Development of Optical Fibre Humidity Sensors for Assessing the Quality of Housing Insulation Materials

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ABSTRACT

A fibre optic-based relative humidity (RH) sensing system has been developed for assessing the qualities of housing insulation materials, based on a Polyimide (PI)-coated Fibre Bragg Grating (FBG) device. This forms the key moisture sensitive element, allowing a carefully-designed and packaged sensor system to be fabricated, evaluated and calibrated, creating the robustness and reusability needed. Following calibration, the system performance evaluated on a range of commercial housing insulation materials shows excellent performance in establishing the key moisture-transport parameters of the materials routinely used by structural engineers. Cross-sensitivity issues are addressed allowing the RH sensor system to operate over a wide range of RH level experienced normally in this application. A sensitivity of 1.1 pm/%RH, with low hysteresis from a ruggedized sensor, is observed.

Keywords: *Fibre Bragg Grating Sensing, Humidity Sensor, Housing Insulation Materials*

1. INTRODUCTION

Relative humidity (RH) has been widely accepted as standard metric of humidity level, being the ratio of the partial pressure of water vapor in the mixture to the equilibrium vapor pressure of water at a given temperature [1]. Humidity measurement has become necessary in a number of areas of structural health monitoring (SHM) [2] – this work discusses such an example in the SHM field to assess the humidity penetration and thus the quality of a range of housing insulation materials, important for minimizing energy use in the housing sector and thus benefitting the environment.

Humidity sensors of this type have been investigated due to their advantages over their conventional electric counterparts, both in terms of their broader sensing range, better repeatability demonstrated and the potential to be used in many different sectors. Furthermore, they are small and light, immune to electromagnetic interference and thus readily configurable into different types of probes, as well as being readily multiplexed over a large area. All this makes them highly suitable for working in harsh environments in the building industry.

Experiments have verified that polyimide (PI), as a moisture sensitive material, gives excellent linear relationship between relative humidity and the wavelength shift of FBG sensors [3, 4], as its volume expansion and shrinkage poses a strain on the FBG itself. Humidity sensors have been developed with differently designed packages tailored to various industrial applications including the building industry, where many insulation materials are extensively used.

To date, investigations into moisture insulation qualities of such materials, especially *in situ* and taking advantage of the properties of optical fibre sensors are rare. This work has focused on developing an FBG-based optical sensing system, targeting real-time and precise measurement of temperature and humidity for assessing the quality and suitability of housing insulation materials, as small changes in thermal conductivity and moisture sensitivity properties influence strongly their use.

2. SENSING PRINCIPLE AND MEASUREMENT PROBLEM

The FBG-based sensors that lie at the core of the devices are wavelength modulated and the operational principle is described elsewhere [1], but illustrated in Fig 1 and based on couple mode theory [5].

Figure 1. Sensing mechanism schematic of an FBG.

The Bragg wavelength shift that encodes the measurand can be expressed by

$$\lambda_B = 2 n_{eff} \Lambda \qquad (1.1)$$

The resonant wavelength λ_B depends on both the grating period Λ and the core mode effective refractive index n_{eff}, which means that strain (and also temperature) will affect the measured value of λ_B. PI, due to its advantages over a wide RH range, high-temperature resistance and corrosion immunity [6], is used to coat the FBG at the core of the sensor to create necessary sensitivity as its volume expansion and shrinkage will have direct effects on the FBG, which leads to the shift of the Bragg wavelength [7]. Thus

$$\frac{\Delta\lambda_B}{\lambda_B} = K_{RH} \cdot \Delta RH + K_T \cdot \Delta T \quad (1.2)$$

where K_{RH} and K_T is moisture and temperature sensitivity of the polyimide-coated FBG. Cross sensitivity can be solved based on the linear relationship using a double matrix method.

Uncontrolled moisture in buildings greatly increases the risk of harm to the building fabric and building occupants, accelerating decay and corrosion. This is generally the result of building defects, poor maintenance or inappropriate design and typically accumulates in interstitial spaces within walls, floors, and roofs, where it is difficult for conventional tools to measure. FBG-based sensors offer several key advantages for in sity use: smaller penetration holes, not requiring off-site laboratory measurement and ease of use in continuous monitoring.

3. SENSOR DESIGN AND IMPLEMENTATION

To deal with the cross sensitivity of temperature and humidity, a bare FBG for temperature compensation (FBG1) was multiplexed in series with a PI-coated FBG (FBG2) to allow the moisture level to be determined, as shown in Fig 2, irrespective of temperature.

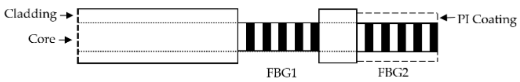


Figure 2. Schematic diagram for sensor structure.

Sensing elements were annealed at 180℃ for at least 4 hours after writing for stability. Subsequently, FBG2 underwent the coating process, using a multi-layer ‘dip coating’ method, after first being treated with 3-Aminopropyltriethoxysilane solution (0.1% 3-APTS) to enhance bonding [8]. A tailor-made package using a perforated stainless steel tube of 20cm length, outer diameter of 1mm and thickness of 0.2mm was developed, following which it was wrapped in Teflon to prevent the ingress of solid impurities. The humidity sensor thus fabricated is shown in Fig 3.

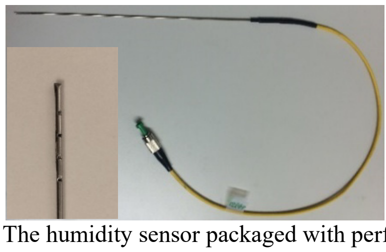


Figure 3. The humidity sensor packaged with perforated stainless steel tube (20cm length, 1mm outer diameter and 0.2mm wall thickness).

4. EXPERIMENTAL RESULTS

A Micron Optics SM130-700 interrogator was used to monitor its measurand-induced shift with temperature or humidity, following calibration. To calibrate the sensor accurately, a reference pre-calibrated humidity sensor was utilized to determine the environmental conditions for cross-comparison. The parameters thus obtained were then input into the LabView-based software, allowing users to monitor RH changes in real-time. The detailed calibration procedure used has been described elsewhere [1].

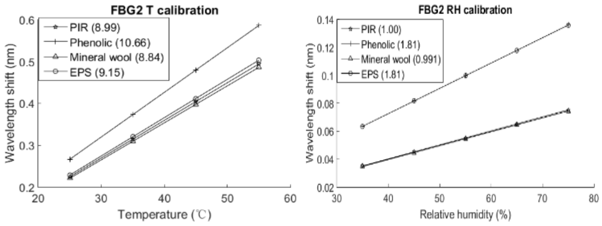
4.1 Testing results for house insulation material

Four familiar building insulation materials were tested for their qualities, these being PIR, Phenolic, Mineral wool, and EPS. The materials were chosen for two reasons, (i) they are some of the most commonly used insulation materials in the building industry and, (ii) they have significantly different porosity values and are therefore expected to absorb/release moisture at different rates. Each sample used had dimensions of 300(H) x 300(W) mm, while thicknesses used follow the industry standard (PIR: 9 cm, Phenolic: 8 cm, Mineral wool: 10 cm, EPS: 9 cm). To make the measurements, the sensor probes, designed as discussed to be sufficiently robust, were easily pushed into the center of each of the material samples and sealed with silicone sealant to maintain a relatively enclosed space, as shown in Fig.4. In the test, the temperature was kept constant at 25℃. To determine the moisture transport effects, the humidity in a controlled test chamber was increased from 30%RH to 85%RH, then kept at 85%RH for approximately 2 weeks and then allowed to fall to 30%RH – this being done to monitor the drying process.

Figure 4. Experimental setting of four types of insulation materials (FLTR: Mineral wool, PIR, Phenolic, BPS), each inserted by a humidity sensor.

Fig 5 shows the temperature and RH evaluation results for the four humidity sensors (type FBG2) implemented in this work. Here the legend indicates the specific insulation material measured by the sensor – it can be seen that each sensor shows a clear linear relationship between the wavelength shift and the change in humidity.

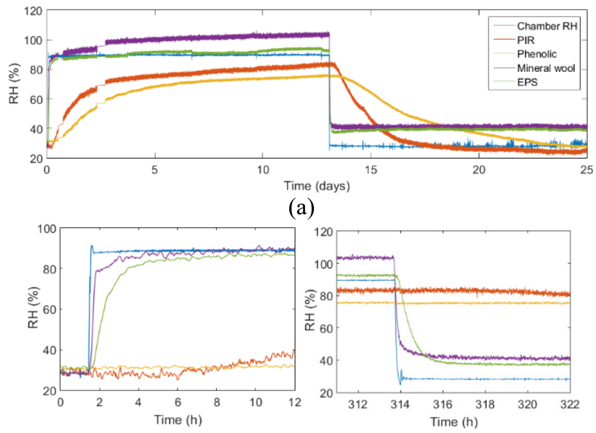
The purpose of the presented initial evaluation is to verify the suitability of the proposed sensing technology for this particular application. A 10-point average was implemented on the data to reduce the noise, and the humidity sensing results are shown in Fig. 6. The gaps in the data during day 1 and day 3 are due to a bug in the data logging software, but otherwise the results were unaffected. It can be observed that the rate of moisture absorption varies significantly depending on the porosity of the respective materials (a detailed analysis is currently being carried out as part of on-going work). Mineral wool and EPS absorb and release moisture very quickly while PIR and Phenolic take much longer to saturate.



(a) (b)

Figure 5. The temperature and RH calibration curves of the four humidity sensors implemented, where sensitivities presented in legend with units of ‘pm/℃’ or ‘pm/%RH’ respectively.

In Fig. 6, the absolute humidity values read by two of the sensors, i.e., those used to monitor the mineral wool and the EPS samples, differ from the expected calibration values of 85 %RH and 30 %RH (which indicates the necessity for refinement of the calibration routine for future tests). The key result is the measurement of the saturation time, which however, is not affected by this as it simply results in an offset.



(a) (c)

Figure 4. Humidity sensing results (a) entire monitoring period of approximately four weeks (b) the initial increase in humidity (c) the decrease in humidity after 13 approx. days.

Although a more comprehensive set of calibration tests is required to quantitatively determine the saturation time, τ, to a higher degree of accuracy, an exponential fit to the function $y = y_0 + Ae^{-(x-x_0)/\tau}$ was used to estimate it, with 10 times of the time constant τ usually being considered as full saturation. The results are shown in Table 1 for both increasing RH (middle column) and decreasing RH (right-hand column).

Table 1. Time constants τ of each material by exponential fit with ±5% uncertainty.

Material	τ (RH increase)	τ (RH decrease)
PIR	28.30 h	40.78 h
Phenolic	47.93 h	95.94 h
Mineral wool	0.34 h	0.16 h
EPS	0.78 h	0.60 h

5. CONCLUSIONS AND DISCUSSIONS

A novel tailored the design of humidity sensor system for the building industry, with temperature compensation integrated, was developed and successfully applied in the evaluation of key parameters on the quality of current housing insulation materials. The positive results demonstrate that *in situ* measurements on the four different materials can readily be obtained with this probe, which is small and lightweight, yet robust and reusable.

Future evaluations are planned to study the progression of humidity in multilayer materials with brick, insulation material and plasterboard, (as used widely by the construction industry), exploiting multiple sensing probes.

6. ACKNOWLEDGMENTS

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