Breathe Easy - Volatile Organic Compounds

Introduction

In recent years, in line with an explosion in Internet of Things (IoT) devices, the Architecture, Engineering and Construction (AEC) industry has seen an explosion in largely consumer-targeted internal environmental monitoring devices – particularly in health-conscious commercial office environments. Building users from all walks of life have found themselves empowered with new ways of quantifying and understanding their environment. These devices often come equipped with a multitude of sensors, covering temperature, humidity, CO_2, noise, light, specific or total volatile organic compounds, ozone, oxides of nitrogen, and many others. Due to their low-cost, they can provide valuable real-time, spatial feedback to help improve health and wellbeing, influence user behaviour, and identify problems with building systems.

Despite these opportunities, many of the devices are not without their problems. Originating as a consumer driven trend, the quality of devices being installed, and the data generated by them, is highly variable. Their performance can be obscured by clever marketing, reviews and endorsements by non-scientific 'tech' publications, and an opaque approach to product specifications. As a result, the data being gathered and reported can be easily misinterpreted, which could lead to false conclusions and unintended consequences.

The CIBSE Air Quality Task Group has reviewed the existing scientific literature on the most common air quality sensors found inside these devices and have prepared a number of short technical notes. The notes are based on a rigorous approach and should provide some clarity on the types of technologies used by these sensors, what they are capable of, and what they are not.

It is worth noting that the market for IAQ sensors is changing rapidly, both in terms of new products being introduced, and existing products being modified, for example by changing the component sensors or data processing algorithms. (B.C. Singer, 2018) As such, the guidance in this article is relatively generic, with the intention of raising industry awareness of the benefits and limitations of using these devices. We would also point out that while the products themselves may evolve, the criteria on which they should be selected will remain largely the same.

We intend to publish this information alongside a description of the target pollutants, to give a thorough understanding of the reasons why you would want to monitor them in the first place, and what that monitoring might tell you.

The pollutants we'll be covering first are probably the widest ranging, and most complex – Volatile Organic Compounds.

VOCs

Volatile organic compounds (VOCs) and semi volatile organic compounds (SVOCs) are gases or aerosols that may be emitted from many indoor sources, as well as originate from outdoor air brought indoors.

The definition of a VOC is an organic chemical compound whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure. In simple terms, this means particles that could become gases at indoor temperatures. These particles are emitted both from indoor products and during some activities as per Figure 1.

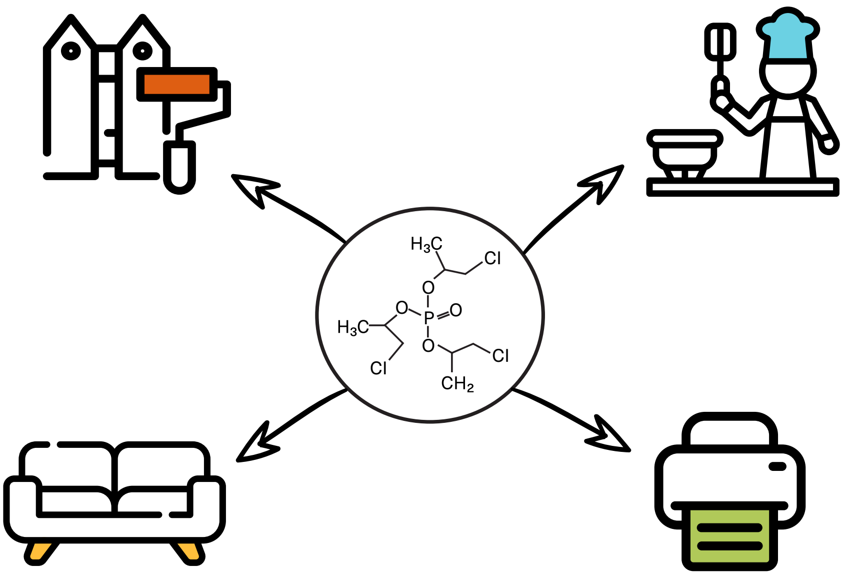

Figure 1. Example for sources of VOCs (building materials, human activities, furniture and equipment)

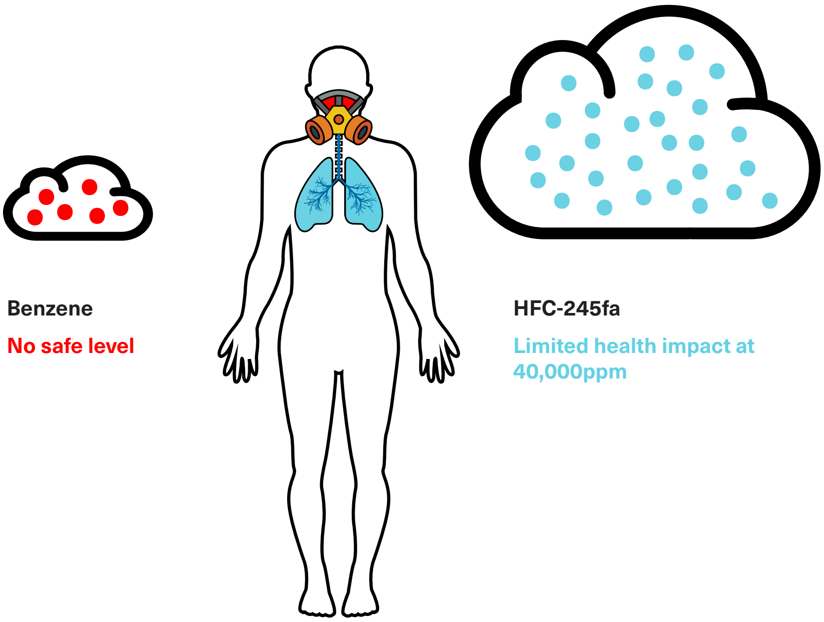

Figure 2. Every VOC has a unique impact, and implications on human health

Although the health impacts of many individual VOCs are known, the combination of numerous compounds in the indoor environment make it very difficult to calculate any health impacts for the individual occupant.

The term VOC is not related to health. Just because a chemical is classified as a VOC does not mean it will, or will not, impact human health. Each individual chemical has its own toxicity and potential for causing health effects. Common symptoms of short-term exposure to high levels of VOCs include irritation to the eyes, nose and throat, headaches, nausea/vomiting, dizziness and exacerbation of asthma symptoms.

Chronic (long-term) exposure to high levels could carry carcinogenic risks, could affect the reproductive systems, damage to various organs (kidneys, lungs, liver) or central nervous system. Most health-related studies usually only consist of a single chemical and its individual implications.

There are hundreds, and even thousands, of VOCs in the indoor environment at any given time and many interact with each other, and with other types of pollutants. This is why it is very difficult to prove that a specific VOC, in an office or at home, is responsible for us sneezing, having headaches or experiencing long term health impacts. As a result of this complexity, there is currently no comprehensive evidence on the cumulative impact of combinations of VOCs and their implications on health, which are a subject for further research. Scientists have taken a precautionary approach with regards to chemicals and there is consensus amongst academics, health professionals, and practitioners that source control is the best strategy to eliminate VOCs.

Once they are in the indoor environment, it is often difficult to measure them, find their source, and remove them. There are many existing guidelines on individual VOCs, such as the PHE guidelines, and if the presence of VOCs is suspected, an air quality specialist should be engaged to conduct a detailed test to determine the risk to occupants.

Many of the lower-cost sensors appearing in buildings report on Total VOC (TVOC) concentrations. One of the reasons for the common use of TVOCs as a metric is that the interpretation of one single parameter is simpler and faster than the interpretation of the concentrations of several dozens of VOCs typically detected indoors (European Commission JRC, 1997). However, TVOC measurements may at best only be used to establish a baseline against which excursions may be identified. (ASHRAE, 2013).

Sensor terminology

Before diving into the specific capabilities of different sensor types, it is worth ensuring clarity over the general terms which cover all types of sensors.

Accuracy is defined as the amount of uncertainty in a measurement with respect to an absolute standard. For example, if a sensor is placed in a sealed chamber with a known concentration of 100ppm, and the sensor returns a reading of 105ppm, that sensor is accurate to 5ppm. Note that the accuracy is often given as a percentage of the measured reading.

Precision describes the reproducibility of a measurement. For example, if we measure the concentration in the chamber above over a number of minutes it will likely return a number of slightly different readings. If the values are close together then it has a high degree of precision. **Note that a sensor can be both precise and inaccurate if it reproduces values close to each other, but far from the absolute standard.**

Sensitivity is an absolute quantity, the smallest absolute amount of change that can be detected by a measurement device.

Resolution is the smallest unit of measurement that can be indicated by an instrument.

Selectivity is the ability of the sensor to discriminate a response from adjacent inputs. For example, if a gas sensor is designed to detect methane then how does it respond to methane in the presence of other gases.

Cross-Sensitivity is the sensitivity of the sensor to other gases, usually of a similar type.

Calibration and drift

All sensors require regular calibration. The frequency of this calibration, known as the calibration interval (CI) is usually specified by the manufacturer.

The calibration process involves the comparison of the measurement values of a device against those of a calibration standard of known value. This could be another device that is known to be accurate, or against something that delivers a known quantity e.g. a test chamber containing a known quantity of gas.

After calibration, devices can be adjusted to provide a more accurate output.

Drift is the deviation from a known calibrated value over time. This varies from sensor to sensor, and can be combated by regular calibration.

An increasing number of devices incorporate “self-calibration” or “auto-calibration” using software techniques. This often involves using expected or recent minimum values to re-adjust a notional baseline. Sensors utilising these techniques should be used with caution, as they can often mask inaccurate performance (such as drift) in favour of providing a better user experience. Recording the raw value returned by the device’s hardware alongside the software adjust value is recommended to detect any software induced errors.

Note that the latest edition of CIBSE TM40 lists existing standards available for high-quality testing and calibration through companies such as BSRIA.

VOC Sensor Technologies

The majority of VOC sensors are based on one of the following technologies, in approximate order of ascending cost and accuracy:

- Metal oxide (MOx) sensors
- Electrochemical sensors
- Photo-ionization detectors (PID)
- Electronic noses and sensor-arrays
- Optical sensor spectrometers
- Portable or micro-gas chromatograph (µGC)

In general, the most common types found in low-cost (<£500) consumer-type devices are of the MOx and electrochemical type, with more expensive hand-held devices using PID or sensor arrays to improve accuracy.

Quantification is a challenge for low-cost sensors as they often display strong cross-sensitivity to environmental factors, such as temperature and humidity, and also to confounding gases. (Lewis, 2016). There are currently limited studies correlating, or comparing, VOC concentration using analytical chemistry tools (TD-GC-MS) with VOC data from sensors.

Metal-Oxide (MOx) sensors

Semiconductor metal oxide sensors consist of one or more oxides from the transition metals. The sensing properties are based on the reaction between the semiconductor metal oxide and oxidising or reducing gases in the atmosphere which lead to changes in conductivity. This change in conductivity is measured over a pair of electrodes embedded into the metal oxide. A heating element is used to regulate the sensor temperature. The sensors have to be heated to 200 to 400°C to increase sensitivity and decrease response time (AQMD.gov). If choosing a device which includes this type of sensor, be aware that the heat they generate is significant and can influence other sensors around it leading to inaccuracy, particularly in temperature and humidity.

Electrochemical (Amperometric or Potentiometric) sensors

Electrochemical gas sensors are one of the oldest known technologies and widely used for gas concentration measurements. The electrochemical reaction is due to the transfer of a charge from the electrode to the electrolyte. This electrolyte can be a solid, gel-like, liquid or gaseous electrolyte.

An amperometric sensor is made of a measuring and a counter electrode together with an additional reference electrode. The gaseous species to be measured diffuses through the sensor's membranes and to the measuring electrode. A direct electron transfer takes place which produce an internal current which gives a measured electric current proportional to the gas concentrations. (Spinelle, Gerboles, Kok, Persijn, & Sauerwald, 2017)

Most amperometric sensors need humidity to function properly. The usual measuring range for VOCs for this type of sensor is between 100 ppb and 20 ppm.

PID sensors

Photo-ionization detectors (PIDs) tend to be more expensive than MOx or Electrochemical sensors. They use high-energy photons, typically in the ultraviolet (UV) range. The use of UV light to excite the molecules results in the ionization of gas molecules. The resulting ions produce an electric current proportional to the signal output of the detector. The greater the number of molecules present in the air, the greater the number of ions produced, resulting in a higher current. Finally, the ions recombine after the detector to reform their original molecules. Intrinsically, PIDs sensors are not selective (meaning they can't tell the difference between similar gases) as they ionize everything with an ionization energy less than or equal to the lamp output. (Spinelle, Gerboles, Kok, Persijn, & Sauerwald)

Limitations

In order to better understand the limitations of the sensors often found within IAQ monitoring devices, it is useful to understand some examples of the thresholds, set by organisations such as the WHO.

Figure 3 shows a comparison of a wide range of actual sensors used in the detection of VOCs in monitoring devices.

Pollutants	WHO Indoor Air Quality Guidelines (2010)[1]	The Air Quality Standards Regulations 201077	Limit – ppm (approx.)
Benzene (μg/m^3)	No safe level	5 (1 yr)	0.002
Formaldehyde (μg/m^3)	100 (30 min)		0.076
Naphthalene (μg/m^3)	10 (1yr)		0.002

1 WHO Indoor Air Quality Guidelines, 2010 online at the WHO website

By comparing the sensor manufacturer's stated detection ranges and the target concentrations for health outcomes, it quickly becomes clear that the majority of both MOx and Amperometric sensors are unlikely to be suitable for monitoring at the ranges required for human health. The detection range of the vast majority of MOx sensors starts in the ppm range, 3 orders of magnitude higher than the recommended limit for human health for both Naphthalene and Benzene.

Amperometric sensors are slightly more sensitive and some may able to detect breaches of the recommended Formaldehyde limit, though the majority are still too insensitive to measure many Benzene, for example.

PID sensors are available in the measurement range required, but are significantly more expensive, with Portable PID based devices starting at £1000 for a basic monitor. They have the drawback, however, of not being selective enough.

It is important, therefore, that when selecting a sensor or device, the specifier reviews the expected level at which the pollutant will be present, to be sure that the sensor is capable of detecting with accuracy in the range of interest.

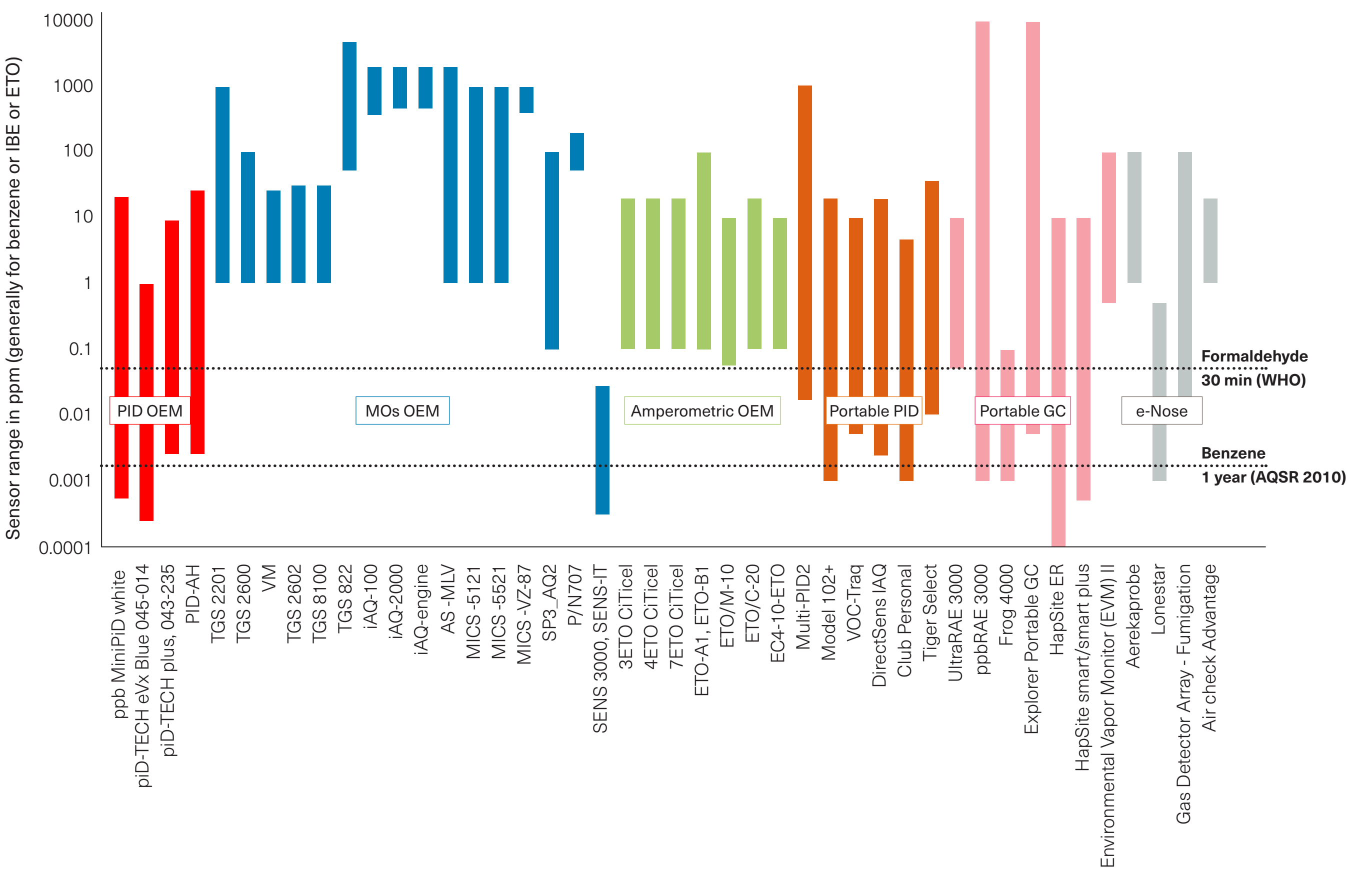

Figure 3 OEM VOC Sensor Ranges (Spinelle, Gerboles, Kok, Persijn, & Sauerwald)

A further drawback of these devices is the lack of sensitivity, often combined with a lack of selectivity. Figure 4 highlights this issue. The graph shows how the sensor's resistance changes as a result of exposure to different gases. Not only does the reliable detection range of the sensor stop at 1ppm, the sensor is unable to differentiate between the gases to which it is exposed, and therefore neither is the user. One of the gases shown on the graph must be chosen to calibrate the device, but clearly the sensor will react to any of the other gases, giving an unclear picture of what gases are actually present, and in what concentration.

To deal with this issue, manufacturers of monitoring devices often define this bundle of mixed VOCs as Total Volatile Organic Compounds (TVOCs). In reality, a more accurate description would be "Toluene equivalent", or "ethanol equivalent" as the total number is a function of the gas to which the device has been calibrated.

Finally, accurate measurements rely on correct procedures, not only the equipment itself. Readings from consumer devices can be inaccurate because of how they are used. For example, the location of sensors should be representative of the environment and occupants within that environment. Typically that will mean deploying the sensors in the 'breathing zone' and not adjacent to a known pollutant source. If in doubt about how to use a device effectively, consult an air quality specialist.

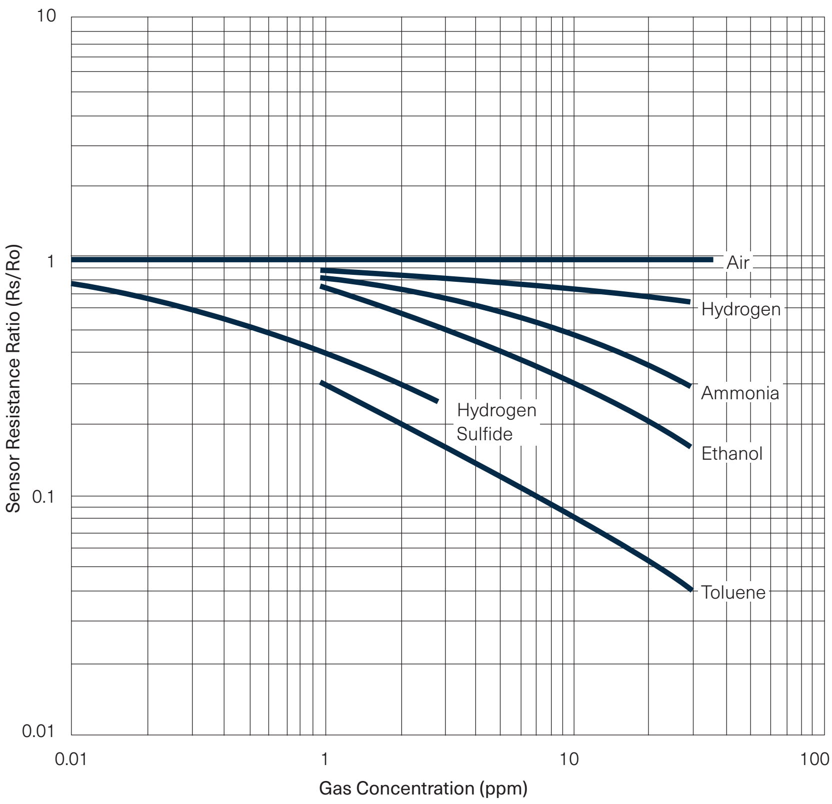

Figure 4 Typical MOx Sensor cross-sensitivity chart (Figaro)

Use-cases

Despite the drawbacks in the technologies highlighted above and the crude nature of TVOC as a metric, low cost VOCs sensors do have some utility – largely for detecting departures from a 'normal' state and raising awareness of end users about environmental quality. As a result of the relatively low-cost of many of the devices, there is potential for high spatial and temporal resolution which may help provide some useful information from even relatively poor sensors, particularly if they are used alongside a smaller number of more accurate sensors, used for regular calibration and checking.

As an indicator of insufficient or poorly designed ventilation

Typically, VOC concentrations correlate with occupancy, as people tend to bring a cocktail of perfumes, bio-effluents and other chemicals into buildings. A calibrated VOC sensor can highlight VOC concentrations over a certain threshold, and as a result can help to identify zones within a building which either suffer from insufficient fresh air - due to not being able to maintain low VOC concentrations when areas are highly occupied - or the presence of a relatively high-emission internal source, which would be visible as a constant high level regardless of occupancy. Both could then be investigated further.

As an indicator of high-emitting activities

If the monitoring device takes readings often enough, it is likely that spikes in VOCs concentrations (e.g. as a result of cleaning processes, or the introduction of any high emitting source into a space), will be highlighted as departures from the normal pattern of exposure. Again, this would likely warrant further investigation to determine the source, and the health impact on the building users.

Conclusion

There are a variety of pitfalls to avoid when measuring VOCs with low-cost devices. The first of which is the limits of the technologies – care should be taken to cross check sensor ranges, sensitivity and resolution against the type of sensor to ensure manufacturers are not claiming capabilities which they cannot deliver.

When undertaking monitoring, be aware of the flaws in the metrics themselves – sensors which measure a specific VOC are often cross-sensitive to other similar compounds and so may under or over-report problems. Similarly, TVOC sensors which detect a variety of compounds and try to aggregate them into a simple metric may obfuscate real problems or cause undue alarm.

Overall, the message is to treat the measurement of VOCs with care – particularly with low-cost sensors. In sufficient number, and with a high enough number of readings, or when co-located with more accurate equipment to enable re-calibration, they can provide useful pointers to improve building performance and wellbeing, but in most cases further investigation will be warranted. One thing is certain - they should never be used as a guarantee of a healthy environment.

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