Laboratory for Electrical Instrumentation and Embedded Systems
IMTEK – Department of Microsystems Engineering
University of Freiburg
Sensors Lab Course
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Lab Report M3
Gas Sensors

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1. Introduction

Air quality refers to the physical, chemical, and biological characteristics of the air in a particular environment. It is a crucial aspect of environmental and public health, as poor air quality can lead to respiratory and cardiovascular diseases, as well as a range of other health problems. One of the main indicators of air quality is the concentration of carbon dioxide (CO_2) [1] in the air. CO_2 is a greenhouse gas that is produced by human activities such as burning fossil fuels and deforestation, and it is one of the main contributors to global warming and climate change. To mitigate the effects of CO_2 and other pollutants on air quality, proper ventilation is crucial. Ventilation helps to remove contaminated air from indoor spaces and bring in fresh outdoor air, which can improve air quality and reduce the risk of health problems related to poor air quality.

In this module, parameters such as the IAQ [2] index, VOC [3], and CO_2 concentration will be calculated/measured with the help of the BME688 [4] metal oxide sensor by Bosch Sensortec.

2. Theory

Metal Oxide (MOX) sensors [5] are commonly used to measure the concentration of carbon dioxide (CO_2), and volatile organic compounds (VOCs), and to calculate the indoor air quality (IAQ) index. These sensors work by measuring the resistance of a metal oxide material to determine the presence of various gases. The resistance of the metal oxide material changes in response to changes in the concentration of the target gas, which can then be converted into a numerical value that represents the concentration of the gas.

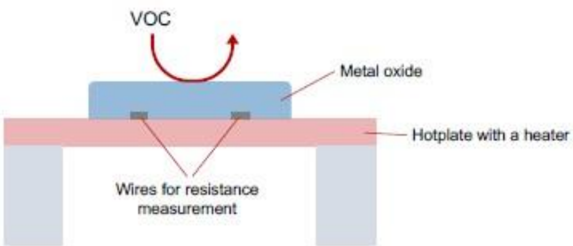

Figure 1 - The metal oxide (MOX) gas sensor operates based on a principle where the sensing element is placed on a hotplate, which is heated to a temperature of several hundred degrees Celsius. At this high temperature, gases undergo oxidation or reduction, leading to a change in the resistivity of the layer. [9]

To measure volatile organic compounds (VOCs), the MOX sensor is exposed to air that contains VOCs. The resistance of the metal oxide material changes in response to the presence of VOCs in the air and this change in resistance is used to calculate the concentration of VOCs. This measurement is used to monitor indoor air quality and to determine the presence of VOC sources such as paints, cleaning supplies, and air fresheners.

To calculate the indoor air quality (IAQ) index, the MOX sensor is used in combination with other environmental sensors, such as temperature and humidity sensors. The data from the MOX sensor and the other environmental sensors are combined and processed to calculate an IAQ index, which provides a numerical value that represents the overall quality of indoor air. The IAQ index is often expressed on a scale from 1 to 100, with higher numbers indicating better air quality.

IAQ Index	Air Quality	Impact (Long-term Effect)	Suggested Action
0 – 50	Excellent	Pure air; Best for well-being.	No measures are needed.
51 – 100	Good	No irritation or impact on well-being.	No measures are needed.
101 – 150	Lightly Polluted	Reduction of well-being possible.	Ventilation suggested.
151 – 200	Moderately Polluted	More significant irritation is possible.	Increase ventilation with clean air.
201 – 250	Heavily Polluted	Exposition might lead to effects like headaches depending on the type of VOCs	Optimize ventilation
251 – 300	Severely Polluted	More severe health issues are possible if harmful VOC is present.	Contamination should be identified if the level is reached even w/o the presence of people; Maximize ventilation & reduce attendance.
> 351	Extremely Polluted	Headaches and additional neurotoxic effects are possible.	Contamination needs to be identified; Avoid presence in the room and maximize ventilation.

Table 1 - Indoor Air Quality (IAQ) Index as returned by the BME688 [4]

In conclusion, MOX sensors are widely used to measure the concentration of carbon dioxide (CO_2), and volatile organic compounds (VOCs), and to calculate the indoor air quality (IAQ) index. These sensors are low-cost, low-power, and have a fast response time, making them a popular choice for indoor air quality monitoring applications.

