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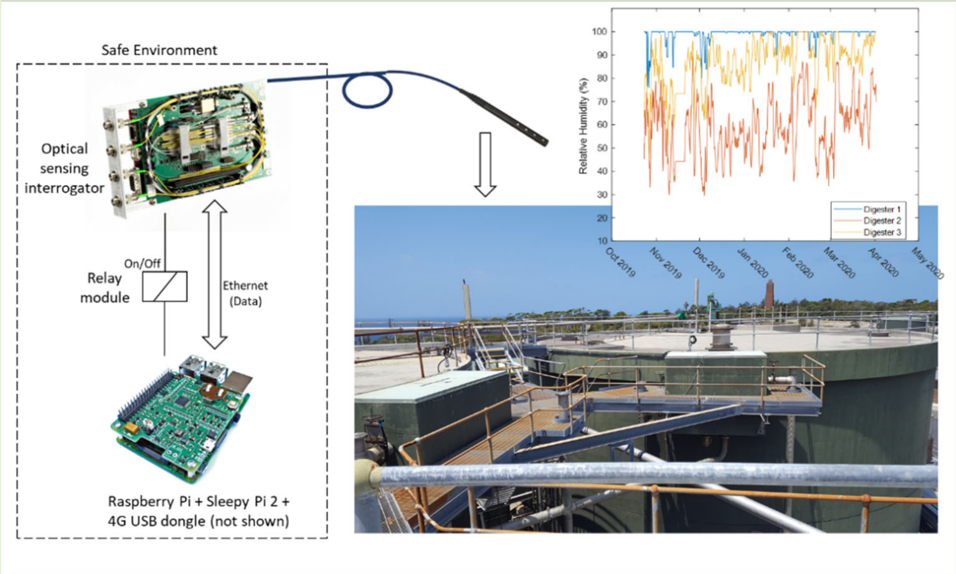
Citation: Rente, B., Fabian, M., Vidakovic, M., Sunarho, J., Bustamante, H., Sun, T. ORCID: 0000-0003-3861-8933 and Grattan, K. T. V. ORCID: 0000-0003-2250-3832 (2021). A Fiber Bragg Grating (FBG)-Based Sensor System for Anaerobic Biodigester Humidity Monitoring. IEEE Sensors Journal, 21(2), pp. 1540-1547. doi: 10.1109/JSEN.2020.3017108

A Fiber Bragg Grating (FBG)-based sensor system for anaerobic biodigester humidity monitoring

Bruno Rente, Matthias Fabian, Miodrag Vidakovic, Jerry Sunarho, Heriberto Bustamante, Tong Sun, and Kenneth T. V. Grattan



Abstract— **An operational, Fiber Bragg Grating (FBG)-based sensing system, specifically designed to monitor conditions in a harsh industrial environment is reported. The sensors used were placed inside tanks with high levels of methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S) gases and high relative humidity in the North Head sewage treatment plant in Sydney, Australia. The sensor system was developed primarily to monitor the effect of >98% relative humidity and temperature changes on the corrosion rates of various materials inside the tanks. Data have been obtained from the use of the system for eight months: these have been correlated with key climate data including the changing weather conditions experienced during the continued monitoring activity. The sensor system specifically developed has been shown to be sufficiently robust to work well, and safely, in such a harsh environment (due to the gaseous H_2S and CH_4 present) with no signs of deterioration of the sensors or of the signals obtained from the system. The remote operation through flexible data transmission has allowed continuous and up-to-date monitoring of the conditions inside the tanks.**

***Index Terms*— Fibre Bragg grating, humidity sensor, anaerobic digester.**

I. INTRODUCTION

HUMIDITY PLAYS a key role in the microbiologically induced corrosion (MIC) of concrete structures, including wastewater networks and treatment systems. Often the exposed surfaces of these assets are coated with protective coatings or liners to stop the MIC process from taking place. However, despite that, there remains the need to understand the performance behaviour of various coating and cementitious materials used, when operated long term in such a corrosive environment [1]. This enables both the asset owners and the system operators to select the most effective approach for managing and maintaining their concrete assets, given their susceptibility to the common problem of MIC.

The corrosion of the structural concrete is a common problem which affects sites like these, where the wastewater treatment process generates a large amount of gaseous hydrogen sulfide (H_2S), that is microbiologically oxidized to sulfuric acid resulting in concrete corrosion.

It is known that the high levels of relative humidity present have been shown also to accelerate the MIC reaction [2]. Thus, monitoring the humidity in the concrete sewer pipes or plant infrastructure used, where H_2S is known to be present, is important to understand better the potential for the creation of the corrosive, wet, acid environment. Prior work has shown that conventional electrical sensors often fail to deliver reliable data because they are prone to degrade due to the corrosive

This paper was submitted on 12th of July 2020.

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environment and their performance deteriorates within a relatively short period of time, making long term monitoring expensive – or in some cases impossible. Recent collaboration between City, University of London and Sydney Water to develop and use innovative techniques in monitoring had generated sufficient data to prove the feasibility of employing photonic sensors successfully, and for long term operation, in such an environment [3,4]. As a result, asset owners could optimize the ambient conditions, creating the good ventilation needed to allow humidity values to drop to where the formation of significant quantities of sulfuric acid is thus greatly reduced.

