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Report from the AIVC Webinar: "*Using Metal Oxide Semiconductor (MOS) sensors to measure Volatile Organic Compounds (VOC) for ventilation control*", held on September 4, 2018

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1. Introduction

The application of Metal Oxide Semiconductor (MOS) sensors measuring Volatile Organic Compounds (VOC) gains increasing attention in the ventilation community because of their low price and claimed ability to supplement or even substitute CO_2 sensors for demand controlled ventilation (DCV). Even though there are many "Indoor Environmental Quality" meters available on the market, in which these sensors are used, the amount of scientific studies focused on their reliability and applicability is still limited. Moreover, it seems that, although several ventilation producers offer VOC based control, these solutions are not implemented at large scale in the market.

During the AIVC webinar held on 4 September 2018, participants of IEA EBC Annex 68 presented research results, experiences and thoughts related to MOS VOC sensors. The aim of the webinar was to intensify discussion on the topic of low-cost sensors in the ventilation community.

The focus of the webinar was to introduce research projects focused on providing insight in functionality, behaviour and usability of MOS VOC sensors for ventilation control. This paper summarizes the presentations from the webinar. Section 3 discusses "Can MOS VOC sensors be used for ventilation control?", presented by Nadja L. Lyng, section 4 "MOS VOC sensors' properties and suitability for DCV control" by Jakub Kolarik and section 5 "VOC versus CO_2 controlled DCV: A case study" by Jelle Laverge. The main take-aways and perspectives for MOS VOC sensors in ventilation systems are summarised in the conclusion section.

2. Background

MOS sensors measuring VOC seem to be an obvious step towards broadly available Demand Controlled Ventilation (DCV) [1]. Firstly, MOS VOC sensors offer the possibility to not only account for pollution related to human presence, like currently used CO_2 sensors, but also register diverse odorous events taking place in a space. The fact that these sensors are sensitive to a broad range of chemicals can be advantageous from the point of view of indoor air quality – ventilation is started also in the cases of emission of pollutants that are undetectable by standard CO_2 sensor. Secondly, MOS technology allows producing sensor units that are cheaper and less power demanding than current Non-dispersive infrared (NIDR) CO_2 sensors. This indicates that DCV ventilation could be applied also in projects, where high price of sensors as well as installation costs disqualify traditional DCV.

All above mentioned arguments speak for MOS VOC sensor technology in comparison to the currently used CO_2 based one. However, recent research shows that simple replacement of CO_2 sensors with VOC sensors is not enough to achieve the desired effect [2, 3, 4]. A ventilation control strategy needs to be tuned specifically for use of VOC sensors so that their potential can be utilized. In addition, recent studies on use of MOS VOC sensors for ventilation control [3, 4, 5, 6] focused mostly on potential energy savings, but the fact whether their application influences indoor air quality with respect to concentration of particular pollutants was not investigated. The broad sensitivity of the MOS sensors, mentioned earlier as an advantage, turns out to be a disadvantage when issues like measurement accuracy and calibration are taken into account. Broad sensitivity is also a disadvantage if the sensors react to short-term "non-problematic" VOCs emissions like ethanol, perfume or limonene from oranges.

If MOS VOC sensors should be widely applied in practice, as not only air quality indicators in cheap "home IEQ data loggers", but for control of ventilation, more rich and detailed information about their performance is needed.

3. Can MOS VOC sensors be used for ventilation control?

As mentioned in the introduction, the MOS VOC sensors seem to present an inexpensive method to measure real time changes in concentration of the total amount for VOCs (this aggregated measure is usually called Total Volatile Organic Compounds - TVOC). The research project conducted in collaboration between Technical University of Denmark, Danish Technological Institute and Aarhus University had the objective to study the response of commercially available MOS VOC sensors to pollutants emitted during activities typical for residences.

The experiments were conducted at a full-scale test room. Investigated activities included painting, cleaning, candle burning, emission of human bioeffluents, changes of relative air humidity, emission from linoleum flooring and dosing of ethanol into the test room.

