AN0138 Application Note: System design consideration in a mainstream capnograph

1. Introduction

Capnography is a clinical method of measuring patients' CO_2 levels in the inhaled and exhaled breath. Concentration (or partial pressure) of CO_2 is measured in a form of a temporally well-resolved waveform. The amount of CO_2 as a function of time can be analysed further in order to inform about any present lung diseases, or as a diagnostic method in medical and emergency procedures. Exhaled CO_2 is the most definitive vital sign in a person.

Pyreos ezPyro™ SMD is a world leading solution for digital IR detection. Both our SMD and the TO-39 analogue IR pyroelectric gas sensors for capnography are used heavily by the main capnography manufacturers around the world: https://pyreos.com/capnography/

Figure 1 Prior care main-stream capnograph using Pyreos IR detectors

Our capnography customers, who implement our IR detectors are benefiting from Pyreos main technological advantages:

- High speed of data readout (10Hz – 30Hz optimal)
- Low profile SMD package (3.7mm x 5.6mm x 1.3mm)
- Instant start-up
- Low power consumption (1 to 23µA)

Infrared detector speed is particularly important to achieve a good temporal resolution of the measured CO_2 concentration waveform. Low profile SMD package of our ezPyro™ in comparison to a traditional TO-39 package may come as an advantage in certain cases if device size reduction is driving the system design process.

From a capnograph system design perspective there are certain parameters that are important and need to be taken into account when making a system suitable for volume manufacturing. This app note will describe these parameters in detail.

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2. What is capnography?

Capnography is a method of measuring CO_2 content in the exhaled and inhaled breath. Concentration (or partial pressure) of CO_2 are measured. Information gathered from this measurement are represented on a graph of concentration as a function of time called a waveform, or a capnogram (Figure 2 below).

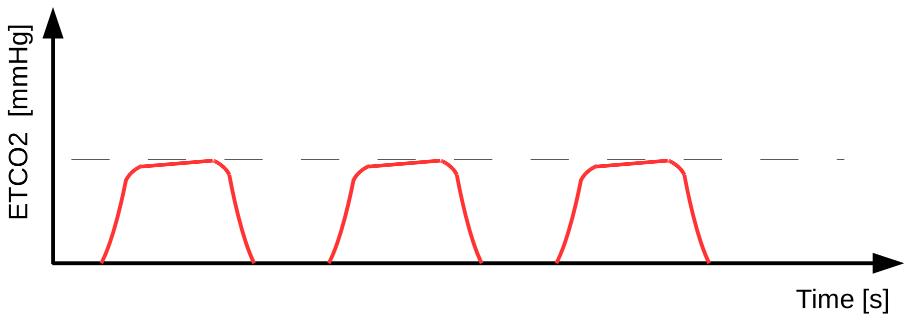

Figure 2 Simplified sketch of a CO2 capnogram

The most important information gathered from a capnogram is the, so-called, end-tidal CO_2 ($EtCO_2$). This is the partial pressure at the end of an exhale process. Typically, a healthy person should produce a waveform represented by a quasi-square function. By analysing deviations from that shape, one can learn about any present pulmonary diseases, patient's state, as well as diagnostic or procedure problems such as the patient being incorrectly intubated.

3. Capnography systems

There are two main system designs used for capnography. These are: side-stream and main-stream systems. Both use an NDIR spectroscopy method for measuring CO_2.

3.1 NDIR spectroscopy

NDIR spectroscopy is based on a simple yet effective principle of absorption of a wide spectral source by a chosen gas and monitoring detector signal changes at a particular detection wavelength, which correlate to the gas absorption characteristics. A simplified sketch of such system can be found in the Figure 3 below.

