) Does frequent testing increase fuel savings?

By adjusting the combustion process and therefore improving combustion efficiency one ultimately saves fuel.

Although some combustion experts do weekly tests others consider three or four checks a year an acceptable level of testing. The appropriate level for a particular unit can only be determined by experience, and is partly dependent on the fuel consumption of the burner. The higher the consumption, the more important it is to optimise the process.

13) How to calculate savings through higher efficiency

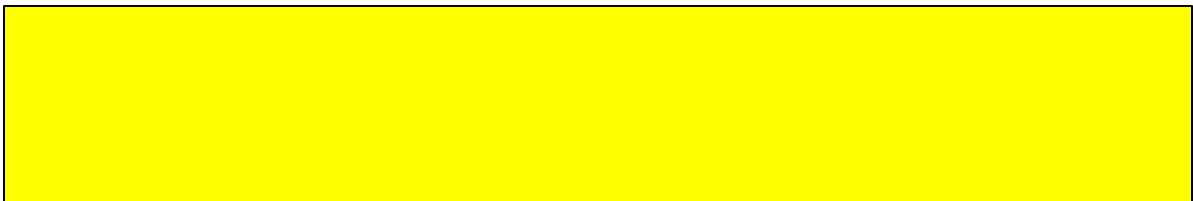
First of all, the relevant combustion parameters are measured. After that, starting off with high excess air, the air supply is reduced, until an increase in CO is realised. Now the burner is adjusted to a small amount of excess air, and the following result appears:

(EXAMPLE)

Readings X (before adjustment):

Reading Y:

Oxygen	8 %	Oxygen	
3 %			
Temperature ($T_{\text{gas}} - T_{\text{amb}}$)	250°C	Temperature	190°C
Efficiency X	85 %	Efficiency	91 %
CO	--	CO	100ppm



With assumed annual fuel costs of USD 150.000 the savings would be as follows:

$$\frac{91 (Y) - 85 (X)}{85 (X)} \times 150.000,- = \text{USD } 10.588,-$$

14) The difference between "Wet" and "Dry" analysis

"**Wet-Basis**" is analysis without removing the water from the flue gas

"**Dry-Basis**" is the analysis after the water has been removed (theoretically completely, but usually in part)

A typical "**Wet-Basis**" measurement would be an In-Situ or across the stack measurement

"**Dry-Basis**" measurement is performed with extractive system such as a portable flue gas analyser with condensation trap and /or built in gas cooler/dryer.

A look at a typical flue gas composition could show the following values.

oxygen	2.20 %
carbon dioxide	13.20 %
nitrogen	71.10 %
water vapour	13.34 %
sulphur dioxide	0.04 %
carbon monoxide	0.10 %
oxides of nitrogen	0.02 %

If the water vapour is removed now, the volume of the gas decreases and the concentrations of the other components increase. If the sample is conditioned at +4°C the partial pressure of water vapour at 4°C should be used to determine the water content of the gas. However, we can ignore this concentration for our example, since this is an extremely small error well within normal measuring accuracy limits.

<u>COMPOUND</u>	<u>WET BASIS</u>	<u>DRY BASIS</u>
Oxygen	2.2 %	2.53 %
Carbon dioxide	13.2 %	15.23 %
Nitrogen	71.1 %	82.05 %
Water vapour	13.34 %	NIL
Sulphur dioxide	0.04 %	0.047 %
Carbon monoxide	0.1 %	0.115 %
Oxides of nitrogen	0.02 %	0.023 %

As we see, one can obtain different results depending on the methods used. This is not a problem as long as the methods used are stated and not compared with those made under another basis without correction.

Some authorities require results to be reported on a dry basis and others leave it open as long as the basis employed is stated clearly.

15) What type of sensors are used in *madur* instruments?

Most of the sensors used in madur flue-gas analysers are of the electrochemical type.

The major elements of **Toxic Gas** electrochemical sensors are three coated electrodes (sensing, counter, and reference) and a small volume of an acidic or alkaline solution.

In use, the gases diffuse through an orifice on the sensing face of the sensor onto the electrode surface and cause a small electrical current. This current is amplified and measured by the electronics. The measured value is then displayed and available for printing, storing or downloading to a computer.

In its simplest form, a sensor operating on electrochemical principles requires two electrodes – a *sensing* and a *counter* – separated by a thin layer of electrolyte. Gas diffusing to the *sensing* electrode reacts at the surface of the electrode either by oxidation or reduction. This reaction causes the potential of the electrode to rise or fall with respect to the *counter* electrode. With a resistor connected across the electrodes, a current is generated which can be detected and used to determine the concentration of gas present.

One of the conditions required for the above sensor to work accurately is that the potential of the *counter* electrode should remain constant. In reality, however, the surface reactions at each electrode causes them to polarise. This effect may be small initially, but it increases with the level of reactant gas and effectively limits the concentration range the sensor can be used to measure. This effect can be counteracted by the introduction of a *reference* electrode of stable potential.

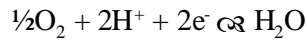
The reference electrode is shielded from any reaction, and so maintains a constant potential. Instead of the signal therefore being measured between the counter and sensing electrodes, it can now be more accurately measured between reference and sensing. With this arrangement, the change in potential of the sensing electrode is due solely to the current generated at the electrode by the reactant gas.

As the reference electrode must maintain a constant potential for correct operation, it is important that no current is drawn from this electrode. In order therefore to measure the potential difference between sensing and reference, it is not sufficient just to place a load resistor across them, as this would draw current. For this reason a potentiostatic feedback operating circuit is used.

