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

Roopa Keshava Rao Ghatke (5452862)

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Data generated in a team together with

- Tanmayee Ravishankar (5576921)

1 Introduction

Earth's atmosphere is a layer of gases that surrounds the planet and is held in place by earth's gravity. The atmosphere is composed of various gases, with the most abundant being nitrogen (N_2) about 78% and oxygen (O_2) about 21%. Gases like carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), particulate matter (PM), volatile organic compounds (VOCs), methane (CH_4), ammonia (NH_3) degrade the atmospheric air quality. Indoor air quality depends upon the carbon dioxide (CO_2), volatile organic compounds (VOCs) exhaled by humans and other factors such as ventilation, humidity, temperature, and atmospheric pressure [1].

Outdoor pollutants can enter indoor spaces and affect the overall air quality. In this module, the metal oxide gas sensor BME688 of the Nicla Sense ME board by Bosch is used to measure the quality of indoor air.

2 Theory

2.1 Indoor Air Quality

The quality of indoor air, commonly referred to as Indoor Air Quality (IAQ), is a measure of the cleanliness and healthiness of the air inside buildings. Several factors contribute to indoor air quality, and a good IAQ is essential for the well-being and comfort of the occupants. Poor IAQ effects include irritation of the eyes, nose, throat, headaches, dizziness, and fatigue. Long-term health effects including respiratory diseases, heart disease, and cancer may emerge years after exposure to poor IAQ. Maintaining good indoor air quality (IAQ) involves a combination of preventive measures, regular monitoring, and adopting healthy practices such as promoting natural ventilation, air filtration, source control, reducing VOCs, regular cleaning, and maintenance which eliminates pollutant gases like carbon monoxide, nitrogen dioxide and particulate matter [2].

2.1.1 Volatile Organic Compounds (VOCs)

Several volatile organic compounds (VOCs) are synthetic chemicals and generated during the production of paints, pharmaceuticals, and refrigerants. They include a variety of chemicals like carbon, some of which may have short- and long-term adverse health effects. Household products frequently incorporate organic chemicals as constituents. Organic solvents are present in paints, varnishes, waxes, as well as numerous cleanings, disinfecting, cosmetic, degreasing, and hobby items. Additionally, fuels consist of organic chemicals. These products have the potential to emit organic compounds during both usage and, to some extent, storage [3].
Increased ventilation with open windows and doors regularly, air purifiers with activated carbon filters, indoor plants which absorb VOCs, avoiding indoor smoking, storing paints, solvents, and other chemicals in sealed containers, choosing eco-friendly furniture, regular vacuum can enhance the indoor air quality and reduce the VOCs.

2.1.2 Carbon dioxide (CO_2)

Carbon dioxide is a colorless, non-flammable, non-toxic gas at normal temperature and pressure. In normal atmospheric concentrations, CO_2 is not harmful to human health. However, high concentrations in enclosed spaces can lead to discomfort, dizziness, and difficulty in breathing. Concentrations of atmospheric CO_2 are commonly measured in parts per million (ppm).
For indoor air quality, carbon dioxide levels are often used as an indicator of ventilation adequacy. The typical recommendation for indoor spaces is to maintain CO_2 levels below 1000 parts per million (ppm) to ensure adequate ventilation and to prevent discomfort and potential health issues associated with poor air quality.

2.1.3 Indoor Air Quality Index

The Indoor Air Quality Index (IAQI) is a numerical scale used to communicate the quality of indoor air in a way that is easily understandable. It provides a quantitative assessment of the level of pollutants present in indoor air and their potential impact on health. The IAQI is typically expressed as a single number or a color-coded scale, indicating the overall indoor air quality. The specific pollutants included in the IAQI may vary depending on the region or organization providing the index. The IAQI returned by low power gas sensor BME688 developed by Bosch is mentioned below in figure 1.

IAQ Index	Air Quality	Impact (long-term exposure)	Suggested action
0 – 50	Excellent	Pure air; best for well-being	No measures needed
51 – 100	Good	No irritation or impact on well-being	No measures needed
101 – 150	Lightly polluted	Reduction of well-being possible	Ventilation suggested
151 – 200	Moderately polluted	More significant irritation possible	Increase ventilation with clean air
201 – 250[9]	Heavily polluted	Exposition might lead to effects like headache depending on type of VOCs	optimize ventilation
251 – 350	Severely polluted	More severe health issue possible if harmful VOC present	Contamination should be identified if level is reached even w/o presence of people; maximize ventilation & reduce attendance
> 351	Extremely polluted	Headaches, additional neurotoxic effects possible	Contamination needs to be identified; avoid presence in room and maximize ventilation

Figure 1: Indoor Air Quality (IAQ) Index as returned by the BME688 [1]

Regular monitoring of indoor air quality and understanding the IAQI can help individuals and organizations take appropriate actions to improve ventilation, reduce pollutant sources, and create healthier indoor environments.

2.2 Metal Oxide Gas Sensors

Metal oxide gas sensors are devices that detect the presence of specific gases in the air based on changes in the electrical conductivity of metal oxides when exposed to those gases. These sensors are widely used for monitoring air quality, industrial safety, and various applications where the detection of specific gases is essential. When a metal oxide semiconductor is exposed to a target gas, the gas molecules adsorb onto the surface of the metal oxide, leading to changes in the sensor's electrical conductivity. Metal oxide gas sensors typically operate at elevated temperatures (200-500°C) to enhance their sensitivity. These sensors may have cross-sensitivity to other gases, and their performance can be affected by environmental factors such as humidity. Calibration may be necessary to ensure accuracy.

