

PRINCIPLES OF CALCULATING RESULTS BY THE MADUR GAS ANALYSERS

Information brochure

madur
E L E C T R O N I C S

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1. UNITS OF THE MEASURED VALUES

The **madur** analysers are most frequently used for examining the combustion gases. The measurement results help adjust the parameters of the coke-oven and other boilers in which the combustion proceeds. Thanks to the use of the latest technology the measurements are precise and allow the user to regulate the parameters of the combustion process so that it runs in the most efficient way (reduced fuel consumption, limited emission of toxic substances).

The aim of this brochure is to present the abilities of our analysers and to describe thoroughly the parameters crucial to the accurate adjustment of the combustion process.

1.1. *ppm (parts per million)*

The *ppm* unit is used for expressing the concentration of the chemical solutions and it determines how many parts of the particular substance there are in a million parts of the solution. The values given in the *ppm* can be easily translated into percentage.

$$1\text{ppm}=10^{-4}\%$$

For instance the content of 100*ppm* of the carbon oxide (CO) in the combustion gas equals 0,01%.

As shown in the example above the *ppm* unit is convenient for expressing the particularly low concentrations.

[<i>ppm</i>]	[%]
10 000 <i>ppm</i>	1%
1 000 <i>ppm</i>	0,1%
100 <i>ppm</i>	0,01%
10 <i>ppm</i>	0,001%
1 <i>ppm</i>	0,0001%

Table 1. An example of values expressed in ppm and translated into percentage.

1.2. *The absolute mass concentration [mg/m³]*

This unit is used for expressing how many milligrams [*mg*] of a particular substance there are in one cubic meter [*m³*]. The values in *mg/m³* are directly dependent on

the pressure and the temperature and as such are not reliable separately. As the analysers measure the concentration values in *ppm* or as a percentage, if they are switched to present the values in mg/m^3 they convert the data according to the formula below (the example of the formula for the CO concentration has been given):

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

During the conversion process the A coefficient is used. It represents the amount of the mg/m^3 of gas there is in 1*ppm* in the standard conditions, i.e. the pressure of 1013 *hPa* and the temperature of 0°C. The A coefficient differs between various gases.

Gas	A $\left[\frac{mg}{m^3 \cdot ppm}\right]$
O ₂	1,428
CO ₂	1,964
CO	1,250
CH ₄	0,716
NO	1,340
NO ₂	2,056
NO _x	2,056
SO ₂	2,860
H ₂ S	1,521
H ₂	0,090
NH ₃	0,760
Cl ₂	3,164
HCl	1,627

Table 2. The coefficients used for converting the concentrations expressed in [*ppm*] into the mass concentrations [mg/m^3] (for the standard conditions 1013*hPa*, 0°C)

Attention!

The analyser calculates the mass concentration of the nitric oxides NO_x using the value of the A coefficient for the nitrogen dioxide NO₂ (according to norms).

The majority of the analysers enables the user to change the value of the A coefficient for any of the gases, in case the measurement takes place in different conditions of temperature and pressure.

1.3. The mass concentration related to the content of the oxygen in the combustion gas

As well as the absolute mass concentration, the mass concentrations related to the amount of the oxygen in the combustion gas are calculated. The concentration of a particular substance related to the oxygen content can be described by the formula (the example of the formula for the CO concentration value has been given below):

$$CO_{rel} \left[\frac{mg}{m^3} \right] = \frac{20,95\% - O_{2Ref}}{20,95\% - O_{2meas}} \cdot CO \left[\frac{mg}{m^3} \right]$$

where:

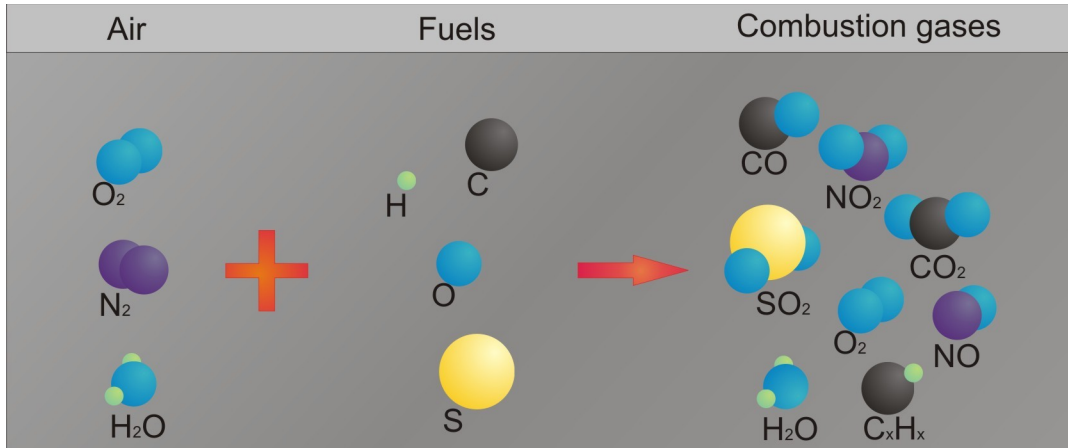
- CO_{rel} – CO content in relation to the oxygen, expressed in [mg/m³]
- O_{2ref} – reference oxygen, conventional parameter, chosen by indicating the used fuel or typed independently with the help of the keyboard, expressed in [% vol.]
- O_{2meas} – measured O₂ content in the combustion gas, expressed in [%vol.]
- 20,95% – content of the oxygen in the fresh air
- CO – measured CO content in the combustion gas, expressed in

$$\left[\frac{mg}{m^3} \right] \text{ (the absolute mass concentration)}$$

The Co_{rel} value is used for assessing the amount of the toxic substances in the combustion gases, regardless of the combustion parameters.

2. VALUES MEASURED DIRECTLY

The **madur** analysers measure directly the amount of the gases being the part of the exhaust fumes. The chemical composition of the combustion gas differs according to the kind of the used fuel and the amount of the air supplied during the combustion process.



Picture 1. A combustion process diagram.

The measurements are run with the help of the independent sensors. The analysers can be equipped with either the electrochemical or the NDIR sensors (measuring on the basis of the infra-red radiation dispersion). The readings of these sensors are expressed in *ppm* (parts per million) or as a percentage.

3. CALCULATED VALUES

3.1. Calculating the carbon dioxide concentration

In case the analyser is not equipped with the CO₂ sensor, the volumetric content of the carbon dioxide in the combustion gas can be calculated and expressed in [% vol.]. This value is determined on the basis of the CO_{2max} parameter of the particular fuel. This parameter indicates the maximum amount of the carbon dioxide which can be produced during the combustion process of the specific fuel if the excess air coefficient $\lambda = 1$. In an ideal case there would be no oxygen in the exhaust fumes and the CO₂ value would equal the CO_{2max} level. If $\lambda > 1$, the larger amount of oxygen will appear in the combustion gas and the content of carbon dioxide will decrease. Therefore the CO₂ concentration in the combustion gas can be calculated on the basis of the oxygen measurement:

$$CO_2 = CO_{2max} \cdot \left(1 - \frac{O_{2meas} [\%]}{20,95 [\%]}\right)$$

where:

- CO₂ – calculated CO₂ content in the combustion gas (as a percentage)
- CO_{2max} – parameter characteristic of the particular fuel (see: chapter 6.).
- O_{2meas} – oxygen content in the combustion gas (as a percentage).

As the calculation result depends on the CO_{2max} parameter it is necessary to remember to set the fuel parameter in the analyser correctly, i.e. so that it matches the fuel that is being combusted. Otherwise the calculated value is inaccurate.

3.2. Calculating the nitric oxides NO_x concentration

In the combustion gas, apart from the nitric oxide NO, the other nitric oxides appear (including mainly NO_2). The concentration of the nitric oxides expressed in [ppm] can be quite accurately calculated as a sum of the NO and NO_2 concentrations. It can be assumed that the nitric oxide NO found in the combustion gas constitutes about 95% of the total amount of the NO_x nitric oxides. The **madur** analysers assess the total concentration of the nitric oxides NO_x according to the formula below:

$$NO_x [ppm] = \frac{NO [ppm]}{0,95}$$

In case the analyser is equipped with the NO_2 sensor, the NO_x concentration is the sum of the directly measured NO and NO_2 concentrations.

Should the analyser be used in the non-standard conditions, the content of the NO in the combustion gas can be set to a value different from 95% through the program's menu or with the help of the computer software for operating the device.

