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Metal Oxide Semiconductor sensors (MOS) for measuring Volatile Organic Compounds (VOC) - performance evaluation in residential settings

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ABSTRACT

Metal Oxide Semiconductor (MOS) sensors measuring Volatile Organic Compounds (VOC) seem to be an obvious step towards broadly available Demand Controlled Ventilation (DCV). The previous research shows that MOS VOC sensors can detect high pollution events such as cleaning, painting, or high occupation density. These abilities seem to make MOS VOC sensors suitable to complement ventilation control systems, especially concerning residential ventilation. However, several questions come from the practice: “Are the MOS VOC sensors reliable and stable enough to be applied in practice?” “Are there any benefits concerning energy efficiency and indoor environmental quality?” They remain unanswered. Studies on the long-term performance of MOS VOC sensors exposed to real-life environments are lacking. Some producers test their sensors in a laboratory environment, but such data are often not publicly available. Data about the influence of ventilation control based on MOS VOC sensors on energy efficiency are also missing. The present paper reports first results from a project aiming to answer aforementioned questions having following objectives: investigate performance of MOS VOC sensors exposed to a typical residential environment. Determine sensor properties – sensitivity, linearity, hysteresis by comparing their signal with a reference measurement conducted by PID (Photo Ionization Detector). Discuss the suitability of the sensors for control of residential ventilation. We measured in a typical Danish row house occupied by a family of four. We used two sets of three commercially available sensors installed two locations-bedroom and kitchen. PID gas analyzer served as a reference measurement. The results show that all tested sensors were able to indicate the pollution events like human presence or cleaning. There was a fair agreement among the signals of the two tested sensors. These sensors produced also signals, which were in a clear relationship to the reference measurements. In the opposite, the signal from the third sensor could be clearly related neither to the reference signal nor to the other two tested sensors. This is potentially problematic for sensor’s application for ventilation control.

KEYWORDS

Residential Ventilation, Volatile Organic Compounds, Metal Oxide Semiconductor, Indoor Air Quality

1 INTRODUCTION

Today's energy efficient buildings are airtight and need therefore an efficient ventilation to maintain high quality of indoor air. Smart ventilation (Durier et al. 2018) allows for continuous adjustment of ventilation airflow in time, and optionally by location, to provide the desired indoor air quality while minimizing energy consumption. The smart ventilation is slowly but steadily finding its way into new or renovated houses across Europe, the USA and beyond. It is mostly the specific sub-type of smart ventilation, so called Demand Controlled Ventilation (DCV), which is becoming increasingly popular even in residential sector where we would not expect it to be applied some decades ago. It is mostly due to technological advances in the field building control (digital and internet enabled controllers, EC fans) as well as due to the advances Indoor Air Quality (IAQ) sensing. Sensors measuring "demand" variables like temperature, concentration of CO_2 and Volatile Organic Compounds (VOC) or relative humidity are produced cheaper and in compact dimensions. Metal Oxide Semiconductor (MOS) sensors for measuring Volatile Organic Compounds (VOC) represent such sensors (Herberger and Ulmer 2012). They offer possibility to account for air pollution related to human presence and activities as well as other pollution sources that worsen IAQ. Considering indoor air quality, it is a clear advantage. Outdoor air supply rate is increased also when pollutants originating from cleaning, cooking etc. are detected. Other advantages include low energy consumption, small dimensions and durability. Moreover, Herberger et al. (2010) developed sensor that uses data collected by Burdack-Freitag et al. (2009) correlating the measured VOC signal with human emission of CO_2. Consequently, the sensor output is converted to so-called CO_2 equivalent concentration. As "CO_2 concentration" had become known to the public as an indicator of IAQ, the intention was that the sensor signals could be more easily interpreted by building occupants. These arguments speak in favour of MOS VOC sensor technology. However, there are also, several studies, such as Won and Schleibinger (2011), which state that currently available MOS VOC sensors suffer from several drawbacks, mainly related to cross sensitivity to relative humidity, low resolution and inability to measure concentration of individual chemicals. Despite that, ventilation producers offer VOC controlled DCV also for residential applications. Studies evaluating performance of MOS VOC sensors in the field are sparse. Kolarik (2014) showed observed agreement in need for increased ventilation expressed by VOC or CO_2 sensor during 49% of occupied time. During 11% of occupied time it was only VOC sensor that indicated need for increased ventilation. Despite the fact that the study considered office spaces, it indicated that simple replacement of CO_2 sensor by VOC sensor would lead to significantly longer time with high airflows. Challenges related to direct replacement of CO_2 sensors with VOC sensors were illustrated in a field study by De Sutter et al. (2017). The results showed notable increase of ventilation rates related to the sharp peaks in the VOC signals when the same set point was used for both CO_2 and VOC based control of ventilation. The authors suggested a correction algorithm that would filter the VOC signal; however, its application was not practically demonstrated. Finally, yet importantly, besides the publication by Fahlen et al. (1992) and recent publication by Alonso et al. (2021), there are no publications dealing with evaluation of MOS VOC sensors performance characteristics both in laboratory and in the field. An objective of the present paper was to examine MOS VOC sensors during operation in realistic residential environment. Determine their properties – sensitivity, linearity, hysteresis by comparing their signal with a reference measurement conducted by PID (Photo Ionization Detector) and discuss their suitability for control of residential ventilation.

