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# Survey Report

**subject:** **Signal processing on metal oxide gas sensors to estimate the indoor carbon dioxide concentration on the example of IDT's ZMOD4410 gas sensor module**

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**Report**

Metal oxide gas sensors (MOX-GS) are applied extensively to characterize indoor air quality (IAQ). This indoor air quality is influenced by a variety of parameters such as concentrations of volatile organic compounds (VOC) and carbon dioxide ($CO_2$) to address the most important gases [1]. To sum up all individual occurring VOC without discrimination the term “total volatile organic compounds” (TVOC) was introduced. The TVOC concentration in indoor air environments depends on human activities, evaporations from furniture, floor covers and equipment as well as from the air exchanged by conditioning or aeration [2]. Since TVOC and $CO_2$ are breath gas components, their temporal courses in populated rooms shows specific gradients. If more “exotic indoor environments” like green houses, indoor pools, industrial environment, laboratories, wine cellars and others are excluded, only TVOC can be emitted at significant rates from immobile sources.

Since $CO_2$ is the gas component with the most extensive knowledge on its impacts on human feeling and health, automatic control systems for indoor air quality are designed increasingly to use this $CO_2$ concentration as the reference input [3]. Although MOX-GS are not able to measure $CO_2$ directly, increasing efforts are observable in the last years to use their signals as reference input for air conditioning or aeration systems as well [4]. The motivation for this development comes with their availability as highly reliable, miniaturized and economic sensors and the fact that indoor air quality is governed to a considerable extent also by TVOC, which can be measured directly with MOX-GS. Furthermore, it is discussed intensively in the sensor community if it is possible to derive an estimated value for the $CO_2$ concentration ($eCO_2$) from the signals from MOX-GS [5] by intelligent signal processing. Taking all above-mentioned facts into account, such a processing can indeed provide a trustable $eCO_2$ value, if the following preconditions are fulfilled:

1. The indoor environment contains no other significant source of $CO_2$ than human breath.
2. There is a resilient correlation between TVOC and $CO_2$ exhaled by humans.
3. TVOC, emitted by other sources than humans can be considered in the algorithm, for instance by a subtraction from the signals as an offset.

The first precondition can be easily observed and maintained in most indoor environments.

To find out to which extend the second precondition is valid in offices, meeting rooms and other suited indoor environments large studies were carried out. They prove that $CO_2$ is emitted by humans without physical or mental workout at a rate around 0.25 L/min [6] and that the rate of the emitted TVOC is more than 2 orders of magnitude smaller and differs strongly between persons, during daytime and can increase during and after physical workout [7, 8]. Furthermore, a baseline level of TVOC is observable which can be correlated to the mass of a healthy person. Therefore, postulating a constant relationship between the exhaled $CO_2$ and TVOC of a single person seems to be possible only on very short time scales of several minutes. But studies show that individual fluctuations of that relationship and variations between different persons are canceling out each other in a way that indeed a pattern for the TVOC/$CO_2$ relationship can be established if more than one person stays in the environment to be controlled [9].

The simplest form of that relationship is a linear one, described by the following equation:

$$c(CO_2) = a + b \cdot c(TVOC) \tag{1}$$

with:

- $c(CO_2)$ = $CO_2$ concentration
- c(TVOC) = TVOC concentration
- a = additive constant ranging at around 400 vol.-ppm $CO_2$ in pollutant-free outdoor air
- b = factor between exhaled $CO_2$ and TVOC

The third condition is difficult to establish, since a great variety of temporal and permanent TVOC sources can occur in indoor environments. One possibility to address this problem is the analyzes of the TVOC release rate of these sources: Furniture, floor covers and other immobile TVOC sources cause relatively long-term stable base concentrations of TVOC which can be considered, when the MOX-GS base line is established after turning them on. Temporal sources like burning candles or deodorants lead to an increase of TVOC concentration, which is significantly faster than that caused by human breathing. Taking these phenomena into account it seems therefore reasonable to use also temporal signal gradients as inputs for algorithms for estimating $CO_2$ concentration from TVOC concentration.

The company Integrated Device Technology (IDT) develops, produces and sells MOX-GS for several years. To enlarge their possible applications an algorithm for estimating $CO_2$ concentration for MOX-GS was developed and patented by IDT. This algorithm is based on the following considerations for ZMOD4410:

1. The $eCO_2$ value is calculated by the linear equation (1) from the TVOC concentration, where the constant a was set to 400 vol.-ppm.
2. The TVOC concentration measured by the MOX-GS is corrected by the algorithm by subtracting constant base levels and temporal increases which are much faster than could be caused by human breathing.
3. The maximum $CO_2$ concentration found in common indoor environments at any circumstances cannot exceed 5000 vol.-ppm. If the algorithm leads to higher concentrations, the values are cut back to this upper limit.

IDT carried out long-term tests in offices and meeting rooms by installing several MOX-GS ZMOD4410 together with infrared $CO_2$ sensors MX1102 (Onset Computer Corporation) in a closed vicinity to each other. From the results the constant b of equation 1 and the limits of temporal gradients of TVOC increase, which describe those caused by human breathing, were adjusted. As expected, the results also indicate that these parameters depend also on the size of the room to be controlled. Therefore, IDT can optimize the parameters after preliminary tests in a customer application. The tests carried out at IDT indoor environments proved so far, that it is possible to calculate $eCO_2$ values from MOX-GS signals with a deviation of less than 30 % of the measuring range.

KSI has inspected the measurement locations at IDT and checked the hardware used. Furthermore, KSI investigated the IDT algorithm in detail. It can be concluded that no error sources or misleading signal corrections have been found. Data recording, processing and analyzes are well documented and comprehensible.

Summarizing the arguments above it is possible to estimate the actual indoor carbon dioxide concentration with IDT's ZMOD4410 sensor signals in case:

- No other carbon dioxide sources than breathing persons are in the room,
- Base lines and fast emitting TVOC sources are considered by taking temporal signal gradients into account and
- Fixing the lower and upper limit of estimated carbon dioxide to 400 and 5000 vol.-ppm respectively.

The efficiency and reliability of aeration systems using these $eCO_2$ values as reference input should not deviate significantly from those using values from infrared $CO_2$ monitors.

Within the last decades, KSI gained expertise on carbon dioxide measurements. Recently, a scientific book on $CO_2$ measuring principles was published on all related topics for carbon dioxide [10]. Although data from IDT ZMOD4410 gas sensor module are trustful, KSI will carry out a more intensive study on $eCO_2$ starting early 2019 using ZMOD4410 among others.

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