Mobile Robots with Novel Environmental Sensors for Inspection of Disaster Sites with Low Visibility

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Characterisation of response of high-bandwidth chemical sensors to pulses and plumes of gas in a wind tunnel

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1. Introduction and purpose of this report

Gas sensors are often tested and refined in laboratory environments. In these controlled environments, sensors can be optimized to respond to a step change in a gas concentration. For the application of mobile robot sensing, the conditions are not constrained in this way, and the sensors are likely to be exposed to varying concentrations of gases with an unknown time series. Work package 2 (WP2) of the Smokebot project involves the development of sensors for a mobile robot, capable of operating outside of a laboratory environment.

Task 2.2 addresses the validation of the high-bandwidth (HBW) sensors for exposure to pulses of gases in a more realistic environment. The sensors were tested in a wind tunnel, which enabled the effects of pulse broadening and open-air mixing to be investigated.

Pulses of volatile organic compounds (VOCs) were injected into one end of a small wind tunnel and the response from the sensors, placed at the other end of the tunnel, was observed. When compared to a step gas concentration change (created for example on a bench-top gas rig) a broader response peak would be expected from the gas sensors for an injection of a given period. The broader pulses are created as the VOC injected into the tunnel becomes distributed with the other gas (air was drawn in using a fan) inside the tunnel.

In a mobile application, the gas sensing unit should not be directional when trying to detect the presence of gases. For localizing purposes, it is useful to be able to indicate the orientation of the source, but the sensor must be sufficiently sensitive to warn of plumes of gases approaching from any direction. In the wind tunnel, the sensor module was rotated as to simulate the robot rotating away from the direction of the VOC source.

Previously, three deliverables have been submitted related to this work.

- Deliverable 2.1 – The technical specification for the HBW chemical sensors.
- Deliverable 2.2 – Characterization of the HBW sensors.
- Deliverable 2.4 – Fabricated sensor and interface circuitry for the HBW sensors.

The work reported in this deliverable continues the characterization of the gas sensors reported in deliverable D2.2. The successful characterization of two metal oxide (MOX) sensors is demonstrated. The HBW sensors have been tested to various VOCs such as acetone inside a wind tunnel; their performance has been assessed in a range of scenarios.

2. Wind Tunnel Design and Development

A custom wind tunnel was designed to aid development the sensor module for the Smokebot Project. To comply with safe gas testing procedures, the wind tunnel must be placed inside a fume cupboard during operation. This is to ensure any VOCs injected into the tunnel are passed through the tunnel and then extracted. A drawing of the tunnel is shown in Fig. 1. The exhaust from the tunnel was left open-ended, which allowed quick extraction into the fume cupboard, and furthermore did not create turbulent flows near the sensor module location.

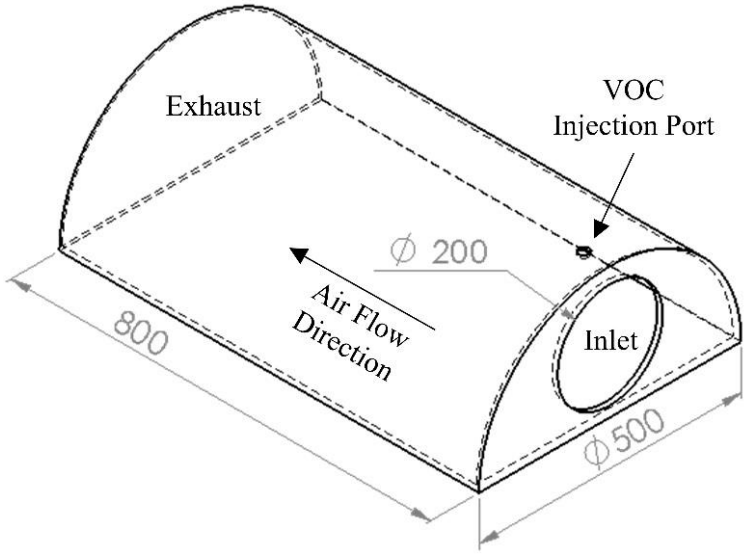


Fig. 1 – Drawing of wind tunnel, showing inlet hole where the fan is positioned and hole in top of tunnel to inject VOCs. Tunnel far side is left open.

The dimensions were selected to be able to house the gas sensor module without blocking the flow of air out of the exit of the tunnel. The size of the tunnel is smaller than the dimensions of wind tunnels reported for mobile robots in the literature [1,2]. In the case of this work, the wind tunnel most be confined to dimensions for testing inside a fume cupboard, whereas previous reports have used room sized wind tunnels.

A 0.5 m diameter tube formed the outer housing of the tunnel. The tunnel has a flat base so the sensor module can be placed inside and rotated as desired. In order to ensure pulses of gas were generated, the length of the tunnel was chosen as 0.8 m. A hole in the top of the tunnel allowed VOCs to be injected. A fan (Sanyo Denki 109E2024MH001) was installed at the end of the tunnel, to blow air (and the VOC) from the inlet of the tunnel towards the sensor unit. The total dead space or volume of the chamber was calculated as 0.08 m^3 (78.5 L).

Flow simulations were performed to verify the airflow through the tunnel. Solidworks (2016) was used to simulate the airflow generated by the fan and the injected VOC into the system. It was noted the software was limited in generating accurate flow simulations, however, for comparison purposes the software produced acceptable results. The flow is injected from the top, Fig. 2 a), and then propagates through the chamber. Fig. 2 b) shows the flow trajectories from a side view, with an injection of a VOC from the top of the chamber. A transient simulation, Fig. 2 c), shows the operation

of the wind tunnel, prior to any VOC being injected. The simulation indicated that the gas sensor module should be located in the centre of the tunnel, because less circulation occurs in the corners of the tunnel.

