



Flue Gas Analysis in Industry

Practical guide for
Emission and Process
Measurements



°C

O₂

CO

NO_x

λ

qA

Eta

CO₂

ΔP

m/s

m³/h

SO₂

t/a

2. Edition



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1. Foreword

This handbook is a valuable reference work for the application of portable flue gas analyzer in industry. Frequent questions arising from practical use are answered based on the worldwide experience of many thousands of testo analyzer users.

The handbook will save you the time consuming and sometimes difficult search for information in various sources.

What is missing? What was not described as detailed as required?
Your comments, amendments and suggestions are very much appreciated!
They will be incorporated into a next edition. Just write to us; see the form for that on page 138.

We thank Dr. Ulrich Jecht for his commitment in writing this handbook.

The Management

Burkart Knospe
Lothar Walleser

2. The combustion process

2.1 Energy and combustion

Energy

is defined as the ability of a material or system to perform labor. Energy exists in different modifications which can be classified into six categories as follows:

- Mechanical energy (flowing water, driving car)
- Thermal energy (boiling water, gas flame)
- Chemical energy (chemical reaction, burning process, explosion)
- Electrical energy (car battery, electricity)
- Electromagnetic energy (light radiation, microwave radiation)
- Nuclear energy (nuclear fission)

The different energy modifications can be converted into each other, within an ideally closed system, with the sum remaining constant (conservation of energy). In practice, however, energy losses occur during the conversion process thereby reducing the efficiency.

The natural **energy carriers** (coal, natural gas, crude oil, sun radiation, water power etc.) are described as *primary energies*, while the term *secondary energies* stands for what is received from energy conversions (electricity, heat, etc.). Energy carriers differ in **energy content**. For comparison reasons the energy content is described as amount of energy which could be released from a certain quantity of an energy carrier in case of its total combustion. The energy scale unit is 1 Joule [J]. Some energy content values are given in table 1.

Energy carrier, 1 kg of...	Energy content [MJ]
Brown coal	9,0
Wood	14,7
Hard coal	29,3
Natural gas (1 m ³)	31,7
Crude oil	42,6
Fuel oil, light	42,7
Gasoline	43,5
For comparison: 1 kWh	3,6

Table 1: Energy content of fuels

Combustion

is the conversion of primary chemical energy contained in fuels such as coal, oil or wood into heat (secondary energy) through the process of oxidation. Combustion therefore is the technical term for the chemical reaction of oxygen with the combustible components of fuels including the release of energy.

Combustion processes proceed with high temperatures (up to 1000 °C and above). The oxygen required for the combustion is supplied as part of the combustion air fed to the process. From that a considerable volume of exhaust gas (flue gas, off gas) is produced together with, depending on the kind of fuel, a certain amount of residues (slag, ash).

Oxidation

Term for all chemical reactions of oxygen with other substances. Oxidation processes proceed with the release of energy and are of great importance in many technical (combustion) and biological (breathing) areas.

Greenhouse effect

Principally the greenhouse effect is a natural process and one of the reasons for human life on earth. Without this effect, the global average temperature near the earth surface would be at -18 °C instead of +15 °C as it is; the earth would be inhabitable for human beings! The cause for this natural effect is that the light radiation of the sun passes through the air and is absorbed by the earth. The earth then re-radiates this energy as heat waves that are absorbed by the air, specifically by carbon dioxide. The air thus behaves like glass in a greenhouse, allowing the passage of light, but not of heat.

By excessive firing of fossil fuels (emission of carbon dioxide) and release of certain substances from chemical industry and agriculture (halogen hydrocarbons, methane e.a.) the natural effect will be amplified causing a slow increase of the surface temperature with influence to the climatic conditions.

More details to the objective of combustion are given in chapter 2.4

2.2 Combustion plants

Combustion plants are facilities that generate heat by burning solid, liquid or gaseous fuels. They are required for many tasks, e.g.

- heating (heating plants, building heating)
- generation of electrical energy
- generation of steam and hot water for use in process industries
- manufacturing certain materials (cement, glass, ceramics)
- thermal surface treatment of metallic parts
- incineration of waste materials and residues

See detailed application examples in chapter 5!

Combustion occurs in a combustion chamber; other control units are required for fuel supply and fuel distribution, combustion air supply, heat transfer, exhaust gas cleaning and for discharge of exhaust gases and combustion residues (ash, slag). Solid fuels are fired on a fixed or fluidized bed or in a flue dust/air mixture. Liquid fuels are fed to the burning chamber together with the combustion air as mist. Gaseous fuels are mixed with combustion air already in the burner.

The exhaust gases of combustion plants contain the reaction products of fuel and combustion air and residual substances such as particulate matter (dust), sulfur oxides, nitrogen oxides and carbon monoxide. When burning coal, HCl and HF may be present in the flue gas as well as hydrocarbons and heavy metals in case of incineration of waste materials.

In many countries, as part of a national environmental protection program, exhaust gases must comply with strict governmental regulations regarding the limit values of pollutants such as dust, sulfur and nitrogen oxides and carbon monoxide. To meet these limit values combustion plants are equipped with flue gas cleaning systems such as gas scrubbers and dust filters.

For further information on the regulations see chapter 3.

2.3 Fuels

are available in different forms and composition:

- *Solid fuels* (hard coal, bituminous coal, peat, wood, straw) contain carbon (C), hydrogen (H₂), oxygen (O₂), and smaller quantities of sulfur (S), nitrogen (N₂), and water (H₂O). A major problem when handling such fuels is the formation of large quantities of ash, particulate matter and soot.
- *Liquid fuels* derive mainly from crude oil and can be classified into light, medium and heavy fuel oils. Light fuel oil (i.e. diesel fuel) is widely used in small combustion plants.
- *Gaseous fuels* are a mixture of combustible (CO, H₂ and hydrocarbons) and non-combustible gases. Today very often natural gas is used, which contains methane (CH₄) as the main component.

The knowledge of fuel composition is important for an optimum and economical combustion process. Increasing percentage of incombustible (inert) fuel components reduces the gross and net calorific value of the fuel and increases contamination of the furnace walls. Increasing water content raises the water dew point and consumes energy to evaporate water in the flue gas. The sulfur contained in the fuel is burnt (oxidized) to SO₂ and SO₃, which, at temperatures below the dew point, may lead to the formation of aggressive sulfurous and sulfuric acids. See also chapter 2.7.

The composition of some solid fuels is shown in the following table:

Fuel	Mass content in %			
	Carbon in dry material	Sulfur	Ash	Water
Hard coal	80-90	1	5	3-10
Bituminous coal	60-70	2	5	30-60
Wood (air-dried)	50	1	1	15
Peat	50-60	1	5	15-30

Table 2: Composition of solid fuels

For details of gross and net calorific value see chapter 2.6

2.4 Combustion air; excess air value

The oxygen required for a combustion process is supplied as part of the combustion air which consists of (see table 3) nitrogen (N₂), oxygen (O₂), a small amount of carbon dioxide and rare gases, and a variable content of water vapor. In some processes pure oxygen or a air/oxygen mixture is used for the combustion.

The combustion air components, except oxygen, are all contained in the resulting raw flue gas.

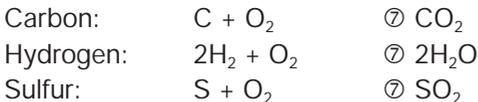
Component	Content [%]
Nitrogen	78,07
Oxygen	20,95
Carbon dioxide	0,03
Hydrogen	0,01
Argon	0,93
Neon	0,0018

Table 3: Composition of clean and dry air

2.4.1 Stoichiometric and excess-air combustion; material balance

The minimal amount of oxygen required to burn all combustible components completely depends on the fuel composition. 1 kg of carbon e.g. requires 2,67 kg oxygen to be burnt completely, 1 kg of hydrogen requires 8 kg oxygen, 1 kg of sulfur however only 1 kg oxygen! Combustion occurring at these exact gas quantity ratios is called *ideal combustion or stoichiometric combustion*.

The relevant equations are



The ideal combustion procedure is shown schematically in figure 1. The amount of oxygen supplied to the combustion is just sufficient to burn all fuel combustibles completely. No oxygen nor combustibles are left. The excess air value (ex.air) is 1 in this case.

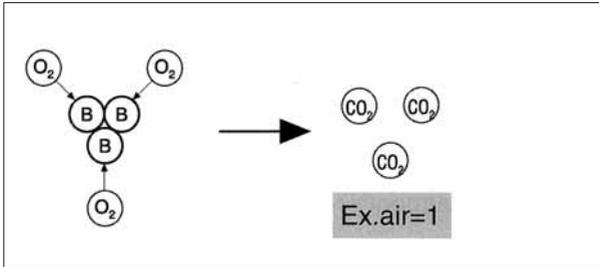


Fig. 1: Stoichiometric combustion model

In a real process this ideal oxygen volume is not sufficient for complete burning because of insufficient mixing of fuel and oxygen. The combustion process, therefore, must be supplied with more than the stoichiometric volume of oxygen. This additional amount of combustion air is called *excess air* and the ratio of the total air volume to the stoichiometric air volume is the *excess air value* $ex.air$; another expression for that is λ (lambda). Fig. 2 shows this excess air combustion model ($ex.air > 1$) schematically.

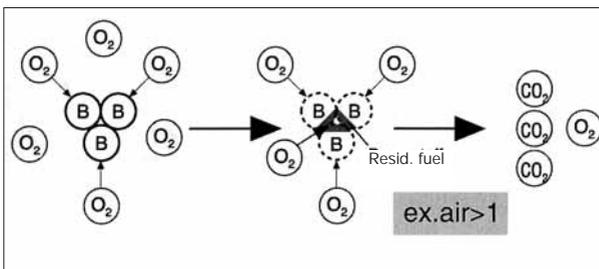


Fig. 2: Excess air combustion model

Consequently the highest combustion efficiency is achieved with a (limited) excess volume of oxygen, i.e. $ex.air > 1$ (oxidizing atmosphere).

The excess air value is of great importance for an optimum combustion process and economic plant operation:

- Unnecessary high excess air volumes reduce combustion temperatures and increases the loss of energy released unused into the atmosphere via the hot flue gas stream.
- With too little excess air some combustible components of the fuel remain unburned. This means reduced combustion efficiency and increased air pollution by emitting the unburned components to the atmosphere.

Table 4 shows various excess air value ranges of specific types of combustion processes. In general: The smaller the reactive surface/mass volume ratio of the fuel particles is the more excess air volume is required for optimum combustion. This is also correct conversely and therefore solid fuels are ground and liquid fuels are sprayed to get a larger reactive surface. Only a few processes exist which are operated definitely at deficient air ($ex.air < 1$) conditions because of their special process requirements (e.g. heat treatment processes).

Combustion plant	Range of ex.air	Excess O ₂
Combustion engines	0,8-1,2	8 ... 20 %
Gas burner	1,1-1,3	10 ... 30 %
Oil burner	1,2-1,5	20 ... 50 %
Coal powder burner	1,1-1,3	10 ... 30 %
Brown coal roast	1,3-1,7	30 ... 70 %

Table 4: Typical ranges of excess air value

Oxidizing atmosphere

In an oxidizing atmosphere more oxygen is available as necessary for complete combustion of all combustible components existing in the gas volume.

The combustion (oxidation) will be complete.

Simplified: Oxidation = Addition of oxygen (e.g. CO is oxidized to CO₂)

Reducing atmosphere

In a reducing atmosphere less oxygen is available as necessary to burn (oxidize) all combustibles.

Simplified: Reduction = Removal of oxygen (e.g. SO₂ is reduced to S)

2.4.2 Determination of the excess air value

The excess air value can be determined from the concentrations of CO, CO₂ and O₂ in the flue gas. These relations are shown in the *combustion diagram*, fig. 3. At ideal fuel/air mixing conditions each CO₂ content value is related to a certain CO value (area with $ex.air < 1$) or to a certain O₂ value (area with $ex.air > 1$). The CO₂ value for itself is not definite because of the curve showing a maximum. Therefore it must additionally be checked whether, besides the CO₂, CO or O₂ is present in the gas. When operating the combustion with excess air (i.e the normal case) nowadays the definite determination of only O₂ is preferred. The curves are fuel-specific which means a separate diagram for each fuel with a fuel-specific value of CO_{2,max} is used for efficiency calculation, see table 7, page 21.

For calculation of the excess air value from the measured values of CO_2 or O_2 the following two formulas may be used:

$$\lambda = \frac{\text{CO}_{2 \text{ max}}}{\text{CO}_2}$$

$$\lambda = 1 + \frac{\text{O}_2}{21 - \text{O}_2}$$

$\text{CO}_{2 \text{ max}}$: fuel-specific maximum CO_2 value (see table 7, page 21)
 CO and O_2 : measured or calculated concentration values in the flue gas

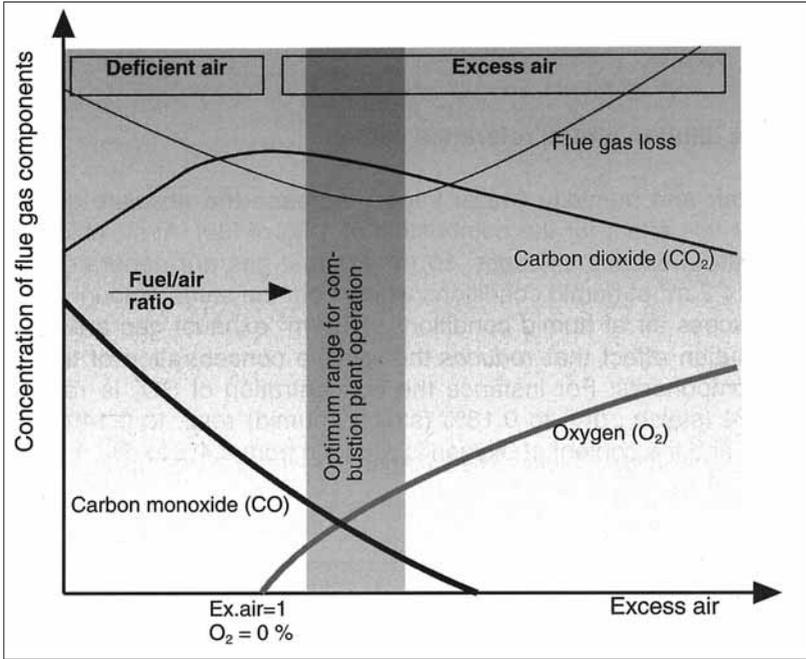


Fig. 3: Combustion diagram

For more information regarding the combustion diagram see chapter 3.1.

2.4.3 Required combustion air volume

The actually required volume of combustion air can be calculated

- from the air volume needed for the ideal combustion (depending on the kind of fuel),
- the desired excess oxygen value and
- the relative oxygen content of the used air or the air/oxygen mixture

The oxygen content of dry air at 1 bar pressure is 20,95%. In practice, however, ambient air is not dry, therefore the water content must also be considered for correct air volume calculation.

2.4.4 Gas volume; dilution effect; reference values

Both combustion air and humidity (water vapor) increase the *absolute* gas volume. Fig. 4 shows this effect for the combustion of 1 kg of fuel. At stoichiometric conditions (i.e. without excess air) appr. 10 m³ exhaust gas are generated from that at dry resp. 11,2 m³ at humid conditions whilst from the same amount of fuel, burnt with 25% excess air at humid conditions, 13,9 m³ exhaust gas are generated. This is a dilution effect that *reduces* the relative concentration of the particular flue gas components. For instance the concentration of SO₂ is *relatively* reduced from 0,2% (stoich., dry) to 0,18% (stoich., humid) resp. to 0,14% (25% excess air, humid) and the content of oxygen is reduced from 4,4% to 4%. See table 5 and fig. 4.

	Nitrogen	CO ₂	SO ₂	Water	Oxygen
Stoich./dry	82,6	16	0,20	0	0
Stoich./humid	74,7	14,4	0,18	10,7	0
25% EA/dry	82,8	12,7	0,16	0	4,4
25% EA/humid	75,6	11,6	0,14	8,7	4

Table 5: Relative exhaust gas composition in % under different gas conditions
EA = Excess air

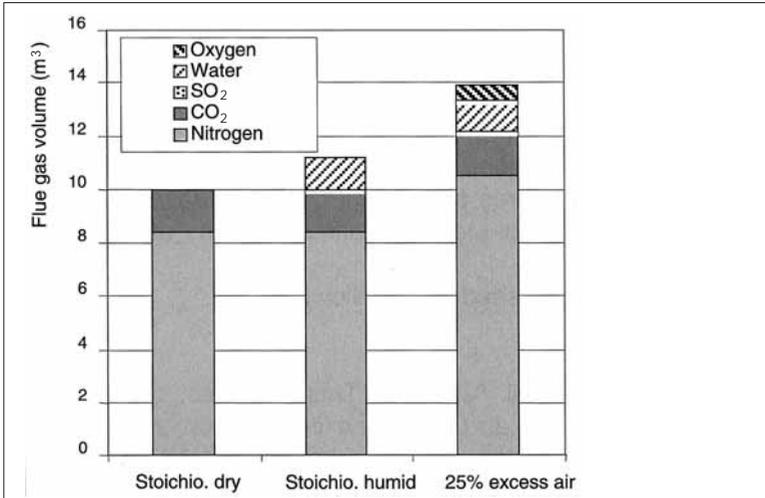


Fig. 4: Dilution effect of flue gas through humidity and excess air

Reference values

Concentration values are typically reported in relation to a known resp. specified reference value. Only then can the measured value be comparable with other values, e.g. specified pollution limits.

In practice three definitions of setting a reference are used:

- ∞ Reference to a certain **value of dilution through excess air**. For that the oxygen concentration is used as reference measure by the expression e.g. "Reference value 8% oxygen".
- ∞ This reference is generally applied for regulatory reporting. Sometimes it is also used for a specific application so that the oxygen value is characteristic for the standard operational conditions of the plant.
- ∞ Reference to a certain **value of dilution through the humidity content** of the gas. Typically the gas temperature is expressed e.g. by "at dew point of 4 °C"; but expressions as "related to dry gas" are also used.
- ∞ Reference to the **standard conditions of a gas**. This refers to the influence of pressure and temperature on the gas volume. See chapter 4.1.1.

2.5 Exhaust (flue) gas and exhaust gas composition

Exhaust gas generated through combustion processes is called flue gas or stack gas. Its composition depends on the type of fuel and the combustion conditions, e.g. the air ratio value. Many flue gas components are air pollutants and must therefore, due to governmental regulations (see chapter 3.3), be eliminated or minimized by special cleaning procedures before the gas is released to the atmosphere. The exhaust gas in its original status is called raw gas, after cleaning it is called clean gas.

The main flue gas components are discussed in the following.

Nitrogen (N₂)

Nitrogen is the main constituent (79 Vol. %) of air. This colorless, odorless and tasteless gas is fed to the combustion as part of the combustion air but is not involved directly in the combustion process. It acts as ballast material and carrier of wasted heat and is released again into the atmosphere. However, minor quantities of this combustion air related nitrogen are, together with the nitrogen released from the fuel, responsible for the formation of the dangerous nitrogen oxides (see below).

Carbon Dioxide (CO₂)

Carbon dioxide is a colorless and odorless gas with a slightly sour taste. It is produced during all combustion processes including respiration. It contributes considerably to the green house effect through its ability to filter heat radiation (see page 7). In ambient air CO₂ concentration is 0,03%; at concentrations of over 15% loss of consciousness will occur immediately.

Water vapor (humidity)

The hydrogen contained in the fuel will react with oxygen and form water (H₂O). This, together with the water content of the fuel and the combustion air, exists either as flue gas humidity (at higher temperatures) or as condensate (at lower temperatures).

Oxygen (O₂)

The portion of oxygen that has not been consumed by the combustion process remains as part of the flue gas and is a measure for the efficiency of the combustion. It is used for the determination of combustion parameters and acts also as reference value.

Carbon Monoxide (CO)

Carbon monoxide is a colorless, odorless, toxic gas. It is formed predominantly during incomplete combustion of fossil fuels and other materials containing carbon. Outdoors in ambient conditions CO is not very dangerous for human beings because of its fast reaction to CO₂ with oxygen. However, indoors or within enclosed spaces it must be considered as very dangerous, as at concentrations of only 700 ppm in the breathing air it will lead to death within a few hours! The working place threshold value is 50 ppm.

Oxides of nitrogen (NO and NO₂, sum formula NO_x)

In combustion processes nitrogen of the fuel and, at high temperatures, also of the combustion air reacts to a certain amount with oxygen of the combustion air and forms first nitric oxide (fuel-NO and thermal-NO). This NO will react with oxygen already in the stack and/or later on in the atmosphere and form the dangerous nitrogen dioxide (NO₂). Both oxides are toxic! Specifically NO₂ is a dangerous lung poison and contributes, in connection with sun light, to the formation of ozone. Extensive technologies are used to clean flue gases from NO_x, e.g. the Selective Catalytic Reaction (SCR) process. In addition to that, special measures (e.g. staged air supply) have been developed to reduce the formation of nitrogen oxides already during combustion process. See chapter 3.3.4.

Sulfur dioxide (SO₂)

Sulfur dioxide is a colorless, toxic gas with a pungent smell. It is formed through oxidation of sulfur that is present in the fuel.

The working place threshold limit value is 5 ppm. Together with water or condensate sulfurous acid (H₂SO₃) and sulfuric acid (H₂SO₄) are formed, both of which are responsible for various damages to e.g. nature and buildings (acid rain). Scrubbing technologies are used to clean flue gases from sulfur oxides.

Hydrogen sulfide (H₂S)

Hydrogen sulfide is a toxic and, even at very low concentrations (appr. 2,5 µg/m³), very odorous gas. It is a component of crude oil and natural gas and is therefore present in refineries and Natural Gas plants but also generated during some other industrial processes and, as product of an incomplete combustion, in catalysis of motor vehicles. H₂S is removed from exhaust gases by conversion to SO₂ through certain absorption processes or, for larger quantities, through reaction to elemental sulfur (Claus process).

Hydrocarbons (C_xH_y or HC)

Hydrocarbons are an extensive group of chemical compounds that are composed of hydrogen and carbon. C_xH_y are the most important substances in organic chemistry; in nature they are contained in crude oil, natural gas, and coal. Emissions may occur during production of Hydrocarbon products (e.g. in refineries) as well as during their use and disposal. Other examples include solvents, plastics, varnish, vehicle fuels etc. Sources of C_xH_y emissions are also formed through incomplete combustion processes e.g. forest fires and cigarettes as well. Hydrocarbon emissions also contribute to the green house effect.

Hydrocarbons include thousand of compounds, methane (CH_4), butane (C_4H_{10}), benzene (C_6H_6), and also carcinogenic compounds such as benzo[a]pyrene. The total amount of volatile hydrocarbons in a flue gas is often described as "total hydrocarbon". In emission control normally the value of "total hydrocarbon" is specified and measured.

Hydrocyanic acid (HCN)

Hydrocyanic acid (known also as prussic acid) is a very toxic liquid with a boiling point of only 25,6 °C; it may exist in flue gases of incineration plants.

Ammonia (NH_3)

Ammonia is relevant in flue gases in connection with denitrification plants using the SCR process. It is fed to the flue gas in exact quantities and causes a reaction that splits the nitrogen oxides into nitrogen and water. The unconsumed portion of ammonia is further reduced; its concentration in the clean gas is normally below 2 mg/m³.

Hydrogen halides (HCl, HF)

From combustion of coal and/or waste material the formation of the hydrogen halides HCl and HF may result which form aggressive acids in humid atmospheres. These compounds are eliminated almost totally from the flue gas through scrubbing processes.

Solids (dust, soot)

Solid pollutants in flue gases originate from the incombustible components of solid or liquid fuels. These include oxides of silica, aluminum, and calcium in case of coal, or sulfates of different elements in case of heavy fuel oil. Dust is dangerous for human beings as dust particles may be covered with toxic and/or carcinogenic substances.

2.6 Calorific value; combustion efficiency; flue gas loss

Gross and net calorific value

The *gross* calorific value is a characteristic parameter of a fuel that describes the amount of energy released from the fuel during *complete* combustion in relation to the amount of fuel involved. The net calorific value is the energy released less the heat of evaporation of the water vapor at a temperature of 25 °C generated during the combustion, again related to the amount of fuel involved.

The gross calorific value is principally higher than the net value.

Condensing value boilers

Condensing boilers are boilers that make use of the condensation heat of the flue gas added to the combustion heat by means of heat exchangers. Related to the net calorific value these boilers can reach an efficiency of 107%. Condensate is formed, however; this process may transfer pollutants from the gas to the water which may need special discharge considerations.

Combustion efficiency

Combustion efficiency is a value determined from input and output data of a combustion process at constant operational conditions. Total efficiency (it is always below 100%) is the ratio between the total energy fed into the firing chamber and the amount of energy available for the actual process (heating, melting, sintering etc.). The total efficiency value is composed as follows:

- The term *combustion efficiency* describes the portion of the total energy (fed to the combustion chamber) that is available in the combustion chamber after the combustion.
- The term *furnace efficiency* depends on the furnace design and operation and describes the portion of the combustion energy which can finally be applied to the process of interest.

The total efficiency is the combination of combustion and furnace efficiency.

Energy balance of a combustion process; flue gas heat loss

At constant operation the sum of all energies fed into a combustion process is equal to the sum of all energies delivered by the process, see table 6.

Energies fed into the process	Energies delivered by the process
Net calorific value of fuel and energy of fuel	Sensible heat and chemical energy of flue gas components (flue gas loss)
Heat of combustion air	Heat and calorific values of residues in slag and ash.
Heat equivalent of mechanical energy produced in the plant	Energy losses through thermal conduction
Heat content of work fuel fed to the furnace	Heat content of fuel released from the furnace
	Heat losses through furnace leaks

Table 6: Contributions to energy balance of a combustion plant

The most important and most negative balance contribution is the **flue gas loss (or efficiency)**. It depends (a) on the temperature difference between flue gas and combustion air, (b) the concentrations of O₂ or CO₂ in the flue gas and (c) on fuel-specific parameters, see table 7. Using condensing value boilers the flue gas loss is reduced considerably by utilizing the condensation heat and thus lowering the flue gas temperature at the same time.

