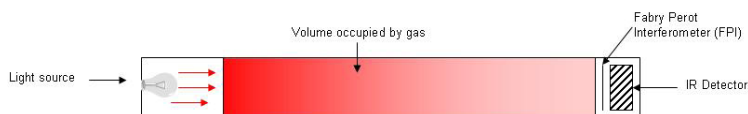# CO$_2$ Measurement in Incubators

Frequently Asked Questions:

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

2. How do temperature and pressure effect CO$_2$ measurement?

3. How can temperature and pressure errors be corrected when using Vaisala CO$_2$ products?

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

5. Why is the CO$_2$ concentration reading higher than expected when using the pump sampling method?

Vaisala CARBOCAP' Hand-held Carbon Dioxide Meter GM70.

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. 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 near-by, non-absorbing wavelength. 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 (*See Illustration 1*).

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 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 dual-beam 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.

2. How do temperature and pressure effect 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 volume concentrations change with changing ambient atmospheric pressure and temperature, which means the output is temperature and pressure dependent *(See Illustration 2)*.

At the CO$_2$ absorption wavelength, light is absorbed by the carbon dioxide present in the gas. The FPI tunes out 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.

Here 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 effect both measurments equally, preserving the difference between both measurements and therefore the calibration of the sensor.

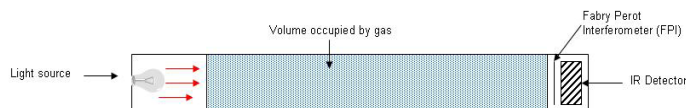*Illustration 1: Different light absorption at different wave lengths.*

The blue dots represent CO$_2$ molecules in air at sea level.

As elevation increases and pressure decreases, fewer CO$_2$ molecules occupy the same space even though the percentage of CO$_2$ relative to other gases remains the same. Because NDIR sensors "count molecules" in the optical path, to properly display % CO$_2$ the measurement must be adjusted for pressure difference or the instrument will display an erroneous low reading.

Illustration 2: The effect of pressure on CO$_2$ measurement with NDIR sensors.

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 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:

$$P_{total} = P_1 + P_2 + P_3...$$

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.

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.

Instruments calibrated at 25 °C and 1013 hPa

Altitude Above Sea Level (ft)	Pressure (hPa)	Measured Concentration (%CO_2)	Corrected Concentration (%CO_2)	Difference (%CO_2)
0	1013	5.00	500	0.00
500	992.8	4.90	500	0.10
1000	979.1	4.83	500	0.17
1500	958.4	4.73	500	0.27
2000	937.7	4.63	500	0.37
2500	923.9	4.56	500	0.44
3000	903.2	4.46	500	0.54
3500	889.4	4.39	500	0.61
4000	868.7	4.29	500	0.71
4500	854.9	4.22	500	0.78
5000	834.3	4.12	500	0.88
5500	820.5	4.05	500	0.95
6000	806.7	3.98	500	1.02

Table 1. Effect of uncompensated pressure changes on %CO_2 readings in an NDIR sensor.*

Instruments calibrated at 25 °C and 1013 hPa

Temperature (°C)	Measured Concentration (%CO_2)	Corrected Concentration (%CO_2)	Difference (%CO_2)
25	5.00	500	0.00
26	4.98	500	0.02
27	4.97	500	0.03
28	4/95	500	0.05
29	4.93	500	0.07
30	4.92	500	0.08
31	4.90	500	0.10
32	4.89	500	0.11
33	4.87	500	0.13
34	4.85	500	0.15
35	4.84	500	0.16
36	4.82	500	0.18
37	4.81	500	0.19

Table 2. Effect of uncompensated temperature changes on %CO_2 readings in an NDIR sensor.*

*Formula used in both Table 1 and Table 2:

$$c_{corrected}(\%/ppm) = c_{measured}(\%/ppm)*\frac{(1013*(t(°C)+273))}{(289K*p(hPa))}$$

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

Carbon dioxide measurements made at temperatures and pressures different from the calibration conditions need to be corrected. The required compensation for any NDIR sensor is based on the ideal gas law. The simplest form of correction for a volume percent reading can be done using a formula according to the ideal gas law:

$$c_{corrected}(\%/ppm) = c_{measured}(\%/ppm)*\frac{(1013*(t(°C)+273))}{(289K*p(hPa))}$$

The Vaisala CARBOCAP® Hand-Held Carbon Dioxide Meter GM70 does not require any calculations for pressure and temperature compensation. The temperature and pressure of the environment at the measurement point can be easily set using the graphical GM70 interface. Compensations are made internally and the instrument displays the corrected measurement. The internal correction is a more accurate way to make compensations because in addition to taking into account the ideal gas law, it takes into account dependencies caused by real gas laws, as well as the electronics and optical components of the instrument.

