DOI 10.5162/16dss2022/P23

Monitoring Indoor Air Quality with low-cost Sensor Systems

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Introduction

Today, people spend most of their time indoors [1]. With regard to air quality monitoring, most of it still revolves around outdoor air quality (NO_x, particles, etc.). In most cases, CO_2 is still measured as the main air quality parameter indoors, although Pettenkofer established as early as 1858 that CO_2 is only an indicator for Indoor Air Quality (IAQ) caused by the human metabolism while "bad air" is mainly caused by Volatile Organic Compounds (VOCs), leading to fatigue and headaches [2].

A distinction can be made between VOCs and their individual health assessment and the total concentration of all VOCs, which is summarized as total volatile organic compounds (TVOC).

There are different definitions for TVOC depending on the measurement methodology. According to DIN EN ISO 16000-6, those VOCs that elute on a specific gas chromatography column in a specific retention window (n-hexane to n-hexadecane) are included in the TVOC value [3].

There are not only improvements in analytics since the time of Pettenkofer, but sensor technology has also developed further. Nowadays, a large number of low-cost sensors are available that offer great potential for online monitoring of IAQ. But in the case of indoor air quality and VOCs, there is not just one target value but many hundreds of different VOCs, which still poses a challenge.

Therefore, as a complementary approach to the guideline activity of the VDI/VDE GMA FA 4.64 Multigassensors, the scientific research project VOC4IAQ was set up. The aim of the project is to study the potential of low-cost, especially metal oxide semiconductor (MOS), gas sensors currently on the market for IAQ, to establish a test guideline and, if possible, a novel IAQ index based on sensor data.

In this work, the potential of low-cost sensors for monitoring VOC activities indoors is outlined.

Materials and Methods

Setup

As part of the project, four so-called benchmark systems were set up to monitor indoor air in various locations over one year. Each benchmark system consists of various MOS sensors (Sensirion SGP40, Bosch BME688, Renesas ZMOD4410 & ZMOD4510, Sciosense ENS160) in temperature cycled operation (TCO) [4], an EC cell for formaldehyde (Sensirion SFA30), temperature and humidity sensor (Sensirion SHT35) and two CO_2 sensors (Sensirion SCD30 & SCD40).

The CO_2 sensors measurement is based on diffusion with them being attached to the outside of an aluminum box. The other sensors are operated in a pumped system, with a pump (Xavitech V200) drawing in the air with a constant flow rate. The air sample is then analyzed by the different sensors. The MOS sensors are connected to a Teensy 4.0 based hardware which controls the TCO with a temperature cycle according to Fig. 1 and records the data [5].

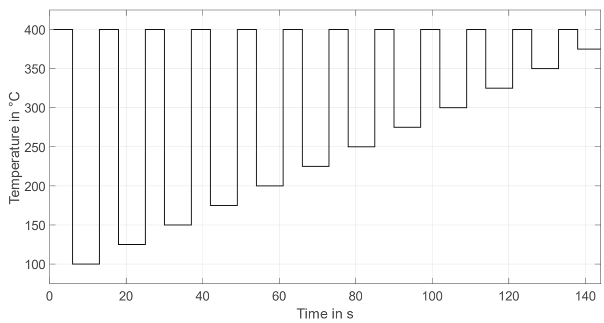

Fig. 1: Temperature cycle with 12 low temperature steps (100-375 °C in 25 °C steps, duration 7 s each), high temperature steps of 400 °C (duration 4 s each) with a total duration of 144 seconds.

All sensors and the pump are controlled by a Raspberry Pi Model 4, where also the data is stored on an SD card. Additionally, the Raspberry Pi is connected to the internet and sends the data to a database. All the parts are installed in an 25 x 25 x 10 cm³ aluminum box, cf. Fig. 2, that only requires a power supply. Two benchmark systems are installed in private living rooms, the two others are installed in professional work areas (an office at Saarland University and a meeting room at 3S GmbH, both in Saarbrücken), to cover different indoor scenarios.

The aim of the benchmark system is to measure outside the laboratory in realistic environments for over one year by monitoring IAQ (especially VOC levels and specific events or activities). By using several sensors and sensor types in combination with advanced data evaluation, the potential of these sensors in terms of accuracy and stability can be examined.

Fig. 2: Inner view of the benchkmark system with MOS sensors in measuring chambers (I), control hardware (II), pump (III) and Raspberry Pi for control and data storage (IV).

All sensors used in the benchmark system are commercially available. Besides the standard manufacturer mode, some sensors are operated in temperature cycled operation which boosts the sensitivity and selectivity further [4,6].