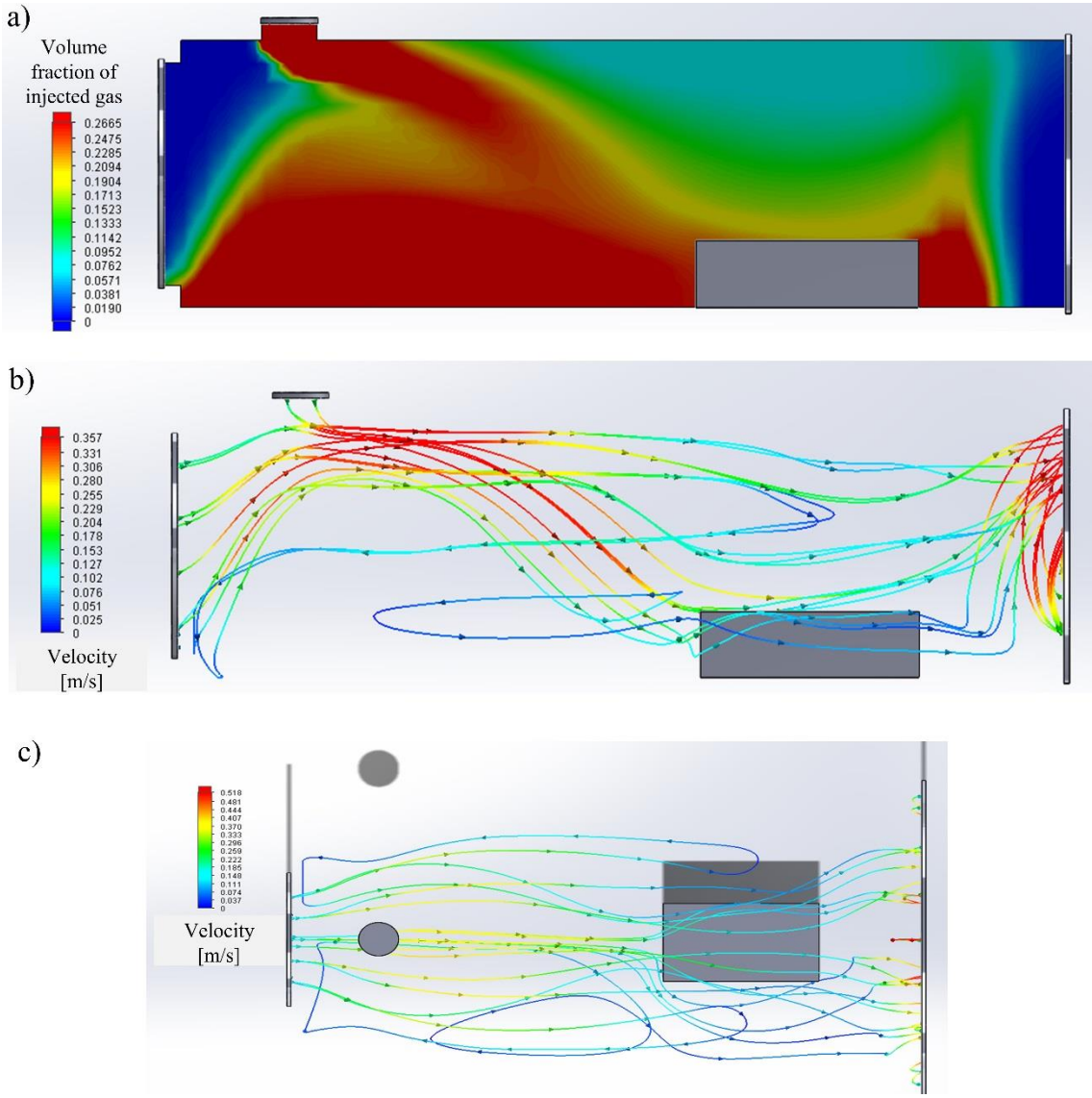


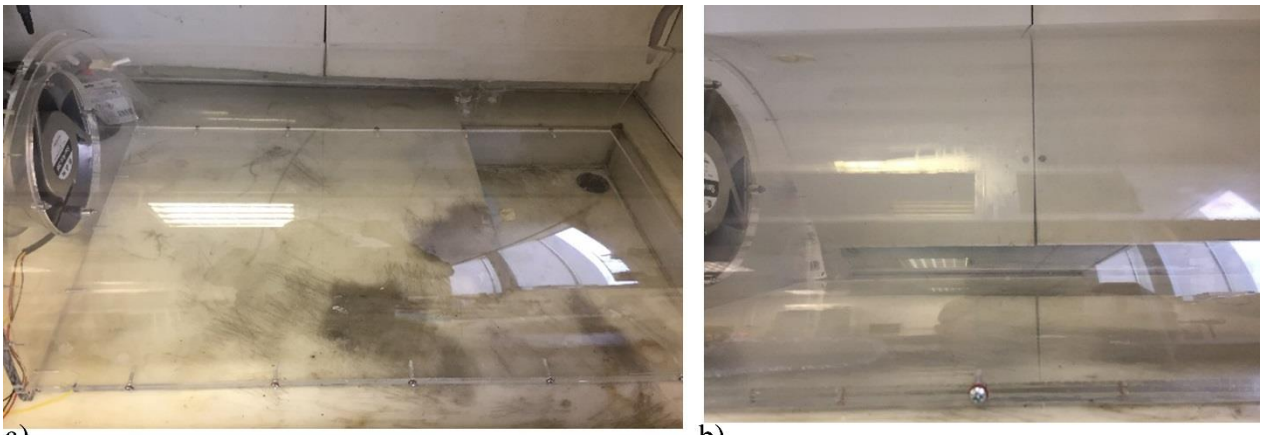
Fig. 2 – Screen prints from Solidworks flow simulations, a) spray injected from the top of the tunnel mixes with the air inside the chamber; b) flow trajectories viewed from the side; c) flow trajectories viewed from the top.

The flow speed of the wind tunnel can be adjusted using a pulse width modulation (PWM) control built into the fan. The speed of the flow was measured using an anemometer (Testo 405i probe). The adjustability of the flow rates was limited only by the operating range of the fan. Microcontroller (Teensy 3.2) software was developed to control the fan speed via a National Instruments LabVIEW virtual instrument. The system was trialled at the minimum and maximum flow velocities, which were

recorded as 1.8 and 2.3 m/s respectively (the reference probe was located in the centre at the end of the tunnel close to where the gas sensor module is positioned).

The tunnel was constructed from transparent acrylic plastic, which provided a durable but reasonably lightweight and manoeuvrable frame. To ensure a safe testing environment, suitable non-toxic VOCs (specify which ones, please) were selected for testing. If harmful VOCs, that can be absorbed into the acrylic surface, were to be used, the surface can be coated with PTFE (spray application).

A photograph of the constructed wind tunnel (inside a fume cupboard) is shown in Fig. 3 a). To verify the operation of the wind tunnel, the flow through the tunnel was visualised using a smoke generator. The smoke is shown to be evenly distributed across the centre of the tunnel in Fig. 3 b). The smoke is quickly dispersed through the chamber, taking approximately 0.5 s from entry to exit of the tunnel. The test was performed at minimum flow velocity of ?.



a) b)

Fig. 3 – Photographs of wind tunnel, a) constructed chamber installed in fume cupboard; b) smoke injected into the tunnel to show the distribution of gas flow.

The smoke test demonstrated the functionality of the wind tunnel system. The chamber was sufficient in size to house the sensor unit and allow different orientations to be trialled.

3. VOC Injection Procedure

The VOC was injected from the top of the chamber in liquid spray form. The VOC was contained in a small (300 ml volume) plastic dispenser, with compressible trigger. The force of the trigger to initiate a single spray was measured as 15 N. To measure the contents injected into the chamber per every spray of the dispenser, the mass of the instrument was measured pre- and post-injection. After the injection of 5 sprays, on average the instrument had decreased in mass by 0.27 g. Thus an average spray injects 0.054 g of VOC into the chamber. Fig. 4 shows a VOC being injected into the chamber. The spray is visible travelling through the hole in the top of the chamber and into the air flow produced by the fan. Using the injection system, it was found 5 sprays could be performed over a period of 3 s.

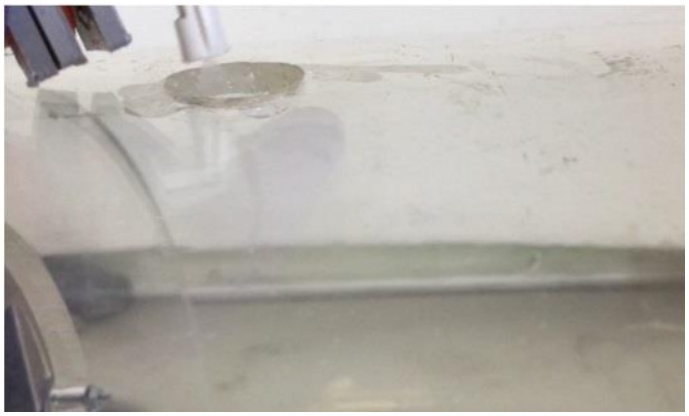


Fig. 4 – Photograph of VOC being injected into the wind tunnel using spray nozzle system.

The gases of interest to the Smokebot project (e.g. NO_2, CO) are not safe to test in the wind tunnel, without a means of sealing the exhaust of the system, which would affect the air flow characteristics. The VOCs previously presented in Deliverable 2.2 (toluene with the SMR sensor) were also unsafe to use in the environment of a wind tunnel above low ppm level.

The VOCs selected for use in the tunnel were acetone (C_3H_6O) and ethanol (C_2H_5OH). These chemicals were less hazardous than their counterparts, but also of interest to the Smokebot project. The VOCs were injected in pure form, without any dilution. The concentration of each VOC injected can be calculated, considering the density of the liquid (the densities of acetone and ethanol are 790 kg/m^3 and 789 kg/m^3 respectively, at atmospheric pressure with a room temperature of 20 °c).

Given a single injection of each VOC is 0.054 g in mass, the volume of each VOC injected can be calculated using eq. (1), where V is volume (m^3), ρ is density (kg/m^3) and m is mass (kg).

$$\mathrm{V} = \frac{\rho}{m} \tag{1}$$

Thus, the volumes of acetone and ethanol injected per spray are 6.83×10^{-8} m^3 and 6.84×10^{-8} m^3, respectively. The volume of the chamber was calculated as 0.08 m^3. Each injection adds a concentration of 854 ppb or 855 ppb of acetone or ethanol respectively, inside the chamber, considering a static environment. With the flow rate, set by the fan, these concentrations will likely never be achieved at the sensor unit. Multiple injections were used for each VOC. The dispenser was operated at the fastest rate of injection possible, which equalled on average 0.5 s between dispersions.

