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Formula catalogue for measuring of particulate matter in flowing gas

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List of used symbols

t	temperature	[°C]
T	273 K	
b	ambient air pressure	[hPa]
+p	overpressure	[hPa]
−p	vacuum	[hPa]
f	weight of the water	[kg/m³]
$p_{(H_2O)}$	water vapour	[hPa]
δ	density	[kg/m³]
υ	gas speed	[m/s]
v	volumetric flow rate	[m³/h]
V	Volume	[m³]
A	surface	[m²]

a	distance:	
	pipe wall – measure point	[m]
D	diameter	[m]
i	number of split surface	
n	ordinal number	
F	moisture	[%]
NTP	normal state (DIN 1343 p: 1013 hPa, T: 273 K)	

lower indices:

n	normal state
b	operating state
tr	dry
f	wet

contents

Considerations Regarding Emission Samples

For the analytic determination of the specific particulate and the flow rate of emissions, a working knowledge of the processes that give rise to gas streams is required. If the particulate is composed of particles greater in size than 5 micron or found in concentrations greater than 5 mg/m³, it cannot be considered as homogenous; therefore, the sampling must be made at a specific nozzle velocity as ISOKINETIC.

The term ISOKINETISM means that the sampling flow rate must be in such way that the velocity of the gas upon entry to the sample extraction nozzle must be equivalent to or as close as possible to the velocity cause in the corresponding point in the duct. Nozzle velocities lower than the stream velocity cause an enrichment of larger particles in the sample because these enter the nozzle by the force of their dynamic energy and do not follow the normal laminar flows; the contrary occurs when sampling is made using nozzle velocities which are higher than the duct velocity. The importance of isokinetic sampling is evident from these considerations, especially when particle samples for granulometric analysis must be taken.

The relations between the dynamic fluidity parameters of the gas in the duct (velocity, temperature, pressure, molecular weight) require the formulation of complex mathematical equations that can easily lead to mistakes and erroneous sampling evaluations. Furthermore the dynamic fluidity conditions often change, and the operator to constantly update the sampling flow rate.

The position and distribution of the sampling or measurement points is also of particular importance because the gas stream are not always laminar and in any case, the granulometric distribution of the particles is never uniform. The selection of sampling points as far away as possible from any obstacles that may cause flow disturbance is recommended, as well as the choice of circular sections whenever possible, and in vertical ducts in any case. Sampling distributed throughout the entire section with a sufficient number of measurement points should then be performed; the German guideline VDI 2066 have been found to provide satisfactory results.

Measure points in a Flue Gas Pipe

This guideline is according to German regulations. No guarantee can be given with respect to the English translation. The German version of the guideline VDI 2066 / EN 13284 shall be taken as authoritative.

The number of measure points depends on the size of the flue gas pipe surface, see table 1.

Table 1: number of measure points

Pipe surface	Number of measure points
0,3 – 1 m²	4
> 1 m²	4/m²

For a representative measurement in a dust loaded gas volumetric flow rate the total surface of the duct should be split up into smaller measuring-surface similar to the original. That means for a rectangular cross section like figure E1 or for a round cross section use circle like figure E2.
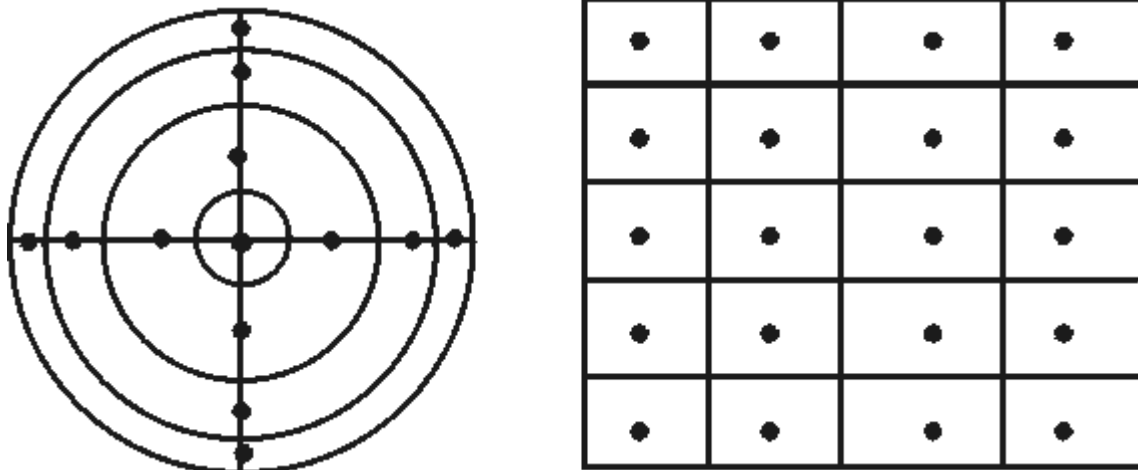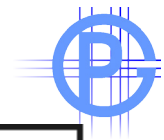
Figure E 1 and E 2

The distance between the wall of the pipe and the measure points can be calculated by formula 1 or by using table 2.