BSEC library was used to derive the IAQ index, CO2 & VOC concentration, temperature and humidity values. BSEC stands for Bosch Sensortec Environmental Cluster. It is a software library that provides advanced algorithms for processing sensor data from environmental sensors, such as temperature, humidity, pressure, and gas sensors. BSEC algorithms use machine learning and signal processing techniques to provide accurate and reliable environmental data to applications that rely on sensor data.

3. Methods

In this module, the BME688 [4] sensor on the Arduino Nicla Sense ME board will be utilized to measure the indoor air quality of a room.

The BME688 is a multi-functional environmental sensor developed by Bosch Sensortec. It is a sensor that measures temperature, humidity, pressure, and indoor air quality (IAQ) with a high degree of accuracy. [4]

The temperature measurement range of the BME688 is -40 to 85°C with a resolution of 0.1°C. The relative humidity measurement range is 0 to 100% with a resolution of 0.008% and the pressure measurement range is 300 to 1100 hPa with a resolution of 0.18 Pa. The IAQ measurement range is from 0 to 8192 with a resolution of 1. [4]

The BME688 also features a gas sensor that measures volatile organic compounds (VOCs), which are common indoor air pollutants that are often associated with health problems. The gas sensor measures the resistance of a metal oxide (MOX) material to determine the presence of VOCs. The BME688 also features an integrated heater that warms the MOX material, which helps to improve the accuracy and stability of the gas sensor readings. [4]

For this experiment, an Arduino Nicla Sense ME is connected to a battery-powered notebook via USB. The notebook is used as both a power supply and a data logger. The board was programmed using the Arduino IDE with the Arduino_BHY2 library version 1.5 (Bosch Sensortec). Putty and Excel were used for data logging.

The sensor is put on the table in the room which is used both for studying and eating.

4. Results and Discussion

In this module, the resistance change of the MOX sensor will be investigated, when exposed to three different VOC sources.

Task 1

Three examples of volatile organic compound (VOC) sources were tested. Namely, tea leaves, oats, and coffee. One by one, the sensor was dangled into containers consisting of these samples without touching them.

In tea leaves, a total of 82 different VOCs exist. These include 27 hydrocarbons, 2 furans, 9 alcohols, 11 ketones, 7 esters, 17 aldehydes, and 9 nitrogen compounds. [6]

The main type of VOCs released by oat is green leaf volatiles (GLVs), which primarily consisted of (Z)-3-hexanol and (Z)-3-hexenyl acetate. Other minor compounds present are 1-octen-3-ol, nonanal, and methyl salicylate (MeSA). [7]

Both roasted coffee and many coffee flavorings give off volatile organic compounds (VOCs), including diacetyl and 2,3-pentane-dione. [8]

The result of the experiment is given below in Figure 2. As can be seen, the resistance value decreases once a substance is introduced to the sensor.