2 METHODS

2.1 Investigated sensors

Table 1 summarizes the technical parameters of tested sensors. We investigated three different sensors from established manufactures. We have chosen the sensors based on previous experiments (Kolarik et al. 2018). We purchased two specimen of each sensors and created two measuring sets. We integrated the sensors into one casing with common power supply. Arduino board with Wi-Fi module ensured wireless transfer of the measured data into a laptop equipped with the Lab View software connected to the same wireless network. The data logging interval was set to 1 minute. We used a portable photo-ionization (PID) gas detector Photo Check TIGER to conduct reference measurements of Total Volatile Organic Compounds (TVOC) concentration. We performed a custom calibration of the PID gas detector 100 ppm of isobutylene (zeroing on zero gas mixture) before the measurements. The TVOC concentrations measured by the PID device were thus representing isobutylene equivalents. Besides the MOS VOC signals, we also monitored standard indoor environmental quality (IEQ) parameters: room temperature (±0.3 °C 5-60 °C), relative humidity (±2 % RH 20-80 % RH) and CO_2 concentration (non-dispersive infrared, 400-2000 ppm, ±30ppm ±3 % of reading). We used internet connected commercial indoor climate monitors providing measurements in 5-minute intervals. In the case of comparison between MOS VOC signals and the IEQ variables, we averaged the 1-min MOS VOC data into 5-min intervals.

Table 1: Technical parameters of investigated sensors based on manufacturer data sheets

Abbreviation	A	B	C
Output (units)	VOC index [-] [(a)]	Voltage [V]	TVOC eq. [ppb][(b)] CO2 eq. [ppm]
Sensing range	0 – 500 VOC index points; 0 – 1000 ppm ethanol equivalents	0 – 3.0 V DC; 1 – 30 ppm H_2	0 – 29206 ppb TVOC eq. 400 – 32768 ppm CO_2 eq.
Measuring accuracy	± 15 VOC index points	NA	NA
Measurement interval/ response time	NA/ < 10 s	NA	NA
Power Supply	1.7-3.6 V DC	4.9-5.1 V DC	1.8-3.6 V DC
Communication	I^2C bus	0 – 3.0 V DC	I^2C bus
Warm up time	NA	NA	20 min
Operation temperature range	-20 – 55 °C	-10 – 50 °C	-40 – 85 °C
Operation humidity range	0 – 80 %, non-condensing	NA	10 – 95 %, non-condensing

(a) A built in proprietary algorithm processes a raw signal of the sensor, corresponding to the logarithm of the sensor resistance a "VOC index". The index value 100 refers to the typical concentration over 24 h period.

(b) The sensor processes the raw signal into so-called TVOC and CO_2 equivalents. The algorithm is proprietary, the manufacturer states that CO_2 equivalents are determined based on the relationship between human production of VOC (bioeffluents) and CO_2.

