2) What is combustion efficiency?

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

1. The chemistry of the fuel.

2. The net temperature of the stack gases.

3. The percentage of oxygen or CO_2 by volume after combustion.

COMBUSTION PROCESSES AND THEIR COMBUSTION EFFICIENCY RANGES

PROCESS	TYPICAL COMBUSTION EFFICIENCY RANGE
HOME FIREPLACE	10-30 %
SPACE HEATER	50-80 %
COMMERCIAL GAS BOILER	70-82 %
RESIDENTIAL GAS BOILER WITH ATMOSPHERIC BURNER "LOW EFFICIENCY"	70-82 %
OIL BURNER HEATING SYSTEM	73-85 %
INDUCED DRAFT FURNACE "MEDIUM EFFICIENCY"	74-80 %
BOILER WITH GAS BURNER	75-85 %
CONDENSING FURNACE (GAS & OIL) "HIGH EFFICIENCY"	85-93 %

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

Combustion efficiency relates to the part of the reactants that combine chemically. Combustion efficiency increases with increasing temperature of the reactants, increasing time that the reactants are in contact, increasing vapour pressures, increasing surface areas and increasing stored chemical energy. One way of increasing the temperature of the reactants and their vapour pressures is to preheat them by circulating them around the combustion chamber and throat before being injected into the combustion chamber. The specific heat of combustion is a chemical property that refers to the amount of energy that can theoretically be extracted from a fuel at 100 % combustion efficiency. The heating value is a more realistic term and does not include the condensation of the water vapour produced. It is thus more easily applied to real combustion processes.

Air preheating is one method used in steel works, for instance, to increase combustion efficiency. This uses the heat in the flue gases to heat one of a pair of chambers and the inlet air passes through the other one. The use of the chambers is switched as soon as the one chamber has reached temperature, so the air passes through the heated chamber. This is one of the simplest and best methods of increasing combustion efficiency in this kind of process. Such preheaters are standard euipment these days for larger systems.

The introduction of the condensing burner has led to the strange situation where combustion efficiencies in excess of 100 % are reported. These devices also use the specific heat of vaporisation as a surce of energy and therefore have an increased yield, provided they are operated in the

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

$$S_L = \left(T_{gas} - T_{amb}\right) \bullet \left(\frac{A1}{CO_2} + B\right)$$

where:

S_L -chimney loss - the percentage of heat produced in combustion process which is convected with the combustion gases.

T_{gas} - flue gas temperature

T_{amb} -the temperature of the boiler inlet air (it is assumed by the analyser to be the ambient temperature)

CO_2 -the calculated (on the basis of oxygen concentration and CO_{2max}) amount of CO_2 in combustion gases, expressed in [% vol]

A1, B - factors characteristic for a given fuel type (see Table 6)

Based on the calculated chimney loss the analyser estimates the efficiency of the combustion process η (this should not be confused with total boiler efficiency)

$$\eta = 100\% - S_L$$

where: η - combustion efficiency

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

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

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

It is possible to take into account the efficiency reduction caused by incomplete combustion. This loss is represented by a quantity called the loss by incomplete combustion I_L. It determines the percentage of energy loss caused by the presence of flammable gases (in this case mainly CO) in the combustion gases. There will be some formation of methane in the flue gases, which will also add to the level of incomplete combustion. In most cases, however, this will be a negligible amount and can generally be ignored. The loss caused by incomplete combustion is calculated on the basis of the measured CO concentration in the combustion gases according to the following formula:

$$IL = \frac{\alpha \bullet CO[\%]}{CO[\%] + CO_2[\%]}$$

where:

CO, CO_2 - volume concentrations of CO and CO_2 in the combustion gases

α - the factor specific for a given fuel

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

$$\eta^* = \eta - IL$$

The last combustion parameter calculated by madur instruments is the excess air factor λ. This factor expresses how many times the amount of air supplied to the boiler is larger than the minimum amount which is theoretically necessary to burn the fuel completely. The system calculates the λ factor on the basis of the known CO_{2max} value for the given fuel and the calculated concentration of CO_2 in the combustion gases using the formula:

$$\lambda = \frac{CO_{2max}}{CO_{2meas}}$$

The above formula may be transformed into the form:

$$\lambda = \frac{20.95\%}{20.95\% - O_{2meas}[\%]}$$

I Heating value

1. Procedure

The heating value of a material is measured using the following system:

The sample of natural gas is passed through a wet gas meter for measuring and humidifying before being burned.