The study described in this paper has been carried out to assess the performance of the photonic-based humidity and temperature sensors developed for the purpose and installed in this corrosive environment that exists inside the three field-based testing chambers that were evaluated. The chambers used mimic various conditions that exist in the wastewater network and in the treatment system. This enables the engineers from Sydney Water (working with its partner research organization) to test various sewer coating material specimens to evaluate their durability in the corrosive sewer environment present. The three chambers used for the tests contain different levels of gaseous H_2S and relative humidity. In tests like these, both parameters need to be monitored to understand their effect on the corrosion rates of specimens within the chambers. A non-optical H_2S gas monitor sensor, (but which, unfortunately, was determined could last for only 4-6 weeks in this environment) has also been employed. No durable (being able to operate reliably for >1 week) sensor to monitor humidity in this environment has been available up to now, thus limiting the development of useful models to better manage corrosion and better schedule preventative maintenance, with the consequent considerable saving of costs.

Previous work carried out in similar environments have demonstrated the use of optically-based, durable humidity sensors, designed as optical fiber-based systems [5]. As these are neither metallic nor electrical in the nature of the transduction mechanism, they offer the potential for satisfactory performance, which as prior work by Sydney Water has shown, cannot easily be achieved by other means as the commercial electronic sensors fail to survive [6]. Further, the gaseous products from the biodigesters consists of ~62% of methane gas, which is highly inflammable (in addition to other gases which do not present a hazard). The use of optical fiber sensors (as compared to conventional electrical sensors) eliminates any risk of explosion due to sparking, for example from electrical short circuits, in this dangerous atmosphere.

Several different approaches to design and implement high quality optical sensing systems have been studied, targeting a range of potential applications in industry. As the aim of the sensor system developed and implemented in this work has been to achieve temperature-compensated humidity data, several different methods have been considered and evaluated, such as tilted Fiber Bragg Gratings [7] and Fibre Bragg Gratings written into polymer optical fiber [8,9]. However, the issues involved in using these latter approaches for this application is that they would require further preliminary, feasibility studies such as is seen in the work of Leal-Junior *et al* [10,11], prior to their being used in industry to establish any problems with their long-term use that would need to be overcome. From the prior work done by the authors for several different applications, it has been verified that systems based on fibre Bragg gratings (FBGs) represent an excellent means to acquire data on humidity and temperature reliably and in the long-term [3].

The focus of this particular study is the real-time monitoring of the three testing chambers discussed above, to ensure their long-term and reliable measurement of humidity and temperature using an approach which is intrinsically safe. The key issue here is to create a system in which such measurements allow better monitoring and thus control of corrosion within the digesters.

This paper thus reports on a series of measurements taken with the use of the sensor system described and developed, installed and operated, over a continuous period of six months during which important information on their functioning could be seen. The aim of the tests carried out was to validate their performance and report on the reliability and robustness of the sensor system used in this biodigester. Such a study is important as this is typical of treatment plants used not just in Australia, but internationally, and therefore the results obtained and the performance observations made will be of significance in many countries across the world where similar treatment regimens are used.

II. THE SENSING SYSTEM AND DEPLOYMENT

As noted, the combined fibre optic-based sensor system developed specifically for the particular application in this work builds on prior research carried out to make high quality, reliable measurements in a range of hazardous environments [3,4]. The fundamental principles of the sensor system have been reported before, with Fiber Bragg Grating-based devices chosen due to their reliability and robustness. Figure 1 shows the sensor layout, where FBG1 is uncoated and used for temperature measurement (alone) with a central wavelength of typically 1537 nm at room temperature; FBG 2 is coated with a layer of polymer so measures both humidity induced strain and temperature changes and its typical central wavelength is 1543 nm. Their wavelength separation is greater than 5 nm, to avoid any ambiguity in the measurements made by each. While the use of such FBGs in sensor systems is familiar in this quasi-distributed approach, what is critically important is the way the sensor itself is actually fabricated for field use – how it is 'packaged' and thus tailor-designed to meet the physical demands of the environment into which it is to be placed. The FBGs themselves were ~5 mm in length, written using light from a KrF* excimer laser (at a wavelenth of 248 nm through a phase mask) to imprint the refractive index change on the fibre (and thus create the FBGs) [12]. A hygroscopic coating was then applied to the fiber through a multiple dip-coating process to build up sufficient material to coat the FBG to create a sufficient mositure sensitivity (the dip-coating process is described in detail in prior work by some of the authors [4]). Polyimide (PI) was chosen as the active element for coating the sensor (supplied by HD Microsystems PI-2525).