The flue gas heat loss can be calculated using the following formulas (German):

$$qA = (FT-AT) \times \left[\frac{A_2}{(21-O_2)} \right] + B$$

- FT: Flue gas temperature
- AT: Ambient air temperature
- A2, B: Fuel-specific factors (see table 7)
- 21: Oxygen level in air
- O₂: Measured oxygen level

For solid fuels the factors A2 and B are zero. With that and using the factor f and the value of CO₂ (see table 7) the above formula will be simplified to the so called **Siegert Formula**

$$qA = f \times \frac{FT - AT}{CO_2}$$

Fuel-specific factors used in the formula (German calculation) are listed in the following table:

Fuel	A2	B	f	CO _{2 max}
Fuel oil	0,68	0,007	-	15,4
Natural gas	0,65	0,009	-	11,9
Liquid gas	0,63	0,008	-	13,9
Coke, wood	0	0	0,74	20,0
Briquet	0	0	0,75	19,3
Brown coal	0	0	0,90	19,2
Hard coal	0	0	0,60	18,5
Coke oven gas	0,60	0,011	-	-
Town gas	0,63	0,011	-	11,6
Test gas	0	0	-	13,0

Table 7: Fuel-specific factors (German calculation)

Calculation formulae (British)

Flue gas loss (efficiency)

$$\text{EffG} = 100 - \left[\left[\frac{K_{gr} \times (FT-AT)}{CO_2} \right] + \left[\frac{X \times (2488 + 2.1 \times FT - 4.2 \times AT)}{Q_{gr} \times 1000} \right] + \left[\frac{K1 \times CO}{CO_2 + CO} \right] \right]$$

$$\text{EffG} = 100 - \left[\left[\frac{K_{net} \times (FT-AT)}{CO_2} \right] + \left[\frac{X \times (210 + 2.1 \times FT - 4.2 \times AT)}{Q_{gr} \times 1000} \right] + \left[\frac{K1 \times Q_{gr} \times CO}{Q_{net} \times CO_2 + CO} \right] \right]$$

- FT Flue gas temperature
- AT Ambient temperature
- K_{gr}, K_{net}, K1 Fuel-specific factors, see table 7a
- X M + 9 x H
- M, H Fuel-specific factors, see table 7a
- Q_{gr}, Q_{net} Fuel-specific factors, see table 7a

Fuel	K_{gr}	K_{net}	CO_{2max}	K_1	K_2	H	M	Q_{gr}	Q_{net}	$O_{2\ ref}$	F Br
Natural gas	0.350	0.390	11.9	40	44.3	24.4	0	53.42	48.16	3	0.2304
Fuel oil Class D	0.480	0.510	15.4	53	56.4	13.0	0	45.60	42.80	3	0.2434
Fuel oil Class E,F,G	0.510	0.540	15.8	54	57.2	11.5	0.2	42.90	40.50	3	0.2545
Coal	0.620	0.650	18.4	63	66.0	4.0	13.0	26.75	25.50	6	0.2561
Anthracite	0.670	0.690	19.1	65	66.5	3.0	12.0	29.65	28.95	6	0.2551
Coke LPG	0.750	0.760	20.6	70	71.1	0.4	10.0	27.9	27.45	6	0.2919
Propane LPG	0.420	0.450	13.8	48	51.8	18.2	0	50.0	46.30	3	0.2341
Butane	0.430	0.460	14.1	48	51.6	17.2	0	49.30	45.80	3	0.2301
Fuel 1	0.350	0.390	11.9	40	44.3	24.4	0	53.42	48.16	3	0.2304
Fuel 2	0.480	0.510	15.4	53	56.4	13.0	0	45.60	42.80	3	0.2434
H: Hydrogen content of fuel M: Moisture content of fuel F Br: Conversion factor mg/m^3 in g/GJ											
Factors of fuel 1 and fuel 2 set by the factory can be freely selected											

Table 7a: Fuel-specific factors (British calculation)

2.7 Dew point; condensate

Dew point

The *dew point* or *dew point temperature* of a gas is the temperature at which the water vapor contained in the gas is transformed into the liquid state. This transition is called condensation, the formed liquid is called condensate. Below the dew point temperature humidity (moisture) exists as liquid, above the dew point as gaseous component of the gas. An example for that is the formation and decomposition of fog or dew as a function of the temperature.

The dew point temperature is a function of the moisture content of the gas: The dew point of air with 30% moisture content is at appr. 70 °C, while dry air with only 5% moisture content has a dew point at appr. 35 °C, see fig. 5.

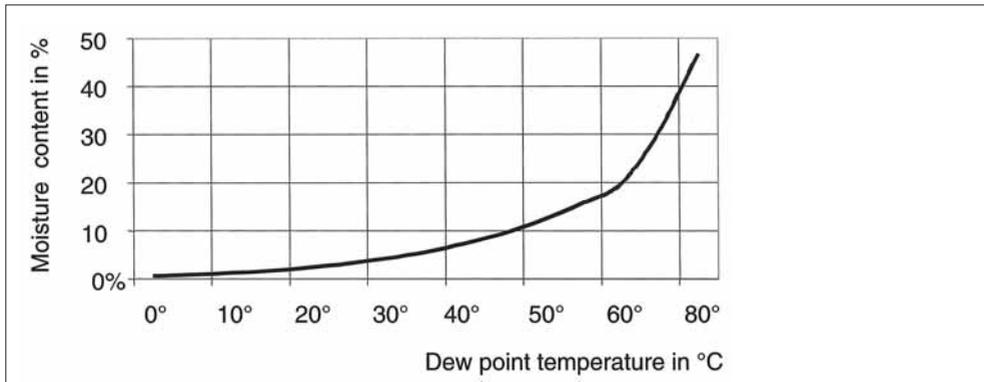


Fig. 5: Moisture content of air as function of dew point temperature (1013 mbar)

For an analyzer operated *without* sample gas conditioning the dew point temperature of the sample gas corresponds approximately with the ambient temperature, e.g. 25 °C. Comparison of measured values obtained from that with those of an analyzer *with* sample gas conditioning at e.g. 5 °C dew point temperature will show a difference of appr. 3% due to this moisture content effect. See also chapter 4.1.2

Heated sample lines; gas cooler

Flue gases with e.g. 8% moisture content have a dew point at appr. 40 °C. Below this temperature moisture will exist as liquid condensate resulting in two important consequences for the combustion plant as well as the measuring equipment:

- In case of sulfur oxides existing in the flue gas, corrosive sulfurous and/or sulfuric acid will be formed at temperatures below 40 °C (e.g. in unheated sample lines or analyzer parts) therefore damaging components coming into contact with the condensate. For this reason, all components of the combustion process upstream the gas cleaning scrubber should be kept at temperatures **above the dew point**.

The same is true for components of the measuring device including sample probe and sample lines that are in contact with the flue gas: All these parts should be kept at temperatures above the dew point. Consequently heated sample probes and sampling lines are used upstream the gas cooler. Otherwise the equipment will be damaged and the measured values will be incorrect.

Another alternative to reduce or suppress the formation of condensate is the use of a very **high gas flow velocity** in the sample lines, as developed and patented by **Testo**. This principle utilizes turbulent flow and minimal residence time as the mechanism to keep the moisture entrained in the flue gas. This method replaces the heated sample line which is a very important benefit for portable analyzers because of the reduced power input requirements.

- Depending on the gas cooler temperature, a certain amount of water vapor is condensed and removed in the cooled flue gas which results in the other gas species (e.g. CO) showing (without any change in their absolute quantity) a higher relative concentration value. Therefore, in order to compare the results of two different measurement methods the sample gases must have the same temperature and humidity.

Consequently a **sample gas cooler** or a sample gas dryer are used to get the sample gas to a defined and constant temperature and level of humidity. This procedure is called sample conditioning.

Note:

- To cool a gas means to dry the gas
and
- In dry gas the measured (relative) concentration values are higher than in the same gas with a higher level of humidity

Testo analyzers are equipped with sample gas cooler according to the **Peltier principle**:

The joint surface between two different metals, with an electric current flowing through, is heated up or cooled down depending on the flow direction of the current. The cooler of the testo 350 and testo 360 is designed to cool the sample gas down to +3 °C and to keep this temperature constant. Therefore the temperature and moisture extracted is constant.

Another water removal method operates according to the **Permeation principle**:

These coolers, however, show some disadvantages:

- a They cannot keep a specified dew point at a constant level and
- b they may be blocked through dust particles and organics resulting in higher maintenance and spare part costs.

3. Combustion analysis of process gases in industry

Combustion analysis (i.e. measuring technology for analyzing combustion gas compositions) is an indispensable tool for reliable and economical process control in almost all industries. All *combustion processes* are concerned with production and material treatment processes. Fig. 6 shows the various segments of a combustion process from feed of fuel and combustion air to the furnace, the combustion itself with the variety of connected processes, up to flue gas cleaning and emission control.

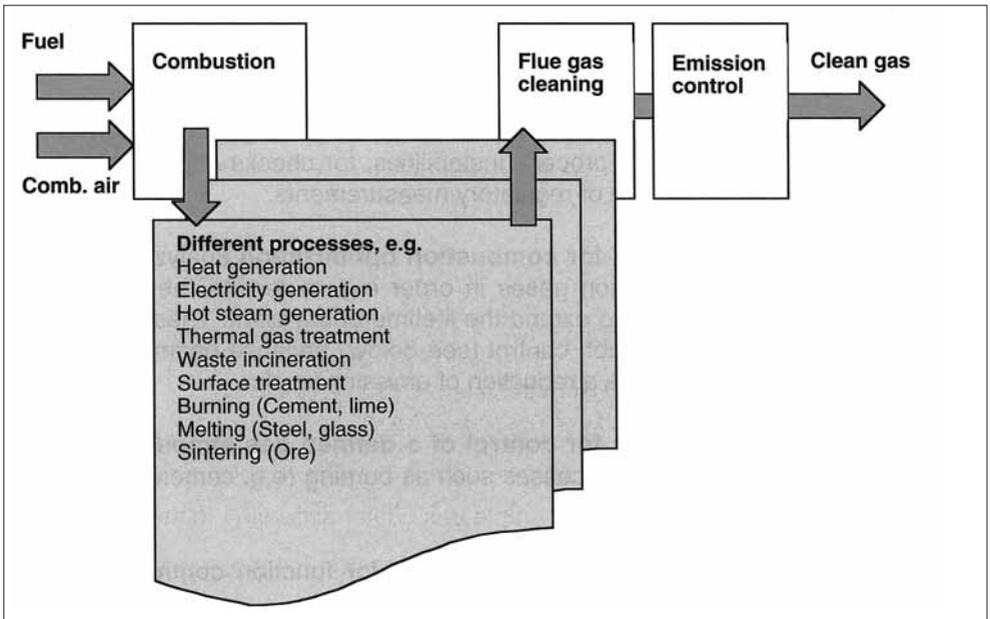


Fig. 6: Segments and variety of combustion processes

In all segments of a combustion process combustion analysis provides important information about combustion details and composition of the flue gases. Thus combustion analyzers are indispensable process devices for reliable and economical plant operation, to guarantee product quality and to comply with emission regulations.

Gas analyzers are offered in great variety by many manufacturers. Analyzers are based on different measuring principles, mostly optimized for the analysis of certain components. More details are available in chapter 4.

Testo gas analyzers are extensively utilized in industry for the analysis of combustion gases with the area of emission control being just one field of application. The following applications are well established:

1. **Adjustment and service measurements** for general plant upgrade purposes, for localization of process instabilities, for checks after repair work or as preparation in advance of regulatory measurements.
2. **Process measurements for combustion optimization** analyzing fuel, combustion air and combustion gases in order e.g. to reduce fuel costs, to improve plant efficiency or to extend the lifetime of the plant. These applications are also related to emission control (see below) because optimized plant operation normally will cause a reduction of emission levels.
3. **Process measurements for control of a defined gas atmosphere** in special furnaces or kilns for processes such as burning (e.g. cement), sintering or surface treatment.
4. **Process and emission measurements** for function control of flue gas cleaning installations.
5. **Emission measurements** at the stack to monitor the emission values of pollutants and to ensure compliance with the official regulations.

3.1 Gas analysis for combustion optimization

Major contributions to combustion optimization are made by

- Composition of fuel and combustion air
- Ignition procedure and combustion temperature
- Details of burner and combustion chamber design
- The fuel/air ratio

For a given plant and a given fuel the optimum fuel/combustion air ratio (ex.air value) can be determined from gas analysis results using the combustion diagram, see fig. 7. In this diagram the concentration of the gas components CO, CO₂ and O₂ are displayed in function of the excess air value. The line representing ideal combustion without any excess air (ex.air=1) is in the center of the diagram; to the right the excess air value increases; air deficiency (ex.air<1) exists to the left. Air deficiency also means deficiency of oxygen.

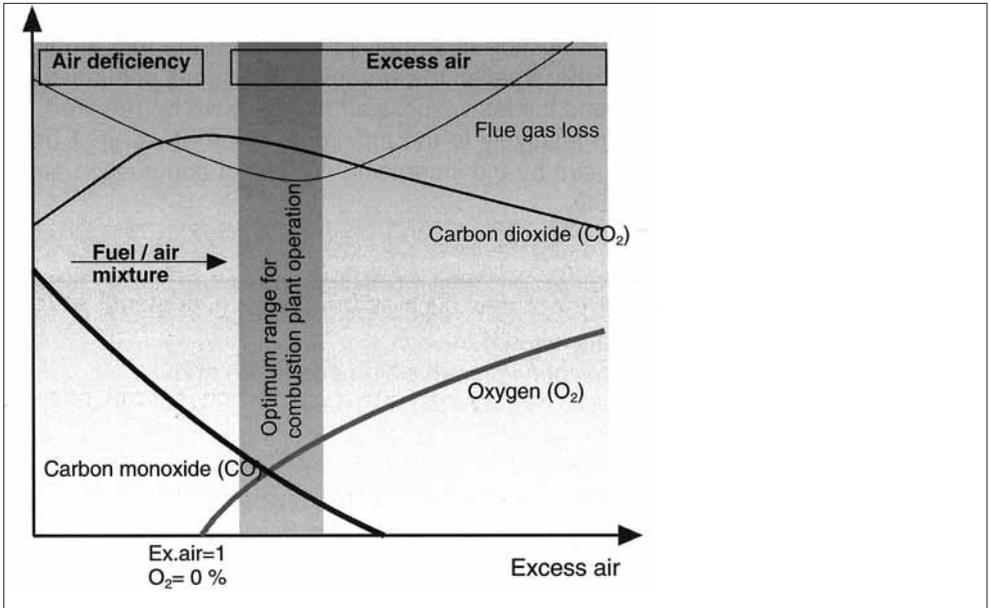


Fig. 7: Combustion diagram

The combustion diagram provides the following information:

Left area with $ex.air < 1$ (deficiency of air)

- CO exist because there is not enough oxygen available to oxidize all CO to CO_2 .
Note: CO may be dangerous to people when it escapes through leaks.
- With increasing oxygen content the CO concentration decreases through oxidation to CO_2 ; CO_2 concentration increases accordingly. This reaction will be stopped at or slightly above $ex.air=1$, CO will be zero and CO_2 reach its maximum value.
- Oxygen is not or almost not present in this area because all oxygen supplied to the system is consumed immediately to oxidize CO to CO_2 .

Right area with $ex.air > 1$ (excess of air)

- Here O_2 increases because the amount of oxygen supplied as part of the increasing volume of combustion air is no longer consumed for oxidation (CO is almost zero). Practically, however, some amount of air (oxygen) excess is required for complete combustion because of the inhomogeneous distribution of air (oxygen) in the combustion chamber. Furthermore the fuel particle size influences combustion: the smaller the particles, the more contact between fuel and oxygen will be and the less excess air (oxygen) will be required.
- CO_2 will decrease again relatively to the maximum value at $ex.air=1$ because of the dilution effect caused by the increasing volume of combustion air which itself carries almost no CO_2 .

Conclusion

Optimum combustion is achieved if

- excess air and thus oxygen volume is high enough to burn all CO completely
- and at the same time
- the excess air volume is limited in order to minimize the energy loss through the hot flue gas emission to the atmosphere

The optimum range of excess air for a particular combustion plant can be determined from the concentration values of CO₂ and CO (CO₂ alone is not definite due to the curve maximum). Currently the O₂-method is more often used. Sampling point locations may differ from plant to plant depending on the plant design and plant operator.

The functions shown in the combustion diagram are substantiated for the combustion of hard coal in table 8:

Air value λ	Excess air [%]	Oxygen content [%] (dry flue gas)
0,9	Air deficiency	Oxygen deficiency
1,0	0	0
1,1	10%	2
1,2	20%	3,5
1,3	30%	4,8
1,4	40%	6,2

Table 8: Air value, excess air and oxygen content for the combustion process of hard coal

Economic relevance

Optimization of a combustion process through plant operation at the most effective excess air level has, besides reduction of emission levels, the objective of *saving fuel costs*. Based on experience and documented in the literature is the fact, that reduction of oxygen excess of 1%-point, e.g. from 4,5% to 3,5%, will improve the efficiency of the combustion plant by 1%. With fuel costs of \$ 15 Mio. per month for a middle sized power station this results in monthly cost savings of \$ 30.000 if, by means of reliable gas analysis, the plant can be operated at only 0,2%-point closer to the optimal excess air value than before! Similar savings are possible if short time deviations from optimum operation conditions are recognized and eliminated early by using gas analysis continuously.

3.2 Combustion analysis for process control

3.2.1 Combustion plant for firing processes

A process firing plant, in contrast to the well known boiler plants, is characterized by a direct contact between the flame and the hot firing gases and a material or work pieces that shall be treated thermally. The heat as well as the specific atmosphere to which the material is exposed causes certain steps in their production process.

Production of cement clinker is a good example for such a firing process (see also the application examples in chapter 5.3):

- The moist raw material is crushed and dried using hot off gases
The precipitated raw meal is heated up to 800 °C by hot gases in counter-current
- CO₂ is driven off the raw meal at appr. 950 °C in the calcinator through a multi-stage firing process (de-acidification)
- The raw meal together with additives is finally sintered in the kiln at appr. 1400 °C.

Combustion analysis at these locations provides critical information with regard to excess air values, to detect and calculate false air flows and to perform balances for each step separately. It is critical for the calcinator performance (measurement of CO₂ and O₂) because a deficient level of calcination can cause considerable malfunctions in kiln operation

During firing processes substances from the treated material may be released into the "firing" gas and thus increase the emission rate of the flue gas. In some cases, however, components including pollutants may be transferred from the gas into either the production material or into substances (e.g. slag) especially provided for this purpose. An example is the cement or lime industry where the sulfur of the fuel is transferred as SO₂ to the product instead of being released to the atmosphere. Inversely during glass or brick production SO₂ will escape from the material and increase the level of emission considerably. Another example is an increased CO content in processes where material and hot gases are in contact in counter-current, e.g. in rotating kilns. Heavy metals may be either integrated into the burnt material (cement, lime) or released from the material into the flue gas (glass or metal industry).

By measuring combustion parameters furnace design, flame guidance, furnace temperature and combustion air supply, the emissions caused by the process can be reduced. For that portable gas analyzers provide the necessary information.

3.2.2 Industrial furnaces

Industrial furnaces are used to produce steam and hot water or to heat up other heat carrier materials. Industrial furnaces also include those that are used for material conversion e.g. in refineries or coke oven plants. Heat output of industrial furnaces normally is in the MW range.

Combustion analysis in this application are for combustion optimization, control of flue gas cleaning installation and monitoring of the pollutant emissions.

3.2.3 Thermochemical surface treatment

Thermochemical surface treatment is a heating procedure with the objective to modify the property of the surface of parts or work pieces etc. by means of diffusion processes. The parts are exposed to a hot gas atmosphere with certain elements diffusing from the gas into or out of the material. This includes steel hardening or the process of stoving colors or lacquer in the ceramic industry. Thermochemical processes are characterized by species and concentration of the used elements (e.g. nitrogen for nitrating, chrome for chrome plating) and process temperatures (400 up to 1400 °C). Furnaces are available in very different design for continuous flow or batch operation.

Gas analysis is used to achieve optimum plant operation (cost reduction, safety) and for controlling the process-specific gas atmosphere (product quality including documentation according to ISO 9000 ff.). The most common measuring components are O₂, CO, CO₂ and SO₂. See also the application example in chapter 5.4.6.

3.2.4 Safety measurements

Process applications of gas analysis also include measuring tasks which are performed to protect persons and plants from combustible, explosive or toxic gases. Monitoring CO is the main concern in plant atmospheres, in coal mills or coal powder silos (to detect smouldering fire in time) or, in connection with the use of electrostatic filters, to avoid the formation of explosive gas mixtures in the filter. Similar applications are monitoring of plants for dangerous concentrations of methane or other explosive gases.

Explosion limits

Mixtures of combustible substances and air or oxygen are ignitable in certain concentration ranges. For each mixture *low and high ignition limit values* are specified that depend on temperature and pressure of the gas. Both limit values describe the concentration values of the combustible substance for a given temperature and pressure (normally 20°C and 1 bar) in Vol. % or g/m³. The range between the two limit values is the *ignition range*, see table 19.

Combustible substances	Formel	Ignition limits in air (Vol. %) T=20 °C and p=1 bar	
		low	high
Ammonia	NH ₃	15,0	28,0
Carbon monoxide	CO	12,5	74
Hydrogen	H ₂	4,0	75,6
Methane	CH ₄	5,0	15,0
Propane	C ₃ H ₈	2,1	9,5
Butane	C ₄ H ₁₀	1,5	8,5
Acetylene	C ₂ H ₂	1,5	82,5

Table 9: Ignition limits of combustible gases

A special measuring sensor is typically used in gas analysis to determine combustibles in gas mixtures (see chapter 4.2.2.). However, this sensor only detects the sum of all combustible components. Therefore, when monitoring a gas mixture for its lower ignition limit, the measuring range of the analyzer should be adjusted according to the combustible component with the *lowest* ignition limit.

3.3 Gas analysis for emission monitoring

In most countries many types of plants ranging from power stations, steel works, cement plants, chemical plants etc. down to smaller production units or municipal facilities are liable to comply with legal regulations regarding emission of pollutants into the atmosphere. It must be ensured that the emission of specified pollutants does not exceed specified limit values. Many countries have issued laws and ordinances containing instructions for emission control measures including limit values for the emission of pollutants. In Germany this is the "Bundesimmissionschutzgesetz" (BImSchG) or Federal Immission Control Act, in the United States it is the Environmental Protection Agency (EPA) Clean Air Act. For larger regions such as Europe or Asia a uniform legal regulation does not yet exist. Many countries therefore use the German BImSchG or the US Clean Air Act as basis for their own specifications.

Gas analysis plays a key role in achieving effective pollution control and compliance with the regulations.

Emission

Material released into the atmosphere either by a discrete source (primary emission from smokestacks, other vents, motor vehicle etc.) or as the result of a photochemical reaction

Immission

The transfer of contaminants (chemical substances, noise, ...) from the atmosphere into receptors such as human beings, animals, plants, soil, buildings etc.

3.3.1 Legal fundamentals of Emission and Immission regulations in Germany

Legal basis of the entire prevention of harmful effect in the environment in Germany includes

- the *Bundesimmissionsschutzgesetz (BImSchG)*, *Federal Immission Control Act*, a law amended as of 1990 and 1994
- numerous *Rechtsverordnungen (BImSchV)*, ordinances resp. regulations for the implementation of the law and
- the TA Luft, Technische Anleitung Luft, Technical Instruction Air (TI Air), a specific regulation to support the authorities with definite instructions for approval and monitoring of installations according to the 4. BImSchV.

The **BImSchG** is categorized as follows:

- General provisions (§§ 1ff)
- Establishment and Operation of Installations (§§ 4 for 31)
- Nature of Installations, Substances, Products, (§§ 32 to 37)
- Nature and Operation of Vehicles (§§ 38 to 43)
- Monitoring of Air Pollution, ... (§§ 44 to 47a)
- Joint Provisions (§§ 48 to 62)
- Final Provisions (§§ 66 to 74)

27 ordinances (regulations) have been released for implementation of the law, a selection of which is shown in table 10. Those with relevance to combustion plants are marked. The relation between ordinances and definite types of installations (fuel and power output as parameter) is shown in fig. 8.

1. Ordinance	Small-scale firing installations
3. Ordinance	Sulfur content of light fuel oil
4. Ordinance	Installations subject to licensing
9. Ordinance	Basics of licensing of installations
11. Ordinance	Emission declaration
13. Ordinance	Large-scale firing installations
17. Ordinance	Waste incineration installations
27. Ordinance	Crematoria

Table 10: Ordinances of the German Federal Immission Control Act (Selection)

Fuel \ Power output	MW					
	0...1*	1...5 (20)	5...10 (20)	10...50	50...100	>100
Solid fuels						
Light fuel oil	1. Ordinance		4. Ordinance			13. Ordinance
Other fuel oils			TI Air			
Gaseous fuels						

Fig. 8: Relation of type of installations and valid ordinances

Emission values and emission limit values

- *Emission values* are standards with a liability ranging below emission limit values. Emission values are defined as values, which, according to the state of the art, may not be exceeded. Emission values for air pollution control are specified in the TI Air.
- *Emission limit* values are legal standards with a high range of liability. Such limit values are specified e.g. in the 1., 4., 13., 17., and 27. ordinance and the TI Air.

3.3.2 Specifications of the BImSchG for Germany (Selection)

1. Ordinance on small-scale firing installations

This ordinance concerns all firing installations which must *not be licensed* up to 1,5 resp. 10 MW power output depending on the type of fuel used, see fig. 8. Official monitoring of these installations is in the responsibility of the chimney sweep. Once a year the firing installation must be tested whether it complies with the specified limit values: Dust and sometimes CO must be monitored in the flue gas of solid-fuel-fired installations, while for gas and oil fired installations the flue gas heat loss must be calculated from measured values of O₂ or CO₂ concentration and the difference between flue gas and ambient air temperature.

More information about flue gas measurements on small-scale firing installations is available in the Testo handbook "Flue Gas Analysis for Practical Users".

4. Ordinance on installations subject to licensing

This ordinance comprises in groups (see table 11) a list of about 150 types of installations with a power output of some MW which *require a license* for operation. The instructions for implementation of the 4. ordinance are comprised in the TI Air, see the following section.

Group	Type of installation
1	Heat generation, mining, energy
2	Stone and clay, glass, ceramics, building material
3	Steel, iron, other metals
4	Chemical products, crude oil (refinery and processing), pharmaceuticals
5	Processing of plastics
6	Wood, pulp
7	Food stuff e.a.
9	Storing, loading and unloading of materials

Table 11: Grouping of installations according to the 4. ordinance

TI Air (Technical Instruction Air)

The TI Air is an administrative document on the control act (BlmSchG). It comprises all regulations required for an installation, from first application on construction up to monitoring the routine operation. The TI air regulates all installations subject to licensing which are listed in the 4. ordinance.

The TI air is grouped in four parts:

- Part 1: Regulations on application areas
- Part 2: General provisions on air pollution control
- Part 3: Requirements on limitation and detection of emissions
- Part 4: Reconstruction of old installations

Part 3 of the TI air is of particular interest for gas analysis, because it includes the specification of limit emission values of pollutants of definite installations.

Section 3.1 contains general regulations with a classification of pollutants into 4 classes: The limit value of class I substances (the most dangerous substances, e.g. phosgene) amounts to only 1 mg/m³ while the class IV limit value (e.g. sulfur and nitrogen oxides) is 500 mg/m³.

These general specifications, however, are replaced in definite cases (section 3.3) by more strict requirements!

Section 3.2 handles in detail the procedures of monitoring and controlling emissions. Section 3.2 demands:

- that suitable **sampling point locations** have to be defined during licensing which allow representative and correct emission measurements;
- that through first and repeated **single measurements** the emission values are determined of those substances that have been listed including limit values in the license documents of the installation;
- that, in case of particular high mass flow of limited substances, these substances have to be monitored by **continuous measurements**; and
- that for particular dangerous substances whose continuous determination is desirable but either not possible or too expensive, a regularly **single measurement** is obligatory.

Single measurements according to TI Air

After construction of a new plant (or after reconstruction) a first measurement is performed within 3-12 months after start-up by a certified testing organization. This first measurement is considered as acceptance test. After the initial test, single measurements are performed every 3 years in such a way, that the measuring values of the limited components are averaged over a period of 30 minutes and compared with the specified limit values. 3 measurements are required on installations with continuous operation, otherwise 6 measurements. The firing plant shall be optimized by the operator before the measurements start.

Continuous measurements according to TI Air

The average value of 30 minutes measuring time is calculated every half an hour during normal operation of the plant. From this values an *average value of the day* is generated, stored and processed statistically; this value must not exceed the specified limit value.

- Official single measurements according to TI Air must be performed by using devices that have been certified for that by passing successfully a dedicated *suitability test*. This is as well obligatory for stationary equipment to perform continuous measurements.
- **Testo**-gas analyzers are suitable, tested and certified for single as well as for continuous measurements.

Section 3.3 handles regulations concerning definite sorts of installations, see table 12.

Section of TI Air	Sort of installation
3.3.1	Heat generation, mining, energy
3.3.2	Stone and clay
3.3.3	Steel, iron, and other metals
3.3.4	Chemical products, pharmaceuticals, refineries
3.3.5	Surface treatment, foil production, processing of plastics
3.3.6	Wood, pulp
3.3.7	Food stuff, agriculture products
3.3.8	Waste incineration (meanwhile replaced by the 17. Ordinance)
3.3.9	Storing, loading and unloading of materials
3.3.10	Other
Special case	Power stations >50 MW (gas-fired: >100 MW) are handled separately by the 13. ordinance!

Tab. 12: Grouping of TI Air, section 3.3, for definite sorts of installations

Please note:

Limit values specified for definite sorts of installations are included in most of the application examples given in chapter 5 of this handbook.