Formula 1: $a = D \bullet \dfrac{1}{2} \bullet \left(1 \pm \sqrt{\dfrac{2i - 2n + 1}{2i}}\right)$ D: Diameter of the duct

Table 2: settings of measure points

| Number of measure-points	1. point	2. point	3. point	4. point	5. point	6. point	7. point	8. point
2	D · 0,146	D · 0,854						
4	D · 0,067	D · 0,250	D · 0,750					
6	D · 0,044	D · 0,147	D · 0,296	D · 0,704	D · 0,854	D · 0,956		
8	D · 0,033	D · 0,105	D · 0,194	D · 0,323	D · 0,677	D · 0,806	D · 0,895	D · 0,968

For isokinetic exhausting the air pressure, the operating pressure at the measure point, the moisture of the gas and the gas speed must be determined.

Determination of the Water Vapour Content in Flue Gases

There are many methods for the determination of the water content in gases; the most commonly-used for flue gases is sampling.

Take the sampling over numerous points in the stack, as during flow rate measurement, using both the isokinetic probe and a probe for gas sampling. Isokinetic conditions are not a necessity, and the filter as well may be eliminated; however, a bit of glass wool may left to withhold the dust.

Connect the probe outlet to a cooling and condensate collection system using a short connection tube.
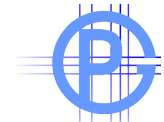
Connect the condensation system (four bubblers previously prepared with distilled water or silica gel individually before performing the sampling) to the probe and take a constant flow rate of 20 l/min at the respective sampling conditions in the stack. The total duration of the sampling must be sufficient to collect enough condensate for a satisfactory weighting; a total of 30 minutes is usually sufficient.

During sampling, make sure that the condensate collected if this occurs, interrupt the sampling.

At the end of the sampling, weight the bubblers once again under the same conditions and calculated the increase in weight of each of the same caused by water collected.

Formula 2: The calculation of the water vapour volume in flue gases (rw):

$$rw = \frac{V_{w,N} + V_{w,sg}}{V_{w,N} + V_{w,sg} + V_N}$$

where:

$V_{w,N}$ = the volume of water vapour in the condensate collected reconducted to standard conditions;

$V_{w,gs}$ = the volume of water vapour collected in the silica gel reconducted to standard conditions;

V_N = The volume of dry gas measured by the dry gas meter reconducted to standard conditions;

Formula 3:

$V_{w,N}$ = 1.24 * ($W_{fc} - W_{ic}$)

where:

W_{fc} = the final weight of the bubblers due to condensate
W_{fc} = the initial weight of the bubblers due to condensate;

Formula 4:

$V_{w,gs}$ = 1.24 * ($W_{fsg} - W_{isg}$)

where:

W_{fsg} = the final weight of the bubbler with silica gel
W_{isg} = the initial weight of the bubbler with silica gel.

For greater detail, consult the EPA Method 4 „Reference Method for Determining the Moisture Content of a Stack Gas".

Gas Moisture

Two-thermometer-method

Two thermometers - one wrapped with gaze and dipped just before using into water - must be placed at the same time in the flue gas. The thermometer progression of the wet thermometer will be rising up in two steps with a plateau between it. If the temperature comes after the first
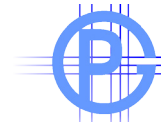
rising up to a standstill, the evaporation point is reached. By using the temperature of the evaporation point and the hot gas temperature, it is possible to calculate the partial vapour pressure of water.

Formular 5: partial vapour pressure of water:

$$e = E_f - \left(\frac{1}{2} \bullet \Delta t \bullet \frac{b \pm p}{p_n} \right) \text{ [hPa]}$$

E_f	saturation vapour pressure calculated with the temperature of the wet thermometers by using table 6319
Δt	difference between the dry and wet thermometer
b	air pressure
p	operation pressure at the measure point
p_n	normal pressure (1013 hPa)

Formula 6: weight of the water

$$f_n = \frac{0{,}804 \bullet e}{(b \pm p) - e}$$

Exampel:

wet thermometer: 54°C ($\Rightarrow$ 149,96 hPa saturation vapour pressure, see table 6319), dry thermometer: 82°C ($\Rightarrow$ 513,07 hPa saturation vapour pressure), air pressure: 1017 hPa, vacuum: -10 hPa.

$\Delta t = 28°C$, $(b \pm p) = 1007$ hPa.

$$e = 149{,}96 - \left(\frac{1}{2} \bullet 28 \bullet \frac{1007}{1013} \right) = 136{,}04 \text{ hPa}$$

$$f_n = \frac{0{,}804 \bullet 136{,}04}{1007 - 136{,}04} = 0{,}126 \text{ kg/m}^3$$

Determination of the Molecular Weight of an Anhydrous Gas

The molecular weight of a gas is the combination of the molecular weights of its single components multiplied by the respective percentage concentration.

In the case of an anhydrous flue gas, the following composition may be considered valid:

% N_2 + % O_2 + % CO + % CO_2 = 100 %

where:

% N_2 = the percentage of volume of anhydrous nitrogen
% O_2 = the percentage of volume of anhydrous oxygen
% CO = the percentage of volume of anhydrous monoxide
% CO_2 = the percentage of volume of anhydrous carbon dioxide

Density of the Dry Gas (NTP)

The density of a gas is the combination of the density weights of its single components multiplied by the respective percentage concentration.

In the case of an anhydrous flue gas, the following composition may be considered valid:

% N_2 + % O_2 + % CO + % CO_2 = 100 %

where:

% N_2 = the percentage of volume of anhydrous nitrogen
% O_2 = the percentage of volume of anhydrous oxygen
% CO = the percentage of volume of anhydrous monoxide
% CO_2 = the percentage of volume of anhydrous carbon dioxide

Example:

15 % CO_2 (NTP-density: 1.9770) = 0.29655
80 % N_2 (NTP-density: 1.2505) = 1.00040
3,5 % O_2 (NTP-density: 1.4290) = 0.05001
1,5 % CO (NTP-density: 1.2505) = 0.01875

NPT-density of the gas: 1.36571 kg/m³

Gas Speed

If the moisture of the gas negligible, it is possible to determine the speed directly with the SERO-PRESSURE-PROBE or with a Pitot-tube by using the formula:

Formula 7:

$$v_{dry} = \sqrt{\frac{2 \bullet \Delta P_p}{\delta_{dry} \bullet c}}$$

where:

P_p= difference pressure (Attention: Unit: N/m²)

δ_{dry}= dry density in operating state [kg/m³]

c= 1

Formula 8: Density of the dry gas (operating state)

$$\delta_{dry} = \delta_{NPT,dry} \bullet \frac{(b \pm p) \bullet T_{NPT}}{p_{NPT} \bullet (T_{NPT} + t)}$$

where:

b= ambient air pressure [hPa]

p= static pressure [hPa]

T= NPT-Temperature (273 K)

t= operating temperature (°C)

Formula 9: Determination of gas speed in gas with high moisture:

$$\delta_{wet} = \frac{(b \pm p) \bullet T_{NPT}}{p_{NPT} \bullet (T_{NPT} + t)} \bullet \frac{(\delta_{dry,NPT} + f_{NPT})}{1 + \left(\dfrac{f_{NPT}}{0,804} \right)}$$

where:

f_{NPT}= moisture content [kg/m³$_{dry,NPT}$] under Standard Condition

Formula 10:

$$v_{wet} = \sqrt{\frac{2 \bullet \Delta P_p}{\delta_{wet} \bullet c}}$$

Formula 11: Quantitation of the gas

$V = v \bullet A \bullet 3600$

Formula 12:

$$V_{dry;NPT} = V_{dry} \bullet \frac{(b \pm p) \bullet T_{NPT}}{p_{NPT} \bullet (T_{NPT} + t)}$$

where:

V_{dry} = Dry Gas-Volume [m³/h], operating condition

Formula: 13:

Calculation of the volume wet under standard conditions:

$$V_{wet;NPT} = V_{wet} \bullet \left[1 + \left(\frac{f_{NPT}}{0,804} \right) \right] \frac{p_{NPT} \bullet (T_{NPT} + t)}{T_{NPT} \bullet (b \pm p)}$$
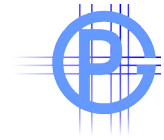
Calculation of the NPT-Sample Gas Volume:

Formula 14:

$$V_{NPT,gasmeter,dry} = V_{gasmeter,dry} \bullet \frac{(b - p_{gasmeter}) \bullet T_{NPT}}{p_{NPT} \bullet (T_{NPT} + t)}$$

Correction Factor for the Rotameter

The scale of the rotameter is for air at 20°C and density: 1.2047 kg/m³. Correction factor (K) must be used if the temperature and/or pressure and/or the density change:

Formula 15:

$$K = \sqrt{\frac{\delta_E}{\delta_B}}$$

Formula 16:

$$\delta_B = \delta_N \bullet \frac{(b \pm p) \bullet T}{p_N \bullet (T + t)}$$

where:

δ_E = calibrate density (1.2047 kg/m³)

δ_N = NPT-density

δ_B = operating-density

Formula 17:

$$Volume(gasmeter) = scale(rotameter) \bullet K$$

Formula 18:
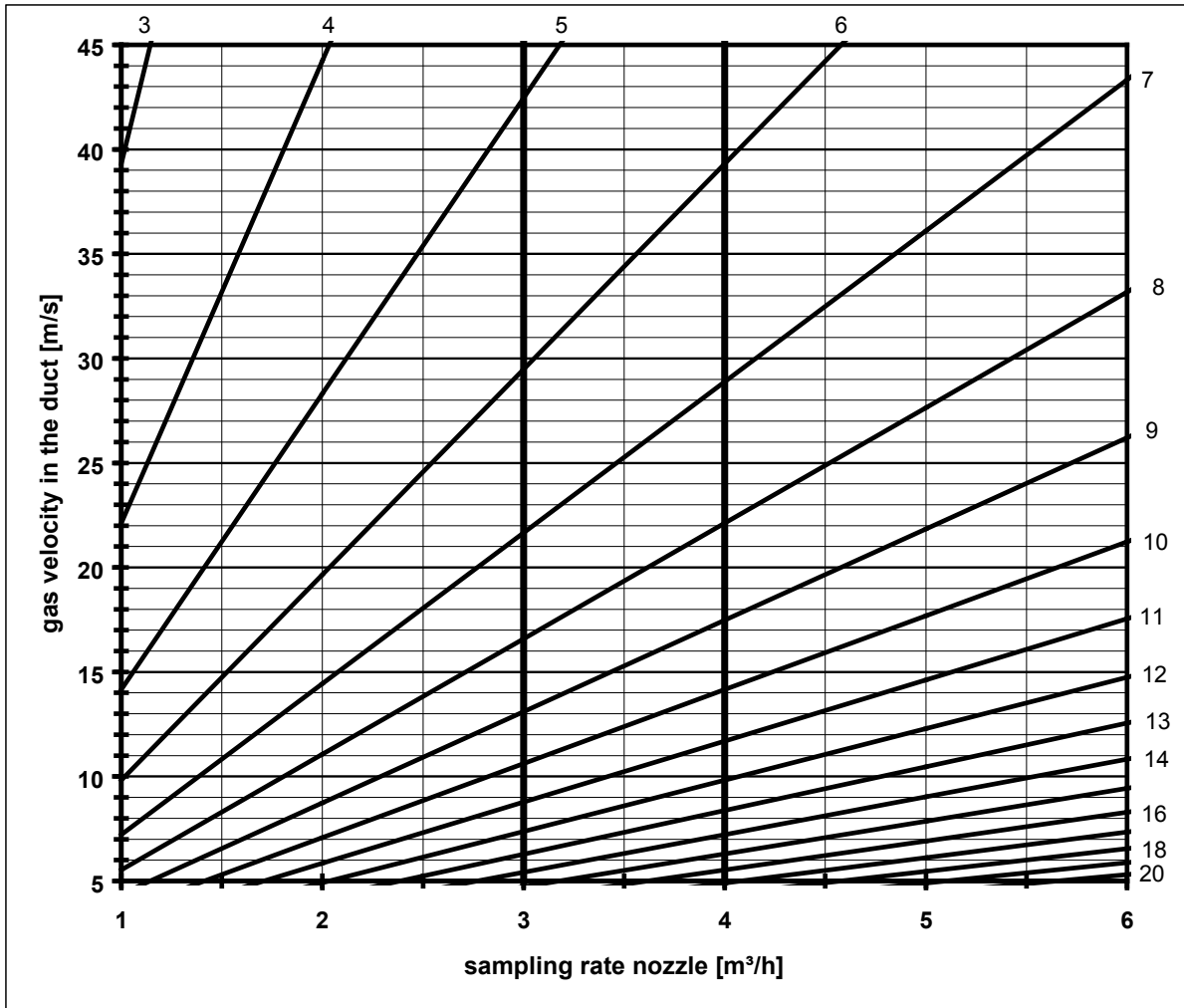
$$scale(rotameter) = \frac{volume(gasmeter)}{K}$$

Figure: Diameter of the nozzle corresponding to the gas volume sampling rate and the gas velocity of the duct