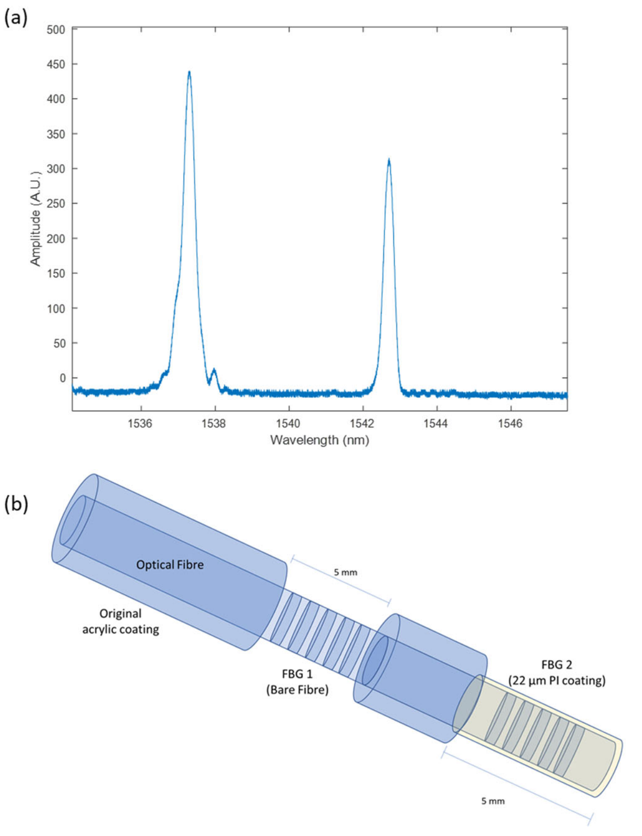

Fig. 1. (a) Spectral response of the FBGs written in the fiber, after the PI coating has been applied and (b) schematic of the sensor used in this work (where FBG 1 is the temperature (only) sensor and provides compensation for FBG 2, the humidity (and temperature) sensor).

Typically, ~20 layers were used to create an overall coating thickness of ~22 µm on the fiber and adhesion was improved by treating the bare fibre with 3-APTS (3-Aminopropyltrietoxysilane). Thus strain induced in one of the FBGs through the swelling of the hydroscopic coating can be monitored and noted as a wavelength change, and calibrated with respect to the level of relatively humidity which induces that change.

Using the wavelength change data obtained from the FBGs forming the basis of the sensors, the relative humidity (RH) could then be determined and appropriate compensation for any temperature (T) changes experienced could be included in the measurement. Fig. 2 shows representative data from the calibration procedure from one of the sensor systems used in the chambers for FBG1 (FBG(T)) and FBG2 (FBG(RH)).

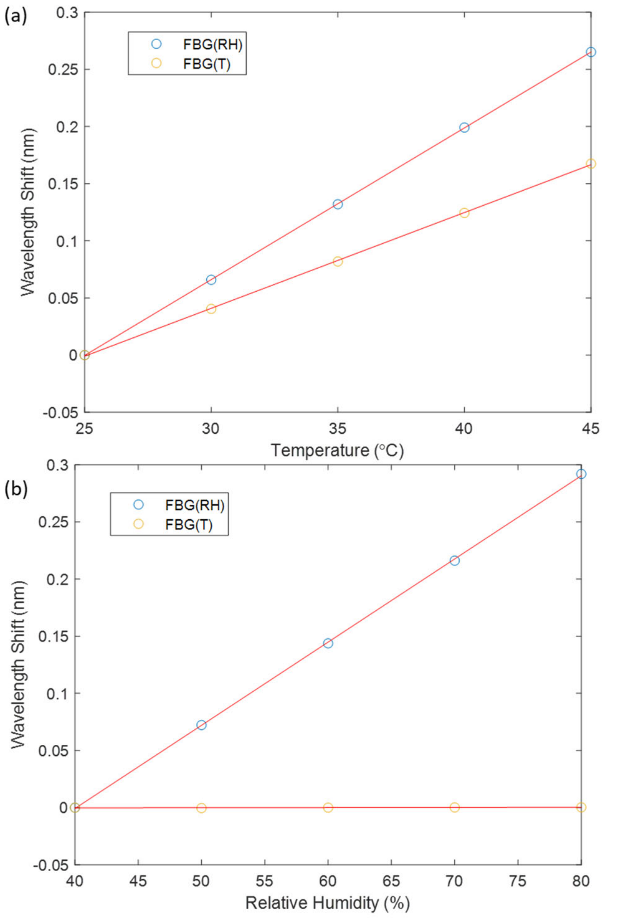

Fig. 2 Calibration graphs for the sensors used – FBG1 (FBG(T)) and FBG2 (FBG(RH)): (a) temperature effect at constant humidity and (b) humidity effect at constant temperature, showing data from one of the sensor systems employed and from (b) the stability of FBG1 (FBG(T)) with humidity changes.

The equations given below set out how both Temperature, T and Relative Humidity, RH could be measured for each sensor in the systems used:

$$T = \frac{1}{C_{T1}}\left(\lambda_1 - \lambda_{1(0)}\right) \qquad (1)$$

$$RH = \frac{1}{C_{RH2}}\left(\lambda_2 - \lambda_{2(0)} - C_{T2}\;T\right) \qquad (2)$$

where the parameters of the equations are as follows:

- $\lambda_{i\ (i\,=\,1\text{ or }2)}$ are the Bragg wavelengths (nm) of the two sensor FBGs, (FBG(T) and FBG(RH));
- $\lambda_{i(0)}$ their Bragg wavelengths at 0 °C (at which temperature the sensors are calibrated) so that the calibration parameters are directly calculated from the fitting of the calibration curve;
- $C_{Ti\ (i\,=\,1\text{ or }2)}$ are the coefficients for the temperature calibration (nm/°C), and
- $C_{RHi\ (i\,=\,1\text{ or }2)}$ are the coefficients for the moisture calibration (nm/%RH).