13. Ordinance on large-scale firing installations

The 13. ordinance is for firing installations with power output >50 MW (solid fuels) and >100 MW (liquid and gaseous fuels). Emission limit values are specified for particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide and gaseous compounds of chlorine and fluorine depending on heat power output and plant type. Some values are subject to a dynamic regulation that allows to reduce the limit values according to progress in the state of the art of the measurement or control technology.

Pollutant	Limit values [mg/m ³] according to the 13. ordinance		
	Fuel		
	Solid	Liquid	Gaseous
Particulate matter	50	50	5 10 (blast furnace gas) 100 (industrial gas)
CO	250	175	100
SO ₂ (plants > 300 MW)	400	400	35 5 (LG) 100 (coke oven gas) 200-800 (composite gas)
SO ₂ (plants > 50 MW)	2000	1700	-
NO _x (plants > 300 MW)	200	150	100
NO _x (plants > 50 MW)	400	300	200
O ₂ -reference value	5-7% depending on firing	3%	3%

Table 13: Limit values of pollutants according to the 13. ordinance (selection)

17. Ordinance on waste incineration installations

Waste incineration installations are used for thermal treatment of solid, liquid and pasty waste materials from households or hospitals as well as from industry, including used tires, solvents, sewage sludge etc. with the objective to reduce volume and pollution potential of the waste material. The flue gases produced during the waste incineration must, regarding their content of pollutants, comply with the regulations and specifications of the 17. ordinance as of 1990, see table 14.

Pollutant	Limit value [mg/m ³] according to the 17. ordinance
Particulate matter	10
Carbon monoxide CO	50
Sulfur oxides (as SO ₂)	50
Nitrogen oxides (as NO ₂)	200
Organic compounds (as C _{total})	10
Compounds of chlorine (HCL)	10
Compounds of fluorine (HF)	1

Table 14: Limit values of pollutants according to the 17. ordinance (selection)

27. Ordinance on cremation installations

The 27. ordinance contains regulations including limit values concerning cremation installations. (See also chapter 5.6.1).

Analyzers for use in emission control

Analyzers for use in emission control are of identical design to those used in other areas of process analysis. They must, however, meet particular requirements and, in many countries, pass a dedicated *suitability* test to get the certification for use in emission monitoring applications.

The high number of components which may be present in the exhaust gases requires selective analyzers whose cross sensitivity is either very low or well known and thus can be taken into account by calculations. Furthermore, the analyzers must be easy to calibrate and deliver correct and reproducible results. High availability and low maintenance requirements are also part of the certification conditions.

Emission monitoring measurements require also well designed sample gas extracting and conditioning systems because of the high temperatures as well as dust and water content of the flue gases. Gas sampling must deliver a representative proportion of the flue gas stream which sometimes requires more than one sampling point.

Suitability test of emission analyzers

Analyzers for use in official emission monitoring and control must pass successfully a certification test in many countries. Thus high quality and comparability of the measurement results are ensured and uniform conditions can be realized in monitoring different plants. The certification test procedure is specified in detail and includes laboratory and field measurements by a licensed organization over a time period of several weeks. Finally the certified analyzers are listed and the list published by the authorities.

The testo 360 analyzer has been certified in Germany for measuring O₂, CO, NO, NO₂ and SO₂ for use according to the 13. and 17. ordinance and TI Air. For certifications of other testo analyzers and in other countries see table 47 on page 121 of this handbook.

3.3.3 Emission Monitoring in the USA

The legal basis of emission monitoring in the United States is through the federal authority, the US Environmental Protection Agency (EPA). The administration and enforcement of air quality regulations can also be found at other agencies including State Departments of Environmental Protection (DEP's), county or local cities, or regional air districts. EPA regulations dictate the minimum requirements for air quality. In addition the other authorities may require different or more stringent standards.

The EPA developed regulatory standards with the purpose of identifying the sources of air pollutants, develop test methods to measure the air pollution, and mandate controls on equipment to reduce the pollution for the protection of human health and the environment. The Clean Air Act (CAA), first established in 1963, set the initial frame work of how to develop air quality standards, who or what air pollution sources would be effected, and how the law would be enforced.

CAA

In 1970 the CAA was approved as law. The law targeted larger single-point air pollution sources, such as utilities, power plants, and large industrial smoke stacks and area sources such as cars and trucks. The CAA is generally divided into **7 Titles**.



- **Title 1 - National Ambient Air Quality Standards (NAAQS)** – Lists the criteria Air Pollutants and the maximum allowable levels in ambient air. The pollutants are:
 - Sulfur Oxides (SO_x)
 - Nitric Oxides (NO_x)
 - Carbon Monoxide (CO)
 - Ozone (O_3)
 - Particulate Matter (PM)
 - Lead (Pb)
- **Title 2 - Mobile Sources** - Regulations regarding the emission from cars, truck, ships, etc.
- **Title 3 - Hazardous Air Pollutants (HAPS)** – Regulations regarding more than 188 different compounds that are hazardous to life.
- **Title 4 - Acid Rain Deposition Program** – Requires emission monitoring of SO_2 , NO_x , CO , and opacity at utilities & larger sources to address acid rain and interstate transport.
- **Title 5 - National Operating Permits Program** - An administrative program designed to identify large polluters (in a given air district) and requires a facility (source) to have a single Title V permit that incorporates all the other air regulations.
- **Title 6 - Stratospheric Ozone Protection** – Regulates sources associated with Ozone depletion or degradation
- **Title 7 - Enforcement** – Provides the method for government to implement criminal and/or civil penalties & fines for sources not in compliance with air regulations.
- **Title 8 - Miscellaneous** – Other items not address above

In 1990 the CAA Amendments (CAAA) lowered the allowable emission limits to be implemented through year 2010. The CAA also established other regulations. The most notable ones are the:

New Source Performance Standards (NSPS)

- Sets emission limits for all new sources of air pollution.

State Implementation Plan (SIP)

- Requires each state to come up with a plan to reach the federal air quality standards.

State Requirements

Each State in the United States is responsible for implementing the federal laws through the SIP. In addition they are also responsible for many other state-

specific regulations which can be much more stringent than the federal requirements. The state agencies (i.e. DEP, DEQ, DNR, TNRCC, etc.) and the local authorities (i.e. SCAQMD, APCD, etc.) also have enforcement divisions that have the authority to prosecute or fine facilities. Fines vary according to compliance for example fines can be as small as \$25/day up to millions of dollars and prison time for willful negligence.

Of importance is the designation of “attainment” & “non-attainment” as a means to target bad air quality areas. Geographical areas where the ambient air is relatively clean are considered “Attainment Areas” or areas where federal air quality standards are met (i.e. typically rural areas). “Non-Attainment Areas” are polluted areas generally located in and around a larger city. “Severe Non-Attainment Areas” are areas like Los Angeles California and Houston Texas where air pollution is very bad.

Monitoring Methods

The emission monitoring of sources have historically been performed using two methods. A source test method, commonly called a “stack test” or the use of a continuous emission monitoring system (CEMS). A stack test is initially performed using wet chemistry and reference method analyzers. The older reference methods were developed years ago with the available technology, now consider to be out-dated. For a majority of sources, the frequency of testing depended on many factors, but often it was either a single one-time test or in other cases a yearly or every 5-year test. Compliance only needed to be shown during this test. Facilities requiring to have a CEMS usually had a yearly stack test, which verified the CEMS data.

Most large sources can afford a CEMS. These systems ranges from \$80,000 to \$250,000 for the initial set-up costs. In addition, considerable maintenance and labor costs (\$30,000-100,000/year) are also necessary to keep the system operating accurately. Such large CEMS investments are not practical and cannot be justified for smaller sources. As the air regulations continue to target smaller sources, an alternative to a CEMS is desired by industry.

Title V Permit Program

A source is required to have a Title V permit if they have the potential to emit more than the emission standard (could be for a single pollutant like NO_x or combination of air pollutants for example volatile organic compounds (VOCs). In general, the standard is a pollutant mass quantity and the maximum allowable quantity varies according to the area designation. For example:

- Attainment Area = 100 tons per year (t/y)



- Non-Attainment Area = 25 tons per year (t/y)
- Severe Non-Attainment Area = 10 tons per year (t/y)

As such, a facility must look at ALL of their air pollution sources, combine the total and if it exceeds the limits stated above, they are NOW considered a large source. With this large source designation comes extensive data gathering and reporting and it also triggers other federal and state regulations.

Once designated as a Title V facility, each source must propose what methods it will do to control and monitor emissions. The acceptance of each proposal depends upon the local and/or state requirements. The sources have a variety of ways to monitor their emissions. They may use f-factors and fuel calculation; to temperature or other parametric monitoring; to measuring flue gas with either portable analyzers, stack testing trailers, or CEMS. The authorities wish is to have real flue gas measurements and portable analyzers provide a very good means to collect true, accurate and less costly data.

Title V regulations, including the Compliance Assurance Monitoring (CAM) and Periodic Monitoring (PM) are the driving force in targeting these smaller sources. CAM and PM were developed to address all the sources not previously identified through the other programs.

Fundamental Change in Compliance

A fundamental regulatory change has recently taken place. Historically, sources only needed to be in compliance during their stack test (generally tested once every 1 or 5 years). Now, sources are required to be in compliance 100% of the time. The proof of compliance is now the responsibility of the source and not the one-time emission (stack) test.

A company officer is now legally responsible for his facility's air quality compliance. The regulatory enforcement agencies have the authority to issue civil fines and/or take criminal action if compliance is not met. These two new concepts of continuous compliance and enforcement authority provide the incentive to comply with the regulations. This opens a whole new market for portable analyzers.

Trends for Portable analyzers

The step to testing smaller sources provided a good reason to utilize another analyzer technology, namely electrochemical sensors. They provide accurate data, are more cost effective, and are widely available. Portable electrochemical analyzers are now accepted at the federal, state, and local levels for monitoring emissions.

Test Methods utilizing Portable Electrochemical Analyzers

The US EPA does not approve or certify an instrument or analyzer for emission monitoring. Instead, EPA uses approved *test methods*. The US EPA and the American Society for Testing and Materials (ASTM) have issued test methods specifying the use of portable analyzers the test method are:

- CTM-030
- CTM-034
- ASTM Method D6522-00

These methods are performance-based, meaning the analyzer must perform within a tight specification and the testing data must meet special quality control standards. The specifications were developed specifically for electrochemical technology. The methods require the use of calibration gas for the verification of analyzer accuracy. For example, calibration checks are performed before and after each test, for stability testing, for linearity testing, etc. The same or similar testing is used in all US EPA test methods.

CTM-030 contains the highest specification or in other words the highest quality assurance and quality control (QA/QC) procedures. It is used for testing NO, NO₂, CO, and O₂ emission from natural gas fired sources. It is a more complex and time-consuming test method. It requires numerous pre- and post-test runs with calibration gas, linearity testing, interference testing, stability testing, etc.

ASTM Method D6522-00 is based upon CTM-030. It is also used for testing NO, NO₂, CO, and O₂ emission from natural gas fired sources in the US and Internationally. This method is expected to be approved by EPA as the next alternative reference method.

CTM-034 is for testing sources on a periodic basis (i.e. Title V Periodic Monitoring, CAM, & state specific regulations). It can be used for testing NO, NO₂, CO, and O₂ emission from natural gas and fuel-oil fired sources. The method is less costly in terms calibration gas and time expended therefore providing an easier and more practical methodology for more frequent testing.

The **testo 350 and 360** meet the requirements of these testing methods (Conditional Test Method CTM-030, & CTM-034, and the ASTM Method D6522-00) In addition the **testo 360** gas analyzer meets the requirements of EPA's test method found in 40 CFR, Part 60, Appendix A & B part 75 subpart C.

3.3.4 Flue gas purification/Cleaning

The amount of air pollutants carried in flue gases and their emission into the atmosphere can be reduced by installation of dedicated purification units in the flue gas path between boiler and stack:

- **Emission of particulate matter**
is reduced or almost eliminated by installation of dust precipitators of numerous designs and operating principles
- **Emission of gaseous pollutants**
can be reduced to a certain extent by using low-emission fuels; a more effective reduction is achieved by combustion optimization (fluidized bed combustion, staged air supply) and even more by flue gas purification processes such as adsorption, thermal treatment, etc.

Gas analysis is an important tool to monitor and control such processes.

Particulate matter control

- **Centrifugal separators (cyclones)**
Cyclones are devices in which particles are caused by means of centrifugal forces to be propelled to locations outside the gas stream from where they may be removed and discharged. Reverse flow cyclones are the most common ones with tangential inlet and axial gas and particle outlet.
- **Electrostatic precipitators**
Electrostatic precipitators are devices in which an electrical field is maintained to cause particles to acquire an electrical charge. The charged particles are forced to travel to a collector electrode where from they are removed and discharged from the process. Electrostatic precipitators are preferably used to filter high volume gas streams in power stations, cement plants, metallurgical plants etc.

Electrostatic filters may be damaged in case of an explosive gas mixture enters the filter chamber and passes through the electric field. Effective protection from that may be realized by measuring the CO content of the flue gas upstream the filter.

- **Fabric filters**

Fabric filters remove particulate matter from gas streams by retention of the particles in or on a porous structure (bags, beds) where the gas flows through. The porous structure is most commonly a woven or felted fabric, but can also include materials such as coke, sand, ceramics, etc.

- **Scrubbers**

Scrubbers are primarily employed to remove gases and vapor phase contaminants from the flue gas, but are sometimes used to remove particulate matter. The particles are brought into contact with a liquid (introduced e.g. by sprayers) resulting in a reaction that collects the particles in the liquid.

Flue gas denitrification

Primary and secondary measures are available to reduce NO_x ($\text{NO} + \text{NO}_2$) content of flue gases:

- *Primary measures* include staged combustion by staged air supply, fluidized bed combustion and the use of specifically designed burners. All of these measures will considerably reduce the formation of nitrogen oxides. More details see below.
- A *secondary (postcombustion) measure* is the *Selective Catalytic Reduction* (SLC) process, which is by far the most accepted one. Ammonia is injected into the flue gas to react with NO_x forming nitrogen and water. The use of a catalyst improves this reaction and reduces the quantity of ammonia required. Sometimes the term DENOX plant is used to describe such a denitrification plant.

Fluidized bed combustion (FBC)

Fluidized bed technology is based on the physical principle that particles can be fluidized in a reactor (e.g. pulverized coal in a combustion chamber) by blowing hot air against them from below. This principle allows for more complete contact between fuel particles and oxygen resulting in an almost complete combustion with low emission levels. Combustion temperature is as high as 900 °C which prevents the formation of thermal nitrogen oxides almost completely. Addition of limestone to a FBC process will reduce also the sulfur oxide formation at the same time.

Staged air supply

Staged air supply is a very effective *primary measure* to suppress nitrogen oxide formation by reducing fuel - NO as well as thermal NO. Combustion air supply is reduced at the burner (first stage, primary air), the air value is <1 resulting in the NO_x content remaining low and being even more reduced by forming stable N_2 molecules; CO content, however, is relatively high. Above the burner (second stage) the deficient volume of combustion air is supplied and completes the combustion. Thus CO content is reduced but no further NO formed as the nitrogen is present at this stage as stable N_2 molecules.

Low- NO_x burners

Low- NO_x burners are designed for operation very similar to the staged air supply principle (*primary measure*). Combustion air is supplied to the burner at two or more different spots including air recirculation within the burner. This results in complete combustion and considerably reduced formation of nitrogen oxides.

Flue gas desulfurization

The wet scrubbing principle using limestone injection (secondary measure) is the most common flue gas desulfurization process. In a scrubber (washing) tower the flue gas is sprayed with a suspension of ground limestone in water that chemically reacts with the gaseous SO_2 of the flue gas forming gypsum. The gypsum is discharged and, at least partly, further utilized as building material.

Thermal flue gas incineration

See application example 5.2.3 on page 86.

4. Gas analysis technique

4.1 Terms of gas analysis technique (selected)

4.1.1 Concentration

The term *concentration* describes the amount of a substance, expressed as mass, volume, or number of particles in a unit volume of a solid, liquid, or gaseous substance e.g. alcohol in beer or oxygen in air.

Different units are in use to describe *concentration in gases*:

- **Mass concentration**
Concentration expressed in terms of mass of substance per unit volume [g substance/m³ gas volume]
- **Volume concentration**
Concentration expressed in terms of gaseous volume of substance per unit volume [cm³ substance/m³ gas volume]
- **Part concentration**
Concentration expressed as number of particles of substance per a certain number of particles

In flue gas analysis both the terms *mass* concentration and *part* concentration are common and used in parallel. The *mass* unit is gram (and mg, μ g, see table 15) and the most popular expression for *part* concentration is ppm (parts per million). "ppm" means "x number of parts in a million parts". ppm is usually used for low concentrations; larger concentrations are expressed in "percent" (%), see table 16.

Consequently the concentration of a gaseous pollutant is expressed

- either using **g** (or mg or μ g etc.) with reference to a definite gas volume, usually cubic metres (m³), e.g. 200 mg/m³
- or using **ppm** without any reference, e.g. 140 ppm

Expression	Spelling	
Gram	g	
Milligram	mg	10 ⁻³ g
Mikrogram	μ g	10 ⁻⁶ g
Nanogram	ng	10 ⁻⁹ g
Picogram	pg	10 ⁻¹² g
Femtogram	fg	10 ⁻¹⁵ g

Table 15: Mass unit gram with subdivisions

Expression	Spelling	
	Parts per billion	0,001 ppm
Parts per million	1 ppm	0,0001%
	10 ppm	0,001%
	100 ppm	0,01%
	1000 ppm	0,1%
	10000 ppm	1%

Table 16: Particle concentration in ppm and % with subdivisions

Please note

Because of the variation of a gas volume with temperature and pressure changes it is necessary to use one of the following alternatives for describing a concentration value:

- additional specification of gas temperature and pressure values existing during measurement
or
- conversion of the measured concentration value into the corresponding value at *standard zero conditions*, see the following chapter.
After conversion, the volume is expressed as standard volume (standard cubic meter, Nm³ or m³_N).

Standard zero conditions of a gas

The volume of a gas depends on its actual temperature and pressure. To achieve comparable results a *standard zero volume* has been defined: A gas has its *standard zero volume* at a pressure of 1013 mbar (hPa) and a temperature of 273 K (corresponding to 0 °C).

Conversion of concentration values

Conversion of a measured value to standard conditions

The conversion of an actual measuring value (status 1) to standard conditions (status 2) is performed using the formula

$$c_2 = c_1 \cdot \frac{T_1 \cdot p_2}{T_2 \cdot p_1}$$

with the following expressions:

Status 1 Conditions during measurement	T_1 : Gas temperature during measurement (273 + actual temperature in °C) p_1 : Gas pressure during measurement in hPa c_1 : measured concentration value
Status 2 Standard conditions	T_2 : Standard zero temperature (=273 K) p_2 : Standard zero pressure (=1013 hPa) c_2 : Concentration converted to standard conditions

Example

The value "200mg/m³" at conditions of 35 °C and 920 hPa results, after conversion into standard conditions, in the value "248,4 mg/Nm³".

Conversion of ppm to mass concentration [mg/m³]

ppm (*parts per million*) is a very common concentration unit as expression for a relation of particles in a gas volume. Simultaneously the unit *mass concentration* is used.

A concentration value in [ppm] can be converted to the corresponding value expressed as mass concentration [mg/Nm³] using the standard density of the gas as a factor. For that the dilution of the gas by air (excess air, specially added air or false air from leaks) must be considered by using the oxygen concentration as reference. All measured values must be in reference to a certain oxygen content ("reference O₂"). Only concentration values with identical oxygen reference values are comparable to each other! Therefore, in official regulations, limit concentration values of pollutants are always specified together with a certain oxygen reference value.

The actual oxygen concentration value is also required for the conversion calculation as measure for the actually existing gas dilution level.

Conversion formulas for CO, NO_x, and SO₂

$$\text{CO (mg / m}^3 \text{)} = \left[\frac{21 - \text{O}_2\text{- refer.}}{(21 - \text{O}_2)} \right] \times \text{CO (ppm)} \times 1,25$$

$$\text{SO}_2 \text{ (mg / m}^3 \text{)} = \left[\frac{21 - \text{O}_2\text{- refer.}}{(21 - \text{O}_2)} \right] \times \text{SO}_2 \text{ (ppm)} \times 2,86$$

$$\text{NO}_x \text{ (mg / m}^3 \text{)} = \left[\frac{21 - \text{O}_2\text{- refer.}}{(21 - \text{O}_2)} \right] \times (\text{NO (ppm)} + \text{NO}_2 \text{ (ppm)}) \times 2,05$$

The factor (1,25 etc.) applied in the above formulas corresponds to the standard density in mg/m³ of the gas concerned. For that please note the following comments:

- for SO₂ standard density values are reported in the literature between 2,86 and 2,93; the difference is caused by the difference between calculated and measured values;
- for NO_x the standard density value of NO₂ (2,05) is used, because only NO₂ is a stable compound and NO will react very fast with oxygen to NO₂ and
- for H₂S (formula not shown) the factor is 1,52.

For conversion calculations without reference to the oxygen concentration the above formulas are simplified to (shown only for CO)

$$\text{CO in [mg/m}^3 \text{]} = \text{CO in [ppm]} \times 1,25$$

This is also true for the other gases.

Conversion of ppm in energy related units

To describe gas concentrations in energy related units [g/GJ] resp. [mg/kWh] conversion calculations are necessary using fuel-specific factors (FF). See the following formulas and the factors listed in table 7:

Conversion of ppm in g/GJ

$$\text{CO (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{CO (ppm)} \times \text{FBr} \times 1,25$$

$$\text{NO}_x \text{ (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{NO}_x \text{ (ppm)} \times \text{FBr} \times 2,05$$

$$\text{SO}_2 \text{ (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{SO}_2 \text{ (ppm)} \times \text{FBr} \times 2,86$$

Light Fuel Oil EL	0,2466	Briquett	0,2685
Heavy Fuel Oil S	0,2460	Brown coal	0,2661
Natural Gas	0,2525	Hard coal	0,2643
Liquified Gas	0,2332	Coke, wood	0,2633
Coke oven Gas	0,2220		
Town Gas	0,2238		

Table 17: Fuel Factor FF for various sorts of fuel

Conversion of ppm in mg/kWh

For that the factor 3,6 must be applied additionally to all of the above formulas:

$$\text{CO (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{CO (ppm)} \times \text{FBr} \times 3,6 \times 1,25$$

$$\text{NO}_x \text{ (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{NO}_x \text{ (ppm)} \times \text{FBr} \times 3,6 \times 2,05$$

$$\text{SO}_2 \text{ (mg / kWh)} = \frac{21}{21 - \text{O}_{2\text{meas.}}} \times \text{SO}_2 \text{ (ppm)} \times \text{FBr} \times 3,6 \times 2,86$$

4.1.2 Sample gas extraction and conditioning

Extractive sampling

Most of gas analysis measurements are performed using the *extractive gas sampling method*. A representative portion of the process gas is *extracted from the process stream* (in contrast to the in-situ principle) via a sampling probe and, after passing a conditioning unit, fed to the analyzer. Sample conditioning (sometimes also called sample preparation) means to clean the gas of particles and to cool the gas down to a defined temperature level below the dew point. This cooling results in *drying* the gas. A gas extraction and conditioning installation is shown schematically in figure 9.

Advantages of extractive sampling are:

- the analyzer itself is separated and protected from the process stream and its harsh and often aggressive environment,
- the sample gas, through the conditioning procedure, is transformed into a status that is defined and thus comparable, and
- more than one analyzer may be operated with one sampling unit or one analyzer may be connected to several sampling points using a sample line switching unit.

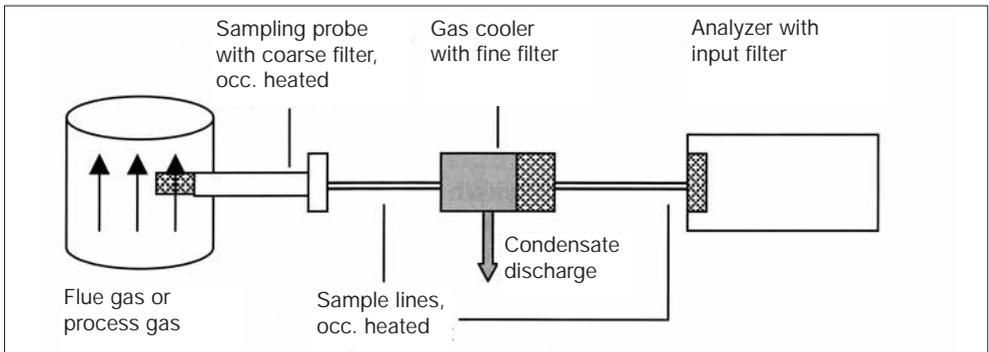


Fig. 9: Sample gas extraction and conditioning (schematic)

- Gas extraction is done by means of **sampling probes** that are positioned in the flue gas or process gas stream. They are available in different design, materials and for different temperature ranges up to 1200 °C (3200 °F) and above. A coarse ceramic filter is built in the head of the probe and, in certain probes (e.g. the Testo *multiple function probe*), sensors for determining pressure and temperature of the sample gas are also built in the probe head. The gas extraction is performed by means of a sample gas pump in the analyzer.
- The **sample gas cooler** is located between the sample probe and the analyzer. Flue and process gases always carry a certain amount of humidity that at high temperatures of the gas (above the dew point) exists as water vapor and at low temperatures (below the dew point) as liquid. In both cases the measuring result is influenced by the humidity itself and by chemical reactions of other gas components with the water. Furthermore, the measuring equipment may be damaged by aggressive compounds (acids) formed through reactions of SO₂ or SO₃ with water. See also chapter 2.7.
Sample gas cooler are used to cool the sample gas and thus to dry it to a definite and constant level, e.g. 4 °C. The remaining level of humidity is low at that temperatures (see fig. 5, page 23). It is kept constant and is thus comparable with that of other measurements. The cooling procedure results in forming a liquid (condensate) that is discharged from the cooler by a pump.
- **The sample lines** (made from metal or plastics) are either unheated (in case of uncritical gases or very high ambient temperatures) or heated to keep the gas above the dew point and thus to avoid the formation of condensate in the sample lines.
- The **analyzer**, depending on the design, may as well contain gas filter, gas cooler and heated internal sample lines.

The content of humidity in a sample gas is critical for gas analysis twice:

- As *vapor* it dilutes the sample gas and, with varying levels of humidity, the dilution levels and thus the measured concentrations values will vary.
- As *water* it will react with components of the gas and thus reduce the concentration of the components and consequently their measured concentrations values.

Remedial measures:

- The humidity level should be measured together with the gas components.
- The humidity should be dropped to a low level and kept constant by using a sample gas cooler.
- The formation of condensate in the analyzer equipment should be avoided by appropriate heating of the analyzer gas path.

4.1.3 Cross-sensitivity

Cross-sensitivity of a detector (sensor) system is caused by the fact, that the species-specific resolution of the system is not unlimited. With that the detector is not only sensitive for the component of interest but also, more or less, for other ("interfering") components present in the gas. Changes in concentration of those components will therefore also influence the measured value of the component of interest. This effect must be compensated in order to obtain correct and reliable measuring values. For that also the concentration of the interfering gases must be known for use as correction values.

Cross-sensitivity is expressed by the influence (*increase or decrease* of the measured value, in concentration units) that is affected by the interfering component. The extent of cross-sensitivity depends on the characteristics of the detection system (i.e it is analyzer-specific!) and on the concentration of the interfering components. The results for the testo 360 gas analyzer are shown in table 18. These values are typically lower than with other analyzers.