2.2.1 BME688 Sensor

The BME688 sensor provided by Bosch Sensortec facilitates the testing and development of scenarios centered around temperature, barometric pressure, humidity, and gas sensing. Through measuring the distinctive electronic fingerprint of gases, the BME688 can identify and differentiate various gas compositions. This capability opens a wide range of possibilities for innovative applications [4].
The sensor is structured with the application-specific integrated circuit (ASIC) positioned on the left side. Below the ASIC, the humidity and temperature components are located, while the pressure sensors are situated on the top. The MOX gas sensor, represented by the smaller section on the right, is positioned independently. In the top view of the gas sensing element, there is a hotplate (dark square) with the MOX situated on top as a black round spot as shown in the below figure 2.

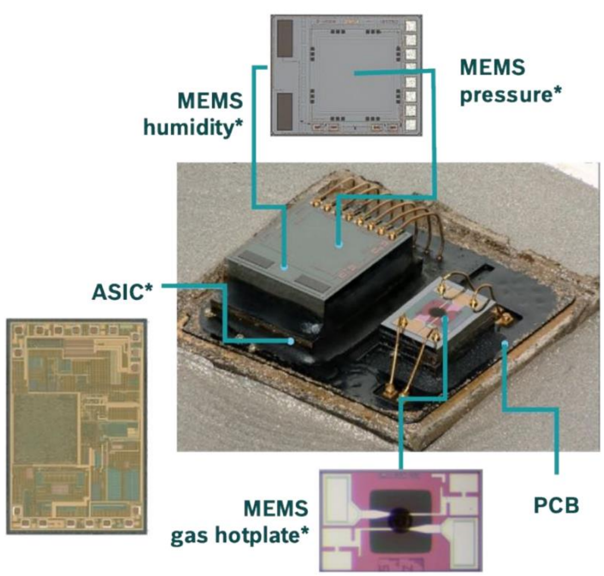

Figure 2: BME680 gas sensor, which is closely related to the BME688 by Bosch Sensortec [1]

The MOX gas sensor in BME688 facilitates a direct measurement, delivering the resistance value via the virtual sensor SENSOR_ID_GAS. The resistance can be obtained using the "gas.value()" function, returning the value in Ohms. The sensing element is sensitive to volatile organic compounds (VOCs) and exhibits reactions to additional gases, including sulfur compounds, carbon monoxide (CO), and hydrogen (H_2).
The Bosch Software Environmental Cluster (BSEC) algorithm provides readings for the Indoor Air Quality (IAQ) with (bsec.iaq()), the VOCs concentration considering human breath as the primary source with (bsec.b_voc_eq()), and even the CO_2 concentration with (bsec.co2_eq()). Although the MOX sensor doesn't exhibit sensitivity to CO_2, the algorithm utilizes alternative features to estimate CO_2 concentration, assuming humans as the primary source of the detected VOCs. Moreover, the BSEC library offers temperature (bsec.comp_t()) and humidity (bsec.comp_h()) readings. The algorithm continuously recalibrates its estimation. The (bsec.accuracy()) function returns different levels. Consequently, this sensor proves highly valuable for assessing indoor air quality [1].

3. Methods

The Arduino Nicla Sense ME boards typically come with a variety of sensors, including those for environmental sensing such as temperature, humidity and pressure and motion sensing such as accelerometers and gyroscopes. In this module, the integrated BME688 sensor on the Arduino Nicla Sense ME board is utilized to identify and classify different gas compositions.

The board operates independently, interfacing with a laptop via USB for serial data transmission. Programming is carried out utilizing Arduino IDE version 2.0 along with the Arduino_BHY2 library version 1.5 (Bosch Sensortec). A serial terminal software, MobaXterm is employed to capture sensor data readings, saving them to a text file and displaying them on a serial monitor.

The Arduino program read sensors using virtual sensors (SENSOR_ID_GAS) for resistance values (in ohms) and (SENSOR_ID_BSEC) for BSEC functionality. The BSEC algorithm provides values for the IAQ (Indoor Air Quality), VOCs (Volatile Oxide Compounds) concentration (in ppm), CO_2 concentration (in ppm). The BSEC library also provides the temperature (in $\circ$C) and the humidity values.

In tasks 1, sensor was kept in steady condition at room temperature and resistance values are recorded and in task 2, resistance values are recorded after reaching the accuracy level 3 at least once. The samples used are red chilli, perfume, and coriander powder. The data is then imported using Python script and corresponding graphs are plotted.

In task 3, the sensor was kept in steady condition close to the laptop for 24 hours in shared kitchen in student dormitory as shown in figure 3 and the values are recorded for the Indoor Air Quality, temperature and humidity as specified. The data is then imported using Python script and corresponding graphs are plotted.

Figure 3: Experimental setup for task 3 in shared kitchen

4. Results and Discussion

Task 1

A program was developed to read resistance values every 10 seconds and output them via the serial interface. The program was executed to run continuously for 10 minutes before recording the readings.