In matrix form, these changes in temperature and humidity reflected in the wavelength changes seen for the FBG peak wavelengths can then be described as:

$$\boldsymbol{\Lambda} = \boldsymbol{CX} \qquad (3)$$

where, in this case:

$$\boldsymbol{\Lambda} = \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} \quad \boldsymbol{C} = \begin{bmatrix} C_{T1} & C_{RH1} \\ C_{T2} & C_{RH2} \end{bmatrix} \quad \boldsymbol{X} = \begin{bmatrix} \Delta T \\ \Delta RH \end{bmatrix}$$

Here, C_{RH1} equals zero as FBG(T) has been designed so that it does not respond to the changes in relative humidity which are monitored by FBG(RH). The other coeficients are shown in Table 1. They were calculated using the linear fitting of the graphs in Fig. 2 (which also confirms the above-mentioned lack of sensitivity to RH of FBG2, FBG(T)).

Table 1. List of the sensitivities achieved and used in the calibration matrix (C) included in this work

	C_{T1} (nm/°C)	C_{T2} (nm/°C)	C_{RH2} (nm/% RH)
Sensor 1	0.011	0.011	0.002
Sensor 2	0.010	0.011	0.005
Sensor 3	0.010	0.012	0.003

The two Bragg wavelengths, $\lambda_{i\,(i = 1 \text{ or } 2)}$, are measured using a commercial Fibre Bragg Grating interrogation system. The two FBGs forming the sensors were calibrated in a commercial humidity chamber, in which a carefully controlled temperature and humidity environment was established and controlled (Binder KBF115). Sensor linearity had previously been determined, across a wide operational range, from 20% to saturation, as shown in Figure 3 [13], this being achieved both before and after a long duration exposure to H_2S gas in a sewer. For simplicity and in light of ensuring further viability in different industrial applications, the calibration was simplified so that it can be done in a way that is satisfactory in a standard humidity chamber, using 40% to 80% values of relative humidity, without jeopardizing the quality of the sensors.

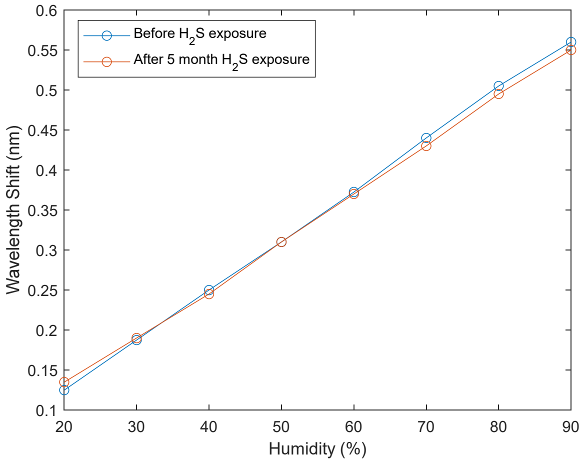

Fig. 3. Linear response of the FBG-based sensor system used over the humidity span from 20% to 90% and showing also the stability over a long-time exposure to H_2S [13].

A key aspect of the research plan has been to design and implement a sensor ‘packaging’ which will enable the sensors to be installed and used effectively in the challenging conditions of the biodigester. A design, based on that used in the prior work referenced, was adapted in which the optical fibres used were carefully placed inside a perforated PEEK (polyether ether ketone) tube. An outer diameter of 8 mm was seen as suitable for ease of handling, for this application [4] and this ‘packaging’ material was used because of its mechanical strength and chemical inertness. It also can be used at the higher temperatures experienced, which in this case was from 15 to 40 degrees (although it can withstand much higher temperatures if needed).

The design used mirrors, as implemented in the previous design, where an inner and outer tube with an in-between PTFE (polytetrafluoroethylene) layer was used to prevent any solids entering the tube and thereby causing damage in its operation. Thus the design was tailored specifically to the anaerobic biodigester, where high levels of humidity are experienced and to replace conventional electronic humidity sensors (which had been trialled unsuccessfully previously as the key driver for this work was that these sensors had been shown to have an unsatisfactorially short service lifetime – running in some cases to merely between 1 to 3 days), and thus unsatisfactory for the longer term monitoring required.

An important aspect of the sensor system designed is that it is intrinsically safe for deployment inside biodigesters, an environment with high levels of methane and other gases that could be inflammable. This safety consideration is ensured by the sensor system deployed near the biodigestors has been designed to be ‘all-optical’, thus avoiding electrical components being used at the actual biodigester measurement site. It is also important to note that the laser output of the sensing intrument meets the requirements of ATEX certification in terms of laser power (thus not to allow sufficient laser energy to be used to cause ignition of any of the explosive gases that may be present).

