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APPLICATION NOTE

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How to Measure Carbon Dioxide

Carbon dioxide measurement is required in many applications from building automation and greenhouses to life science and safety.

This document covers the following topics:

- *Operation principle of infrared carbon dioxide (CO_2) sensors*
- *The ideal gas law and how to use it to compensate the CO_2 measurement for environmental factors*
- *Optimal locations for CO_2 transmitters*
- *Safety issues related to CO_2*

Operation Principle of Infrared Sensors

Carbon dioxide and other gases consisting of two or more dissimilar atoms absorb infrared (IR) radiation in a characteristic, unique manner. Such gases are detectable using IR techniques. Water vapor, methane, carbon dioxide, and carbon monoxide are examples of gases that can be measured with an IR sensor. Their characteristic absorption bands are shown in Figure 1.

IR sensing is the most widely applied technology for CO_2 detection. IR sensors have many benefits over chemical sensors. They are stable and highly selective to the measured gas. They have a long lifetime and, as the measured gas doesn't directly interact with the sensor, IR sensors can withstand high humidity, dust, dirt, and other harsh conditions.

The key components of an IR CO_2 detector are light source, measurement chamber, interference filter, and IR detector. IR radiation is directed from the light source through the measured gas to the detector. A filter located in front of the detector prevents wavelengths other than that specific to the measured gas from passing through to the detector. The light intensity is detected and converted into a gas concentration value.

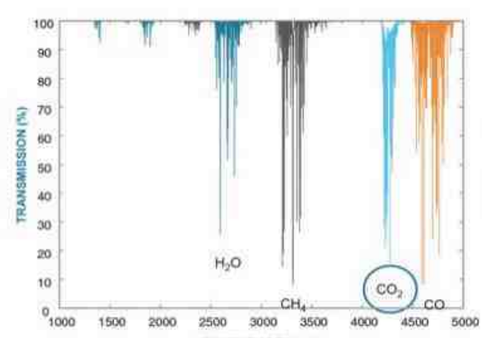


Figure 1. IR absorption of CO_2 and some other gases.

The Vaisala CARBOCAP® carbon dioxide sensor uses IR sensing technology to measure the volumetric concentration of CO_2. It features a unique electrically tunable Fabry-Perot Interferometer (FPI) filter for dual-wavelength measurement. This means that in addition to measuring CO_2 absorption, the CARBOCAP® sensor also performs a reference measurement, which compensates for any changes in the light source intensity as well as for dirt accumulation and contamination. This makes the sensor extremely stable over time. View the complete range of Vaisala products for CO_2 measurement at www.vaisala.com/CO2

Ideal Gas Law

The ideal gas law is useful when estimating the effect of temperature and pressure changes on CO_2 measurement. It can be used to compensate the CO_2 readings.

Ideal gas is a hypothetical gas consisting of randomly moving identical point particles that are negligible in size and possess negligible intermolecular forces. Ideal gas molecules are assumed to undergo elastic collisions both with each other and with the container walls.

In reality, gases do not behave exactly like ideal gases, but the approximation is often used to describe the behavior of real gases. The ideal gas law relates the state of a certain amount of gas to its pressure, volume, and temperature, according to the equation:

$$pV = nRT$$

where

p = pressure [Pa]
V = volume of the gas [m3]
n = amount of gas [mol]
R = universal gas constant (= 8.3145 J/mol K)
T = temperature [K]

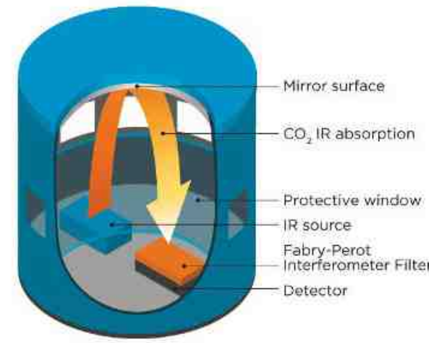
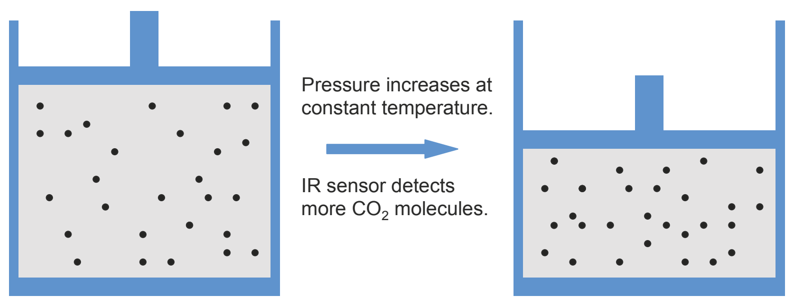
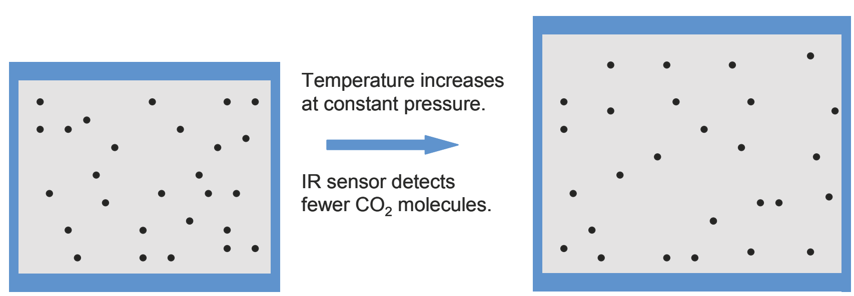