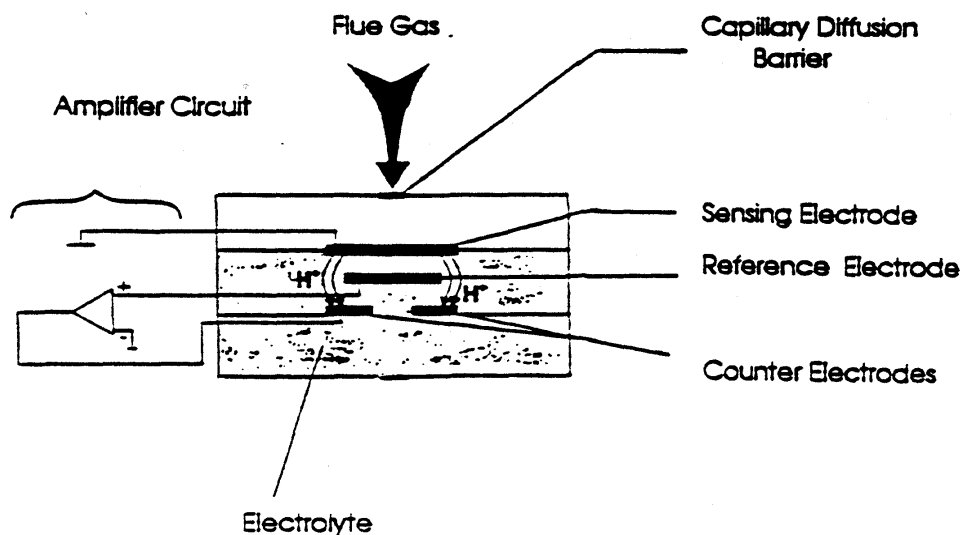
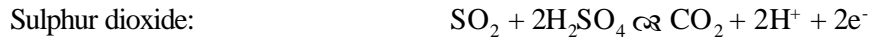
The oxidation of carbon monoxide, for example, at the sensing electrode can be represented by the equation:



The counter electrode acts to balance out the reaction at the sensing electrode by reducing oxygen in air to water:

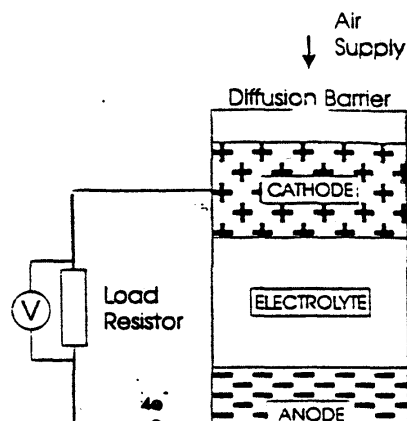


A similar equation can be given for other sensors depending on the reaction of the gas they are designed for on the sensing electrode:

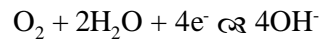


Oxygen sensors are slightly different. In use, oxygen diffuses through a membrane and the gas contacts the sensing electrode and the base solution and reacts at the wet surface of the electrode, this reaction consumes the counter electrode. The chemical change in the counter electrode allows a circuit in the instrument to measure a potential (voltage) between the electrodes.

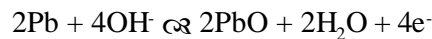
All oxygen sensors used are of the self-powered, diffusion limited, metal-air battery type comprising an anode, electrolyte and an air cathode as shown below.



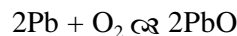
At the cathode oxygen is reduced to hydroxyl ions according to the equation:



The hydroxyl ions in turn oxidise the metal anode as follows:



Overall the cell reaction may be represented as:



The oxygen sensors used are current generators, and the current is proportional to the rate of oxygen consumption (Faraday's Law). This current can be measured by connecting a resistor across the output terminals to produce a voltage signal. If the passage of oxygen into the sensor is purely diffusion limited, this signal is a measure of oxygen concentration.

15.1) Cross-sensitivity of electrochemical sensors and how to handle it

When the first electrochemical sensors were introduced years ago, cross-sensitivity was a serious handicap for the sensors as well as for the flue gas analysers where they were used. There are several ways to handle the problem now.

At first there was the idea of eliminating the influencing agents. That was, and still is, done by means of an NO_x/SO_x filter to eliminate their respective interferences caused on the CO cell. Furthermore, the supplier of the sensors equipped the sensors directly with the respective filters. The problem that occurred when using filters is that they used to be clogged long before the sensors were consumed. That is a particular problem when the filter is incorporated in the sensors. Since they can not be replaced, the whole sensor is useless when the filter is gone.

The need to eliminate the H₂ interferences on CO sensors was initiated by the TÜV in Germany. This is partly done using filters, but there are also sensors where the hydrogen concentration is measured independently of the CO and the compensation carried out electronically. These are then manufactured as 4-electrode sensors with a second sensing electrode.

madur was one of the first suppliers of instruments equipped with electrochemical sensors to introduce a cross-sensitivity calculation in their instruments.

When calibrating the instrument (GA-40T, GA-40 plus and GA-60), every influence detected is stored and goes into that particular calculation. That gives **madur** instruments an outstanding

performance in comparison to most other instruments, although it is often difficult to convince people that the new instrument is correct when they have been used to incorrect readings for years.

The main problem with this method of calculating and then compensating for the effects of other gases present is that the cross-sensitivities can, of course, only be calculated for the gases measured directly i.e. no cross-sensitivities can be calculated between gas components the respective instrument is not equipped to measure directly.

Particularly when testing for HCl, the cross-sensitivity can become a real problem due to the large response caused by SO₂. The HCl sensor has a 35% cross-sensitivity to SO₂ and a maximum operating concentration of 100 ppm. This means that a concentration of SO₂ in excess of about 250 ppm will cause the HCl sensor to go over-range. This is a simple sensor problem that can not be cured by any type of calculation or changes to the software. When the sensor exceeds the maximum range the response becomes unpredictable. The signal can climb to a high value or drop off without warning, thus invalidating the calculations carried out by the instrument. The only real way to avoid this is to know of the problem and to use filters to remove the SO₂ when testing for HCl.

At lower concentrations of SO₂ and, to a lesser extent, NO₂, there is no problem and the results shown by the analyser are trustworthy.

15.2) What is the expected lifetime of electrochemical sensors?

The expected lifetime of oxygen sensors used to be one year. New developments made possible an **oxygen sensor** with **two years** expected lifetime. There are some manufacturers who claim a much longer life-time for their oxygen sensors, but this can only be at the cost of sensitivity, since the signal is caused by consumption of the material of the sensor. To make a sensor last longer, one must either reduce the rate of consumption and hence resolution or increase the size of the sensor.

For **toxic sensors** (CO, NO, NO₂, SO₂ etc.) **two years** lifetime is common. Experience shows that one can expect these sensors to last about three years if the instruments are maintained properly, and the concentrations the sensors are exposed to are within the range regulations in most developed countries require.

15.3) How often do electrochemical sensors need to be calibrated?