		Measuring components resp. type of sensor (testo 360) with cross-sensitivity values, expressed in % of the measured value of the interfering component				
		CO with H ₂ - compensation	CO without H ₂ - compensation	NO	NO ₂	SO ₂
Interfering gas components	CO	100	100	0	0	0
	H ₂ S	0	0	0	approx. -25	approx. 200
	SO ₂	0	0	0	approx. -3	100
	NO	<1	<1	100	0	0
	NO ₂	0	0	0	100	0
	H ₂	0	<60	0	0	approx. 3
	Cl ₂	50	0	0	<90	approx. -80
	HCN	0	<5	0	<-3	approx. 30
	HCl	0	0	<5	0	approx. 15
	C ₂ H ₄	approx. 35	0	0	0	approx. 50

Table 18: Cross-sensitivities of the testo 360 gas analyzer

- Expression 0 means "no influence"
- Expression 0 (shaded) means "no influence because of automatic correction in the analyzer" (the sensors for the interfering components must be available in the analyzer)
- No algebraic sign means positive influence (increase of the measured value)
- Sign "-" means negative influence (decrease of the measured value)
- Oxygen as measuring component is not shown as, except for CO₂ (internally compensated, no cross-sensitivity exist).
- CO₂ and NH₃ as well as saturated hydrocarbons do not produce cross-sensitivities.

Further information about influencing components:

- Unsaturated hydrocarbons at higher concentration levels can cause zero point drifts and reduce sensor sensitivity, particularly for the CO and NO cell.
- High concentration levels of aggressive gases such as HCN, HCl or Fluorides may attack sample lines and sensor housings.

4.1.4 Calibration

Calibration

Calibration is the process of adjusting the instrument read-out so that it corresponds to the actual concentration value or a reference standard. Calibration involves checking the instrument with a known concentration of a gas or vapor to see that the instrument gives the proper response. Calibration results in calibration factors or functions establishing the relationship between the analyzer response and the actual gas concentration introduced to the analyzer.

Calibration is an important element of quality assurance in emission control. Reference gases are used with very accurately specified composition.

Traceability

Traceability means that the reference measure used for calibration has a fixed precision.

Calibration gas, test gas

Calibration gas is a gas of known concentration which is used to establish the response curve of an analyzer.

Zero gas

Zero gas is a null; it may contain everything except the analyte or cross interference gases.

Reproducibility

Reproducibility of a method is the measure of its repeatability

Accuracy

Accuracy indicates how close a method come to the true value.

4.2 Gas analysis

4.2.1 Terms and application areas

Gas Analysis

Gas analysis includes the detection of gases and vapors in connection with control of chemical and metallurgical processes, control of environment and in the field of safety control. A whole class of analytical instruments is available using physical or physico-chemical detecting methods. Although analyzers are considered to be electrical instruments some knowledge of chemistry is required to understand their operating principle and to obtain correct and accurate measuring results.

Process analysis

Process analysis, in contrast to laboratory analysis, includes all continuous measuring methods for real-time determination of physical and chemical properties and concentrations in process streams. The equipment is defined as **Process Analytical Instrumentation (PAI)** or process analyzers. Because of the harsh environment of many processes, and the use of untrained personnel, the measurement systems must meet higher standards of automation, ruggedness, and ease of operation than do laboratory instruments.

The most common applications of process analysis are those in plants of chemical and petrochemical industries, energy generation, metals and minerals, food, pulp and paper, cement and ceramics, but to some extent also in research and development. In the case of gaseous process streams (combustion or flue gases, process gases, also air) the term **process gas analysis** is used.

Measuring points with continuously operating sampling devices, including the analyzers are located at various spots in a plant (at the burner or boiler, at the stack, at the cement kiln, close to the electrostatic filter etc.) in partially very rough ambient and operating conditions. The difference to **laboratory analysis**, is where the analyzers are installed in a laboratory at the best operating conditions and where the samples are taken discontinuously from the process and brought to the laboratory. Laboratory analyzers are normally designed for sophisticated measurements and require trained operators.

The results of process gas analysis are utilized for

- *process control* by e.g. controlling raw material and additives supply and by optimizing the process steps,
- *protection of persons and plants* by controlling the plant atmosphere for explosive or toxic gas mixtures,
- *product quality control* by monitoring the production process steps and controlling the final product specification and
- *environmental protection* by monitoring the exhaust gases for compliance with the standard limits specified for the various pollutants.

Analyzers

Heart of any analyzer is a species-specific sensor or sensor system. Its functionality is based on a definite physical or physico-chemical principle such as absorption, adsorption, transmission, ionization, conductivity, magnetism etc. The sensors react on variations of the property in question of the sample with a corresponding variation of their property (increased light absorption or reduced electrical conductivity for instance) where from a measuring signal is obtained.

Regarding their design analyzers may be classified as follows:

- *portable analyzers* for mobile application of one analyzer at different measuring locations for short time measurements and
- analyzers for *fixed installations* at definite locations of a plant for continuous measurements over months and years

and

- *in-situ analyzers*, which are installed and operated directly in the process stream
- *extractive analyzers*, which are installed in a rack or an analyzer house (container) outside the process stream and which use a sample probe and a sample gas conditioning unit for sample gas supply.

Resulting from recent technology developments portable analyzers are now available, which combine mobility with the suitability for stationary continuous measurements over longer time periods! One example for that is the **testo 360** gas analyzer that is portable and easy to handle and nevertheless successfully tested and certified for continuous operation over several weeks.

Application areas

Process gas analyzers have different major application areas:

1. Combustion optimization

Optimization of combustion processes with the objectives to save energy, to protect the plant (service life extension) and to minimize emissions.

2. Process control

Control of a specified gas composition to monitor a manufacturing process for obtaining certain product specifications and qualities.

3. Emission control

Control of gas cleaning plants for correct operation and monitoring the pollutant concentrations of flue gases for their compliance with the limit value specifications.

Table 19 provides examples of these applications in various industries

Gas analysis applications and objectives			
	1	2	3
	Combustion optimization	Monitoring of a specified gas atmosphere	Scrubber control and monitoring the exhaust gas for compliance with emission limit specifications
	Minimizing operational costs and emission of pollutants	Generation and conservation of a specified product quality	Compliance with emission regulations
	Combustion control	Process control	Emission control
Utilization			
Cement, lime, glass	X	X	X
Metal production	X		X
Metal treatment	X	X	X
Heat generation	X		X
Waste disposal	X		X
Research and development	X	X	X
Chemical, Petrochemical	X		X

Table 19: Application areas and objectives of gas analysis

Sensors

The term *sensor* generally describes all kind of devices that measure a physical quantity or the change in a physical quantity such as temperature, pressure, gas concentrations etc. A sensor consists of the actual sensing element (*elemental sensor*) and a *transmitter*. The sensing element must have a feature (e.g. conductivity, light absorption) that changes with variations of the measuring component. This "reaction" of the sensing element is then transformed by the transmitter into a measuring signal.

The most common groups of sensors are

- Sensors for temperature measurement
- Sensors for pressure measurements
- Sensors for flow and level measurements
- Sensors for measurements of concentrations and material properties (*Analyzers*)

Some common sensor groups for gas analysis are listed in table 20.

Please note:

In analyzer technology the term *sensor* is sometimes used especially for very small sensing elements, while larger sensors or sensor systems are described as analyzers.

Sensor	Measuring principle
Electrocatalytic sensor	Electrical conductivity
Polarographic sensor	Interaction between chemical and electrical energy
Optical sensor	Optical features
Calorimetric sensor	Heat reaction during interaction with certain gases
Photometric sensor	Absorption of radiation, e.g. infrared (IR) or ultraviolet (UV)
Paramagnetic sensor	Paramagnetic feature of oxygen

Table 20: Sensor principles used in gas analysis (Selected)

Chemiluminescence sensors	Chemical reaction with emission of chemiluminescence radiation
Flame ionization (FID)	Gas ionization in a flame resulting in a current
Biological sensors	Biochemical reactions

Table 20: continued

Portable analyzers

Portable analyzers in process applications are a great challenge to the instrumentation manufacturer. The harsh measuring environment, the required accuracy and reliability of the measuring values together with small dimensions and low weight of the analyzer form a profile of requirements, which could not be fulfilled until a few years ago. The development of the testo 350 and testo 360 gas analyzers, however, has established a new standard that have been confirmed by official certifications: both analyzers are mobile instruments with the qualification of performing continuous measurements over longer time periods!

testo 350 and **testo 360** are portable extractive gas analyzers, which are, because of their specific features (i.a. sample gas cooler, automatic calibration, automatic sample probe cleaning) also qualified for stationary installations and continuous measurements over several weeks. With that they open new fields of applications and offer very universal and cost effective instrumentation solutions to the user. Electrochemical sensors are preferably used that, because of their small dimensions and low power requirements, are very well suited for portable analyzers. The measuring principle of these sensors, however, requires extensive know how and experience of the manufacturer during development and production to meet the strong specifications of process applications.

4.2.2 Measuring principles used in Testo analyzers

A variety of measuring principles is utilized to determine the concentration of different gases in a gas mixture. Table 21 gives an overview with highlights of which principles are used in Testo analyzers.

Measuring principle	Measured components						
	SO ₂	CO	CO ₂	NO _x	H ₂ S	O ₂	KW
Conductivity	•	•					
NDIR	•	•	•	•			•
NDUV	•			•			
Paramagnetism						•	
Chemiluminescence				•			
Calorimetry		•					•
Flame ionization							•
Polarography	•	•		•	•	•	
Solid state conductivity						•	
•	Suitable principles						
•	Principles used by Testo						
HC	Hydrocarbons						

Table 21: Gas components and suitable measuring principles

Electrochemical (potentiometric) sensors

Sensors suitable for the determination of oxygen as well as of CO, SO₂ and NO_x work according to the electrochemical principle of *ion selective potentiometry*. The sensors are filled, specifically for their measuring task, with an aqueous electrolytic solution. Two or three electrodes (again task-specific) are placed in the solution with an electrical field applied to them. The sensors are sealed to the outside with a gas-permeable membrane, see figures 10 and 11.

Detailed design and operating principle differ depending on the gas component to be measured as shown in the following two examples:

Example 1: Sensor for oxygen (2 electrodes)

The flue gas resp. the oxygen molecules pass through the membrane and reach the sensor cathode. Because of the material composition of the cathode a chemical reaction takes place resulting in the release of OH⁻-ions (ions = charged particles) from the cathode. The free ions migrate through the liquid electrolyte to the anode of the sensor thus generating an electric current in the external electrical circuit that is proportional to the oxygen concentration.

This current creates a voltage drop across the resistor R, which is the measuring signal and used for further electronic processing.

The integral resistor is a thermistor with negative temperature coefficient, NTC. It serves to compensate for temperature influences and thus ensures thermally stable sensor performance.

Oxygen sensors have a service life of around 3 years.

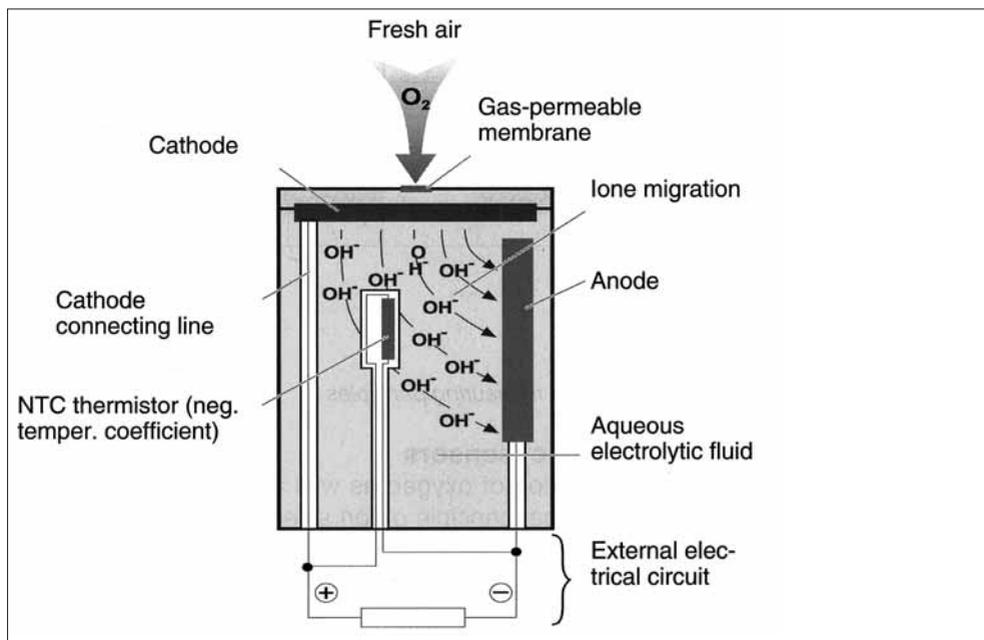
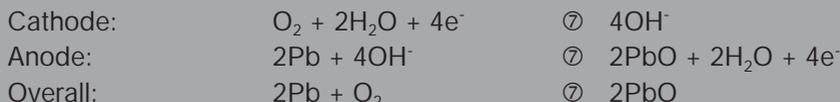


Fig. 10: Schematic of an Oxygen Sensor

Reaction equations



Example 2: Sensors for CO, SO₂, and NO_x (three electrode sensor)

To determine gases such as CO, SO₂ or NO_x, three-electrode sensors are used. The operating principle is explained in the following using the CO sensor as example.

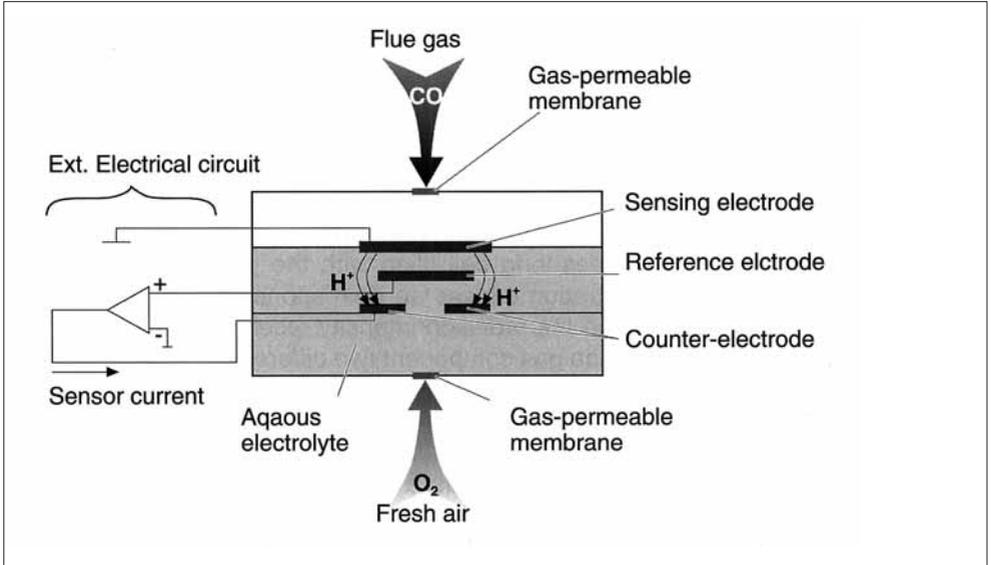
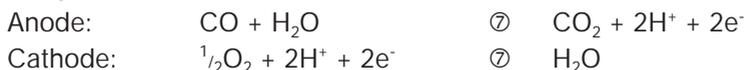


Fig. 11: Schematic of a Carbon Monoxide Sensor

The carbon monoxide (CO) molecules pass through the gas-permeable membrane to the sensing electrode of the sensor. There a chemical reaction takes place that results in the formation of H⁺-ions migrating from the sensing electrode to the counter electrode. At the counter electrode a second chemical reaction occurs with the aid of oxygen delivered from fresh air. This second reaction causes a current to flow in the external circuit. The current can be evaluated as measure of the carbon monoxide concentration. The reference electrode is used to stabilize the sensor signal.

This type of sensor has a service life of around 2 years.

Reaction equations for CO



Reaction equations for SO₂, NO, and NO₂



Infrared absorption (IR)

Infrared radiation (IR, wavelength range is some μm) is absorbed by gases such as CO, CO₂, SO₂, or NO at a wavelength that is specific for the gas. As IR radiation passes through a measuring cell filled with the gas to be analyzed an increase in the gas concentration causes an corresponding increase in IR absorption and thus a decrease in the radiation intensity received by the IR detector. To ensure selectivity for just one gas component two different principles are used:

The **dispersive** principle uses radiation, which has been dispersed by a prism or grating before entering the measuring cell. Only two wavelength (or narrow wavelength ranges) of the entire spectrum are used, one that the component in question absorbs and one that not, as a reference. The ratio of absorption at these two wavelength is a measure for the gas concentration.

The non **dispersive (NDIR)** principle uses a broad band of radiation from a lamp or glower without dispersion before entering the measuring cell. When a component that does absorb IR radiation is present in the sample gas the radiation intensity reaching the detector will be reduced at the specific part of the spectrum. Two methods are in use for detecting the level of absorption:

- a *gas detector* filled specifically with the gas of interest will, from the broadband radiation leaving the measuring cell, detect only the component of interest resp. its variations caused by the varying concentration of the component in the sample gas passing through the measuring cell. Radiation absorption affects the gas pressure in the detector cell; these pressure variations are used to generate a detector signal as measure of the concentration of the gas of interest.
- A *solid state IR detector* is used together with a narrow-band interference filter that allows from the broadband spectrum of IR radiation only the radiation range of the component of interest (e.g. CO₂) to pass through. As the IR radiation passes through the measuring cell a variation in CO₂ concentration will cause a proportional variation in the IR absorption and thus in the detector

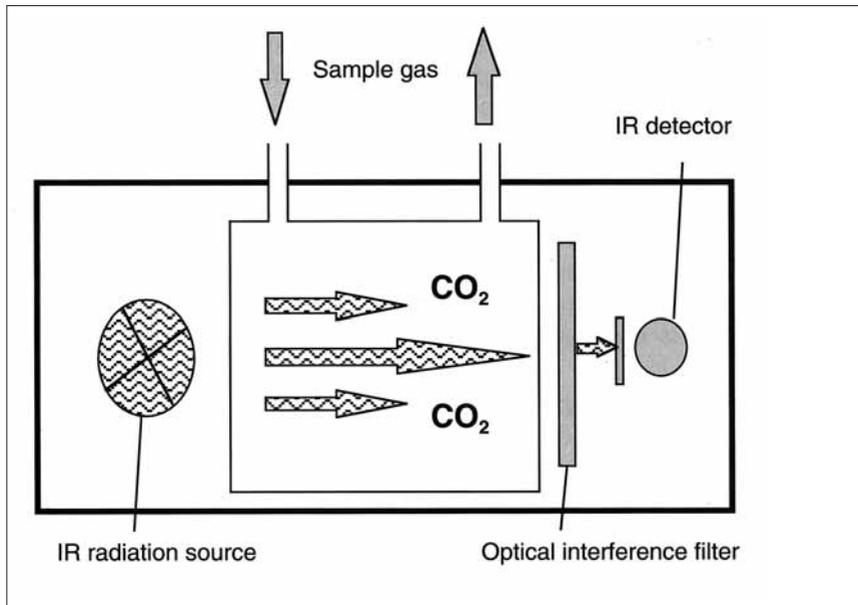


Fig. 12: NDIR Sensor (Testo compact design) for determination of CO_2

Ultraviolet absorption (UV)

Certain gas components, e.g. SO_2 or NO , absorb also ultraviolet (UV) radiation. For these components the UV method competes with the IR method offering the major advantage, that water does not cause any interference effect in the UV absorption range. In contrast to IR, however, UV light sources are more expensive and therefore the UV method is used preferably for particular applications.

Chemiluminescence Detector (CLD)

This method is mainly used for the determination of low concentrations of NO and NO_2 . It is based on the feature of NO to react with ozone (O_3) resulting in the emission of characteristic light radiation (chemiluminescence). The intensity of the emitted radiation is proportional to the NO concentration. Such analyzers (CLD, chemiluminescence detectors) are very common for analysis of NO and NO_2 in car exhaust gases. They comprise essentially an ozone generator, an enrichment and reaction chamber, and a photomultiplier detector.

Paramagnetic method

This method is applied particularly for the analysis of oxygen. Oxygen is the only gas with a considerably high value of paramagnetism with the result, that oxygen molecules are attracted by a magnetic field. This effect is used to determine oxygen concentration in gases. Different analyzer designs are available:

The dumb-bell analyzer

Two balls made of glass and filled with nitrogen are mounted at the ends of a thin bar, forming a dumb-bell, which is suspended in the sample gas stream in a strong inhomogeneous magnetic field. With oxygen present in the sample gas, the oxygen molecules will be attracted by the magnetic field and get the dumb-bell swinging. This effect is compensated with a pre-stressed spring resulting in a measuring signal.

The differential pressure analyzer

The pressure produced at the contact surface of two gases with more and less magnetic characteristics is used here. Between the sample gas containing more or less paramagnetic oxygen molecules and an oxygen-free reference gas, e.g. nitrogen, a pressure difference is generated resulting in a gas flow that is a measure of the oxygen concentration.

Thermal conductivity method (TC)

This principle (mostly applied for the analysis of H_2) uses the different values of thermal conductivity of two gases (sample and reference gas). In the analyzer a Wheatstone bridge circuit is built in the filaments of which act at the same time as source of heat and as detector of temperature changes. The bridge is positioned with one part in the sample gas and with the other part in the reference gas. The different cooling of the filaments due to the different gas compositions result in an electrical signal that is used for further processing.

Catalytic filament method

Oxidation of combustible gases at a heated catalytic filament is used to detect the *total* concentration of combustibles in a sample gas. The combustibles react with a pre-heated catalytic material (wire or a bead, supported on a platinum coil) and increase, through their combustion heat, the temperature of the wire resulting in a change of its electrical conductivity. This process will only work with sufficient oxygen available in the gas for the combustion.

The change in conductivity is a measure for the content of *all* combustibles present in the sample gas. These are mainly hydrocarbons (acronym: HC or C_xH_y) but also CO or H_2 . Cross sensitivities therefore exist between these components and must be considered in data evaluation.

Cross sensitivity values:

The measured value of methane is increased by CO (0,27 Vol. % per 1 Vol. % CO) or H₂ (1,5 Vol. % per 1 Vol. % H₂).

Furthermore cross sensitivity exist with water vapor.

The Testo module used in some analyzers for detection hydrocarbons is based on the principle described above, see fig. 13. A current flows through the wire made of platinum heating it including the catalyst material to a temperature of appr. 500 °C. The combustibles are burnt at the surface of the catalyst (as long as sufficient oxygen is available) and the resulting temperature increase changes the electrical conductivity of the wire. This is determined via a "Wheatstone" bridge circuit and used to generate a measuring signal.

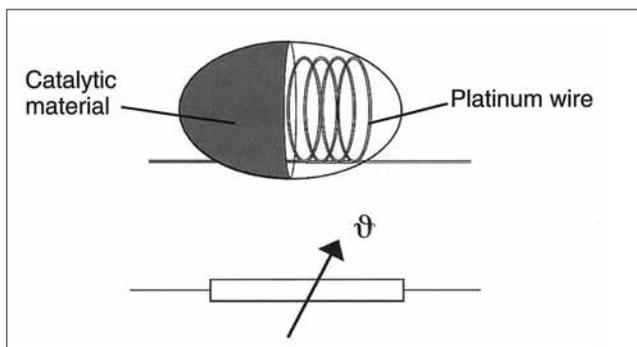


Fig. 13: Schematic of the testo HC heat effect sensor

The use of the testo *heat effect HC* sensor requires special attention because of its cross-sensitivity and the possible damaging influences of components such as H₂S, Silicones or hydrocarbons containing sulfur to the sensor. The "instructions for use" handbook delivered with the analyzer provides the necessary information for that.

Flame ionization detection (FID)

The sample gas together with the hydrocarbons is introduced into a flame (usually hydrogen/air) where the hydrocarbons are ionized. The positively charged ions are collected by a negatively charged collecting electrode generating a current proportional to the hydrocarbon concentration. The different sensitivity of this principle to different hydrocarbon compounds is taken into account by applying specific response factors during data evaluation.

Solid state electrolyte method

A very common oxygen measuring principle uses a solid state electrolyte sensor (made of zircon oxide ceramics) coated with layers (electrodes) of porous platinum as catalyst on two surface sides. At high temperatures $>500\text{ }^{\circ}\text{C}$ oxygen molecules coming in contact with the platinum electrodes become oxygen *ions* with great mobility that intend to move through the molecular "holes" of the zirconium cell. As the two electrodes are in contact with gases of different oxygen concentration (sample gas and reference gas, e.g. ambient air) oxygen ions will move through the cell from one electrode to the other and generate a differential voltage across the electrodes. From that, with a known oxygen concentration of the reference gas, the sample gas oxygen content can be determined.

Such analyzers are known as oxygen or *zirconium probes*. They are capable to measure correctly even under very harsh conditions and are, therefore, very often installed directly in the process flow (in situ). They measure the gas *in its original state including the content of humidity!* Because of the dilution effect caused by the humidity content the oxygen values measured by zirconium probes are generally lower than of analyzers that measure dry sample gas.

Oxygen concentration values measured with in-situ zirconium probes usually are lower than those received with other (extractive) oxygen analyzers but both are correct! The difference is caused by the different humidity resp. temperature of the sample gas. Humidity (present in the hot original gas) dilutes the gas, the relative oxygen concentration is lower accordingly. The cooled gas measured by extractive analyzers contains much less humidity resulting in a higher relative concentration of oxygen. Both measurements, however, will deliver the same values as soon as the variation of humidity is considered either by calibration or by calculation.

Testo uses the effect described above in some analyzers for determining the humidity of flue gas as in a configuration as follows (see also fig. 14):

- Measurement of oxygen in the humid flue gas using a zirconium sensor
- Cooling and drying the gas in a gas cooler
- Measurement of oxygen in the dry flue gas using an electrochemical sensor
- Calculation of the humidity content from both values taking the temperature of the gas cooler into account

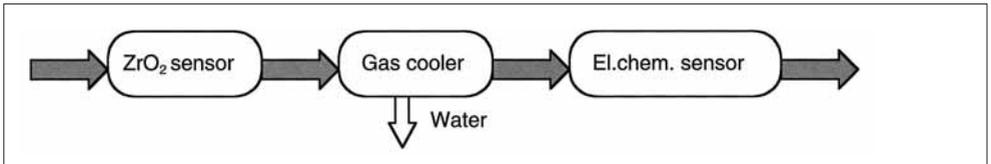


Fig. 14: Schematic of humidity measurement used by testo

5. Application of Testo gas analyzers

Preface

- The following descriptions of gas analysis applications should be considered as examples. The objective is to show in compact form the great variety of industrial processes where Testo gas analyzer are in use. The tasks of gas analysis for a given application are mentioned briefly together with information about the location of the measuring points. Process flow charts are also included that display the process schematically. In reality plant design may show considerable deviations depending on modification of the process, changing specifications of the engineering or constructing companies and on local conditions and regulations.
- Relevant measuring components and measuring ranges, resulting from practical experiences, are listed with each application together with, as far as available, limit concentration values that refer to the emission control regulations in Germany.
These data should be considered as guide values which are not always complete and may more or less deviate from the actual conditions on site.

5.1 Power generation

5.1.1 Solid-fuel-fired furnaces

Solid-fuel-fired furnaces are part of firing plants to generate heat energy by burning *solid* fuels such as hard coal, brown coal, wood etc. The fuel is crushed or ground and then fed to the burner. Combustion occurs in a combustion chamber on a fixed or fluidized bed or in a fuel dust/air mixture. The combustion air is supplied through a fan, sometimes already mixed with powdered coal. In Germany the flue gases, regarding their content of pollutants, must comply with the regulations of the TI Air resp., for plants with power output > 50 MW, those of the 13. ordinance (13. BImSchV). In the US may sources come under the control of the State or Federal EPA regulations.