Another way to compensate for temperature is to connect a Vaisala HUMICAP® Humidity and Temperature Probe HMP75B, HMP76B or HMP77B to the MI70 indicator alongside the CO_2 probe. The temperature measured with one of these probes can be set to automatically compensate the CO_2 reading.

The Vaisala MI70 indicator with the humidity probe alongside the carbon dioxide probe.

In the Vaisala CARBOCAP® Carbon Dioxide Transmitter GMT220 Series and the Vaisala CARBOCAP® Carbon Dioxide Module GMM220 Series, the compensations can also be applied internally. The settings can be changed through a PC. The GMT220 and GMM220 are linked to PC via a serial cable equipped with a COMadapter (part number 19040GM).

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

The Vaisala CARBOCAP® Hand-held Carbon Dioxide Meter GM70 has two alternative sampling methods: diffusion and pump-aspirated. The GM70 with the pump-aspiration option is designed to draw a sample from spaces where diffusion-based 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.

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, Part No. 212807GM). The core technology of the tubing is Nafion®, a Dupont co-polymer of tetrafluoroethylene (Teflon) and perfluoro-3,6-dioxa-4-methyl-7-octene-sulfonic acid 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 perevaporation. 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 for applications involving a very humid sample drawn to room temperature. The humidity of the gas sample can easily be reduced with only a short length of the tubing. More information on tubing can by obtained from www.permapure. com.

Things to consider when using the GM70 with the Nafion® membrane tube:

- The measurement setup should be built in such a way that a part of the membrane tubing is placed inside the space to be measured. This part should be only a few centimeters. The majority of the length of the tube should be kept in the ambient. *Illustration 3* shows a correct measurement setup.

- It is important that if there is condensation inside the space where the sample is drawn, that this water is not running through the membrane tubing into the pumping chamber.
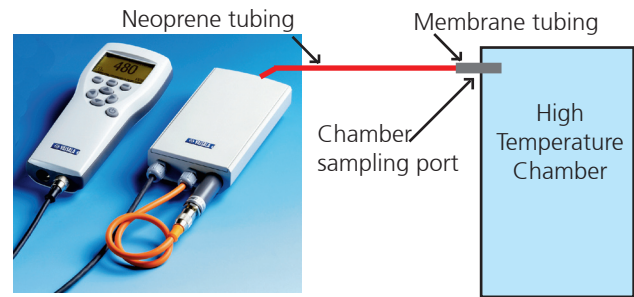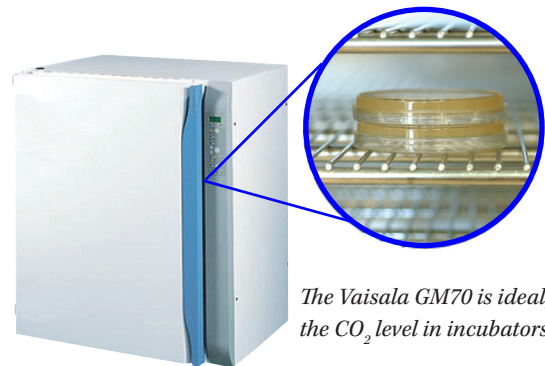

Illustration 3. Sampling system with membrane.

- The probe can be pulled out from the measurement chamber of the pump to verify that no condensation has reached the probe.

- The operating temperature range is specified as -20...+65 °C (-4...+149 °F).

The Vaisala GM70 is ideal for verifying the CO_2 level in incubators.

The GM70 pump-aspirated mode is used to check incubators in the field.

Nafion tubing.

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

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. Dewpoint (at 1013 hPa) of the gas sample in the incubator is chosen on the horizontal axis, and the dewpoint of the gas sample at the measurement point is chosen on the vertical axis. Dewpoint of the gas sample at the measurement point can be determined with a humidity probe (HMP75B, HMP76B or HMP77B).

As an example: A gas sample is drawn from a 40°C (Td) environment and introduced into a 10 °C (Td) enviroment, 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 high water content diluted the sample.

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	0.9997	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	0.927	0.878	0.803
-20			1.0000	0.998	0.995	0.989	0.978	0.959	0.928	0.879	0.804
-10				1.0000	0.997	0.990	0.979	0.961	0.930	0.880	0.805
0					1.0000	0.994	0.983	0.964	0.933	0.884	0.809
10						1.0000	0.989	0.97	0.939	0.890	0.815
20							1.0000	0.981	0.950	0.901	0.826
30								1.0000	0.969	0.920	0.845
40									1.0000	0.951	0.876
50										1.0000	0.925
60											1.0000

Table 3: Dilution Coefficients

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