The resistance of the BME688 gas sensor is measured in the surroundings of different VOCs sources. Samples of red chilli, perfume, and coriander powder were utilized to measure the resistance values.

BME688 demonstrated high sensitivity, changing its resistance quickly in reaction to environmental changes. Utilizing the Nicla Sense ME board to measure resistance in ohms (Ω), noticeable decrease and increase in resistance was observed when introducing or removing a VOC source from its vicinity. It was noted that maintaining the VOC sources close to the Nicla Sense ME board resulted in relatively stable resistance readings with minor fluctuations shown in the below figures 4, 5 and 6. The highest variation in resistance is observed in the case of perfume where perfume is sprayed on tissue, kept near sensor for 3 minutes and the observed recovery time is approximately 1100 seconds whereas for red chilli is 20-30 seconds and coriander powder is 900 seconds.

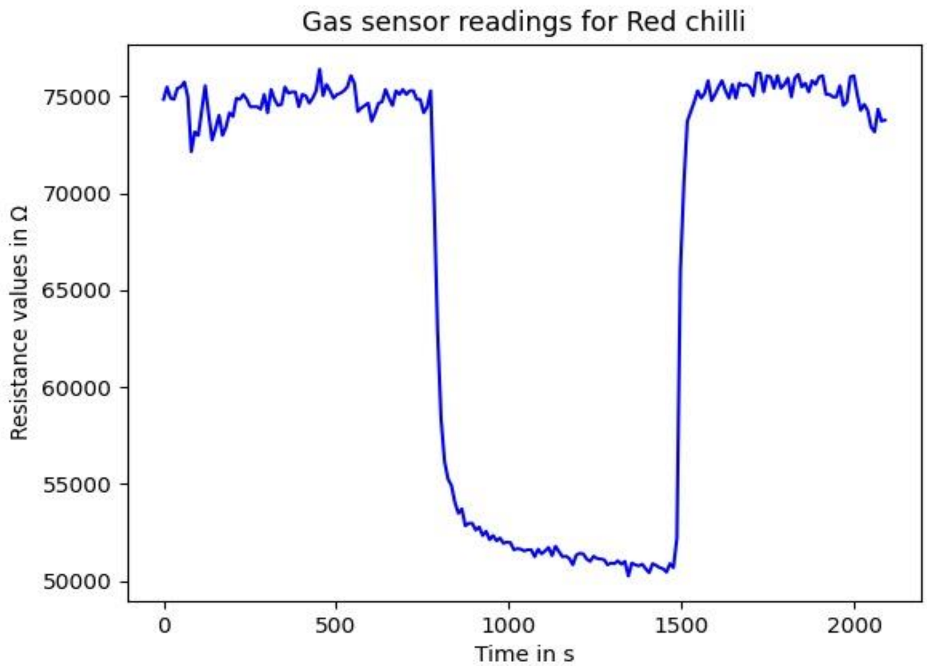

Figure 4: Gas sensor BME688 readings for red chilli

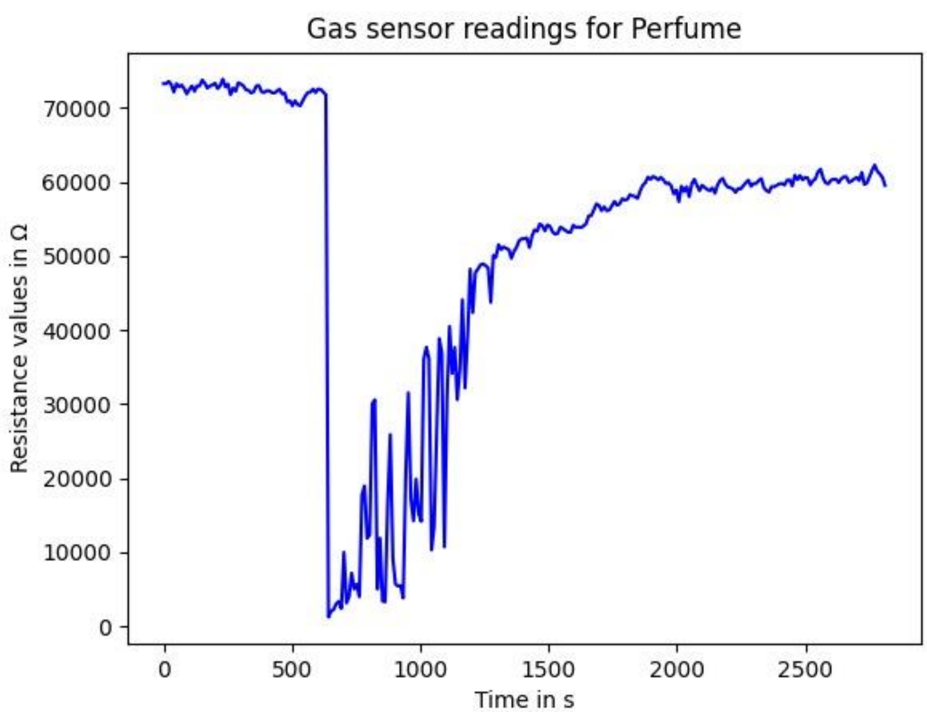

Figure 5: Gas sensor BME688 readings for perfume

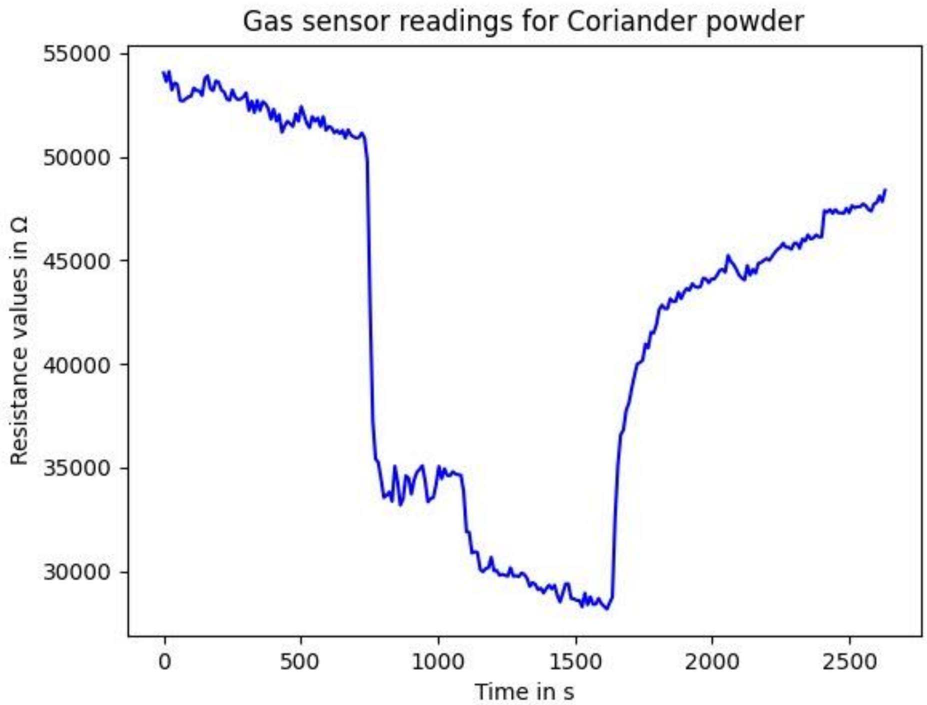

Figure 6: Gas sensor BME688 readings for coriander powder

Task 2

The BSEC Library is employed to read the VOC and CO_2 concentrations, ensuring the accuracy of the BME688. Data recording is started once the BME688 accuracy reaches level 3. The same samples utilized as in the previous task are employed to determine the VOC and CO_2 concentrations.

The concentration of VOC (in ppm) and CO_2 (in ppm) in the three environments are recorded in steady conditions at measurement rate of 0.1 Hz (every 10 seconds) are shown in below figures 7, 8, 9, 10, 11, 12.