Use of gas analysis e.g. for

- Optimum adjustment of the plant components
- Determination of the energy balance
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

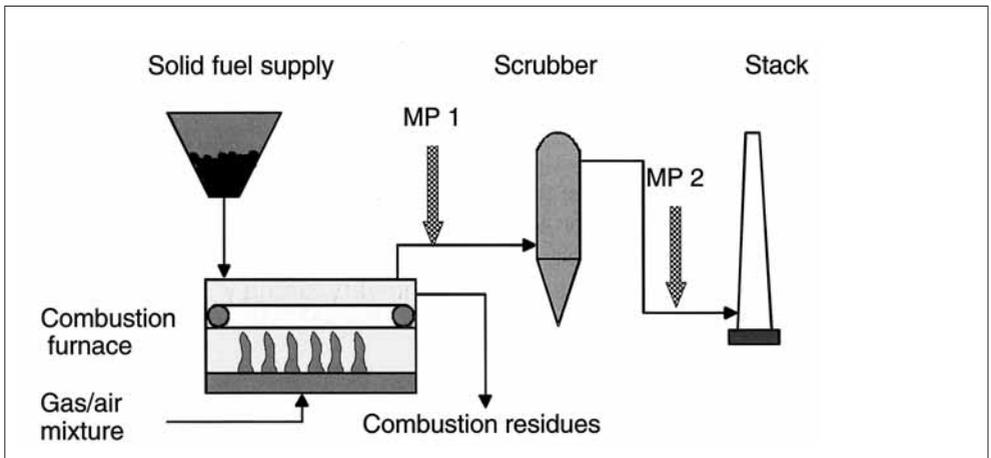


Fig. 15: Process flow chart of a solid fuel furnace with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace outlet for optimum burner adjustment (reduced fuel costs, profitability), identification of CO pockets, reliability of plant operation
- MP 2 in the clean gas at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values	Limit values
	MP 1	MP 2
CO	150 ... 170 mg/m ³	250 mg/m ³
NO		-
NO ₂		-
NO _x (as NO ₂)	650 ... 750 mg/m ³	200 mg/m ³ (>300 MW) 400 mg/m ³ (50-300 MW)
SO ₂	25 ... 35 mg/m ³	400 mg/m ³ (>300 MW) 2000 mg/m ³ (100-300 MW)
O ₂	7%	5% (slag tap furnance) 6% (dry furnance) 7% (fluidized bed furnance)
Humidity		-
Gas flow		-
Flue gas temperature	250 °C	-

Table 22: Typical and limit values of a solid fuel firing plant

Comments to this application

1. A major content of soot may be present in the flue gas
2. In case of complete combustion strong variations of the CO concentration must be expected.
3. Depending on the fuel the content of SO₂ can vary strongly and HCl and HF may be present.

5.1.2 Gas-fired furnaces

Gas-fired furnaces are part of firing plants to generate heat energy by burning gaseous fuel such as natural gas, industrial gas, blast furnace gas e.a. Such furnaces provide a combustion that is almost free of emissions and residues. The supply of fuel and combustion air is done by vents or, in larger plants, by high pressure burners. In Germany the flue gases, regarding their content of pollutants, must comply with the regulations of the TI Air or, for plants with power output > 100MW, with those of the 13. ordinance (13. BImSchV).

Use of gas analysis for e.g.

- Optimum adjustment of the plant components
- Provision of the energy balance
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

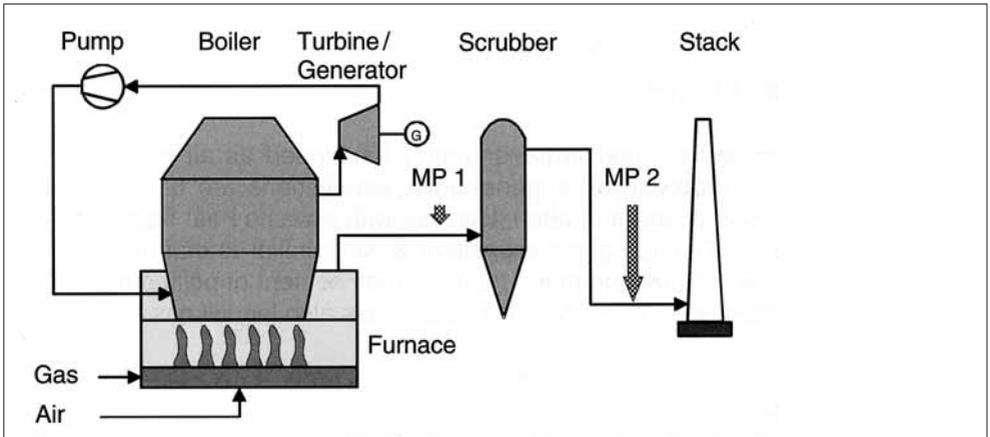


Fig. 16: Process flow chart of a gas fired furnace with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace outlet for optimum burner adjustment (reduced fuel costs, profitability)
- MP 2 in the clean gas at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values	Limit values
	MP 1	MP 2
CO	0 ... 5 ppm	100 mg/m ³
CO ₂	9 ... 11% (control value)	
NO	30 ... 50 ppm	
NO ₂	0 ... 2 ppm	
NO _x		200 mg/m ³
SO ₂		5 mg/m ³ (liquified gas) 1700 mg/m ³ (crude oil gas)
O ₂	2 ... 3%	3% (reference value)
Flue gas temperature	180 °C	

Table 23: Typical and limit values of a gas fuelled firing plant

5.1.3 Gas turbine plants

Stationary gas turbines were originally developed as air craft engines and are applied preferably to drive generators. Installations are used to generate peak load electrical power and often, together with a waste heat boiler, to generate also heat energy. The flue gas composition is very similar to that of gas fired furnaces. In Germany the flue gas must, regarding the content of pollutants, comply with the regulations of the TI Air. Besides natural gas also landfill gas or biogas is used as fuel.

Use of gas analysis for e.g.

- Monitoring the turbine emission for optimum operation
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

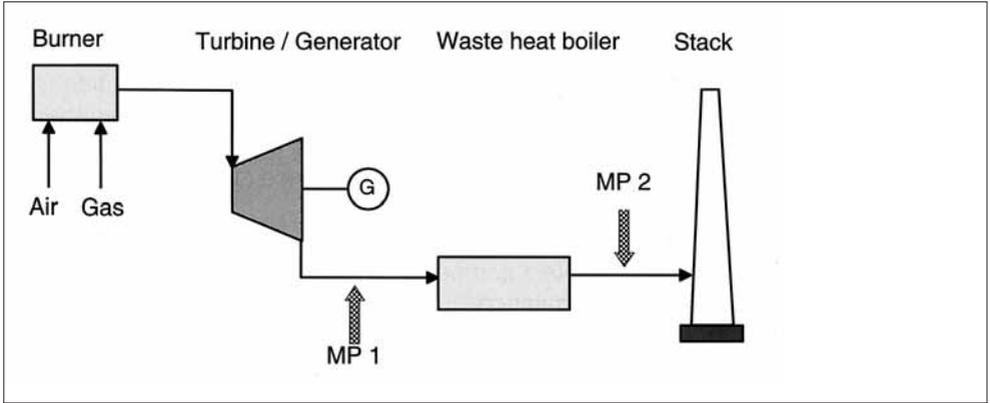


Fig. 17: Process flow chart of a gas turbine plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the turbine outlet for monitoring the turbine emission (optimum operation)
- MP 2 at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values	Limit values
	MP 1	MP 2
O ₂	15 ... 18%	15% (Reference value)
NO _x	25 ... 60 ppm	300 ... 350 mg/m ³
CO	0 ... 30 ppm	100 mg/m ³
CO ₂		
Dust		
Flue gas temp.	300 ... 400 °C	
Gas flow		
Humidity		

Table 24: Typical and limit values of a gas turbine plant

Comments to this application

1. A dynamic partial vacuum exists at the measuring point MP 1. The sampling point therefore must be carefully sealed in order to prevent ambient air from being sucked in and cause incorrect measurements.

5.1.4 Oil-fired furnaces

Oil-fired furnaces are part of firing plants that generate heat energy by burning oil of different quality. Fuel (oil) and combustion air are sprayed as a mixture into the combustion chamber by the burner. Oil is burned with almost no residues and the amount of flue dust is very low. In Germany the flue gases, regarding their content of pollutants, must comply with the regulations of the TI Air or, for plants with power output >100 MW, with those of the 13. ordinance (13. BImSchV).

Use of gas analysis for e.g

- Optimum adjustment of plant components
- Determination of energy balance
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

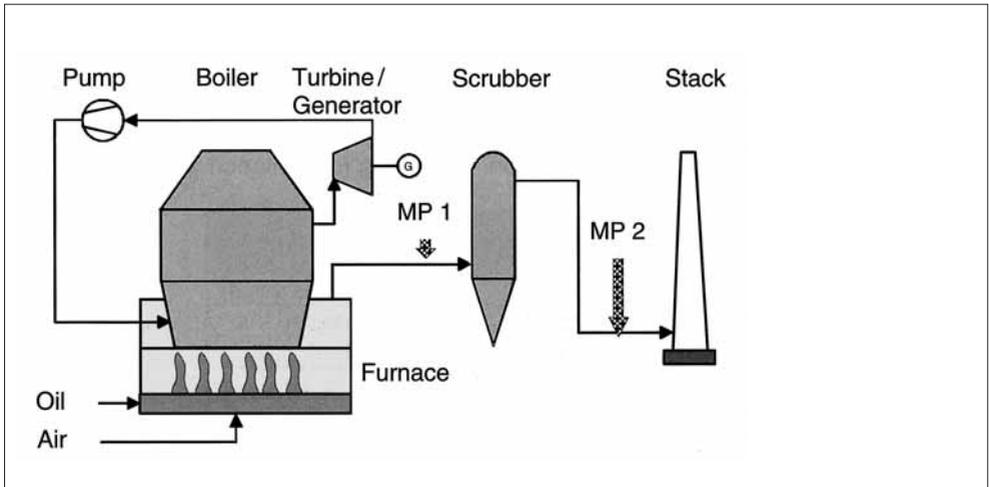


Fig. 18: Process flow chart of a oil-fired furnace with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace outlet for optimum burner adjustment (fuel cost reduction, profitability) and for energy balance determination
- MP 2 at the stack for emission monitoring (compliance with regulations)

Measured components	Typical values	Limit values
	MP 1	MP 2
O ₂	2,5 ... 3,5%	3%
CO	0 ... 5 ppm	175 mg/m ³
CO ₂	13 ... 15%	Control value
NO	50 ... 150 ppm	-
NO ₂	0 ... 5 ppm	-
NO _x (als NO ₂)		150 mg/m ³ (>300 MW) 300 mg/m ³ (50-300 MW)
SO ₂	50 ... 100 ppm	400 mg/m ³ (>300 MW) 1700 mg/m ³ (100-300 MW)
Humidity		-
Gas flow		-
Flue gas temp.	200 °C	-

Table 25: Typical and limit values of an oil-fired combustion plant

5.1.5 Coal-fired power station

Coal-fired power stations belong to the group of thermal power stations that generate electricity (secondary energy form) from coal as primary energy source. Hard coal as well as brown coal are used as fuel.

The coal is crushed, dried, and ground in a mill. Together with preheated combustion air the powdered coal is blasted into the furnace and burned at temperatures of appr. 1000 °C. The furnace is surrounded by the steam generator which comprises a tightly packed pipe system with boiler water flowing through. The water is heated up and thus fresh steam is generated with a pressure of appr. 200 bar to drive a turbine. The flue gases escape from the furnace, pass through different gas scrubbers and are released into the atmosphere through the stack. The steam, after leaving the turbine, is cooled down to water and recharged into the boiler system again.

In Germany flue gases of coal fired power stations, regarding their content of pollutants, must comply with the regulations of the TI Air or, for plants with a power output > 50 MW, with those of the 13. ordinance (13. BImSchV).

Use of gas analysis for e.g.

- Optimum adjustment of plant components (fuel cost reduction, profitability of the plant operation)
- Performance control of the gas cleaning units
- Monitoring emission concentrations for compliance with regulations
- Safety of personell and plant (CO monitoring)

Process flow chart and measuring points

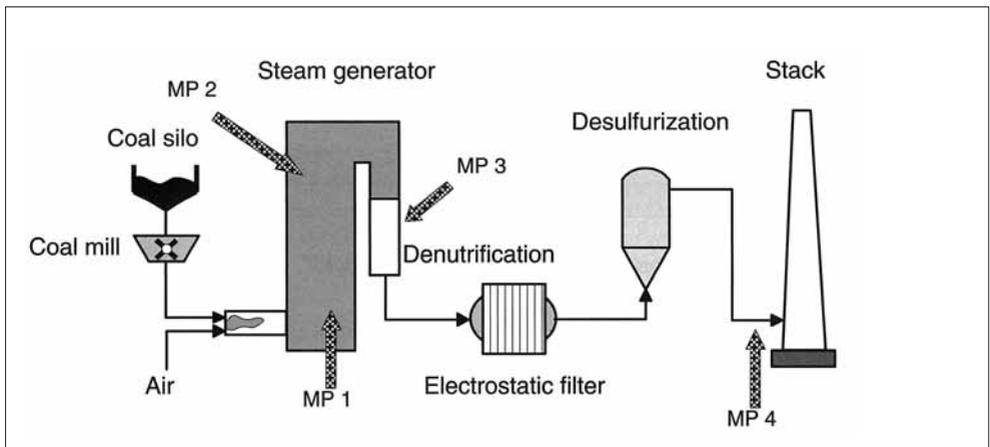


Fig. 19: Process flow chart of a coal-fired power station with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace for controlling constant combustion and air value, identification of CO nests and providing reliable operation
- MP 2 at the furnace outlet for combustion control and optimization (profitability)
- MP 3 at the denitrification plant for performance control
- MP 4 at the stack for emission monitoring (compliance with regulations)

Measured components	Typical values			Limit values
	MP 1	MP 2	MP 3	MP 4
O ₂	5 ... 9%	5 ... 9%		5 ... 7%
CO	10 ... 5000 ppm	10 ... 5000 ppm		250 mg/m ³
CO ₂		15 ... 18%		
NO _x		500 ... 600 ppm		200 mg/m ³
SO ₂		500 ... 2000 ppm		400 mg/m ³
Dust		2 ... 20 g/m ³		50 mg/m ³
Flue gas temp.	ca. 1000 °C	ca. 1000 °C		
Humidity		10 ... 15%		

Table 26: Typical and limit values of a coal-fired power station

Warning!

For measurements after the electrostatic filter, the sample probe must be grounded to avoid dangerous static electric shocks.

5.1.6 Combined heating and power stations (Reciprocating engines/turbines)

Combined heating and power stations (block-type power stations) are stationary gas or diesel engines that produce electricity and heat simultaneously in accordance with the principle of the heat/power link. They can easily be installed very close to a consumer and are suitable for use in residential premises and public buildings. Generators driven by gas turbines or combustion engines are used for electricity generation; the heat energy is gained by using the waste heat contained in the exhaust gas and the cooling water of the engines or turbines. Preferred fuel, besides diesel oil, is natural or landfill gas; the output of such a power station is in the range of 15 kW to 30 MW. In Germany the exhaust gases of the driving engines must, regarding their content of pollutants, comply with the regulations of the TI Air which requires the use of catalysts.

Use of gas analysis for e.g.

- Optimum adjustment of the driving engine (Economic fuel consumption, emission reduction)
- Performance control of the catalyst
- Emission monitoring for compliance with regulations

Process flow chart and measuring points

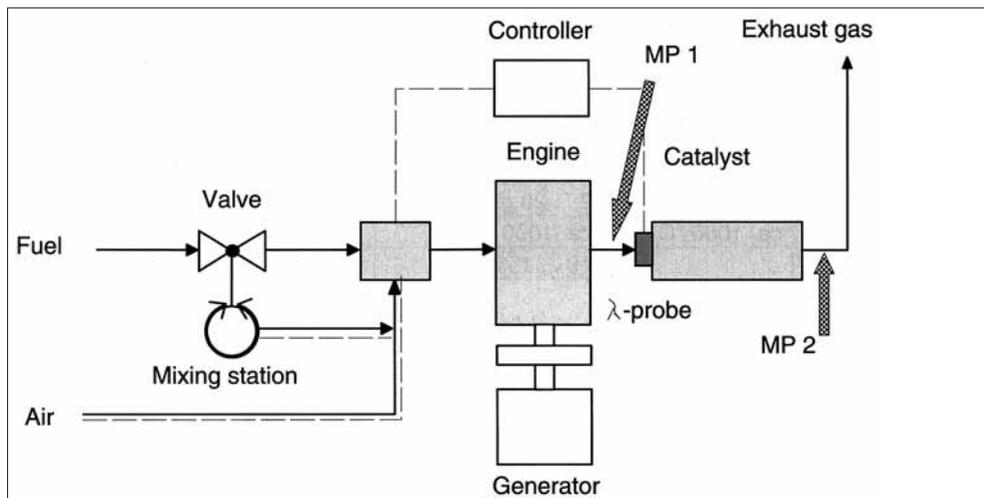


Fig. 20: Process flow chart of a block-type power station with measuring points

Measuring point locations and analysis tasks

- MP 1 between engine and catalyst for engine adjustment and catalyst efficiency control
- MP 2 behind the catalyst for catalyst efficiency control and emission monitoring (compliance with regulations)

Measured component	MP 1		
	Typical values for different fuels		
	Natural gas	Landfill gas	Oil
O ₂	8%	5 ... 6%	8 ... 10%
NO	100 ... 300 ppm	100 ... 500 ppm	800 ... 1000 ppm
NO ₂	30 ... 60 ppm	90 ... 110 ppm	10 ... 20ppm
CO	20 ... 40 ppm	350 ... 450 ppm	450 ... 550 ppm
CO ₂	10%	13%	7 ... 8%
SO ₂		30 ppm	30 ... 50 ppm

Table 27: Typical values for a block-type power station at MP 1

Measured component	Type of engine	MP 2 Limit values
CO	Natural gas	650 mg/m ³
NO+NO ₂	Diesel engine <3 MW	4000 mg/m ³
NO+NO ₂	Diesel engine >3 MW	2000 mg/m ³
NO+NO ₂	Other 4-cycles	500 mg/m ³
NO+NO ₂	Other 4-cycles	800 mg/m ³
O ₂	Reference value	5 Vol. %
SO ₂	According to DIN 51603	

Table 28: Limit values for combined power station engines (MP 2)

Comments to this application

1. The use of λ -controlled engines may result in high H₂ values with the danger of damaging the CO cell!

5.1.7 Combined gas and steam power station

In combined gas and steam power stations fossil fuels are burned (for electricity generation) with high efficiency and low emission level by an optimum combination of gas and steam turbines in one plant. Different combinations are in use; very often a gas turbine is operated primarily with natural gas or fuel oil, the hot exhaust gases generate high pressure steam for driving a steam turbine. In other cases the exhaust gases of a pressure-loaded coal firing plant drives a gas turbine. In Germany the exhaust and flue gases, regarding their content of pollutants, must comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Optimum burner adjustment (Fuel cost and emission reduction)
- Emission monitoring (Compliance with regulations)

Process flow chart and measuring points

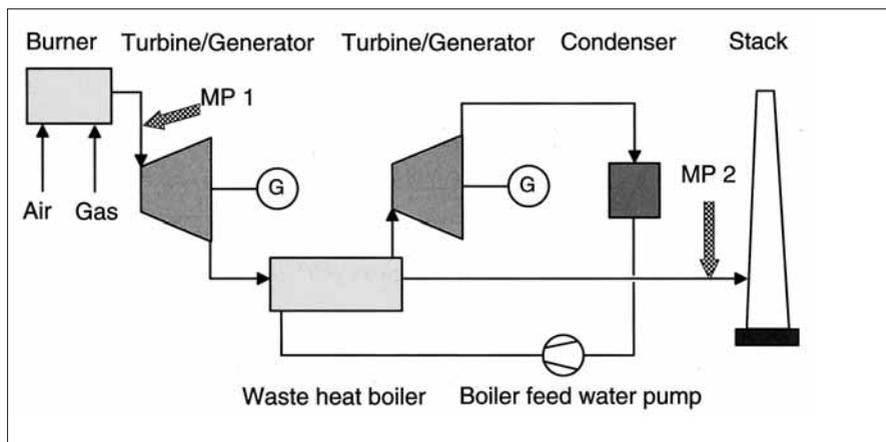


Fig. 21: Process flow chart of a gas and steam power station with measuring points

Measuring point locations and analysis tasks

- MP 1 at the burner outlet for combustion and emission optimization
- MP 2 at the stack for emission monitoring (compliance with regulations)

5.2 Waste disposal

5.2.1 Waste incineration

Solid, liquid and sludge materials from households, industry or sewage plants are nowadays thermally treated and disposed including reuse of the waste heat of the process instead of being deposited in landfill plants.

In *waste pyrolysis plants* the waste material is decomposed under exclusion of oxygen with simultaneous generation of pyrolysis gas that can be further used.

More common are *waste incineration plants* where the waste material is incinerated at temperatures as high as 1200 °C in furnaces and kilns of different design. The resulting flue gases must be cleaned from various pollutants in different gas cleaning processes. In Germany the clean gas after leaving the purification process must, regarding the content of pollutants, comply with the regulations of the 17. ordinance (17. BlmschV).

Use of gas analysis for e.g.

- Control of waste supply (reduced filter load and emission level)
- Constant level of the fuel value
- Performance control of gas cleaning processes
- Emission monitoring (compliance with regulations)

Process flow chart with measuring points

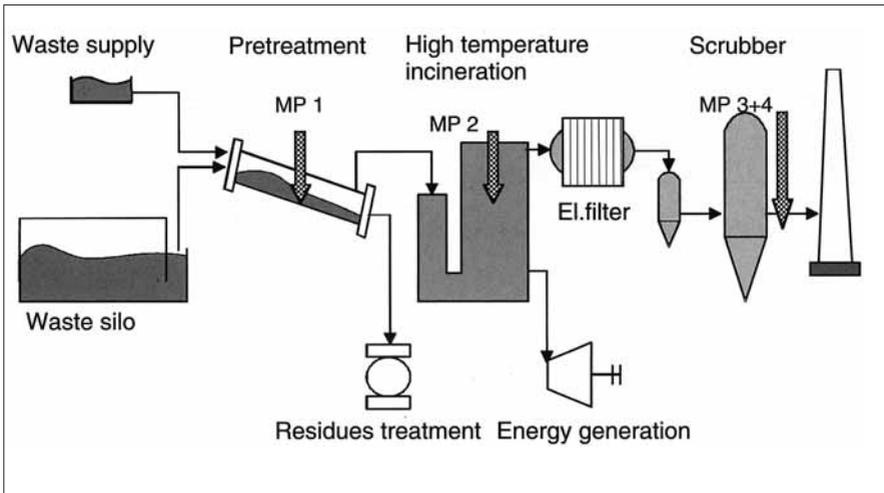


Fig. 22: Process flow chart of a waste incineration plant with measuring points

Measuring point locations and analysis tasks

- MP 1 and MP 2 at the ovens for optimized waste supply (low filter load and low emission levels) and control of constant fuel value
- MP 3 behind the cleaning plants for cleaning performance control
- MP 4 at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values		Limit values
	MP 1 and 2 in the raw gas	MP 3 and 4 in the clean gas	
O ₂	8 ... 11%	7 ... 9%	11 Vol.-%
NO	150 ... 200 ppm	50 ... 70 mg/m ³	
NO _x	10 ... 40 ppm	11 ... 17 mg/m ³	200 mg/m ³
CO	15 ... 25 ppm		50 mg/m ³
CO ₂	10 ... 12%		
SO ₂	40 ... 60 ppm	5 ... 11 mg/m ³	50 mg/m ³
HCl	... 500 ppm		10 mg/m ³
HF	... 30 ppm		1 mg/m ³
C _{total}			10 mg/m ³
Dust	2 ... 3 g/m ³		10 mg/m ³
Flue gas temperature	300 °C		
Humidity			

Table 29: Typical and limit values of a waste incineration plant

Comments to this application

1. Aggressive components such as HCl, HF and HCN are often present in the raw gas. Therefore a heated sample extraction system is necessary. Additionally the cross sensitivity of the SO₂ sensor to Cl₂ (80%) and HCl (15%) must be considered.
2. The composition of the waste material will vary considerably resulting in a corresponding variation of the measured values.
3. For measurements after the electrostatic filter, the sampling probe must be grounded to avoid severe static electric shocks.
4. For plants where waste material is only a portion of the fuel supplied the limit values of the 17. ordinance must be referred only to this portion of the entire amount of fuel! Related to the entire flue gas quantity this means that a reduced level of pollutant limit concentrations are to be measured!

5.2.2 Waste pyrolysis

Waste pyrolysis is a process that decomposes organic material (contained in waste) under oxygen exclusion. This process is applicable e.g. to plastics, used tires, rubber, and household waste. From the reaction pyrolysis gas and coke are generated, which both can be further used. The advantage of this process compared with waste incineration is a by far smaller volume of flue gas (no combustion air required!) and smaller plant dimensions. Regarding operation of pyrolysis plants, however, some technical problems have been reported recently.

In Germany waste pyrolysis plants, regarding their content of pollutants, must comply with regulations of the TI Air, which are comparable to those of the 17. ordinance (17. BImSchV). The oxygen reference value has been reduced to 3%.

Use of gas analysis for e.g.

- Performance control of the flue gas cleaning installations
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

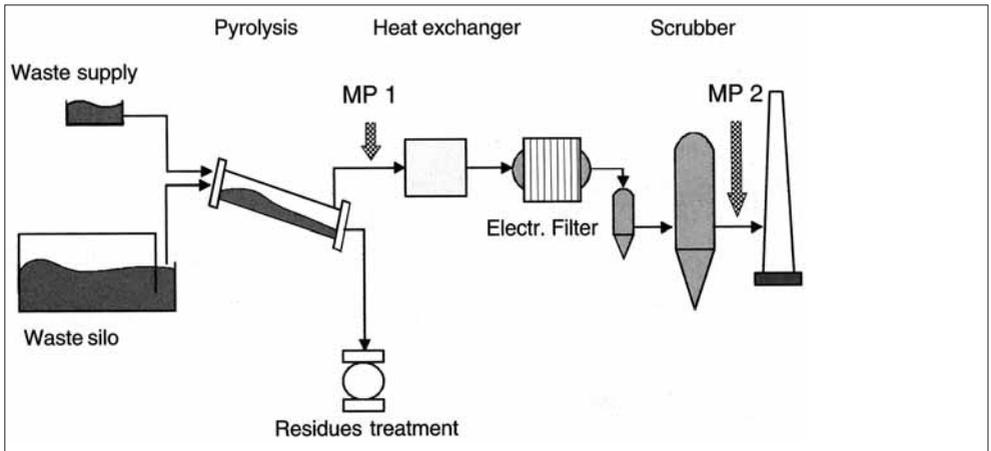


Fig. 23: Process flow chart of a waste pyrolysis plant

Measuring point locations and analysis tasks

- MP 1 in the exhaust gas of the pyrolysis furnace for control of waste supply and pyrolysis process
- MP 2 at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values	Limit values
O ₂		3 Vol.-%
NO		
NO _x		200 mg/m ³
CO		50 mg/m ³
CO ₂		
SO ₂		50 mg/m ³
HCl		10 mg/m ³
HF		1 mg/m ³
C _{total}		10 mg/m ³
Dust		10 mg/cm ³
Flue gas temp.		
Humidity		

Table 30: Limit values of a waste pyrolysis plant

5.2.3 Thermal gas incineration

With a thermal gas incineration process combustible components of an exhaust gas are burned with oxygen at temperatures of 700-900 °C. By that, CO and water are generated but also, depending on the gas components, SO₂, HCl e.a. The thermal incineration process differs from flame incineration (operated at 1300 °C) and catalytic incineration (operated at 250-500 °C).

Thermal incineration plants require a high energy supply (auxiliary firing) and are used only where other processes are not efficient enough or special components must be decomposed.

In Germany most of these plants, regarding their pollutant concentrations in the flue gas, must comply with the TI Air regulations.

Use of gas analysis for e.g.