The air for combustion is also humidified before combustion.

The air and natural gas are then mixed in the Junkers Calorimeter and burned.

The exhaust gas is passed through a cooling spiral in the calorimeter and cooled to ambient temperature. The heat produced during combustion is passed completely into the coolant. The water formed during combustion is also condensed and measured.

2. Protocol

The following values are measured every 60 seconds for a period of 10 minutes:

- Gas temperature Θ_{gas}
- Exhaust gas temperature Θ_{rgas}
- Air temperature Θ_{luft}
- Coolant inlet temperature Θ_{wein}
- Coolant outlet temperature Θ_{waus}
- Gas gauge pressure P_{gas}

The coolant is collected in a bucket during the test and weighed afterwards. The gas meter is read before the test and after 10 minutes. The quantity of condensate at the end of the test is also noted.

3. Calculation

3.1 Specific heat of combustion $H_{o,n}$

The First Law gives for $H_{o,n}$:

$$H_{o,n} = \frac{\dot{m}_w \cdot \overline{cp_w} \cdot \Delta\vartheta_w}{\dot{V}_{G,n}}$$

Partial pressure of water $P_{s,H2O}$

$$p_{s,H_2O(19{,}628^\circ C)} = \frac{(\vartheta_g - \vartheta_u) \cdot (p_{s,o} - p_{s,u})}{(\vartheta_o - \vartheta_u)} + p_{s,u}$$

$$p_{s,H_2O(19{,}628^\circ C)} = \frac{(19{,}626^\circ C - 19^\circ C) \cdot (0{,}023370 bar - 0{,}021960 bar)}{(20^\circ C - 19^\circ C)} + 0{,}021960 bar$$

$$p_{s,H_2O(19{,}628^\circ C)} = 0{,}022922 bar$$

Gas pressure P_g:

$$p_g = p_\infty + p_{eG} - p_{s,H_2O(\vartheta_g)}$$

$$p_g = 1{,}0048 bar + 0{,}0035 bar - 0{,}022922 bar$$

$$\underline{p_g = 0{,}985378 bar}$$

Converting the volume to STP using the ideal gas formulae:

$$V_{g,n} = V_g \cdot \frac{T_n}{T_G} \cdot \frac{p_g}{p_n} = 0{,}028350 m^3 \cdot \frac{273{,}15 K}{292{,}832 \mathrm{K}} \cdot \frac{0{,}985378 bar}{1{,}01325 bar}$$

$$\underline{V_{g,n} = 0{,}025717 m^3}$$

Calculation of cp_{mw}:

$$cp_{mw}\Big|_{10{,}6^\circ C}^{25{,}8^\circ C} = \frac{cp_m\Big|_{0^\circ C}^{25{,}8^\circ C} \cdot \vartheta_{waus} - cp_m\Big|_{0^\circ C}^{10{,}6^\circ C} \cdot \vartheta_{wein}}{\vartheta_{waus} - \vartheta_{wein}} = \frac{4{,}1915 \, ^{kJ}\!/_{kg \cdot K} \cdot 25{,}8 K - 4{,}202 \, ^{kJ}\!/_{kg \cdot K} \cdot 10{,}6 K}{25{,}8 K - 10{,}6 K}$$

$$\underline{cp_{mw}\Big|_{10{,}6^\circ C}^{25{,}8^\circ C} = 4{,}1842 \, ^{kJ}\!/_{kg \cdot K}}$$

Specific heat of combustion:

$$H_{o,n} = \frac{m_w \cdot \overline{cp_{mw}} \cdot \Delta \vartheta_w}{V_{G,n}} = \frac{16,54kg \cdot 4,1842 \,{}^{kJ}\!/_{kg \cdot K} \cdot \left(298,95\mathrm{K} - 283,75\mathrm{K}\right)}{0,025717m^3}$$

$$\underline{\underline{H_{o,n} = 40904,5 \,{}^{kJ}\!/_{m^3}}}$$

3.2 Heating value

The heating value is the specific heat of combustion less the specific heat of evaporation for the condensate.

