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Quasi-Distributed Fiber Optic Temperature and Humidity Sensor System for Monitoring of Grain Storage in Granaries

Lin Zhao, Jiqiang Wang, Zhen Li, Moyu Hou, Guofeng Dong, Tongyu Liu, Tong Sun and Kenneth T. V. Grattan

***Abstract*—Mildew is an important issue in grain storage, due to the very expensive losses that can arise due to grain spoilage by mildew. Monitoring the conditions which allow mildew to develop is important and current monitoring technology cannot readily, or safely, be used for internal humidity monitoring of the very large quantities of grain kept in storage. In this work, a quasi-distributed, tailored fiber optic temperature and humidity sensor system suitable for use in the large granaries has been developed. Dust from the grain is a major issue and the sensor system copes well with this. Various sensor designs have been evaluated and building on prior work, a design with a humidity sensitivity of 5.8pm/%RH, a measurement error of 2%RH, and response time of 4.3 minutes, which is more than adequate for the applications discussed has been developed. Field-testing of the sensor system was carried out at a major storage facility in China, monitoring over an extended period of 4 months, giving results consistent with the outputs from other point sensors currently used in the granary. The fiber optic sensor system developed shows the additional advantages that as a quasi-distributed system, it can be used to record the temperature and humidity distribution across a longitudinal section of the large size of the grain pile, in real time, reflecting the changes in the internal moisture content. The results obtained showed the sensor system has broad market application prospects in this and other important areas of agricultural and food storage.**

***Index Terms*—grain storage safety, fiber optic sensors, temperature and humidity monitoring, distributed fiber optic sensing.**

I. INTRODUCTION

GRAIN is a major agricultural product globally and its safe storage is important to maximize the timing and financial return on its sale. However, the annual losses caused by mildew, pests and other hazards which cause spoilage to grain in storage across the world accounts for about 9% of total grain production, which bring enormous losses to the countries involved and especially to the grain farmers themselves [1]. This is a harsh environment due to the presence of dust particles from the grain itself and a further problem arises when the internal moisture content of the grain increases to more than 20% (the safe level of internal moisture content for long term storage is <12%), as the metabolism of the grain accelerates and the local temperature rises, which then readily accelerates mildew development in the grain. Thus, the internal temperature of the grain storage pile will be affected by the accelerated metabolism of the humid grain. To minimize losses, it therefore is necessary to maintain a proper temperature and humidity balance inside the granary – and this is facilitated by accurate, real-time temperature and humidity data being available across the pile of grain in storage. Such monitoring will facilitate making the changes needed to the ventilation and in the levels of costly (and environmentally damaging) insecticidal treatment otherwise needed. All this is strategically very important for the more effective and longer-term storage of the gain, thereby avoiding the conditions where grain mildew can form and ensuring the quality and safety of grain storage at a national and strategic level [2].

Grain monitoring silos, to date, mainly use digital electronic temperature sensors and resistance or capacitive humidity sensors to form what is currently described as a “Digital Grain Monitoring System (DGMS)”, which has been designed to monitor both the temperature of the granary itself and that inside the grain pile, as well as the humidity level inside the granary [3-6]. In the process of grain mildew formation, humidity is the prime parameter, followed by the inevitable internal temperature change both then accelerating damage. Through a closer knowledge of the temperature and humidity parameters *inside* the bulk of the grain itself, the changing grain quality can be more accurately evaluated and thus the conditions for the production of mycotoxins, especially aflatoxins, can be reduced and the quality of the grain more easily assured. A key weakness with current methods is that there is still no effective and safe technical means for monitoring the humidity change *inside the bulk of the grain pile itself* when in store [7]. Simply to monitor the humidity in a large granary space above the grain pile is not adequate and in order to prevent mildew formation, the grain moisture content needs to be sampled periodically during the actual storage

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process and across the bulk of the gain in store, to assess better the whole grain storage environment. The presence of grain dust can affect the performance of many possible humidity sensor systems that could be used. However, using conventional sensor methods, making such measurements across a large grain silo is both very time-consuming and laborious and not readily compatible with the real-time, online monitoring needed for accurate measurement of the humidity and temperature profiles across the breadth of the grain storage environment, to tackle spoilage.