2.2 Data processing

As each studied sensor provided different output signal, we normalized these signals to avoid the influence of the absolute value of each observation. Each observation was normalized against the difference of its maximum value and minimum value (so called min-max normalization), as shown in Equation (1):

$$y = (x - \min(x))/(\max(x) - \min(x)) \tag{1}$$

Where x is the i-th observation in the measured data and y is i-th normalized observation for the particular sensor signal. We used only the normalized data in our analyses.

According to Fahlen et al. (1992), the sensor properties can be described by so called characteristic curve. Fahlen et al. (1992) determined the curve exposing the sensor to the set of steady state concentrations of a known VOC in ascending and descending order. It is thus a linear relationship between known-reference signal and the signal from evaluated sensor. In the present paper, we established the characteristic curve by fitting the linear regression model to the data where with PID measurements as independent and respective MOS VOC data as dependent variable. Thus, the slope of the relationship represented sensor's sensitivity. The R^2 value for the linear model indicates the linearity of the sensor. To evaluate hysteresis, we selected one-day measurements from the data. We fitted linear regression model to the build-up and decay separately. Consequently, we express hysteresis as a mean distance from the two regression lines. To determine such distance, we used the obtained linear models to predict MOS VOC signal for three distinct levels of the reference signal (150 ppb, 250 ppb and 350 ppb isobutylene equivalent). The mean difference between such predictions for build-up and decay determined the hysteresis.

2.3 The test house and the measurement period

We have installed the senor sets in a typical Danish row house occupied by a family of two adults and two children (elementary school age). We placed the sensor sets at two locations-a kitchen/dining room open to a living room and in the main bedroom (Figure 1). In the present paper we report on a part of the total measuring period. Reported measurements include September-November 2021 and February-March 2022. The whole dataset covers almost one year of measurements.

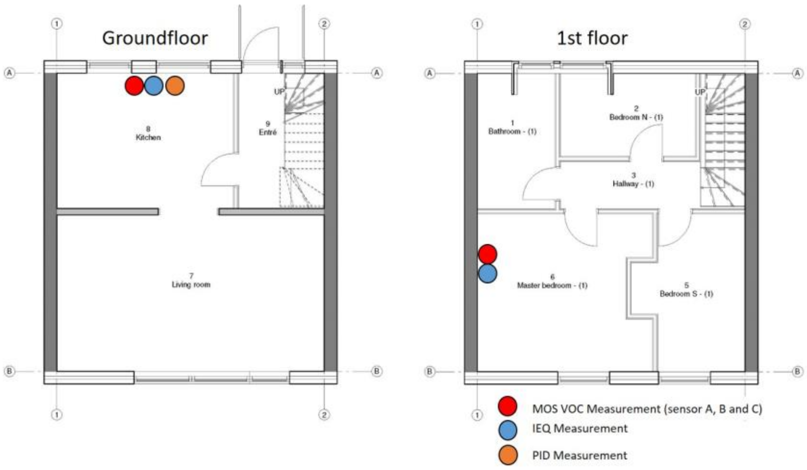

Figure 1: Placement of the sensors

3 RESULTS AND DISCUSSION

3.1 Long term data

Figure 2 gives an example of not normalized sensor signals from the kitchen. The figure illustrates a typical variability of the signal during periods when the house was empty and consequently occupied. There is a clear difference in the amplitude of the signal regardless the type of the sensor.

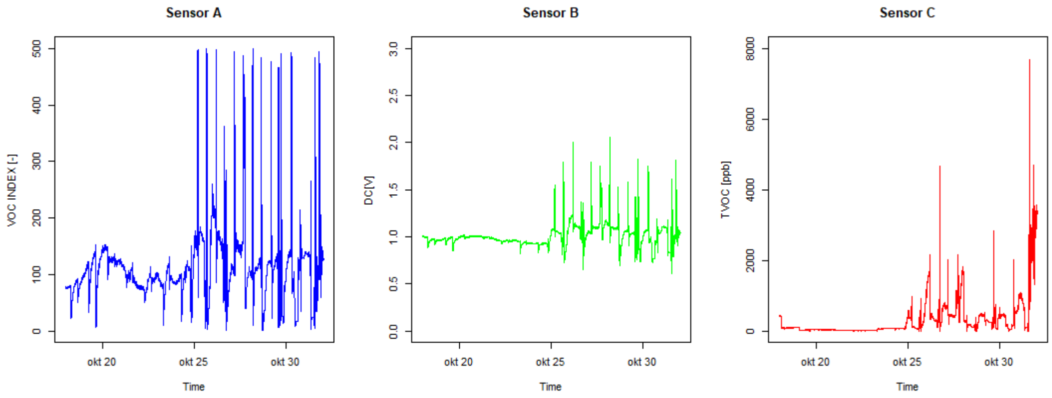

Figure 2: Absolute signal of the tested MOS VOC sensors placed in the kitchen for two weeks in October 2021 (the house was unoccupied during the first week)