4. SMR Sensor Characterisation

The SMR sensor was performing adequately to detect ppm concentrations of acetone in a laboratory gas rig environment. The plot shown in Fig. 5 demonstrates the sensor was able to detect 200 ppm of acetone. The frequency shift was on average 1412 Hz for the 5 minute 200 ppm pulse of acetone, corresponding to a shift of 7.06 Hz per ppm. The sensor demonstrated a stable baseline in the conditions of the test rig. The output has been filtered with a median filter of 19 points.

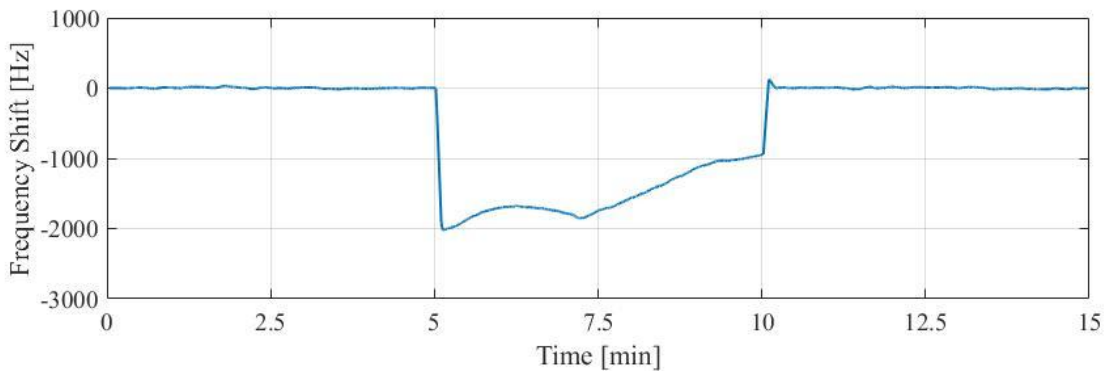


Fig. 5 – Response of SMR sensor to a 5 min pulse of acetone, measured on a gas testing rig with continuous flow of 200 SCCM.

The SMR was coated with a SXFA solution, which has good sensitivity to acetone. The solution was applied in a very thin layer using a spray coating instrument. The measurements were taken in differential configuration (one coated sensor, one uncoated). A National Instruments DAQ unit was used to acquire the output from the mixer on the SMR sensor circuitry.

However, once placed inside the Smokebot gas sensor module, the operation of the device was y affected by the pump which draws the air through the module. The flow rate fluctuated (by ~10 % around 200 SCCM) during operation. SMR sensors are sensitive to the flow rate presented across the devices, which affected the performance of the sensor. Various chamber designs were trialled, including exposing the bare sensor to the wind tunnel, but a satisfactory configuration could not be found to allow the sensor to maintain a stable baseline.

Furthermore, SMR devices are sensitive to vibration, which became apparent when the VOCs were injected into the wind tunnel. The additional noise, caused by vibrations, could not be removed to allow the effect of VOC injection to be visualized. The SMR devices were running in differential mode (i.e. a mixer subtracts a reference signal from the sensing device), however this method was not able to completely remove the interference from vibration.

Work is ongoing to make a robust SMR sensor for inclusion in the Smokebot gas sensor module. The second generation unit will contain a compact SMR sensor design, which will help reduce the problems faced with flow rate change and vibration cross-sensitivity. The variation of the pump flow rate inside the unit will also be investigated, to see if a smoother and stable flow rate can be achieved.

5. Wind Tunnel Experimentation

The response of the gas sensor unit was tested to plumes of acetone and ethanol, created through the injection of each VOC into the wind tunnel. The VOCs were injected into the chamber in as shorter period as possible (although the speed of injection was limited to ~ 0.5 s per spray). The results presented in this section demonstrate the performance of the MOX sensors to the injection of the VOCs. The charts are labelled in terms of number of sprays injected, where Table 1 shows the conversion of the number of sprays to mass and ppm concentration.

Table 1 – Concentration of each VOC injected into the tunnel per spray.

Number of Sprays	Mass Injected (average) [g]	Concentration Acetone / Ethanol [ppm]
1	0.054	0.854 / 0.855
3	0.162	2.56 / 2.56
5	0.27	4.27 / 4.28
8	0.432	6.83 / 6.84

The two MOX sensors are labelled as MOX 1 Sensor (Pd/Pt doped tin oxide coated) and MOX 2 Sensor (tungsten oxide coated).

5.1. Repeatability of Measurements

To test the repeatability of the injection system, three identical runs, each injecting a number of pulses into the system, were performed. For these experiments, ethanol was injected into the top of the tunnel, with the fan operating at minimum speed. The injections were performed at 1, 4, 7, 10 and 13 min points in the experiments.

Figs. 6, 7 and 8 show the results of these experiments, where plots denoted as a) and b) are for the tin oxide and tungsten oxide sensors respectively.

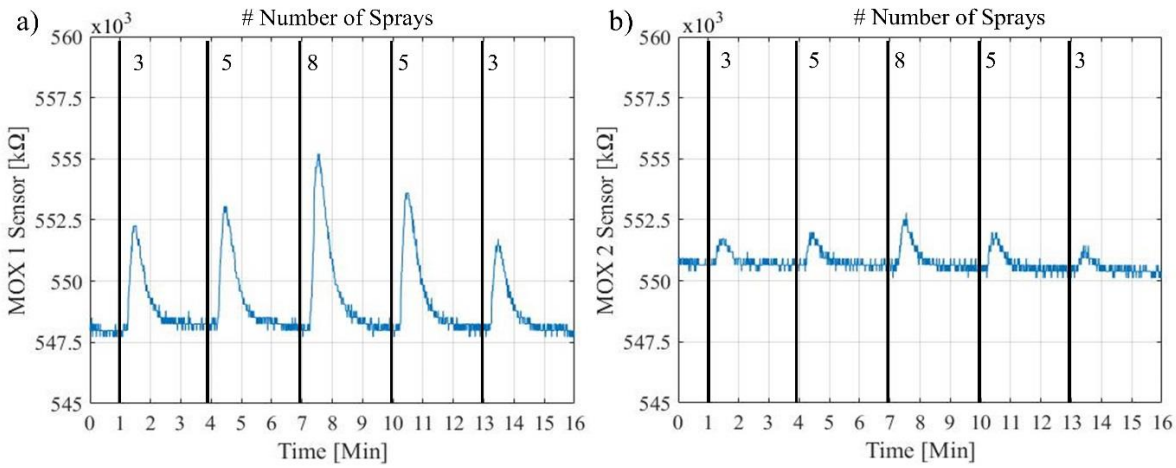


Fig. 6 – Run 1, response of MOX sensors to five test pulses of ethanol, vertical lines indicate time of injections, a) tin oxide sensor; b) tungsten oxide sensor.

