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Reliability and performance of real-time gas sensors for continuous monitoring of indoor TVOC concentrations

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SUMMARY
We studied reliability and performance of four metal oxide semiconductor sensors and one photo ionization detection sensor in continuous monitoring of volatile organic compounds (VOCs) in laboratory and field experiments. In the laboratory experiments, we examined responses of the sensors using zero and isobutylene gases. In the field experiment, we monitored indoor air TVOC concentration continuously for eight-day period in a classroom of a high school building. We used active sampling of indoor air on Tenax TA sorbents and analysis of samples with gas chromatography as a reference method. In the laboratory experiments, all tested sensors showed the lowest values of their measuring range for the zero gas, but variation between different sensors occurred in the isobutylene gas experiment. In the field experiment, TVOC concentrations measured with the sensors were significantly higher compared to the reference method. Our results suggest that real-time gas sensors are not suitable for monitoring absolute TVOC concentrations. However, it is possible to use them to detect and understand temporal changes in indoor air quality.

KEYWORDS
Indoor air quality, continuous monitoring, volatile organic compounds

1 INTRODUCTION
During the last decade, use of real-time gas sensors has become increasingly popular in indoor air quality monitoring, and a wide variety of sensors exists in the markets. However, there is a lack of scientific information about the performance of these sensors. Therefore, the aim of this study was to examine how reliable real-time gas sensors are in monitoring the levels of total volatile organic compounds (TVOC) from indoor air.

2 MATERIALS/METHODS
Performance of real-time sensors was studied with laboratory and field experiments. The study included altogether ten sensors: five devices from different manufacturers and two of each device. Four of the devices were metal oxide semi-conductor (MOS) sensors and one was photo ionization detection (PID) sensor. The characteristics of the sensors are presented in Table 1.

In the laboratory experiments, the sensors were tested with two gasses: zero gas that did not contain any VOCs and isobutylene gas with concentration of 7500 ppb or 8000 ppb. Depending on the shape of the device, the test gasses were introduced to the sensors using a plastic “hood” or a closed plastic box. During the laboratory experiments, the temperature was 25±1°C and the indoor relative humidity between 20 – 30 %. Logging intervals of the devices were set to one

minute in order to receive ten data points from the ten-minute experiment. The zero-gas experiment for Device B was extended to 25 minutes, because the minimum logging interval of Device B was ten minutes, and with the extended experiment we were able to get three data points. During the isobutylene gas experiment, we noticed that the devices with MOS-sensors reacted to the gas with delay. Therefore, the length of the isobutylene gas experiments was extended to 20 minutes. The logging interval of Sensor E was 30 minutes, and it was excluded from the laboratory experiment due to limited amount of test gasses.

Table 1. Sensor properties.

Device	Sensor	Sensor type	Measurement range (TVOC)	Laboratory test
Device A	AMS-iAQ-core	MOS	125 - 600 ppb	Box
Device B	- *	MOS	450 - 2000 CO_2-ekv. ppm (125 - 600 ppb)	Hood
Device C	IQ-610	PID	20 - 20 000 ppb	Hood
Device D	- *	MOS	0 - 60 000 ppb	Box
Device E	Sensirion SGPC3	MOS	0 - 60 000 ppb	-**

* unknown sensor model and manufacturer

** logging interval was not appropriate for laboratory testing

The field experiments were done in a classroom of a high school building located in Helsinki metropolitan area. The devices were placed within two-meter radius in the classroom to monitor air quality for eight days (17 – 25.4.2019). The classroom was occupied on April 18th between 11.10 – 14.30, on 23rd between 11.10 – 16.30, on 24th between 8.20 – 15.30, and on 25th from 11.10 until the end of research period. Active sampling of indoor air on Tenax TA Carbograph 5TD - absorbent tubes and TD-GC-MS analysis according to ISO 160000-6 (2011) was used as a reference method for TVOC measurements. The samples were collected from the vicinity of the sensors with sampling time of 40 minutes and air flow rate of 200 ml/minute. The first sample was collected from empty classroom before the school day when the classroom had remained unoccupied for 16-20 hours. The second sample was collected during a class when there were 15 students with their teacher.

The high school building had been completely renovated in 2016. During the field experiment, the classroom was used normally, and it was cleaned daily between 16.00 and 19.00. Interior surfaces of walls and ceiling were made of concrete, and it had a vinyl flooring. A few acoustic panels were attached to the ceiling, and the furnishing included desks and chairs. Demand-controlled ventilation system of the classroom was controlled by a CO_2-sensor.