Fiber optic sensing technology, as an approach successfully developed in recent years, can offer better measurement solutions for real time, *in situ* grain silo monitoring. Compared to traditional monitoring methods, fiber optic sensors show the advantages of being light weight and being non-electrical in nature, as well as being suitable for multi-parameter and quasi-distributed measurement in the grain silo. Further, the insulating nature of the fiber itself will not cause contamination to the grain and thus it can be used without any harm to the ultimate consumers of the product. Various fiber optic-based methods that could be employed have been reported, summarized and evaluated in the literature [8]. Amongst these approaches proposed are those based on Fiber Bragg Gratings (FBGs), Long Period Gratings (LPGs) and Tilted Fiber Bragg Gratings (TFBGs), for example, as well as interferometric-based methods, evanescent wave sensors and the use of Surface Plasmon Resonance (SPR)-based methods. Various sensors developed using these methods have different characteristics and are applied in many different fields. However, humidity sensors based on interferometric methods typically have high sensitivity, but are more difficult to use in the quasi-distributed, multi-sensor configuration needed for this application. Further, SPR sensor schemes are easily subject to interference by dust and other detritus adhering to the sensitive surface, so again the practicability of this approach *for this application* is poor. A brief summary of key methods discussed in the literature and their reported performance can be seen from Table I, below.

TABLE I

TYPICAL FIBER HUMIDITY SENSOR TYPES AND SPECIFICATIONS

Sensor method	Range (%RH)	Sensitivity and Response time	Ref.	Year
FBG	20-88	1.7pm/%RH , 33s	[9]	2017
LPG	60-95	0.15db/%RH	[10]	2018
TFBG	20-80	10pm/%RH ,12.25min	[11]	2017
TFBG	10-80	0.129db/%RH	[12]	2016
Michelson Interferometer	40-75	2.72nm/%RH , 3.6s	[13]	2019
F-P Interferometer	25-95	4.2nm/%RH, 336ms	[14]	2018
Evanescent wave	35-85	0.157dbm/%RH	[15]	2017
SPR	0-70	5.4nm/%RH	[16]	2017
SPR	0-100	0.03° /%RH	[17]	2018
SPR	40-90	1.01nm/%RH	[18]	2018

In light of the above, the approach chosen for this work was that based on FBGs as it represented the best compromise between ease of fabrication, use in a quasi-distributed mode and capability to be packaged to cope with being installed by non-specialists in the granary. The work reported also addresses the current requirement for combined temperature and humidity monitoring in a single packaged device used in the grain store and distributed across a large area of the stored grain pile, for which the quasi-distributed fiber optic temperature and humidity sensor has been developed specifically. To do so effectively, a simple, rugged sensor system was required, one that could be configured to be driven into the grain pile with some force applied, to be able to measure the temperature rise (and compensate for it) and also work well in the presence of the considerable grain dust present. For that reason, the work builds on an approach whereby a FBG in a fiber is coated, creating in this case a quasi-distributed measurement of temperature and humidity undertaken *in situ* and building on the coated fiber method which, as is shown, could be successfully created as ruggedized sensor system [19]. The successful in-the-field performance of the sensor system was proven in tests carried out in a wheat granary, with a high storage capacity (of 2700 tonnes), in Tai'an Grain Depot, Shandong Province, China operating under the jurisdiction of the China Grain Reserves Corporation. This technical approach thus provides solutions for online monitoring of grain storage, not only in China but globally, as similar monitoring problems are seen in many different countries.

II. SENSING PRINCIPLE

The approach used for the fiber optic temperature and humidity sensors employed is based on the principle of monitoring the change to a Fiber Bragg Grating (FBG), which is used as the basis of the transducer. Details have been published elsewhere [e.g. 8, 19] but in summary when the grating is subjected to external strain and thermal effects, the relative shift in the Bragg wavelength is given by

$$\frac{\Delta\lambda}{\lambda} = (1 - P_e)\varepsilon + [(1 - P_e)\alpha + \xi]\Delta T \tag{1}$$

where P_e is the photo-elastic constant of the optical fiber, ε is the longitudinal strain coefficient, α is the thermal expansion coefficient and ξ is the thermo-optical coefficient. After a uniform coating of the fiber containing the FBG is made with moisture-sensitive material, the expansion (and then subsequent shrinkage of the humidity-sensitive polymer coating when the humidity is removed) causes changes in the characteristic wavelength of the FBG, due *both* to the strain experienced by the grating from the humidity changes and from a further, typically larger strain change due to thermal changes to the sensor. As a result, the total shift in the Bragg wavelength is given by