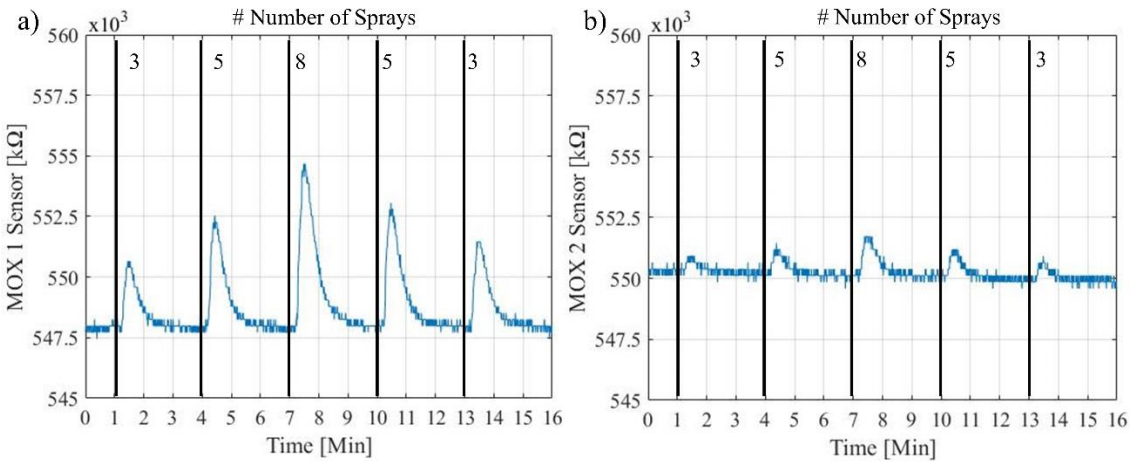


Fig. 7 – Run 2, response of MOX sensors to five test pulses of ethanol, a) tin oxide sensor; b) tungsten oxide sensor.

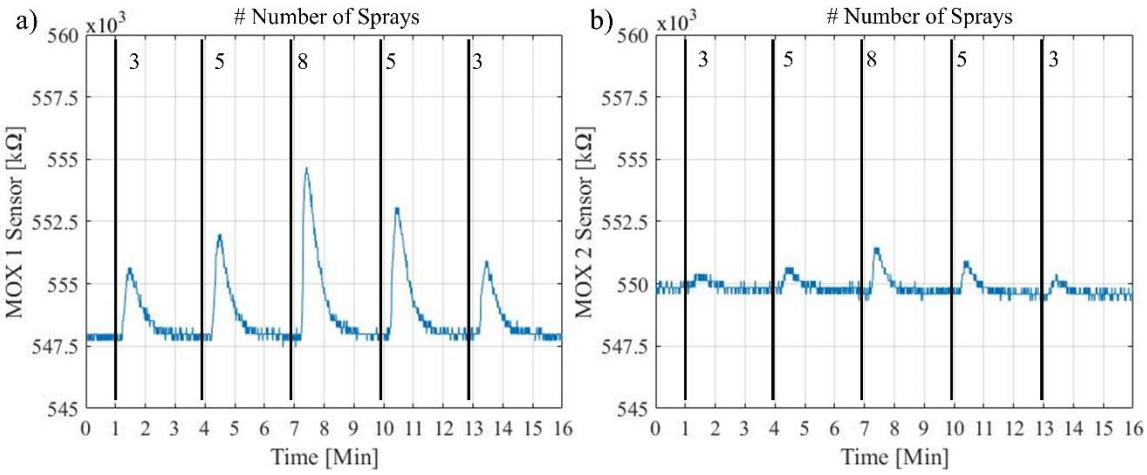


Fig. 8 – Run 3, response of MOX sensors to five test pulses of ethanol, a) tin oxide sensor; b) tungsten oxide sensor.

The results in terms of change in sensor resistance are summarized in Table 2 below. The tin oxide sensor demonstrates a higher response to the ethanol injected. The average change from baseline resistance is listed as the delta change in resistance for each sensor.

Table 2 – Summary of results from three runs of ethanol experiment.

Injected VOC		**Sensor 1**			**Sensor 2**			**Average**	
Num. Injects	**Conc. [ppm]**	**Run 1 [kΩ]**	**Run 2 [kΩ]**	**Run 3 [kΩ]**	**Run 1 [kΩ]**	**Run 2 [kΩ]**	**Run 3 [kΩ]**	**Delta S1 [kΩ]**	**Delta S2 [kΩ]**
3	**2.56**	552.3	550.7	550.7	551.7	550.9	550.4	3.13	0.77
5	**4.28**	553.1	552.5	552	552	551.5	550.7	4.43	1.17
8	**6.84**	555.2	554.7	554.6	552.8	551.7	551.5	6.73	1.77
5	**4.28**	553.6	553.1	553.1	552	551.2	550.9	5.17	1.13
3	**2.56**	551.8	551.5	550.9	551.3	550.8	550.4	3.30	0.60

The time until the sensor started to respond is shown in Table 3. There is no notable change in sensor output at the time the VOC is injected. There is a delay in the response of over 10 s. This delay is unlikely to be due to the sensor response time alone. The VOC will take a period of time to propagate through the system. Initially, it is injected into the top of the tunnel and takes approximately 0.5 s to reach the other end of the chamber. This would be assuming ideal plug flow. In reality, the mixing occurring inside the chamber is likely to delay the VOC reaching the sensor unit by approximately a factor of 5, given the volume of the chamber is large.

At the end of the tunnel, the gas is sampled by the gas sensor module. This is performed using a pump (average flow rate through system of 200 SCCM). The dead volume of the system is estimated as 10 ml, given the sensor chamber size and tubing required (up to the MOX sensor location). Therefore, it will take ~3 s for the gas to travel from the inlet of the module to the MOX sensors.

Table 3 – Summary of response time data from three runs of ethanol experiment.

Injected VOC		**Sensor 1**			**Sensor 2**			**Average**	
Num. Injects	**Conc. [ppm]**	**Run 1 [s]**	**Run 2 [s]**	**Run 3 [s]**	**Run 1 [s]**	**Run 2 [s]**	**Run 3 [s]**	**S1 [s]**	**S2 [s]**
3	**2.56**	14.5	15.2	12.3	13.0	16.8	15.8	14.0	15.2
5	**4.28**	12.7	7.8	13.1	14.7	11.6	13.4	11.2	13.2
8	**6.84**	15.7	14.3	11.3	16.6	12.7	13.5	13.8	14.3
5	**4.28**	13.8	14.4	11	13.8	13.8	13.8	13.1	13.8
3	**2.56**	14.4	13.8	12.6	13.2	15.0	12.0	13.6	13.4

The sensor system shows good repeatability throughout the experiments. On average, the tin oxide sensors increase in resistance from baseline (550.1 kΩ) by 3.1, 4.4, 6.7, 5.2 and 3.3 kΩ in response to the injections of 2.6, 4.3, 6.8, 4.3 and 2.6 ppm of ethanol. The overall average response time was 13.1 s and 14.0 s for the tin oxide and tungsten oxide sensors respectively. The majority of this response time is likely due to the wind speed set by the wind tunnel, where the slower speed increases the time for the VOC to mix with the air inside the chamber.

5.2. Wind Tunnel Ethanol Air Flow Speed

The results presented above were recorded with the wind tunnel airflow speed set to the minimum rate (1.8 m/s). In this section, the test pattern with 5 injection periods of ethanol was repeated with the wind speed set to maximum (2.3 m/s). Fig. 9 shows the output produced from the two MOX sensors for the 16 min experiment.

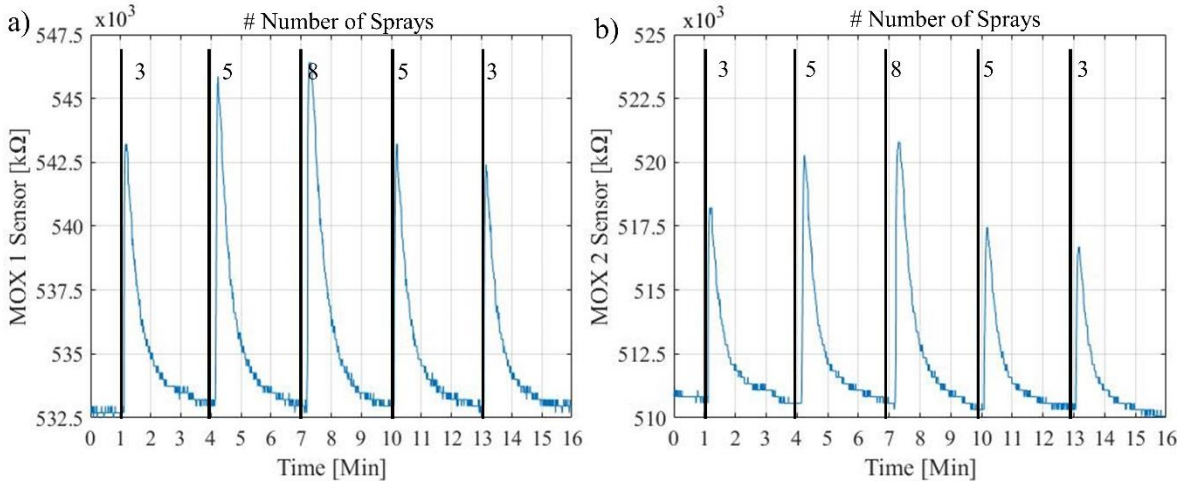


Fig. 9 – Experiments with wind tunnel speed of 2.3 m/s, a) tin oxide MOX sensor result; b) tungsten oxide MOX sensor result.

