Contents

List of Figures

List of Tables

1. Introduction

The IDT ZMOD4410 Gas Sensor Module is designed for monitoring indoor air quality (IAQ) by detecting total volatile organic compounds (TVOC). Both TVOC and the more familiar gas carbon dioxide (CO_2) are among the factors in IAQ, and both are emitted by humans. Since CO_2 is better understood by the general public than TVOC, IDT has developed methods of estimating CO_2. The correlation between TVOC and CO_2 concentration has been investigated for indoor environments and implemented in IDT's algorithm libraries.

For an additional overview of the methodology used for the ZMOD4410, refer to the *ZMOD4410 Datasheet* and the *White Paper – TVOC and Indoor Air Quality*.

2. Rationale for Monitoring Carbon Dioxide

Carbon dioxide (CO_2) in the ambient air has negative influences on human productivity and causes effects such as dizziness, weakness, dyspnea, and even unconsciousness up to death. Depending on the country and its legislation, there are variations in the maximum level of CO_2 that can be considered to be "Good Air." Table 1 gives an overview of CO_2 levels that should not be exceeded for long-term exposure ("Safe Level") or an 8-hour day ("Critical Level"). Carbon dioxide is dangerous because it has no smell and no visible color; therefore it is not detectable by humans without additional instrumentation.

Table 1. Warning Levels for Carbon Dioxide

Name of Standard	Safe Level [ppm]	Critical Level [ppm]	Year of Publication
Pettenkofer Number, Germany [1]	< 1000		1858
German Federal Environmental Agency (UBA), Germany [1]	< 1000	> 2000	2008
American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), USA [2]	< 1000	> 5000	2016
Indian Society of Heating, Refrigerating, and Air Conditioning Engineers (ISHRA), India [3]	< 1200	> 1200	2015

In general, CO_2 sources can be divided into natural and artificial sources. Examples of natural sources include humans, animals, and plants, which generate CO_2 by respiration. Examples of artificial sources include fire, carbonated drinks, and volcanos. A special property of natural sources, such as humans and animals, is that they produce VOCs (volatile organic compounds) proportional to their exhaled CO_2. This fact can be used to derive an estimate for CO_2 concentration from the concentration of TVOCs (total volatile organic compounds).

Knowing the actual indoor CO_2 concentration is useful for many applications. For instance, room ventilation systems can be automatically turned on for high CO_2 concentrations.

Conventionally, CO_2 is measured using CO_2 sensitive sensors or very sophisticated instruments, such as spectroscopic infrared sensors (NDIR). However, these instruments are expensive and rather large compared to other sensors. Chemical sensors, such as solid sodium-superionic conductor (NASICON) electrolyte sensors, on the other hand, may be used but suffer from high drift and a short lifetime.

Alternatively, it is well known that TVOC sensors, such as IDT's ZMOD4410 metal oxide (MO_x) gas sensor module, provide a very reliable method for accurately determining TVOC concentrations. Based on the assumption that the TVOC produced by humans is proportional to their exhaled CO_2, these sensors can be used to estimate a CO_2 concentration indoors. In order to distinguish between an estimated CO_2 concentration and a true CO_2 measurement, the term eCO_2 (estimated CO_2 concentration) is used.

[1] Umweltbundesamt, *Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft*, (Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 2008).

[2] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, *Ventilation for Acceptable Indoor Air Quality*, ANSI/ASHRAE Standard 62.1-2016, (Atlanta, USA, 2016).

[3] Indian Society of Heating Refrigerating and Air Conditioning Engineers, *ISHRAE Position Paper on Indoor Environmental Quality*, (New Delhi, India, 2015).

3. Description of the Working Principle

3.1 Existing Approaches

MO_X sensors can be used to measure the TVOC concentration and calculate an estimate of the human-generated CO_2 concentration (eCO_2) based on the measured TVOC concentration. Most existing sensor products consider a simple constant proportionality between TVOC and emitted CO_2 concentration as shown in Equation 1:

$$eCO_2 = a + b * TVOC \quad \textbf{Equation 1}$$

where b is the constant ratio between the humanly generated CO_2 and TVOC and a is a constant offset.