3.3. The concentration of the undiluted carbon monoxide CO_u

In order to be able to disregard the excess of the air supplied for the combustion process, when assessing the content of the carbon oxide in the combustion gas, the undiluted carbon monoxide value has been introduced according to the formula below:

$$CO_u = CO \cdot \lambda$$

where:

- CO – volumetric concentration of CO expressed in [ppm]
- λ – excess air coefficient

4. COMBUSTION PARAMETERS

Aside from determining the fuel features, the analyser calculates some of the combustion parameters. The formulas, according to which the calculations are made, are

empirical. The combustion parameters are computed in accordance with the *DIN* standard requirements.

4.1. The stack loss

The stack loss qA is one of the most crucial combustion parameters. It determines the amount of heat emitted to the environment with the combustion gas.

During the combustion process the energy contained in the fuel changes into thermal energy which is then used for heating purposes. In reality it is never possible to use the thermal energy completely as a part of it is emitted to the environment with the combustion gas. The stack loss determines the amount of the energy lost with the exhaust fumes. It is calculated according to the empirical formula (called the *Siegert's* formula) as the difference between the temperature of the combustion gas and the temperature of the air supplied to the boiler related to the amount of the heat that can be obtained from the particular fuel:

$$qA[\%] = (T_{gas} [^{\circ}C] - T_{amb} [^{\circ}C]) \cdot \left(\frac{A_1}{CO_2[\%]} + B \right)$$

where:

- qA – stack loss – the amount of the thermal energy emitted in the combustion process which is fumed with the exhaust gas, expressed as a percentage
- T_{gas} – temperature of the combustion gas
- T_{amb} – temperature of the boiler inlet air (assumed to be the ambient temperature)
- CO_2 – calculated (on the basis of the oxygen and CO_{2max} content) amount of the CO_2 in the combustion gas, expressed in [%vol.]
- A_1, B – Siegert's coefficients characteristic of a particular fuel (see: chapter 6.)

4.2. Combustion efficiency

The analyser assesses the combustion efficiency (not to be confused with the boiler efficiency) on the basis of the calculated stack loss.

$$\eta[\%] = 100[\%] - qA[\%]$$

where:

η – combustion efficiency

The formula above assumes that the only parameter decreasing the combustion efficiency is the stack loss. It disregards the incomplete combustion loss, the radiation loss, etc. Regarding the significant simplification of the above formula it is necessary to remember that the efficiency value calculated in such a way cannot be regarded as precise. However, the calculated efficiency is useful as a comparative parameter for the boiler adjustments. The formula, despite its simplification, closely reflects the tendencies of the efficiency to change i.e. it allows the user to notice whether the efficiency is increasing or reducing. The information gained from that observation is sufficient during the adjustment process.

However, it is possible to regard the efficiency drop due to the incomplete combustion. The loss is described by the parameter called the loss by incomplete combustion IL . It expresses the percentage heat loss caused by the presence of the combustible gases (i.e. CO) in the exhaust fumes.

The loss by incomplete combustion calculated on the basis of the measured CO content in the combustion gas, according to the formula:

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

where:

CO, CO₂ – volumetric content of CO and CO₂ in the combustion gas

α coefficient characteristic of the particular fuel

Calculating the IL value makes it possible to correct the combustion efficiency computed beforehand. Therefore the difference between the efficiency - η and the loss by incomplete combustion - IL is calculated:

$$\eta^*[\%] = \eta[\%] - IL[\%]$$

4.3. The excess air coefficient

Another combustion parameter is the excess air coefficient- λ (lambda). The coefficient determines how many times the amount of the air supplied to the boiler outnum-

bers the minimum amount of the air required for the complete fuel combustion. The device calculates the λ coefficient on the basis of the given particular fuel's CO_{2max} value and the measured CO_2 content according to the formula below:

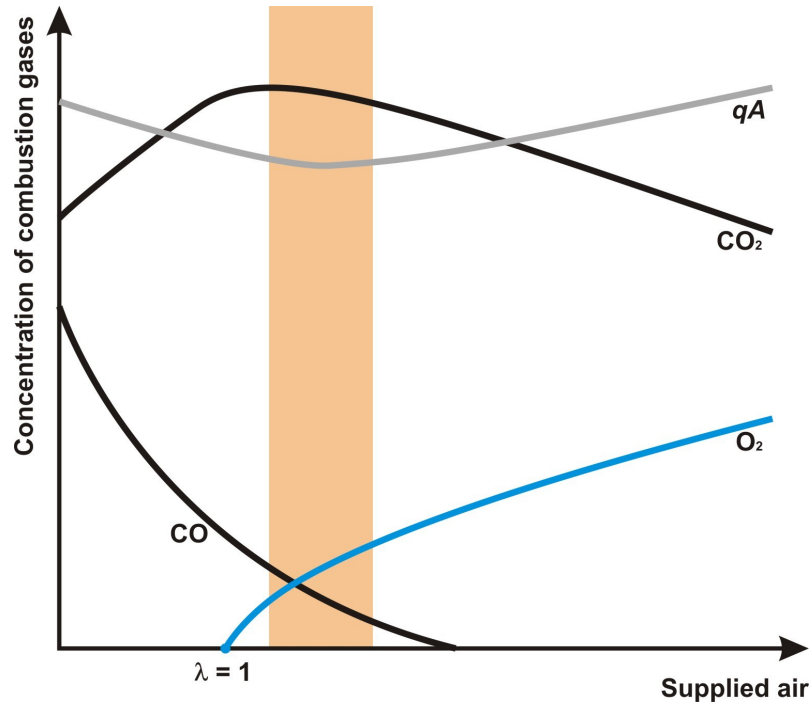
$$\lambda = \frac{CO_{2max}}{CO_{2meas}}$$

The above formula can be transformed into:

$$\lambda = \frac{20,95\%}{20,95\% - O_{2meas} [\%]}$$

In the perfect conditions the excess air coefficient $\lambda = 1$. It is the so-called stoichiometric amount that has been defined on the basis of the chemical formula of the combustion reaction for the particular fuel. The stoichiometric amount signifies that the amount of the oxygen used during the combustion process equals the amount of the oxygen needed for the complete combustion of the supplied amount of the fuel. In reality, however, both the fuel and the air contain the additional substances (the pollution), which, during the combustion process, bond with the oxygen. If the amount of the oxygen supplied for the combustion process is not sufficient ($\lambda < 1$ – a rich mixture), the toxic gases will appear in the exhaust fumes (i.e. the carbon monoxide (CO), the nitric oxide (NO) or the sulphur oxide (SO)). If the excess of the oxygen is supplied, the whole amount of the fuel is combusted and the combustion gas contains smaller amounts of the toxic substances ($\lambda > 1$ – a poor mixture).

Familiarity with the λ parameter makes it possible to adjust the combustion parameters in order to accomplish the required combustion gas purity and the boiler efficiency (see: picture 2). The excess air coefficient depends directly on the type of the fuel in use.



Picture 2. The example of CO₂, CO and O₂ concentrations in the combustion gas in relation to the amount of the supplied air. The optimum range of the λ factor has been highlighted in orange (the lowest qA value).

4.4. The excess air coefficient EA

The EA coefficient is the American equivalent of the excess air coefficient λ , only its value is expressed as a percentage. It determines the proportion of the amount of air needed for burning one kilogram of the fuel to the stoichiometric amount given as a parameter characteristic of a particular fuel (V_{air}). $EA=0\%$ corresponds to $\lambda=1$ and signifies that the combustion process is proceeding stoichiometrically. Whereas $EA=100\%$ means that the amount of the air needed for the combustion is twice as big as in the ideal conditions ($\lambda=2$). For instance, if the EA coefficient required for the combustion of the natural gas in a particular boiler equals 10%, the λ coefficient is 1,1.