$$\frac{\Delta\lambda}{\lambda} = (1 - P_e)\alpha_{RH} \cdot \Delta RH + [(1 - P_e)\alpha_T + \xi]\Delta T \tag{2}$$

where α_{RH} and α_T are the moisture expansion coefficient and thermal expansion coefficient of the coated FBG used [9]. The equation can be further simplified to

$$\frac{\Delta\lambda}{\lambda} = K_H \Delta H + K_T \Delta T \tag{3}$$

where ΔT and ΔH are the changes in temperature and relative humidity, K_T is the temperature sensitive coefficient of the grating and K_H is the humidity sensitive coefficient. For an uncoated FBG, (i.e. in the absence of the addition of a moisture sensitive material), equation (3) can be simplified to

$$\frac{\Delta\lambda}{\lambda} = K_T \Delta T \qquad (4)$$

With referencing of the output wavelength shift against a prior calibration, the ambient temperature of the grain can be determined [20,21].

III. SENSOR DESIGN AND TESTING

In light of the literature review undertaken and the need for a rugged sensor suitable for harsh, dusty conditions to be made available, a design using a polyimide coating on a FBG was used (Fiber type: Acrylate SMF-28e; FBG reflectivity: 95%, 3dB bandwidth: 0.205nm; Side-Mode Suppression Ratio:18.5dB) as the basis of the humidity measurement. This built on successful prior work [19] and thus was chosen as the basis of a new, ruggedized design for this specific application. Sensor fabrication was based on the FBG being written in a bare fiber and then treated with 3-aminopropyltriethoxysilane (3-APTS) solution, before being slowly coated with polyimide solution (POME Technology Co. Ltd, solid content: 12%~13%, viscosity: 5000-6000cp). To create the coating, it was dipped into the polyimide solution for 30 seconds and dried in a drying cabinet at 150°C for 300 seconds. This process repeated several times in order to obtain the desired film thickness and sensor sensitivity, following which a final curing at 180°C for 60 min was undertaken. In this way, a uniform, optimized coating of the grating surface was achieved, as was discussed in prior work by use of the dip-coating method. This type of sensor was seen as superior to other possible sensor methods e.g. SPR-based sensors which would readily be contaminated by the dusty environment. A photograph of the coated grating forming the basis of the sensor is shown in Fig. 1.

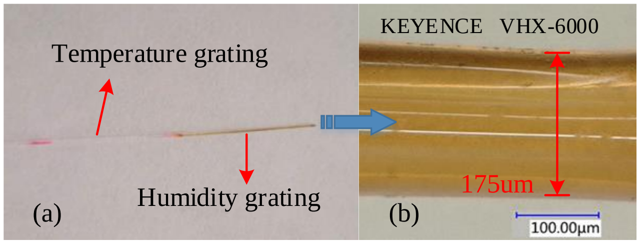

Fig. 1 (a) 'Bare fibre' sensor showing the position of the 'temperature' and the 'humidity' monitoring gratings; (b) close up photograph of the coated region (including scale)

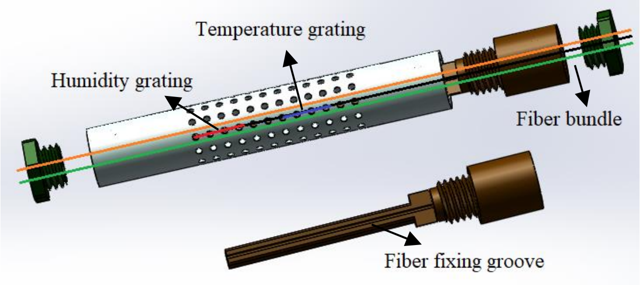

Fig. 2 Fixed groove structure for the sensor system developed

To provide a robust housing for the sensors for use inside the grain pile, and minimize the effects of the dust present, the coated grating-based sensor was then placed inside a fiber fixing groove, as shown schematically in Fig. 2. Each of the several sensor nodes used in the quasi-distributed sensor device was formed from one fiber with, as is shown in the figure, a combination of a humidity/temperature and temperature (only)-sensing FBGs. The several fibers used to form the quasi-distributed sensor are connected (to next sensor node) through the fiber fixing groove. The serial connection of multiple sensor nodes in this way creates the quasi-distributed fiber temperature and humidity sensor prototype, as shown in Fig. 3.