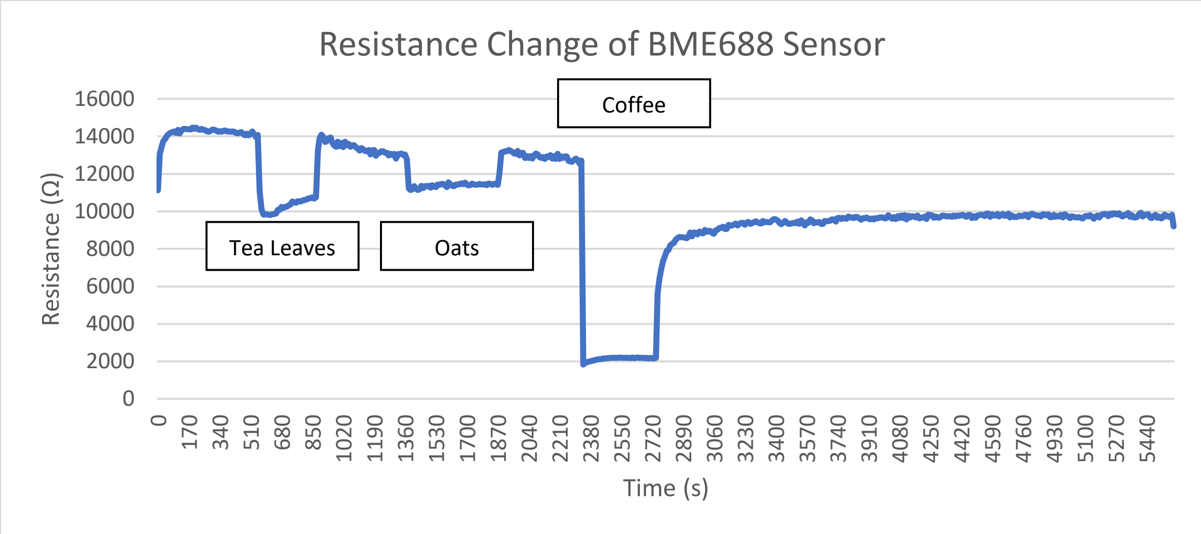

Figure 2

The resistance takes some time to recover. However, mostly it does not recover to its original value. The average measured resistance and the recovery time for all three examples are given in Table 2 below. The resistance values were not constant because there was a change in the environment (temperature, humidity, oscillation in the medium) once the sensor was introduced. The values settled after keeping the sensor in the respective environment for some time.

	Average Resistance	**Recovery Time**
Tea Leaves	10317.2 Ω	490 s
Oats	11396.3 Ω	400 s
Coffee	2144.6 Ω	1020 s

Table 2

As can be observed from Table 2, the larger the resistance, the less time is needed to recover.

Task 2

In this task, the same experiment as Task 1 is repeated, but this time, the VOC and CO_2 concentrations are measured using BSEC. Because the sensor is incapable of detecting only CO_2, it uses other parameters to estimate it. After waiting for the accuracy level to get to 3 and testing all three examples, the sensor was covered with hands (without touching) to increase the humidity and temperature. An increase in CO_2 concentration is observed as can be seen in Figure 3 below.

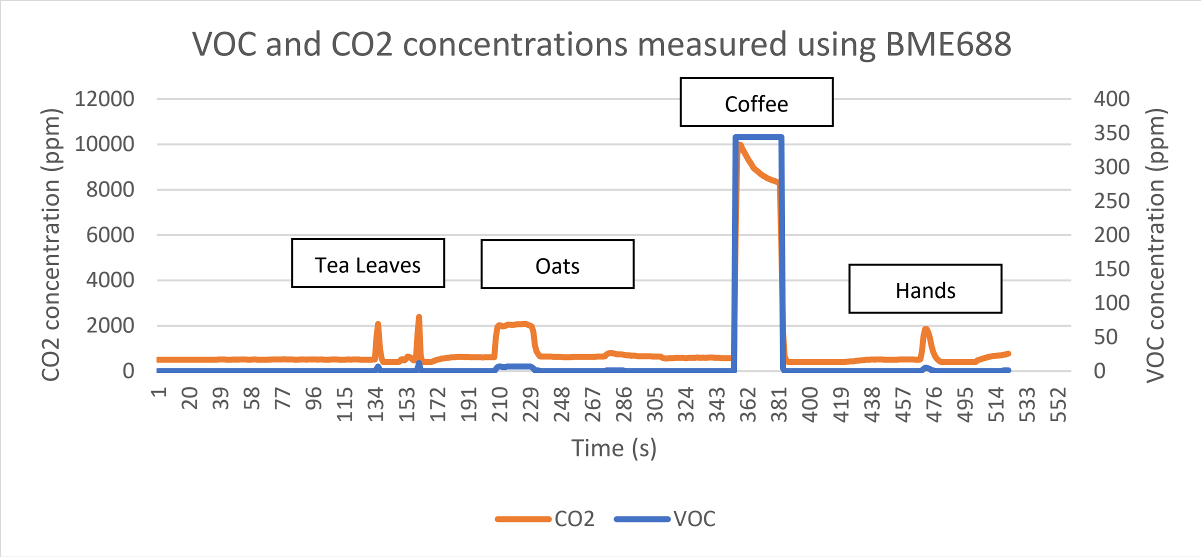

Figure 3

The average VOC and CO_2 concentrations as well as the recovery times are given in Table 3 below.