The results are summarised in Table 4, demonstrating that the response times of the sensors are greatly reduced, less than half the previous values (average 5.64 s and 5.26 s for the MOX 1 and MOX 2 sensors respectively). The baseline of MOX 1 was 533.2 kΩ and the baseline for MOX 2 was 510.3 kΩ (on average). The change in resistance in response to the VOC is listed in the delta resistance columns.

Table 4 – Summary of results for MOX 1 and MOX 2 sensor when the wind tunnel was operating at maximum wind speed.

Injected VOC		**Sensor 1**			**Sensor 2**		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	543.2	10.0	6.7	518.2	7.9	5.2
5	**4.28**	545.9	12.7	6.9	520.3	10.0	7.2
8	**6.84**	546.4	13.2	6.1	520.8	10.5	5.4
5	**4.28**	543.2	10.0	4.8	517.5	7.2	4.8
3	**2.56**	542.4	9.2	3.6	516.7	6.4	3.6

If the normalised resistance is considered, to the baseline resistance, the MOX responses have increased by a factor of 2.6 for the tin oxide and 9.0 for the tungsten oxide sensors. The mixing inside the chamber has greatly improved with the faster wind speed. The concentration of the VOC received by the sensor unit is likely to encounter significant dilution inside the chamber (given the rate of injection and the wind speed) compared to the idealised injected concentration listed in Table 4. However, the higher response from the sensors (compared to the results shown for lower wind speed

in Table 2) demonstrate the injected VOC has been more evenly distributed with the air inside the chamber.

5.3. Orientation of Gas Sensor Module

On a mobile robot, the orientation of the gas sensor inlet will likely be fixed in one direction, relative to the robot. To aid the localization of a gas source, the direction of a gas source must be identified. The wind tunnel was used to view the effect of rotating the sensor unit from the standard location (inlet faces entrance to tunnel with fan), to a side orientation (inlet faces a side of the tunnel) to rear orientation (inlet faces exhaust of tunnel).

The unit was first rotated to a left view (gas inlet faces left side wall of tunnel). The experiment was performed in an identical manner to the one detailed in Table 1. For these experiments, as with the ethanol experiments in section 5.1, the wind speed was set at minimum. It was considered safer to operate at minimum wind speed inside the fume cupboard.

The response of the MOX sensors to the 5 injection periods of ethanol are shown in Fig. 10, where the gas sensor module is orientated facing the left of the tunnel. The time response of the sensor unit (from baseline to initial response) was comparable with the maximum wind speed setting (5.7 s and 5.9 s respectively for MOX 1 and MOX 2 sensors).

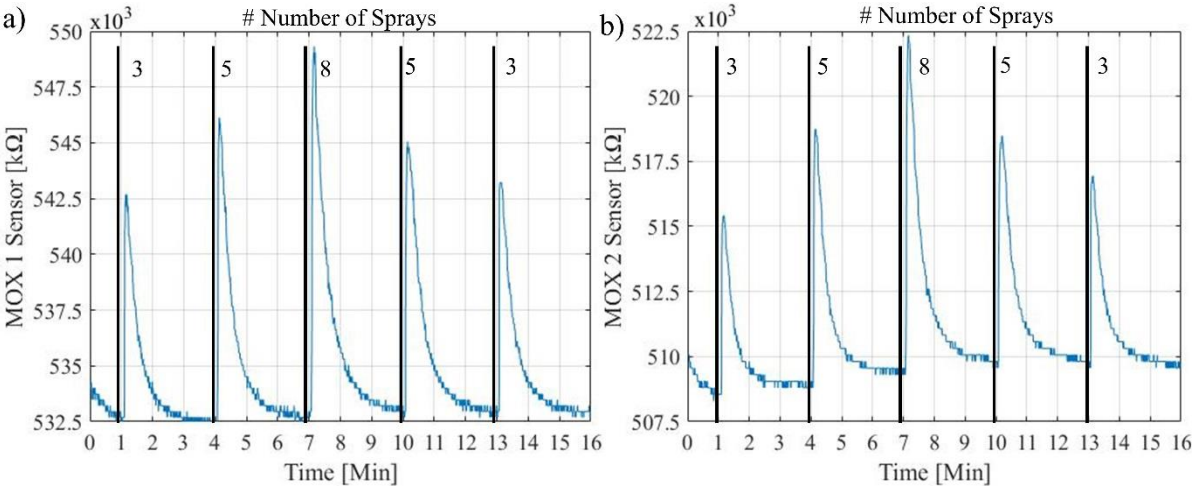


Fig. 10 – MOX sensor responses with module inlet facing the side of the wind tunnel,
a) MOX 1 sensor response; b) MOX 2 sensor response.

The results are tabulated in Table 5 for both MOX sensors. The change in resistance from baseline to peak value is displayed in the delta resistance column. The ethanol concentrations are shown, generated from the identical spray routine as described in the initial experiments in section 5.1.

Table 5 – Summary of results for MOX sensors with gas sensor unit facing side of tunnel.

Injected VOC		Sensor 1			Sensor 2		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	542.7	9.7	5.9	515.4	5.6	5.8
5	**4.28**	546.1	13.1	6.1	518.7	8.9	6.2
8	**6.84**	549.3	16.3	5.4	522.3	12.5	5.7
5	**4.28**	545.1	12.1	5.5	518.5	8.7	6

3	**2.56**	543.2	10.2	5.8	516.9	7.1	5.9

The sensor unit was then orientated so the gas inlet faced the exhaust of the wind tunnel. The results for the identical experiment as performed above, are shown in Fig. 11. The MOX 1 sensor, shown in Fig. 11 a), shows an unusual un-stable baseline. A change in baseline from 532.7 to 536.1 kΩ is notable at the 8.5 min point in the experiment. The variation could be caused by airborne dust coming into contact with the sensor surface. The MOX 2 sensor is not affected by any baseline shift during the experiment.

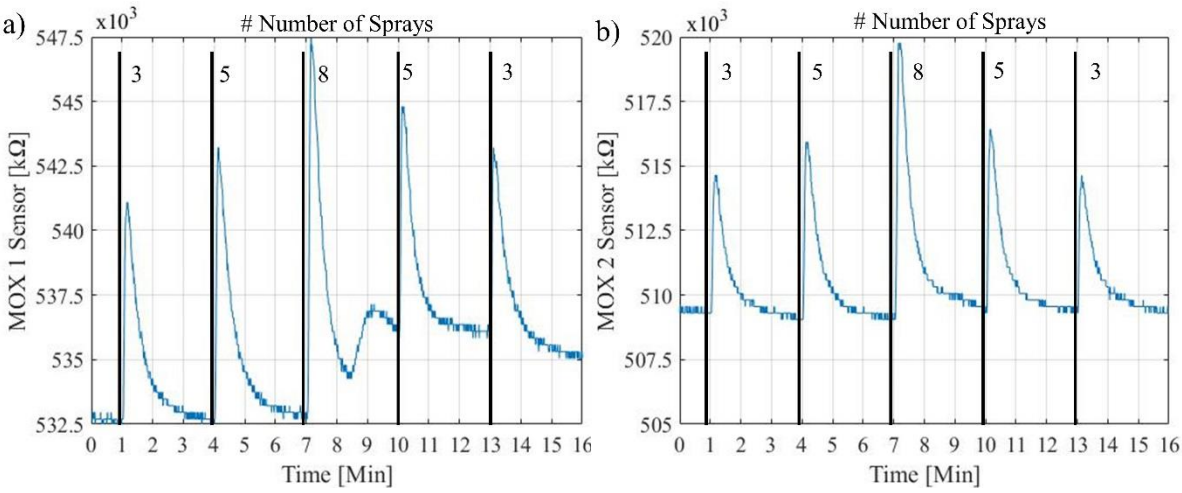


Fig. 11 – Sensor response plots to five injection periods of ethanol with gas inlet facing exhaust of tunnel, a) tin oxide MOX sensor; b) tungsten oxide MOX sensor.