Sometimes linear filtering is applied to reduce noise or to remove spikes and notches.

3.2 IDT Smart Algorithm

Although metal oxide sensors offer state-of-the-art technology, applying a linear correlation between TVOC and CO_2 as in Equation 1 is insufficient for most scenarios. In a more realistic scenario, artificial sources of both TVOC and CO_2 must be taken into account. These include artificial CO_2 sources and also TVOC sources such as deodorants, air freshener, white board cleaner, cooking odors, etc. Unlike artificial CO_2 sources, artificial TVOC sources only increase the TVOC but do not contribute to the CO_2 concentration. Thus, the assumption of Equation 1 used in existing eCO_2 technology is not complete and will lead to large errors in the estimated CO_2 concentration. Even algorithmic post-processing tools such as linear low-pass filtering are not suitable to suppress these non-human TVOC sources.

The accuracy of the estimated CO_2 concentration can be much improved by introducing the following boundary conditions. For the lower limit, the CO_2 concentration in the earth's atmosphere is about 400ppm, which means that an indoor concentration cannot be lower than this value. Hence, this can be seen as a lower concentration boundary. For the upper limit, it has been proven that concentrations above 5000ppm are extremely unlikely in home or indoor environments.

In addition, with the assumption that natural CO_2 sources will only lead to slow changes in the CO_2 concentration, rapid increases or decreases in the eCO_2 can be attributed to artificial VOC sources or sudden regeneration of the indoor air; for example, by ventilation. Thus, IDT's smart eCO_2 algorithm does not only apply a linear correlation between TVOC and eCO_2 but also considers the time dependence of the TVOC concentration.

The differentiation between natural and artificial CO_2 sources is illustrated by the two measurement series in Figure 1 and Figure 2. Both data were recorded using ZMOD4410 gas sensor modules.

Figure 1 shows a measurement series taken in a kitchen over a period of 1 hour. At the beginning of the data acquisition, people enter and leave the kitchen and the TVOC (ordinate y-axis in mg/m^3) level rises, as well as the eCO_2 (ordinate y-axis in in ppm). However, during cooking, only the TVOC level rises from kitchen odors while the eCO_2 level remains constant.