$$H_{u,n} = H_{o,n} - \frac{m_k}{V_{G,n}} \cdot r_{H_2O(25°C)} = 40904,5 \,{}^{kJ}\!/_{m^3} - \frac{42 \cdot 10^{-6} m^3 \cdot 998,5 \,{}^{kg}\!/_{m^3}}{0,025717m^3} \cdot 2442,5 \,{}^{kJ}\!/_{kg}$$

$$\underline{\underline{H_{u,n} = 36921,50 \,{}^{kJ}\!/_{m^3}}}$$

II. Gas boiler

1. Efficiency and power

This is the measurement of stated heating power and efficiency of a domestic gas boiler, together with the losses due to heat and chemical inefficiency.

2.Equipment

The gas boiler used was a standard household boiler from Junkers/Wernau.

Gas and air pass into the unit and are burnt there. The flue gas passes out through a chimney.

Part of the water circulation system lies above the combustion chamber. This is kept in motion by a circulation pump, which is also part of the gas boiler.

The heat produced is sent to various heat consumers in the laboratory (radiators, heat exchangers).

3. Documentation

The following values are recorded every minute for 10 minutes for calculation of heat output, efficiency and stack losses:

- Gas temperature Θ_{Gas}
- Water outlet temperature Θ_{vl}
- Water inlet temperature Θ_{rl}

- Ambient temperature Θ_a
- Flue gas temperature Θ_{rg}
- O_2 level in flue gas Ψ_{O2}
- Gas gauge pressure P_{gas}
- Ambient pressure P_a
- Time Δt

The following meter readings are recorded at the beginning and end of the period:

- Gas ΔV_{gas}
- Coolant V_{kw}

Flue gas temperature, ambient temperature and CO_2 content are recorded with a flue gas analyser.

4. Calculations

4.1 Heating power

The heating power is calculated as follows:

$$\dot{Q}_N = \dot{m}_w \cdot \overline{cp_w} \cdot \Delta \vartheta_w$$

$$\rightarrow \dot{Q}_N \frac{\Delta V_w}{\Delta t_w} \cdot \rho_{(\vartheta_m)} \cdot \overline{cp_w}\Big|_{\vartheta_{wvl}}^{\vartheta_{wrl}} \cdot \left(\vartheta_{wrl} - \vartheta_{wvl} \right)$$

$$cp_w = \frac{cp_{mwvl}\Big|_{0^\circ C}^{\vartheta_{vl}} \cdot \vartheta_{vl} - cp_{mwrl}\Big|_{0^\circ C}^{\vartheta_{rl}} \cdot \vartheta_{rl}}{\vartheta_{vl} - \vartheta_{rl}}$$

$$cp_w = \frac{cp_{mwvl}\Big|_{0^\circ C}^{81{,}37^\circ C} \cdot 81{,}37K - cp_{mwrl}\Big|_{0^\circ C}^{71{,}68^\circ C} \cdot 71{,}68K}{81{,}37K - 71{,}68K}$$

$$cp_w = \frac{4{,}1865\,{}^{kJ}\!/_{kg \cdot K} \cdot 81{,}37K - 4{,}1855 \cdot 71{,}68K}{81{,}37K - 71{,}68K}$$

$$\underline{cp_w = 4{,}1939\,{}^{kJ}\!/_{kg \cdot K}}$$

$$\dot{Q}_n = \frac{0,261 m^3}{600 s} \cdot 976,8 \, {}^{kg}/_{m^3} \cdot 4,1939 \, {}^{kJ}/_{kg \cdot K} \cdot (81,37 - 71,68) K$$

$$\underline{\underline{\dot{Q}_n = 17,269 \mathrm{kW}}}$$

$\rho_{(Sw)}$ and c_{pm} values are taken from standard tables.

