VAISALA

CO_2 measurement in incubators - questions and answers

1. How does the CARBOCAP®, NDIR (non-dispersive infrared), single beam, dual wavelength sensor work?

2. How do temperature and pressure affect CO_2 measurement?

3. How can temperature and pressure error be corrected when using Vaisala CO_2 products?

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5. Why is the CO_2 concentration reading higher than expected when using the pump sampling method with drying tubing?

The purpose of this document is to answer most frequently asked questions often proposed concerning CO_2 measurement and products.

1. How does the CARBOCAP®, NDIR (non-dispersive infrared), single-beam, dual wavelength sensor work?

The Vaisala CARBOCAP® Sensor has three major components: a light source, an interferometer, and an IR detector. The light source is positioned to shine at the IR detector so that the light travels a fixed distance to the detector, where the intensity of the light is measured.

A Fabry-Perot Interferometer (FPI) is positioned just in front of the IR detector. The FPI is a tunable filter which allows only certain wavelengths of light to pass through to the detector.
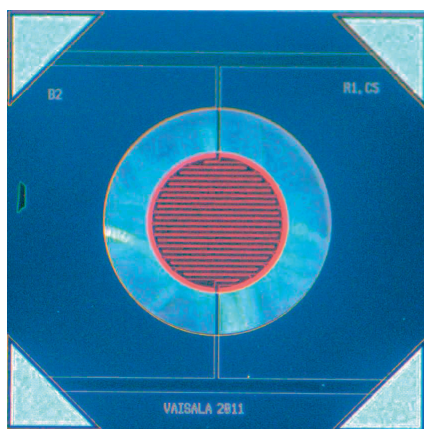

Mirror surface

CO_2 IR absorption

Protective window

IR source

Fabry-Perot Interferometer Filter
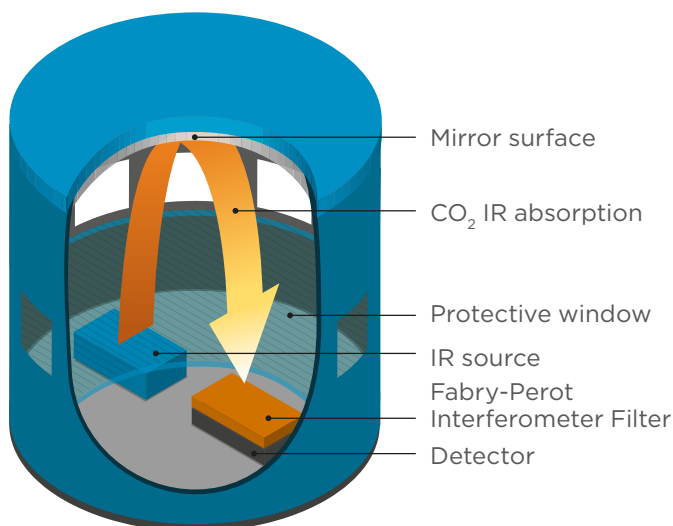
Detector

At the CO_2 absorption wavelength, light is absorbed by the carbon dioxide present in the gas. The FPI tunes out of all other wavelengths, so the intensity of light reaching the IR Detector varies as a function of the amount of CO_2 within the sensor.

Carbon dioxide absorbs certain wavelengths of light and not others, so the FPI is designed to pass light at a CO_2 absorption wavelength (4.26 μm) and a nearby, non-absorbing wavelength. See the illustration on the right.
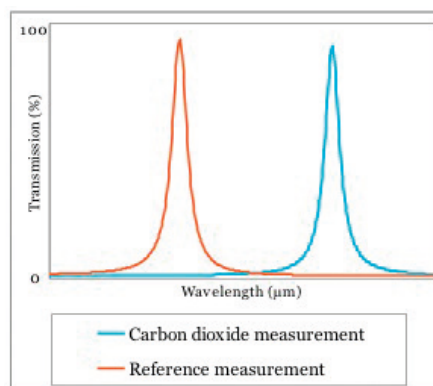
When the sensor is operating, the FPI is regularly tuned back and forth between the two wavelengths. At the CO_2 absorption wavelength, the intensity of detected light is reduced in proportion to the concentration of CO_2 in the optical path. The light intensity measured at the non-absorbing wavelength serves as a baseline for comparison.