In light of the above~~,~~ in operation after the sensor systems were installed, the wavelenght shifts from the Bragg sensors were monitored using a four-channel Smart Fibres 'SmartScan SBI' interrogation unit. This single OEM module is sufficient to provide the measurements required from the three testing chambers, on site, that were studied. Its operation, as shown in Figure 4, was controlled by a Raspberry Pi 3B which also provides 4G connectivity to allow remote data transfer – such a system is both highly effective for this application and relatively inexpensive. In order to minimize the energy consumption (and thus extend the interval between intervention), the system was activated to make measurements at specified intervals e.g. 30 minutes and shut off between those times. Thus energy to power the system was saved as it was idle for the majority of the time – this low power mode of operation was achieved by the use of a Sleepy-Pi 2 module, which allows the rest of the system to go to complete shut down (known as sleep mode). The set of measurements acquired during a measurement period were then transmitted via 4G Network. Figure 4 shows a schematic of all the optoelectronic components of the system used, with the connections to the sensor probes and the 4G Network. The whole monitoring system was, for safety, enclosed in an IP65-rated enclosure, shown in Figure 5, thus being fully protected from dust and water and the fiber cables going up to the measuring site through conduits.

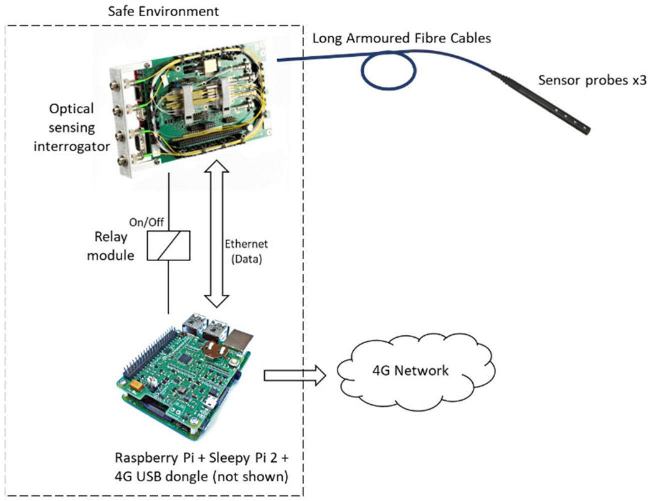

Fig. 4. Schematic of the monitoring system used.

The interrogator and data transmission (monitoring) unit was then installed in a safe place in the another building, well away from the potentially explosive environment experienced within the anaerobic digestors area and connected to the sensors (as described earlier) using long armoured fibres via two junction boxes. One junction box was located next to the monitoring unit and another located next to the testing chambers, above the digester tanks. This arrangement enabled easy servicing of sensors and provided the ability to add or reduce the number of sensors in the monitoring system, as required in the future. The multi-core armoured fibre optic cables ranged in length from 100 metres to 120 metres in total – this being very convenient for use and a valuable, positive feature of the use of a fiber optic device (where signal loss over such a length – or indeed longer if needed) is unimportant. The optical cables were inserted inside communication conduits to protect them from degradation by UV radiation (and accidental mechanical damage). Care was taken to ensure that the cables have long-radius bends when needed to navigate around corners. Prior to being connected to the monitoring unit and sensors, the cables were tested using an OTDR to ensure there were no breaks in the fibers.

A careful validation of the calibration was also carried out on site (an operation advised by most of interrogator manufacturers). A reference sensor (Odalog) was used for validation of the temperature values acquired from the FBG sensors.

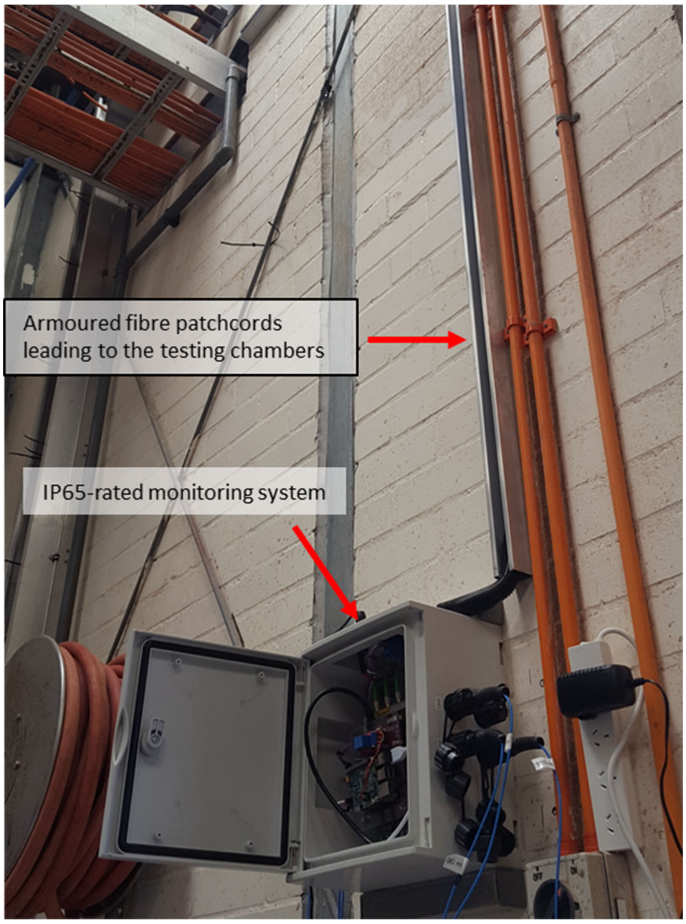

Fig. 5. Installed monitoring system in an IP65-rated enclosure and fiber cables going up to the measuring site through conduits.