Calibration

Since MOS sensors are in general non-selective, an application specific calibration is needed. For indoor air applications, the sensors are calibrated in a complex VOC mixture simulating room air. Since more than 300 different VOCs are typically found indoors [7,8], the biggest challenge is to reduce this large number to a few representative VOCs to be used for lab calibration. In analogy to analytical methods, the VOCs are clustered into substance groups, i.e. alcohols, aldehyde, alkanes, alkenes, aromatics, ester, glycols and glycol ethers, halocarbons, ketones, organic acids, and terpenes. This results from the assumption that the reactions on the sensor surface are mainly determined by functional groups. Thus, representatives of a substance group should react in a similar way.

Based on analytical IAQ studies [7,8], the most dominant substances of each group are then selected and the sum of the individual concentrations results in a $TVOC_{Sens}$ value.

The suffix "Sens" is used to explicitly emphasize the distinction from analytics and accentuates the use of sensors. Due to the restriction to a specific GC elution window the standard DIN EN ISO 16000-6 for analytics [3] neither includes semi-volatile organic compounds (SVOCS) nor very volatile organic compounds (VVOCs) such as ethanol, isopropanol, formaldehyde, etc.. However, especially VVOCs are included in the $TVOC_{Sens}$ value, which is highly relevant as particularly alcohols can occur in high concentrations indoors. Not only this circumstance makes it difficult to compare the two TVOC values.

Additionally, typical inorganic gases, carbon monoxide, hydrogen, and humidity, which also cause a sensor reaction and thus interfere with VOC quantification, are included in the calibration. In total, eleven VOCs and three interfering gases are considered.

The calibration is performed with randomized gas mixtures, where the concentration of each individual VOC and interfering gas is varied independently in a pre-defined concentration range using Latin Hypercube Sampling [9,10]. The sensors are calibrated using a novel gas mixing apparatus (GMA) [11,12]. Fig. 3 shows the resulting sequence for $TVOC_{Sens}$ in a concentration range from 380 ppb to 3200 ppb.

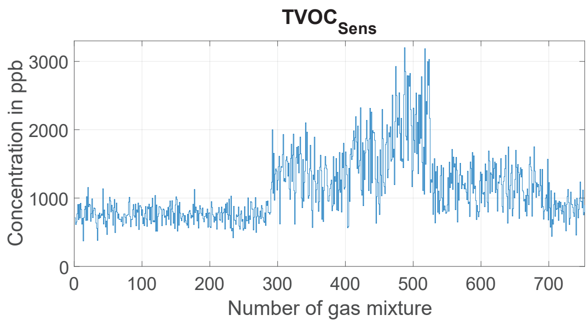

Fig. 3: Set-point values of the $TVOC_{Sens}$ concentrations over the number of different gas mixtures.

Data Evaluation

The sensor raw data are evaluated by means of machine learning. From each temperature cycle shape-describing features are extracted and selected to be used to build a regression model using Partial Least Squares Regression (PLSR) [13]. The performance of the model is determined by the root mean squared error (RMSE) of the model estimates. Based on the same calibration data, several models can be built, i.e. one for each individual VOC, for the inorganic

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gases or for $TVOC_{Sens}$. These models can be derived from individual sensors, but could also make use of sensor data fusion. In this work, measurement data from a SGP40 (Sensirion) is considered.

The trained models are then applied to field test data (measurements in the mentioned private living rooms and professional work areas) and return model estimates for the selected target, for example $TVOC_{Sens}$.

Results

Calibration

Fig. 4 shows the PLSR model for $TVOC_{Sens}$ with an RMSE of 114 ppb for the calibrated range of up to 3200 ppb, which covers the relevant range for hygienic assessment of indoor air according to the Umweltbundesamt (UBA) [14], which recommends an increased ventilation for TVOC concentrations exceeding 1 mg/m³ (corresponding to approx. 1 ppm). Note that this refers to the analytical TVOC value, the $TVOC_{Sens}$ value would be higher because more VOCs are included. The relatively low uncertainty would be suitable for demand controlled ventilation to achieve a good compromise between energy consumption and IAQ for personal well-being and health.