As the concentration of CO_2 varies, the difference in light intensities varies. The exact relationship between IR light intensity and CO_2 volume concentration is determined when the instrument is calibrated using pure nitrogen (0 ppm CO_2) and a known concentration of CO_2.

The CARBOCAP® sensor design is simple and robust, using only one light source and one IR detector. This eliminates errors caused by slight differences in the multiple components of dualbeam sensor designs. The FPI used in the CARBOCAP® sensor is micromachined from silicon and has no moving parts, providing much higher reliability than mechanical "chopper wheel" designs.

*Both absorption and reference are measured with the CARBOCAP® sensor.*
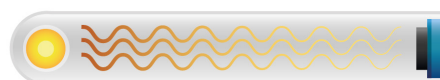
The FPI is tuned to a nearby non-absorbing reference wavelength, where the IR Detector measures the full intensity of light, creating a baseline for comparison. Any changes in the performance of the light source, FPI or IR Detector, affect both measurements equally, preserving the difference between both measurements and therefore the calibration of the sensor. This is a key to the long-term stability of the sensor.

The CARBOCAP sensor also incorporates the latest generation IR light source with the Microglow. Microglow technology solves many of the challenges that impact traditional infrared sources. The key advantages of microglow are greater stability, reduced power consumption, and a greatly extended operational lifetime. Replacing the incandescent light bulb with microglow technology increases the sensor's operational lifetime by 50%, while power consumption is only 25% that of traditional infrared sources.

The intensity of microglow remains extremely stable throughout its lifetime. Other benefits include short response time and superior manufacturability, as the chip can be automatically assembled directly on the component board.

Read more about microglow technology at vaisala.com/microglow.

Vaisala-patented microglow, a silicon MEMS emitter infrared source.
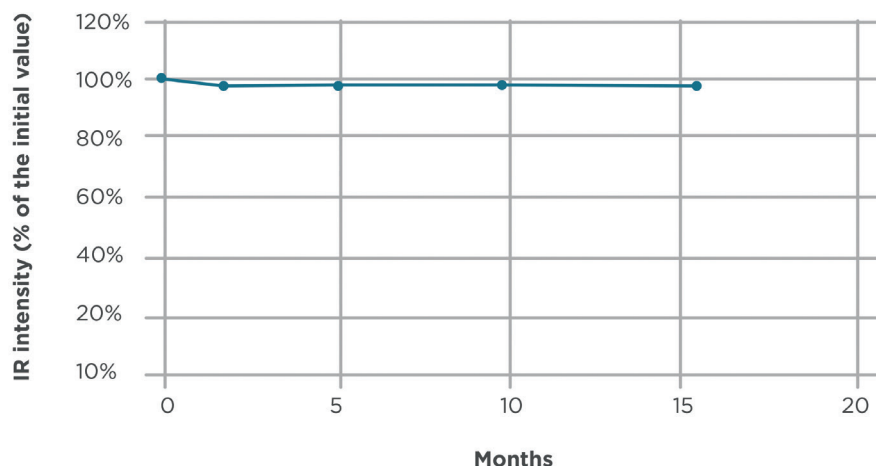
Microglow's superior long-term stability.

2. How do temperature and pressure affect CO_2 measurement?

All non-dispersive infrared instruments fundamentally measure mole density (the number of molecules in the path of the beam). Most users prefer output in volume percent, so the CO_2 instruments are adjusted to display this by correlating the number of molecules to a known CO_2 volume concentration.

Because gases are compressible, their mole densities change with changing ambient atmospheric pressure and temperature, which means the output is temperature and pressure dependent.

The CO_2 measurement needs to be compensated if the measurement conditions deviate significantly from the calibration conditions, which are 1013 hPa and 25 °C. See Tables 1 and 2 on the next page to see the magnitude of the effect of uncompensated changes in pressure and temperature according to the ideal gas law.

For a detailed understanding of the need for compensation, it is helpful to first understand something about the behavior of gases. In any mixture of gases, the total pressure of the gas is the sum of the partial pressures of the component gases. This is Dalton's law and it is represented as follows:

$$P_{total} = P_1 + P_2 + P_3\ldots$$

The quantity of any gas in a mixture can be expressed as a pressure. With air as an example, the major components are nitrogen, oxygen, carbon dioxide, and water vapor so total atmospheric pressure is composed of the partial pressures of these gases.

The partial pressure of each gas is the product of its volume concentration and the total pressure of the system.

The air we breathe consists of about 78% nitrogen, 21% oxygen, 0.9% argon and approximately 0.04% carbon dioxide. These percentages remain roughly constant throughout the atmosphere, regardless of altitude.

The average pressure of the atmosphere at sea level is approximately 1013 hPa, therefore the partial pressure of carbon dioxide is 0.04% of 1013hPa (0.0004*1013), or 0.405 hPa. For example in Denver, Colorado, USA, where the altitude is approximately 5280 feet and atmospheric pressure is about 834.3 hPa, that same 0.04 % carbon dioxides gives us a partial pressure of 0.334 hPa versus 0.405 hPa.

Even though CO_2 still makes up 0.04 % of the atmosphere at this higher altitude, the pressure is less, and when the pressure decreases, the mole density decreases. Since NDIR sensors fundamentally measure mole density, compensation needs to be made when a volume percent or ppmv reading is required. Temperature compensation is also important because as temperature decreases the mole density increases.

Most of Vaisala carbon dioxide transmitters have an integrated temperature sensor, when the device can automatically compensate temperature related variations in the measurement. In addition, also oxygen and relative humidity compensations can be set but these parameters have a minor effect on the measurement accuracy.

Table 1. Effect of uncompensated pressure changes of $%CO_2$ readings in an NDIR sensor according to ideal gas law.

Instruments calibrated at 25 ˚C and 1013 hPa					
Altitude above sea level		Pressure (hPa)	Measurement concentration ($%CO_2$)	Corrected concentration ($%CO_2$)	Difference ($%CO_2$)
feet	meters				
0	0	1013	5.00	5.00	0.00
500	153	992.8	4.90	5.00	0.10
1000	305	979.1	4.83	5.00	0.17
1500	458	958.4	4.73	5.00	0.27
2000	610	937.7	4.63	5.00	0.37
2500	763	923.9	4.56	5.00	0.44
3000	915	903.2	4.46	5.00	0.54
3500	1068	889.4	4.39	5.00	0.61
4000	1220	868.7	4.29	5.00	0.71
4500	1373	854.9	4.22	5.00	0.78
5000	1526	834.3	4.12	5.00	0.88
5500	1679	820.5	4.05	5.00	0.95
6000	1831	806.7	3.98	5.00	1.02

Table 2. Effect of uncompensated temperature changes on %CO_2 readings in an NDIR sensor according to ideal gas law.

Instruments calibrated at 25 ˚C and 1013 hPa			
Temperature (˚C)	Measured concentration (%CO_2)	Corrected concentration (%CO_2)	Difference (%CO_2)
25	5.00	5.00	0.00
26	4.98	5.00	0.02
27	4.97	5.00	0.03
28	4.95	5.00	0.05
29	4.93	5.00	0.07
30	4.92	5.00	0.08
31	4.90	5.00	0.10
32	4.89	5.00	0.11
33	4.87	5.00	0.13
34	4.85	5.00	0.15
35	4.84	5.00	0.16
36	4.82	5.00	0.18
37	4.81	5.00	0.19

The Vaisala GM70 with the humidity probe alongside the carbon dioxide probe.

3. How can temperature and pressure errors be corrected when using Vaisala CO₂ products?

Carbon dioxide measurements made at temperatures and pressures different from the calibration conditions may need to be corrected to achieve the required accuracy. The simplest form of correction for a volume percent reading can be done using a formula according to the ideal gas law:

$$c_{corrected}(\%/ppm) = \frac{c_{measured}(\%/ppm)*(1013*(t(°C)+273))}{(298K*p(hPa))}$$

In the Vaisala CARBOCAP® Hand-Held Carbon Dioxide Meter GM70 the temperature and pressure of the environment at the measurement point can be easily set in the GM70 user menu. Compensations are made internally and the instrument displays the corrected measurement. The internal correction also takes into account dependencies caused by real gas laws, as well as the electronics and optical components of the instrument. The internal correction is more accurate for the GM70 than the ideal gas law correction. Another way to compensate for temperature is to connect a Vaisala HUMICAP® Humidity and Temperature Probe HMP77B to the MI70 indicator alongside the CO_2 probe. The temperature measured with the probe can be set to automatically compensate the CO_2 reading.

The Vaisala CARBOCAP® Carbon Dioxide probes GMP231 and GMP251 have internal temperature compensations, when the probe measures and compensates temperature automatically. Also oxygen and relative humidity compensations can be set for best accuracy.

4. How can condensation be avoided when sampling from incubators?

The GM70 has two alternative sampling methods: diffusion and pump-aspirated. The pump-aspiration option is designed to draw a sample from spaces where diffusion-based direct measurement is not possible.

Precaution must be taken when drawing a gas sample from humid environments, since the optical surfaces of the NDIR sensor inside the probe and the pumping chamber must be protected from condensation.

Incubators and environmental chambers are challenging to measure, as the gas sample is usually drawn from an environment with high temperature and high humidity into a room temperature environment, resulting in condensation.

The Vaisala GM70 is used to verify the CO_2 level in incubators.

Condensation inside of the tubing and sample system can be avoided by using a sample tube made out of a material called Nafion® (available as an accessory, Vaisala Part No. 212807GM).
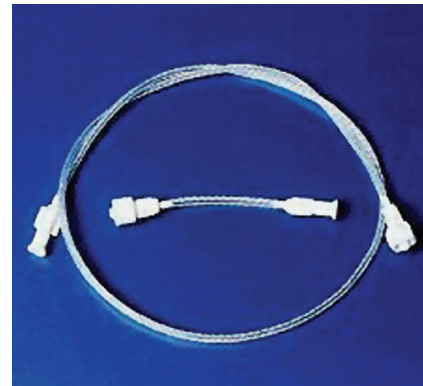

Nafion® tubing, Vaisala part No. 212807GM.

The core technology of the tubing is Nafion®[1] that is highly selective in the removal of water. The water moves through the membrane wall and evaporates into the surrounding air in a process called pervaporation. Nafion® removes water by absorption which occurs as a First Order kinetic reaction. In drying applications, the moisture exchanger transfers water vapor from a wet gas stream into the surrounding atmosphere. Drying is complete when the sample humidity level is equal to the ambient humidity level. Since drying proceeds as a First Order kinetic reaction, this level can be reached extremely quickly, usually within 100 to 200 milliseconds. This behavior makes the tubing ideal applications involving a very humid sample drawn to room temperature. The humidity of the gas sample can be reduced with only a short length of the tubing. For more information on tubing, see www.permapure.com.

1   Nafion® is a Dupont co-polymer of tetrafluoroethylene (Teflon) and perfluoro-3,6-dioxa-4-methyl-7-octene-sulfonic acid.

When using the GM70 pump to sample from an incubator, use Nafion® tubing to eliminate the possibility of moisture condensation in the sample system. These guidelines are recommended:

- It is desirable to have the Nafion® sample tubing present at the transition point between the incubator and the ambient environment. 20 cm of Nafion® in the ambient environment is sufficient to transfer water vapor from the extracted sample to the ambient environment. The remainder of the sample tubing can be Neoprene or some other material. Connect the tubing using hose barb fittings or some other method to prevent leakage of ambient air into the sample. Keep the overall sample line as short as possible.

- If sampling through the incubator door, insert the Nafion® tubing into the incubator and gently close the incubator door, checking to make sure that the door seal does not damage the tubing and seals adequately around it.

- When drawing a gas sample from a chamber, a few centimeters of the sampling line should be placed inside the chamber. If there is a risk for condensation inside the chamber where the sample is drawn, take special care that the condensate is not running to the tube.

- To check that condensation has not reached the probe, you can pull out the CO_2 probe from the GM70 pump. When re-inserting the probe, do not push the probe all the way in. Instead, match the two O-rings together with the smooth probe surface to achieve a tight connection.

- If sampling through a hole or other port in the incubator, insert Nafion® tubing into the incubator and seal around it.

- If sampling through a hose barb fitting/sample port, use a very short length of Neoprene tubing to connect the fitting of the Nafion tubing to the incubator fitting. Use the Neoprene as a "connector" to hold the Nafion® tubing as close as possible to the hose barb. It is undesirable to have the sample gas travel through the Neoprene, as condensation is likely to result within the Neoprene tubing.

