Unit Conversion

Calculation of emission values, which are defined by legal regulations, from the results of measurements.

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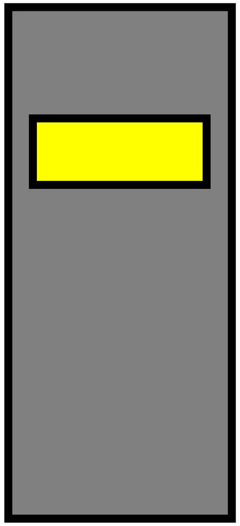
«Measured Values»



«Measured Values»
The values displayed by a emission measuring device may be indicated in [ppm] or [mg/m^3], refers to the gas in dry or wet condition, and is measured at current oxygen (e.g. O_2 in the chimney).

«National Values»
«Measured values» must be converted in accordance with the regulations of the various countries.
e.g. in [mg/m^3], standard conditions, dry gas state, reference oxygen content

Reported emission values worldwide

Countries around the world have different regulations on how emission values from cement plants must be reported
(In the following called «National Value»).

<u>Three different standards for the [m³]</u>

- Standard #1 «Normal Conditions»: t_1= 0 [°C] or 273 [K], 1013 [mbar]
  (EU, included Switzerland)
- Standard #2: t_2 = 20 [°C] or 293 [K], 1013 [mbar]
  (USA, Canada, …)
- Standard #3: t_3 = 25 [°C] or 298 [K], 1013 [mbar]
  (Mexico, Philippines, Indonesia, …)

<u>«Dry gas state»</u>

- In all countries the emission values for cement plants are related to the dry gas state

<u>Oxygen Reference</u>

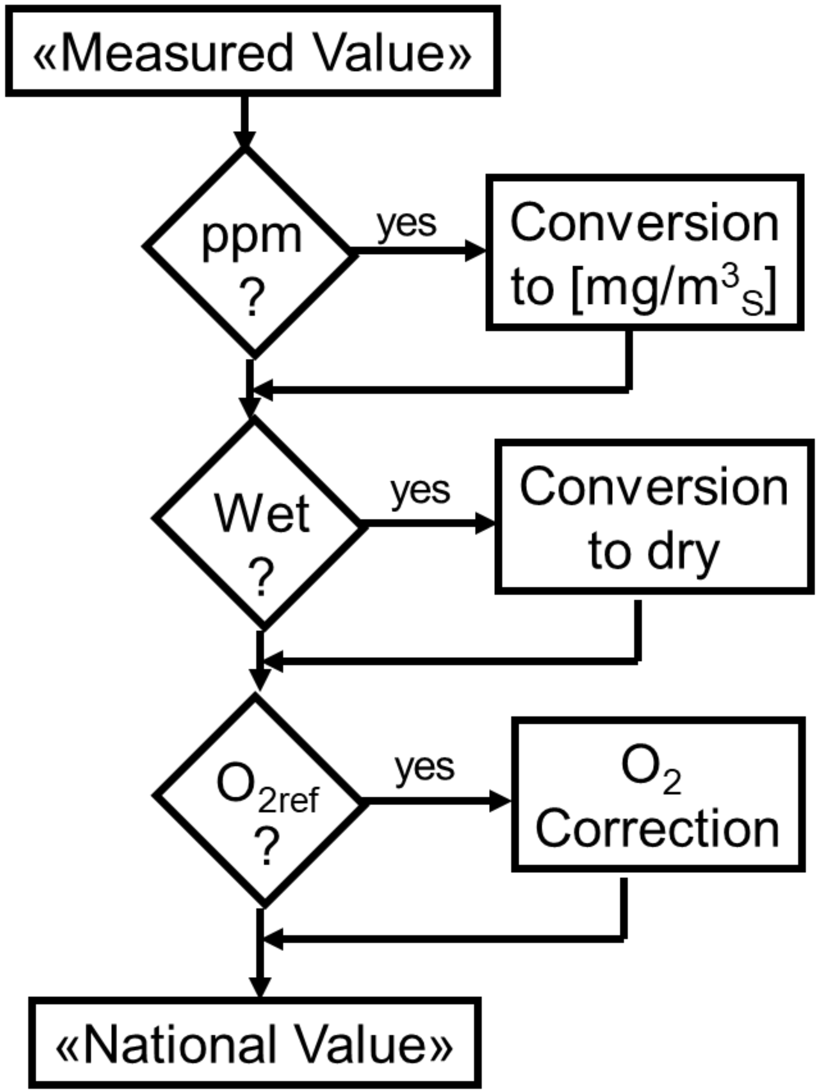
- No correction (seldom)
- Reference oxygen levels: 7, 8, 10 (EU), 11 [vol-%]