The EA coefficient can be calculated according to the formula below:

$$EA[\%] = \frac{(O_2 - 0,5 \cdot CO) \cdot 100}{0,264 \cdot N_2 - O_2 + 0,5 \cdot CO}$$

where:

O₂ – concentration of the oxygen in the combustion gas, expressed as a percentage

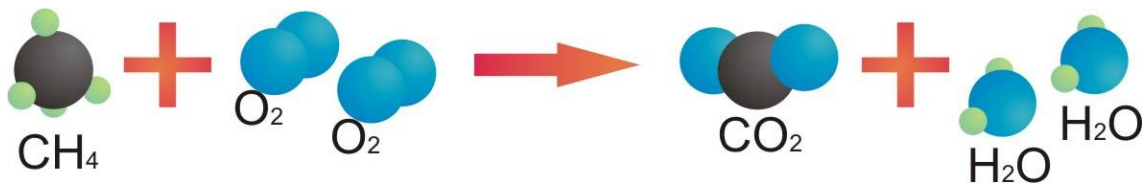
CO – concentration of the carbon monoxide in the combustion gas, expressed as a percentage

N_2 – amount of the nitrogen calculated according to the formula:

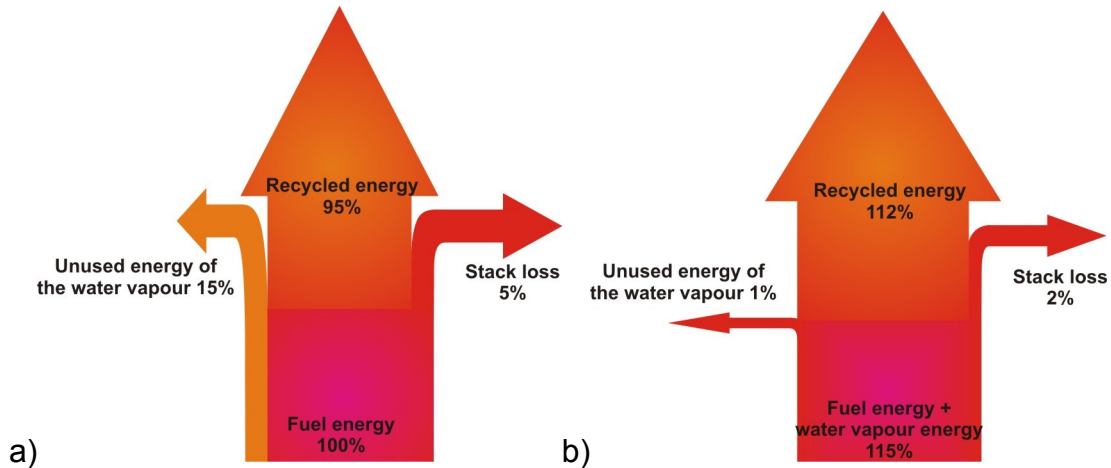
$$N_2 = 100 - (O_2 + CO + CO_2)$$

5. CALCULATING THE EFFICIENCY OF THE CONDENSATION BOILERS

The combustion gas from the hydrocarbon combustion always contains the certain amount of water in the form of the vapour. This can be illustrated by the chemical formula of the combustion process, for instance, the combustion reaction of the methane has been shown below:



As the above reaction shows the product of the stoichiometric combustion (i.e. the combustion process in which the proportion of the substrates to the products are consistent with the chemical reaction formula) is a certain amount of water. Water vapour bears some amount of energy that has been used for its production. When calculating the efficiency of the traditional boilers this amount of energy is not taken under consideration as it is impossible to regain it. It evaporates in the form of heat through a chimney. In order to increase the boiler efficiency the modern devices regain the water vapour energy in the condensation process. Therefore the condensation boilers achieve the efficiency of over 100% (this is only a conventional explanation). By definition the efficiency is the proportion of the used energy E_U to the supplied energy E_D . For that reason it is in fact impossible to achieve the efficiency of over 100%. When calculating the efficiency of the traditional boiler the energy of the water vapour supplied with the fuel is disregarded. In order to avoid changing the formulas for calculating the efficiency of the condensation boiler the traditional efficiency is calculated and increased by the amount of the energy coming from the condensation process. That gives the above 100% value.



Picture 3. The transformation of the energy during the combustion process in the a) traditional boiler; b) condensation boiler

In order for the water vapour contained in the combustion gas to condensate the combustion gas must reach the temperature of below the dew point T_d , that is the temperature in which the condensation process begins. The parameter depends on the type of the fuel used for the combustion process and on the value of the excess air coefficient λ . The analyser measures the combustion gas temperature in order to calculate the efficiency accurately. If the temperature equals or is higher than the dew temperature of the particular fuel the efficiency is calculated in a traditional way. However, if it drops below the dew point the water condensation takes place. It is then necessary to regard the regained water vapour energy when calculating the efficiency. In order to do so it is necessary to calculate the mass of the condensate and define the energetic gain from the condensation process.

The physical basis for the energy gain calculations has been described in the following chapters.

5.1. The water content in the air

The content of the water vapour in the air is strictly defined and cannot exceed the maximum value. The maximum value depends on the current air temperature. The higher the air temperature the more water vapour can the air contain. The content of the water vapour is called the humidity and can be expressed with the help of a several values.

The water vapour resilience (the partial pressure) is the value describing its characteristics. It is the pressure that could be caused only by the vapour molecules themselves if they were 'taken out' of the air and kept in the same temperature and volume

they were in while in the air. The resilience is expressed in *hPa*. The maximum amount of the water vapour in the air of a certain temperature is called the maximum resilience and is symbolised by *E*.

<i>T</i> [°C]	<i>E</i> [hPa]	<i>T</i> [°C]	<i>E</i> [hPa]
50	123,3	0	6,11
45	95,77	-5	4,21
40	73,72	-10	2,68
35	56,20	-15	1,90
30	42,41	-20	1,25
25	31,66	-25	0,80
20	23,27	-30	0,50
15	17,05	-35	0,309
10	12,28	-40	0,185
5	8,72	-45	0,108

Table 3. The maximum resilience of the water vapour in relation to the temperature

If the current resilience of the water vapour $e(T)$ is related to the maximum resilience $E(T)$ the relative humidity of the air is received:

$$f = \frac{e(T)}{E(T)} 100\%$$

To determine the value of the water vapour resilience in a particular temperature the formula defined empirically by D.Ambrose and J. Walton must be used. It makes it possible to determine the molecule pressure of different gases:

$$\ln\left(\frac{p_s}{p_c}\right) = \frac{1}{T_r} \cdot (a \cdot \tau + b \cdot r^{3/2} + c \cdot r^{5/2} + d \cdot r^5); \quad \text{where } T_r = \frac{T}{T_c}; \quad \tau = 1 - T_r$$

where:

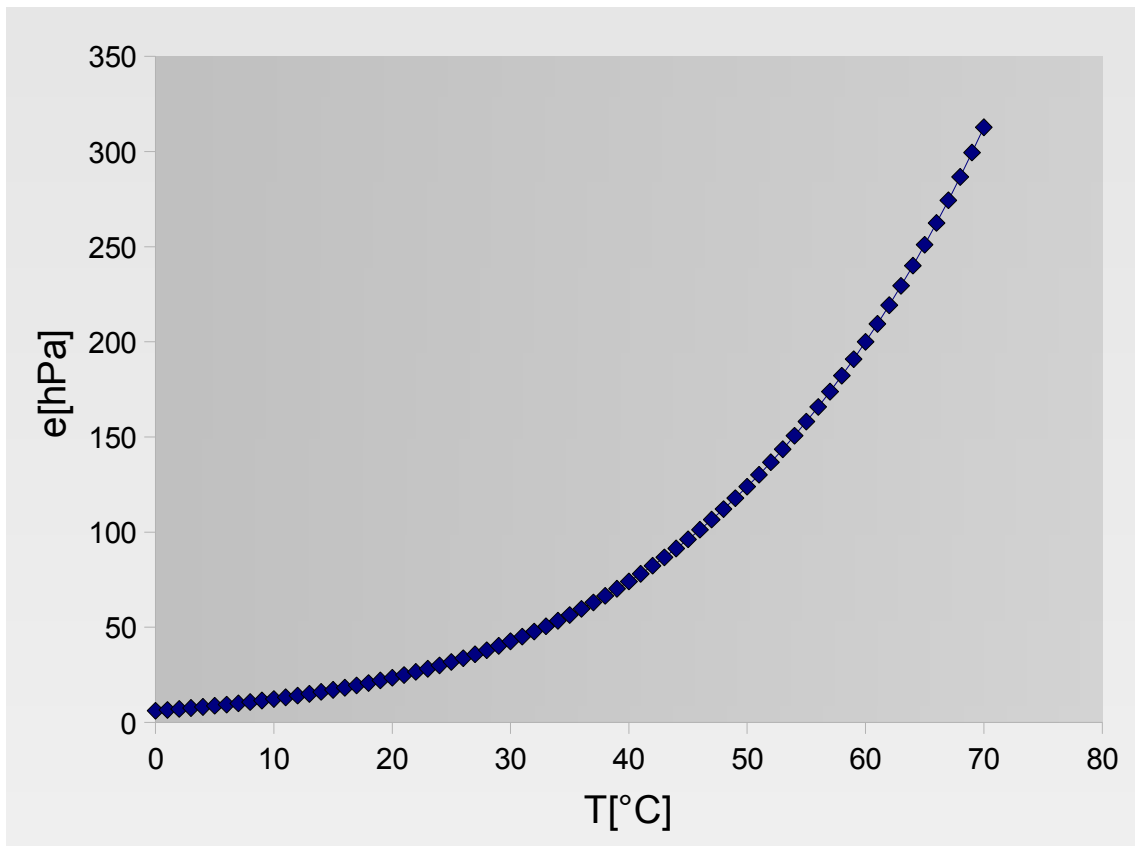
- T - current air temperature
- T_c - critical temperature
- p_s - the molecular pressure
- p_c - critical pressure
- a, b, c, d - coefficients characteristics of a certain substance

For the water vapour the above coefficients take the following values (defined empirically):

- $T_c = 647,096$ K

- $p_c = 220,64$ bar
- $a = -7,8687$
- $b = 1,9014$
- $c = -2,3004$
- $d = -2,0845$

Being familiar with those values makes it possible to calculate the partial pressure (the resilience) of the water vapour in a particular temperature which has been shown in the graph below.