- As a precaution, keep the GM70 pump above the level of the chamber sampling port. If condensation occurs in the sample line, this will prevent liquid water from damaging the CO_2 sensor.
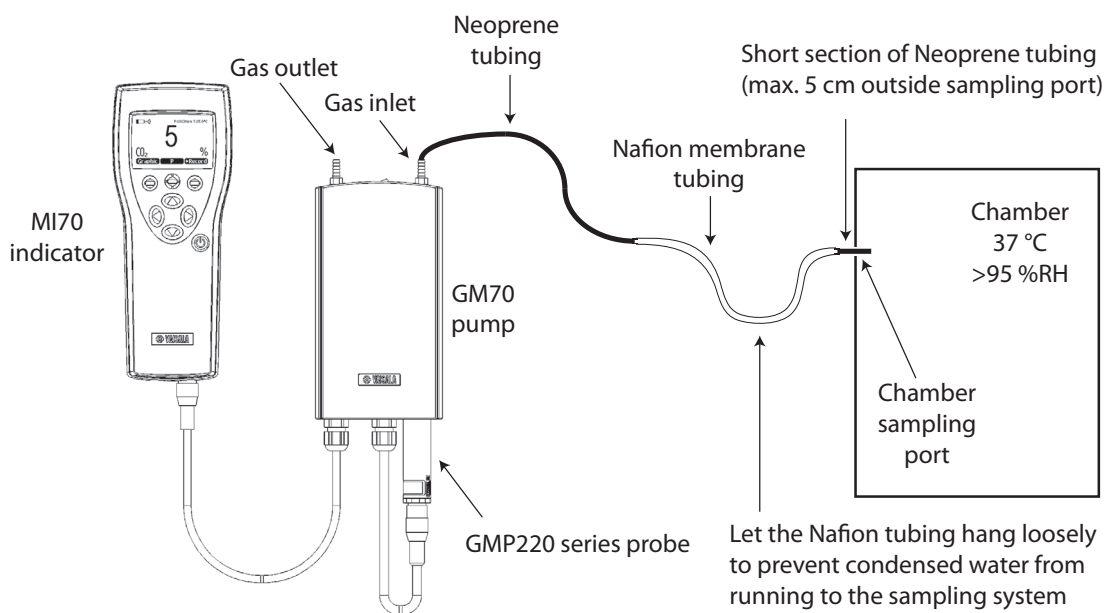
Sampling system with the Nafion® membrane tube.

5. Why is the CO_2 concentration reading higher than expected when using the pump sampling method with drying tubing?

When using the Nafion® tubing to dry the sample, the CO_2 concentration of the dry sample will be slightly higher than in the wet sample.

This is due to a phenomenon called dilution. The CO_2 density is "diluted" in the incubator by the volume that the water vapor occupies. If water vapor is removed from the sample, the fractions occupied by other gases, including CO_2, will increase accordingly.

Table 3 contains the dilution co-efficients for the gas concentration when drying a gas sample. Dew point (at 1013 hPa) of the gas sample in the incubator is chosen on the horizontal axis, and the dew point of the gas sample at the measurement point is chosen on the vertical axis. Dew point of the gas sample at the measurement point can be determined with a humidity probe (HMP75B, HMP76B or HMP77B).

Table 3. Dilution coefficients

Td (°C)	-40	-30	-20	-10	0	10	20	30	40	50	60
-60	0.9999	0.9996	0.999	0.997	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-50	0.9999	0.9997	0.999	0.997	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-40	1.0000	0.9998	0.999	0.998	0.994	0.988	0.977	0.958	0.927	0.878	0.803
-30		1.0000	0.999	0.998	0.994	0.988	0.977	0.958	0.928	0.879	0.804
-20			1.000	0.998	0.995	0.989	0.978	0.959	0.928	0.879	0.804
-10				1.000	0.997	0.990	0.979	0.961	0.930	0.881	0.806
0					1.000	0.994	0.983	0.964	0.933	0.884	0.809
10						1.000	0.989	0.970	0.939	0.890	0.815
20							1.000	0.981	0.950	0.901	0.826
30								1.000	0.969	0.920	0.845
40									1.000	0.951	0.876
50										1.000	0.925
60											1.000

As an example: A gas sample is drawn from a 40 °C (Td) environment and introduced into a 10 °C (Td) environment, where the measured gas concentration is 5.32%. In the 40 °C (Td) environment this corresponds to 5% CO_2 (5.32% X 0.939= 5.00%) since the higher water content diluted the sample.

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