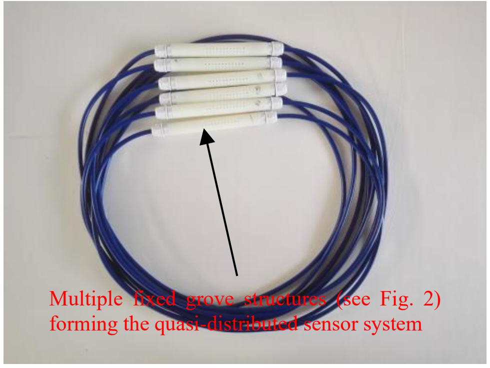

Fig.3 Quasi-distributed fiber optic temperature and humidity sensor system, showing the different sensor elements illustrated in Fig. 2

The sensor coating thicknesses used were 25, 27, 32, 37 and 41μm respectively and the sensor created were calibrated using a Michell temperature and humidity generator, whose technical specification is shown in Table II.

TABLE II
TECHNICAL SPECIFICATION FOR THE MICHELL GENERATOR USED

Parameter	Value
Humidity range	10-90%RH
Humidity measurement accuracy	±1%RH（10-70%RH） ±1.5%RH（70-90%RH）
Humidity stability	±0.2%RH（20-80%RH）
Temperature range	10-50℃
Temperature measurement accuracy	±0.2℃
Temperature stability	±0.1℃

In the experiments carried out, the temperature was fixed at 25°C and the relative humidity was adjusted over the range from 10%RH, through specific values of 25%RH, 40%RH, 55%RH and 70%RH, to 90%RH, where the variation in the sensor performance to monitor humidity is shown in Fig. 4. It can thus be seen that the sensor has good linearity in response to the changes in humidity over the wide range examined. Thus, over the range from 10%RH to 90%RH, the central wavelength of the FBGs used varies from the 'base wavelength', by a change amounting to between 0.295nm to 0.465nm. The humidity sensitivity of the several different sensors (S_1 to S_5) that form the quasi-distributed sensor system vary from 3.7pm/%RH to 5.8pm/%RH, this being determined from the calibration previously carried out. Thus the calibration coefficients for the sensors can be determined from the figure, measuring the slopes of the calibration graphs (this giving data for sensors S_1 to S_5). This has also allowed the calculation of the errors in the measurement to be made with the sensors and the results plotted in Fig.5. It can be seen that in all cases, the humidity measurement can be made to a very satisfactory figure of <±2%RH.

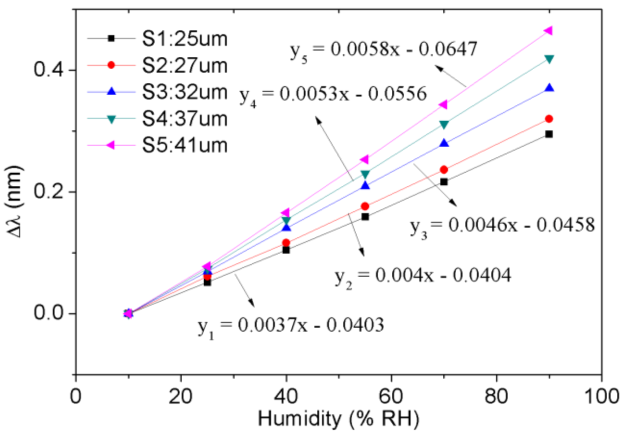

Fig.4 Calibration graph for the five sensors S_1 to S_5: showing the change in the FBG characteristic wavelengths as a function of humidity changes