Having all the cables installed as shown above and running into each of the biodigesters, taking into account the safety considerations mentioned and checking the 4G connectivity, the sensors were then placed ~two metres deep inside the testing chambers, as illustrated by the aerial photograph in Figure 6.

III. DESCRIPTION OF THE INSTALLATION ON THE CHAMBERS ABOVE THE NORTH HEAD WWTP BIODIGESTERS

Sydney Water's North Head Wastewater Treatment Plant (WWTP) maintains three Chambers, where the specimens were placed. Specimens were hung in the chambers to study the behaviour of mortars in this ultra-aggressive environment. The atmospheric concentration of hydrogen sulphide (H_2S) in the chambers often exceeded 500 parts per million (ppm), with daily averages regularly spiking above 150 ppm. Over a three-year analysis, the average daily H_2S conditions was 40 ppm in Chamber 1, 7 ppm in Chamber 2 and 24 ppm in Chamber 3. Overall the operational conditions for Chamber 1 were much more aggressive in nature, compared to those recored in Chambers 2 and 3.

The depth and location inside the tanks at which the sensors were placed was to create the right conditions for the measurements needed. Thus the sensors must be installed away from any digestate that have reached the chambers. They were connected to the long cables using IP67-rated fibre optic adapters, this choice being particularly suitable here due to the potential deleterious effect of the outdoor conditions, in particular the regular rainfall in the region. The satellite image of the North Head treatment plant (Figure 6) reveals the detail of the installation where the sensors were deployed, with a top view of the anaerobic digesters and the system location being illustrated in the photograph.

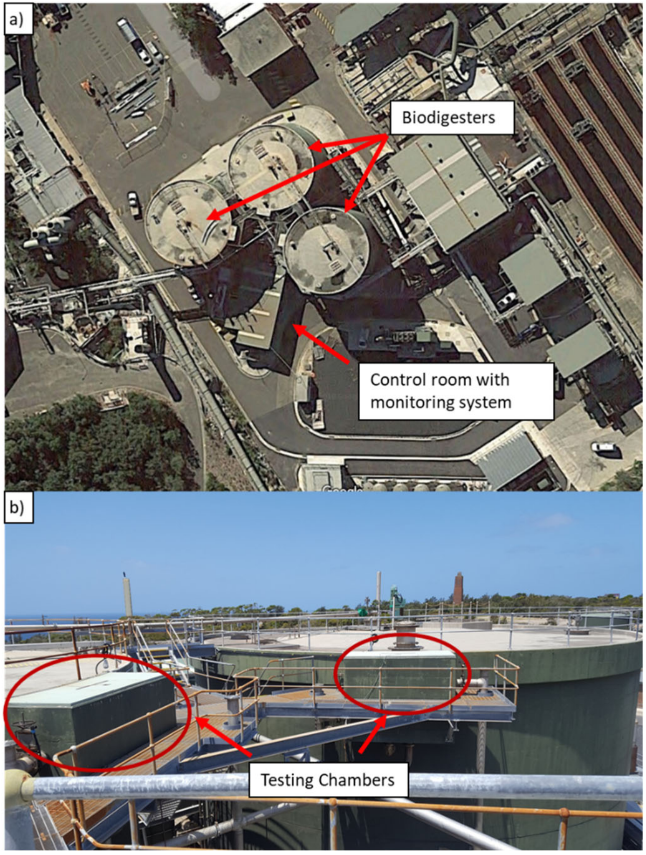

Fig. 6. Satellite image [14] of the anaerobic digester site (a), showing the key installation positions used in this work and the chambers attached to them (b).

IV. RESULTS AND DISCUSSION

With the sensor system intalled and verified as operational, initial measurements inside the three testing chambers were carried out with remote tranfer of the data made once per day. This allowed the team in charge to have a clear overview on the stability of the installed measurement system and the veracity of the measurements being made and transmitted on that daily basis. Key to a better understanding of the corrosion-related issues which underpinned this study, was that it was crucial to obtain accurate measurements which reflected the temperature changes that were occuring within the system, to provide a suitable correction (as can be seen from equations 1-3). As discussed above, a close knowledge of the temperature change is vital (to provide the correction) and thus for a clear knowledge of the humidity (alone) to be obtained.

The temperature data themselves, as obtained, also help to provide a picture of the situation within the chambers and a comparison over a longer period (of many months) can then be made with local weather data [15] which can readily be sourced.

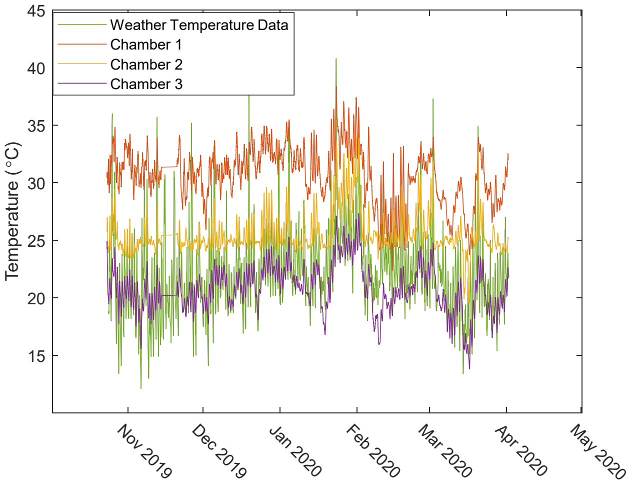

Fig. 7. Temperature data recorded for the three chambers, with, for comparison, weather data on temperature for the same period.