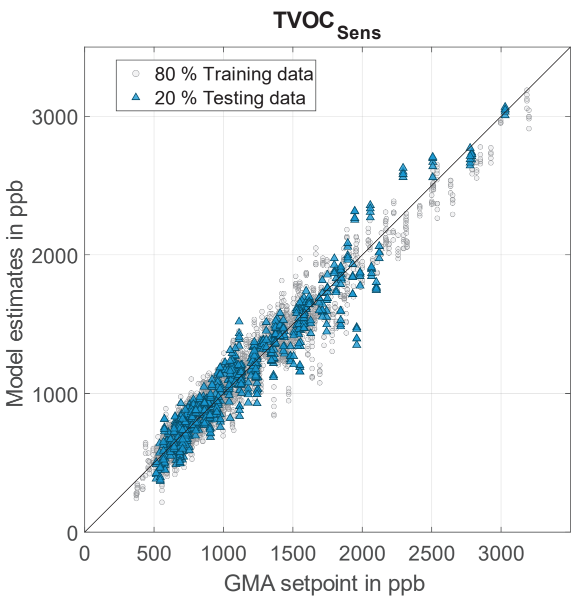

Fig. 4: PLSR model for $TVOC_{Sens}$ from the lab calibration with a relative uncertainty of < 4%.

Field test

In Fig. 5, the model estimates for $TVOC_{Sens}$, acetone and ethanol over one day are shown for a living room as an example. These patterns are typical for the same situation, i.e. similar patterns are observed for most days.

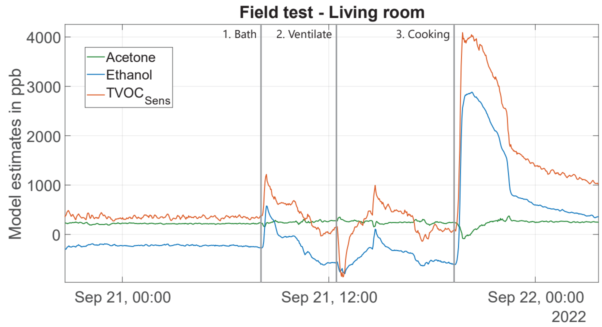

Fig. 5: Model estimates recorded by the benchmark system in a living room over a typical day.

In the following, relative changes are primarily considered rather than absolute concentrations and base levels. Significant increases can be seen in the morning and in the evening. The increase of ethanol and $TVOC_{Sens}$ in the morning indicates use of the bathroom after getting up and can be explained by the use of hygiene articles like deodorant, shampoo, etc.

The signals drop over midday, which is due to the ventilation of the apartment. First, ventilation is only low with a tilted window, hence the initial slow drop in the signal, then high ventilation with fully open windows and doors in the whole apartment.

The climbs in the evening are very well timed and associated to cooking dinner. On this day, home-made pizza was prepared while the $TVOC_{Sens}$ signal increases until the food is ready. While the food is served and eaten, a plateau is reached, at which the concentration is at its maximum.

After that and due to general leaks and slight ventilation of the apartment, the concentration decreases and returns to a base level during the night.

By evaluating the individual VOC models, the dominant VOC for the $TVOC_{Sens}$ increase can also be identified. In this case most models are relatively constant during the cooking event, exemplified by the acetone signal. Only the ethanol signal correlates with the $TVOC_{Sens}$ signal. Ethanol is probably released when the dough is baked, which then also leads to an increase in the $TVOC_{Sens}$ signal.

Discussion

In general, it has been found so far that typical VOC activities in private homes are dominated by cooking events. The result presented here shows a typical course over a day, which is characterized not only by the cooking events but also by the use of hygiene items. These sources and the resulting VOC pollution are not detected by the CO_2 sensor, as this is only an indicator of the presence of people, which results from the increase in the CO_2 content indoors through human breath.

The potential of the MOS sensors is evident. It is not only possible to monitor an overall VOC exposure in high temporal resolution (here < 3 minutes), but also to identify the dominant VOCs or VOC substance group, which lead to an increase of the $TVOC_{Sens}$ signal. This information can be passed to the user as a sign for ventilation at high loads, or as an input for integrated ventilation control systems.

The information that can be measured is also important for an indoor air quality assessment, because each VOC has its own health rating. With such a system, studies can be carried out which establish correlations between health problems and individual VOC expositions.

A challenge with MOS sensors is drift. It is therefore difficult to determine a base level of the signals or absolute values. This will be investigated in further project work with recalibrations, drift compensation methods, and drift-optimized feature selection. Comparative analytical reference measurements will be carried out to validate the VOC curves and to determine absolute values.

Nevertheless, this approach allows evaluating indoor activities like cooking, cleaning, renovation, emissions from building materials, etc. in order to be able to assess their effects on indoor air and also on the human health.

Besides the evaluation of single sensors, the benchmark systems offers the possibility to combine several sensors in order to improve the results.

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Acknowledgement

This research was partly performed within the project “VOC4IAQ” funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) through the program Industrial Collective Research (AiF-iGF) under the grant number 22084N/1. The authors also thank the European Regional Development Fund (ERDF) for supporting their research within the project number 14.2.1.4-2019/1.

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages