ABSTRACT

An underground mining ventilation testing facility (VTF) was designed and constructed at the HySA facility at the North-West University, South Africa. The purpose was to evaluate risks associated with different hydrogen storage technologies in a confined environment. The work included initial calculations of hydrogen movement in specific spaces and the development of simulation tools to compare these modelled results with experimental work. For this purpose, hydrogen sensors that could accurately measure hydrogen concentrations during a controlled hydrogen leak at the VTF were required. Hazardous hydrogen sensors capable of measuring >4% hydrogen are not readily available commercially. Typically, hydrogen sensors rated for hazardous environments are designed for safety actions (e.g., activating emergency measures when hydrogen is detected) at concentrations of ≤8%.

(Measuring concentrations higher than this is not required for commercial use, hence there is no market for such sensors.) At the VTF, it is necessary to be able to measure hydrogen concentrations >4% in order to obtain information on the flammable hydrogen concentrations at specified distances and orientations around a controlled hydrogen leak. Initial experimental work was conducted at low pressures, resulting in very low hydrogen concentrations. Commercial available original equipment manufacturer (OEM) hydrogen sensors were capable of measuring 0.2% hydrogen, which, for the low pressures and gas flows here, proved sufficient to enable us to make sensible conclusions. However, higher pressures and gas flows are essential in practical use, hence higher concentrations of hydrogen need to be measured. A custom sensor was developed by HySA, while commercial sensors (OEM) were investigated. This work reports on the testing and evaluation of several hydrogen sensors. Results of initial ventilation tests are presented.

1. INTRODUCTION

The use of hydrogen fuel cell powered machines in a ventilated underground environment introduces a number of concerns and uncertainties that require evaluation. There is a need for guidelines and, ultimately, standards that can be implemented for the safe operation of hydrogen powered fuel cell vehicles. The main concerns associated with hydrogen powered vehicles and machinery in confined space are hydrogen leaks and the occasional venting of hydrogen from fuel cell systems. These scenarios either need to be avoided, or managed in a safe manner. Hydrogen leaks and venting poses a risk in underground mines due to the confined spaces and pockets where hydrogen can accumulate in higher than the lower flammability limits. In order to simulate such scenarios, applicable hydrogen sensors are required to accurately measure hydrogen concentration under mining environment conditions.

There are currently various hydrogen sensor technologies that are utilized in commercially available sensors [1-6]. A number of performance parameters need to be considered when selecting suitable hydrogen sensors. The main performance parameters generally considered are accuracy, measuring range, response time (90 s), recovery time (10 s), operating temperature range, operating pressure range and ambient relative humidity (RH) range. However, when selecting sensors for use in the mining environment, one also needs to consider how the presence of gasses, such as methane, and dust affect the sensor performance (cross-sensitivity) and the robustness of the sensor. In safety systems, hydrogen sensors are typically used to trigger an alarm (and/or other safety related action) when a hydrogen
concentration above a predetermined level is present in the atmosphere. Measuring concentrations higher than this is not required for commercial use and hence such sensors have no market. At the ventilation test facility (VTF), it is necessary to be able to measure hydrogen concentrations >4% in order to obtain information on the flammable hydrogen concentrations at specified distances and orientations around a controlled hydrogen leak.

There are various types of hydrogen sensors available [7]. Catalytic sensors typically contain two platinum wire coils that are connected with a Wheatstone bridge. Both coils are coated with ceramic to form sensing beads. The one bead is impregnated with a catalyst that selectively catalyzes the oxidation of hydrogen. The other bead serves the purpose of a compensating bead. When a voltage is applied to the sensor, the platinum coils heat up to around 500–550 °C. When the sensor comes into contact with hydrogen, the hydrogen will oxidize on the surface, resulting in a temperature increase and increase in the resistance of the platinum wire coil. The difference between the resistances of the two wire coils, as measured by the Wheatstone bridge, is linearly related to the concentration of hydrogen.