Conversion Proceeding

Conversion [ppm]→ [mg/m^3_S]
(if value is indicated in [ppm])

Conversion wet → dry
(if value is related to wet gas condition)

Correction to reference oxygen level



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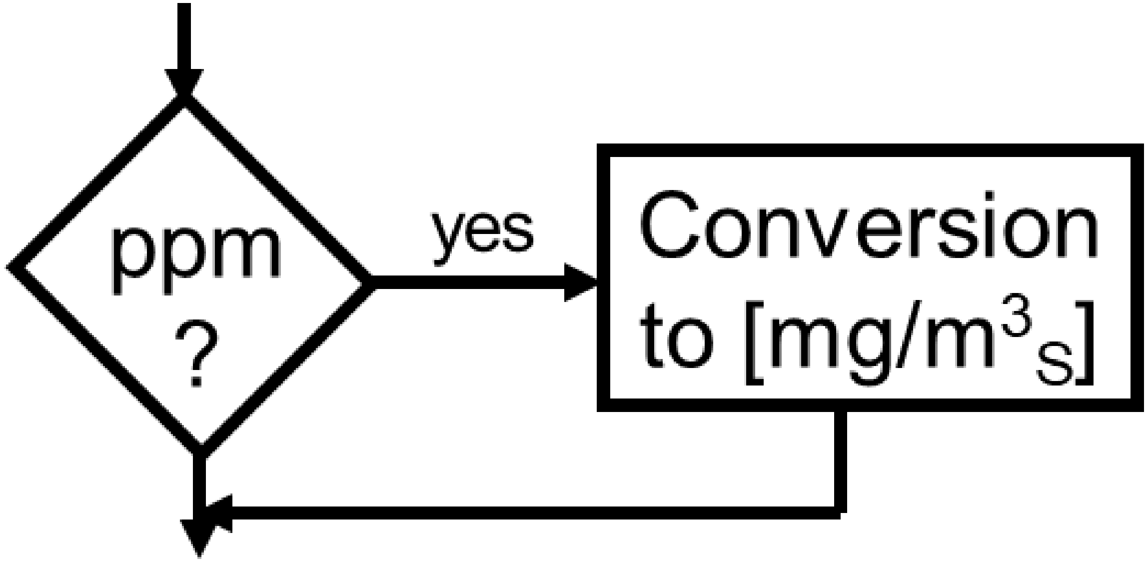
Conversion [ppm] to [mg/m^3_S]



Standard Cubic Meter:
This cubic meter is defined on certain standard sizes (temperature, pressure) and for the distinction different designations are used, for example [m^3] STP, [Sm^3], etc. Here the designation [m^3_S] is chosen.

In Europe, the standardized cubic meter, which is based on the European standard, is also referred to as normal m^3 and with the unit [Nm^3]. Here the designation [m^3_N] has been chosen.