4.2 Heating power

$$Q_F = \dot{V}_{G,n} \cdot H_{u,n} = \frac{\Delta V_G}{\Delta t_G} \cdot \frac{T_n}{T_G} \cdot \frac{p_G}{p_n} \cdot H_{u,n}$$

$$p_G = p_\infty + p_{gas} = 1,0048 bar + 0,0158 bar = 1,0206 bar$$

$$Q_F = \frac{0,3705 m^3}{600 s} \cdot \frac{273,15 K}{294,38 K} \cdot \frac{1,0206 bar}{1,01325 bar} \cdot 36921,50 \, {}^{kJ}/_{m^3}$$

$$\underline{\underline{Q_F = 20,945 kW}}$$

$H_{u,n}$ taken from the calculation of heating value

4.3 Calculated efficiency

$$\eta_N = \frac{\dot{Q}_N}{\dot{Q}_F} = \frac{17,269 kW}{20,945 kW} = 0,82453$$

$$\underline{\underline{\eta_N = 82,45\%}}$$

4.4 Stack loss

$$q_a[\%] = (\vartheta_{rgas} - \vartheta_L) \cdot \left(\frac{A_1}{20,9 - \psi_{O_{2,tr}}[\%]} + B \right) = (174,025 K - 21,35 K) \cdot \left(\frac{0,66}{20,9 - 3,525\%} + 0,009 \right)$$

$$\underline{\underline{q_a = 7,1735\%}}$$

4.5 Combustion efficiency

$$\eta_F = 1 - q_A = 1 - 0,071735 = 0,92826$$

$$\underline{\underline{\eta_F = 92,826\%}}$$

The practical measurement and evaluation of combustion efficiency is described more fully on the linked page, and the calculations carried out by a combustion analyzer to determine stack loss, combustion efficiency and other combustion parameters are to be found in the section on calculations.

5. Discussion

The value $H_{u,n}$ for heating value was used in the calculation of heating power, taking over any errors.

The values for c_{pm} are very close together due to the slight rise of the curve at this point.

This reduces the accuracy with which they can be read. $\Delta\left(cp_m\big|_{0°C}^{\vartheta}\cdot\vartheta\right)$ would be larger if the coolant water could be reduced to room temperature. This would also increase $\Delta\Theta$ and hence reduce the effects of inexact readings from the curve.

III Appendices

1. Measured values

1.1 Heating value

t [min]	V_{gas} [m³]	Θ_{gas} [°C]	Water column [mm]	Θ_{luft} [°C]	Θ_{wein} [°C]	Θ_{waus} [°C]	mw [kg]	Θ_{rgas} [°C]	Vkondensat [ml]	p∞ [bar
0	3.4295	19	35	11.5	10.6	25.8	0	15	0	
1		19.5	35	11.4	10.6	25.8		15		
2		19.5	35	11.4	10.6	25.8		15		
3		19.5	35	11.3	10.6	25.8		15		
4		19.5	35	11.3	10.6	25.8		15.1		
5		19.5	35	11.2	10.6	25.8	8.26	15		
6		20	35	11.3	10.6	25.8		15		
7		20	35	11.2	10.6	25.8		15		
8		20	35	11.3	10.6	25.8		15		
9		20	35	11.4	10.6	25.8		15		
10	4.45785	20	35	11.3	10.6	25.8	8.28	15	42	
Average		19.682	35	11.327	10.6	25.8		15.009		1.0048
Total	0.028350						16.54		42	

1.2 Gas boiler

t [min]	V_{gas} [m³]	Θ_{gas} [°C]	V_{kw} [m³]	Θ_{vl} [°C]	Θ_{rl} [°C]	Θ_{luft} [°C]	Θ_{rg} [°C]	Ψ_{O2} [vol%]	P_{gas} [ml]	p∞ [bar]
0	2518.9135	21	62.89	81.2	71.5	21	176.6	3.6	0.015	
1				81.2	71.5					
2		21.2		81.3	71.6				0.016	

3				81.3	71.7	21.7	174.4	3.5		
4		21.3		81.4	71.7					
5				81.4	71.7				0.016	
6		21.3		81.4	71.7	21.4	172.6	3.5		
7				81.4	71.7					
8		21.3		81.5	71.8				0.016	
9				81.5	71.8					
10	2519.284	21.3	63.151	81.5	71.8	21.3	172.5	3.5	0.016	
Average		21.233		81.373	71.682	21.35	174.025		0.0158	1.0048
Total	0.3705		0.261							