3 RESULTS

Laboratory experiments

In the zero-gas experiments, most of the sensors showed the lowest values of their measuring range. Both sensors of Devices C and D resulted in 0 ppb concentrations. Both sensors of Device A gave the lowest value of the measuring range (125 ppb). Apart from other devices, Device B used CO_2-equivalent ppm as a unit of TVOC concentration, which caused complications when comparing the results with other devices. Device B measured concentrations between 745 and 767 CO_2-equiv. ppm for the zero gas and the results are presented in Figure 1.

We observed more variation between the devices in the 7500 ppb isobutylene gas experiments. After the ten-minute exposure, both sensors of Device C gave values close to the true concentration of the isobutylene, between 7432 – 7722 ppb. Both sensors of Device D started

reacting to the gas after approximately 10 minutes of exposure, and the values continued to rise after the gas supply was closed. Eventually the values settled to 360 and 458 ppb. Sensors of Device A reacted quickly to the gas exposure and their highest values were 229 and 303 ppb. Device B, which was tested with 8000 ppb isobutylene, measured concentration of 808 CO_2-equiv. ppm (Figure 1).

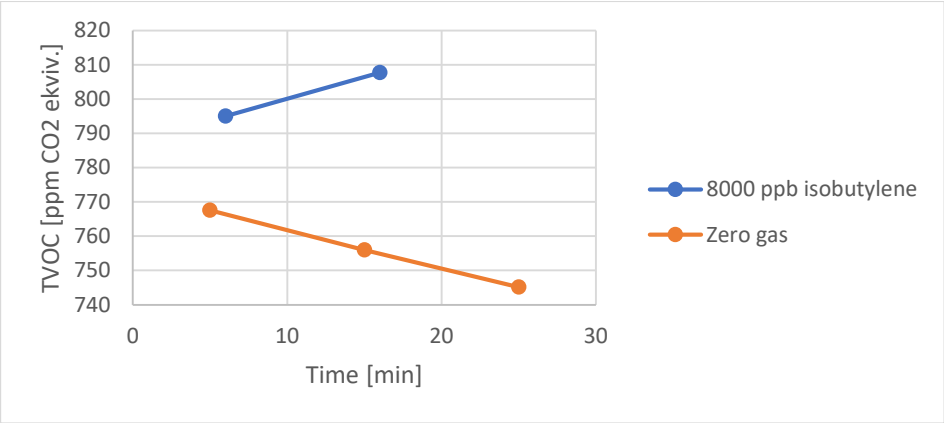

Figure 1. Results of zero gas and isobutylene gas experiments on Device B.

Field experiments

Monitored TVOC concentrations from the eight-day experiment in the classroom varied between different devices. Measurement ranges and average values of each sensor are presented in Table 2.

Table 2. TVOC measurement ranges and average values during the field experiment.

Device	Measurement range	Average
Device A (1)	125 - 814 ppb	299 ppb
Device A (2)	125 - 940 ppb	335 ppb
Device B (1)	438 - 1121 CO_2 equiv. ppm	641 CO_2 equiv. ppm
Device B (2)	455 - 1106 CO_2 equiv. ppm	677 CO_2 equiv. ppm
Device C (1)	37 - 95 ppb	66 ppb
Device C (2)	20 - 50 ppb	28 ppb
Device D (1)	0 - 276 ppb	58 ppb
Device D (2)	1 - 332 ppb	73 ppb
Device E (1)	0 - 292 ppb	77 ppb
Device E (2)	0 - 302 ppb	85 ppb

TVOC concentration data, apart from Device B, is presented in the Figure 2. Generally, we observed greater variations within the TVOC concentrations from MOS-sensors, and the highest values were significantly higher compared to PID-sensors. For example, during the afternoon of 18th of April, measured concentrations from Device A sensors were around 900 ppb, while sensors of devices D and E measured concentrations between 200 and 300 ppb. Simultaneously, PID-sensors of Device C measured concentrations between 30 and 50 ppb. The highest values of Devices A, D, and E were measured during the school days when the classroom was occupied, and the TVOC concentrations correlated with the classrooms' CO_2 concentration (data not presented). Concentration variations of Devices A, D, and E resembled each other also when the classroom was unoccupied. Especially, the magnitude of TVOC concentrations was similar for Devices D and E, while the concentration range of Device A was more extensive.