Figure 1. Example of a Typical Measurement in a Kitchen

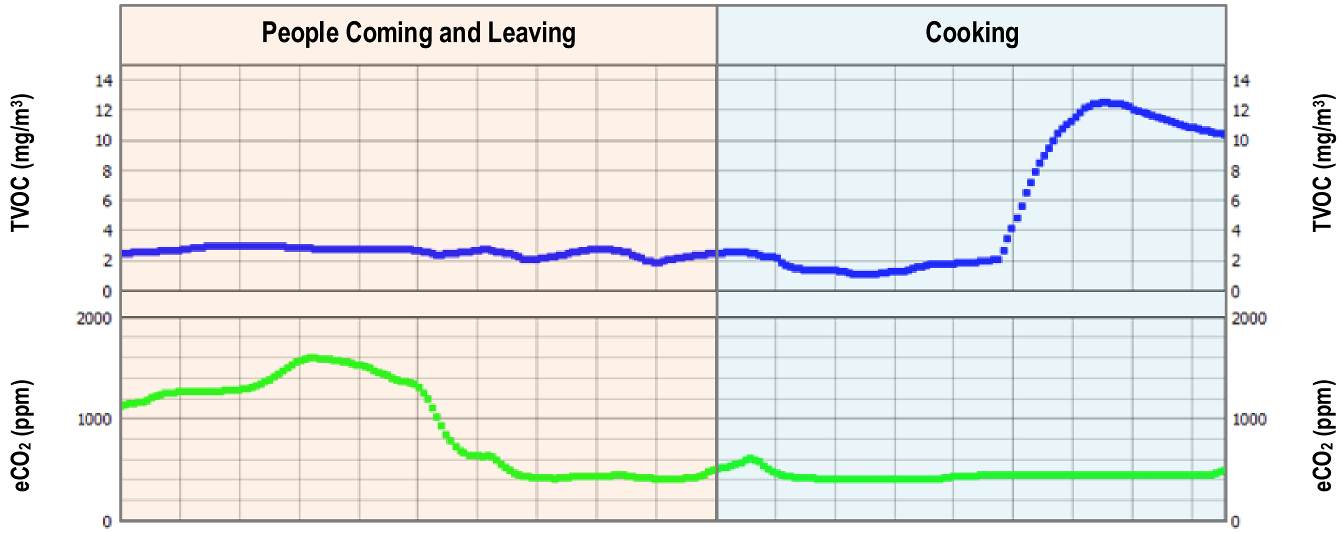
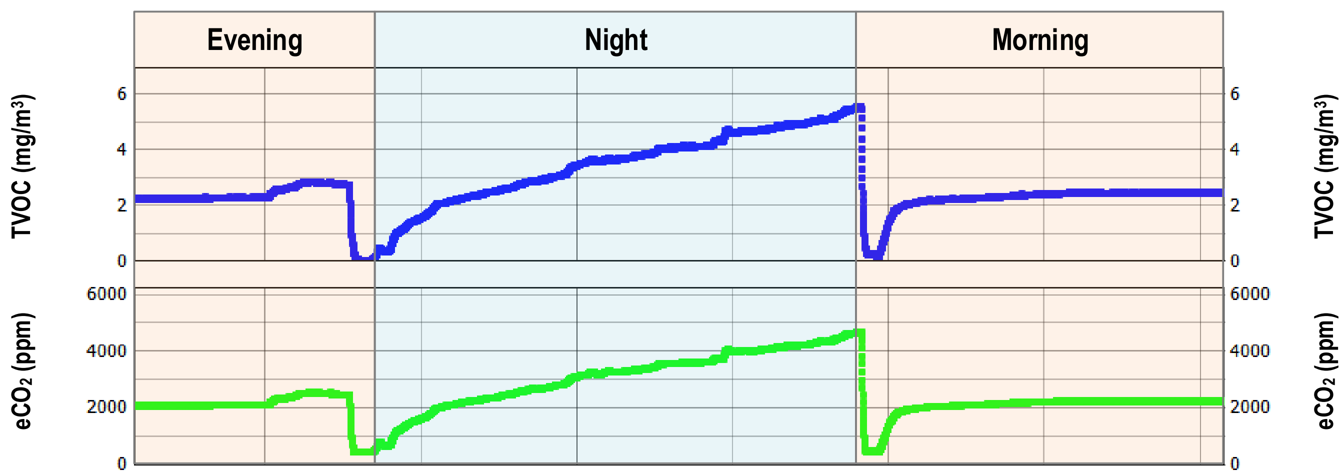


Figure 2 shows data measured in a bedroom over a period of 18 hours. The presence of people leads to a slow increase of the TVOC and eCO_2, while opening the window in the evening and morning leads to rapid decreases of both gas concentrations.