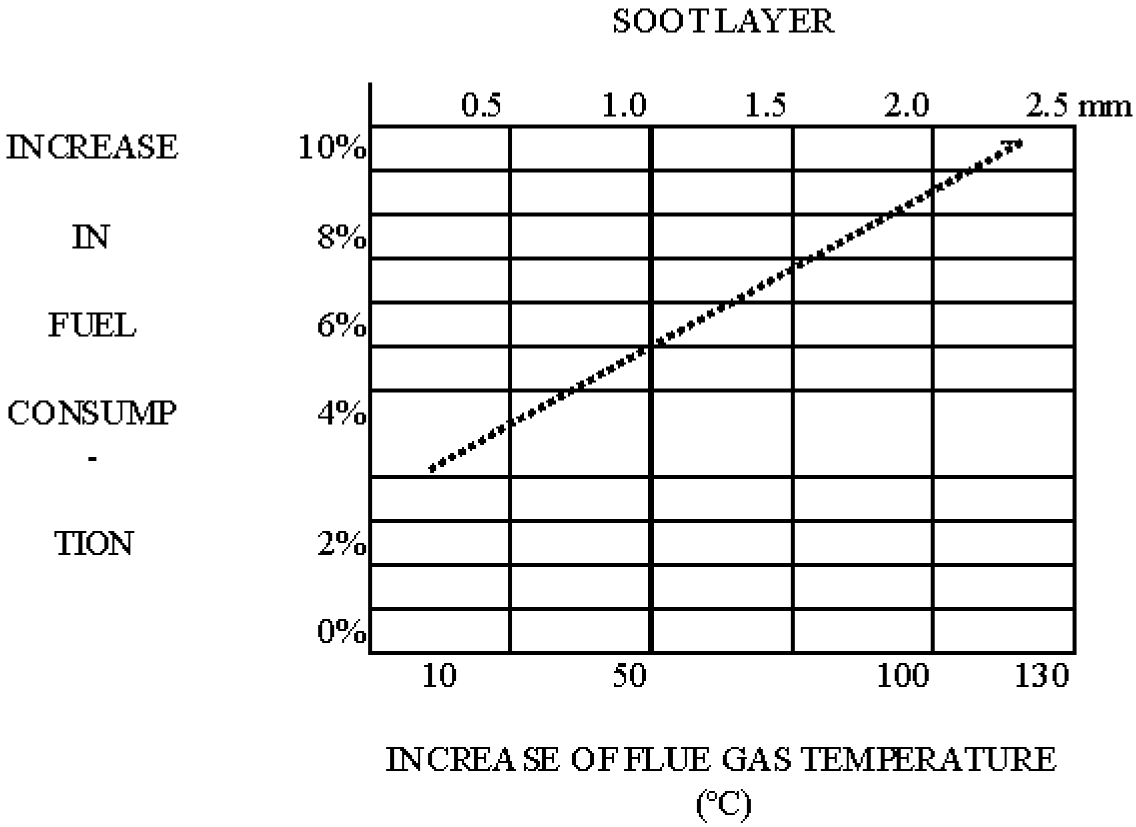
Is it important to measure smoke in oil-fired furnaces?

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

A smoke test is important. This procedure is generally done when servicing fuel oil furnaces or setting up power burners. If the air/fuel mixture is not correct, you will see it in the flue gas as smoke or soot. Generally, equipment is adjusted for a trace or less of smoke (some manufactures will tell you to set their units up for a trace of smoke, then back it off). Smoke in the flue gas eventually will create a soot build up in the furnace, and that will cause a whole list of problems, including difficulties with draft, efficiency, and carbon monoxide. The use of the flue gas analyser will then allow this somewhat empirical formula to be improved and correctly implemented.

The terms soot test and smoke test are used in different wasy in different countries. What you can see and measure is the smoke in the flue gas, but this causes the soot layer to form on the inner sides of the burner. No soot without smoke could be the catch phrase!

EFFECT OF SOOT ON FUEL CONSUMPTION



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

Does frequent testing increase fuel savings?

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

Although some combustion experts do weekly tests others consider three or four checks a year an acceptable level of testing. The appropriate level for a particular unit can only be determined by experience, and is partly dependent on the fuel consumption of the burner. The higher the consumption, the more important it is to optimise the process. Fuel consumption will be affected by a number of factors that can be measured with a flue gas analyser. The air/fuel ratio is an obvious candidate, together with the pressure drop in the stack. The carbon monoxide produced and a few other factors all add up together to change the efficiency of the burner. What works at low load my not work so well at full or half load.