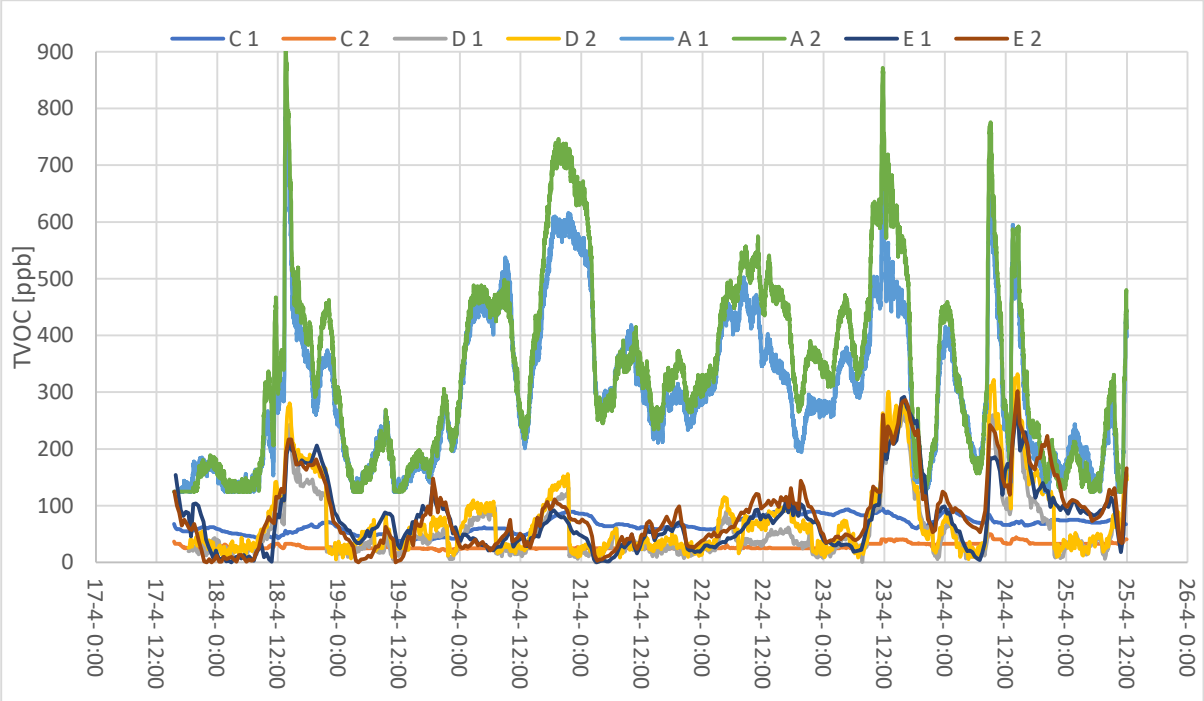

Figure 2. TVOC concentrations from Devices A, C, D, and E during the field experiment.

The variations of TVOC concentrations from the PID-sensors of Device C were smaller compared to the MOS-sensors. Use of the classroom was visible in the TVOC data, but its effect was significantly smaller than in the data from Devices A, D, and E. The results from the sensors of Device B differed from those of the other MOS-sensors. Concentration variations occurred somewhat simultaneously, but the concentration levels increased towards the end of the research period. The results from each pair of sensors from the same manufacturer were similar although slight variations were visible.

TVOC concentrations from the air samples analyzed with TD-GC-MS were substantially smaller compared to concentrations measured with the sensors during the sampling. Analyzed TVOC concentrations in toluene equivalent were 10 µg/m^3 for the empty classroom and 60 µg/m^3 for the occupied classroom. These values equal to approximately 3 ppb and 16 ppb, respectively, when the values are converted based on molar mass of toluene and molar volume of ideal gas. The average TVOC concentrations and ratios between levels in empty and occupied classrooms during the 40-minute sampling are presented in Table 3.

Table 3. Average TVOC concentrations and empty/occupied ratios during the air sampling.

Device	Empty classroom	Occupied classroom	Ratio E/O
Tenax TA air sample	3 ppb	16 ppb	0.17
Device A (1)	127 ppb	266 ppb	0.48
Device A (2)	140 ppb	293 ppb	0.48
Device C (1)	67 ppb	68 ppb	0.99
Device C (2)	33 ppb	40 ppb	0.83
Device D (1)	73 ppb	119 ppb	0.61
Device D (2)	69 ppb	127 ppb	0.54
Device E (1)	32 ppb	104 ppb	0.31
Device E (2)	38 ppb	115 ppb	0.33

Compared to the empty classrooms' TVOC concentration from the air sample, the sensors measured at least ten times higher concentrations, although the concentrations were on the lower

end of the eight-day research period (averages 32 – 140 ppb). For example, concentrations measured with sensors of Device A were close to the detection limit of the sensors. TVOC concentration of the air sample from the occupied classroom was six times higher compared to the empty classroom. One PID-sensor of Device C measured similar concentrations for both empty and occupied classroom, while the concentrations measured with the other sensor increased slightly. Concentrations measured with the MOS-sensors were approximately two to three times higher from the occupied classroom compared to the empty classroom. The results from Device B are excluded because we were not able to convert the values to a comparable unit.

4 DISCUSSION

Apart from Device B, all tested sensors showed the lowest values of their measurement range in the zero-gas experiment. Differences between the sensors occurred in the isobutylene gas experiment. The PID-sensors of Device C gave values close to the true concentration of the test gas. However, isobutylene test gas was used also as a calibration gas for Device C sensors, which probably influenced the results. The MOS-sensors reacted to the isobutylene gas, but they resulted in concentrations far below its true concentration. This may be caused by several factors. Concentration of the test gas (7500 or 8000 ppb) was significantly higher than the measuring ranges of Devices A and B provided by the manufacturers. However, both devices resulted in concentrations clearly below the upper limits of their measuring ranges. Alternatively, measuring range provided by Device D's manufacturer was almost ten times higher than the concentration of the test gas, but its sensors gave somewhat similar values as the other MOS-sensors. Furthermore, the concentration of the isobutylene gas was significantly higher than concentrations normally measured from indoor air. Other factors could be that the sensors had been calibrated with other compounds than isobutylene or that they are optimized to detect other compounds. Therefore, it would be more suitable to test TVOC sensors with a combination of different compounds as it is presented in ISO 16000-29 (2014). However, this was not possible in this study.

During the field experiment, variation occurred in the monitored TVOC data of the classroom, especially between the PID- and MOS-sensors. The MOS-sensors reacted more clearly to the presence of people in the classroom, which was noticed from the correlation between the TVOC and CO_2 data of the devices. Therefore, one reason for the differences between the sensor types can be that the MOS-sensors reacted to CO_2. It is also possible that different sensors detected different compounds, or their calibration was insufficient. Further, the sensors were placed in the classroom within two-meter radius from each other, so it is possible that local air flows caused differences in the measured concentrations. However, the reference air samples analyzed with TD-GC-MS showed that there were significant differences in the TVOC concentrations between the empty and occupied classroom, which emphasizes the effect of human presence. Concentration variation between the empty and occupied classroom was small in the data from PID-sensors during the air sampling, and the concentrations maintained on low level throughout the experiment. Additionally, we noticed more differences in the data between the two similar PID-sensors compared to other pairs of sensors.

Device B displayed the TVOC concentration in CO_2-equivalent ppm, which made it difficult to compare the results with other devices. CO_2-equivalent ppm unit is used in TVOC sensors to control building automation related to demand-controlled ventilation, and it is linked to outdoor CO_2 concentrations (Ulmer and Herberger, 2012). According to the device manufacturer, 500 CO_2-equiv. ppm corresponds approximately TVOC concentration of 73 µg/m^3. However,

without further information we were not able to convert the results into same unit with other devices.

When considering suitability of real-time gas sensors in monitoring indoor air quality, it is important to notice the detection limits of the devices. In the Finnish Degree of the health and health-related conditions of housing and other residential buildings, action limit for indoor TVOC concentration is 400 $\mu g/m^3$ toluene equivalent (Ministry of Social Affairs and Health, 2015), which equals approximately to 105 ppb in 21 ℃. The detection limit for some of the devices is 125 ppb, which causes difficulties to use such devices for indoor air quality monitoring.

5 CONCLUSIONS

We noticed differences in the measured TVOC concentrations between the tested real-time gas sensors in both laboratory and field experiments. The measured concentrations were significantly higher compared to concentrations analyzed from air samples with standardized TD-GC-MS method used as a reference. However, the standardized method considers volatile organic compounds between n-decane and n-hexadecane while the sensors may react to other compounds as well, which complicates straightforward comparison. Additionally, the sensor manufacturers provided only limited information related to calibration, sensitivity, and selectivity of the sensors. Therefore, our results suggest that real-time gas sensor are not suitable for monitoring absolute TVOC concentrations. This finding is in line with review where they conclude that generally current sensor technology in low-cost sensors has limitations to measure lower concentrations expected in indoor air (Szulczynski and Gebicki, 2017). However, real-time sensors can enable long-term monitoring of indoor air quality and detecting transient variations in TVOC concentration, which are not possible with the standard method that gives average concentration of certain time period. Additionally, especially MOS-sensors appear to be suitable to detect human based effluents.

6 ACKNOWLEDGEMENT

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