Zero calibration is carried out automatically every time the instrument is switched on, or, as is possible in some madur instruments, every time the auto-calibration of the oxygen sensor is performed (usually used for continuous measurements over a couple of hours - in connection with a gas cooler/drier).

Span calibration for toxic sensors, is recommended to be performed at least every six months. Basically, it is dependent on the expectations in regard to accuracy one has and the amount of use the analyser sees. Some companies perform a span calibration every other week. Therefore they are able to achieve accuracies around +/- 2%. An auto-calibration for the oxygen sensors to 20.9% O₂ in air is performed every time the instrument is switched on. Or, as is possible in some madur instruments, at pre-set intervals to ensure good readings during continuous measurement sessions.

16) Types of analyser produced by madur electronics

For every job there is the correct tool. This old piece of wisdom applies equally well to flue gas analysis. For this reason there are hand-held analysers, analysers in soft or hard cases, 2 gas analysers, 4 gas analysers and so on. Somebody doing a quick boiler tune up will not need a 5 gas analyser and somebody doing an annual inspection of a 600 MW coal-fired power station will be lost with a 3 gas analyser. To cover this wide range we produce up to 9 gas analysers, both stationary and portable for various ranges and working conditions. Infrared analysis is now more common and is integrated into the portable equipment as option where possible. A 6 gas analyser may easily include 2 infrared sensors for CO₂ or CH₄. Customer feedback is one of the most important factors in determining what equipment is to be developed or improved, and a series of requests for a 7 gas analyser will lead to optimisation of these types. We take pride in being at the forefront and offering what is required, from simple oxygen analyser to portable infrared or stationary equipment, otherwise known as CEMs (Continuous Emissions Monitoring Systems). Data transfer is essential with this type of analyser, and a range of industry standards exist, most of which are offered such as RS232C (the standard serial communication protocol), RS485 (industry standard allowing 256 instruments to be connected in a bus). Analogue outputs for both current and voltage are to be had and the newest developments are also Ethernet compatible. This allows for an easy connection to the global internet.

17) Sample conditioning

There are several portable sample conditioners available on the market.

These range from a simple panel containing a knock-out pot and silica gel drier, (only suitable for very short term operation without the risk of damage to the analyser and not at all suitable for the measurement of soluble components such as NO₂, SO₂ and HCl) to mains powered units which combine Peltier coolers, filters, sample and condensate pumps and simple sample probes. More sophisticated units are becoming available which include heated sample probes and heated sample lines. Most of these sample conditioners, with a good portable flue gas analyser, are very useful tools for checking permanent installations, for use where permanent analysers are not justifiable, or technical problems exist in a particular process or furnace prohibiting the installation of a permanent system.

The success of sample systems and their associated analysers is entirely dependent on good maintenance. Any analyser system requires a maintenance schedule which must be adhered to. Experience shows that over 97% reliability is achievable with good preventive maintenance. The fuel saved because of that can alone often pay for the analyser and its maintenance, not to mention the positive effects on our environment.

Analyser maintenance is part of the cost of ownership.

In the conventional flue gas system the sample is cooled rapidly and transported to the analyser. This is satisfactory for oxygen, carbon monoxide and nitric oxide analyses.

When the gases being analysed include **sulphur dioxide, nitrogen dioxide, hydrogen chloride or ammonia** the sample is transported hot (**heated sample line**) to the sample cooler and then rapidly cooled.

It is preferable, but not essential, that the temperature of the sample line is capable of being controlled. It is only necessary to remain above the dew-point of the components of the gas stream. Prevention of condensation is essential and a temperature above the sample dew-point aids good reproducibility of analysis as well as accuracy. Where ammonia is to be analysed, a temperature control must be used and kept at a higher temperature.

The cost of these sample lines is high and may be considered a luxury. This is a mistake, and their omission may cost more in maintenance than their initial cost. Analysis errors will also result which may be the subject at a later date of litigation due to breach of legislation.

17.1) Sampling for sulphur dioxide

Like all sample systems the requirements for flue-gas analysis follow certain basic rules. There are, however, some extra points which must be borne in mind if consistent and accurate results are to be obtained.

In all cases the probes should have built-in filters, preferably heated at the exit of the probe prior to the sample line.

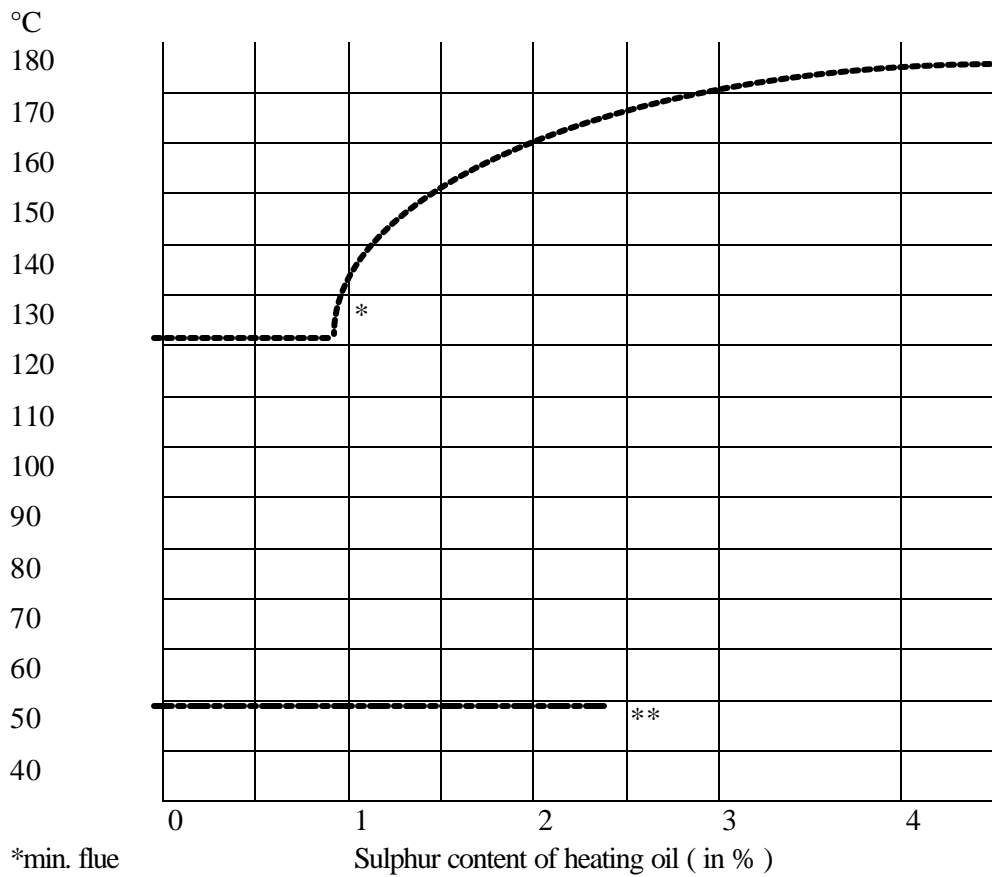
The next item in the sample system is the sample line. If the dew-point is high, as is the case with most flue gases then it should be heated to about 120°C, (better 180°C for some flue gas measurements). For sulphur dioxide (SO₂), nitrogen dioxide (NO₂) and other acidic gases a sample transport line with a core tube of PTFE is preferable as this will not react with the aggressive gases in the sample line.