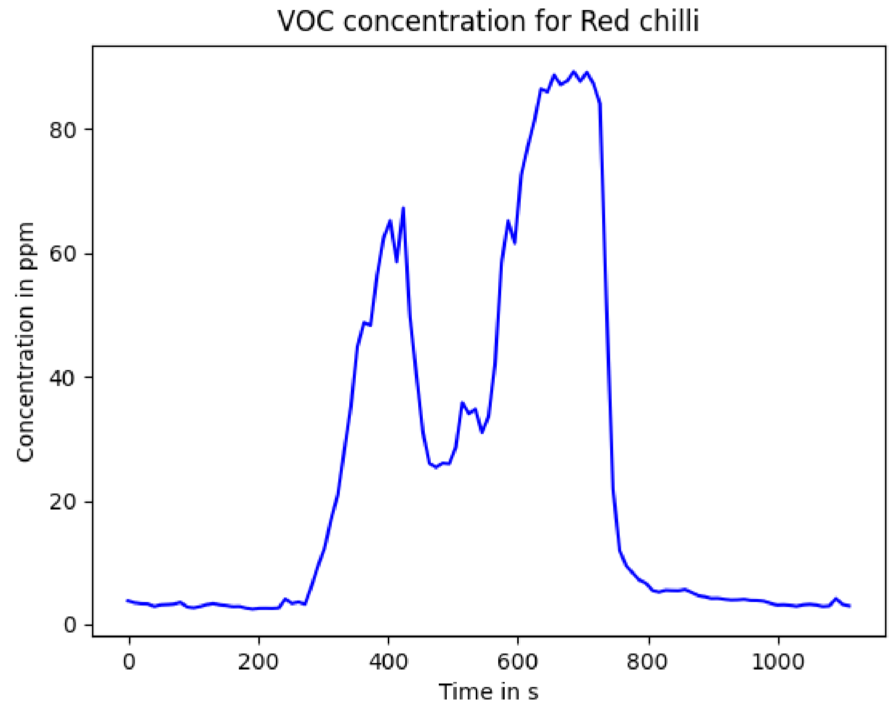

Figure 7: VOC concentration (in ppm) for Red chilli

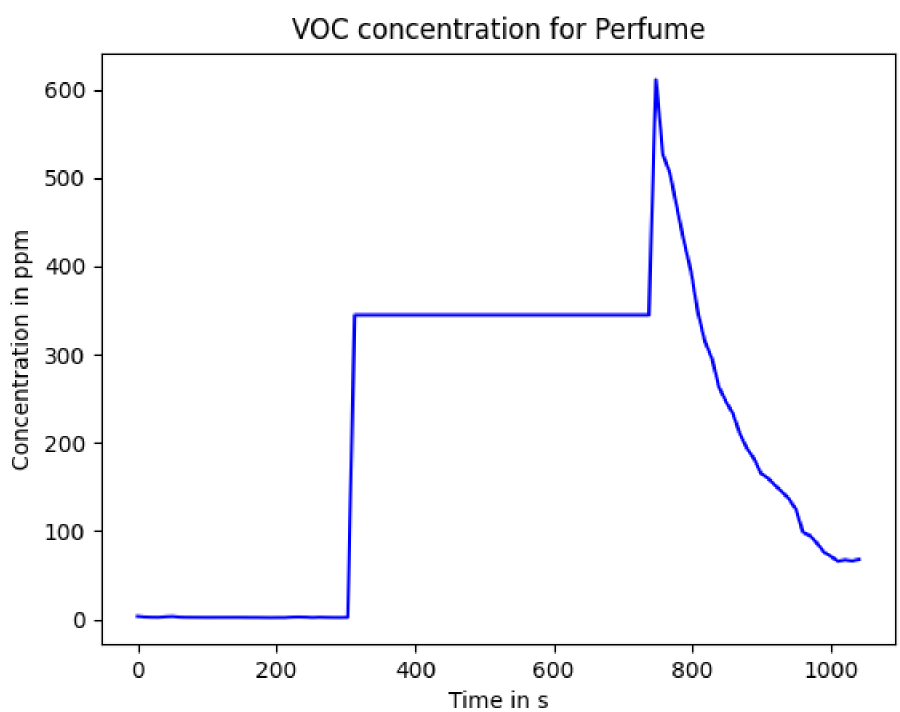

Figure 8: VOC concentration (in ppm) for Perfume

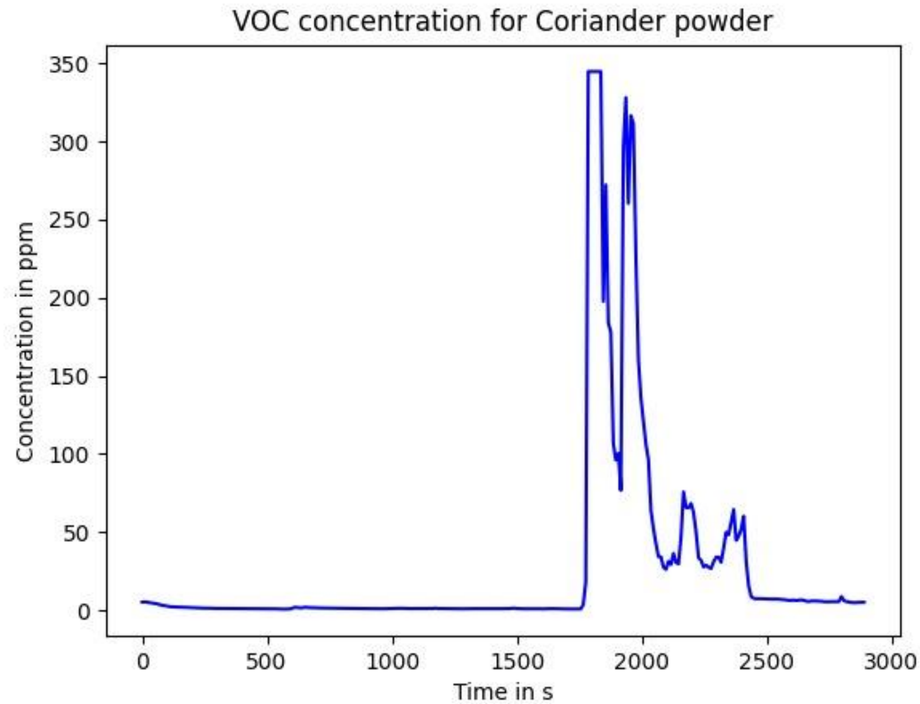

Figure 9: VOC concentration (in ppm) for Coriander powder

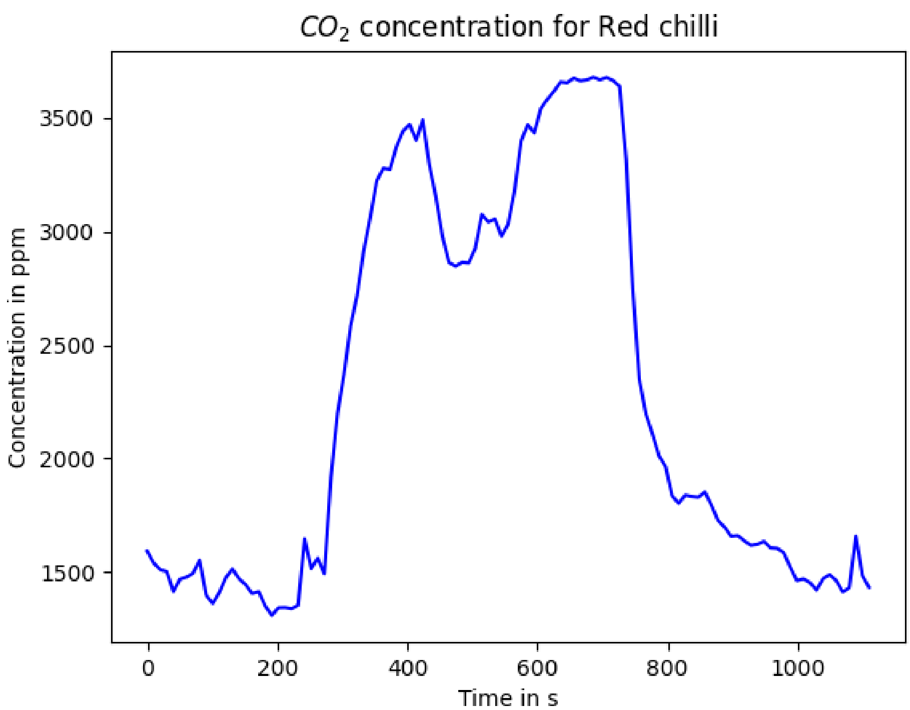

Figure 10: CO_2 concentration (in ppm) for Red chilli