Figure 3 shows the same period as Figure 2, but displaying normalized data. Using such interpretations it is possible to see that despite the fact that the trend in amplitude of the signals is the same for empty and occupied house, there is a clear difference in character of the signal. Signal from sensor C is almost zero when the house is empty, on the contrary, signals from sensors A and B still represent some development and despite the difference in amplitude of the build-ups and delays, there seems to be an agreement between these two signals. During the occupancy period, the sensor A seems to have largest fluctuations.

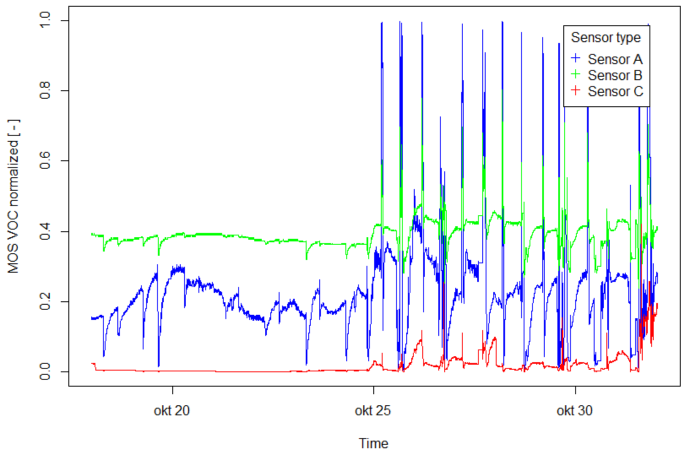

Figure 3: Normalized signals of the tested MOS VOC sensors placed in the kitchen for two weeks in October 2021 (the house was unoccupied during the first week)

Figure 4 represents a cross plot of normalized signals of the MOS VOC sensors placed in the kitchen for the same period as presented in Figures 2 and 3. It is clear from the plots, that there was a somewhat consistent relationship between responses of sensor A and B. Such relationship did not seem to exist comparing sensors A and B with sensor C. The Figure 4 shows only two weeks, but the patterns were similar through the analysed period. Analysis of the exact character of the relationship between sensor A and B is out of the scope of this paper, as it would require removal of the autocorrelation contained in the data caused by high frequency of sampling (Alonso et al. 2021).

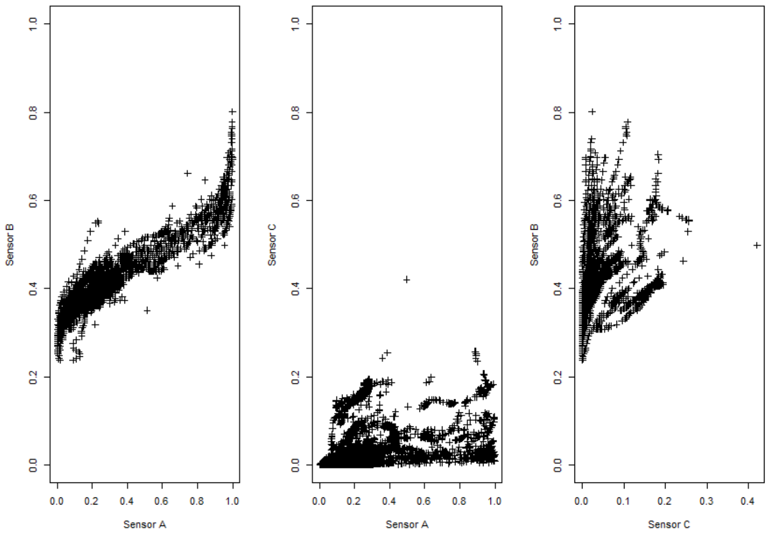

Figure 4: Cross-plot of normalized signals of the tested MOS VOC sensors placed in the kitchen for two weeks in October 2021 (the house was unoccupied during the first week)

3.2 Sensor characteristics

The Figure 5 represents characteristic curves determined using measurements from period of 7.3.2022 – 12.3.2022. The figure depicts the linear regression fit to the data in the case of sensor A (blue) and sensor B (green). In the case of sensor C, the variance explained by the linear model was too low to consider linear relationship between sensor C signal and the reference PID signal. Table 2 summarizes the sensitivity values and R^2 values of the linear regression models for particular sensors. It is clear from the table as well as from the Figure 5, that the response of the sensor C did not show any meaningful relation to the reference signal. Therefore, the sensor C seemed not to represent the indoor air quality changes in the house.

Table 2: Summary of slope and variance explained by characteristic curves

	Sensitivity (95% conf. int.)	R^2
Sensor A	2.497e-03 (2.432e-03, 2.562e-03)	0.40
Sensor B	1.383e-03 (1.350e-03, 1.416e-03)	0.44
Sensor C	7.413e-05 (2.042e-05, 12.78e-05)	0.0007

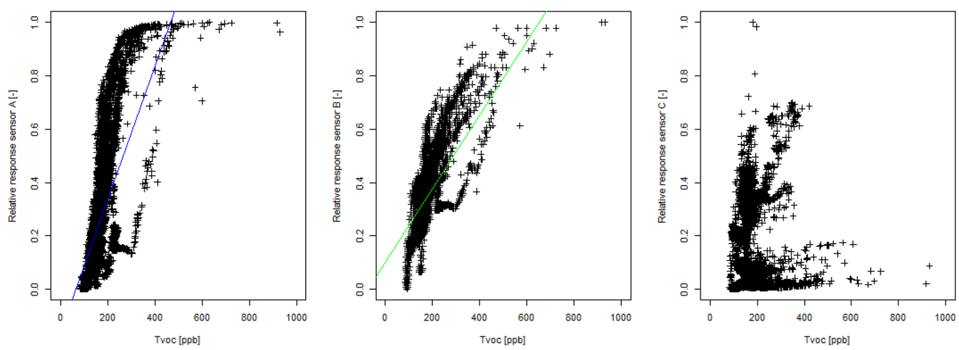

Figure 5: Characteristic curves for tested sensors determined for period of continuous parallel measurements with MOS VOC sensors and the PID monitor (7.3.2022 – 12.3.2022); regression line is not depicted for sensor C as the R^2 value does not indicate linear relationship

Analysis of the hysteresis required separation of build-up and decay periods. This is a relatively easy task in laboratory conditions, when sensors are exposed to controlled pollution events.

However, with the field data, the analysis is more demanding. For this paper, we conducted the analysis of the sensors' hysteresis on data from one particular day, Friday 11.3.2022. After 15:00 the whole family gathered at home and started weekly cleaning of the house. This initiated excitement of the sensor signals suitable for separation of decay and build-up periods. Figure 6 shows the normalized data.

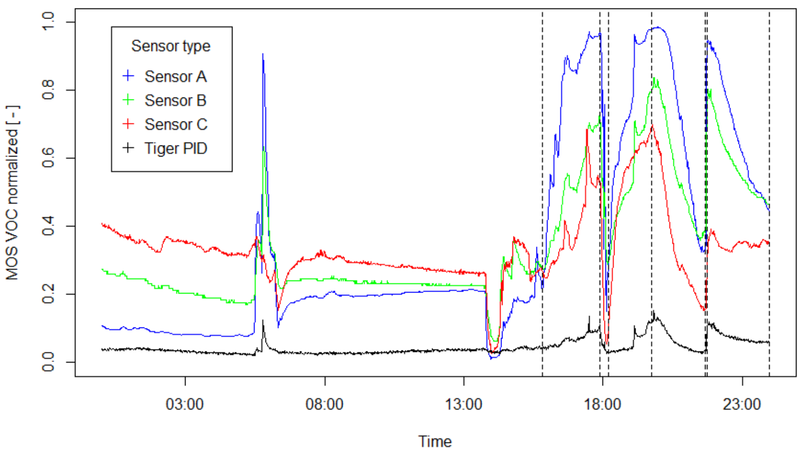

Figure 6: Data used for evaluation of hysteresis. Vertical dashed lines indicate selected build-up and decay periods during afternoon cleaning activities in the house

Figure 7 illustrates the hysteresis of the three investigated sensors for the tested period. The determined hysteresis were 0.123, 0.014 and 0.121 for sensors A, B and C respectively. The hysteresis was in general rather low, 12.3%, 1.4% and 12.1% of the measuring range, which is preferable. The sensors A and C had comparable hysteresis while sensor B showed practically no hysteresis. In the present paper, the hysteresis was evaluated only using one day measurements. In future analysis, we will analyse several days distributed through the whole dataset to determine, whether the hysteresis remained consistent. Figure 7 also shows that the relationship between the reference signal and the signal of sensor C seemed to be more consistent than when longer measurement period was considered (Figure 5).

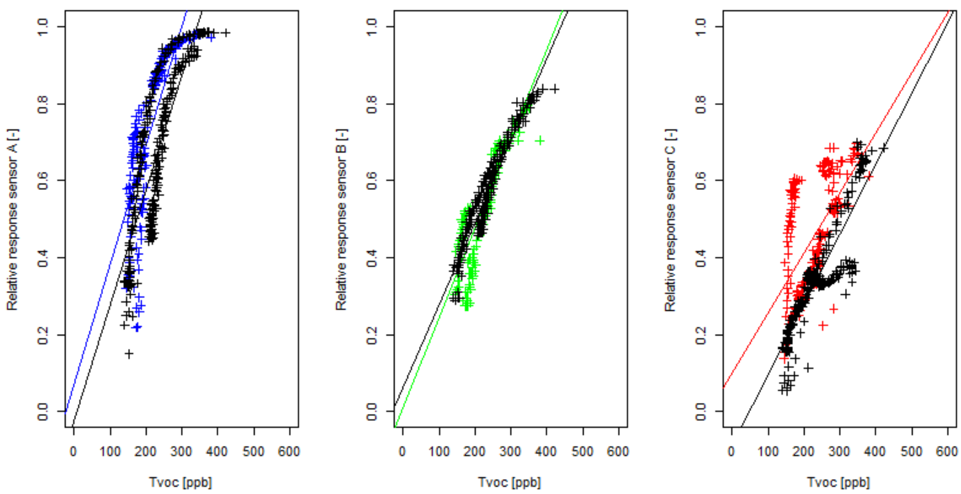

Figure 7: Separated build-up and decay periods and corresponding linear fits for the three tested sensors. Build-up is depicted in colour, decay in black

While the sensitivity determined using longer period and during one day measurements was comparable for sensors A and B, with sensor C the sensitivity differed significantly. This indicates that the sensor C had unstable behaviour when exposed to the pollution emitted in the kitchen. The identification of reasons for this requires further analysis.

3.3 Relation between MOS VOC and CO_2 measurements, usability for control

Besides TVOC signal, offered the Sensor C also a so-called CO_2 equivalent. The Figure 8 offers a comparison between CO_2 and CO_2 equivalent signals measured in the kitchen and bedroom. It is clear, that while in the bedroom the CO_2 equivalent signal followed the pure CO_2 measurements rather closely, this was not the case in the kitchen. Human bioeffluents were the main pollution source in the bedroom, while the kitchen was the place most of the other pollutants were emitted. This was even more pronounced due to the fact that the kitchen is directly connected to the living room and represents therefore the area where the occupants of the house spent majority of time besides sleeping. It seems from the obtained data, that in the cases, where the sensor C got excited by stronger pollution event, its CO_2 equivalent signal drifted from the real CO_2 values. This would, of course represent a challenge with respect to the ventilation control. De Sutter et al. (2017) observed “overventilation” in connection with the use of CO_2 equivalent signals in their study. Further analysis of the data from the present study will focus on relationship between CO_2 and CO_2 equivalent signals for all measured data.