Electrochemical sensors typically contain two or three electrodes: the working electrode, reference electrode (three electrode sensors only) and counter electrode. These electrodes are stacked parallel to each other, separated by a thin layer of electrolyte. The working electrode is also in contact with the ambient air to be measured, normally via a gas diffusion layer. These sensors essentially operate on the same principle as fuel cells. Hydrogen is oxidized when it comes in contact with the working electrode. At the counter electrode, the other molecule, such as oxygen, is reduced. This results in generation of an electrical current between the two electrodes, proportional to the hydrogen concentration. The reference electrode has a stable potential from which no current is drawn. It is used to eliminate interference from side reactions with the counter electrode [2,6,8-10].

Semiconductive metal oxide sensors have an active material, usually SnO₂, which is deposited on the substrate where two metal electrodes are placed. This enables measurement of the active layer resistance, which varies due to the chemical reaction that occurs at the surface of this active layer. The optimum operating temperature of the sensor is reached by heating it, using a resistive heating element placed on the other side of the substrate [6, 11-13].

The principle of operation of optical sensors is based on the change in a sensitivity layer following hydrogen absorption. Micromirror-based sensors detect changes in reflected light due to the absorption of hydrogen, while optical fibre hydrogen sensors may operate in two ways. They can detect a change in light transmittance across an optical fibre due to a change in the absorption coefficient and refractive index. Optical fibre hydrogen sensors can exploit a special feature, known as surface plasmon resonance. Surface plasmons are surface electromagnetic waves that propagate in a parallel fashion along a metal/dielectric interface. On absorption of hydrogen, the resulting change in resonance energy of the surface plasmons may be detected [6,14-16].

Thermal conductivity sensors make use of the thermal conductivity of hydrogen, which differs significantly from that of clean air. Similar to catalytic sensors, these sensors also have two inert beads, connected with a Wheatstone, which measure the difference between the resistances of these beads. The one bead is sealed off and the other is in contact with the atmosphere. Both electrodes are heated. When the composition of the target gas changes, the rate of heat loss will change. This will lead to a change in the temperature of that bead and its resistance. This change in resistance is proportional to the change in the thermal conductivity of the gas, which is then used to determine the hydrogen concentration [6,17].

Metal oxide semiconductor sensors typically have three layers: a metal layer, an oxide layer and a semiconductor layer (similar to capacitors). The capacitance of these sensors varies with the applied voltage and the width of the depletion region affect the value of capacitance. In the presence of hydrogen, atoms are absorbed at the interface of the oxide, changing the work function of the metal layer of the sensor [6,13,18].
Three commercially available hydrogen sensors were evaluated; they were tested under different RH conditions and at various temperatures. A custom-built flameproof hydrogen sensor (Zone 0) was developed and characterized under the same conditions.

2. EXPERIMENTAL

2.1 Environmental Chamber

The effects of RH and temperature on the performance of the different hydrogen detectors were evaluated by performing tests inside a bench-top-type temperature and humidity chamber (Espec SH-221). Fig. 1 shows the experimental setup used to evaluate the hydrogen detectors.

![Setup used for evaluating the hydrogen detectors](image)

In Fig. 1, the hydrogen containing cylinder is on the left. Each detector was placed inside the bench-top type temperature and humidity chamber, the temperature and humidity conditions of which could be varied as required. To ensure that the sensor was directly in contact with the hydrogen source, a custom holder was used; it was placed over the sensor, as shown on the right of the figure. A 2% hydrogen/air mixture was used as a source of hydrogen and the flow was controlled via a controller. Once the set conditions were reached, the fan of the chamber was switched off and the data logger commenced. The hydrogen valve was opened, until the sensor reached a maximum hydrogen reading. The process was repeated for all sensors, under identical conditions.

2.2 Ventilation Test Facilities

2.2.1 Kloppersbos Facility

The first site that was used for hydrogen leak tests was at the Kloppersbos facility. The facility represents a full-scale underground coal mine section arranged in a last through road, heading and pillar split configuration [7]. Fig. 2 shows the layout of the facility and the setup of the equipment.