Five commercially available sensors were tested (abbreviated as A, B, C, D and E). Four of them were equipped with an embedded algorithm for so-called auto-calibration. The functionality of the algorithms was unknown to the researches, however a general functionality of auto-calibration is to utilize the lowest measured concentration over a longer period as a "clean air" baseline. A very precise analytical instrument - the Reaction-Time of Flight-Mass Spectrometer (PTR-ToF-MS) was used as a reference measurement. This measurement was used to determine total concentration of VOC in the test room, so called $TVOC_{PTR\text{-}TOF\text{-}MS}$.

All pollution activities resulted in changes in the air quality that were detected by the MOS VOC sensors as well as the PTR-ToF-MS. Figure 1 shows an example of results for emission of human bioeffluents and changes in relative air humidity. The grey areas indicate the duration of the pollution activity. The top three graphs show the signal of the MOS VOC sensors and the bottom graph shows the $TVOC_{PTR\text{-}TOF\text{-}MS}$ concentration. The top graph shows sensors A and B (two specimen of each type). The yellow and green coloured data shows sensor A. The measuring signal is incomplete for sensor B1 because the sensor was by mistake set to the low measuring range with upper border of 600 ppm. The second top graph shows sensor type C, of which five specimens were tested. The second bottom graph show result from sensor type D of which two specimens were tested.

During emission of human bioeffluents, data for all MOS VOC sensors clearly show similar concentration patterns, but there are clear differences in absolute concentrations. This difference was observed among the sensor types, but also among specimen belonging to each sensor type. The data obtained during tests with alternated relative humidity levels show that relative humidity levels in the test room clearly had an influence on measured signals.

The experiments showed that tested MOS VOC sensors were able to detect changes in VOC concentration during different pollution activities, but the measured signals differed in absolute values as well as in the amplitude of signal change. As documentation provided by manufacturers and suppliers was very limited regarding calibration and accuracy of the sensors, further testing would be necessary to characterize performance of particular sensors. The results indicate that in order to use MOS VOC sensors for controlling ventilation, there is a need for further post processing of the sensor signals. And since the effect of temperature or long time use was not tested during the present test, it should be tested in future if or how temperature affect the sensor signals and the reliability of the sensors being in use over longer periods. To answer the question "Can TVOC sensors be used for ventilation control?" in short it is important to highlight that MOS VOC sensors cannot directly replace CO_2 sensors in existing ventilation systems. This conclusion is supported by other research studies, for example Moreno-Rangel et al. [7]. Their application needs to be accompanied with additional signal processing, which needs to be specifically tuned for a particular type of sensor and application.

4. MOS VOC sensors' properties and suitability for DCV control

The second presentation at the webinar aimed to illustrate the nature of the MOS VOC signal and suggest how to determine sensor properties like sensitivity or linearity. The presented analysis was based on the data collected during the experiments described in Section 3P a g e | **3** of this paper. Data from the air polluting activity "Cleaning" will be used as an example.

Due to the operating principle of the MOS technology, the MOS VOC sensors provide a relative signal – a relative change of VOC concentration. Because of that, it is difficult to compare absolute values of concentrations measured by several sensors, even from the same producer. To deal with this problem, sensor signal data can be normalized, for example using mean concentration calculated using data for 3 hours before initiation of the polluting activity, or so called min-max normalization known from the field of data mining.

Figure 2 shows the difference between absolute and normalized concentrations for the cleaning activity. The figure shows data for two specimens of two of the tested MOS VOC sensor types. The sensors produce signals of a similar pattern, but it can be clearly seen that absolute concentrations (Figure 2Figure 1- top) differ even between sensors of the same type (producer). When sensor signals were normalized by the background concentration obtained in the empty test room before the cleaning activity (Figure 2-bottom), the sensors produced signals that were comparable not only with respect to the pattern, but also the magnitude of the concentration change.

Several producers try to address the problem of the relative nature of the measurements using so called auto-calibration algorithms embedded in the sensors' print boards. Auto-calibration algorithms are obviously proprietary, and producers do not disclose their exact functionality on the product data sheets. In general, the auto-calibration is supposed to ensure a "measurement baseline" determined using lowest measured concentration over certain (sufficiently long) period. Such approach assumes firstly, that sensor is activated in "clean air" conditions, secondly, that periods with "clean air" are ensured from time to time during the operational lifetime. Violation of the latter assumptions may lead to establishing of a wrong baseline, which does not represent "clean air". Consequently, harmful VOCs, such as formaldehyde, which are continuously emitted from some building materials, will not be accounted for. As the sensor itself cannot determine whether baseline conditions truly represent "clean air", this would need to be ensured by the operator of the ventilation system.