	VOC Concentration	**CO_2 Concentration**	**Recovery Time**
Tea Leaves	5.9 ppm	1875.6 ppm	10 s
Oats	1 ppm	759 ppm	10 s
Coffee	344 ppm	8706.3 ppm	10 s
Hands	2.9 ppm	1404.5 ppm	10 s

Table 3 – Average VOC and CO_2 Concentrations & Recovery time

Task 1 and Task 2 show that the coffee displays the most VOC and CO_2 concentration overall. This is because of the fine-grained particles of the coffee. Because more particles hit the sensor surface, a higher concentration is detected. Moreover, it is proven that the CO_2 concentration is not a measurement, but an estimation because the increased heat and humidity are detected as CO_2 once the sensor is covered with hands. The values are not constant over time and they change when a substance is introduced to the sensor.

Task 3

On Task 3, the BME 688 sensor was run for 32 hours and 50 minutes in a student room in a shared flat. The VOC concentration. CO_2 concentration, IAQ index, temperature, and humidity are measured once the accuracy is reached 3. Plots of all these parameters are given below, along with the Table of events that took place in the room during the experiment.

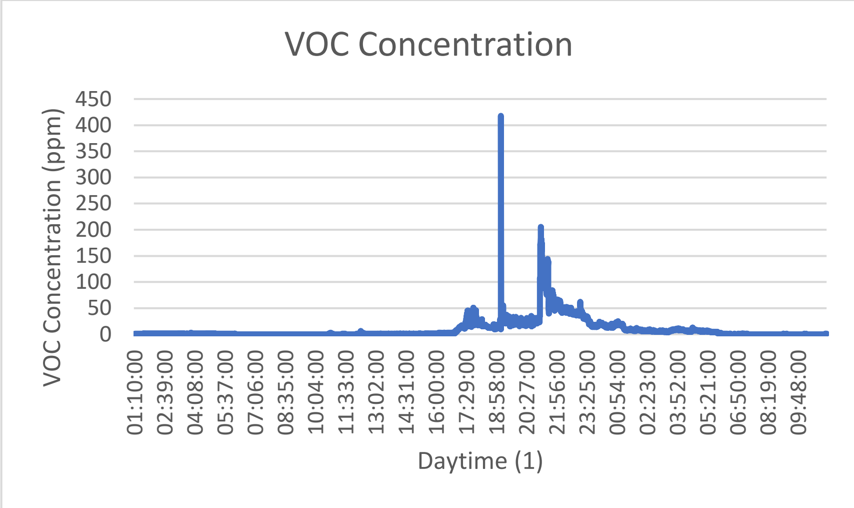

Figure 4

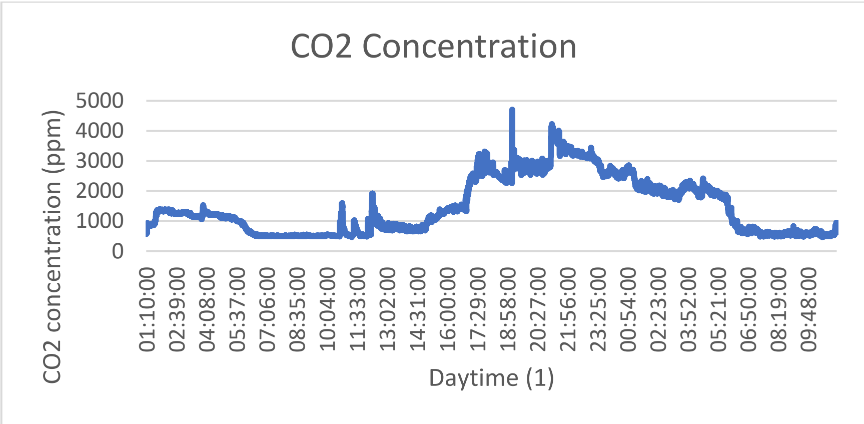

Figure 5

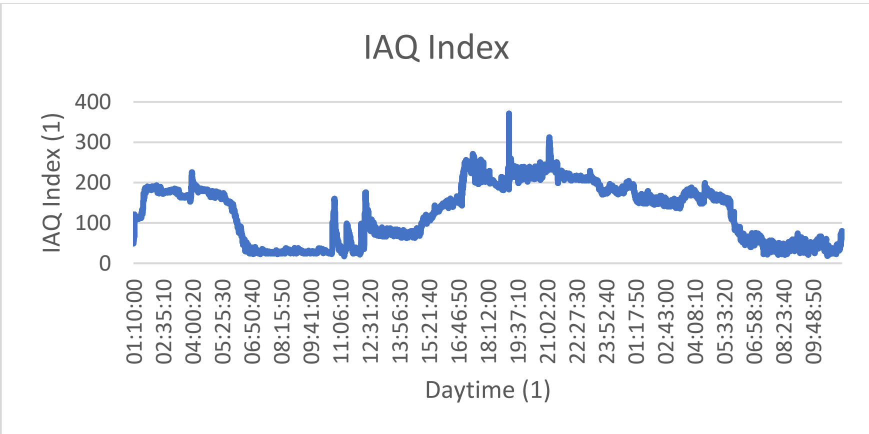

Figure 6

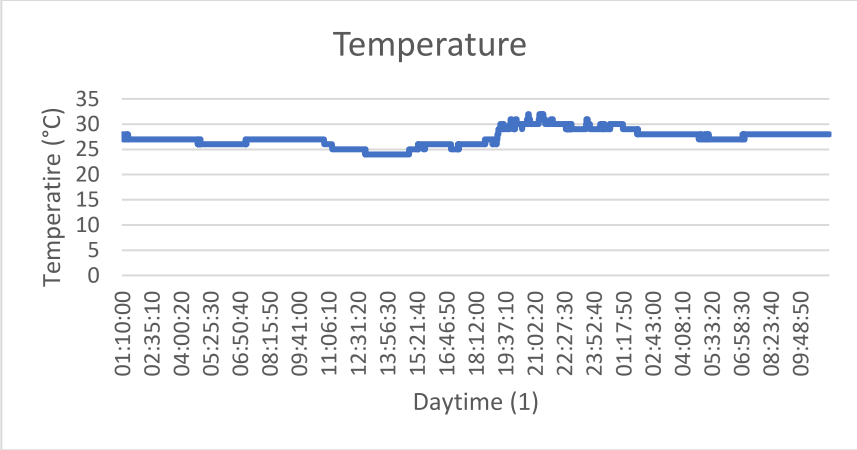

Figure 7

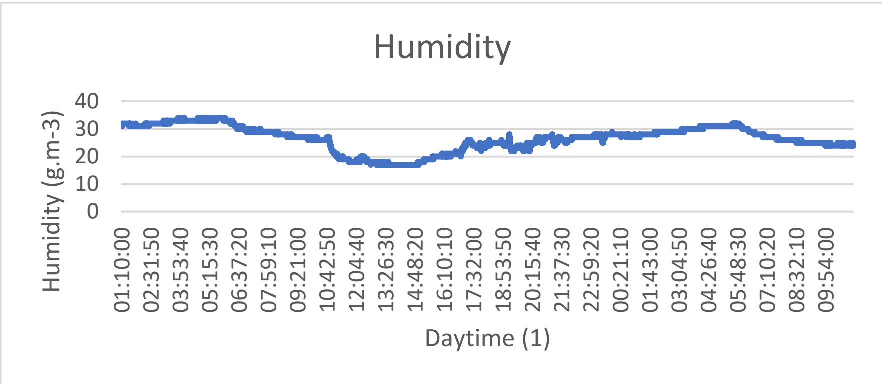

Figure 8

Time	Event
01:10	Accuracy of 3 reached
01:30 – 05:20	One person sleeping in the room (the door is closed and the window is shut)
05:21 – 10:00	One person sleeping in the room (the door is closed and the window is open)
10:01 – 11:30	The person in the room is awake, they had breakfast closeby to the sensor
11:31 – 18:00	The person had a study session in the room
18:01 – 19:00	A guest arrives at the room
19:01 – 20:00	The guest and the host had dinner near the sensor
22:00	The guest leaves
01:00 – 07:00	One person sleeping in the room (the door is closed and the window is shut)
10:00	Experiment is concluded

Table 4 – Table of events that took place in the room.