- Monitoring of the raw gas
- Optimization of incineration
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

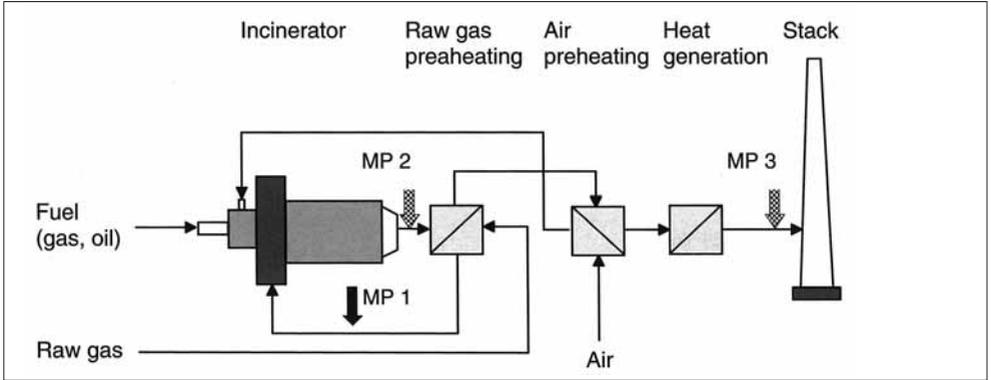


Fig. 24: Process flow chart of a exhaust gas incineration with measuring points

Measuring point locations and analysis tasks

- MP 1 in the raw gas supply line to monitor raw gas composition
- MP 2 at the outlet of the incinerator to optimize incineration
- MP 3 at the stack to monitor emissions for compliance with regulations

Measured components	Typical values
O ₂	10 ... 100 mg/m ³
NO _x	10 ... 100 mg/m ³
CO	
CO ₂	
SO ₂	
HCl	
HF	
C _{total}	5 ... 20 mg/m ³
Flue gas temp.	
Humidity	

Table 31: Typical values of a gas incineration

5.3 Stone and day industry

5.3.1 Cement production

The material known as cement consists of ground cement clinker mixed with gypsum. It is the end product of a firing process in the cement furnace. Raw materials are limestone (CaCO_3) and additives such as clay, ash, or sand. Powdered coal, oil, and waste material (used tires) are utilized as fuel. The major process steps are:

Grinding of the raw materials, drying of the material using hot exhaust gases, heating of the raw meal up to $800\text{ }^\circ\text{C}$ with removal of CO_2 , firing in a rotating kiln, cooling, mixing with gypsum, and grinding to cement. The exhaust gases pass through an evaporation cooler and some gas cleaning plants (not shown in fig. 25) including an electrostatic filter before they are released to the atmosphere.

Use of gas analysis for e.g.

- Optimization of the evaporation cooler operation
- Protection of the electrostatic filter by monitoring CO
- Control of sampling probe position of the stationary analyzer
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

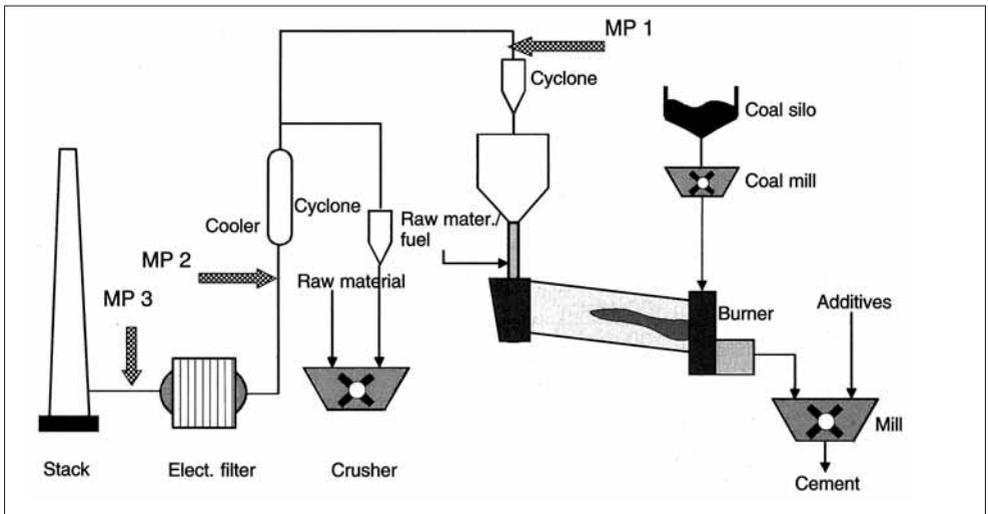


Fig. 25: Process flow chart of cement production with measuring points

Measuring point locations and analysis tasks

- MP 1 between calcinator and cooler to determine a plant balance
- MP 2 between cooler and filter to determine plant balance and filter efficiency
- MP 3 at the stack for emission monitoring (compliance with regulations)

Component	MP 1 in raw gas		MP2 and 3 in clean gas		Limit values
	Typ. values	Meas. range (extended)	Typ. values	Meas. range (extended)	
O ₂	up to 10%	0 ... 21 %	see raw gas		10%
CO	100 ... 10000 ppm	0 ... 10000 ppm (0,1 ... 20%)	see raw gas		
CO ₂	ca. 20 ... 40%	0 ... 25% (0,1 ... 100%)	see raw gas		
SO ₂			low	0 ... 5000 ppm	400 mg/m ³
NO _x			200 ... 700 ppm	0 ... 5000 ppm	500 mg/m ³
Dust	up to 100 g/m ³	up to 100 mg/m ³			50 mg/m ³
Temp.	300-400 °C		100-150 °C		
Flow					
Humid.					

Table 32: Typical and limit values of a cement production plant

Comments to this application

1. High dust loading of raw gas and sometimes of ambient air
2. Very high concentration of CO₂, partially outside the measuring range
3. The O₂ sensor is, at high O₂ concentrations, cross-sensitive against high CO₂ concentrations
4. Gas flow measurements are not possible at high dust concentrations and high gas flow velocities
5. The sampling probe must be grounded when mounted at a stack built of bricks!
6. Depending on the kind of fuel also limit values of lead (as dust) as well as of thallium and cadmium may be relevant.

5.3.2 Production of ceramics/porcelain

The term *ceramic* describes various kinds of material resp. products made from clay and additives and solidified by firing at high temperatures. The raw materials are Kaolin (a clay of certain composition), quartz (SiO_2) and feldspars (a rocky mineral of different silicates). The materials are prepared by grinding, washing, filtering, and mixing, pass then through the shaping processes and are, at the end of the process, fired in a tunnel kiln in several steps: pre-firing at appr. $900\text{ }^\circ\text{C}$, firing (sintering) at $1400\text{ }^\circ\text{C}$ and finally cooling. Colors and glaze are applied either during the sintering phase or in a separate step. Firing temperature and the composition of the oven atmosphere are decisive for the quality (solidity and appearance) of the final product. The exhaust gases of the oven pass through several gas cleaning installations; very often the collected powdered material is recycled to the process. In Germany the exhaust gases, regarding their content of pollutants, must comply with the regulations of the TI air.

Use of gas analysis for e.g.

- Optimum adjustment of the burner for fuel saving
- Control of gas composition for securing product quality
- Monitoring the level of drying for process control
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

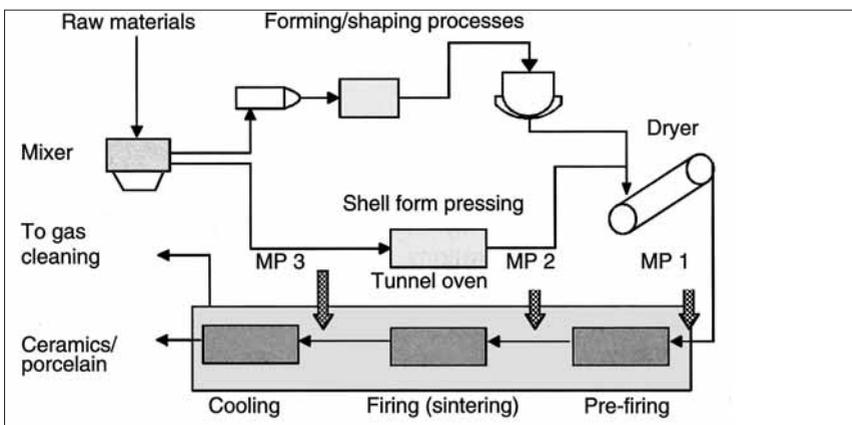


Fig. 26: Process flow chart of ceramic production with measuring points

Measuring point locations and analysis tasks

- MP 1-3 in the raw gas between the different firing steps to optimize burner adjustment, to secure high and constant product quality, and to determine the drying level.
- MP 4 (not shown in fig. 26) in the clean gas to monitor the performance of the cleaning installations and the emission concentrations (compliance with regulations).

Measured component	Typical values		Limit values
	MP 1-3 in the raw gas	MP 4 in the clean gas	
O ₂	13 ... 16%	13 ... 16%	18%
NO _x	30 ... 40 ppm	30 ... 40 ppm	200 mg/m ³
NO			
NO ₂			
CO	40 ... 60 ppm	40 ... 60 ppm	100 mg/m ³
CO ₂			
SO ₂	700 ... 1300 ppm	450 ... 900 ppm	500 mg/m ³
HCl			
HF			
Dust			
Gas temp.			
Humidity	10 ... 14%	10 ... 14%	

Table 33: Typical and limit values of a ceramic processing plant

Comment to this application

1. Aggressive components (HF, HCl) may be present in the exhaust gas. Therefore the use of a heated sampling system is recommended.

5.3.3 Production of bricks

Bricks are manufactured from clay that is fired in brick kilns. The raw materials are crushed, mixed and dried to a given level of humidity and then pass through a forming and drying process before they are placed on a car riding through the tunnel oven for firing at 900-1300 °C.

The flue gases mainly include dust particles but also sulfur and nitrogen oxides or HF may be present.

Use of gas analysis for e.g.

- to perform optimum burner adjustment (fuel saving)
- to ensure product quality
- to determine the level of drying
- to monitor compliance with the emission regulations

Process flow chart and measuring points

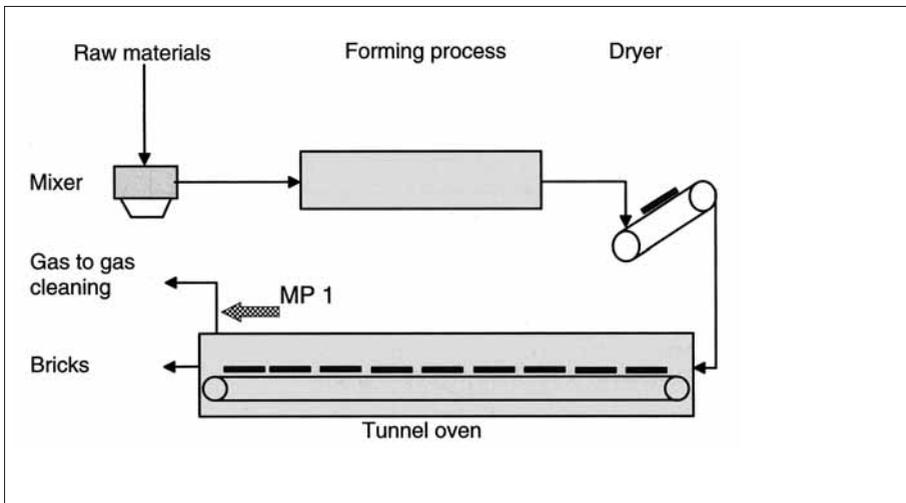


Fig. 27: Process flow chart of brick production with measuring point

Measuring point locations and analysis tasks

- MP 1 at the tunnel oven for optimum burner adjustment, to ensure high and constant product quality, and to determine the level of drying
- MP 2 (not shown in fig. 27) in the clean gas to monitor performance of the cleaning process and the emission concentrations for compliance with the regulations

Measured components	Typical values	Limit values
	MP 1 at the tunnel oven	MP 2 in the clean gas
O ₂	16%	
NO _x		
NO		
NO ₂		
CO	1600 ... 1800 ppm	
CO ₂	3 ... 5%	
SO ₂		
Dust		
Gas temp.		
Humidity		

Table 34: Typical values of brick production

5.3.4 Glass production

Glass production includes a variety of different products with hollow glass ware and flat glass as major categories.

Different raw materials are used; important are sand, soda, and limestone with specific additives (e.g. metal oxides) including recycled glass. The raw materials are crushed, mixed and then fed into the melting furnace as mixed conglomerate. A distinction is made between furnaces with batch ore continuous operation. The process operates at temperatures up to 1500 °C. Furnace design and firing process details vary considerably. Natural gas, fuel oil, and electricity are used for energy supply and additives such as nitric acid are used to homogenize the molten mass.

The exhaust gases mainly contain dust, sulfur and nitrogen oxides (resulting from the high temperatures) as well as compounds of fluorine and chlorine from the raw material and the added waste glass materials. The exhaust gases must pass through various purification stages before they are released to the atmosphere. In Germany their content of pollutants must comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Optimum burner adjustment (Energy saving)
- Ensurance of product quality
- Extension of plant life time
- Emission limit value control

Process flow chart and measuring points

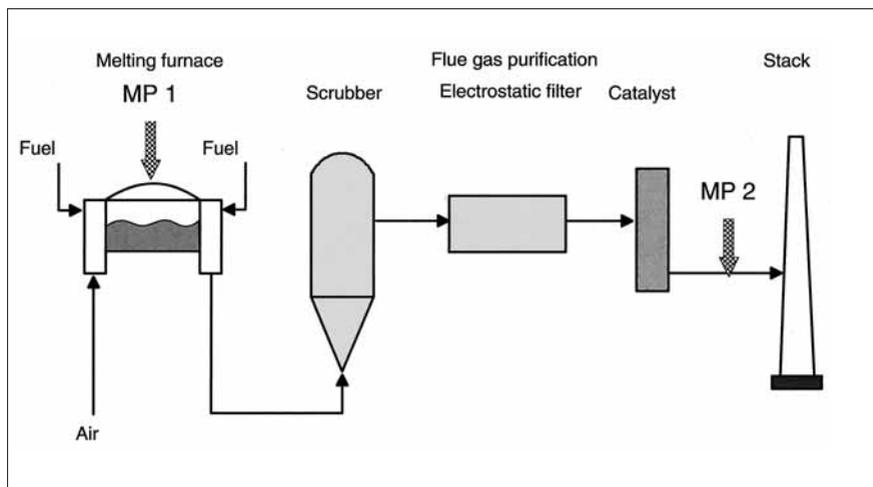


Fig. 28: Process flow chart of a glass melting plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace for increased plant life time, reduction of fuel consumption and product quality control.
- MP 2 in the clean gas behind gas purification for gas cleaning control and for emission monitoring (compliance with regulations).

Measured value	Typical values		Limit values	
	MP 1 at the furnace	MP 2 behind gas purification	Gas firing	Oil firing
O ₂	0 ... 9%		3%	3%
NO _x	30 ... 40 ppm			450 mg/m ³
NO	800 ... 3000 ppm			
NO ₂	0 ... 100 ppm		200 mg/m ³	250 mg/m ³
CO	0 ... 1000 ppm		100 mg/m ³	170 mg/m ³
CO ₂	35 ... 45%			-
SO ₂	0 ... 5000 ppm			1100 mg/m ³
Cl comp.				30 mg/m ³
F comp.				5 mg/m ³
Dust				50 mg/m ³
Gas temp.	1400 ... 1600 °C			
Humidity				

Table 35: Typical and limit values in a glass melting plant

Comments to this application

1. The exhaust gas may be very humid with the danger of causing condensation in the sampling probe. Therefore the use of a heated sampling system is strongly recommended.
2. The concentration of CO₂ is high and will often exceed the measuring range.
3. The oxygen content of the air near the furnace may drop below 21%. The fresh air supply hose therefore should be installed from the outside of the building.
4. The temperature near the furnace may rise up to 70 °C. Therefore the use of a heated sample line is recommended.
5. The dust content of the raw gas can reach 400 mg/m³.

5.3.5 Production of quicklime

Quicklime is an expression for CaO that is produced from Calcit (CaCO_3) by firing it at temperatures of 700-900 °C. For that continuously operated furnaces of different design are used (shaft or rotating kilns) which differ in the principle of how calcit and fuel (coke and gas) are fed to the firing chamber. Quicklime is used as additive in the iron and steel industry, in the chemical industry, as building material and also in the environmental area as absorption substance for flue gas purification plants.

The exhaust gases pass through several gas purification stages before they are released to the atmosphere. In Germany their content of pollutants must comply with the regulations of the TI Air.

Use of gas analysis e.g. for

- Process optimization (fuel reduction)
- Monitoring of CO concentration values (process-specific high)
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

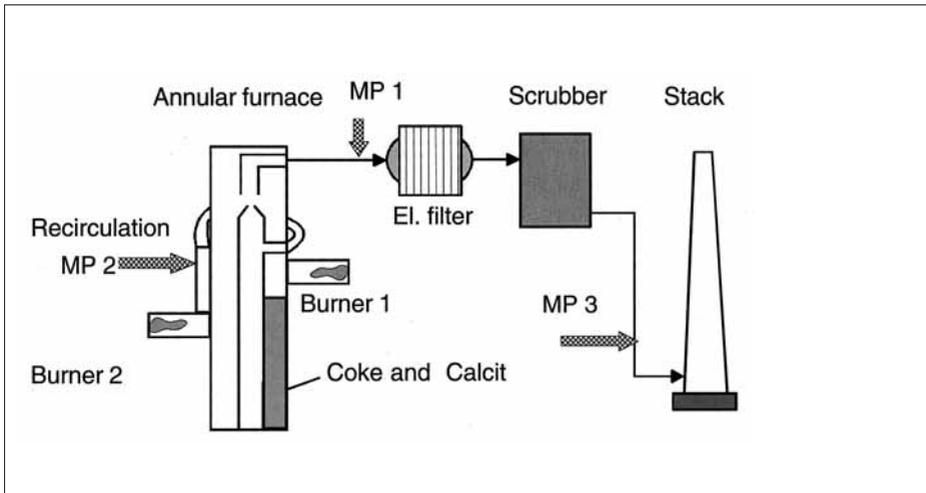


Fig. 29: Process flow chart of a quick-lime production plant with measuring points

Measuring point locations and analysis tasks

- MP 1 in the raw gas for efficiency control (cost reduction) and preventive emission control (high CO values)
- MP 2 in the raw gas (recirculation) for plant balance determination
- MP 3 in the clean gas for monitoring the gas purification process and emission values for compliance with the regulations.

Measured value	Typical values		Limit values
	MP 1 and 2 before gas purification		MP 2 at the stack
Furnace	Shaft kiln	Annular kiln	
Fuel	Coke	Natural gas	
O ₂ dry	5 ... 6%	5,5 ... 6%	
O ₂ wet	2 ... 3%	5 ... 5,5	
CO	6 ... 7%	1,5 ... 2%	
CO ₂	28 ... 32%	24 ... 26%	
SO ₂	300 ppm	100 ppm	50 mg/m ³
NO _x	200 ppm	200 ppm	500 mg/m ³
HF			10 mg/m ³
C _{total}			
Gas temper.			
Humidity	5 ... 8%	5 ... 8%	
Dust			50 mg/m ³

Table 36: Measuring ranges and limit values in a quicklime production plant

Comments to this application

1. High dust loading in the ambient air near to the plant
2. High temperatures may exist due to heat radiation; the measuring equipment should be shielded.

5.4 Metal industry

5.4.1 Processing of ores (Sintering)

Metals are produced from the corresponding metal ores through chemical reduction processes. Before that, however, the ores have to be treated properly by processes like sintering or forming pellets (agglomerates of sintered ore). The ore is ground, mixed with additives, formed to pellets, and supplied to a furnace. At temperatures of over 1000 °C the pellet surface melts and the pellets will bake together to a concrete material. In such a shape the ore is suited for further processing e.g. in a blast furnace to produce iron. During the sintering process particulate and gaseous emissions are generated with the dust particles often carrying additional substances such as cadmium, lead, or zinc. SO₂ and NO_x and also compounds of fluorine and chlorine exist as gaseous pollutants.

In Germany the sintering plant flue gases, concerning their content of pollutants, must comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Optimum process operation (energy consumption)
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

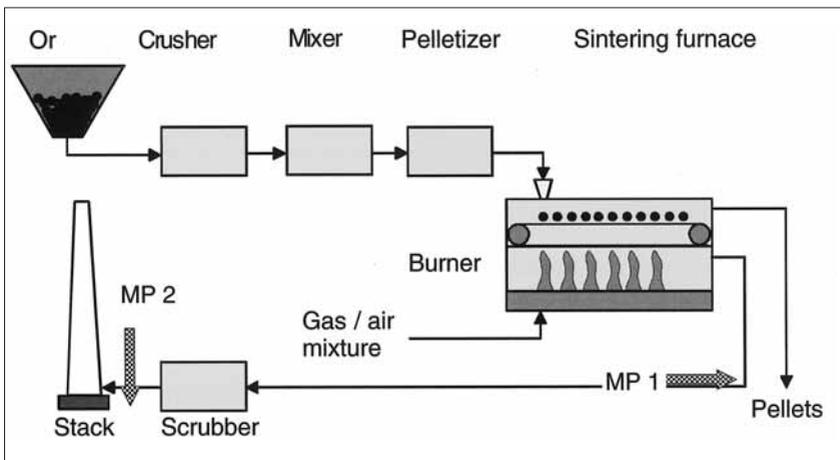


Fig. 30: Process flow chart of a sintering (pelletizing) plant with measuring points

Measuring point locations and analysis tasks

- MP 1 behind the furnace for optimization of the sintering process
- MP 2 in the clean gas at the stack for monitoring the gas purification process and emission concentrations for compliance with the regulations.

Measured value	Typical values		Limit values
	MP 1	MP 2	MP 2
SO ₂	500 ... 3000 mg/m ³	500 ... 600 mg/m ³	
NO _x	150 ... 350 mg/m ³	150 ... 350 mg/m ³	400 mg/m ³
F comp..	2 ... 10 mg/m ³		
Cl comp.	20 ... 60 mg/m ³		
Dust	up to 3000 mg/m ³	50 mg/m ³	50 mg/m ³
Gas temp.	1000-1200 °C		

Table 37: Typical and limit values of a sintering plant

5.4.2 Production of iron (blast furnace process)

Iron is produced by chemical reduction in a blast furnace or in a direct reduction furnace with coke, coal, or natural gas acting as reducing agents. In the blast furnace process the pellets together with coke and other additives are fed to the furnace from above. Hot air as additional energy carrier is blown into the furnace from below. The mixture of reduction gases and hot air ascends in the furnace counter-current to the solid raw material and is extracted at the top of the furnace as blast-furnace gas for further use. The fluid iron together with residual substances is collected and discharged at the bottom of the furnace and usually delivered to a steel plant further processing.

The flue gas (blast-furnace gas) still contains large amounts of CO and dust and is used, after filtering the dust, for heating purposes in the plant or is delivered to separate power stations.

Use of gas analysis for e.g.

- Process optimization (reduction of energy and raw material)
- Monitoring the composition of the blast-furnace gas
- Monitoring the plant for leakage of CO
- Monitoring of emission concentrations for compliance with regulations

Process flow chart and measuring points

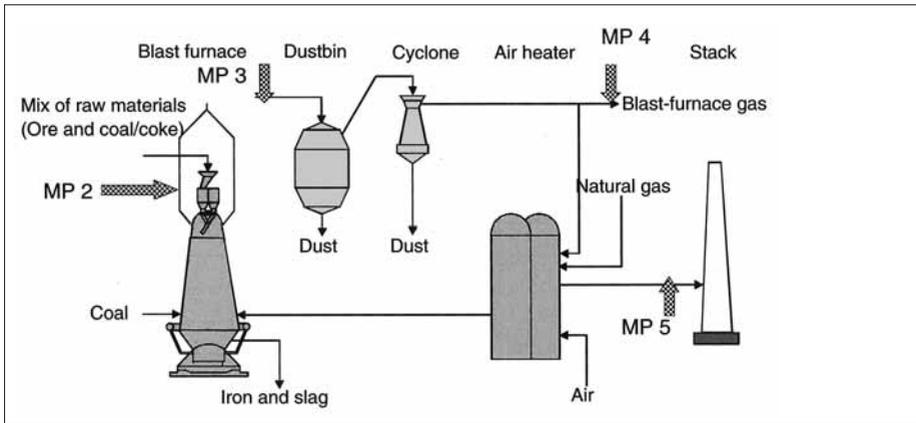


Fig. 31: Process flow chart of an iron (blast-furnace) plant with measuring points

Measuring point locations and analysis tasks

- MP 1 (not shown in fig. 31) in the raw material silo for CO monitoring
- MP 2 in the uptake tube of the furnace for process control
- MP 3 in the downpipe before dustbin for plant balance determination and dustbin explosion protection by monitoring CO
- MP 4 at the blast-furnace discharge for determination of gas composition
- MP 5 at the stack for emission monitoring (compliance with regulations)

Meas. comp.	Typical values				Limit values
	MP 1	MP 2	MP 3	MP 4	MP 5
	0 ... 50 ppm	0 ... 50%	0 ... 50%	0 ... 50%	
CO ₂		0 ... 30%	0 ... 30%	0 ... 30%	
CH ₄		0 ... 4%	0 ... 1%	0 ... 1%	
H ₂		0 ... 15%	0 ... 10%		
Dust			50 ... 100 g/m ³	1 ... 10 g/m ³	50 mg/m ³
Gas temp.		up to 1300 °C	100 ... 500 °C	100 ... 150 °C	100 ... 130 °C

Table 38: Typical and limit values of an iron (blast-furnace) plant with measuring points

Comment to this application

1. Extreme conditions with respect to gas temperature and dust content exist at MP 2! A very special sampling technology is therefore required!

5.4.3 Production of raw steel

Raw steel production is the first step of iron processing by reacting with oxygen in converter plants. Through that the amount of carbon still contained in iron (appr. 4%) is reduced to less than 1%. During this process *converter gas* is generated that still contains a high level of CO and is, after removal of the dust content, further on used in the steel plant. After that it is released to the atmosphere and must, regarding its content of pollutants, comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Optimization of the converter process
- Monitoring the converter gas composition
- Monitoring emission concentrations for compliance with regulations

Process flow chart and measuring points

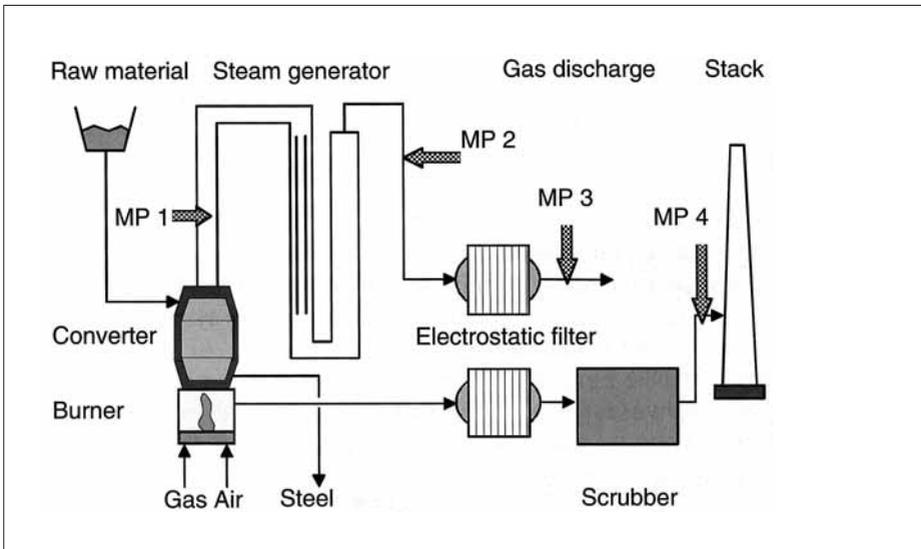


Fig. 32: Process flow chart of a raw steel plant with measuring points

Measuring point locations and analysis tasks

- MP 1 behind converter for process optimization
- MP 2 behind steam generator for process optimization
- MP 3 at the gas discharge for monitoring gas composition
- MP 4 at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values/ranges			Limit values
	MP 1	MP 2	MP 3	MP 4
CO	0 ... 80%	0 ... 80%	0 ... 80%	1 g/m ³
CO ₂	0 ... 40%	0 ... 20%	0 ... 20%	
SO ₂				500 mg/m ³
H ₂	0 ... 10%	0 ... 10%	0 ... 10%	
O ₂	0 ... 1%	0 ... 1%	0 ... 1%	
Dust	10 ... 50 g/m ³	10 ... 50 g/m ³	20 ... 50 mg/m ³	50 mg/m ³
Gas temper.	appr. 1600 °C	appr. 150 °C		

Table 39: Typical and limit values of a raw steel plant

5.4.4 Coke oven plant

In coke oven plants hard coal is thermally treated in a dry distillation process under deficiency of oxygen and at temperatures of 800 °C and above. The objective of that process is the production of coke with its very high content (97%) of carbon and low level of volatile substances for industrial use in metallurgy. *Coke gas* is produced during the process and is further used.