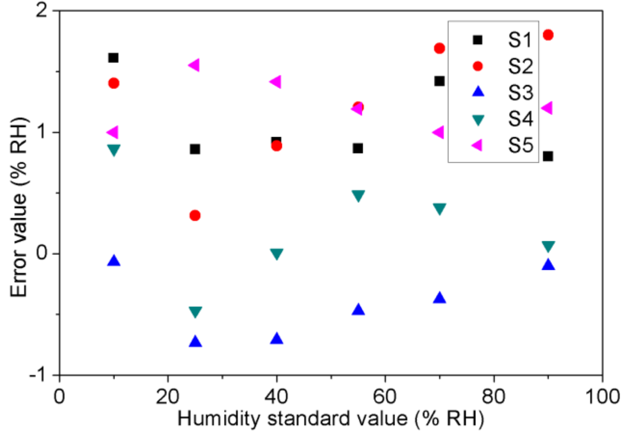

Fig. 5 Errors in the measurement of humidity for sensors S_1 to S_5

Calibration of the temporal response of the sensors, S_1 to S_5, was carried out in the following way. The sensors were placed successively in a chamber containing saturated salt solutions of LiCl (giving 11.3%RH) and NaBr (giving 57.6%RH), at a constant temperature of 25 °C. The wavelength change that occurred as the sensors responded to the different humidity levels created can be seen from Fig. 6. The temporal response of each humidity sensor can be represented, as is shown in Equation (5) below

$$t = |\Delta RH| \times 63\% \tag{5}$$

The data show that the response times of the various sensors are broadly similar, in the region 4.3 – 7.5 minutes [22].

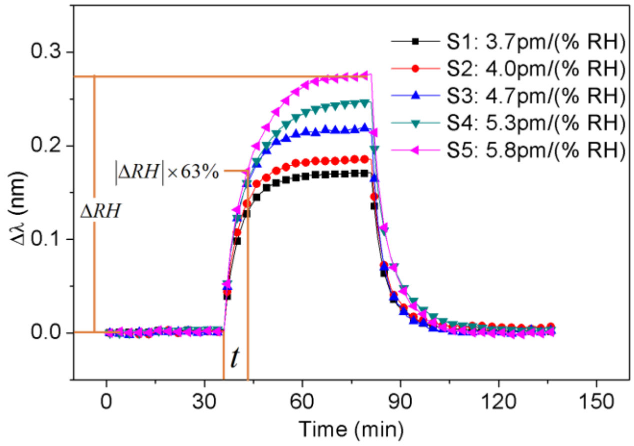

Fig.6 Sensor response time curve for sensors S_1 to S_5 showing the change in wavelength as a function of time

IV. IN-THE-FIELD EVALUATION OF THE SENSOR SYSTEM

In order to further establish the feasibility of the fiber optic temperature and humidity sensor in-the-field and monitor the performance achieved there, tests of the sensor system were carried out in a 2700-ton wheat granary at Tai'an Grain Depot of Shandong Province. A schematic of the sensor installation, (showing where the sensors were distributed across and through the grain store), is illustrated in Fig.7 for eight fiber optic temperature and humidity sensors numbered 1 to 8 ($F\text{-}T_1/H_1$ to $F\text{-}T_8/H_8$) distributed in such a way as to provide information about the condition of the grain. The system was evaluated for a period of four months and comparative data on the temperature and humidity from the fiber optic sensors used were obtained, comparing the outputs with the currently used sensors with those from the DGMS system ($E\text{-}T_1/H_1$ to $E\text{-}T_4/H_4$ and $E\text{-}T_5$ to $E\text{-}T_8$).

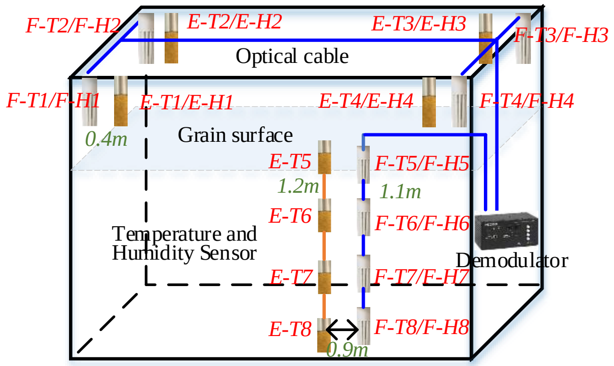

Fig. 7 Schematic of the placement of the fiber optic (F) and conventional (E) sensors (F/E-T_1/H_1 to F/E- T_8/H_8) cross-compared in the granary store