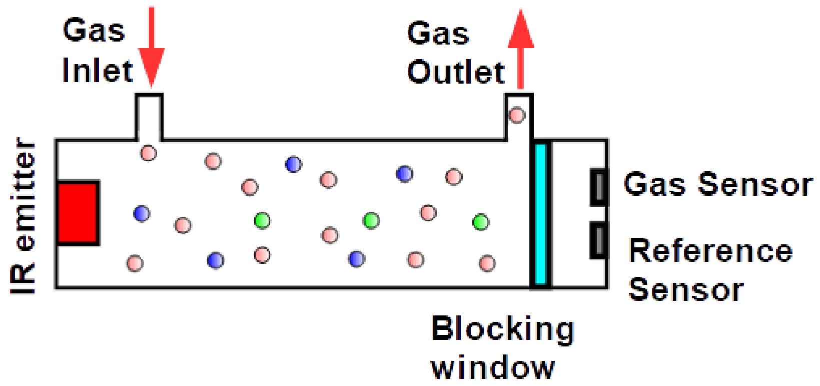

Figure 3 Simplified sketch of an NDIR spectroscopy system

IR emitter is usually a pulsed blackbody source which can be modulated at 30 to 100 Hz rates, such as a MEMS based device. The emitter fills the gas tube with a broad range of wavelengths corresponding to the blackbody radiation. Some of these wavelengths will become absorbed by the gas, e.g. CO_2 absorbs well in ~4.26µm. If such broad spectrum interacts directly with a detector, it would not be possible to measure changes at the gas absorption band. A narrowband filter is required to block everything but the gas absorption, e.g. 4.26/90 (CWL/FWHM) in case of CO_2.

3.2 Side-stream capnograph

In a side-stream capnograph the measuring device is located away from a patient. In such system, patient is intubated with a tube and a pumping mechanism is used to transport its breath sample (and often anaesthetic gases) for measurement. In this system a small part of the gas is taken away from the main tube and passed through the NDIR spectroscopy device. There, a Pyreos IR detector is used in order to create the $ETCO_2$ waveform which is then analysed further. A simple sketch depicting a side-stream system for capnography can be seen in Figure 4.

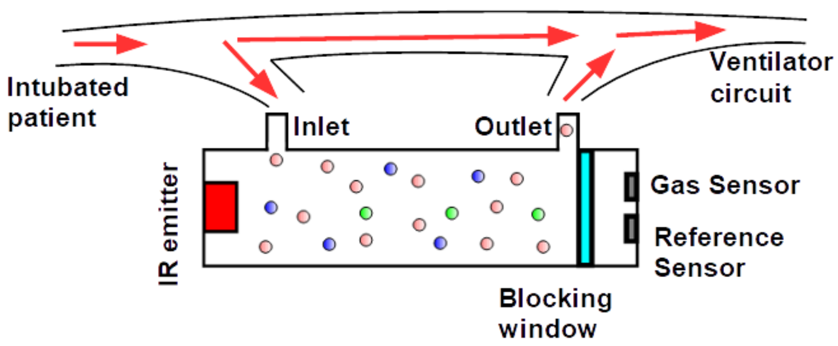

Figure 4 Side-stream capnography sketch

3.3 Main-stream capnograph

In a main-stream capnograph the measuring device is located directly by the patient. In such system exhaled breath is measured directly in the breath stream in contrast to a partial measurement in the side-stream method. It allows for a more pronounced and real-time signal, since more CO_2 is present and the distance from the patient to the NDIR spectroscopy device is minimal.

A simple sketch depicting a main-stream capnograph can be seen in Figure 5.

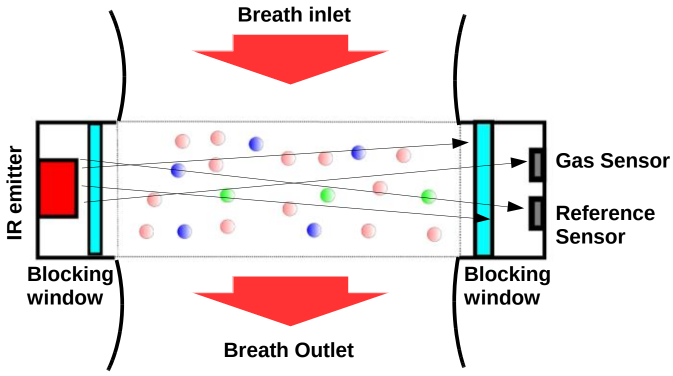

Figure 5 main-stream capnograph sketch

4. Main-stream capnograph manufacturing

Main-stream capnographs are compact and direct measuring devices. They are typically better suited for a high volume and affordable manufacturing, since they can be sold separately from the whole ventilation system. Or, as shown in our case-study (https://pyreos.com/case-studies/), with no ventilation system at all.

4.1 Calibration

Two main steps for calibrating a mainstream capnograph exist. They are in fact not exclusive for capnography but are used widely for NDIR gas sensing systems.

First step, a production step, uses an already calibrated environmental chamber located in a factory. In such chamber, gas is driven inside at known concentrations, while the temperature is varied. NDIR spectrometers (here, main-stream capnographs) are placed in such chamber and calibration functions are derived from these readings while the concentration and temperature is varied.