Picture 4. The graph illustrating the resilience of the water vapour in relation to the temperature.

In case the relative air humidity reaches 100% in the temperature of, for example, 20°C the water vapour resilience in the air equals the maximum resilience and equals 23,27hPa (according to the Table 3.). It also means that in this temperature the air cannot contain any more water vapour, it is completely saturated. If the temperature drops down by, for example, 5°C the air becomes supersaturated and the part of the vapour must 'vanish', as, according to the table above, the maximum resilience for the temperature of 15°C equals 17,50hPa. The 'vanishing' process is called condensation. It begins when the air is completely saturated with the water vapour in the temperature called the dew point and marked T_d . During the condensation process a certain amount of the energy is

being emitted (as heat). It equals the energy supplied to the water during its evaporation. The energy is regained in the condensation boilers from the water vapour contained in the exhaust fumes. Making use of the condensation energy in such boilers lowers the use of the fuel.

5.2. Calculating the energetic gain from the condensation

The energetic gain from the water vapour condensation is proportional to the amount (the mass) of the water which condensates from the exhaust fumes. To calculate the energetic gain the analyser calculates the volume of the water vapour in the combustion gas. The volume equals the difference between the wet fumes volume V_{wf} and the dried fumes volume V_{df} . The dried fumes volume V_{df} is the parameter characteristic of the particular fuel (dependent on the temperature) and the V_{wf} is the volume of the wet fumes produced in the combustion process compound of the dried fume and the water vapour. If the water vapour volume is known, its density and mass can be calculated as well. Basing on the known amount of the heat emitted during the condensation of one gram of the water vapour it is possible to determine the amount of the energy produced during the condensation.

When calculating the energy gain the analyser measures the combustion gas temperature. If the temperature is lower or equal to the dew temperature of the particular fuel T_d , the device determines the content of the water vapour in the combustion gas according to the formulas below (for $\lambda = 1$):

1. the analyser calculates the volume of the dried fumes V_{df} on the basis of the V_{df} fuel parameter (determined for the temperature of 0°C)

$$V_{df}(T_d) = V_{df} \cdot \frac{T_d}{273,15^\circ\text{C}}$$

2. the analyser calculates the molecular pressure of the water vapour for the dew temperature T_d : $E(T_d)$ (see: table 3).
3. the device calculates the wet fumes volume V_{wf} for the dew temperature T_d (assuming that the sum of the dry fumes pressure $V_{df}(T_d)$ and the water vapour resilience $E(T_d)$ equals 1013hPa)

$$V_{wf}(T_d) = V_{df}(T_d) \cdot \frac{1013\text{hPa}}{1013\text{hPa} - E(T_d)}$$

4. the water vapour volume for the dew temperature T_d is calculated:

$$V_w(T_d) = V_{wf}(T_d) - V_{df}(T_d)$$

5. the density of the water vapour for *the dew temperature* T_d is calculated:

$$d(T_d) = 0,7932 \left[\frac{\text{g/m}^3}{\text{hPa}} \right] \cdot 1013 \text{hPa} \cdot \frac{273,15 \text{ K}}{T_d}$$

6. the analyser calculates the mass of the water vapour m_w for *the dew temperature* T_d :

$$m_w(T_d) = V_w(T_d) \cdot d(T_d)$$

7. the calculations are later repeated in order to determine the mass of the water vapour for the current combustion gas temperature: $m_w(T_{\text{gas}})$.

8. the analyser calculates the mass of the condensate:

$$\Delta_m = m_w(T_d) - m_w(T_{\text{gas}})$$

9. with the use of the condensation heat ($c_p = 2257 \text{ J/g}$) the energetic gain from the water vapour condensation process is calculated:

$$\Delta_w = \Delta_m \cdot c_p$$

10. as a consequence, the device determines the energetic gain in relation to the energy from the combustion process (expressed as a percentage):

$$\eta_{\text{Bonus}} = \frac{\Delta_w}{H_v} \cdot 100\%$$

The example below illustrates the energy gain from the water vapour condensation for the natural gas combustion (the appropriate fuel parameter can be found in the table 4):

1. calculating the dried fumes volume for $T_d = 54^\circ\text{C} = 327,15^\circ\text{K}$ – the natural gas parameter:

$$V_{df}(T_d) = V_{df} \cdot \frac{T_d}{273,15^\circ\text{K}} = 8,53 \cdot 1,197 = 10,25 \text{ m}^3$$

2. calculating the maximum resilience of the water vapour for T_d :

$$E(T_d) = 150,63 \text{ hPa}$$

3. calculating the dry fumes volume for T_d :

$$V_{wf}(T_d) = V_{df}(T_d) \cdot \frac{1013 \text{hPa}}{1013 \text{hPa} - E(T_d)} = 10,25 \text{ m}^3 \cdot 1,174 = 12,04 \text{ m}^3$$

4. calculating the water vapour volume:

$$V_w(T_d) = V_{wf}(T_d) - V_{df}(T_d) = 12,04 \text{ m}^3 - 10,25 \text{ m}^3 = 1,79 \text{ m}^3$$

5. calculating the water vapour density for T_d :

$$d(T_d) = 0,7932 \left[\frac{\text{g/m}^3}{\text{hPa}} \right] \cdot 1013 \text{hPa} \cdot \frac{273,15 \text{K}}{T_d} = 803,5116 \cdot 0,83495 = 670,88 \frac{\text{g}}{\text{m}^3}$$

6. calculating the mass of the condensate for T_d :

$$m_w(T_d) = V_w(T_d) \cdot d(T_d) = 1,79 \text{m}^3 \cdot 670,88 \frac{\text{g}}{\text{m}^3} = 1200,88 \text{g}$$

7. recalculating the above values for the combustion gas temperature $T_{\text{gas}} = 30^\circ\text{C}$:

$$V_{\text{df}}(T_{\text{gas}}) = 9,50 \text{m}^3; E(T_{\text{gas}}) = 42,61 \text{hPa}; V_{\text{wf}}(T_{\text{gas}}) = 9,92 \text{m}^3; V_w(T_{\text{gas}}) = 0,42 \text{m}^3; \\ d(T_{\text{gas}}) = 724,00 \text{g/m}^3; m_w = 304,08 \text{g}.$$

8. calculating the mass of the condensate:

$$\Delta_m = m_w(T_d) - m_w(T_{\text{gas}}) = 1200,88 \text{g} - 304,08 \text{g} = 896,8 \text{g}$$

9. calculating the energetic gain from the water condensation:

$$\Delta_w = \Delta_m \cdot c_p = 896,8 \text{g} \cdot 2257 \frac{\text{J}}{\text{g}} = 2024,07 \text{kJ}$$

10. calculating the gain from the condensation:

$$\eta_{\text{Bonus}} = \frac{\Delta_w}{H_v} \cdot 100\% = 5,63\%$$

6. FUEL PARAMETERS

Calculating the combustion parameters accurately requires thorough knowledge of the fuel parameters. The parameters of some fuels are stored in the analyser's memory permanently. Those fuels are called the standard fuels. The parameters of the standard fuels are listed in the Table 4.