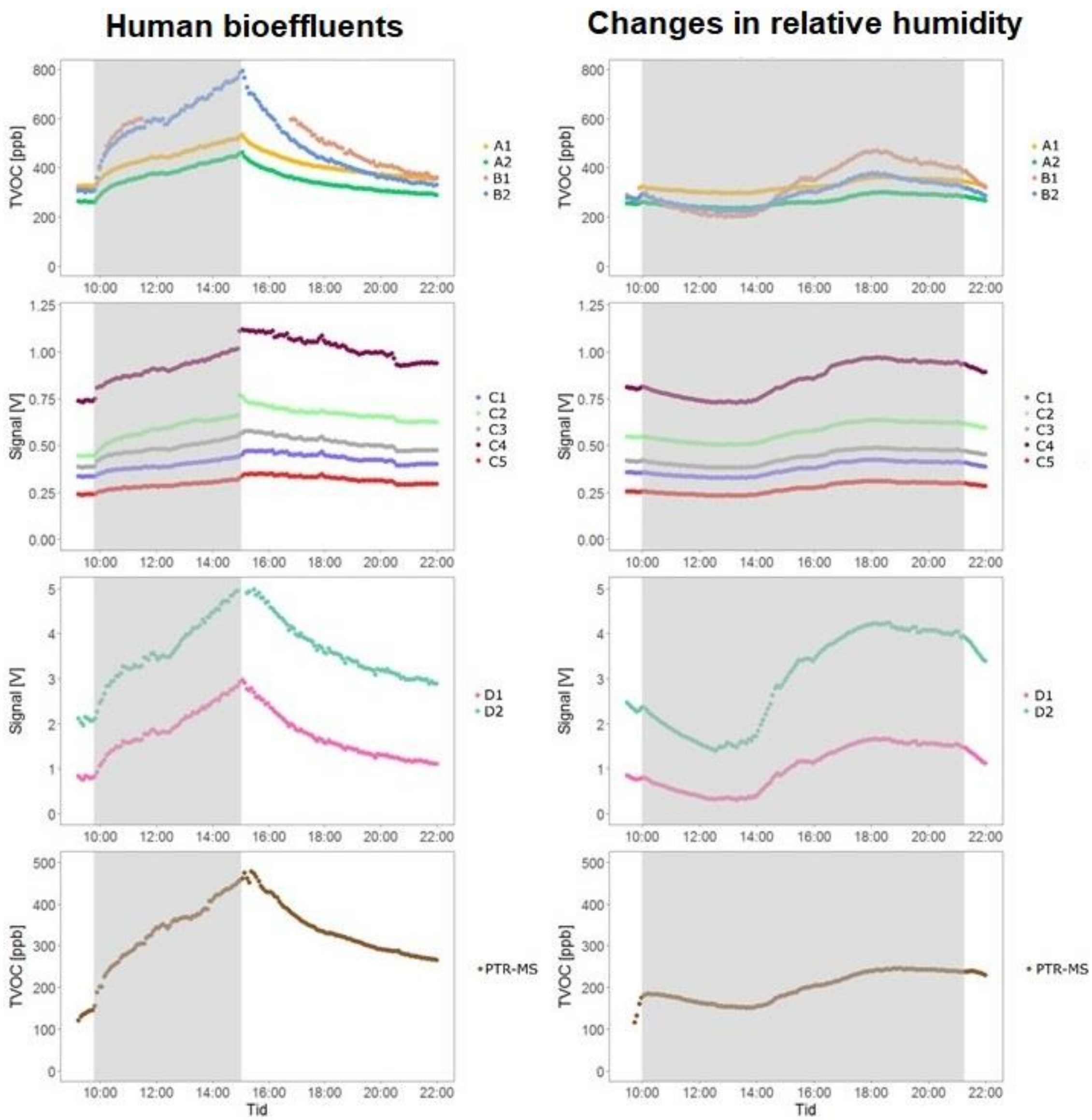

Figure 1: VOC-sensor response to activities with people as pollution source and changes of the relative humidity; the graph in the bottom is the sum of all measured compounds by PTR-ToF-MS and can be used as a reference

Knowledge of the sensor properties can help with identification of a suitable sensor for a practical application. Figure 3 shows a comparison of sensitivity for MOS VOC sensors A and B when exposed to pollution activities cleaning, emission of bioeffluents and emission from linoleum. The sensitivity represents a magnitude of change of MOS VOC signal related to a change in a reference signal. It was determined using work by Fahlen et al. [9]. It can be seen from the figure that the sensitivity differed among the pollution activities. It was highest during the cleaning activity. Moreover, sensor B was in general more sensitive than sensor A. The differences in sensor sensitivity under different pollution activities can most probably be explained by the fact that different compounds were emitted during the activities and therefore characterize the emissions. MOS VOC sensors' active layers reacted differently to those chemicals. It is not a goal of the present paper to analyse the undergoing mechanisms, but the results seem to support practical observations that MOS VOC sensors react strongly to pollution generated by detergents, paints or human presence, while reaction to background pollution from building materials is rather moderate.

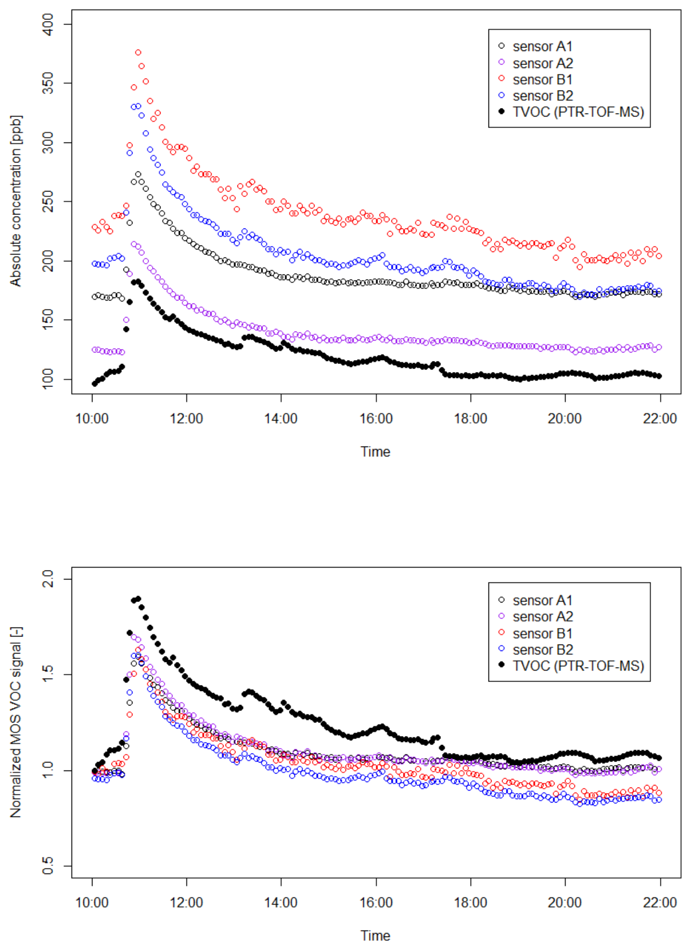

Figure 2: (top) Comparison of TVOC (PTR-TOF-MS) signal and absolute signal from two types of MOS VOC sensors (A and B) during cleaning activity, (bottom) normalized signal from two types of MOS VOC sensors; data from two specimens per MOS VOC sensor type are shown

In practice, the sensitivity of the sensor can help in the selection for an appropriate sensor with respect to its application. For example, if the sensor is supposed to account both for human occupancy and short term pollution events like cleaning, sensor B seems to be more suitable, because its sensitivity to human generated pollution is comparable to the sensitivity to pollution from cleaning.

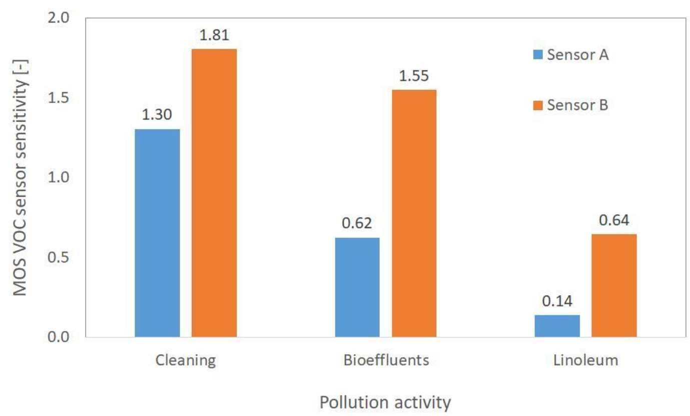

Figure 3: Sensitivity of MOS VOC sensors A and B during cleaning, emission of bioeffluents and emission from linoleum

However, these data do not give any advice regarding ventilation control. More precisely, due to the need for normalisation, it is very hard to establish limit concentration values corresponding to minimum and maximum airflow provided by ventilation system. The need for auto-calibration makes these sensors mainly useful for event detection. An option to determine limit concentrations for practical event based controls is using exposure to a pollution activity, during which the ventilation system must provide maximum available airflow. One example could be painting, but in office environment different cleaning activities would represent more suitable events.

5. VOC versus CO_2 controlled DCV: A case study

As discussed above, DCV possesses the ability to control ventilation rates by using concentration levels of pollutants in occupied space. Most commercially available systems use CO_2 as an IAQ control signal based on established correlations between the perceived air quality and CO_2 concentration [10]. There are, however, important drawbacks with CO_2 sensors from an engineering point of view: the most common types, based on Non-dispersive Infrared (NDIR) technology, are still rather expensive and, energy intensive due to the necessity to heat them for good operation, . MOS VOC sensors are a much more energy efficient and cost effective alternative, but, as clearly demonstrated above, their signal value is non-compound specific and they are not able to measure real CO_2. The appear to be mostly suited to detect additional ventilation events.

In the case study introduced in the third presentation of the webinar, the effect of using the auto-calibrated MOS VOC sensor signals in in the field was studied by controlling real DCV systems by either the real CO_2 concentration or a CO_2 equivalent VOC concentration.

For the test, 32 newly built or renovated dwellings in a social housing complex near the Kortrijk city center in Belgium, with recently installed mechanical exhaust ventilation systems with demand controlled dampers in each of the individual exhaust ducts were selected. CO_2 and MOS VOC sensors were installed side by side on the extraction dampers of the kitchens and (in some dwellings) bedrooms. These were designed to be controlled by either of these sensors in a flexible demand controlled ventilation approach.

The MOS VOC sensors provided sensors that can output so-called CO_2 equivalent concentration [7, 10]. Thus, the amount of emitted VOC was correlated to human emission of CO_2. The system started with CO_2 based control, but switched to MOS VOC based control after two weeks of operation.

The sensor signals, as well as the damper positions were logged with the internal of 90 s. In the end, 12 weeks of data was gathered from 29 of the selected dwellings (dampers for 28 kitchens and 18 bedrooms).

Figure 4 shows the CO_2 and CO_2-equivalent MOS VOC concentrations over the course of 2 weeks of measuring. In the first week, the flow rate was controlled by adjusting the damper position based on the CO_2 concentration, with a set point of 900 ppm. As can be seen in the figure, the set point is barely reached and the damper remains closed (bottom grey line in the graph) except one time. During the second week, the flow rate was controlled by VOC concentration. The concentration was more variable and affected by higher peaks. The damper was opened much more frequently when occupants were present due to high concentrations, but the system was not able to keep the CO_2-equivalent MOS VOC concentration below or around the set point.

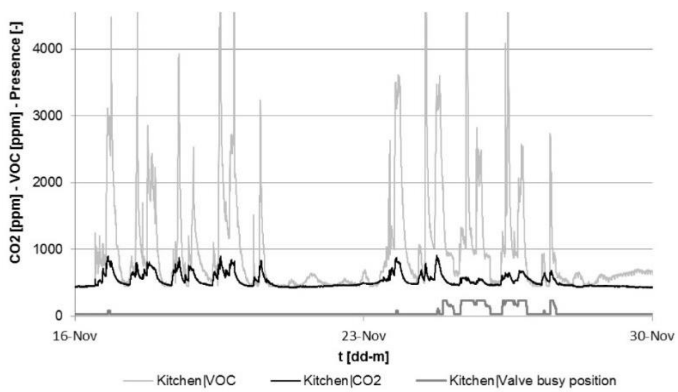

Figure 4: CO2, MOS VOC and damper position over 2 weeks

When the CO_2 and VOC concentrations are compared (note that they were measured at the same point in the damper), the general pattern is rather similar, but the MOS VOC concentration has, as was mentioned above, a much higher variability, and is affected by the higher VOC peaks. This is consistent with the claim of the manufacturers of the sensor that it is calibrated to represent metabolic CO_2, but also reacts to other sources. As was shown in the experiments presented above, the sensor may be much more sensitive to these events, explaining the peaks observed.

The mentioned divergence between CO_2 and MOS VOC concentrations is clearly visible through the differences in daily concentration patterns. Figure 5 shows a plot with all concentrations measured during a time scale of 24 hours. The largest differences among these patterns can be characterized as:

(1) generally higher MOS VOC concentrations compared to CO_2;
(2) strong variability of the MOS VOC concentration, with high peaks during day time (more ‘events’);
(3) steep build-ups and decays of the MOS VOC concentration

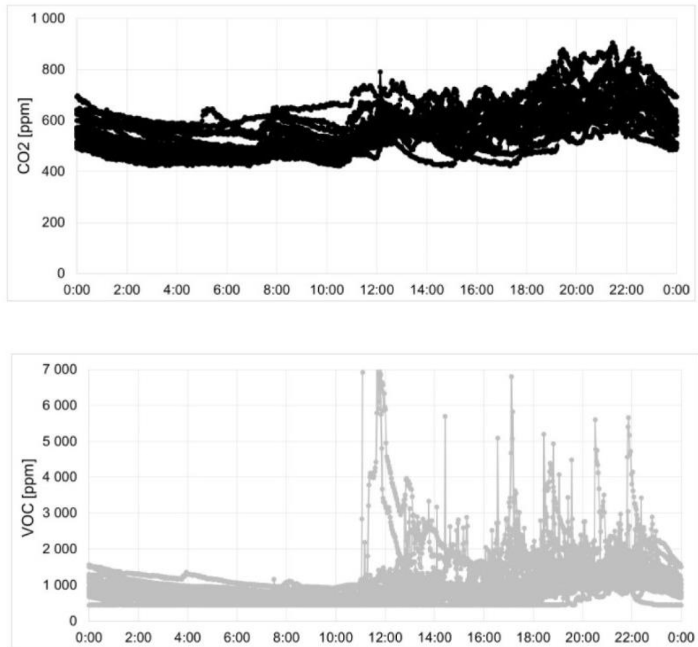

Figure 5: CO_2 (top) and VOC (CO_2 equivalent) (bottom) concentration day profiles in kitchens during the measurement campaigns

Based on the results from this case study, it is concluded that, when considering MOS VOC sensor based concentration as a control signal for DCV, HVAC designers need to take into account that the total ventilation rate will likely be significantly higher compared to CO_2 based DCV control, with more frequent and steeper changes in flow rates. This will likely result in better IAQ since more pollution events can be detected. However, the design flow rate for the system can still be a limiting factor. In addition, as the MOS VOC sensors are non-selective, their use in the control can potentially trigger unnecessary ventilation, especially if the signal is used for both bioeffluents and other events. The consequences for energy performance, and especially user acceptability of such a system, e.g. due to higher perceived noise levels, need to be studied further.

6. Conclusions

MOS VOC sensors are inexpensive, consuming low power and very often internet connected. They can be deployed in large amounts. Their data can be easily accessible using different mobile platforms. However, their ability to indicate indoor air quality and their applicability for control of ventilation systems is associated with many pitfalls and challenges, which are often unclearly articulated.

The experiments demonstrate that suitability of a specific sensor for a specific purpose should be carefully evaluated in practice. In general, MOS VOC sensors seem to be capable of indicating increased emissions of VOC in indoor spaces. However, due to the relative nature of their signal, their integration into ventilation control remains challenging.

The results show that MOS sensors are useful to detect VOC intensive events such as high occupancy, cleaning, painting, or toilet use. In practice, it is important to ensure sensor start-up in clean air and provide regular thorough ventilation to ensure that the sensor's baseline represents clean air compared to the events that it is used to target. MOS VOC sensors can be successfully used to trigger the ventilation in such events, but are not reliable enough for continuous monitoring for typically nearly constant pollution sources such as emissions from building materials.

7. Acknowledgments

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