Figure 2. The structure of the Vaisala CARBOCAP® CO_2 sensor.

Pressure Increase at Constant Temperature



Temperature Increase at Constant Pressure



Optimal Locations for CO_2 Transmitters

- Avoid locations where people may breathe directly onto the sensor. Also avoid placing sensors close to intake or exhaust ducts, or near windows and doorways.
- In demand controlled ventilation wall-mounted sensors provide more accurate data on ventilation effectiveness than duct-mounted sensors. Duct-mounted sensors are best suited to single-zone systems and should be installed as close to the occupied space as possible to allow for easy maintenance access.
- When measuring CO_2 for the purposes of personnel safety, transmitters should be installed close to potential leakage points to enable early detection. The geometry, ventilation, and airflow of the monitored area need to be taken into account. The number and location of the CO_2 transmitters should be based on a risk assessment.

The Effect of Temperature and Pressure on CO_2 Measurement

Most gas sensors give out a signal proportional to the molecular density (molecules/volume of gas), even though the reading is expressed in parts per million (volume/volume). As the pressure and/or temperature changes, the molecular density of the gas changes according to the ideal gas law. The effect is seen in the ppm reading of the sensor.

The following illustrations visualize how an increase in pressure or temperature changes the state of the gas and how it affects CO_2 measurement.

The ideal gas law can be used to calculate the molecular density of a gas at a given temperature and pressure, when the gas density at Standard Ambient Temperature and Pressure (SATP) conditions is known. Replacing the amount of gas (n) with ρV/M, and assuming that the molar mass of the gas (M) is constant in the two different conditions, the equation can be written as in Equation 1.

The density formula can be used to estimate how gas sensor reading changes as temperature and/or pressure is changed.

The density formula can be used to compensate for temperature and pressure variations when measuring CO_2. Typical CO_2 instruments do not measure pressure and thus cannot automatically compensate for pressure variations. When calibrated at the factory, instruments are typically set to sea-level pressure conditions (1013 hPa). When measuring at altitudes other than sea-level, it is recommended to compensate for the pressure effect. This can be done either by entering the correct pressure settings for internal compensation (constant pressure conditions) or by programming the compensation into an automation system or PC (changing pressure conditions).

The same compensation rules apply to the temperature effect. However, there are more and more CO_2 meters available that both measure and compensate for temperature variations, and therefore do not require any external compensation.

$$\rho(t,p) = \rho(25°C, 1013hPa) \times \frac{p}{1013} \times \frac{298}{(273+t)}$$

where

ρ = gas volume concentration [ppm or %]
p = ambient pressure [hPa]
t = ambient temperature [°C]

Equation 1. Calculation of gas concentration at given temperature and pressure.

Pressure (hPa)	Temperature (°C)									
	-20	-10	0	10	20	25	30	40	50	60
700	814	783	754	728	703	691	680	658	638	618
800	930	895	862	832	803	790	777	752	729	707
900	1046	1007	970	936	904	888	874	846	820	795
1000	1163	1119	1078	1039	1004	987	971	940	911	883
1013	1178	1133	1092	1053	1017	1000	983	952	923	895
1100	1279	1230	1185	1143	1104	1086	1068	1034	1002	972
1200	1395	1342	1293	1247	1205	1185	1165	1128	1093	1060
1300	1512	1454	1401	1351	1305	1283	1262	1222	1184	1148

Table 1. The ppm reading of a CO_2 sensor when measuring a gas with 1,000 ppm concentration under different temperature and pressure conditions.