#	Fuel	CO _{2max} [%]	Hv [MJ/unit]	A1	B	α	O _{2odn} [%]	Vdf [m ³]	Vair [m ³]	T _d [°C]	unit
1.	Light oil	15,4	42,70	0,5000	0,007	52	3	10,53	11,2	48,05	kg
2.	Natural gas	11,7	35,90	0,3700	0,009	32	3	8,56	9,54	56,05	m ³
3.	Town gas	13,1	16,10	0,3500	0,011	32	3	36,1	3,90	60,05	m ³
4.	Coke-oven gas	10,2	17,40	0,2900	0,011	32	3	22,30	24,36	64,35	m ³
5.	Liquid gas	14,0	93,20	0,4200	0,008	32	3	22,30	24,36	55,05	m ³
6.	Natural gas with fan	12,1	35,9	0,4600	0,000	32	3	8,56	9,54	0,0	m ³
7.	Town gas with fan	10,0	16,1	0,3800	0,000	32	3	3,61	3,90	0,0	m ³
8.	Propane with fan	13,7	93,2	0,5000	0,000	32	3	22,30	24,36	0,0	m ³
9.	Propane	13,7	93,2	0,4750	0,000	32	3	22,30	24,36	0,0	m ³
10.	Butane with fan	14,1	123,8	0,5000	0,000	32	3	29,69	32,31	0,0	m ³
11.	Butane	14,1	123,8	0,4750	0,000	32	3	29,69	32,31	0,0	m ³
12.	Biogas with fan	11,7	35,9	0,7800	0,000	32	3	8,54	9,56	0,0	m ³
13.	Biogas	11,7	35,9	0,7100	0,000	32	3	8,54	9,56	0,0	m ³
14.	Bio-Diesel	15,7	41,8	0,4567	0,005	52	3	10,44	11,15	0,0	kg
15.	Extra light oil	15,3	41,80	0,5900	0,000	52	3	10,53	11,20	47,05	kg
16.	Heavy oil	15,9	41,0	0,6100	0,000	52	3	10,08	10,73	0,0	kg
17.	Coal-tar	18,0	37,7	0,6500	0,000	52	3	9,32	9,66	0,0	kg
18.	Mineral coal 31,5	18,8	31,50	0,6830	0,000	69	11	7,92	8,11	0,0	kg

19.	Mineral coal 30,3	18,5	30,03	0,6720	0,000	69	11	7,70	7,91	44,35	kg
20.	Lignite	19,1	8,200	1,1130	0,000	69	11	4,01	4,09	44,35	kg
21.	Lignite Hu 9,34	19,1	9,300	0,9880	0,000	69	11	4,01	4,09	0,0	kg
22.	Dry wood	19,4	15,6	0,6500	0,000	69	11	3,87	3,90	57,55	kg

Table 4. The fuel parameters stored in the analyser's memory.

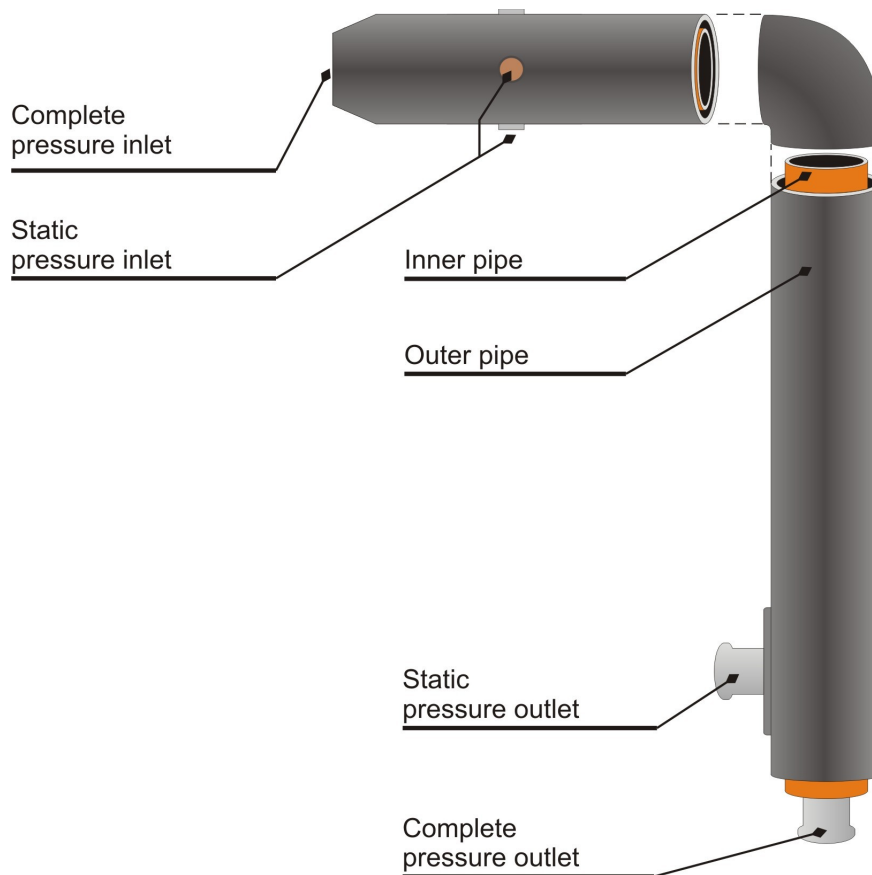
The fuel parameters from the Table 4. has been described below:

- CO_{2max} – maximum content of the carbon dioxide in the combustion gas. The parameter determines the amount of the carbon dioxide appearing in the combustion gas if the combustion process proceeds with the excess air coefficient of 1.
- A_1, B – coefficients can be found in the *Siegert's* empirical formula.
- α – coefficient used for calculating the loss by incomplete combustion, its values for different fuels are listed below:
 - $\alpha = 69$ for solid fuels
 - $\alpha = 52$ for liquid fuels
 - $\alpha = 32$ for gas fuels
- O_{2ref} – reference oxygen- the parameter used for calculating the relative content of components.
- Hv – heating value of the fuel – the amount of the energy emitted during the complete combustion process of 1 kilogram of the fuel (or $1m^3$ in case of gases).
- V_{df} – dried fumes volume, the amount of the fumes produced in the combustion process of the particular fuel with the excess air coefficient λ of 1 (measured after the water vapour has been condensed).
- V_{air} – amount of the air needed if the coefficient λ of the combustion process is to equal 1.
- T_d – dew point temperature, the combustion gas temperature in which the water contents begin to condensate.

7. THE FLOW VELOCITY MEASUREMENT

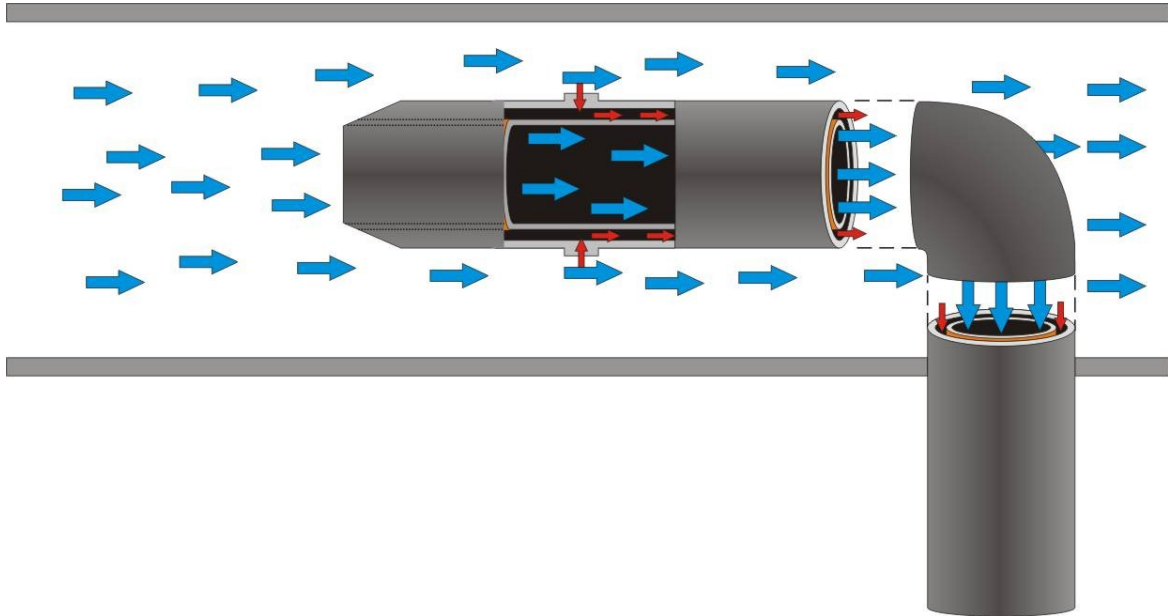
In the XVIII century a French engineer Henri Pitot constructed the device used for the liquid flow velocity measurements called the Pitot's tube. The basic idea has developed in time resulting in construction of the static Pitot's tube. With the help of the Pitot's tube the complete gas pressure p_C and the static gas pressure p_S can be measured. The result of subtracting the p_S from the p_C value is the dynamic pressure p_D , which is proportional to the gas velocity, which has been proven by the Dutch mathematician Daniel Bernoulli.