It is relatively easy to work out a programme of testing frequency. It is common to start with frequent testing and find the rate of change of the process. Testing will be necessary after any major changes, such as a differnet fuel type or large-scale maintenance work. It is omportant to get an idea of the performance of the burner at different levels of load and varying fuel composition (if applicable). This will make it fairly simple to work out a plan for optimal testing, without unnecesary use of manpower.

The stability of the combustion process is perhaps the biggest factor here: a stable combustion process will require less testing than a system where constant changes are being made. Fuel savings are possible with both systems, perhaps more with unstable processes, since there may be factors that make the combustion process much less than ideal under certain circumstances. Fuel savings will depend to a great deal on discovering these conditions and either avoiding them or changing the combustion process to take account of them. In point of fact, these unstable conditions give the biggest potential for fuel savings, since they may be a long way from the ideal state.

In countries with large differences in relative humidity and other factors, these must be taken into account when testing. These can have a large effect on fuel consumption and hence provide the potential for large fuel savings. In general, fuel savings are always theoretically possible and can be realised in most cases. There may be certain cases where the efficiency of the combustion process is secondary to another factor, such as a requirement for a reducing atmosphere, or a necessity to keep the stack temperature above the dewpoint for a certain component, but, even in these cases, it is often possible to achieve a small but noticeable fuel saving.

As can be seen from the discussion above, this question is not easy to answer. The best answer is perhaps, yes, but is it worth it? As fuel prices rise it will become more and more worthwhile to take advantage of any chance to save fuel. It is also not just a question of money. Fuel is an import commodity and is limited in supply. When it has been used up, there is no more. At the moment we still have a reasonable amount available, but there is no real sign of new technology to replace the present fossil fuels. This would imply that we should save as much as possible or risk the consequences.

It is also not in the interest of many countries to be dependent on imports of fuel or other materials any more than is strictly necessary. The potential for political blackmail in this branch was amply demonstrated in the 1970s with the oil crisis paralysing an unprepared Europe. Hopefully, the lesson has been learnt, but reserve stocks of fuels are still very low in many countries. Fuel saving will reduce this dependence and free resources to combat other internal problems. The potential is there and need not be very expensive or complicated at first.

Carbon dioxide (CO_2)

Carbon dioxide is also a colourless and odourless gas that is to be found in human breath as well as in every common combustion process. The maximum allowed concentration of carbon dioxide in offices in Europe is 5000 ppm. A carbon dioxide level of 1000 ppm will reduce the ability to concentrate by about 30%. Concentrations above 15% (150000 ppm) cause immediate unconsciousness.

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

oil burners / boilers 12 - 14%

Oxygen (O_2)

Is, of course a very important part since otherwise combustion could not take place. The oxygen content of the air partly reacts with the hydrogen (H_2) content of the fuel and forms water (H_2O). This water content is, dependent on the flue gas temperature, condensed and collected in a water trap or it remains in the flue gas as water vapour. The rest of the consumed oxygen reacts with the carbon in the fuel to form carbon dioxide and, less desirably, carbon monoxide. These escape as heated gases through the flue pipe.

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

oil burners / boilers 2 - 6%

Carbon monoxide (CO)

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

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

oil burners / boilers 70 - 160 ppm

Nitrogen oxides (NO_x)

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

The nitric oxide formed oxidises with time and forms nitrogen dioxide (NO_2).

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

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

oil burners / boilers 50 - 110 ppm

Sulphur dioxide (SO_2)

The SO_2 content is pretty much dependent on the type and quality of the fuel being used. It is again a toxic gas which contributes to the formation of acid rain. The maximum allowable concentration in offices is 5 ppm. Together with water, sulphurous acid (H_2SO_3) and sulphuric acid (H_2SO_4) are formed.

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

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

Hydrocarbons (C_XH_Y)

Combustibles like methane (CH_4) and butane (C_4H_{10}) occur when incomplete combustion takes place. They are to a large extent responsible for global warming. These are part of a chemical family technically known as alkanes.

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

Soot (smoke)

Smoke is another sign that incomplete combustion is taking place. It is measured by comparison with the well-known Bacharach scale (0 - 9). The smoke in the flue gas will cause soot to form on the internal parts of the burner.