Table 6 shows the results from the tin oxide and tungsten oxide MOX sensors for the experiment. The delta resistance values have been adjusted, according to the baseline shift observed for the MOX 1 sensor.

Table 6 – Summary of results for MOX sensors with gas sensor unit facing exhaust of tunnel.

Injected VOC		**Sensor 1**			**Sensor 2**		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	541.1	8.4	6.5	514.6	5.0	6.8
5	**4.28**	543.2	10.5	6.8	515.9	6.3	7.2
8	**6.84**	547.5	12.5	6.4	519.8	10.2	7.5
5	**4.28**	544.8	9.8	6.7	516.4	6.8	7.1
3	**2.56**	543.2	8.2	7.2	514.6	5.0	7.7

The peaks produced in response to the injection of ethanol are similar for both orientations. The response time of the sensors is similar for the left (average 5.7 s and 5.9 s) and exhaust (average 6.7 s and 7.3 s) facing inlet experiments (MOX 1 and MOX 2, respectively). The response time values do not change considerably, showing the pump is drawing a constant flow into the unit and sampling the

air close to the inlet of the unit. The flow rate produced by the pump is low (0.2 SLPM compared to wind tunnel speed of 1.8 m/s), but by changing the orientation of the sensor unit the distance from the VOC source to the gas sensor inlet has increased by ~ 0.1 m.

The magnitude of the responses has notably decreased, considering when the gas sensor unit was orientated to side and rear of the tunnel. The maximum concentration (6.8 ppm) produced a change of 16.3 kΩ for MOX 1, compared to 12.5 kΩ shift for the same sensor when the unit was changed in orientation from side to rear. For the lowest concentration (2.6 ppm) the average response decreased from 9.95 kΩ to 8.3 kΩ. Fig. 12 shows a comparison between the resistance shifts for both sensors.

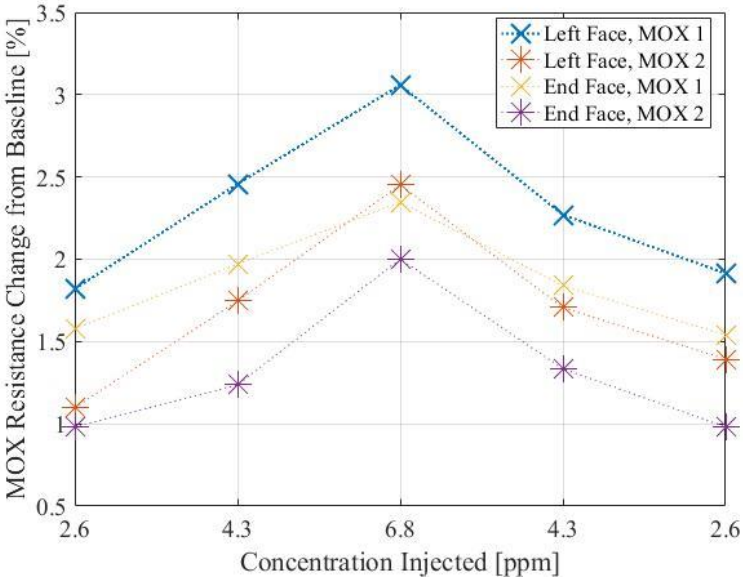


Fig.12 – Comparison of change in response from baseline value due to injections of ethanol VOC for sensors MOX 1 and MOX 2 when the gas sensor module was orientated to the left and to the exhaust of the tunnel.

The response output shown in Fig. 12 shows the MOX 1 sensor produces a greater response in both cases (approximately 1 % change in resistance higher) compared to MOX 2. When the unit is orientated towards the exhaust, a lower change in resistance is noted. On average, a 0.45 % lower response is observed for MOX 1 when the unit is facing the end of the tunnel and a 0.37 % lower response observed for MOX 2.

The plot shown in Fig. 12 can also be used to compare the repeatability of the devices. Injection numbers [1 and 5] and [2 and 4] are of the same concentration. The second injections (5 and 4) for the MOX 1 sensor produce a lower response in both orientations. The opposite effect is observed for the MOX 2 sensor. Overall, the variation between repeat concentrations is low (0.066 % and -0.088 %) for the MOX 1 and MOX 2 sensors (first injection periods compared to second).

When the unit faces the end of the chamber, the sensor responses are lower. This is due to the sampled air being a mixture of gas from the wind tunnel and air from the external environment. This mixture reduces the concentration of VOC received by the sensor unit, and thus reduces the observed response from the sensors. This effect could be used to locate the source of the gas, where the robot or gas inlet

could be rotated to identify the strongest direction of the gas sensor response (and thus the direction of the gas source).

5.4. Acetone Wind Tunnel Experiment

Acetone, a second VOC, was tested inside the wind tunnel, with the same pulse routine (Table 1) performed for the ethanol experiments. Acetone was previously discussed in deliverable 2.2, as of interest in the range of 100 to 300 ppm. Specifically, the MOX 2 sensor (tungsten oxide coated) was noted as being partially sensitive to acetone (although an order of magnitude lower than the sensitivity towards NO_2). The tin oxide sensor would also be expected to produce a response to acetone.

The pulses of acetone were injected into the wind tunnel in the same manner as the ethanol experiments, with a spray trigger used to inject acetone in liquid form, from the top of the tunnel. The tunnel was set to the lowest wind speed. The sensor unit was positioned at the end of the tunnel, with the gas inlet facing into the tunnel (towards the injection location). Fig. 13 shows the response outputs from the MOX 1 and MOX 2 sensors. The baseline of MOX 1 was not stable during this experiment (baseline drift also visible in Fig. 11). The tin oxide material can occasionally produce unstable results, and thus it can be doped with other compounds to help improve such characteristics. The sensor coatings are ongoing work, with the hope to find an ideal doped compound that is stable and produces a high response to the VOCs of interest for the Smokebot project.

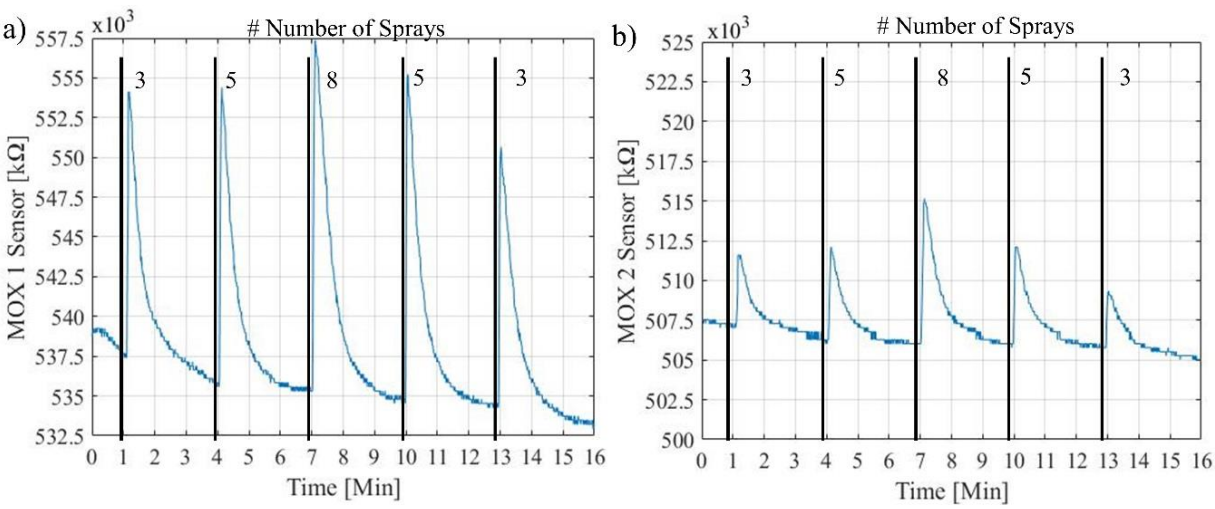


Fig. 13 – Acetone experiment to test the performance of a) a tin oxide coated MOX sensor and b) tungsten oxide coated MOX sensor to the injection of five pulse periods of acetone.