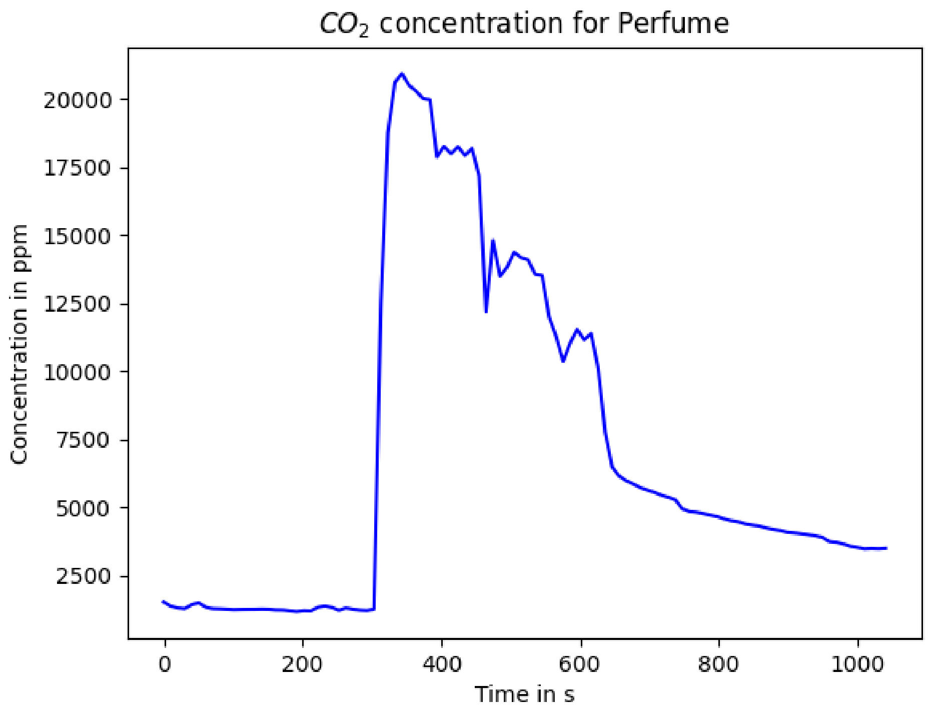

Figure 11: CO_2 concentration (in ppm) for Perfume

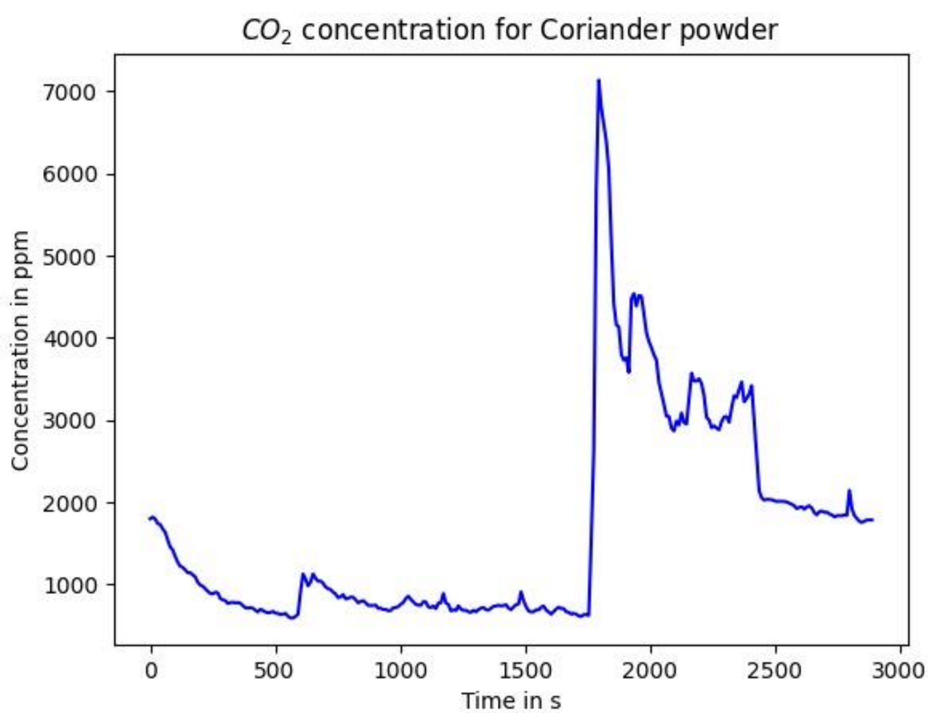

Figure 12: CO_2 concentration (in ppm) for Coriander powder

Observations indicate that the VOC and CO_2 concentration values in parts per million (ppm) remain stable when the samples are brought close to the sensor. However, within 30-40 seconds of removing the sample from the sensor's vicinity, the values decrease. The VOC concentration returns to its initial state after reaching elevated levels, while the CO_2 levels return to steady state in a much more gradual manner. On average, it takes approximately 100 seconds for the sensor readings to stabilize after the removal of a sample.