Table 1 shows an example of the changes in the CO_2 sensor reading (gas contains 1,000 ppm of CO_2 at SATP) as temperature and pressure change, according to the ideal gas law.

Drying a Wet Gas Sample

Processing the ideal gas law further provides a way of understanding what happens when the composition of a gas mixture is varied at a constant pressure, temperature, and volume. This can be used, for example, to estimate the effect of changing humidity on the CO_2 reading.

The molecules of a gas mixture exist in the same system volume (V is the same for all gases) at the same temperature. The ideal gas law can be modified to:

$$p = (n_{gas1} + n_{gas2} + n_{gas3} + \ldots n_{gasn}) \times \frac{RT}{V}$$

where

n_{gas1} = amount of gas 1 [mol]
n_{gas2} = amount of gas 2 [mol], etc.

and

$$p = p_{gas1} + p_{gas2} + p_{gas3} + \ldots p_{gasn}$$

where

p = total pressure of the gas mixture
p_{gas1} = partial pressure of gas 1
p_{gas2} = partial pressure of gas 2, etc.

	T_d (°C)	-40	-30	-20	-10	0	10	20	30	40	50	60
T_d (°C)	ppm H_2O	127	377	1 020	2 580	6 060	12 290	23 200	42 000	73 000	122 000	197 000
-60	11	0.9999	0.9996	0.999	0.997	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-50	38	0.9999	0.9997	0.999	0.997	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-40	127	1.0000	0.9997	0.999	0.998	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-30	377		1.0000	0.999	0.998	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-20	1 020			1.000	0.998	0.995	0.989	0.978	0.959	0.928	0.879	0.804
-10	2 580				1.000	0.997	0.990	0.979	0.961	0.930	0.880	0.805
0	6 060					1.000	0.994	0.983	0.964	0.933	0.884	0.809
10	12 290						1.000	0.988	0.970	0.939	0.890	0.815
20	23 200							1.000	0.981	0.950	0.901	0.826
30	42 000								1.000	0.969	0.920	0.845
40	73 000									1.000	0.951	0.876
50	122 000										1.000	0.925
60	197 000											1.000

Table 2. Dilution coefficients in gas sample drying.

The second equation is called Dalton's Law of Partial Pressure. It states that the total pressure of a gas mixture is the sum of the partial pressures of all the component gases in the mixture.

This information is useful when taking into account the influence of water vapor on CO_2 sensor readings. When water vapor is added to a dry gas at constant pressure, temperature, and volume, water replaces some of the gas molecules in the mixture. Similarly, when a gas sample is drawn from a high-humidity environment and is allowed to dry before entering the measurement chamber of a CO_2 meter, the loss of water molecules changes the composition of the gas and has an effect on the CO_2 measurement.

This so-called dilution effect can be estimated using Table 2. The CO_2 concentration of the high-humidity environment can be calculated when the CO_2 concentration of the dried gas is known. In order to do this, the dew point (T_d at 1013 hPa) or water concentration (ppm) of the wet and dry conditions need to be known. The humidity condition of the high-humidity environment is chosen from the horizontal axis and the condition of the dried gas from the vertical axis.

Example: A gas sample is drawn from an environment with a dew point of 40°C (73,000 ppm of water) to an environment of 20°C T_d (23,200 ppm of water). The measured CO_2 concentration of 5.263% at 20°C T_d translates to 5.00% in the 40°C T_d environment (5.263% × 0.950 = 5.00%). The lower reading is caused by dilution resulting from the higher water content at 40°C T_d.

Carbon Dioxide and Safety

Carbon dioxide is a non-toxic and non-flammable gas. However, exposure to elevated concentrations can induce a risk to life. Whenever CO_2 gas or dry ice is used, produced, shipped, or stored, CO_2 concentration can rise to dangerously high levels. Because CO_2 is odorless and colorless, leakages are impossible to detect, meaning proper sensors are needed to help ensure the safety of personnel.

Effect of Different Levels of CO_2

CONCENTRATION	EFFECT
350 - 450 ppm	Typical atmospheric concentration
600 - 800 ppm	Acceptable indoor air quality
1,000 ppm	Tolerable indoor air quality
5,000 ppm	Average exposure limit over 8-hour period
6,000 - 30,000 ppm	Concern, short exposure only
3 - 8%	Increased respiration rate, headache
> 10%	Nausea, vomiting, unconsciousness
> 20%	Rapid unconsciousness, death

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