Both the MOX sensors produce a response to the injection of acetone. The baseline of the MOX sensors was 534.2 kΩ and 506.0 kΩ (average) for the tin oxide and tungsten oxide devices respectively. The tin oxide sensors demonstrates a higher sensitivity (average change in resistance of 20.2 kΩ compared to 6.1 kΩ for the MOX 2 device). The results are summarized in Table 7.

Table 7 – Summary of results for the MOX sensor responses to the injection of acetone into the wind tunnel (MOX 1 is tin oxide coated, MOX 2 tungsten oxide coated).

Injected VOC		Sensor 1			Sensor 2		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	554.1	19.9	6.4	511.6	5.6	6.5
5	**4.27**	554.4	20.2	4.4	512.1	6.1	4.8
8	**6.83**	557.4	23.2	3.8	515.2	9.2	4.2
5	**4.27**	555.2	21.0	3.6	512.2	6.2	4.1
3	**2.56**	550.7	16.5	3.2	509.3	3.3	3.8

The MOX sensors produce a quick response to the injection of acetone (average time to respond 4.3 s for MOX 1 and 4.7 s for MOX 2). On average, the response time was 1.4 s and 1.2 s faster than the response time observed to the injection of ethanol. Both MOX devices produced a higher response to the presence of acetone compared to ethanol. On average, the tin oxide device changed resistance by 3.8 % and the tungsten oxide device by 1.2 %.

5.5. Acetone Wind Speed Experiment

To verify if the wind speed of the tunnel effects the response time of the MOX sensors, the air flow rate through the tunnel was increased to its maximum value (2.3 m/s). This is a similar experiment to that reported in section 5.2 (previously ethanol was trialled). The position of the sensor unit was not changed from section 5.4 (located in the end of the tunnel, inlet facing towards VOC injection port).

The results from the experiment are shown in Fig. 14. As previously noted in Fig. 13, the MOX 1 sensor produces a higher response to the injection of acetone.

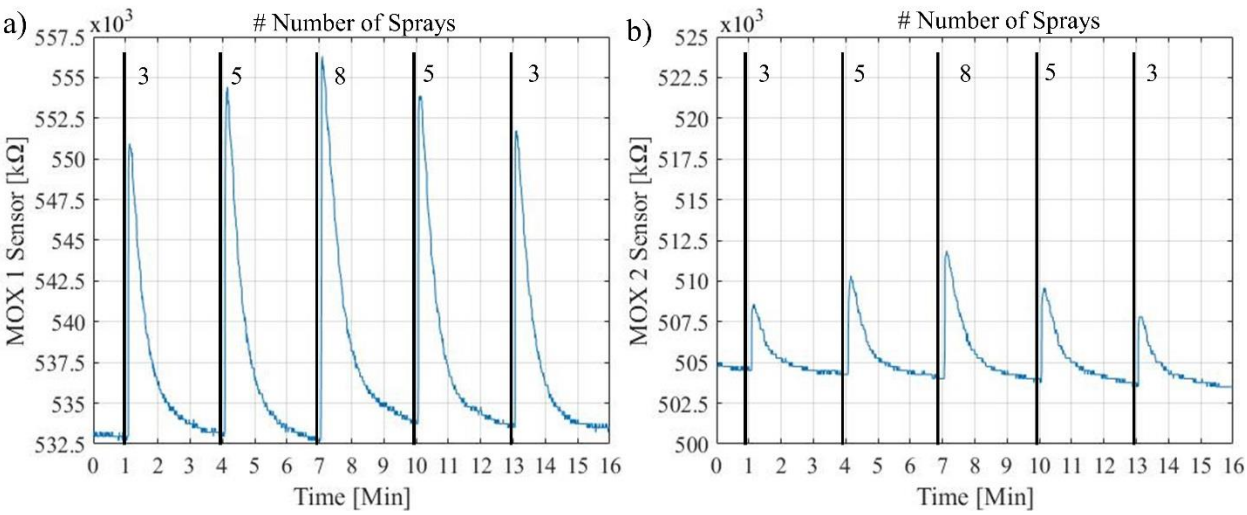


Fig. 14 – Acetone injected into wind tunnel (maximum possible airflow speed), a) MOX 1 and b) MOX 2 sensor responses.

The results are summarized in Table 8. The baseline resistance of the MOX 1 sensor is stable during this experiment. The average baseline is 533.5 kΩ for the tin oxide sensor and 504.3 kΩ for the tungsten oxide coated device. The response times have decreased by an average of 0.4 s and 0.7 s for

the MOX 1 and MOX 2 sensors respectively (average times 3.9 s and 4.0 s before an initial response is observed).

Table 8 – Summary of results for MOX sensors to injection of acetone, with wind tunnel speed set to maximum flow rate (2.3 m/s).

Injected VOC		Sensor 1			Sensor 2		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	550.9	17.4	4.8	508.5	4.2	4.9
5	**4.27**	554.4	20.9	4.5	510.3	6.0	4.7
8	**6.83**	556.3	22.8	3.5	511.8	7.5	3.8
5	**4.27**	553.9	20.4	3.2	509.6	5.3	3.5
3	**2.56**	551.7	18.2	3.3	507.8	3.5	3.2

The average change in resistance from baseline was 19.9 kΩ for the tin oxide and 5.3 kΩ for the tungsten oxide coated MOX sensors. The average percentage change was 3.7 % for the tin oxide and 1.1 % for the tungsten oxide devices. This change has decreased by 0.1 % compared to when the wind tunnel was operating at the slower wind speed (1.8 m/s), reported in section 5.4.

The tungsten oxide sensor produces a lower response to acetone compared to the tin oxide sensor. Neither device is designed particularly to sense acetone, although both have demonstrated satisfactory performance. The increase in wind speed has reduced the response times before the sensors detect the presence of acetone, with a marginal reduction in sensitivity.

5.6. Position of Gas Sensor Module

The position of the gas sensor module is usually located at the end of the tunnel, to allow sufficient time for plumes of VOC to be created. To view the effect of changing the position of the unit, the module was moved closed to the source of the VOC. Fig. 15 a) shows the original position of the unit (for all prior experiments, approximately 0.6 m from the VOC source in horizontal distance). Fig. 15 b) shows the position used in the experiments for this section (0.2 m horizontal distance from the source).

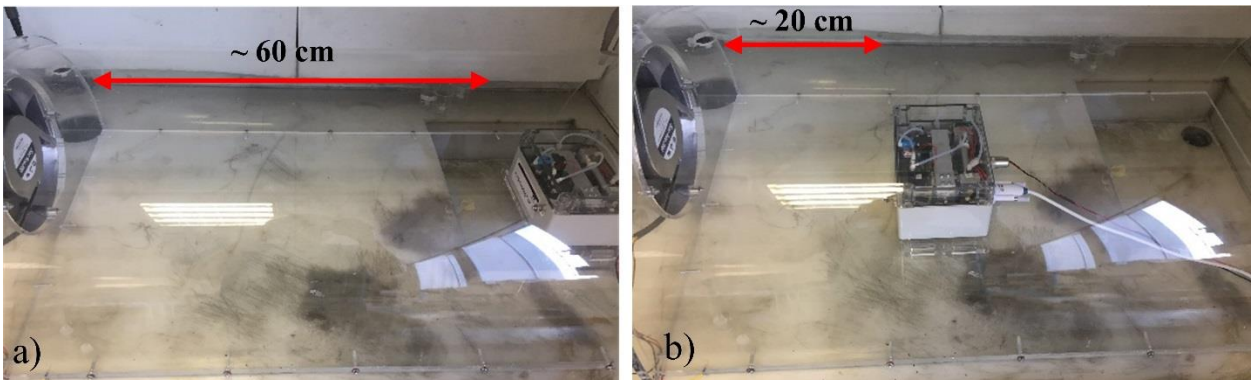


Fig. 15 – Photographs of the gas sensor module located inside the wind tunnel, a) shows the position adopted for all previous experiments; b) shows the position for this experiment.