Second step consists of zeroing the already pre-calibrated capnograph in an open environment. This can be performed in a hospital in an open and non-crowded space or simply outside, where concentration of CO_2 from breath is close to atmospheric.

For more details on procedural requirements on a capnography systems please see *ISO80601-2-55:2018 Medical electrical equipment – Part 2-55: Particular requirements for the basic safety and essential performance of respiratory gas monitors*.

4.2 Detector speed and size

In order to have good quality and well resolved reading from a capnograph, a fast detector is required. Typical requirement for capnography systems is that the detector takes a reading at ~20-30 Hz. Most pyro detectors are most efficient at around 2-10Hz, making them too slow for high quality capnography devices. Thanks to the Pyreos proprietary thin film technology of manufacturing, detectors are faster than other competing technologies and therefore extremely well suited for capnography.

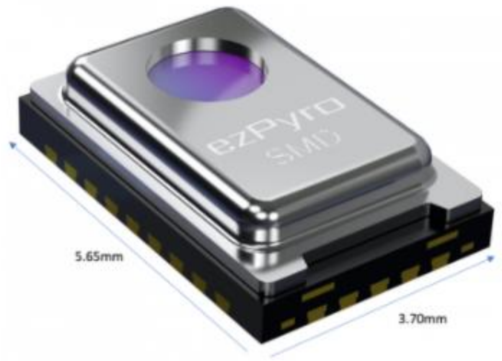

Figure 6 ezPyro™ SMD infrared detector

A standard package for an IR detector used in capnography is a TO-39. Most popular Pyreos analogue detectors are dual channel TO-39 detectors, where the second channel is used for a gas reference (search our website for: PY2343, PY0234, and PY2572). Pyreos low profile SMD detectors, called ezPyro™ are becoming increasingly popular due to the miniaturisation demand on main-stream capnographs (search our website for: ePY12231 and ePY12211). Significantly smaller size than the TO-39 and readiness for high volume manufacturing makes them the detectors for capnography.

4.3 Tolerances

Since main-stream capnographs are manufactured in volume, tolerances on certain parts might be relaxed to reach an affordable cost level. A system designer shall take care in defining these tolerances as they will be crucial in precise ETCO_2 measurements.

For example, mechanical tolerances on a tube inside of a main-stream capnograph will have a significant impact on the overall performance.

4.3.1 Tube surface

Uneven or corrugated tube surface might result in skewing of the emitter light and a signal strength change on the detector (Figure 7Figure 7 below).

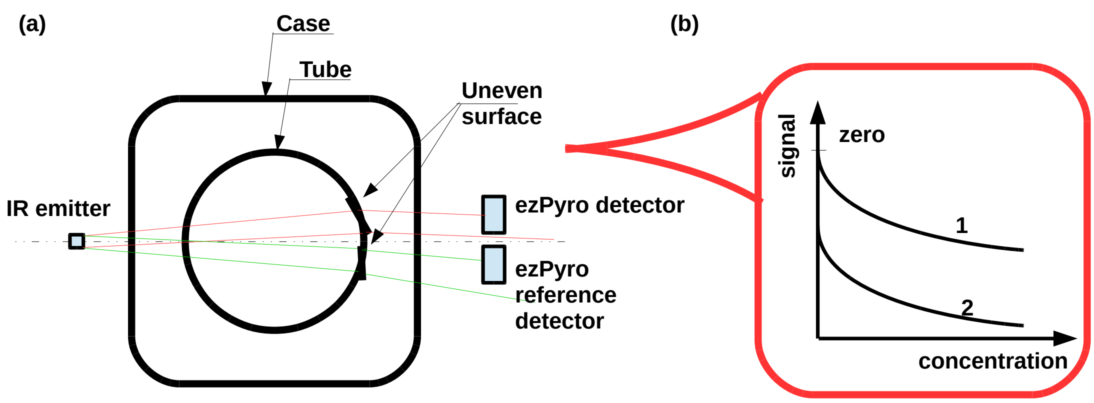

Figure 7 (a) Side cross section of a main-stream capnograph and (b) the effect it may have on the calibration function 1 → 2.

Depending on the refractive index of the tube and the type/amount of deformation on the tube surface, a light ray may be skewed from the path toward the detector and lower the amount of signal reaching it.