An unheated sample line may be used if the sample is already dry or deliberate cooling from the probe to the analyser desirable. In this case the sample line must fall to the analyser and incorporate a drain, usually automatic, at the low point.

The sample is then rapidly cooled to + 4°C using a Peltier cooler. The sample may be either pumped to the cooler or preferably drawn by suction from the flue through the probe, sample line and cooler.

In either case the pump requires the protection of a filter. When the sample is pumped to the cooler the condensate has to be removed. Possible ways are a peristaltic pump or (less effectively) a catch-pot.

Relationship between the dew point of flue gases and the SO₂ content



*min. flue
gas temp.
**Dewpoint
of water
vapour

17.2) Nitrogen Analysis

What are the different sources of NO and NO₂ in stack gases?

Nitric oxide (NO) and nitrogen dioxide (NO₂) are the main components of NO_x, which all combustion processes involving atmospheric air can produce.

NO_x emissions contribute to the formation of acid rain and, additionally, can react with hydrocarbons in sunlight to produce a potent respiratory irritant that is commonly called smog.

There are three different sources of NO_x in combustion processes: thermal NO_x, prompt NO_x, and fuel bound NO_x.

In boilers and furnaces which burn fuels low in nitrogen (gas and light oils), thermal NO_x predominates. By burning nitrogen-rich fossil fuels (heavy oils), higher concentrations of fuel NO_x are generated. Typically, nitric oxide (NO) comprises over 95% of the NO_x found in stack gases, however, a significant amount of NO converts to NO₂ in the atmosphere.

Prompt NO_x is a small amount of total NO_x emissions that occurs during the low temperature stages of combustion. Since NO_x contributes to smog and acid rain, legislation to reduce these emissions has become much tougher.

To a lesser extent there will be formation of NO₃ (nitrogen trioxide), N₂O₄ (dinitrogen tetroxide) and N₂O (commonly known as laughing gas). These form a thermal equilibrium dependent on temperature and pressure, but are not generally present in quantities that cause serious concern.

The three mechanisms of NO formation

Nitrogen source	Place of reaction	Mechanism of the NO formation
N ₂ CONTENT OF THE AIR	COMBUSTION GAS	THERMAL NO
N ₂ OF THE FUEL	FLAMEFRONT	FUEL NO "PROMPT" NO

17.3) Sampling for oxides of nitrogen

The general principles involved are the same as for sulphur dioxide, however the relationship between nitric oxide (NO), nitrogen dioxide (NO₂), dinitrogen tetroxide (N₂O₄), and air (oxygen O₂) is a complex temperature dependent equilibrium.

e.g. {high temperature} O₂ + 2 NO <====> 2 NO₂ <====> N₂O₄ {lower temperature}

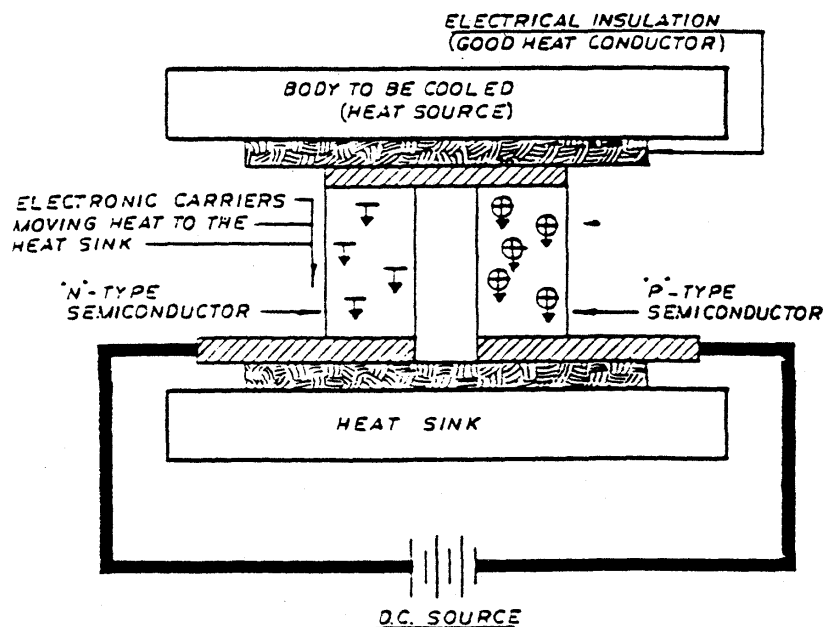
This makes life difficult for all types of spectrophotometer and hence the basic reason for calling this measurement (NO_x)

Most of the oxides of nitrogen become strong acids in the presence of oxygen and/or water. It is therefore important to keep them in the vapour state. For conventional sample systems this is best achieved by using a heated probe and sample line controlled at temperatures around 180°C .

18) Principle of peltier modules used in madur gas coolers / driers

The basic function of a peltier element is the reversed thermoelectric effect that is used to measure temperatures with thermocouples. The so-called Seebeck effect causes two different metals, if welded, to produce a particular voltage depending on the temperature.

A peltier element uses the effect to transport heat from one side of a particular body to the other side when a current is applied.



19) Flue gas contents

The components to be found in flue gases are shown below in the order of their usual concentrations.