Figure 2. Example of a Typical Measurement in a Bedroom



4. Sensor Results

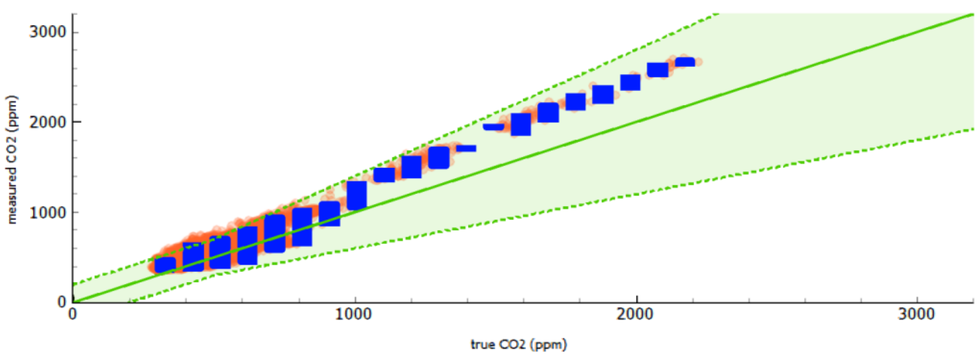
There are various technologies and sensors on the market claiming to have a reliable carbon dioxide measurement. The most commonly used tools for extremely accurate measurements are nondispersive infrared sensor (NDIR) instruments, which are too expensive for a mass market use. To ensure the best possible comparison to a high-end CO_2 reference instrument, a validation study was completed using different NDIR instruments first to validate the CO_2 measurement consistency.

IDT's approach to measure the TVOC and estimate the CO_2 concentration is superior in the market for metal-oxide sensors. It is reliable with a high conformity from sensor to sensor. Compared to competitors' products offering a similar approach by estimating CO_2 via the TVOC measurement, the IDT patent pending algorithm has an advantage.

4.1 Validation of Reference Technology

As there are many CO_2 measurement instruments on the market, a careful choice had to be made to select a suitable reference instrument for IDT's measurements. In a first step, a comparison was made between a high-end and standard NDIR instrument. Figure 3 shows the simultaneously measured CO_2 concentrations of both devices.

Figure 3. Analysis of Measurement Consistency for Two NDIR Instruments for Use as Reference Instruments



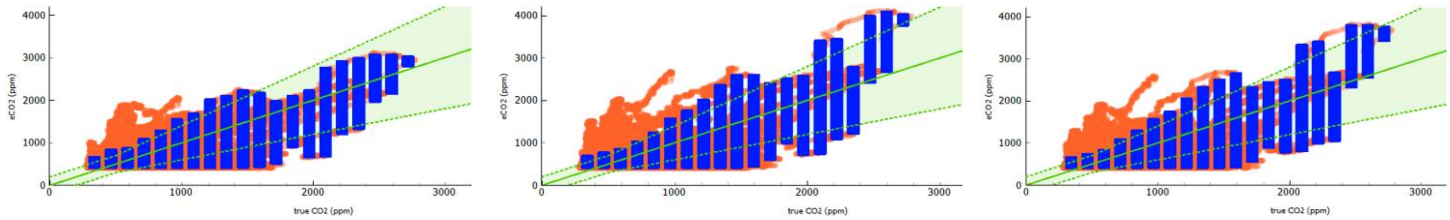
The x-axis and y-axis show the simultaneously measured CO_2 concentrations of the high-end and standard NDIR CO_2 instrument respectively. The solid green line corresponds to a direct proportionality between both CO_2 concentrations. As can be seen, there is an excellent agreement between both devices with an accuracy of approximately 10% (green shaded region). The relative agreement between both instruments validates the use of the high-end NDIR as the reference instrument for validation measurements.

4.2 Reliability of IDT Gas Sensor Modules

The correlation between TVOC and eCO_2 has been carefully investigated for IDT ZMOD4410 gas sensor modules over a time period of one year in an indoor office environment. During these measurements, the reference NDIR instrument was calibrated once a week, and the ZMOD4410 were operated continuously without calibration or synchronization. Figure 4 shows the results of three ZMOD4410 sensor modules, which were operated in close proximity to the high-end NDIR instrument.

In Figure 4, the estimated carbon dioxide levels (eCO_2) from the ZMOD4410s are plotted against the true CO_2 concentration measured by the high-end NDIR CO_2 instrument (see section 4.1). Ideally, the estimated CO_2 should follow the solid green line in each graph in Figure 4 and stay within a tolerance band of 40% (green-shaded area) or ±200ppm (whichever is larger). Red dots are the measurement points of the ZMOD4410s. The blue bars mark the 90% confidence intervals averaged over a 100ppm-wide concentration range.