When the table of events is compared with the given plots, it can be seen that the events have an impact on the gasses present in the room, along with temperature and humidity. The CO_2 concentration and the IAQ index best represent the given events. There may be errors since the sensor's position is close to the laptop, which inevitably heats the sensor. A minimum of 29 and a maximum of 371 IAQ indexes were observed. The average IAQ index is 126,5 which falls into the "Lightly polluted" category given in Table 1. Therefore, it can be concluded that the room should be ventilated more frequently. When table 4is analysed, it can be said that when an object or a human is close to the sensor, IAQ index value increases. However, VOC value change much less compared ti the IAQ index. This is due to the fact that IAQ index value is also affected by the temperature and humidity values

5. Summary

In this experiment, the resistance change of the BME 688 sensor was tested when the sensor was exposed to tea leaves, oat, and coffee. A decrease was observed when these substances were introduced to the sensor. The BMEC functions were also utilized to conduct the same experiment, but this time the IAQ value, CO_2, and VOC concentrations were measured. Coffee had the most impact on all of the readings due to its fine grain structure. Finally, the sensor was rested in a room for 32 hours and the parameters of the room were observed. The room was found to be "lightly polluted" and it was concluded that it needed ventilation.

6. References

[1] *Carbon dioxide* (2023) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/Carbon_dioxide?oldformat=true (Accessed: February 10, 2023).

[2] Hult (2019) *IAQ index: Value and scoring*, *SVACH*. Available at: https://svach.lbl.gov/iaq-index-scores-indoor-air-quality/#:~:text=The%20Value%20of%20an%20IAQ%20Index&text=The%20metrics%20will%20identify%20characteristics,address%20occupant%20perception%20and%20acceptability. (Accessed: February 10, 2023).

[3] *Volatile Organic Compound* (2023) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/Volatile_organic_compound?oldformat=true (Accessed: February 10, 2023).

[4] Global, B. (2023) *Gas sensor BME688*, *Bosch Sensortec*. Available at: https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors/bme688/ (Accessed: February 10, 2023).

[5] *Functional principle of metal-oxide(mox) gas sensor elements* (no date) *UST Umweltsensortechnik GmbH -MOX gas sensors - functional principle*. Available at: https://www.umweltsensortechnik.de/en/gas-sensors/mox-gas-sensors-functional-principle.html (Accessed: February 10, 2023).

[6] Hartikainen, K. *et al.* (2012) *Significance of leaf structure and emission of volatile organic compounds in ozone tolerance of oat and wheat*, *Botany*. Available at: https://cdnsciencepub.com/doi/10.1139/b11-090 (Accessed: February 10, 2023).

[7] Yang, Y.-Q. *et al.* (2018) *Characterization of the volatile components in green tea by Irae-HS-SPME/GC-MS combined with multivariate analysis*, *PloS one*. U.S. National Library of Medicine. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5832268/#:~:text=A%20total%20of%2082%20volatile%20compounds%20were%20identified%20in%2021,compounds%20(see%20Table%203). (Accessed: February 10, 2023).

[8] LeBouf, R.F. *et al.* (2020) *Exposures and emissions in coffee roasting facilities and cafés: Diacetyl, 2,3-pentanedione, and other volatile organic compounds*, *Frontiers*. Frontiers. Available at: https://www.frontiersin.org/articles/10.3389/fpubh.2020.561740/full (Accessed: February 10, 2023).

[9] Kieninger, J. and Rupitsch, S.J. (no date) *Sensors Lab Course - Gyroscope, accelerometer, pressure sensor, magnetometer, gas sensor*, *Ilias Uni Freiburg*. Available at: https://ilias.uni-freiburg.de/goto.php?target=file_2965654_download (Accessed: February 23, 2023).