With reference to Fig 7, the fiber optic sensors $F\text{-}T_1/H_1$ and conventional sensors $E\text{-}T_1/H_1$ (capacitive humidity/temperature sensor from the DGMS, temperature measurement accuracy <±0.5°C, humidity measurement accuracy <±3%RH) were installed above the grain surface. Sensors $F\text{-}T_5/H_5$, $F\text{-}T_6/H_6$, $F\text{-}T_7/H_7$ and $F\text{-}T_8/H_8$ were placed *inside* the grain itself, with a vertical spacing of 1.1m, with sensor $F\text{-}T_5/H_5$ being located about 0.3m below the grain surface and $F\text{-}T_8/H_8$ about 1.5m from the bottom of the grain pile. Several of the conventional sensors ($E\text{-}T_5$, $E\text{-}T_6$, $E\text{-}T_7$ and $E\text{-}T_8$ are DS18B20 type digital temperature sensors, with a measurement accuracy <±0.5°C) and form part of the DGMS system. These were installed with a vertical spacing of 1.2m inside the grain pile and a horizontal spacing of 0.9m from the fiber optic sensors used ($F\text{-}T_5/H_5$, $F\text{-}T_6/H_6$, $F\text{-}T_7/H_7$ and $F\text{-}T_8/H_8$).

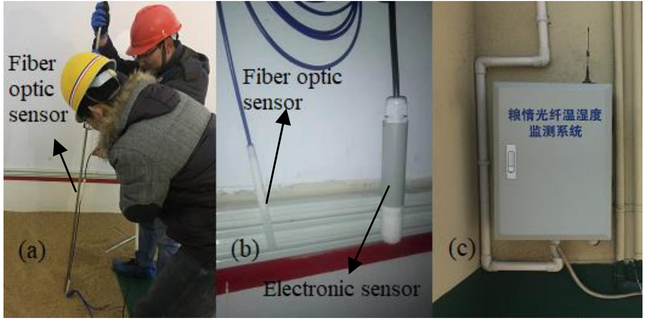

Fig. 8 Photographs of the installation of the sensors: (a) quasi-distributed fiber optic temperature and humidity sensor installed in the grain pile by using a steel chisel; (b) Schematic of the point fiber optic temperature and humidity sensor and the conventional electronic sensor; (c) Field demodulating prototype monitoring system for the “grain situation fiber temperature and humidity monitoring system”

A. *Temperature monitoring*

Figure 8 shows photographs of the installation procedure and this gives a clear indication that the sensors need to be able to withstand this demanding installation process by the technicians involved. Sensors *F-*T_1/H_1 to *F-*T_8/H_8 were used to obtain temperature data from the granary, with the output as shown in Fig. 9. In the study a comparison was made with point data from the conventional DGMS sensors, labelled *E-*T_1 to *E-*T_8 in the figure.

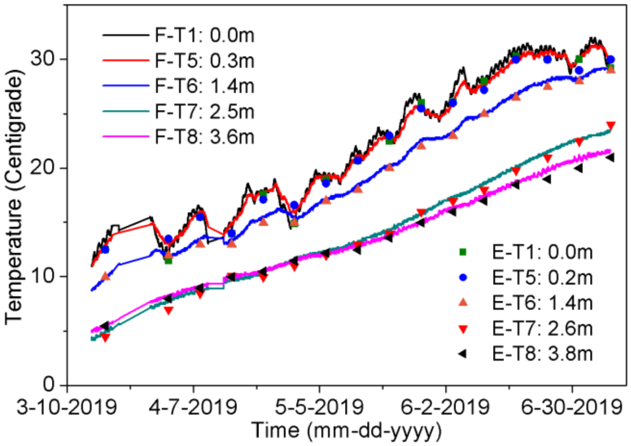

Fig.9 Temperature data from the Granary obtained using sensors F-T_1 to F-T_8 (solid lines) and for comparison sensors E-T_1 to E-T_8 (points) where for each the sensor position below the grain surface is also shown (in meters). Monitoring has occured over a period of almost 4 months (from 3-10-2019 to 6-30-2019).

A key novelty of this work is that long-term operational data has been captured from the installed sensors and the results show there is a close match between the outputs from the fiber optic sensors and the conventional sensors forming the DGMS. Considering that the data collection period was from March to July, the temperature trend *outside* the granary was showing a gradual increase in temperature due to the seasonal influences, and the temperature monitored *inside* the granary also shows a similar, obvious upward trend, (which is consistent with the external seasonal variation). As expected, the sensors located at different positions show different, yet consistent, temperature data. For example, the output from sensor *F-*T_5 reflects that it is close to the surface of the grain pile, experiencing heat coming from above it. Affected by this heating phenomenon, the data seen by sensor *F-*T_5 show a significant and more rapid series of temperature fluctuations (which is consistent with the data from the temperature sensor *F-*T_1 which is located at the grain surface). With the increase of the grain depth, the heat exchange between interior and external environment of the grain becomes slower (in the interior of the grain pile the temperature is more stable). There is a good correlation between the data seen from the fiber optic and the DGMS sensor systems when used for temperature monitoring.

