# DEALING WITH TEMPERATURE AND HUMIDITY WHEN MONITORING AIRBORNE TOXINS

## Introduction

**In applications where gases are measured precisely, even down to the ppb level, such as air quality control or monitoring of dangerous chemicals, it is of safety critical importance that the sensors deliver accurate and reliable results. In climate-controlled areas this presents less of a challenge; however outside of these areas, where temperatures can fluctuate by 15-20 degrees across the day and more with changing seasons, environmental factors can cause noticeable changes in sensor behaviour. The two most important environmental factors are humidity and temperature.**

### Humidity vs. Temperature

Rapid changes in humidity can cause a spike in sensor signal, while the sensor is reacting to the change in environment. This is a short-term signal and should vanish after 1-2 minutes. Afterwards, the sensor behaves as normal. Due to this, a humidity compensation is not required; however if the sensor is used in an environment with frequent sudden humidity changes, this should be considered during measurements and may be an explanation for unusual spikes in sensor signals.

Along with humidity, temperature is a vital environmental component that can affect sensor behaviour. Unlike humidity though, which is usually a transient effect that settles quickly, the temperature will affect the sensor the whole time while it is in that environment. For that reason, it is important to adjust the baseline and the sensitivity of the sensor based on the temperature to ensure accuracy and precision.

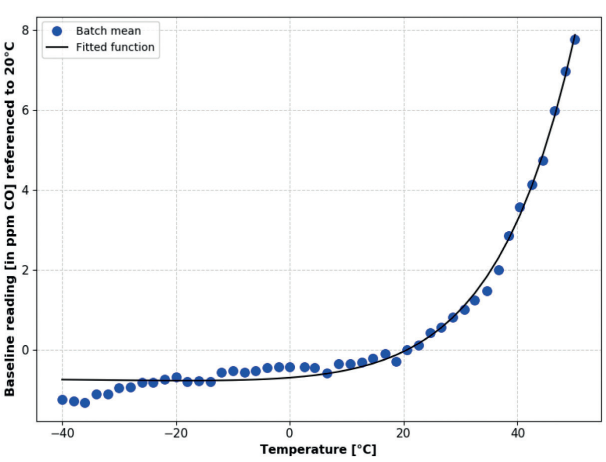


*Figure 1: Baseline shifted with respect to reference point at 20°C.*

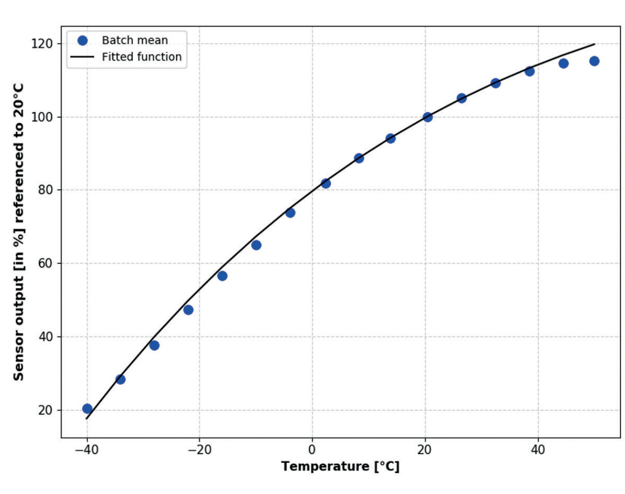


*Figure 2: Sensitivity dependence expressed as a percentage of the output signal at reference point at 20°C.*

Above are two example pictures of temperature measurements from real sensors showing the effect of temperature (-40 to 50 °C) on the baseline (top picture) and on the sensitivity (bottom picture) of the sensor. As can be seen from the graphs, especially the sensitivity can show significant temperature effects, dropping down to 20 % sensitivity in extreme conditions (-40 °C).

These images show batch means, rather than an individual sensor. This is important, because it can show general trends, expected behaviours and provide starting points for temperature compensation. However, each sensor will react differently to changes in the environment's temperature. This is why for the most accurate results it is recommended to compensate for each sensor individually, rather than doing a general compensation using the batch means.

### How to Perform Temperature Compensation

Measuring the baseline requires a climate controlled oven, sensors and an electronic readout. It is recommended that the first data point taken is from the top of the targeted temperature range and that the sensors are placed into the oven at room temperature with the readouts connected. Turn on the oven and set the temperature to the highest temperature in the desired range. Once the oven has reached the target temperature, it is important for the sensor to equilibrate, and the sensor should be kept at that temperature for 3-4 hours. Then, over the next 1-2 minutes, the baselines should be taken 3-5 times or averaged over all collected data points during that time. This will smooth out the noise of the baseline and provide an accurate data point. Then reduce the temperature to the next data point and repeat the procedure. Depending on how wide the range is and how precise the temperature compensation needs to be, the space between two data points can be determined. A standard and sensible starting point would be 5 °C for ranges of around 30 °C degree width up to 15 °C for ranges around 80-90 °C width.

The setup to measure sensitivity is almost identical to the setup for baseline compensation measurement, however it requires a gas bottle containing the target gas, the ability to lead the gas into the oven and a gas cap (for a single sensor) or a plate (for multiple sensors) so that the gas flows reach the sensors. Otherwise, the methodology is very similar. Start with the highest temperature and let the sensor equilibrate for a few hours. Take a baseline measurement value with no gas flow and then switch on the gas flow at an appropriate concentration. Keep it running for two minutes, then take the sensitivity. Turn off the gas flow and let the sensor recover. Repeat this two further times. Then go down to the next temperature and repeat all steps. The sensitivity and baseline can be measured at the same time, however rather than a single point for the baseline, averages should be taken in this case.