Based on the BSEC data and observations, it is noted that VOC levels initially stay elevated for a short duration before declining, while CO_2 levels decrease gradually. The MOX sensor exhibits high responsiveness to VOC, rendering it a dependable indicator of VOC concentration in real-world settings. The gradual decline in CO_2 levels is likely influenced by multiple factors including humidity, pressure, and VOC concentration, indicating that CO_2 concentration is estimated from these parameters rather than being measured directly.

Task 3

The program is modified to include the measurement of IAQ, temperature, and humidity, in addition to the parameters previously recorded. Readings are captured once an accuracy level of 3 is reached.

The task involves assessing the performance of a gas sensor across various parameters including air quality, temperature, and humidity. The Nicla Sense ME Board was positioned in a shared kitchen of student dormitory at Sundgauallee for 24 hours with measurements taken every 10 seconds. Data regarding indoor air quality, temperature, humidity, and CO2 concentration are recorded, ensuring accuracy at level 3 prior to commencing the 24-hour monitoring. All activities conducted throughout the 24-hour timeframe are documented for analysis. Figures 13, 14, and 15 illustrate the influence of routine activities on the measurements.

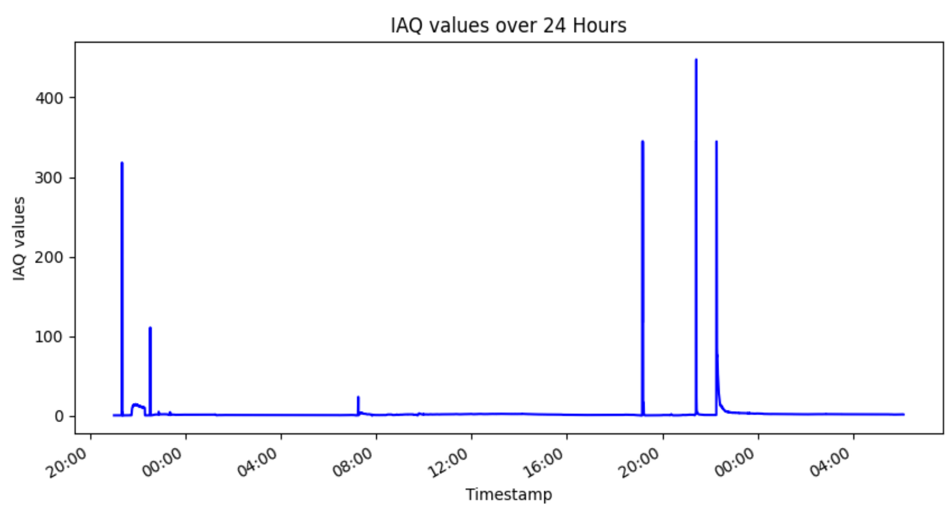

Figure 13: Plot of Indoor Air Quality (IAQ) values over 24 hours in shared kitchen

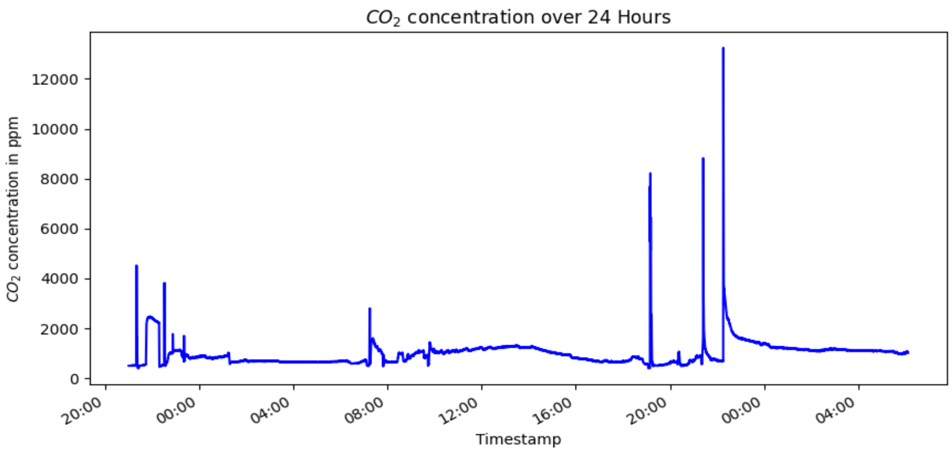

Figure 14: Plot of CO_2 concentration (in ppm) values over 24 hours in shared kitchen