The Pitot's static tube consists of two concentric pipes angled by 90° , which are joint in a way in which the complete pressure is supplied to the inner pipe and the static pressure is supplied to the outer pipe. The operating element of the Pitot's tube is the shorter part which lets the gas of the static pressure in (through the small openings on the outer coating) and supplies the gas of the complete pressure through the hole at the head of the pipe. The pressure measurements are carried with the help of the inlets situated at the bottom of the tube. The construction of the Pitot's tube is shown in the Picture 5.



Picture 5. The construction of the Pitot's static tube.

For the accuracy of the measurement the Pitot's tube operating part must be placed in parallel with the gas flow direction. The complete pressure p_c (symbolised by the blue arrows in the Picture 6.) is transported from the head of the tube to the measurement inlet at the bottom of the tube. The static pressure p_s is transported to the other measurement inlet from the openings in the outer skin (the red arrows in the Picture 6.).



Picture 6. The rules of measurements carried with the help of the Pitot's tube; the blue arrows symbolise the complete pressure whereas the red ones illustrate the static pressure.

After the pressure values has been measured the dynamic pressure p_D is determined and the gas flow velocity is calculated with the help of the Bernoulli's formula:

$$v\left[\frac{m}{s}\right]=1,291\cdot\sqrt{p_D[Pa]}$$

The above equation is accurate only if the gas temperature is 20°C. In other cases the calculations are run according to the formula below:

$$v\left[\frac{m}{s}\right]=1,291\cdot\sqrt{\frac{T_{gas}[K]}{293}\cdot\frac{100000 Pa}{100000 Pa+p_s[Pa]}\cdot p_D[Pa]}$$

where:

v – flow velocity of the combustion gas [m/s]

1.291 – Pitot's tube coefficient

T_{gas} – combustion gas temperature [K]

p_s – static pressure [Pa]

p_D – dynamic pressure [Pa]

Some **madur** analysers are capable of differential pressure measurements and therefore can be equipped with the Pitot's tube for measuring the combustion gas flow velocity. The gas velocity measurement indirectly makes it possible to determine the mass velocity of the combustion gas and the contamination.

When carrying the measurements with the help of the Pitot's tube it is necessary to pay attention to its correct connection to the measuring device. The Pitot's tube complete pressure outlet should be connected to the analyser's (+) inlet whereas the tube's static pressure outlet to the analyser's (-) inlet. The improper connection will result in faulty measurement results.

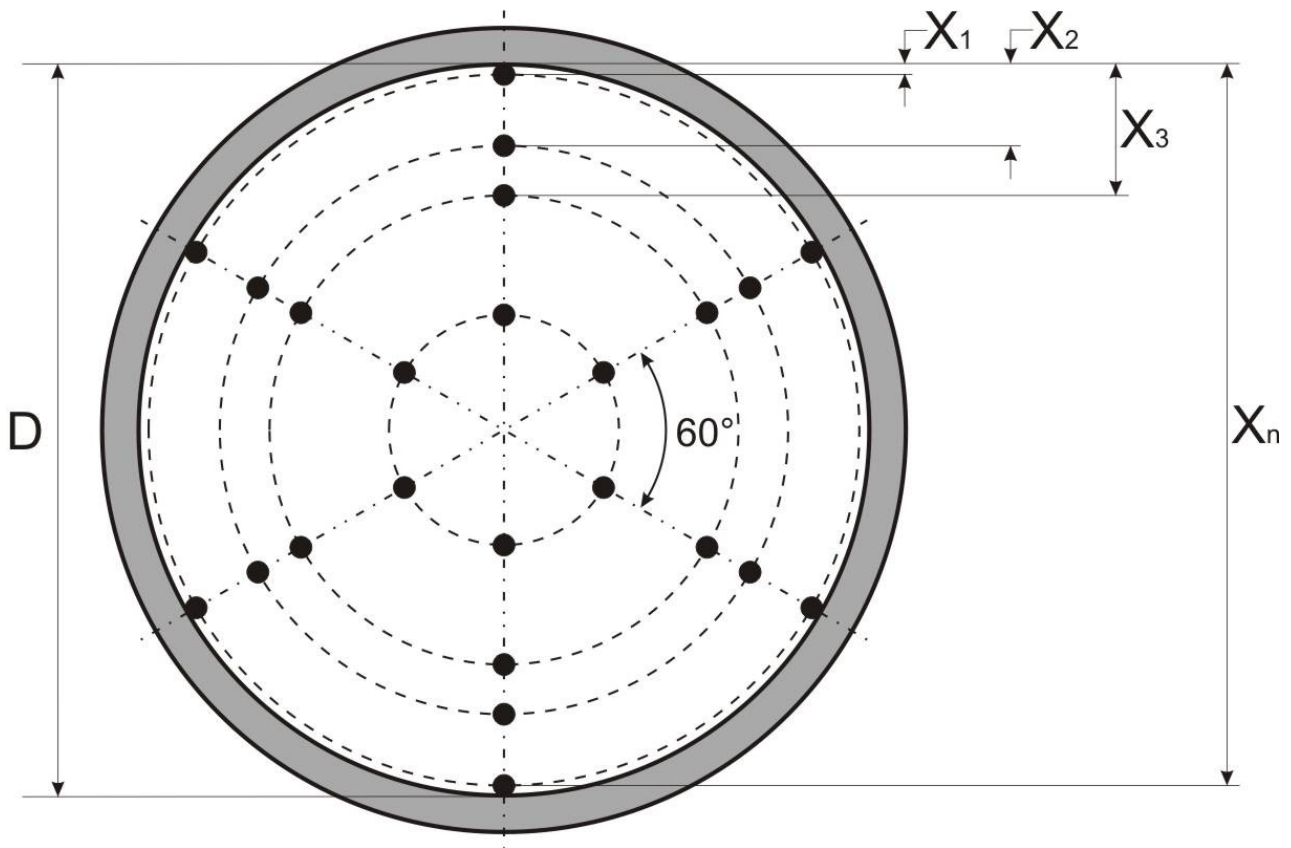


Picture 7. The pressure measurement inlets shown on the *GA12-Plus* device.

During the measurements it is necessary to pay attention to the position of the Pitot's tube in the channel where the measurements are run. The results are accurate if the tube remains in a correct position (in parallel with the gas channel) throughout the measuring process. If the measurement proceeds in the gas channel in which the operating part of the Pitot's tube cannot be seen it is necessary to rotate the tube gently in order to find the optimum position (i.e. the position for which the measurement result is the highest).

In the cases of low flow velocity it can be assumed that the gas velocity is constant throughout the channel. However, for the higher flow values the gas velocity differs across the channel. Therefore it is necessary to run the measurements in a several points of the channel and to calculate the average flow velocity. The measurement points should be chosen appropriately according to the channel's size and its shape. The larger the channel the bigger the number of measurement points. In each point the dynamic pressure should be measured, then the average dynamic pressure can be determined and with the help of the Bernoulli's formula the average gas velocity in the channel can be

calculated. The more precise method is based on calculating the flow velocity in each channel point and then averaging all the results.



Picture 8. The position of the measurement points in the channel of a circular cross-section.

In the channels of a circular cross-section the measurement points should be placed along three diameters situated at an angle of 60° to one another (Picture 8.). The diameter should be measured inside the channel and the distance of the measurement points from the inner edge should be determined according to the formula:

$$X_i = D \cdot K_i$$

where:

X_i – distance of the i point from the channel's edge

D – inner diameter of the gas channel

K_i – coefficient appropriate to the i point (Table 5.)