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Derivation from gas equation

$$p_S \cdot \frac{V_S}{m} = R \cdot T_S \rightarrow \frac{V_S}{m} = \frac{R \cdot T_S}{p_S} = \frac{\frac{R^*}{M} \cdot T_S}{p_S} = \frac{R^*}{p_S} \cdot \frac{T_S}{M} \rightarrow \frac{m}{V_S} = \frac{101325}{8314.7} \cdot \left(\frac{M}{T_S}\right)$$

$$\boxed{\frac{m}{V_S} = 12.19 \cdot \frac{M}{T_S}}$$

p_s = standard pressure, 101325 [N/m^2]
T_s = standard temperature, 273, 293 or 298 [K]]
V_s = standard volume [$m^3{}_S$]
m = mass [kg]
R = (gas) specific gas constant [kJ/kg K]
R* = universal gas constant, 8314.7 [J/kmol K]
M = molar mass, [kmol]

Conversion Factors [ppm] → [mg/m^3_s]

$$\left[\frac{mg}{m_S^3}\right] = \mathrm{f} \cdot [\mathrm{ppm}] \rightarrow \mathrm{f} = 12.19 \cdot \left(\frac{M}{T_S}\right)$$

Standard #1: $T_s = 273\ [K] \rightarrow f = \dfrac{M}{22.41}$

Standard #2: $T_s = 293\ [K] \rightarrow f = \dfrac{M}{24.06}$

Standard #3: $T_s = 298\ [K] \rightarrow f = \dfrac{M}{24.47}$

Conversion to standardized m^3_S

M → Molar Mass [kg/kmol]

T_s → Standard Temperature [K]

T_S [K]= 273 + t_S [°C]

Example (Standard #1)

Concentration SO_2 → 292 [ppm]

National Standard #1 → T_s = 273 [K]

EU: «Standardized m^3_S» → «Normal-m^3_N»

$$T_s = 273\ [K] \rightarrow f = \frac{64.06}{22.41} = 2.86$$

$$\rightarrow 835 \left[\frac{mg}{m_N^3}\right]$$

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Conversion Factors [ppm] → [mg/m^3_S]

$$\left[\frac{mg}{m_S^3}\right] = f \cdot [ppm] \rightarrow f = \frac{M}{0.08206 \cdot T_S} = 12.19 \cdot \left(\frac{M}{T_S}\right)$$

	Molar Mass [kg/kmol]	Standard #1 Normal Conditions, Europe, ...	Standard #2 USA, Canada, …	Standard #3 Mexico, Indonesia, Philippines, ...
NO	44.01	(1.34) 2.05	(1.25) 1.91	(1.23) 1.88
NO_2	46.01	2.05	1.91	1.88
NH_3	17.03	0.76	0.71	0.70
SO_2	64.06	2.86	2.66	2.62
CO	28.01	1.25	1.16	1.14
HCl	36.46	1.63	1.52	1.49
HF	20.01	0.85	0.83	0.82
TOC		1.61	1.50	1.47

NO see conversion NOx (next page)
TOC see conversion of Total Organic Carbon

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Conversion Factors for NOx

The sum of nitrogen oxides NOx (nitrogen monoxide NO and nitrogen dioxide NO_2) is given as nitrogen dioxide NO_2. This is the case in all countries.

$$\left.\begin{array}{r}[\mathrm{ppm}]\ \mathrm{NO} \\ [\mathrm{ppm}]\ \mathrm{NO_2}\end{array}\right\} \cdot f_{\mathrm{NOx}} \rightarrow \left[\frac{\mathrm{mg}}{\mathrm{m_S^3}}\right]$$

Standard #1: $T_s = 273\ [K] \rightarrow f_{NOx} = \frac{46}{22.41} = 2.05$

Standard #2: $T_s = 293\ [K] \rightarrow f_{NOx} = \frac{46}{24.06} = 1.91$

Standard #3: $T_s = 298 [K] \rightarrow f_{NOx} = \frac{46}{24.47} = 1.88$

Caution: Devices which indicate nitrogen monoxide in [mg/m^3] indicate [mgNO/m^3] and not [mgNO_2/m^3]. If this is not the case, it must be documented somewhere (e.g. in the manual).

$$\left[\frac{mg\ NO_2}{m_S^3}\right] = \frac{46}{30} \cdot \left[\frac{mg\ NO}{m_S^3}\right] = 1.53 \cdot \left[\frac{mg\ NO}{m_S^3}\right]$$

Conversion Factors for Total Organic Carbon

Emission monitoring devices (flame ionization devices) measuring Total Organic Carbon (TOC) are adjusted (calibrated) with propane (C_3H_8) and rarely with methane (CH_4).