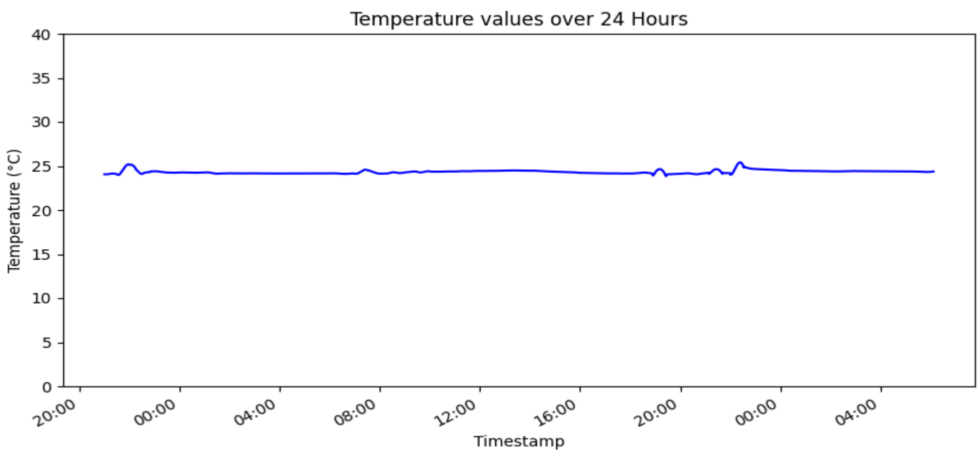

Figure 15: Plot of Temperature (in ºC) values over 24 hours in shared kitchen

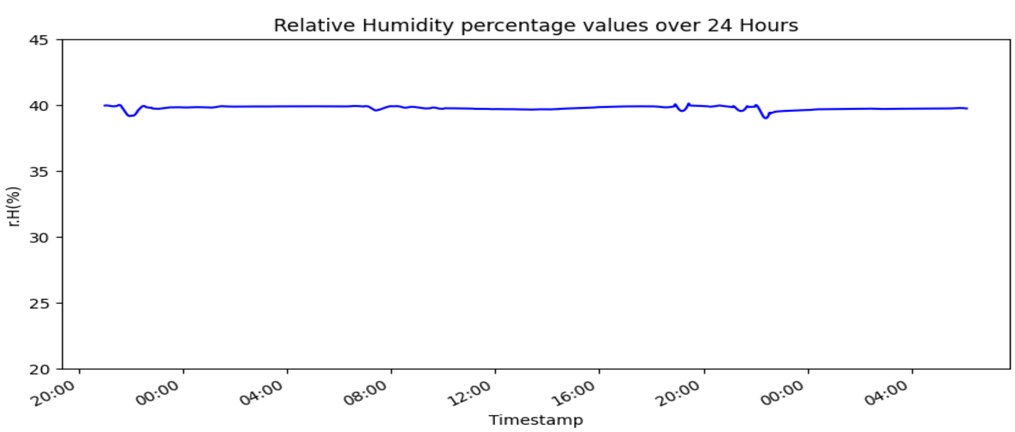

Figure 16: Plot of Humidity (in r.H (%)) values over 24 hours in shared kitchen

Based on the data plots above, the following observations can be made:
From 21:00 - 21:45: Dinner was cooked with slight ventilation where VOC source leading to increase in IAQ.
From 22:45 – 23:00: Tea was prepared leading to a slight increase in IAQ.
From 23:45 - 07:30: No activities during night and therefore no change in IAQ. The temperature and humidity are almost constant during this time duration.
From 07:30 - 08:00: Coffee was being brewed, which caused an increase in Indoor Air Quality (IAQ) due to the presence of volatile organic compounds (VOCs).
From 08:00 – 19:00: No activity, therefore no major change in IAQ as the kitchen is left empty and there are slight changes in CO_2 concentration.
From 19:00 – 19:30: Dinner preparation, peak in IAQ values and CO_2 concentration.
From 20:30 – 00:00: A party in the kitchen, peak in IAQ values and CO_2 concentration.
From 00:00 – 6:00: No activities in kitchen, therefore constant IAQ and slight variation in CO_2 due to slight ventilation.

Summary

Analysis of the raw data values from the MOX Gas sensor, it is evident that the presence of reducing gases correlates with a reduction in resistance and the presence of oxidizing gases results in an increase in the sensor's resistance. Notably, the most significant fluctuation in resistance was observed with perfume, as compared to red chilli and coriander powder.
Under identical conditions to Task 1, the concentration of volatile organic compounds (VOCs) and CO_2 was monitored. The observed behavior mirrored that of the MOX resistance, leading to the conclusion that the sensor does not directly measure CO_2 concentration but instead derives it from a composite of readings obtained from other sensor components.
Over the course of a 24-hour period, data from the BSEC library, including Indoor Air Quality (IAQ), temperature, and humidity measurements, were collected. It was observed that the estimates generated by the BSEC library closely corresponded with the fluctuations in the actual sensor data. Hence, it can be inferred that the BSEC library integrates data from various origins to formulate its estimates of VOC and CO_2 concentrations.

References

[1] J. Kieninger, S. J. Rupitsch, Sensors Lab Course. University Freiburg. Winter term 2023/24.

[2] https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality [Accessed on 08.02.2024, 14:27]

[3] https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs [Accessed on 08.02.2024, 16:30]

[4] https://www.bosch-sensortec.com/software-tools/software/bme688-software/ [Accessed on 08.02.2024, 19:23]