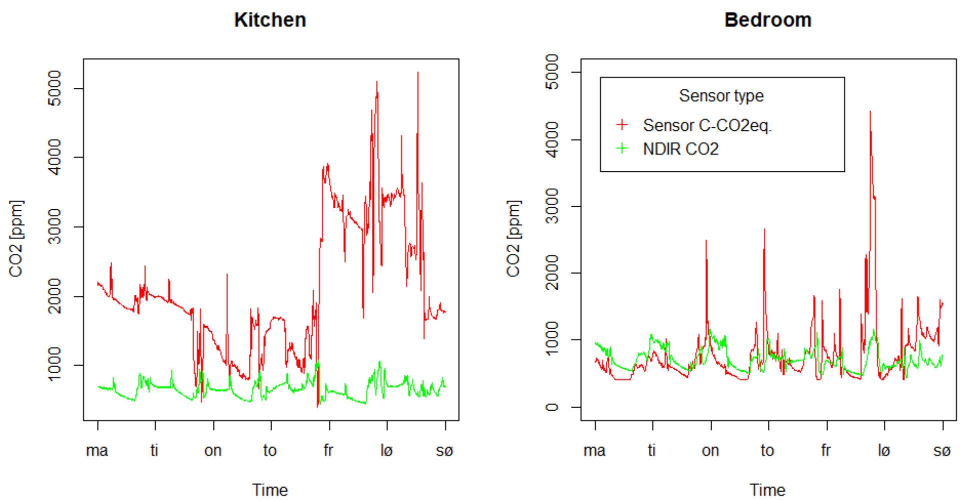

Figure 8: Comparison of CO2 and CO2 equivalent signal for measurements in the kitchen and bedroom

All tested sensors demonstrated ability to react on pollution events in the house. The signal from sensor C (“TVOC” signal or CO_2 equivalent) seemed to be least correlated to the reference PID measurements in the kitchen. However, in the bedroom, sensor C demonstrated rather good agreement with CO_2 measurements. As the absolute signals produced by particular sensors were different, the problem of selection of the right set point value would be apparent if they should be used in a control loop.

Utilization of PID instrument as a reference measurement in this study had its limitations. The instrument is primarily suitable for measurement of higher TVOC concentrations. As it can be seen in Figure 6, under normal pollution patterns in the house the normalized PID signal stays about 20% of the measurement range established from the whole dataset. As PID technology is also based on a relative measurement, its utilization for determination of the MOS VOC sensor characteristics has limitations. More suitable would be application of more precise analytical method like Reaction-Time of Flight-Mass Spectrometer (PTR-ToF-MS) Kolarik et al. (2018).

4 CONCLUSIONS

- All three tested sensors were able to indicate the pollution events.
- Two of the sensors had comparable behaviour in terms their sensitivity determined using reference PID measurements. There was also an obvious cross-relation between their output signals. This indicates that both sensors would behave in similar manner when used for IAQ control. There was however a difference in absolute values of the sensitivity and thus in the amplitude of their response, this needs to be taken into account in the case of their use of control.
- The third tested sensor presented somewhat unclear relationship to the reference measurements and further analysis is needed to analyse causes of such behaviour. In the analysed data, the sensor signal did not correspond to the TVOC concentrations represented in isobutyl equivalents.
- The investigated sensors had small hysteresis, which is preferable. The analysis was however conducted on relatively small sample of measurements. Analysis of broader range of build-up and decay periods is needed to confirm the results.
- The CO_2 equivalent signal corresponded to pure CO_2 measurements in the case of measurements in the bedroom. In the kitchen where the human bioeffluents were not the main pollution source, there were large discrepancies. This is not necessarily a problem for the ventilation control, but careful choice of the set point would be needed to avoid unnecessary ventilation.
- In general the results of the study indicate, that the MOS VOC sensors represent a considerable alternative to currently used sensors. This however requires that their characteristics are properly considered in control algorithms.
- Recent development in low cost sensors measuring particulate matter (PM) brings the usage of MOS VOC sensors in the new perspective. As PM is representing far the highest health risk for humans, one can expect, that low cost PM sensors will soon make their way into the residential ventilation control. However, this does not necessarily mean the disqualify VOC sensors. The future research should focus on controls that effectively combine the two types of sensors.

5 ACKNOWLEDGEMENTS

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