Acetone was the chosen VOC for these experiments, with the wind speed set to the minimum level (1.8 m/s). The same number of test pulses (i.e. same VOC concentrations) was used as specified in previous experiments. The 16 min experiment was performed with the sensor unit facing the VOC injection source. The results are presented in Fig. 16, a) shows the tin oxide coated device and b) the tungsten oxide device. The baseline resistance for both sensors has increased, but there is a notable decrease in response from both devices.

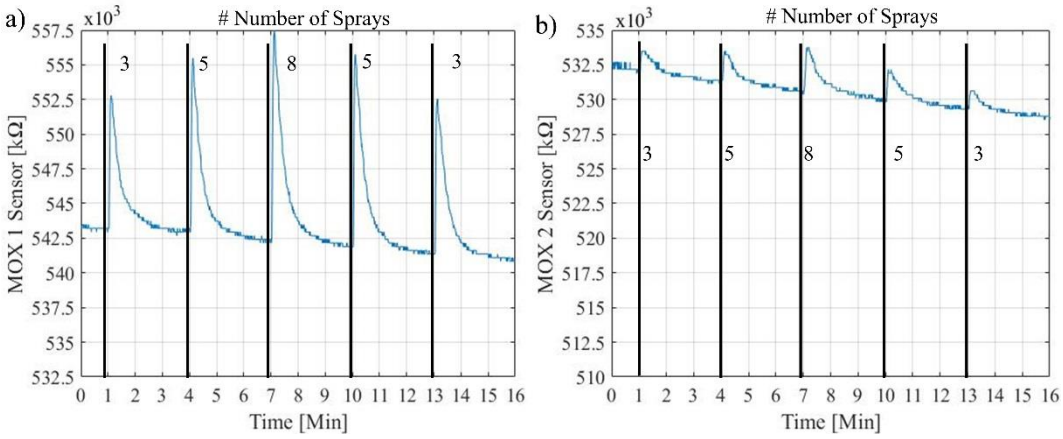


Fig. 16 – Acetone experiment with gas sensor module located closed to VOC source, a) MOX 1 sensor; b) MOX 2 sensor.

The results are summarized in Table 9. The baseline resistances were measured as 542.2 kΩ and 530.4 kΩ (on average) for the MOX 1 and MOX 2 sensors respectively.

Table 9 - Results summary for the acetone experiment with module located closer to VOC source.

Injected VOC		**Sensor 1**			**Sensor 2**		
Num. Injects	**Conc. [ppm]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**	**Res. [kΩ]**	**Delta Res [kΩ]**	**Time [s]**
3	**2.56**	552.8	10.6	2.5	533.5	1.3	2.9
5	**4.27**	555.5	13.3	2.7	533.5	3.3	3.1
8	**6.83**	557.6	15.4	2.5	533.7	3.5	2.8
5	**4.27**	555.7	13.5	2.4	531.9	3.1	2.7
3	**2.56**	552.5	10.3	2.8	530.6	1.8	3.0

The response times for the sensors have decreased, when compared to both the other low wind speed acetone tests (section 5.4) and the high wind speed test (section 5.5). The average response time for the MOX 1 sensor was 2.6 s and 2.9 s for the MOX 2 sensor. The magnitude of response has decreased, with an average percentage change of 2.3 % for the MOX 1 device and 0.5 % for the MOX 2 sensor. The injection point is located approximately 20 cm vertically above the gas inlet on the module (the vertical height was not changed with the horizontal distance). When the module was located closer to the source inside the tunnel, less gas and VOC mixing would occur. Thus it is likely a reduced concentration of VOC would be in the sampled gas close to the inlet of the sensor module.

The position of the gas sensor module in relation to the source has been shown to have a strong relationship with the magnitude of the response recorded. When the gas sensor unit was located

horizontally closer to the source, a lower response was recorded by the MOX sensors. This reduction (1.4 % and 0.6% respectively for the tin oxide and tungsten oxide sensors) was due to less gas mixing occurring and the majority of the injected VOC was at a higher level than the inlet to the sensor module.

6. Wind Tunnel Experiments Conclusions

The Smokebot gas sensor module has been tested inside a wind tunnel developed at the University of Warwick. The module has been tested with the presence of VOCs (ethanol and acetone), injected in various concentrations into the tunnel. The concentrations injected were in the range of 2.5 to 6.8 ppm for each VOC. The sensors were exposed to the VOCs for a short period of time (<10 s), as the injected compounds mixed with the air flow inside the chamber and propagated through the chamber and out through the exhaust.

The repeatability of the test methodology was trialled with an ethanol injection repeated for 3 runs. The results were similar for each repetition. The tin oxide coated sensor (denoted MOX 1) produced a larger response to the ethanol (maximum change from baseline resistance was 6.7 kΩ). The response time for MOX 1 device was recorded as 5.6 s on average and 5.3 s for the MOX 2 device.

In the same configuration as discussed above, the wind speed inside the tunnel was increased from minimum (1.8 m/s) to maximum (2.3 m/s). The response time was found to be reduced for both MOX sensors (5.6 s and 5.3 s for the MOX 1 and MOX 2 sensors, respectively).

To test the ability of the unit to localise a source, the orientation of the sensor unit was varied. For the majority of experiments, the gas inlet on the sensor unit is orientated towards the VOC injection point. In this section (5.3) the unit was rotated first so the inlet faced the side of the tunnel, and then towards the exhaust of the tunnel. The magnitude of the response from the sensors did not greatly reduce comparing the unit being orientated facing the source and facing the side of the tunnel.

When the unit was rotated facing the exhaust of the tunnel, a notable decrease in response magnitude was observed. For example, the response to an injection of 6.8 ppm of ethanol decreased from 3 % (MOX 1 sensor) to 2.4 % when the unit was facing the exhaust. It is likely the system was sampling a mixture of external air and air from inside the tunnel (thus after mixing, a lower concentration of ethanol would be expected).

Acetone was tested in the wind tunnel, following the same experimental procedure as for the ethanol experiments previously detailed. The same number of sprays was injected into the chamber for the 16 min experiments. The MOX 1 sensor was found to produce a higher magnitude response to the acetone, compared to MOX 2 sensor, which did produce a higher response than found for the ethanol experiments (on average tin oxide responded by 3.8 % change in resistance and tungsten oxide by 1.2 %).

The wind speed was changed to maximum, and the injections of acetone repeated. A decrease in response magnitude was recorded (by 0.1 %) for both sensors. The response times for the sensors decreased by 0.4 s and 0.7 s respectively compared to the experiments performed in section 5.4.

To verify if the position of the unit effected the magnitude of the response (i.e. were plumes of VOCs generated in the tunnel) the unit was positioned closer to the VOC source. In the previous experiments the unit was located 0.6 m from the VOC injection point, which was decreased to 0.2 m (horizontal

distance measured, vertical distance of 0.2 m not altered). The response times for the gas sensors decreased, however a decrease in magnitude of response was recorded. The tin oxide sensor decreased by 2.3 % and the tungsten oxide decreased by 0.5 %.

The wind tunnel experiments have demonstrated the gas sensor module is capable of detecting plumes of gas of VOCs injected into air with a flow speed between 1.8 m/s and 2.3 m/s.

7. References

1. D. Martinez, J. Moreno, M. Tresanchez et al., "Measuring Gas Concentration and Wind Intensity in a Turbulent Wind Tunnel with a Mobile Robot, *Journal of Sensors*, 2016.
2. J. Fonollosa, I. Rodriguez-Lujan, M. Trincavelli and R. Huerta, "Dataset from Chemical Gas Sensor Array in Turbulent Wind Tunnel", *Data in Brief*, vol. 3, pp. 169-174, 2015.