Regulations require TOC emission values to be reported as emitted mass of organic carbon per unit volume, and not as emitted mass of propane (C_3H_8) or methane (CH_4)

<u>Calibration with propane C_3H_8</u>

C_3H_8

$$\left[\frac{mg\ C}{m_S^3}\right] = f_{TOC} \cdot \ [ppm]$$

Standard #1: $T_s = 273\ [K] \rightarrow f_{TOC} = \frac{3 \cdot 12}{22.41} = 1.61$

Standard #2: $T_s = 293\ [K] \rightarrow f_{TOC} = \frac{3 \cdot 12}{24.06} = 1.50$

Standard #3: $T_s = 298[K] \rightarrow f_{TOC} = \frac{3 \cdot 12}{24.47} = 1.47$

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Conversion Factors for Total Organic Carbon

Calibration with methane CH_4

CH_4 (C highlighted)

$$\left[\frac{mg\ C}{m_S^3}\right] = f_{TOC} \cdot\ [ppm]$$

Standard #1: $T_s = 273\ [K] \rightarrow f_{TOC} = \frac{1 \cdot 12}{22.41} = 0.54$

Standard #2: $T_s = 293\ [K] \rightarrow f_{TOC} = \frac{1 \cdot 12}{24.06} = 0.50$

Standard #3: $T_s = 298[K] \rightarrow f_{TOC} = \frac{1 \cdot 12}{24.47} = 1.49$

Example (Standard #1):

C_3H_8: 15 [ppm] → f_{TOC}= 1.61 → $24.2 \left[\frac{mgC}{m_N^3}\right]$

CH_4: 45 [ppm] → f_{TOC}= 0.54 → $24.2 \left[\frac{mgC}{m_N^3}\right]$

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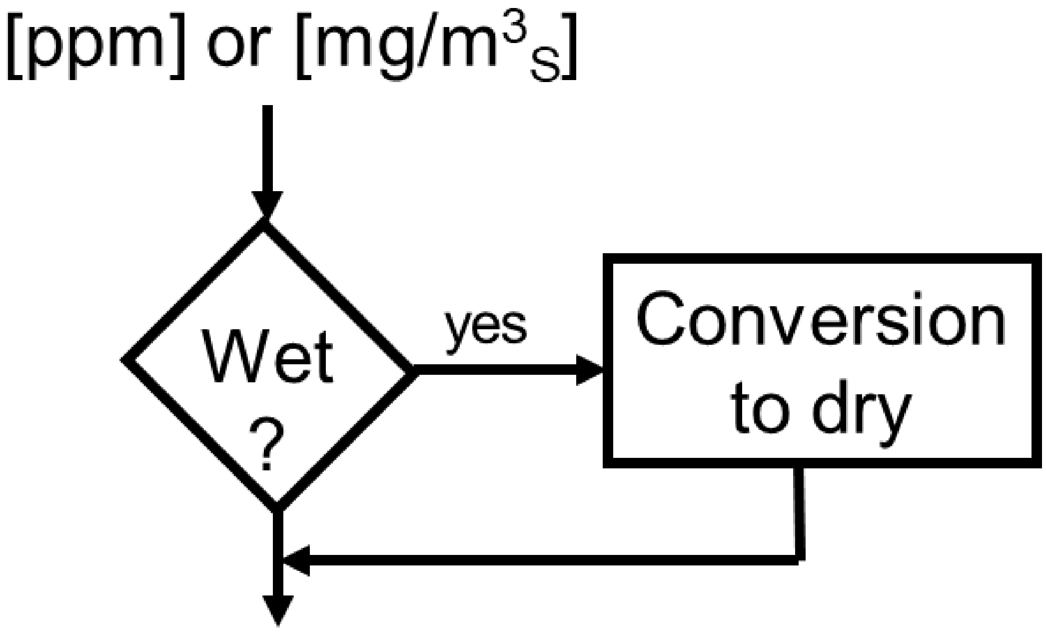
Conversion from «wet» to «dry»