The monitoring system has a more fine temporal resolution than the more coarse data received from the weather stations (and therefore any short term, higher temperature, variations will be seen). It is noted that the chambers are exposed to the environment as can be seen from Figure 7 (so the weather plays an important role on the conditions inside their chambers). Despite the sludge from the anaerobic digesters being at 37 °C, the sensors were placed inside the testing chambers, which were enclosed and connected to the digesters although still separated from them.

As is illustrated in Figure 7, not all the testing chambers experience exactly the same temperature/weather environment, as is evident from the fact that Chamber 3 shows a temperarure behavior that more closely correlates to the weather data, by comparison to the other two. This is likely due to the piping arrangement of the testing chambers. At one time in the study, the plant operator selected a particular (Digester) testing chamber (primary chamber) that received the discharged gas and fluid from the anaerobic digesters, while the other two testing chambers (secondary chambers) only received excess gas and fluid from the primary testing chamber. However, conditions in each chamber will also follow the local conditions, which are influenced by the Digester to which they are connected. To confirm the hypothesis of the weather temperature to influence the temperature inside the chambers, a conventional temperature sensor (as part of the Odalog sensor for gaseous H_2S) was deployed in all chambers. Figure 8 ilustrates this influence of the local temperature on the chamber. It also shows that the chamber has some degree of temperature insutatiol, as it can be seen the FBG-based sensor temperature is always closer to the Odalog sensor data than to the data from the weather station. This would suggest that despite the weather influences the temperature on the chamber, the sludge temperature influence in not negligible.

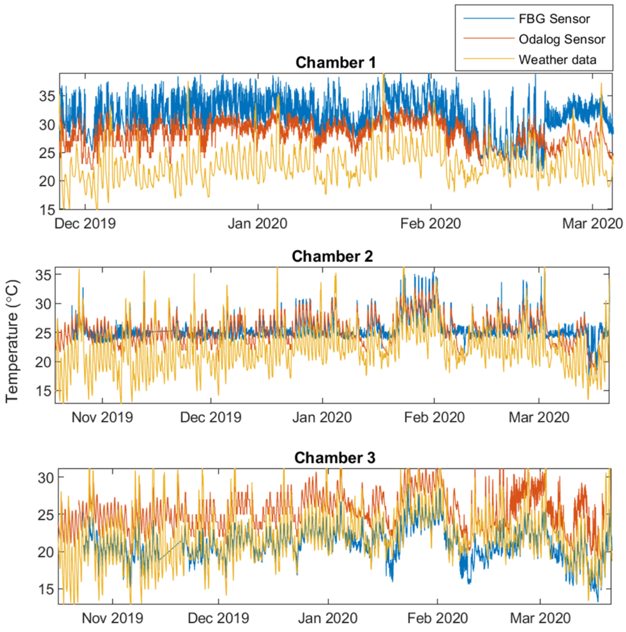

Fig. 8. Comparison between temperature from a conventional sensor, the FBG-based sensor and the weather data.

The measurement of the (temperature-corrected) humidity inside the chambers is particularly important and Figure 9 shows the behaviour monitored from the three chambers connected to each of the chambers (labelled Chambers 1,2 and 3) and for comparison, the humidity data received from the weather station. In this case, Chamber 1, as the primary chamber, shows a much higher humidity level than was seen for the other two. However, all the testing chambers share a common pipework run. So some gas and fluid from testing chamber 1 also went to chamber 2 and 3, (in this case mainly chamber 2). To ensure that this was not an anomoly or the result of measurement error, the data were double-checked by occcasional sampling of them with other sensors, such as the system used in prior work by one of the authors [1]. This showed that the measurements were indeed correct, as the humidity was indeed near the saturation level (~100%) for the whole period of the measurement in that biodigester. The data recorded for the other two biodigesters (Chambers 2 and 3) show a clear correlation with the weather data, but a different overall reading. The error was calculated to be <2 °C for the worst case scenario (Chamber 2) when compared to the Odalog (taking into account the FBG error, the error from the Odalog sensors and the environmental errors, such as could also come from the placement of the sensors). This gives confidence in the measurement: it is not to be expected that each biodigester will give the same humidity reading (due to the different local environment) but what is to be expected that they all will change in a reproducible (and indeed reversible) way with the change the local weather data on humidity, as was seen.