4.3.2 Tube size

A tolerance on tube size/diameter is directly connected to the effective path length of each light ray going through the exhaled breath. NDIR spectroscopy is based on the Beer-Lambert law, which states that the signal change is exponentially proportionate to the path length of a gas cell, given by the equation:

$$I/I_o = e^{-\varepsilon Lc}$$

Where I/I_o is the ratio of the signal absorbed by the gas to the undisrupted signal, ε is a constant depended on the absorption lines of a particular gas, c is the concentration of a gas and L is the gas cell path length. Because of the exponential relationship described above, the path length change will have an impact on the calibration function shape, see Figure 8 belowpyro.

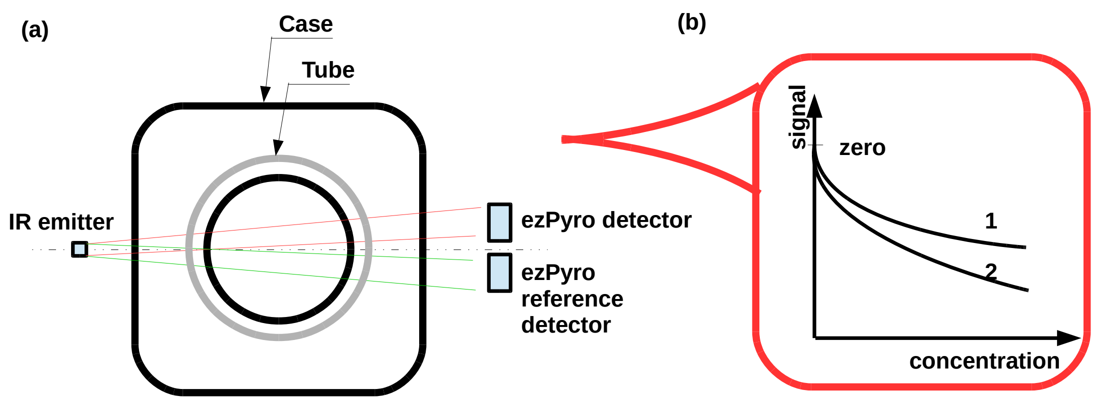

Figure 8 (a) Side cross section of a main-stream capnograph. Light grey circle indicates a diameter change of the tube. (b) calibration function change as a result of the tube size variation 1 → 2

4.3.3 Tube material variations

Tube material variation will not change the calibration function shape but its signal level (similarly to Tube Surface in paragraph 4.3.1), see Figure 9. This is caused by a lower/higher amount of signal absorbed/transmitted by the tube material. Consistency of the tube material is therefore an important part of both tolerancing specification as well as supplier quality checks.

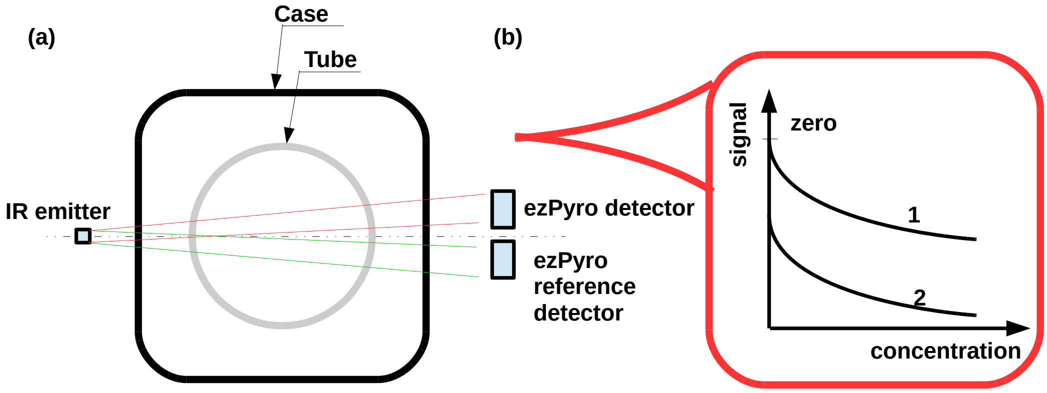

Figure 9 Side cross section of a main-stream capnograph. Light grey circle indicates variation in the tube material. (b) calibration function change as a result of the tube material variation 1 → 2

5. Conclusions

Capnography is an exciting market with even more exciting technology behind it. It helps improving people's health by giving precise respiratory disease diagnosis. Novel exciting applications show up constantly like the mentioned breath analysis device, which measures menstrual cycles through analysing exhaled CO_2 content (https://pyreos.com/case-studies/).

Pyreos manufactures detectors which are particularly well suited for capnography. We have successfully provided our detectors to many capnography businesses partners world-wide.