Ambient temperature (T_A)

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

Flue gas temperature (T_G)

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

Carbon monoxide (CO)

In atmospheric gas installations the CO concentration may need to be detected with a so-called multi-hole probe, because the CO concentration in a chimney varies, and that probe makes it possible to sample across the whole diameter. The further along the flue the measurement is carried out, the better the gas is mixed and when a forced draught system is used, the turbulence is usually enough to mix the gas components homogenously. Such practices appear to be dying out, and most measurements are now carried out simply in the core of the gas stream. Todays equipment produces much lower levels of carbon monoxide, so a low range sensor may be needed for some applications.

Nitrogen oxides (NO_x)

By measuring the amount of nitrogen oxides (NO, NO_2) the appropriate steps can be taken to minimise the NO_x emissions. This is particularly a factor in some areas, where the NO_x emissions are very carefully controlled and excessive emissions are taken very seriously.

Sulphur dioxide (SO_2)

The SO_2 content of flue gases is dependent on the sulphur content of the fuel and is not related to combustion efficiency. This can only really be altered by a change in the fuel or the use of filter systems. Modern fuels have very low levels of sulphur, but this is not the case with old style coal burners or some of the heavy oils in use for power generation.

Hydrocarbons (C_XH_Y)

If incomplete combustion takes place, the (unburned) hydrocarbons in the form of soot can be spotted using a filter paper and, in the case of oil derivates, detected by means of a special solvent. There are usually some gaseous hydrocarbons present, which can be measured with an appropriate sensor. The most accurate method of measuring hydrocarbon gas is an infrared sensor. This does, however, have the disadvantage of being only sensitive to one specific type of hydrocarbon, such as alkanes. There are also catalytic sensors available which react to all hydrocarbons. These have the drawback that they basically operate by combustion and hence require a certain level of excess oxygen to operate. The result will also be increased if any other combustible components of other types are present. In general, they are not especially accurate and the thin filament inside is very prone to damage. These catalytic (Pellistor) sensors are no longer acceptable for most flue gas aplications due to the poor accuracy and the fragility of the element. Such a sensor is really designed for safety applications where there is no movement of the sensor and hence no danger of breakage. The poor accuracy of the Pellistor sensor is also less of a factor since a healthy safety margin is left in all cases. Although they react primarily to haydrocarbons and carbon monoxide, the Pellistor sensors will include any other material that can burn in oxygen, such as H_2S. This type of cross-sensitivity is unpredictable and hence cannot be compensated. The reaction of the Pellistor sensor to sulphur dioxide, SO_2, is extreme. The sensor will be poisoned very quickly with no way of regenerating it. Pellistor sensors have now disappeared from quality instruments almost entirely for these reasons. The only thing that still speaks for the Pellistor sensor is the low price, but this stands in no relationship to the other disadvantages.

Carbon dioxide (CO_2)

For many years, carbon dioxide has been calculated from the oxygen concentration and the maximum CO_2 value for the fuel. Increasingly people are interested in directly measuring this component, partly in a drive for higher accuracy in the face of special regulations about this particular gas and partly due to the use of "indefinable" mixtures of gases that may be available as a waste product from another process. Here it is clearly not possible to calculate the CO_2 concentration with any acceptable degree of accuracy. Attempts have been made to develop an electrochemical sensor for this purpose, but the accuracy was poor, so the only real alternative is to use an infrared sensor. These may be slightly more expensive, but they do not have the disadvantages of limited operational life and regular calibration. They are a legal requirement in some countries nowadays. This information is available from your local government representatives.

Soot (smoke)

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

20.2) Calculated values

Carbon dioxide (CO2)

Is an indicator for the quality of the combustion process. If there is a high CO_2 content together with low excess air, then the stack loss is at its minimum. CO_2 levels will naturally depend on the ratio of hydrogen to carbon in the fuel.

Excess air factor (λ)

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

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

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

Stack loss (S_L)

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

Instead of the oxygen content, the CO_2 value can be used for the calculation as well.

Efficiency (ETA, η)

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

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

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

Dewpoint

This is calculated from a number of factors, such as oxygen content, fuel type and SO_2 concentration, if known. This is the temperature at which the water in the flue gas will commence condensation. The formation of water within the stack is generally undesirable, since this will combine with corrosive gas components to form acid and attack the structure of the flue. This damage occurs more quickly than many people realise.

Flow velocity

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