Coal of special quality is distilled in the furnace in dry atmosphere over appr. 15 hours and discharged afterwards to a cooling process which is usually a dry cooling in a shaft cooler. Thus a recovery of energy is possible through a waste heat boiler including reduction of pollutant emission. Pollutants, besides dust, are SO₂, NO_x, CO, and organic compounds. In Germany the exhaust gases, regarding their content of pollutants, must comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Optimization of the coke oven process
- Monitoring the coke oven gas composition for further use
- Monitoring the gas cleaning process and the emission levels for compliance with regulations

Process flow chart and measuring points

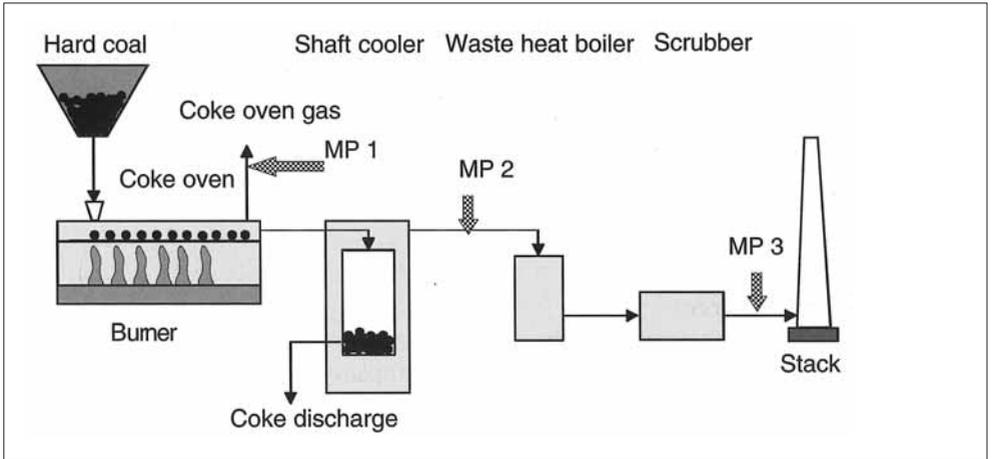


Fig. 33: Process flow chart of a coke oven plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the coke oven gas discharge for monitoring gas composition
- MP 2 behind shaft cooler for optimization of the coke drying process
- MP 3 at the stack for emission monitoring (compliance with regulations)

Measured component	Typical values		Limit values
	MP 1	MP 2	MP 3
O ₂			5%
CO			
SO ₂			800 mg/m ³
NO _x			500 mg/m ³
H ₂			
Dust			20 mg/m ³
Gas temper.			

Table 40: Limit values of a coke oven plant

5.4.5 Production of aluminum

Aluminum is produced through electrolysis of aluminum oxide (alumina). Aluminum is created in a melt of cryolite at a temperature of appr. 950 °C in which anodes made from carbon are positioned. As a direct current voltage is applied to the anodes the alumina is disposed into aluminum and oxygen. The alumina accumulates at the bottom of the furnace, is discharged from there, further processed and finally cast into bars. Electrolytic furnaces exist in different design, nowadays fully encapsulated furnaces are very common. Pollutants are generated during electrolysis including dust, compounds of fluorine as well as SO₂ and CO resulting from the electrodes burning up. The dust material usually is collected from the filters and recharged into the process.

In Germany the flue gases, regarding their pollutant concentrations, must comply with the regulations of the TI Air.

Use of gas analysis for e.g.

- Process optimization
- Monitoring the performance of the sorption reactor
- Monitoring the emission concentrations for compliance with the regulations

Process flow chart and measuring points

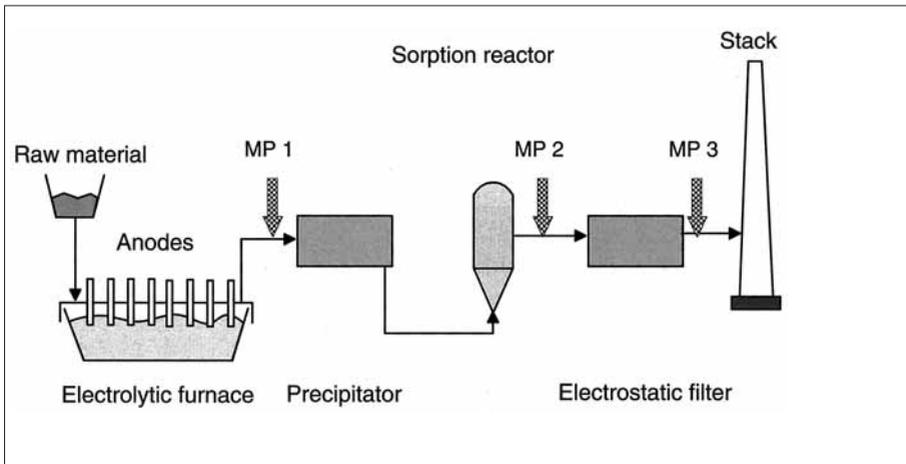


Fig. 34: Process flow chart of an aluminum plant with measuring points

Measuring point locations and analysis tasks

- MP 1 behind melting furnace for process optimization
- MP 2 behind sorption reactor for performance control
- MP 3 at the stack for emission monitoring (compliance with regulations)

Measured components	Typical values/ranges		Limit values
	MP 1	MP 2	MP 3
CO			
CO ₂			
H ₂			
O ₂			
HF	45 ... 60 mg/m ³		
HCl			3 mg/m ³
C _{total}			50 mg/m ³
Dust	500 mg/m ³		20 mg/m ³
Gas temp.			

Table 41: Typical and limit values of a aluminum plant

5.4.6 Thermal surface treatment (Heat treatment)

Heat treatment is a term for all processes where work pieces, typically made from metal, are exposed to temperature changes in a particular gas atmosphere to obtain certain surface characteristics, e.g crystal structure for hardening the material. The composition of the gas atmosphere is decisive for the specific treatment process:

- In some processes the oxidation of the surface through O₂, CO₂ or H₂O must be inhibited. This is performed by keeping the gas atmosphere neutral with no oxidizing nor reducing potential.
- Other processes have the objective, besides heat treatment, to affect the surface of the parts by reaction with certain substances contained in the gas atmosphere. During carburizing, for instance, carbon is implanted from the gas into the surface and additionally nitrogen during the carburnitriding process. For special applications the removal of carbon from the surface is the objective (decarburizing).

Heat treatment processes are carried out in furnaces in batch or continuous operation at temperatures of 800 to 1200 °C. At the end of the process the parts are discharged into a quenching bath. Sealing of the furnace, exact composition of the treating gas and control of the plant for leaks are factors that influence the process operation.

Use of gas analysis for e.g.

- Control of the furnace atmosphere
- Analysis of the treatment and heating gas composition

Process flow chart and measuring points

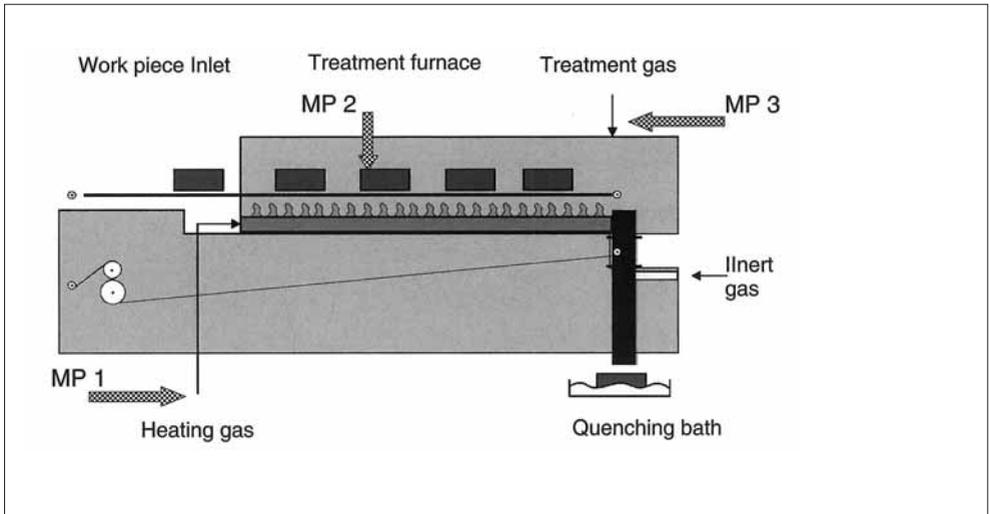


Fig. 35: Process flow chart of a heat treatment plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the heating gas inlet for gas composition monitoring
- MP 2 in the furnace for gas atmosphere control
- MP 3 at the treatment gas inlet for gas composition monitoring and control

The most common measuring components are O₂, CO, CO₂ und CH₄

5.5 Chemical/petrochemical industry

5.5.1 Process Heater

High temperatures are required in almost all plants in the chemical and petrochemical industry to produce final or intermediate products from raw materials. In most cases, superheated steam is used for this purpose and is generated by process heaters. Fig. 36 shows such a plant schematically with a process heater that delivers steam to a double-walled reactor vessel where the production process performs at high temperatures. In Germany the flue gases of process heaters, regarding their content of pollutants, must comply with the regulations of the TI Air or those of the 13. ordinance.

Use of gas analysis for e.g.

- Optimum adjustment of the burner (Fuel saving and emission reduction)
- Monitoring emission concentrations (compliance with regulations)

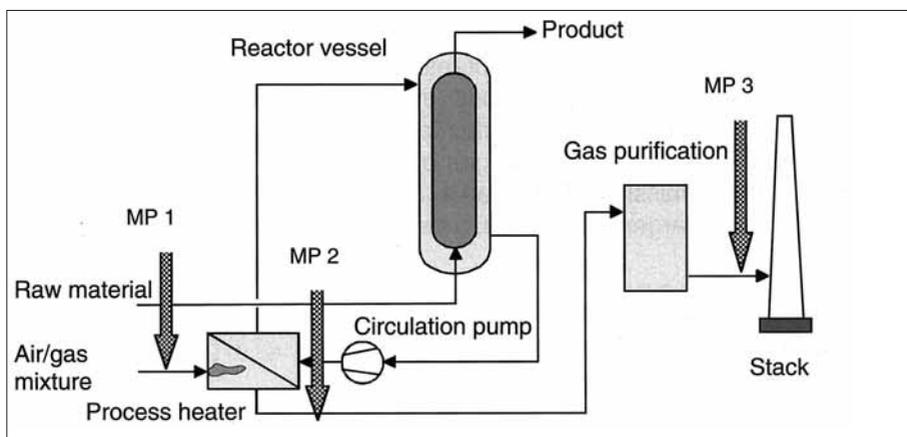


Fig. 36: Process flow chart of a process heater plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the burner for fuel composition control
- MP 2 behind the burner for burner optimization (energy cost reduction)
- MP 3 at the stack for emission monitoring (compliance with regulations)

5.5.2 Refineries

Refineries (more precisely crude oil refineries) comprise a variety of different processing plants at one site where marketable products such as gasoline, diesel oil, plastics, fibres, detergents etc. are produced from crude oil in several processing steps. The production steps proceed at high temperatures causing the need of numerous firing plants in one refinery.

The refining process starts with distillation of crude oil at atmospheric pressure and appr. 350 °C, whereby gasoline, gas oil, or kerosine are separated. The residues are either utilized as heavy fuel oil or further processed in a vacuum distillation at 400 °C to create lubricating oil or bitumen, for instance.

The great variety of products requested by the market, however, cannot be realized through distillation alone. Special processes are used to transform the crude oil distillates into light hydrocarbons (**cracking** processes) with following refinement steps (**reforming** processes). Both processes operate with the use of catalysts at temperatures of 500 °C and above. Fig. 37 shows schematically the distillation columns, the discharge of final and intermediate products and the exhaust gas (tail gas) treatment through incineration and purification.

Refineries are emission sources for pollutants such as SO₂, NO_x, H₂S, particulate matter and many hydrocarbons. Emissions result from diffuse as well as concrete sources, e.g. firing plants. Emission reduction is achieved by using appropriate fuels, special firing measures and flue gas purification plants. In Germany refineries, regarding their emission of pollutants, must comply with the regulations of the TI Air or, in case of larger firing plants, those of the 13. ordinance

Use of gas analysis for e.g.

- Optimum adjustment of the burner (fuel saving and preventive emission control)
- Monitoring the gas purification plant performance
- Monitoring emission concentrations (compliance with regulations)
- Ensuring safety of personell and plants (fire and explosion protection)

Process flow chart

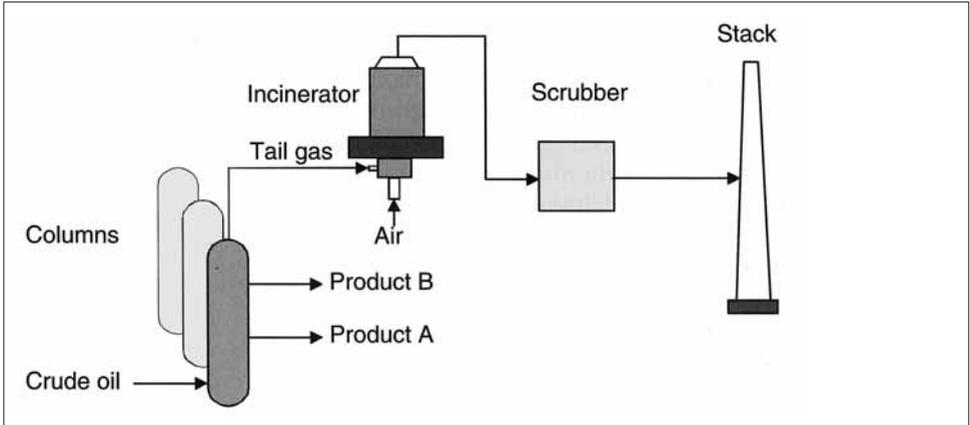


Fig. 37: Process flow chart of a refinery (without measuring points)

Measuring tasks

Because of the very large variety of different plants in a single refinery complex no specific measuring point locations are mentioned here. As an example some limit values of a catalyst regeneration plant as well as of a Claus plant (recovery of sulfur) are given in table 42. Once more, however, it is referred to the large number of firing plants operated in a refinery for steam generation and tail gas incineration, which offer many applications to gas analysis.

Measured component	Limit values	
	Catalyst regeneration plant	Claus plant
O ₂		
CO		
CO ₂		
NO _x	700 mg/m ³	
SO ₂	1700 mg/m ³	
H ₂ S		10 mg/m ³
Sulfur		0,5 ... 3%
Dust	50 mg/m ³	
Gas temperature		
Humidity		

Table 42: Limit values of two different refinery plants

5.5.3 Flare systems

Flare systems are used for safe disposal of excess quantities of waste combustibles from oil-wells, refineries, and other chemical or petrochemical plants or of landfills. Distinction is made between flares with continuous operation and others that are used only in case of emergencies. Flare systems are often equipped with accessories such as steam generators for smoke suppression or additional heaters for burning lean gases. Infiltration of air into the flare stack through leaks or the stack exit is critical because it may lead to a flame flash-back resulting in a destructive detonation in the system.

Use of gas analysis for e.g.

- Monitoring the composition of the off gas
- Detection of leaks

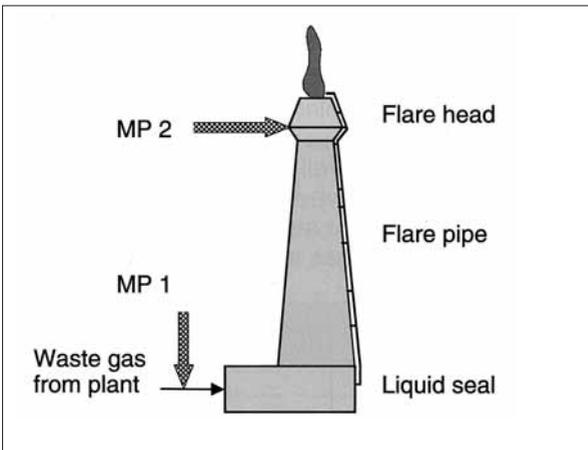


Fig. 38: Typical design of a flare system

Measuring point locations and analysis tasks

- MP 1 at the waste gas entry for monitoring gas composition
- MP 2 at the stack exit for detecting air infiltration

5.5.4 Incineration of waste

Particular liquid or gaseous residues (industrial waste) result from many processes e.g. in chemical or petrochemical industries that can be disposed safely *only by incineration*. For that plants are used that incinerate the waste material in rotating kilns or furnaces at temperatures of 900 to 1300 °C where the waste is converted to ash and slag.

The flue gases pass several purification steps before they are released to the atmosphere. In Germany their content of pollutants must comply with the regulations of the 17. ordinance.

Use of gas analysis for e.g.

Optimization of the incineration process

Monitoring the performance of the purification processes

Monitoring the emission concentrations for compliance with regulations

Process flow chart and measuring points

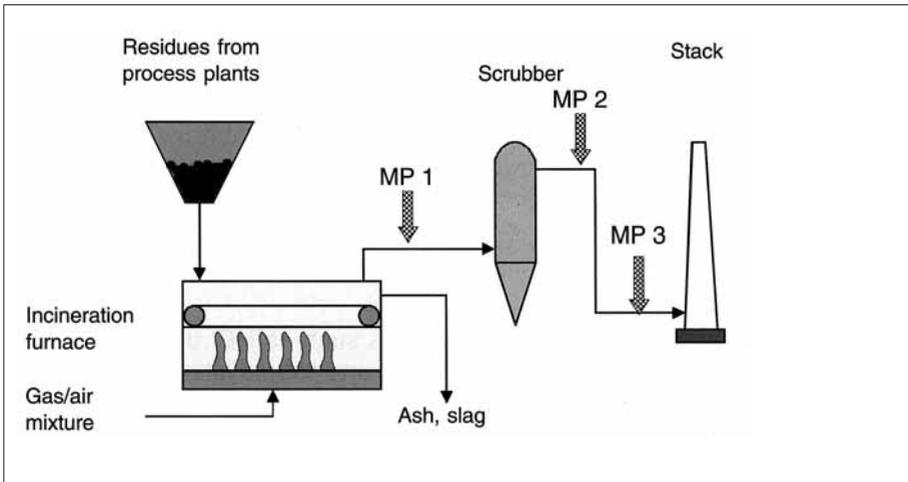


Fig. 39: Process flow chart of an industrial waste incineration plant with measuring points

Measuring point locations and analysis tasks

- MP 1 at the furnace inlet for optimizing waste supply and incineration conditions
- MP 2 at the gas purification for its performance monitoring
- MP 3 at the stack for emission monitoring (compliance with regulations)

Measured component	MP 1 in the raw gas		MP 2 and 3 in the clean gas	
	Typical values	Typical values	Typical values	Limit values
O ₂				11 Vol.-%
NO				-
NO _x				200 mg/m ³
CO				50 mg/m ³
SO ₂				50 mg/m ³
HCl				10 mg/m ³
HF				1 mg/m ³
C _{total}				10 mg/m ³
Dust				10 mg/m ³
Gas temp.				
Humidity				

Table 43: Limit values of a industrial waste incineration plant

Comments to this application

- In the raw gas very aggressive components such as HCl, HF and HCN may be present. Therefore the use of a heated sampling system is strongly recommended. Furthermore the cross sensitivity of the SO₂ sensor with Cl₂ (80%) and HCl (15%) must be considered.
- The fuel material (waste and residues) may vary strongly in its composition resulting in corresponding variations of the measured values.

5.6. Others

5.6.1 Crematoria

Since 1997 the exhaust gases of crematoria in Germany must comply with the regulations of the 27. ordinance, see table 44.

Measured component	Limit values
CO	50 mg/m ³
C _{total}	20 mg/m ³
Dust	10 mg/m ³
Dioxines and furanes	0,1 ng/m ³
O ₂ (Reference value)	11%

Table 44: Limit values of crematoria

5.6.2 Engine test beds

Engine test beds are used during developing and testing of new engines. Distinction is made between engines for vehicles and stationary engines.

Stationary engines are mainly used for generating electricity, in gas compressor stations, in oil and gas production, and in combined heating and power stations. The exhaust gas contains pollutants such as NO_x, SO₂, CO, hydrocarbons, and soot particles in case of diesel engines. The operation of such engines must comply with the regulations of the 4. ordinance and the TI Air.

Use of gas analysis for e.g.

- Measurement during the development process
- Measurements as part of long-term tests
- Measurements as part of certification procedures

Flow chart of a stationary engine system with measuring point

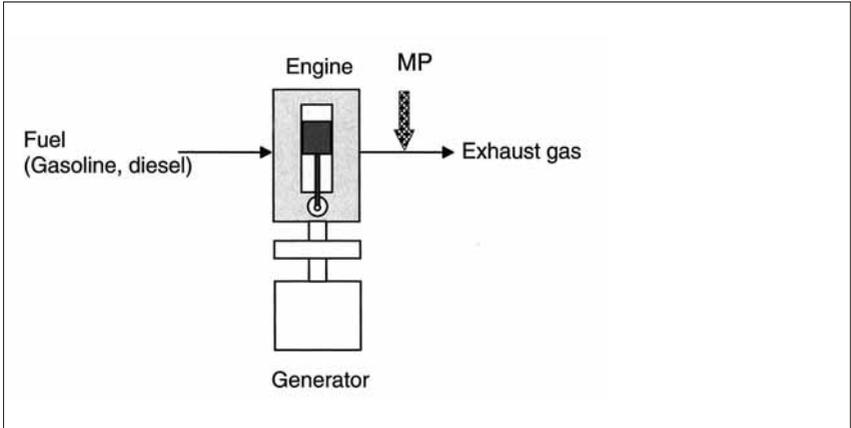


Fig. 40: Flow chart of a stationary engine system with measuring point

6. Testo and Testo gas analyzer

6.1 The company

Electronic measurement of physical and chemical values with portable measuring instruments

Is the competence of the Testo group of companies based in Lenzkirch, Black Forest, Germany for more than 40 years.

Testo GmbH & Co., a medium-sized company, was founded in 1957 and is engaged to develop, manufacture, and sell world wide portable electronic measuring instruments and sensors for

- temperature and humidity
- velocity and pressure
- components in gases (gas analysis)
- water measuring (liquid analysis)
- lux, r.p.m., and sound

Testo's above-average investment in advanced research and development is reflected in a wide range of products that are delivered to branches such as air conditioning, foodstuff, power generation, chemical and process, stone and clay etc. and which are utilized by industrial, craft, and local authority users. Because of its technical capabilities, customer orientation, and product quality Testo is very well accepted world wide as competent supplier and partner.

Portable measuring instruments differ considerably from stationary devices which are installed permanently at the location of measurement.

Differences between both occur from:

- Ambient conditions of *stationary instrument* installations can be optimized in view of air conditioning (analyzer house), vibration protection, stabilized power supply, electromagnetic shielding etc.

Instrument design is not very restricted to weight and dimensions to help reach a high level of measuring performance, analyzer reliability and ease of operation.

- *Portable instruments* are operated normally in harsh and unstable ambient conditions, with no external power supply etc.

Instrument design must comply with strict requirements regarding weight and dimensions resulting usually in lower overall performance.

In view of these contrary instrument development and operation requirements *two different and complementary fields of applications* have been established in gas analysis in the past.

Testo succeeded in *combining both instrument characteristics* as a result of its efficient research and development work. The new testo 350 and testo 360 analyzers are portable instruments but, nevertheless, suitable and certified for certain applications performed previously only by stationary analyzers. This progress is based on testo 350 or testo 360 features such as heated sample lines, sample gas cooler, sample probes with automated cleaning and calibration possibilities, analyzer heating and cooling, and the use of a note book and bus communication for instrument operation as well as data evaluation and processing.

Testo, as the only supplier, offers to day portable gas analyzers that have been tested and certified for long-time measurements. This includes certifications for applications according to the 17. ordinance (17. BImSchV) in Germany and several certifications in the USA. Thus Testo gas analyzers offer a much wider range of applications to the user than before, which may be described as *measurements of flue gases in almost all areas of industry*.

See chapter 5 for characteristic application examples.

On the following pages of this handbook a short survey is provided of the actual line of testo gas analyzers for industrial applications. The objective is to show the diversity of the product line including characteristic features to enable the reader to select the right instrument for his specific analysis task.

Dedicated documentation with complete and detailed information is available for any of the analyzers. Please use the order form at the end of this handbook to get the required literature.

6.2 Characteristic analyzer features

Generals

For more than 15 years, Testo gas analyzers have been proven successfully world wide in many applications. Almost 30,000 instruments are in use and demonstrate day to day performance and reliability of an **advanced technology**.



Fig. 41: Elektrochemical sensor (cell)

To monitor gaseous components, Testo gas analyzer are equipped predominantly with electrochemical measuring cells (fig. 41). This technology, known for low cost and small dimensions, operating under demanding conditions, has been advanced by Testo by intensive research and development work. It is now able to perform routine analysis tasks even on harsh ambient conditions. This concerns the measuring cell itself as well as its environment such as optimization of sampling lines, correct cross sensitivity calculation, reliable sample conditioning, and easy maintenance on site by the user.

Testo complies fully with the high **rate of innovation** in measuring technologies! 70% of the companies total sales is with products younger than 3 years old! This is also correct for the gas analyzer product line which, after the recent introduction of the testo 360, has been expanded once more in spring 2001 by the new testo 350M/XL.

This power of innovation is combined with a very high **standard of quality**. In 1992 Testo gained the ISO 9001 certificate which was reconfirmed in 1997.

The Testo gas analyzer line can be characterized, in short, as follows:

- The analyzers are either hand held units or of the size of a small suitcase that can easily be carried by hand or using a small cart. All analyzers measure continuously.
- The analyzer product line is extensive and includes equipment and accessories of different classes of performance for almost all applications. Single component analyzers are available as well as multicomponent analyzers and analyzer systems.

- The analyzers have successfully passed numerous certification tests including the very demanding one in Germany with respect to the 17. ordinance (see below), and the US EPA Environmental Technology verification (ETV) program.
- The equipment is, compared to competitive gas analyzers, remarkably cost effective in investment and operation (cost of ownership).
- The analyzers require very little maintenance and are, therefore, cost effective in operation. Most of the maintenance can be done by the user, on site.
- Detailed documentation is available with the analyzer delivery. Furthermore Testo supports its customers by providing technical and application literature, see this handbook.

Analyzer Performance (testo 360)

The following data is the product of various certification tests and demonstrate the high performance of the testo 360 technology:

- A performance test for continuous emission measurements was done at a waste incineration plant for the gas components NO, NO₂, SO₂, CO, and O₂. As result the testo 360 was certified in Germany as suitable without limitations for use at plants according the 13. and 17. ordinance and TI Air in continuous operation (maintenance interval 14 days).
- A performance test with respect to DIN 33962 for portable measuring devices for use at plants according to TI air was passed as well without any limitations including fuels such as coal, natural gas, sludge gas, oil, wood, and waste for steam boilers, gas and diesel engines, gas turbines, and waste incinerators.
- In the USA testo 360 complies with the *performance specifications for the measurement of NO_x, CO, and O₂* as well as with the requirements of the *conditional test method CTM-030 and 034*. Additionally it is certified as backup analyzer for stationary equipment.