B. *Environmental humidity monitoring*

The environmental humidity changes in the granary, monitored by the installed sensors, are shown in Fig. 10 with data obtained for both types of sensors over the same long monitoring period as was used for the temperature data.

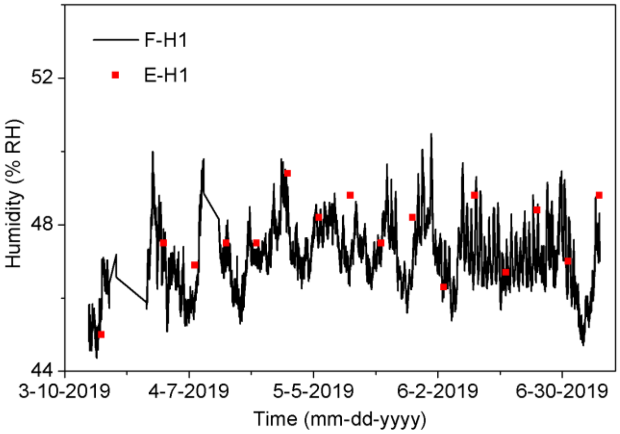

Fig.10 Humidity measurements made within the granary using fiber optic probe F-H_1 (solid line) and conventional probe E-H_1 (points)

The figure shows clearly that the humidity data monitored by the fiber optic sensor (F-H_1) are consistent with the series of single point data obtained from the DGMS sensor. Again, data were taken over the same 3+ months period reflecting, as a result, the variations in the internal humidity changes in the granary due to the similar seasonal and other changes that are occurring.

C. *Longitudinal profile humidity of grain pile*

One of the major advantages of the use of the fiber optic humidity sensors is that they can readily be distributed across the longitudinal section of the grain, and Fig. 11 shows the results of monitoring over the 3+ month period using the following quasi-distributed series of fiber optic sensors: *F-*H_5 、*F-*H_6、*F-*H_7、and *F-*H_8.

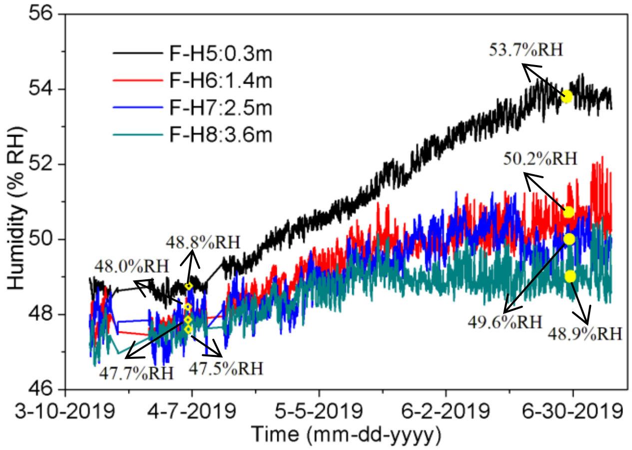

Fig.11 Humidity measurements made across a longitudinal section of the grain pile using sensors F-H_5 to F-H_8, at the various depths shown

When the grain pile is stacked high, there are few voids within the pile and the internal flow of air is relatively slow. Therefore, the small voids that form inside the grain pile can each be regarded as a closed space, at a constant temperature. The stable nature of the grain moisture content that arises is reflected in a stable grain humidity level. This obeys the grain hygroscopic isotherm rule (where there is an equilibrium relationship between the grain moisture content and its relative humidity). A fit of the hygroscopic isotherm, according to the Chung-Pfost model shows:

$$M = \frac{1}{C_3} \bullet \ln\left[- \frac{t + C_2}{C_1 \bullet \ln(ERH)} \right] \tag{6}$$

where ERH is the equilibrium relative humidity (%RH), M is equilibrium moisture content (%), t is the relative temperature (°C), and C_1, C_2 and C_3 are the equation coefficients [23]. In fact, each individual grain type yields a specific set of equation coefficients, taking into account the differences in the types of grain – in this case wheat – inside the granary and Lumai No.1 (SKCS hardness:18; wheat class: soft red winter; producing region: Shandong) is taken as the reference sample [24]. Using the estimation of coefficients C_1, C_2 and C_3 for different wheat types (obtaining data from Xingjun Li et al [25]) and equation 6, the variation of moisture content with relative humidity that results is shown in Fig.12, for temperatures of 10, 20 and 30 degrees Celsius.