Nitrogen (N_2)

Nitrogen is a colourless, odourless and tasteless gas and it does not take a major part in the combustion process. It is the main component of air (79 %) and it reduces the efficiency of the burning process since it is heated and blown out of the stack without actual function for the process.

typical flue gas content: approx. 78 to 80%

Carbon dioxide (CO₂)

Carbon dioxide is also a colourless and odourless gas that is to be found in human breath as well as in every common combustion process. The maximum allowed concentration in offices in Europe is 5000 ppm. Concentrations above 15% (150000 ppm) cause immediate unconsciousness.

*typical flue gas contents: gas burners / boilers 10 - 12%
oil burners / boilers 12 - 14%*

Oxygen (O₂)

Is, of course a very important part since otherwise combustion could not take place. The oxygen content of the air partly reacts with the hydrogen (H₂) content of the fuel and forms water (H₂O). This water content is, dependent on the flue gas temperature, condensed and collected in a water trap or it remains in the flue gas as water vapour.

*typical flue gas oxygen concentrations: gas burners / boilers 2- 3%
oil burners / boilers 2 - 6%*

Carbon monoxide (CO)

A highly toxic gas which is very nasty because it is also colourless and odourless. The maximum permitted concentration in offices is 50 ppm.

*typical flue gas contents: gas burners / boilers 70 - 110 ppm
oil burners / boilers 70 - 160 ppm*

Nitrogen oxides (NO_x)

Nitrogen oxides occur in all combustion processes where fossil fuels are burned, partly through oxidation of the nitrogen content of the air, as well as the organic nitrogen content of the fuel. (The whole process needs high temperatures, therefore one possibility to reduce NO_x contents is to try to keep furnace temperatures and temperatures at metallic surfaces inside the combustion chamber as low as possible.)

The nitric oxide formed oxidises with time and forms nitrogen dioxide (NO₂).

Nitrogen dioxide is a brown, toxic, water-soluble gas that can seriously damage the lungs if inhaled, as well as contributing to acid rain. In connection with the UV-rays in sunlight it helps to form ozone.

*typical flue gas contents: gas burners / boilers 50 - 70 ppm
oil burners / boilers 50 - 110 ppm*

Sulphur dioxide (SO₂)

The SO₂ content is pretty much dependent on the type and quality of the fuel being used. It is again a toxic gas which contributes to the formation of acid rain. The maximum allowable concentration in offices is 5 ppm. Together with water sulphurous acid (H₂SO₃) and sulphuric acid (H₂SO₄) are formed.

typical flue gas contents: oil burners / boilers 180 - 250 ppm

When poor quality coal is being fired, the SO₂ concentration can sometimes exceed 2000 ppm.

Hydrocarbons (C_xH_y)

Combustibles like methane (CH₄) and butane (C₄H₁₀) occur when incomplete combustion takes place. They are to a large extent responsible for global warming. These are part of a chemical family technically known as alkanes.

typical flue gas contents: oil burners / boilers below 60 ppm

Soot (smoke)

Another sign that incomplete combustion is taking place. It is measured by comparison with the well-known Bacharach scale (0 – 9).

20) Measured values

20.1) Directly measured values

Oxygen (O₂)

Measured to calculate CO₂ and efficiency. The value is used in many of the calculations carried out later using the measured values.

Ambient temperature (T_A)

The ambient temperature needs to be measured at the air inlet of the burner / boiler. If the air is sucked from somewhere else, the temperature needs to be measured at a point representative for the inlet air temperature, otherwise there will be errors in the calculation of efficiency.

Flue gas temperature (T_G)

The measurement should be taken in the core (hottest region) of the gas stream. That is where the carbon monoxide concentration is at its peak and the oxygen content is lowest. In industrial equipment the measurement should be carried out as soon after the last heat-exchanger as is practically possible. In many practical applications this is very much easier said than done, but the measurement is important for accuracy.

Carbon monoxide (CO)

In atmospheric gas installations the CO concentration may need to be detected with a so-called multi-hole probe, because the CO concentration in a chimney varies, and that probe makes it possible to sample across the whole diameter. The further along the flue the measurement is carried out, the better the gas is mixed and when a forced draught system is used, the turbulence is usually enough to mix the gas components homogeneously. Such practices appear to be dying out, and most measurements are now carried out simply in the core of the gas stream.

Nitrogen oxides (NO_x)

By measuring the amount of nitrogen oxides (NO, NO₂) the appropriate steps can be taken to minimise the NO_x emissions.

Sulphur dioxide (SO₂)

The SO₂ content of flue gases is dependent on the sulphur content of the fuel and is not related to combustion efficiency. This can only really be altered by a change in the fuel or the use of filter systems.

Hydrocarbons (C_xH_y)

If incomplete combustion takes place, the (unburned) hydrocarbons in the form of soot can be spotted using a filter paper and, in the case of oil derivatives, detected by means of a special solvent. There are usually some gaseous hydrocarbons present, which can be measured with an appropriate sensor. The most accurate method of measuring hydrocarbon gas is an infrared sensor. This does, however, have the disadvantage of being only sensitive to one specific type of hydrocarbon. There are also catalytic sensors available which react to all hydrocarbons. These have the drawback that they basically operate by combustion and hence require a certain level of excess oxygen to operate. The result will also be increased if any other combustible components of other types are present. In general, they are not especially accurate and the thin filament inside is very prone to damage.

Carbon dioxide (CO₂)

For many years carbon dioxide has been calculated from the oxygen concentration and the maximum CO₂ value for the fuel. Increasingly people are interested in directly measuring this component, partly in a drive for higher accuracy in the face of special regulations about this particular gas and partly due to the use of "undefinable" mixtures of gases that may be available as a waste product from another process. Here it is clearly not possible to calculate the CO₂ concentration with any acceptable degree of accuracy. Attempts have been made to develop an electrochemical sensor for this purpose, but the

accuracy was poor, so the only real alternative is to use an infrared sensor. These may be slightly more expensive, but they do not have the disadvantages of limited operational life and regular calibration. They are a legal requirement in some countries nowadays. This information is available from your local government representatives.

Soot (smoke)

According to TÜV Standards a particular gas quantity (1.63 l) has to be sucked through a filter paper within a period of 60 seconds in order to provide accurate and comparable readings. It is generally also necessary to heat the area around the filter paper to prevent condensation altering the result.

20.2) Calculated values

Carbon dioxide (CO₂)

Is an indicator for the quality of the combustion process. If there is a high CO₂ content together with low excess air, then the stack loss is at its minimum. CO₂ levels will naturally depend on the ration of hydrogen to carbon in the fuel.