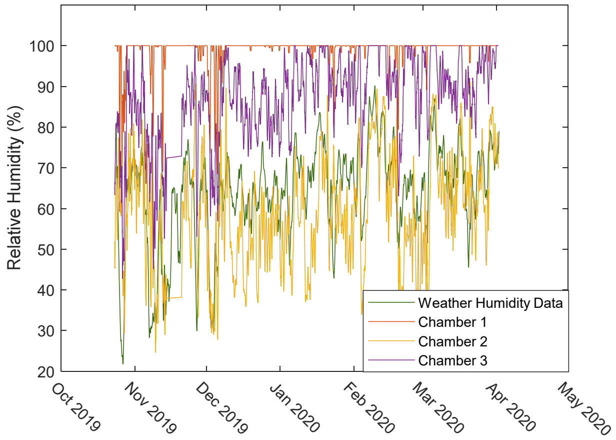

Fig. 9. Humidity data recorded for the three chambers, with, for comparison, weather data on humidity for the same period.

Another comparison that can be made to underscore the value of the data gathered is the measurement of humidity in Chamber 2, as a function of precipitation levels, as depicted in Figure 10. There is positive pressure inside the chambers because of pumping action from the digester tanks. It is then to be expected the conditions inside the chambers were not influenced by the precipitation levels. However, some influence *is evident* from this graph (again representing a period of some six months of continuous measurement). Higher precipitation levels are succeeded by higher humidity levels within the chamber (whenever there is ~20 mm or greater accumulated precipitation in a week). This means that during the rainy season, higher humidity levels are to be expected within the chambers – and this is confirmed by the data recorded.

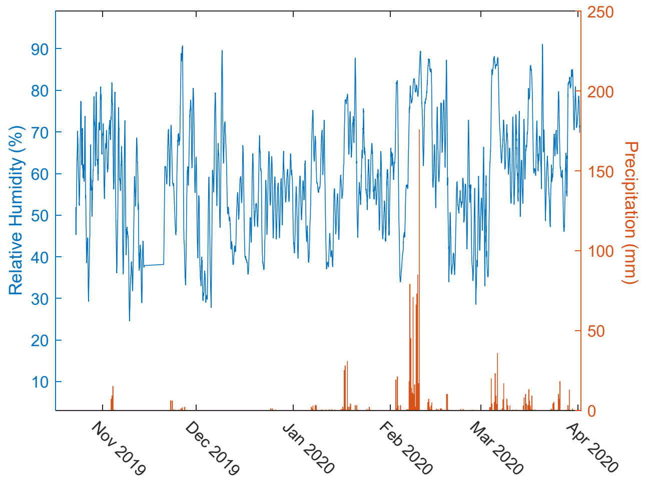

Fig. 10. Humidity data from biodigester 'Digester 2', with precipitation data in Sydney for the same period shown in comparison.

It is interesting to note the correlation of the measured data in the biodigester chambers, with the performance to be expected to result from the local weather conditions (and refected in the correlations seen in Figures 6, 8 and 9 with the weather data). However, this work has shown that humidity and temperature data can be extracted locally from *in situ* sensor systems, thus allowing the measurement of *actual* chamber performance, and it is evident from the data that this is not the same for each of the three chambers investigated. For example, it is interesting to note that the humidity data from Chamber 1 (as shown in Figure 9) – although it should be expected to have the same humidity behaviour than the other two, it has a much higher figure instead. This detailed knowledge of individual performance can then be a key aid for the maintenance team, now being able to assess data relating directly to the biodigester condition, in real time and act accordingly.

V. CONCLUSION

This work undertaken has shown the successful use of innovative fiber optic sensors for the safe, long term monitoring of humidity and temperature in the gas phase in anaerobic biodigesters. This has shown that it is particularly suitable for use in the methane-rich atmosphere of the chambers connected to the biodigesters, allowing the monitoring system to comply with the safety requirements, employing the optically-based approach used in this instrument.

It has thus been sucessful in measuring for the first time, continuous data over a long period of time (six months) under the challenging conditions experienced. The sensors responded well: not only by surviving the harsh environment but also working well under the diverse weather conditions experienced and achieving full, remote operation and data transmission.

This application thus demonstrates the succesful deployment and operation of such pratical, packaged FBG-based sensors, used here to overcome some of the challenges faced, and not met, by conventional electrical sensors. As the sensors are still in operation, visual inspection of their condition was carried out regularly. This inspection showed no signs of degradation or indication of potential 'drift' in comparison to the output of the reference sensors – suggesting that the sensors are 'healthy' thus not requiring stopping the experiment for the recalibration of the sensors. Signals were successfully transmitted from them during the whole period over which the measurements took place. This shows that this proposed method is a good choice to fill the gap in the sensing of key parameters, such as humidity in harsh acidic or explosive environments, experienced in biodigesters.

Along with the tests carried out by some of the authors on gravity sewers [4], this fiber optic sensor-based approach can lead to a full integration of an effective suite of sensors on the whole infrastructure owned and operated by water companies, tackling a long standing problem of lack of stability in convenitonal measurements and providing key data on the monitoring of wastewater structures and treatment plants.

Future work will focus on monitoring of additional parameters, such as the pH of the environment or the presence of other gases – all designed to allow a better understanding of the key corrosion issues and to enable the carrying out of preventative actions in time and ina cost-effective manner.

ACKNOWLEDGMENT

Grattan and Sun are pleased to acknowledge the support from the Royal Academy of Engineering for this work. The authors thank Sydney Water for support and for permission to publish this paper.

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