In all countries the emission values for cement plants are related to the dry gas state. Exceptions are not known

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Conversion to «dry»

Concentration
c = concentration [ppm] or [mg/m³]
w = water content [%]

$$c_{dry} = \frac{c_{wet}}{\left(1 - \frac{w}{100}\right)}$$

Volume stream

$$V_{dry} = V_{wet}\left(1 - \frac{w}{100}\right)$$

Example
Concentration SO_2 → 251 [ppm_{wet}]
Moisture (H_2O)→ 14 [%]
Volume → 100'000 [$m^3{}_{wet}/h$]

$$c_{dry} = \frac{251}{\left(1 - \frac{14}{100}\right)} = 292\ [ppm_{dry}]$$

$$V_{dry} = 100'000\left(1 - \frac{14}{100}\right) = 86'000\ [m^3{}_{dry}/h]$$

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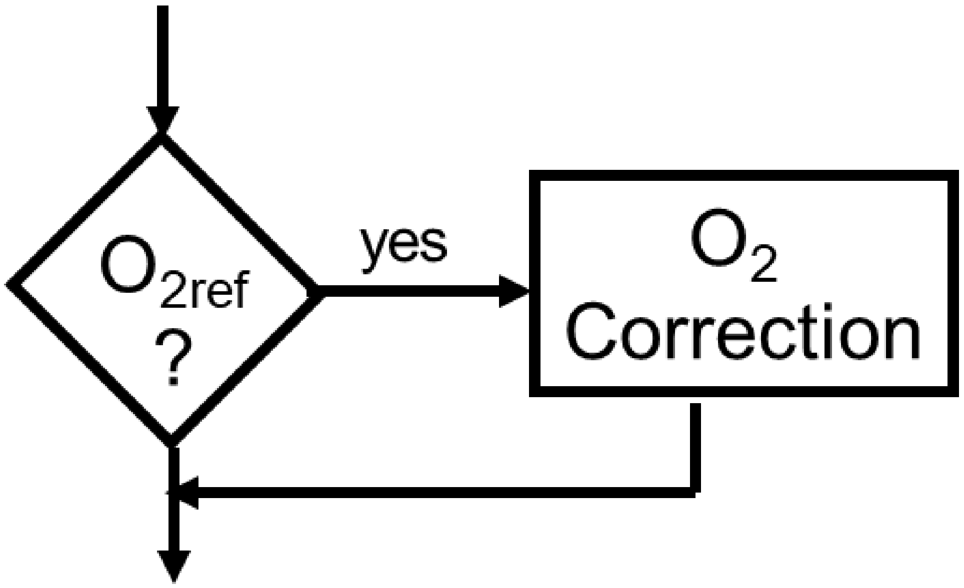
Correction to Reference Oxygen Level



Conversion to Reference Oxygen Level

Concentration

c concentration (dry) [mg/m^3_S]
c_{korr} corrected value [mg/m^3_S] at o_{Ref}
o oxygen content [%] (dry)
o_{Ref} reference oxygen [%]

$$c_{korr} = c \cdot \frac{(21 - o_{Ref})}{(21 - o)}$$

Volume stream

$$V_{korr} = V \cdot \frac{(21 - o)}{(21 - o_{Ref})}$$

Example

Concentration SO_2	c = 835 [mg/m^3_N]
Oxygen content (O_2)	o = 7.2 [%]
Reference ($O_{2,ref}$)	o_{Ref} = 10 [%]
Volume stream	V = 100'000 [m^3_N/h]

$$c_{korr} = 835 \cdot \frac{(21 - 10)}{(21 - 7.2)} = 665 \left[\frac{mg}{m_N^3}\right]$$

$$V_{korr} = 100'000 \cdot \frac{(21 - 7.2)}{(21 - 10)}$$

$$= 125'455 \left[\frac{m_N^3}{h}\right]$$

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