Excess air factor (l)

This is the ratio of the actual quantity of air present to the quantity of air that would be needed for complete combustion to take place under ideal conditions.

In real combustion processes it is necessary to have a slight excess of air present ($\lambda > 1$) in order to burn the fuel completely. This is due to imperfect atomisation of the fuel and less than ideal mixing with the combustion air.

Excess air reduces efficiency and should therefore be kept to a minimum.

Stack loss (SL)

To be calculated after measuring the oxygen content and the difference between the flue gas and ambient temperatures.

Instead of the oxygen content the CO₂ value can be used for the calculation as well.

Efficiency (ETA)

This is the percentage of the energy produced by the fuel that is available for use, not wasted.

It is calculated from the stack loss by subtracting from 100%. A further calculation is possible which takes account of the losses from incomplete combustion caused by the formation of CO.

Modern developments in the field of heat exchangers, especially the introduction of condensing burners has led to the strange condition of some heating units showing efficiencies above 100%. This is explained later.

Dewpoint

This is calculated from a number of factors, such as oxygen content, fuel type and SO₂ concentration, if known. This is the temperature at which the water in the flue gas will commence condensation. The formation of water within the stack is generally undesirable, since this will combine with corrosive gas components to form acid and attack the structure of the flue. This damage occurs more quickly than many people realise.

Flow velocity

This can be measured in a number of ways. The two most common methods are pitot tubes and impellers. The impellers are not usually capable of withstanding the high temperatures met in flue gas applications, so the pitot tube is seen most often. The differential pressure connections measure the difference between static and dynamic pressure, producing a value that can be used for the velocity calculation. Theoretically, there may be a velocity profile across the width of the stack, particularly in the case of low flow rates, but higher flow rates and turbulent flow are to be expected in most cases. Turbulent flow gives a very flat and nearly constant velocity profile, reducing the errors to an insignificant level. The cross-sectional area of the stack can then be used to calculate the mass flow-rate for all components.

21) Basic principles of calculating results

21.1) Quantities obtained from direct measurements (O₂, CO, NO, SO₂)

In direct measurements the temperature values and also the concentration of those gas elements which are detected by independent electrochemical sensors are obtained. The electrochemical cell indications are proportional to the volume concentration of the detected elements expressed in ppm (parts per million).

The following quantities are obtained by means of direct measurement:

flue gas temperature T_{gas} and ambient temperature, expressed in [°C]

volume concentration of CO [ppm]

volume concentration of NO [ppm]

volume concentration of SO₂ [ppm]

volume concentration of O₂ [%]

volume concentration of optional cells NO₂ , H₂S, H₂, Cl₂ , HCl (ppm)

21.2) Calculating the concentration of carbon dioxide

The volume concentration of carbon dioxide, expressed in [% vol], is not usually obtained by direct measurement, but is calculated on the basis of measured oxygen concentration and the CO_{2max} parameter, characteristic for the given fuel.

Formula 1 shows the formula according to which the analyser calculates volume concentration of CO₂:

$$\textcircled{1} \quad \text{CO}_2 = \text{CO}_{2\text{max}} \cdot \left(1 - \frac{\text{O}_{2\text{meas}}[\%]}{20.95\%} \right)$$

21.3) Calculating the concentration of nitrogen oxides NO_x

In addition to nitric oxide NO, combustion gases contain also higher oxides of nitrogen (mainly NO₂). Not all **madur** instruments have the nitrogen dioxide sensor in the basic version. But it is possible to calculate the NO₂ contents on the basis of the measured NO. It is generally assumed that nitric oxide NO contained in combustion gases makes up about 95% of the total amount of nitrogen oxides NO_x. Some **madur** instruments calculate the total concentration of nitrogen oxides NO_x according to the following formula:

$$\textcircled{2} \quad \text{NO}_x[\text{ppm}] = \frac{\text{NO}[\text{ppm}]}{0.95}$$

If the analyser is fitted with NO and NO₂ sensors, there is no need to calculate the amount of NO₂. The NO_x concentration is calculated by the analyser as a simple sum of measured NO and NO₂ concentrations. This may be a requirement in some areas. Calculation of NO_x from NO is only possible if there is a reliable and known ratio between NO and NO₂ in the gas measured. This may not always be the case.

$$\textcircled{3} \quad \text{NO}_x[\text{ppm}] = \text{NO}[\text{ppm}] + \text{NO}_2[\text{ppm}]$$

21.4) Concentration of "undiluted" carbon monoxide CO_{undil}

To make the calculation of the carbon monoxide concentration in combustion gases independent of excess air with which the combustion process is conducted, the idea of "undiluted" carbon monoxide CO_{undil} was introduced (it is also called the CO concentration calculated for 0% O₂). The value of CO_{undil} is calculated according to the formula below:

$$\textcircled{4} \quad \text{CO}_{\text{undil}} = \text{CO} \cdot \lambda$$

where:

- CO - volume concentration CO[ppm]
- λ - excess air number

As can be seen, the concentration of "undiluted" CO is the hypothetical concentration that would have been formed if the same amount of carbon monoxide had appeared in combustion gases when burning without excess air (where λ = 1, so O₂ = 0%).

21.5) Mass concentrations of gas components

madur instruments also make calculations of mass concentration expressed in [mg/m³] from the concentration expressed in [ppm]. Mass concentration of gas elements depends on the gas pressure and temperature. To make comparison of results possible, the idea of standard conditions was introduced, that is standard temperature and pressure values at which the mass concentration of the elements is calculated. In **madur** instruments standard conditions of 1000hPa and 0°C were taken.

The screen displaying, among others, mass concentration of the measured gases is shown below. It should be noticed that the analyser indicates two different values expressed in [mg/m³], they are the so called absolute mass concentration and mass concentration in relation to oxygen. These values are often confused - in the next section the way they are calculated and the differences between them are explained.

? * CURRENT VALUES * ?				