Figure 4. Comparison of Three IDT ZMOD4410 Gas Sensor Modules



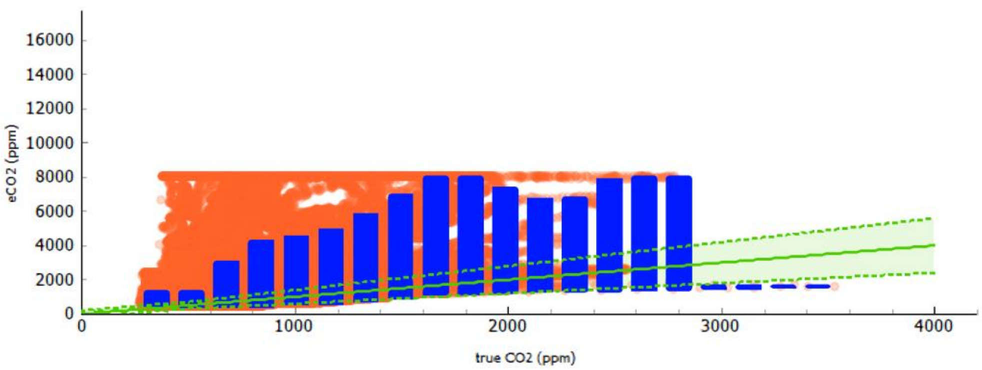
As can be seen, IDT's ZMOD4410s TVOC to eCO_2 algorithm provides an excellent correlation with the validated high-end reference instruments. Also, there is a very good sensor to sensor consistency.

4.3 Competitive Comparison

In order to show the superiority of IDT's gas sensor modules and algorithm over competitors, IDT has investigated several competitors' CO_2 gas sensors in parallel with IDT's ZMOD4410 sensor modules.

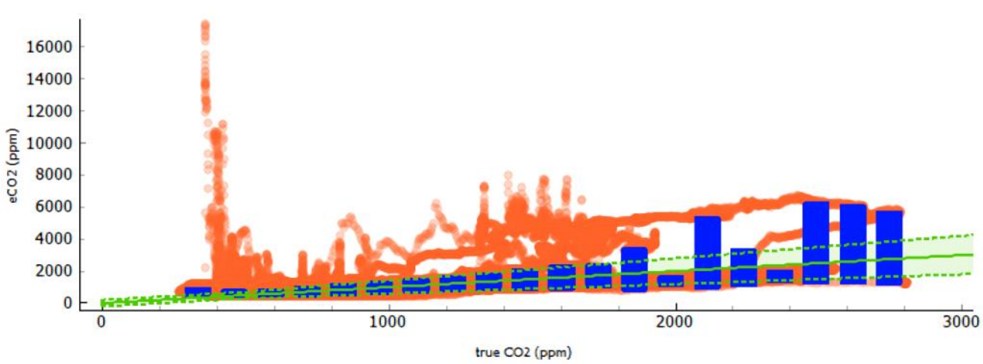
Figure 5 shows the data taken with a MOx sensor from competitor #1. Although lower and upper limits of 400ppm and 8000ppm respectively have been implemented in this sensor, there is hardly any correlation between their TVOC and eCO_2. Especially at lower concentrations, the competitor's algorithm fails completely because of the fundamental correlation issues discussed in section 3.1.

Figure 5. Analysis of Competitor #1



The investigated MOx sensor from competitor #2 already uses a smarter algorithm possibly connected to their Multi-Pixel MOx approach. The data in Figure 6 shows an extremely large range of CO_2 measurements with a pronounced mismatch especially at low concentrations. This competitor claims a CO_2 measurement accuracy of ±15%, which is disproven with these measurements.

Figure 6. Analysis of Competitor #2



5. Revision History

Revision Date	Description of Change
May 24, 2018	Initial release.

IMPORTANT NOTICE AND DISCLAIMER

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
www.renesas.com/contact/

Trademarks