HySA Infrastructure CoC used this facility to perform hydrogen leakage experiments. For these tests, hydrogen was released through an orifice to simulate a hydrogen leak. The hydrogen concentration in the ventilation air was measured at various points. This experiment was repeated for various orifice diameters, supply pressures and ventilation rates. The results of these experiments were used to determine the size of the flammable atmosphere that resulted from the hydrogen leak.
Fig. 2b and 2c shows the geometry of the tunnel and placement of the hydrogen source. The source was placed at a height of 1 m. The hydrogen was released in the direction of the ventilation, with sensors placed at 0.5 m intervals from the source at various heights: 1 m, 1.5 m and 2 m. The tunnel in which the experiments were performed is shown in Fig. 2a (the air intake end of the tunnel is shown). The ventilation fans are located at the opposite end of the tunnel, 50 m further (fans are not shown). Fig. 2d shows the physical sensor and controller placements inside the tunnel. The sensors are placed on frames (white boxes on the right of Fig 2d) and the controllers all together (on the left of Fig. 2d) During experiments, the ventilation through the tunnel was changed in order to obtain results for various ventilation scenarios. Multiple measurements were repeated at the different sensor distances and heights.

2.2.2 Generation 1 Ventilation Test Facility at HySA Infrastructure

Fig. 3 shows the generation 1 ventilation test facility located at the Faculty of Engineering on the Potchefstroom Campus of the North-West University. The generation 1 VTF consists out of a 12 m shipping container which was customized to accommodate hydrogen detectors and equipped with various inlets for hydrogen gas. The design of the facility was based on information provided by Anglo Platinum and Anglo Gold Ashanti, and obtained after a site visit to Agnico Eagle Laronde gold mine, Canada. (The purpose of this visit was to review possible hydrogen fuelling station sites for underground mining equipment.)

The VTF was designed to enable us to perform tests with <4% lower flammability limit (H₂ in air) of hydrogen present, with 15% hydrogen in air. The entire system was designed for a hazardous environment. The ventilation fan blows into the tunnel, similar to a mine face, with fresh air returning to the tunnel opening. The ventilation fan hub and blades were manufactured from a composite material that cannot spark nor create heat, which could otherwise potentially ignite the hydrogen. The fan body was painted with an antistatic material. A 55 kW explosion proof motor (WEG) drives the fan. Fig. 4 shows images of the custom built ventilation fan with the 55 kW variable frequency drive used to control
the fan speed and therefore the volume flow. Volume flow control is required to perform tests at various ventilation volume flow rates.

Figure 4: Custom built ventilation fan with the 55 kW variable frequency drive

3. RESULTS AND DISCUSSION

3.1 Data from Temperature and Relative Humidity Experiments

The same experimental conditions were applied to all the hydrogen detectors here. Table 1 shows the relationship between RH, temperature and the amount of water (in grams) present at the experimental conditions. It is clearly evident that a larger amount of water is present at higher temperatures and RH compared to at higher RH and lower temperatures.

Table 1: Water content in air at 100%, 90% and 70% saturation at various temperatures.

<table>
<thead>
<tr>
<th>Temperature (℃)</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (bar)</td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Water saturation g H₂O/kg Air</td>
<td>10.101</td>
<td>14.199</td>
<td>26.667</td>
<td>49.318</td>
<td>89.227</td>
</tr>
<tr>
<td>Water g H₂O/kg Air (90% humidity)</td>
<td>9.091</td>
<td>12.779</td>
<td>24.000</td>
<td>44.386</td>
<td>80.305</td>
</tr>
<tr>
<td>Water g H₂O/kg Air (90% humidity)</td>
<td>7.071</td>
<td>9.939</td>
<td>18.667</td>
<td>34.523</td>
<td>62.459</td>
</tr>
</tbody>
</table>

3.1.1 OEM Sensor 1

OEM sensor 1 is a thermal conductivity sensor with a built-in temperature compensation function. Fig. 5 shows the detector output value when subjected to 2% hydrogen in air, as a function of temperature (℃) and RH (%), respectively. Once the hydrogen was introduced directly to the sensor, measurements were recorded every 300 ms.
It is evident that the higher RH and temperature has an effect on the response of the detector. At higher RH the response times are slower, while at a higher temperature the only observable difference is the measurement of the final hydrogen concentration, which is slightly lower when compared to lower temperature.

### 3.1.2 OEM Sensor 2

OEM sensor 2 is also a thermal conductivity sensor with a built-in temperature compensation function. Fig. 6 shows the detector output value when subjected to 2% hydrogen in air, as a function of temperature (°C) and RH(%), respectively (%). Once the hydrogen was introduced directly to the sensor, measurements were recorded every 300 ms.

It is evident that the high RH only influences the measurement value of the maximum hydrogen concentration. Both RH and temperature have little to no effect on the response time.
3.1.3 OEM Sensor 3

OEM sensor 3 is also a thermal conductivity sensor with a built-in temperature compensation function. Fig. 7 shows the detector output value when subjected to 2% hydrogen in air, as a function of temperature (°C) and RH, respectively (%). Once the hydrogen was introduced directly to the sensor, measurements were recorded every 300 ms.

Figure 7: OEM hydrogen sensor 3 output value (%) as a function of ambient temperature

It is evident that a change in RH and temperature has little to no effect on the performance of the sensor.

3.1.4 HySA Infrastructure Fast Response Zone 0 H₂ Sensor

Fig. 8 shows the detector output value of the flameproof fast response HySA Infrastructure sensor (HySA H₂ sensor) when subjected to 2% hydrogen in air, as a function of temperature (°C) and RH (%), respectively.

Figure 8: HySA hydrogen sensor output value (%) as a function of ambient temperature (°C)
The measurements were recorded every 20 ms. However, to effectively display the data points, the iterations were converted to every 200 ms. This sensor has a very fast response time compared with the other three OEM sensors (Sections 3.1.1–3.1.4). Higher RH has a slight influence on the response time of the sensor while the temperature has a definite effect on the measurement value of the maximum hydrogen concentration. The overall performance of this sensor is considered very good, especially considering that it is flameproof.

3.1.5 Concluding Remarks

Experiments were set up to test our HySA Infrastructure proprietary hydrogen detector, to evaluate performance and record data output under various temperature and RH conditions. The conditions selected were typical conditions present in deep underground metal mines. These mines experience high temperatures and high humidity conditions. The response and output values of the detectors were compared to the output values at standard conditions.

Results showed that the detector output values are affected by temperature, which is an expected outcome. Temperature compensation is required when using thermal conductivity detectors. The specific detector used was calibrated to measure 2% hydrogen at 25 °C; it requires temperature compensation through the software used for measurement to compensate for all other temperatures. (The information required to perform the compensation programing is known.) Furthermore, the output response time is affected by the RH. At higher RH, the sensor response time became slower; some of the sensors took several milliseconds longer to respond.

3.2 Data from the Ventilation Test Facility at the Kloppersbos Facility

The data obtained from the Kloppersbos ventilation facility are shown graphically in Fig. 9, where the following are included: distance from the source, the ventilation conditions and the concentration of hydrogen in parts per million (ppm) measured. The leak rate of hydrogen in all tests was 5 L/min. The graphs displayed in Fig. 9a and 9b give the average values measured by the sensors placed at positions 1 m and 2 m above ground, respectively. This is also the height above ground of the hydrogen source/leak [7].

![Figure 9: Average hydrogen concentration (ppm) detected by sensors placed (a) 1 m above ground and (b) 2 m above ground](image)

It is important to note that tests were carried out at low pressure/leak rates. Ventilation has been shown to have a considerable effect on the concentration of hydrogen measured. In all scenarios here, noticeable changes in the concentration of hydrogen were recorded at distances of 1 m and closer to the source, with the sensors placed 2 m above ground, in order to measure high hydrogen concentrations at distances up to 7 m. This effect was expected because hydrogen is very buoyant; it will rise once it is
released. Our results further indicated that the ventilation did ensure that the hydrogen reached the further sensors; however, it was dispersed almost completely before reaching 8 m.

Although results of these experiments provided insight into the propagation of hydrogen, they can only be considered as initial experiments, with the purpose of illustrating the proof of concept (PoC) for the tests performed. Our results showed consistent and explainable results. Hence, it was envisaged that similar types of tests would be appropriate, but they should be carried out at higher/more realistic pressures, leak rates and leak diameters.