GAS	[ppm]	[mg/m ³]	[mg/m ³]	O2rel= 5%
-----+-----+-----+-----				
CO	178	219	415	max 1000
NO	56	119	246 !	max 200
NOx	78	165	323 !	max 250
SO2	115	312	240	max 400

21.5.1) Absolute mass concentration of gas components

Absolute mass concentration defines how many milligrams of a given gas is contained in 1m³ of combustion gas at standard conditions (1000 hPa, 0°C). The concentration value is calculated from the concentration expressed in ppm using the factor A from table 5. The following formula shows how the absolute mass concentration is calculated (here CO concentration):

$$\textcircled{5} \quad \text{CO} \left[\frac{\text{mg}}{\text{m}^3} \right] = \text{CO}[\text{ppm}] \cdot A_{\text{CO}}$$

where:

CO[mg/m³] -absolute CO mass concentration in combustion gas (at standard conditions).

CO[ppm] -absolute CO volume concentration in combustion gas (from measurement).

A_{CO} -correction factor from table 5.

Gas	$A \left[\frac{\text{mg}}{\text{m}^3 \cdot \text{ppm}} \right]$
CO	1.250
NO	1.340
SO ₂	2.860
NO ₂ , NO _x	2.056
H ₂ S	1.520
H ₂	0.089
Cl ₂	3.220
HCl	1.693
HCN	1.205

Table 1: Factors to convert concentration in [ppm] into mass concentration in [mg/m³] (at standard conditions 1000 hPa, 0°C).

Note: *mass concentration of nitrogen oxides (NO_x) is calculated by the analyser (according to the standards) using the nitrogen dioxide (NO₂) factor.*

Mass concentration calculated by **madur** instruments is comparable with the results obtained by other methods (or different types of analysers) only when the calculations have been carried out based on the same standard conditions.

21.5.2) Mass concentrations in relation to the concentration of oxygen in combustion gases

As well as absolute mass concentration, the mass concentration in relation to the oxygen concentration in the combustion gases is calculated. The concentration of a given component in relation to the oxygen concentration is expressed by the following formula (as an example for CO value):

$$\textcircled{6} \quad \text{CO}_{\text{rel}} \left[\frac{\text{mg}}{\text{m}^3} \right] = \frac{20.95\% - \text{O}_{2\text{ref}}}{20.95\% - \text{O}_{2\text{meas}}} \cdot \text{CO} \left[\frac{\text{mg}}{\text{m}^3} \right]$$

where:

CO_{rel} - CO concentration in relation to oxygen expressed in [mg/m³]

O_{2ref}	-reference oxygen, conventional parameter (chosen by selecting fuel or entered independently from keyboard) expressed in [% vol]
O_{2meas}	- the measured concentration of O_2 in combustion gases expressed in [% vol]
20.95%	- oxygen concentration in pure air
CO	- the measured concentration of CO in combustion gases expressed in [mg/m^3] (absolute mass concentration)

Using similar formulae, the concentrations in relation to oxygen concentration of sulphur dioxide SO_2 , nitrogen oxides NO_x and other gases are calculated. The concentration related to oxygen concentration was introduced to make the evaluated concentration independent of the way the combustion process is carried out. The absolute value (expressed in [ppm]) can be lowered artificially in the combustion process with an increase in excess air (large amount of O_2 in the combustion gases). It does not have to be a decrease of the total emission. The formula which calculates concentration related to oxygen takes into account the oxygen concentration of the combustion gases, making the results independent of the excess air factor.

The parameter O_{2ref} - reference oxygen is a standard value. Standards recommend different values of this parameter for various types of fuel. In **madur** instruments the value of reference oxygen can be accepted automatically in the process of fuel selection (the so-called *a u t o m a t i c* reference oxygen choice) or entered by the operator from the keyboard (the so-called *m a n u a l* selection of reference oxygen). Relative mass concentration calculated from two different measurements are comparable only if the same reference oxygen and the same standard conditions have been used.

Note: *If $O_{2meas} < O_{2ref}$ then relative concentration CO_{rel} calculated from formula ⑥ is less than absolute concentration. In such a case, the analyser replaces the value of relative concentration with the value of absolute mass concentration.*

21.6) Calculating combustion parameters

Beside calculating gas component concentrations the analyser calculates some parameters describing the combustion process. The formulae for calculating combustion parameters are empirical formulae. **madur** analysers calculate the parameters of the combustion process according to the principles predicted by DIN standards.

The **most important** parameter is the amount of heat convected by combustion gases to the environment - the so-called chimney loss (stack loss) S_L . Chimney loss is calculated on the basis of an empirical formula known as Siegert's formula:

$$\textcircled{7} \quad S_L = (T_{\text{gas}} - T_{\text{amb}}) \cdot \left(\frac{A1}{\text{CO}_2} + B \right)$$

where:

- S_L -chimney loss - the percentage of heat produced in combustion process which is convected with the combustion gases.
- T_{gas} - flue gas temperature
- T_{amb} -the temperature of the boiler inlet air (it is assumed by the analyser to be the ambient temperature)
- CO_2 -the calculated (on the basis of oxygen concentration and $\text{CO}_{2\text{max}}$) amount of CO_2 in combustion gases, expressed in [% vol]
- A1, B - factors characteristic for a given fuel type (see Table 6)

Based on the calculated chimney loss the analyser estimates the efficiency of the combustion process η (don't confuse it with total boiler efficiency)

$$\textcircled{8} \quad h = 100\% - S_L$$

where:

- η - combustion efficiency

The above formula assumes that the only quantity decreasing combustion efficiency is chimney loss. Thus it omits incomplete combustion losses, radiation losses etc. Such a simplification is a result of the inability to measure the size of other losses with the gas analyser. Because of this gross simplification in the formula above it should be remembered that the efficiency calculated in this way can not be treated as precise.

However, efficiency calculated like this is very convenient as a comparable parameter when regulating the furnace.

The formula, though simplified, reflects precisely the tendencies of efficiency change, thus it is possible to observe whether the efficiency increases or decreases. It is sufficient information for the regulation process.