Once the measurement is completed, the oven should be brought back to room temperature before the sensors are removed. This is usually a straightforward procedure; however when measuring sub-zero temperatures, the warm up should proceed slowly, especially around 0 °C. When done too quickly, parts of the setup are still cold, which can cause water to condense, which can damage electronics and sensors. In addition, during heating and cooling, some temperature ovens create extreme humidities. As these occur only for short periods of time these are not damaging to the sensors but will cause baseline shifts due to transient effects.

The gathered data points can then be used to create graphs, like the ones seen above. For the baseline values, take the average data points measured at each temperature and divide them by

the sensitivity at the given temperature. If this data is unavailable, the sensitivity at 20 °C (either from temperature sensitivity measurements, calibration measurements or a Membrapor Data report) can also be used. This gives the baseline shift in ppm. Subtract the value at 20 °C from all other data points to set a reference temperature for comparison.

A similar method is used for the sensitivity. From the data points taken for sensitivity, the baseline signal should be subtracted. This gives the actual signal change due to the gas exposure. Divided by the gas concentration this gives the sensitivity of the sensor, which can also be used to help calculate the baseline. The sensitivity at 20 °C is taken as a reference and considered 100 %. Then the sensitivity for other temperatures is divided by the reference and multiplied by a 100. This gives the factor in a percentage and allows us to draw a graph, as seen above.

The basis formula for any temperature compensation, no matter if it's a baseline or sensitivity compensation, is a third order polynomial of the form:

$$TCX(T) = k_0 + k_1T + k_2T^2 + k_3T^3$$

TCX is a placeholder for every temperature compensation formula. TCZ is for the compensation of the baseline, TCS for the compensation of the sensitivity.

To calculate the most accurate TCZ (Baseline) formula, you need the following information for at least 4 data points:

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| Temperature (°C) | Baseline Signal (nA) | Sensitivity (at given Temperature) (nA/ppm) |
|---|---|---|

In case no sensitivity measurements were taken at different temperatures it is possible to use the sensitivity at 20 °C, however this will make the compensation slightly less accurate. By dividing the baseline signal by the sensitivity it is converted from nA to ppm. It then needs to be normalised, so that the signal at the reference temperature is equal to zero. This is done by subtracting the baseline signal at the reference temperature from all baseline signals. Resulting in a table like this:

| Temperature (C°) | Baseline Signal (ppm) | Normalised Baseline Signal (ppm) |
|---|---|---|

For an equation of the form TCZ(T) = k0 + k1T + k2T2 + k3T3 the normalised baseline signal will be the solution (TCZ), while the temperature will be the variable (T). Using the data points you can either use excel to solve for the coefficients k0 to k3, or you can create 4 simultaneous equations and solve them manually. One of these 4 data points should be the reference temperature; one should be the lower temperature extreme and the other the higher temperature extreme. The 4th point is more flexible and can be chosen freely. Once the TCZ function is calculated this can be used to compensate for the baseline shift within the temperatures that it was calculated for, however using it for extrapolation will be inaccurate the further outside the temperature band it is used.

For the TCS (sensitivity) formula you start with the following data:

| Temperature (C°) | Sensor Signal Change (nA) | Gas Concentration (ppm) |
|---|---|---|

The sensor signal change refers to the sensor signal with gas exposure minus the baseline signal. Using these values, you can then calculate the sensitivity by dividing the signal change by the gas concentration. It should then be normalised to a reference temperature (it should be the same reference temperature as for the baseline measurement) by dividing the sensitivity at a given temperature by the sensitivity at a reference temperature.

A compensation factor is then calculated by taking 1 over the normalised sensitivity resulting in a table like this:

| Temperature (°C) | Sensitivity (nA/ppm) | Normalised Sensitivity | Compensation Factor |
|---|---|---|---|

Finally for the equation TCS(T) = k0 + k1T + k2T2 + k3T3 TCS will be the compensation factor, and the variable T is the temperature. The following procedure is identical to the baseline compensation, where either excel or simultaneous equations are used to calculate the 4 constant coefficients. The same rules for choosing the temperatures to calculate the coefficients (reference, low extreme, high extreme, free choice) apply.

Finally, these two calculated compensations are then applied to ppm value formula in the following way:

$$ppm = \left(\frac{I_s - I_{s,0}}{a}\right) * TCS(T) + TCZ(T)$$

Where:

- Is is the measured signal at the sensing electrode
- Is,0 is the baseline signal (at the reference temperature) of the sensing electrode
- a is the sensitivity of the sensor (measured at the reference temperature)
- TCS(T) is the temperature compensation for the sensitivity (should be evaluated to a value for a given temperature T)
- TCZ(T) is the temperature compensation for the baseline (should be evaluated to a value for a given temperature T)

This will give the most accurate and repeatable temperature compensation for a single sensor. For a generalised compensation, if the accuracy of an individual compensation is not necessary, the same technique can also be applied to batch means calculated from measuring multiple sensors at once and averaging the values over all sensors. The same third order polynomial formulas and techniques used to calculate the coefficients, still apply in the same way to the averaged data points.

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