The **measuring accuracy of the testo 360** analyzer resulting from a TÜV test according to DIN 33962 is better than 1,5% of measuring range end value (span value) for all components. This is better by a factor of 3 and more than specified in DIN 33962 (5%)! See details in table 45.

Measured component	Smallest meas. range	Meas. accuracy [% of span value]	Meas. accuracy absolute
O ₂	21 Vol.%	1,2	0,25%
CO ₂	20 Vol.%	1,2	0,25%
CO	200 ppm	0,7	1,4 ppm
NO	200 ppm	1,3	2,5 ppm
NO ₂	200 ppm	0,5	1,1 ppm
SO ₂	200 ppm	0,2	0,5 ppm
Δp	50 hPa	0,3	0,14 hPa

Table 45: Measuring accuracy of testo 360 (according to TÜV test)

Measuring ranges and stability (drift) of testo 360

(according to the "Suitability Test", established in Germany)

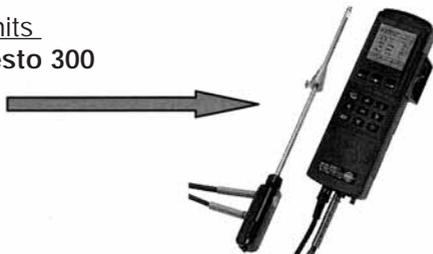
Measured component	Largest measuring range	Smallest meas. range tested	Meas. value fluctuation/2 weeks	
			Zero point	Reference point
O ₂	0 ... 21%	0 ... 21%	<0,02 Vol.%	<0,02 Vol.%
CO	0 ... 3000 ppm	0 ... 60 ppm	<0,1%	<+3,1%
NO	0 ... 1000 ppm	0 ... 146 ppm	<0,1%	<0,1%
NO ₂	0 ... 200 ppm	0 ... 49 ppm	<+1,3%	+1,2%
SO ₂	0 ... 1500 ppm	0 ... 26 ppm	<+0,3%	-1,1%

Table 46: Measuring value ranges and stability of testo 360 (German suitability test)

6.3 The Testo industrial gas analyzers at a glance

The Testo analyzer product line for industrial applications includes basically three different analyzer classes:

The hand held units
testo 325 and testo 300



The **testo 360 analyzer**
 including analyzr box
 and note book



The **testo 350 M/XL analyzer system**
 including several analyzer boxes,
 control unit and notebook



The most important features of these analyzers are presented in table 47.

	testo325-I	testo300-I	testo350 M/XL	testo360
Analyzer category				
Hand held unit				
Portable analyzer				
Number of measuring components				
One component				
Multi-component				
Multiple component (via bus connection)				
Certifications				
Suitability test (4., 13. and 17. ordinance)				
SCAQMD test (California)			planned	
TÜV test (1. ordinance)			planned	
EAM test (Switzerland)			planned	
GOS Standard (GIS)			planned	
ETV test (USA, Canada)			planned	
Preferred applications				
Large-scale firing plants				
Process industry plants				
Official measurements				
Long-time measurements				
Particular features				
Automatic calibration procedure				
Analog output				
Output for printer connection				
Integrated printer				
RS 232 interface				
Additional signal input facility				
Battery operation				
External power supply				
Max. distance sampling point-value display unit	3m	5m	> 200m	200m
Measuring range extension			CO	
Sample gas conditioning integrated				
External sample gas conditioning				
Sensor cells also for H ₂ S and C _x H _y				C _x H _y
Determination of gas humidity integrated				
Det. of velocity, temperature and Δp integrated				

Table 47: Features of Testo gas analyzers

Measuring ranges that are provided by the analyzers for different gas components are important for selecting an analyzer for a certain application task. Table 48 delivers this information.

Gas component	testo 325-I	testo 300XL-I	testo 350		testo 360
			M	XL	
O ₂		0 ... 25%	0 ... 25%	0 ... 25%	0 ... 21%
CO ambient		0 ... 500 ppm	0 ... 500 ppm	0 ... 500 ppm	
COL	0 ... 2000 ppm		0 ... 1000 ppm	0 ... 1000 ppm	
CO		0 ... 10000 ppm	0 ... 10000 ppm	0 ... 10000 ppm	0 ... 10000 ppm
COH	0 ... 40000 ppm		0 ... 40000 ppm	0 ... 40000* ppm	0 ... 40000* ppm
CO ₂		calculated	calculated	calculated	0 ... 25%
SO ₂	0 ... 3000 ppm	0 ... 5000 ppm	0 ... 5000 ppm	0 ... 5000 ppm	0 ... 5000 ppm
H ₂ S				0 ... 300 ppm	
NOL			0 ... 500 ppm	0 ... 500 ppm	
NO	0 ... 1000 ppm	0 ... 1000 ppm	0 ... 3000 ppm	0 ... 3000 ppm	0 ... 3000 ppm
NO ₂			0 ... 500 ppm	0 ... 500 ppm	0 ... 500 ppm
NO+NO ₂			0 ... 3500 ppm	0 ... 3500 ppm	0 ... 3500 ppm
C _x H _y					
Methane min				80 ... 3000 ppm	80 ... 3000 ppm
Methane max				80 ... 50000 ppm	80 ... 50000 ppm
Propane min				80 ... 3000 ppm	80 ... 3000 ppm
Propane max				80 ... 21000 ppm	80 ... 21000 ppm
Butane min				80 ... 3000 ppm	80 ... 3000 ppm
Butane max				80 ... 18000 ppm	80 ... 18000 ppm
CH ₄		0 ... 200/ 10000 ppm		0 ... 200/10000 ppm	0 ... 200/10000 ppm
Leak detec.					
Max. numb. of sensors	1	3	4	6	7

Table 48: List of gas components and measuring ranges of Testo gas analyzers (* with dilution)

6.4 The gas analyzer accessories at a glance

The analyzer (hand held or analyzer box) is built to perform measurements with the relevant accessories. Table 49 shows the different categories of accessories from sampling equipment up to additional data handling options and including accessories for measurements under particular ambient conditions.

Some accessories are analyzer-specific, others are universally usable. Details are available in the relevant technical documentation.

Accessories for..	Description	Application
Sampling	Sampling probes	Sample gas extraction
	Multi-function probes	Sample gas extraction, measurement of temperature and velocity, test gas supply, automated probe cleaning system
	Sample gas conditioning	Drying and cleaning of sample gas to obtain correct measuring values
	Unheated sample lines	Sample gas extraction on uncritical conditions
	Heated sample lines	Sample gas extraction with prevention of condensate formation
Data output and display	DIN A4 printer	Documentation of data
	Box for (6) analog outputs	Documentation of data
System extensions	Box for input of additional sensor signals	Connection of additional sensors (humidity, temperature,...) or external signals (data logging)
Operation	Analyzer cooler	Temperature control of the analyzer at ambient temp. > 45 °C
	Box for calibration gas switching	Automatic calibration gas supply and operation of the multi-function probe
Transport and protection	Transport case	Safe transport of the equipment and protection during long-term measurements

Table 49: List of accessories of Testo gas analyzers

Accessories for sample gas extraction and conditioning

Sample gas extraction and conditioning is, to a large extent, decisive for accuracy and consistency of the measured values and influence the life-time of the measuring equipment. Insufficient sampling will result in

- damages to the measuring equipment by chemically aggressive components of the gas and
- distortion of the measured values due to undefined elimination of certain gas components through chemical reactions with the gas vapor content before the gas arrives in the measuring cell. See also chapter 4.1.2.

Gas sampling probes

In view of different applications Testo offers three categories of sampling probes:

- **an unheated standard sampling probe** with integrated temperature sensor for small and middle-sized firing plants with probe lengths up to 300 mm and gas temperatures of up to 1000 °C,
- **heated ("industrial") sampling probes** of robust design as modular system of various dimensions and materials for use in large-scale firing plants in power stations, process industry plants etc. with flue gas temperatures of up to 1800 °C, and lengths up to 3 meters (9 ft), and
- **a multi-function sampling probe**, that allows continuous measurements carried out over several days through its additionally capabilities of automatic calibration gas supply, dust filter cleaning, and remote control.

Sample gas conditioning

Measurements of humid flue gases will, without appropriate measures, result in incorrect readings for components such as SO₂ and NO₂. This is caused by reactions of these gas components with water which is formed from the humidity through condensation at temperatures below the dew point. The condensate carries undefined (!) quantities of SO₂ and NO₂ away from the measuring gas with the result, that the measured concentrations do not correspond any more with the original gas.

To avoid or (more correct) to quantize this process, sample gas conditioning units (fig. 43) are used. These are gas coolers, operated at a constant low temperature of e.g. 3 °C, that are either integrated in the analyzer or available as separate units. The gas is cooled and the condensate discharged and thus the gas concentrations changed proportionally. This effect can be considered through calibration on the same conditions or through calculations.

Testo offers gas coolers based on the Peltier effect, see chapter 4.1.2.

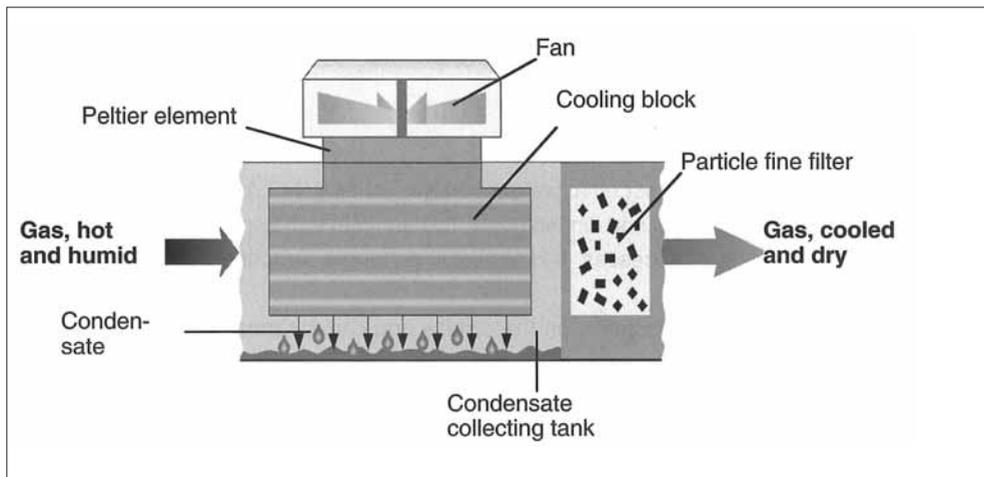


Fig. 43: Testo sample gas conditioning unit (gas cooler and particle fine filter)

Special sample gas hoses

The formation of condensate and thus the influence on the concentration of SO_2 and NO_2 depends also on the time that is available for the chemical reaction. High gas flow velocity will have a positive impact to that. With that in mind, Testo has completed a new development (patent), which makes the heating of the sample hoses unnecessary. Low diameter and a special material of the hose enables the required high gas velocity.

Sampling system solutions

A complete system for sample gas extraction and conditioning comprises sample probe, gas lines (hoses and tubes), coarse and fine filter and cooler. Testo has harmonized the relevant accessory product line resulting in the possibility of combining different units to a required system solution without difficulties. Some of the analyzers (testo 350 M/XL and testo 360) are already equipped with sample conditioning units.

6.5 Technical description and data (Selected)

testo 325-I

Analyzer for industrial flue gases

The testo 325-I is the first step into cost effective gas analysis of SO_2 , NO or CO. It combines precise measurements with ease of operation and limited costs. It is an ideal tool to perform emission "checks" and to monitor thermal treatment processes. It is available as single component hand held device for SO_2 , NO, CO_{low} and CO_{high} .

The measuring results are shown constantly on the display and can, by pressing a button, be printed by the cable-less testo protocol printer together with the actual values of date and time.



Features of testo 325-I

- Easy in handling and operation, large display
- Easy exchange of measuring cells on site by the user
- Magnetic softcase for protection from dirt and shock
- Print out of measured values together with date and time
- Power supply via battery or power supply unit

Fig. 44: testo 325-I analyzer(s)

Testo 325-I SO ₂	<ul style="list-style-type: none"> Emission monitoring of coal and oil fired combustion plants Control of flue gas of desulfurization plants Process control in the glass and ceramic industry
Testo 325-I NO	<ul style="list-style-type: none"> Emission monitoring of engines and firing plants Control of Denox plants Process control in the glass and ceramic industry
Testo 325-I CO _{low}	<ul style="list-style-type: none"> Emission monitoring and adjustment of gas burners Identification of false air leaks in long gas ducts
Testo 325-I CO _{high}	<ul style="list-style-type: none"> Control of gas atmosphere in heat treating plants (hardening furnaces, tunnel furnaces, melting processes) Adjustment of process burners

Table 50: Application examples of testo 325-I gas analyzer

	325-I SO ₂	325-I NO	325-I CO _{low}	325-I CO _{high}
Meas. range	0 ... 3000 ppm	0 ... 1000 ppm	0 ... 2000 ppm	0 ... 40000 ppm
Accuracy	±5% v.MW (>400 ppm) ppm ±20 ppm (< 400 ppm)	5% v.MW (>400 ppm) ppm ±20 ppm (< 400 ppm)	±5% v.MW (>400 ppm) ppm ±20 ppm (< 400 ppm)	±5% v.MW (800 ... 2000 ppm) ppm ±10% v.MW (2000 ... 40000 ppm) ppm ±40 ppm (0 ... 800 ppm)
Resolution	1 ppm SO ₂	1 ppm NO	1 ppm CO	5 ppm CO (0...999 ppm) ppm 0,001 Vol.% CO (1...4 Vol.%)
Response time	80 sec.	60 sec.	60 sec.	70 sec.
Power supply.	Battery or power supply unit			
Battery	4 Mignon cells AA			
Life time	4 h			
Voltages	115/230V / 50/60Hz			
Display	LCD, 2 lines			

Table 51: Technical data (selected) of testo 325-I gas analyzer

testo 300 M/XL-I system overview

Concept

The testo M/XL-I gas analyzer (standard version) includes cells for O_2 and CO and can be further equipped with cells for measuring NO or SO_2 . Change of measuring cells is possible on site by the user without the need of a test gas and field calibration. An interesting option is the integrated capability to measure differential pressure in parallel to gas analysis. When using a Pitot tube the analyzer will also display the gas velocity, the volume flow and the mass flow of CO and NO/ SO_2 . Different Pitot tubes can be used by applying specific factors.

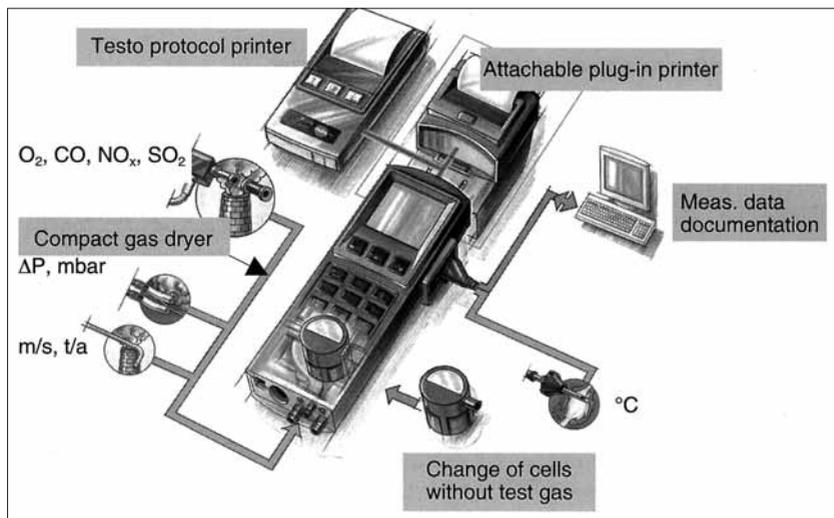


Fig. 45: testo 300 M/XL-I gas analyzer system concept

The compact gas dryer

Is a miniaturized gas conditioning unit that is mounted in the sample line to cool the flue gas down to some °C. The resulting condensate is discharged by an integrated hose pump. This is, particularly, important for long-time measurements because of the aggressive components of the condensate and their impact to the analyzer.

Correct measurements of SO_2

are made possible by cooling the flue gas (see above). This prohibits the absorption of SO_2 by the condensate and thus ensures correct measuring values.

Documentation of the measured values

can be done either via the testo protocol printer or the attachable printer (available with the XL-I) with cable-less data transmission over a distance of 2 m. The first three lines of the printout are freely programmable. This printer offers further capabilities, The printout of a loge for instance.

Data handling

is performed by transmitting the measured data via the RS 232 interface to a PC where they are further processed by the WINDOWS[®] based ECONOMICAL software, e.g. display of the data as table or diagram, display of limit values or on-line operation.

testo 300 M/XL-I

Compact flue gas analyzer

The testo 300 M-I/XL-I flue gas analyzer combines accuracy and reliability of larger measuring systems with very easy operation and low investment costs. It is an ideal tool for e.g. adjustment of burners, emission "checks" and atmosphere composition monitoring of production processes.

Standard version

- Measurement of °C, O₂ and CO
- Calculation of CO₂, air value I as well as of efficiency and flue gas loss

Options

- Measurement of NO or SO₂
- Parallel measurement of partial pressure, velocity and mass flow
- Calculation of flue gas dew point



Fig. 46: testo 300 M/XL gas analyzer

Standard features of testo 300 M-I/XL-I

- Compact design
- Easy operation through function keys and cursor
- Illuminated display with clear text
- Power supply unit or battery operation
- Change of batteries and measuring cells possible on site
- RS 232 interface
- Cable-less protocol printer
- Wide selection of gas sampling probes

Additional features of the XL-I version

- Attachable plug-in printer, also to be used separately
- Extended data memory for 100 complete measurements; option for 400 measurements
- Measurement of differential temperature
- Manual switch off of the CO cell for ongoing measurements at too high CO concentrations

Application examples

- Fast emission monitoring including gas flow velocity measurement; thus also position-check of the stationary gas sampling probe possible
- Measurements for filter check and air leak identification at gas duct locations with difficult access
- Detection of CO nests and tests regarding reducing gas atmosphere in the firing chamber. Gas sampling probe usable up to 1800 °C.
- Burner adjustment through measurement/calculation of air value and efficiency; parallel measurement of pressure, particularly for multi-stages burners

testo 350 M/XL system overview

Concept

For many applications in industry more than one portable analyzers are required. There is a need for time synchronous analysis at different measuring locations without sample point switching, for input of further measuring signals, for links with other analyzers or control systems etc. The testo 350 gas analyzer system complies with these requirements. Up to 8 analyzer boxes, equipped with different sensor combinations, and up to 10 data logger units can be connected to each other via the testo data bus. As an option even a wire-less connection is possible using radio communication. The system is controlled by the control unit including programming and data transfer; interfacing to a PC is possible using the bus interface card of the PC.

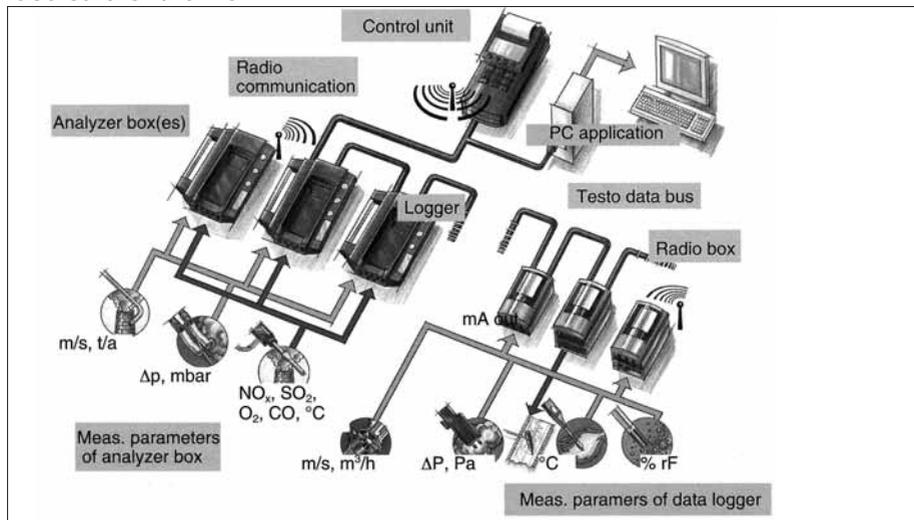


Fig. 47: testo 350 M/XL gas analyzer system concept

Control-Unit

- To be used both for system control and (as hand held in manual operation) for monitoring the "Climate" parameters
- RS232 interface, illuminated display
- Menu driven operation with free programmable function keys
- Integrated data memory (2 MB)
- "Touch panel" operation (option)
- Power supply through analyzer box, battery or power supply unit

Logger

Links to up to 4 sensors; integrated memory for data storage without bus connection

Testo data bus

The system components can be connected via the data bus over a distance of 100 m max.

Radio box

The wire-less radio data communication (option) can be applied to distances of up to 300 m in open landscape; can be integrated into analyzer box and control unit; additional unit for hand held climate-box.

testo 350 M/XL

A versatile gas analyzer system

The testo 350 is a versatile, portable gas analyzer system that can be adapted to various application tasks. The standard version testo 350 M includes control unit, analyzer box, and a gas sampling probe. The gas components are (4 cells maximum) O₂, CO, NO (option), NO₂ or SO₂ (option); additionally temperature and differential pressure sensors included. The values of CO₂, qA and some others are calculated as usual. The control unit is detachable and may be used separately as measuring device for parameters such as temperature, differential pressure including the calculated values ("climate" box). The analyzer box comprises a complete sample gas conditioning unit including Peltier cooler for controlled condensate disposal. The testo 350 XL version offers additionally the measurement of C_xH_y and H₂S (6 cells maximum).



Fig. 48: testo 350 M/XL gas analyzer

Measuring ranges

Component	Meas. range 350 XL
O ₂	0 ... 25 Vol.%
NO	0 ... 3000 ppm 0 ... 6160 mg/m ³
NO ₂	0 ... 500 ppm 0 ... 1030 mg/m ³
NO _x (NO+NO ₂)	0 ... 3500 ppm 0 ... 7190 mg/m ³
SO ₂	0 ... 5000 ppm 0 ... 14650 mg/m ³
CO ₂	calculated
CO	0 ... 10000 ppm 0 ... 12560 mg/m ³
C _x H _y	0 ... 5 Vol.%
H ₂ S	0 ... 300 ppm

Table 52: testo 350 M/XL measuring ranges

Features

- Operation independent of external power supply even with sample gas conditioning
- Analyzer box includes data storage even without control unit
- Easy operation through touch panel
- Measuring range extension for CO (option)
- Choice of different sampling probes according to application
- Very high accuracy for CO and NO in low concentration ranges

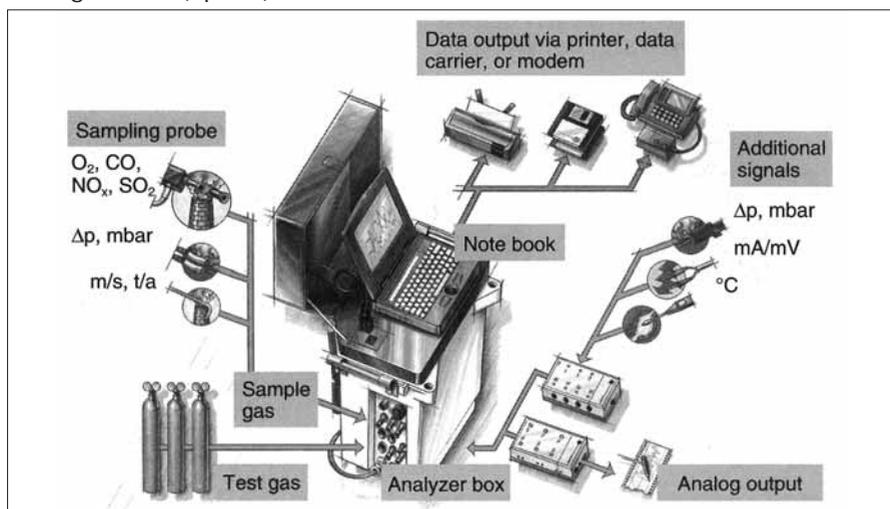
Application examples

- Adjustments of all sorts
 - Monitoring concentrations values of raw and clean gas over longer time periods
 - Control of gas atmosphere in all sorts of process furnaces
 - Maintenance work on stationary engines, e.g. in block-type power stations
 - Check of gas pressure and velocity in flue gas and inlet air
-
- Suitable probes (gas, velocity, temperature, heated or unheated) are available for different application tasks
 - Temperature sensors available for measurements on surfaces, in gases or in liquids

testo 360 system overview

Concept

The testo 360 system comprises analyzer box, note book, and gas sampling probe. The analyzer box includes the analyzing units (7 measuring cells maximum) and modules for humidity measurement (option), measuring range extension (gas dilution, option), velocity measurement (option), and sample gas conditioning (Peltier cooler). The sample gas is supplied by the sampling probe via a heated hose to the analyzer box, where the gas concentrations are determined. The measured signals of Δp , mbar, m/s and t/a are supplied by the gas sampling probe or by separate sensors. Additional sensor signals can be transmitted to the system via the external signal box (option).



Operation and data processing

The note book is, during long-term operation, protected from outside influences (rain etc.) by a lockable cover. Measurements are controlled and the data stored as ASCII files by means of a user-friendly WINDOWS[®] software. The data may be implemented into arbitrary data handling programs or transmitted via modem to a data communication network from where, vice versa, also remote control of the system is possible. For obtaining constant accuracy during long-term measurements test gas can be supplied to the probe via the test gas switch box (option) or

to the analyzer via a separate input (option).

Analyzer handling

The testo 360 can be carried conveniently by one person using the special trolley, which may be disassembled if required and which keeps the analyzer at the right height for working.

Maintenance and service

The testo 360 design allows the user to change sensors on site by himself without the need of a test gas.

testo 360

Portable multicomponent gas analyzer for industrial applications

testo 360 is a powerful and versatile gas analyzer which complies with the high requirements of gas analysis in environmental (emission) and industrial applications. Because of its compact design the testo 360 can be transported conveniently in a private car. It is suitable and certified for short term single measurements as well as for continuous operation over a longer period of time.



Fig. 50: testo 360 on the trolley

Features of testo 360

- Fully comparable regarding accuracy with stationary measuring equipment
- All measuring parameters comprised in one device
- Long-time sensor stability, no test gas required on site
- Low absorption Peltier cooler based sample gas conditioning unit integrated (patented)
- Operable also on extreme ambient conditions
- Programmable fresh air and test gas supply cycles for high accuracy during long-term measurements
- Data logging operation over days and weeks without personnel expenses
- Very high measuring ranges up to the % range with high measuring accuracy at low concentrations
- Low maintenance requirements (low costs)

Measuring ranges

Component	Standard measuring range (MR)	Highest MR with MR extension
O ₂	0 ... 21 Vol.%	0 ... 21 Vol.%
NO	0 ... 3000 ppm 0 ... 6160 mg/m ³	0,1 ... 6,0 Vol. %
NO ₂	0 ... 500 ppm 0 ... 1030 mg/m ³	0,1 ... 1,0 Vol. %
NO _x (NO+NO ₂)	0 ... 3500 ppm 0 ... 7190 mg/m ³	0,1 ... 7,0 Vol. %
SO ₂	0 ... 5000 ppm 0 ... 14650 mg/m ³	0,1 ... 10 Vol. %
CO ₂	0 ... 25 Vol. %	0,1 ... 100 Vol. %
CO	0 ... 10000 ppm 0 ... 12560 mg/m ³	0,1 ... 20 Vol. %
C _x H _y	500 ... 100000 ppm	
Humidity	2,0 ... 31 Vol. % H ₂ O +15 ... +70 °C dew point	
Velocity	5 ... 40 m/s	

Tests and certifications

Germany

Unlimited certification for use in plants according to 13. and 17. ordinance and TI Air

USA (selected)

Performance Specification for NO_x, CO and O₂; In California for NO_x

Russia

GOS approved for all parameters

Switzerland

Certified for official emission measurements by BUVAL

Table 53: testo 360 gas analyzer measuring ranges

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 testo 300XL-I testo 350-XL

I propose the following improvement / supplement to this handbook:

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