The ventilation tunnels at Kloppersbos were actually designed specifically for coal mines. The geometry of mine tunnels typically found in coal mines is considerably larger than the mining tunnels found in South Africa’s gold and platinum mines. Furthermore, the ventilation requirements in metal mines are much higher (air flow ca. 8 m/s). This ventilation tunnel could only provide up to 2.5 m/s. At the low leak rates and pressure of these initial experiments, this low ventilation was considered sufficient. However, at higher leak rates and particularly pressures, more realistic higher ventilation rates are required. The ventilation tunnel at Kloppersbos is therefore not considered adequate for experiments that could provide suitable results for metal mine conditions. An experimental setup is required that is comparable to the geometries and ventilation conditions that are actually experienced in metal mines. The sensors that were used have a very narrow range and low hydrogen detection ability.

Our experiments provided repeatable and reliable test results, showing that they were indeed successful, however, they could only be considered as PoC-type experiments. Future experiments will also require considerably more sampling points and thus more sensors in various configurations, and with more sensors that can measure up to 10% hydrogen.

3.3 Data from the Ventilation Test facility at NWU Engineering Campus, Potchefstroom

Preliminary tests were performed in the VTF at the NWU Engineering Campus [19]. The sampling point positions are given in Table 2. The stand on which the sensor was mounted was positioned in line with the leak point at various distances and heights.

Table 2: Sensor positioning inside the VTF at NWU Engineering Campus.

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>1.05</th>
<th>1.05</th>
<th>1.05 / 1.30</th>
<th>1.05 / 1.30</th>
<th>1.05 / 1.30</th>
<th>1.05 / 1.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>0.75</td>
<td>1.0</td>
<td>1.25</td>
<td>1.5</td>
<td>1.75</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The hole size of the hydrogen leak and the pressure were varied. The test parameters are given in Table 3.

Table 3: Sensor test parameters used in tests at NWU Engineering Campus.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Hole size (mm)</th>
<th>Pressure (bar)</th>
<th>Air flow rate 3.14 m³/s</th>
<th>Air flow rate 4.84 m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.572</td>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>8</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>12</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 10 provide a graphical presentation of the data obtained during the leak tests in the generation 1 ventilation test facility shown in Fig. 3.

![Graphs showing hydrogen leak data](image)

Figure 10: Preliminary hydrogen leak data obtained from the VTF site at NWU Engineering Campus at constant air flow (fan speed: 500 rpm)

The location of the ventilation ducting is situated in the right corner in each of the graphs and are represented by a dark blue color (zero H₂ concentration). The dark red area (high H₂ concentration) to the left bottom in the leftmost image of each experiment (1 m distance) is the location of the hydrogen release. The generation 1 ventilation test facility (Fig. 3) has multiple sensors with wider measuring ranges and results are represented in 3D plots, which eased visualization and interpretation. Until recently, several experiments were conducted with varying pressures and leak hole sizes.

Three data sets are represented in Fig. 10, 20 bar hydrogen release through 0.8 mm and 1.5 mm hole sizes respectively and a 50 bar hydrogen release through a 0.8 mm hole size. All three data sets clearly show the movement of hydrogen through the tunnel. The 50 bar release results in higher concentrations and mixing of hydrogen whereas the 20 bar release shows less mixing and lower hydrogen concentrations. It is further observed that for the 20 bar release, the hydrogen cloud moves to the bottom right of the tunnel before it exits, with a surprisingly high concentration of H₂ resulting in low diffusion. This effect is a result of the hydrogen velocity and airflow patterns caused by the ventilation in the tunnel.
At this point, our results are only initial values and tests are ongoing. They nonetheless provide valuable information regarding safety distances from leak points to ensure no operation inside an area where the hydrogen concentration is in the flammability range.

4. CONCLUSION

Three OEM sensors was evaluated and tested under conditions similar to those experienced in deep underground metal mines. These tests showed the effect of RH and temperature on the performance of these sensors. Furthermore, a flameproofed hydrogen sensor (Zone 0) developed by HySA Infrastructure was also tested and yielded satisfying results compared to the other commercially available sensors. Initial data were obtained for both the Kloppersbos and NWU Engineering Campus VTF.

5. AKNOWLEGEMENTS

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5. REFERENCES