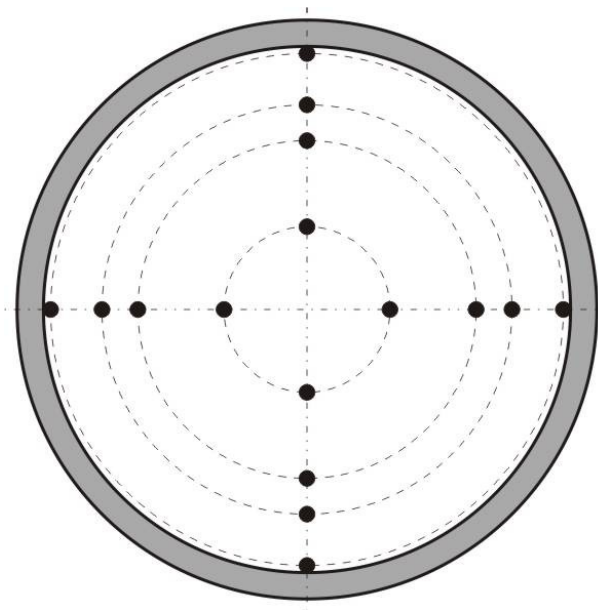
The number of the measurement points depends on the channel's diameter. The larger the gas channel the bigger the number of the measurement points that should be determined for the accuracy of the measurement. On each of the three diameters at least six measurement points should be determined. Table one contains the values of the coef-

ficients necessary for determining the accurate position of the measurement points in relation to the channel size.

Channel diameter [cm]	The number of the measurement points on each of the three diameters	K ₁	K ₂	K ₃	K ₄	K ₅	K ₆	K ₇	K ₈	K ₉	K ₁₀	K ₁₁	K ₁₂	K ₁₃	K ₁₄	K ₁₅	K ₁₆
<200	6	,032	,135	,321	,679	,865	,968	-	-	-	-	-	-	-	-	-	-
200÷250	8	,021	,117	,184	,345	,655	,816	,883	,978	-	-	-	-	-	-	-	-
250÷300	10	,019	0,77	,153	,217	,361	,639	,783	,847	,923	,981	-	-	-	-	-	-
300÷365	12	,014	,075	,114	,183	,241	,374	,626	,750	,817	,886	,925	,986	-	-	-	-
>365	16	,010	,055	,082	,128	,166	,225	,276	,391	,609	,724	,775	,834	,872	,918	,945	,990

Table 5. The coefficients used for calculating the position of the measurement points in relation to the channel size.

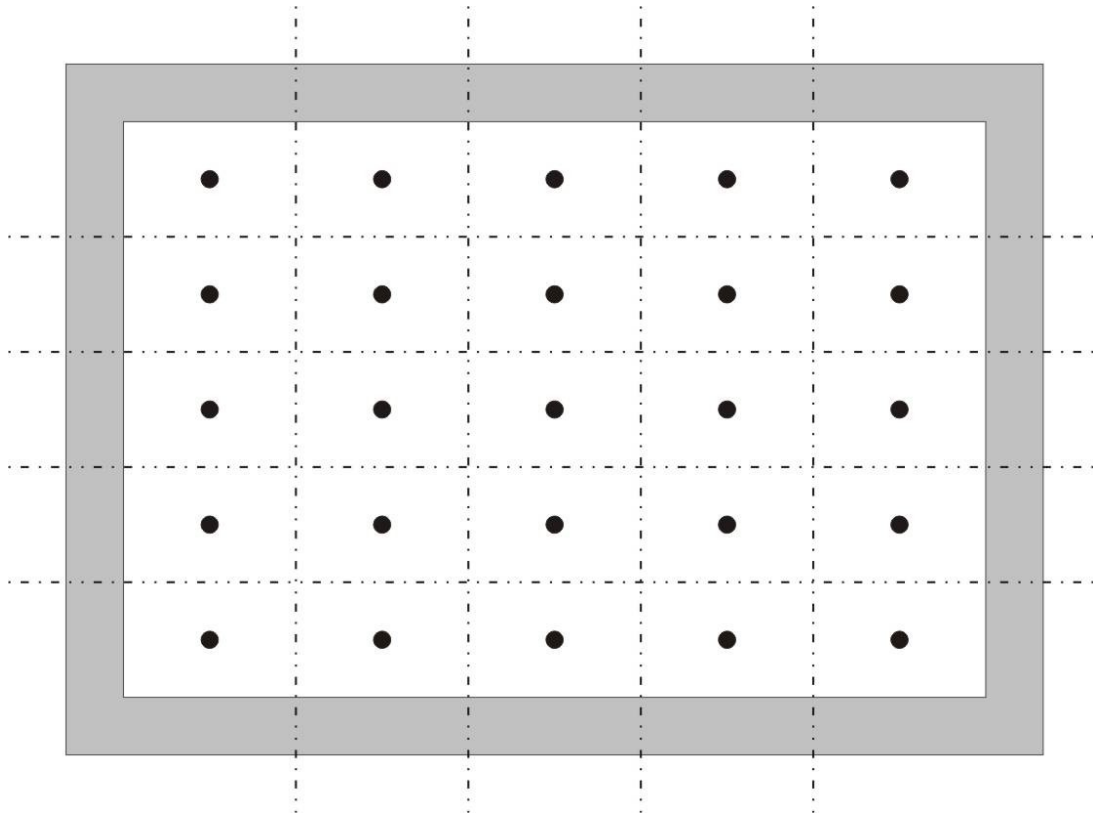
If the measurement site is hard to reach the measurement points can be determined along two diameters at a right angle to each other.



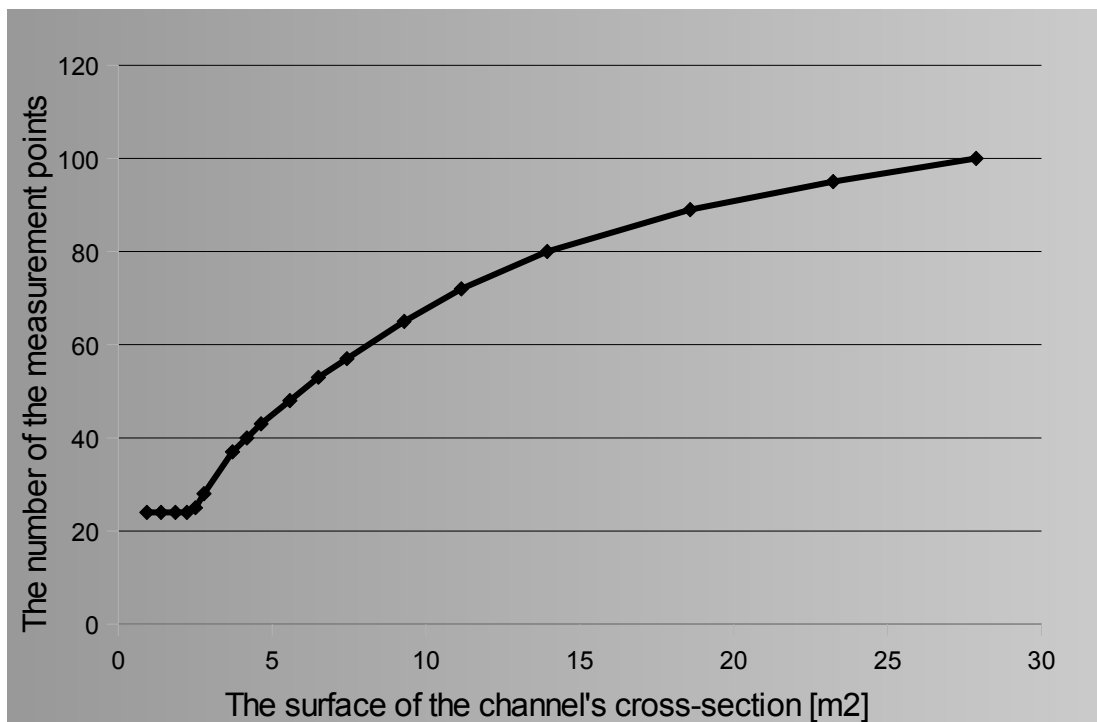
Picture 9. An example of positioning the measurement points along two diameters.

In the channels of the rectangular cross-section the measurement points are determined accordingly to the size of the channel's cross-section surface. In the picture 10 the method of determining the position of the measurement points has been illustrated. It is necessary to divide the cross-section of the channel into smaller rectangles and place the measurement points in the middle of them. The number of the rectangles (and the measurement points) depends on the surface of the channel's cross-section. If it is less than 2,2 m² (24 ft²) the number of the measurement points should be at least 24. The surface is determined on the basis of the channel's inner dimensions. The Picture 11. illus-

trates the relation of the measurement points number to the channel's cross-section sur-
face.



Picture 10. An example of the position of the measurement points in the channel of the rectangular cross-section.