It is possible to take into account the efficiency reduction caused by incomplete combustion. This loss is represented by a quantity called the loss by incomplete combustion IL. It determines the percentage of energy loss caused

by the presence of flammable gases (in this case mainly CO) in the combustion gases. The loss caused by incomplete combustion is calculated on the basis of the measured CO concentration in the combustion gases according to the following formula:

$$\textcircled{9} \quad \text{IL} = \frac{\alpha \cdot \text{CO}[\%]}{\text{CO}[\%] + \text{CO}_2[\%]}$$

where:

- CO, CO₂ - volume concentrations of CO and CO₂ in the combustion gases
- α - the factor specific for a given fuel

Calculating IL enables correction of the previously calculated (formula 8) combustion efficiency. Then the so-called corrected efficiency η^* is calculated:

$$\eta^* = \eta - \text{IL}$$

The last combustion parameter calculated by **madur** instruments is the excess air factor λ . This factor expresses how many times the amount of air supplied to the boiler is larger than the minimum amount which is theoretically necessary to burn the fuel completely. The system calculates the λ factor on the basis of the known CO_{2max} value for the given fuel and the calculated concentration of CO₂ in the combustion gases using the formula:

$$\lambda = \frac{\text{CO}_{2\text{max}}}{\text{CO}_{2\text{meas}}}$$

The above formula may be transformed with the use of formula $\textcircled{1}$ into the form:

$$\textcircled{10} \quad \lambda = \frac{20.95\%}{20.95\% - \text{O}_{2\text{meas}}[\%]}$$

21.7) Fuel components

The basis for correctly determining the quantities describing the combustion process is the knowledge of fuel parameters. **madur** instruments have stored parameters for several standard fuels. Table 6 presents parameters for all the standard analyser fuels.

Some of these parameters are not used at present in the calculations carried out by the analyser. They are simply present to enable them to be used in the future, should it be necessary. This may seem strange, but makes life easier for software development.

No	Fuel type	CO _{2max}	A1	B	a	O _{2ref}	Heating value
1.	Light oil	15.4	0.500	0.007	52	3	37.80 MJ/kg
2.	Natural gas	11.7	0.370	0.009	32	3	37.35 MJ/m ³
3.	Town gas	13.1	0.350	0.011	32	3	16.34 MJ/m ³
4.	Coke-oven gas	10.2	0.290	0.011	32	3	
5.	Liquid gas	14.0	0.420	0.008	32	3	
6.	BIO-Diesel	15.7	0.457	0.005	52	3	37.40 MJ/kg
7.	Extra light oil	15.3	0.590	0	52	3	42.70 MJ/kg
8.	Heavy oil	15.9	0.610	0	52	3	39.90 MJ/kg
9.	Coal-tar oil	18.0	0.650	0	52	3	38.80 MJ/kg
10.	Natural gas with fan	12.1	0.460	0	32	3	37.35 MJ/m ³
11.	Town gas with fan	10.0	0.380	0	32	3	16.34 MJ/m ³
12.	Propane with fan	13.7	0.500	0	32	3	93.60 MJ/m ³
13.	Propane	13.7	0.475	0	32	3	93.60 MJ/m ³
14.	Butane with fan	14.1	0.500	0	32	3	128.00 MJ/m ³
15.	Butane	14.1	0.475	0	32	3	128.00 MJ/m ³
16.	Biogas with fan	11.7	0.780	0	32	3	24.00 MJ/m ³
17.	Biogas	11.7	0.710	0	32	3	24.00 MJ/m ³
18.	Mineral coal HV 31.5	18.8	0.683	0	69	11	31.50 MJ/kg
19.	Mineral coal HV 30.3	18.5	0.672	0	69	11	30.30 MJ/kg
20.	Lignite HV 8.2	19.1	1.113	0	69	11	8.20 MJ/kg
21.	Lignite HV 9.4	19.1	0.988	0	69	11	9.40 MJ/kg
22.	Dry wood	19.4	0.650	0	69	11	15.30 MJ/kg

Table 2: Parameters of fuels stored in the memory of **madur analysers.**

Table 2. shows the following parameters:

- CO_{2max} -the maximum concentration of carbon dioxide in the combustion gas, a quantity specific for a given type of fuel. The parameter determines the amount of carbon dioxide in the combustion gases if the combustion process is carried out with excess air factor λ equal 1.

- A1, B - factors which appear in Siegert's empirical formula
- α - the factor used to calculate loss caused by incomplete combustion.
It should be assumed
 $\alpha = 69$ for solid fuels
 $\alpha = 52$ for liquid fuels
 $\alpha = 32$ for gaseous fuels
- O_{2ref} -reference oxygen - the parameter used to calculate relative concentrations of components (formula 4). It is a standard quantity. In the table, it has been assumed as in DIN standards that it is 11% for solid fuels and 3% for gaseous and liquid ones.
- HV - fuel quality - the amount of energy produced during the complete combustion of 1 kilogram (or 1m³ in the case of gas) of fuel. This is the lower energy of combustion.

21.8) The influence of fuel parameters on the accuracy of result calculations

As has already been mentioned, **madur** instruments do not generally measure the concentration of carbon dioxide, but calculate it from the measured oxygen concentration and the CO_{2max} parameter. On the basis of CO₂ concentration calculated in this way, the chimney loss, combustion efficiency and loss by incomplete combustion are calculated. Obviously, the fuel parameters (especially CO_{2max}), have a fundamental influence on calculations of combustion processes. The following results calculated by **madur** instruments are affected by fuel parameters:

- CO₂ contents - depends on CO_{2max}
- S_L chimney loss - depends on CO_{2max}, A1 and B
- η and η^* - depends on CO_{2max}, A1 and B
- S_L chimney loss- depends on CO_{2max}, A1 and B
- IL loss by incomplete combustion - depends on CO_{2max} and a.

As can be seen from formula ⑩, the value of the excess air factor does not depend on the fuel parameters. The calculated results of gas quantities (except CO₂)

and the results of temperature measurements and power quantities do not depend on fuel parameters either.

22) Recent developments

There have been many developments in the field of combustion technology in the last few years. This is especially true for gas burners. The newest gas burners are of the condensing type, where the flue gas temperature is below the dew-point of the gases, which lies by about 57°C for flue gases from gas burners. The water in the gas condenses on a set of special heat exchangers mounted in the gas stream. This enables the evaporation energy to be extracted from the gas as well, raising the efficiency greatly at no extra cost.

Care has to be taken to use corrosion-resistant materials, since the condensate is relatively aggressive and the flue channel has to be fitted with a stainless steel liner or equivalent, otherwise it will be destroyed fairly quickly.

The traditional calculation of combustion efficiency uses the temperature of the gases at inlet and in the stack for the calculation. A separate correction must be made to take account of the specific heat of evaporation when working with condensing equipment. This correction is of interest for the owner of the equipment, but may not be accepted officially as a measure of efficiency. Regulations in most countries specify how these parameters should be calculated and may not allow a different method.

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