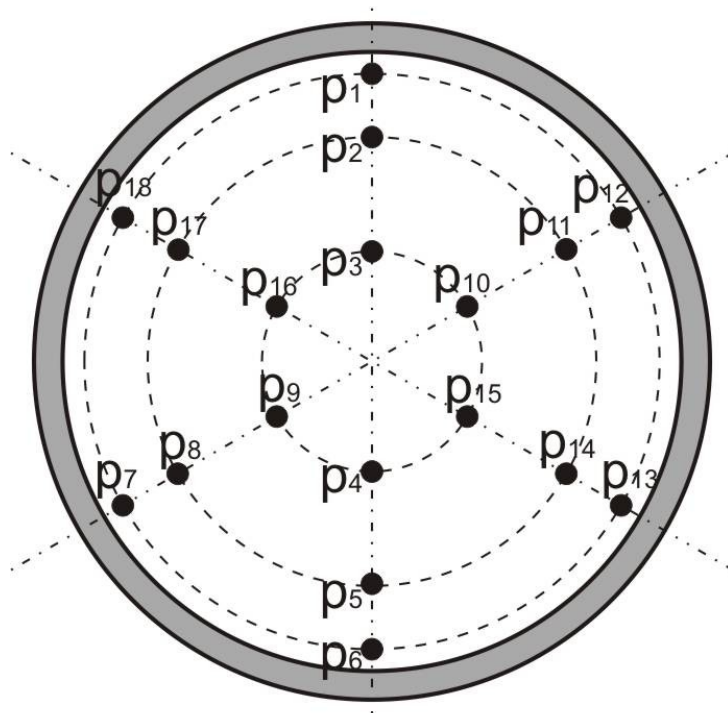
Picture 11. The relation of the measurement points number to the channel's cross-section area.

Regardless of the channel's type, the measurement place should be easily accessible and the channel should be straight within the distance equalling at least six times the length of the channel's diameter or its diagonal at the both sides of the measurement point.

The above methods of determining the measurement points for calculating the flow velocity in the gas channel has been thoroughly described in the appropriate norms: PN-EN 12599, ISO 3966 and BS 1042 .

The example below shows the flow velocity measurement of the combustion gas in the channel of the circular cross-section and the diameter of 1 m:

1. Firstly it is necessary to determine the measurement points with the help of the Table 5..



2. Moving successively along each of the diameters, measure the dynamic pressure in each of the measurement points (it is crucial that the measurement lasts at least several dozen of seconds). The measurement results table should be filled in:

Diagonal	p ₁ [Pa]	p ₂ [Pa]	p ₃ [Pa]	p ₄ [Pa]	p ₅ [Pa]	p ₆ [Pa]
1	49981	50011	50089	50122	50023	49887
	p ₇ [Pa]	p ₈ [Pa]	p ₉ [Pa]	p ₁₀ [Pa]	p ₁₁ [Pa]	p ₁₂ [Pa]
2	49989	50056	50131	50112	49988	48999
	p ₁₃ [Pa]	p ₁₄ [Pa]	p ₁₅ [Pa]	p ₁₆ [Pa]	p ₁₇ [Pa]	p ₁₈ [Pa]
3	49989	50054	50023	50012	50001	49988
Average pressure	49969,72 [Pa]					

- The next step is to measure the combustion gas temperature. $T_{\text{gas}} = 50^{\circ}\text{C} = 323,15^{\circ}\text{K}$.
- The formula should be filled in with the particular values and the flow velocity should be calculated regarding the static pressure of 3050 Pa:

$$v\left[\frac{m}{s}\right] = 1,291 \cdot \sqrt{\frac{323,15^{\circ}\text{K}}{293} \cdot \frac{100000\text{ Pa}}{100000\text{ Pa} \cdot 3050\text{ Pa}} \cdot 49969,72\text{ Pa}} = 5,49 \frac{m}{s}$$

The above method is not suitable if the measurement values differ from the average dynamic pressure value by more than 25%. If this requirement is not fulfilled it is necessary to calculate the flow velocity in each of the measurement points and then to determine the average flow velocity.

8. CALCULATING THE EMISSION

Lately a great pressure is put on the preservation of the natural environment and the control of the amount of pollution emitted to the atmosphere. To meet those requirements the **madur** analysers calculate the emission of the chemical compounds to the atmosphere on the basis of the combustion gas analysis.

The basic emission unit is *g/GJ*. It determines how many grams of a particular substance has been created during the production of 1GJ of the energy in the fuel combustion process. For example, if the CO₂ emission equals 98,0 kg/GJ, 98,0kg of carbon dioxide has been produced in the emission of 1GJ of energy.

Determining the emission value proceeds in a several steps and requires knowing the following parameters:

- **H_v** – fuel heating value, expressed in *MJ/m³* for gases or in *MJ/kg* for the other fuels.

- V_{air} – air volume needed for the complete combustion of $1\text{ kg } (1\text{ m}^3)$ of the fuel in the ideal conditions.
- V_{df} – volume of the dried fumes produced in the stoichiometric combustion.
- A – coefficient used for calculating the absolute mass concentration (see chapter 6.).
- λ – excess air coefficient.

If the values of the above coefficients are known it is possible to calculate the emission. In order to determine its value it is necessary to:

1. Measure the concentration of the particular substance in the combustion gas. In the example it can be assumed that the amount of the **CO** in the combustion gas equals **2000ppm**.
2. Transform the value expressed in *ppm* into an absolute mass concentration according to the description in the section 1.2.

$$CO_{\text{mas}} \left[\frac{\text{mg}}{\text{m}^3} \right] = 2000 \text{ ppm} \cdot 1,25 \frac{\text{mg}}{\text{m}^3 \cdot \text{ppm}} = 2500 \frac{\text{mg}}{\text{m}^3}$$

3. Calculate the total volume of the combustion gas regarding the excess air:

$$V_{\text{TOT}} \left[\frac{\text{m}^3}{\text{kg}} \right] = V_{\text{SS}} \left[\frac{\text{m}^3}{\text{kg}} \right] + (\lambda - 1) \cdot V_{\text{air}} \left[\frac{\text{m}^3}{\text{kg}} \right]$$

In case of the natural gas the $\lambda=1,2$ and:

$$V_{\text{TOT}} \left[\frac{\text{m}^3}{\text{m}^3} \right] = 8,56 \left[\frac{\text{m}^3}{\text{m}^3} \right] + (1,2 - 1) \cdot 9,54 \left[\frac{\text{m}^3}{\text{m}^3} \right] = 8,56 \left[\frac{\text{m}^3}{\text{m}^3} \right] + 1,908 \left[\frac{\text{m}^3}{\text{m}^3} \right] = 10,468 \left[\frac{\text{m}^3}{\text{m}^3} \right]$$

4. Calculate the total mass of the measured component (CO) per fuel's unit:

$$CO_{\text{TOT}} \left[\frac{\text{mg}}{\text{kg}} \right] = V_{\text{TOT}} \left[\frac{\text{m}^3}{\text{kg}} \right] \cdot CO_{\text{mas}} \left[\frac{\text{mg}}{\text{m}^3} \right]$$

$$CO_{\text{TOT}} = 10,468 \left[\frac{\text{m}^3}{\text{m}^3} \right] \cdot 2500 \left[\frac{\text{mg}}{\text{m}^3} \right] = 26170 \left[\frac{\text{mg}}{\text{m}^3} \right]$$

5. Determine the emission in relation to the amount of the energy:

$$E \left[\frac{\text{g}}{\text{GJ}} \right] = \frac{CO_{\text{TOT}} \left[\frac{\text{mg}}{\text{kg}} \right]}{Hv \left[\frac{\text{MJ}}{\text{kg}} \right]}$$

$$E_{CO} \left[\frac{g}{GJ} \right] = \frac{26170 \left[\frac{mg}{m^3} \right]}{35,90 \left[\frac{MJ}{m^3} \right]} = 729 \left[\frac{g}{GJ} \right]$$

6. The final formula can be obtained after all of the above formulas has been substituted with the appropriate values and the proper transformation has been made:

$$E \left[\frac{g}{GJ} \right] = \frac{V_{SS} + ((\lambda - 1) \cdot V_{air})}{Hv} \cdot CO_{mas}$$

$$E \left[\frac{g}{GJ} \right] = \frac{V_{air}}{Hv} \cdot \left(\frac{V_{SS}}{V_{air}} + (\lambda - 1) \right) \cdot CO_{mas}$$

7. The above formula makes it possible to determine the values of two coefficients:

$$Z = \frac{V_{air}}{Hv} \quad \text{and} \quad Y = \frac{V_{SS}}{V_{air}}$$

$$E \left[\frac{g}{GJ} \right] = Z \left[\frac{m^3}{MJ} \right] \cdot (Y + (\lambda - 1)) \cdot CO_{mas} \left[\frac{mg}{m^3} \right]$$