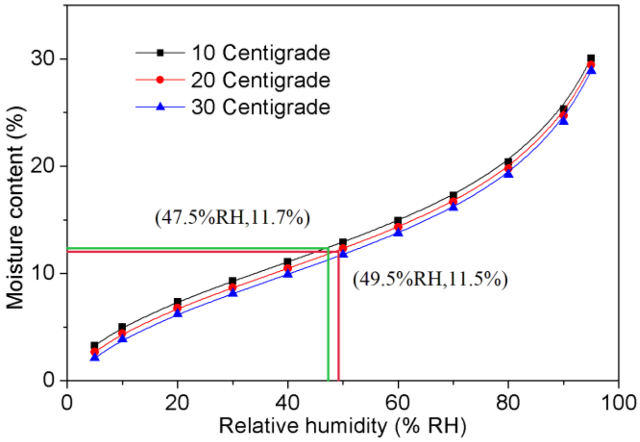

Fig.12 Wheat hygroscopic isotherm based on the use of the Chung-Pfost model

Granary management regulations require that the staff must regularly sample the wheat, and then test the moisture content after mixing samples from different positions in the silo. During the test period, the wheat was sampled at 11 different points, monitored over 4 different depths in the Granary on specific dates across the different seasons (in this case on April 5, where the average internal temperature of the grain was 10 °C and on June 28 where the average internal temperature of the grain was 20°C). After uniformly mixing the sampled wheat, the measured equilibrium moisture content was determined to be 11.7% and 11.5%, respectively. According to the Chung-Pfost model, the relative humidity values for moisture content 11.7% and 11.5% are 47.5%RH and 49.5%RH respectively, as shown in Figure 12. Calculating the daily average of the sensor detection data, a similar averaging process was performed on the humidity monitoring data from sensors $F\text{-}H_5$, $F\text{-}H_6$, $F\text{-}H_7$ and $F\text{-}H_8$ on April 5 and June 28, where the calculated relative humidity values in the grain pile were 48.0% RH and 50.6% RH respectively, data which are consistent with the above model calculation results (being monitored to within ~1% RH: the errors in the various fiber optic sensor measurements are given in Fig.5 above).

In addition, the hygroscopic isotherm of the grain studied is related to the temperature of the environment. When the moisture level of the grain stored lies in the range 10% - 20% and the moisture level is constant, for every 10°C rise in temperature, the corresponding equilibrium relative humidity increases by about 3% RH. The hygroscopic isotherm, shown in Fig.12, also confirms this. Referring to the internal temperature curve of the grain shown in Fig. 9, the temperature rises by about 15°C during the 3+ month monitoring period (from Spring to Summer), with a corresponding humidity change of 2 - 3% RH as monitored by the sensors $F\text{-}H_6$, $F\text{-}H_7$ and $F\text{-}H_8$, all of which is consistent with the humidity change predicted by the hygroscopic isotherm.

It should be noted that the period over which the experimental work was carried out was from March to July, covering the late Spring and early Summer seasons. As a result, the external temperature of the granary gradually increased with the outer grain temperature also rising gradually, while the interior of the grain pile was still maintaining a lower temperature. There is a warm airflow inside the granary which gradually penetrates into the interior of the grain pile, and a high-humidity area is readily generated at the junction of the cold and warm airflow, 300 to 500 mm from the surface of the grain pile. The sensor $F\text{-}H_5$ penetrates the grain pile 300 mm from the surface, in a zone prone to high-humidity, and the experimental data obtained further confirm this.

V. CONCLUSION

The motivation for this work has been the China Grain Protection Law which requires that temperature and humidity of grain in granaries must be sampled regularly, to prevent the occurrence of grain mildew and consequent financial loss. The work reported in this paper has discussed the choice and evaluation of a suitable technology to create a quasi-distributed fiber optic temperature and humidity sensor: with its performance validated in the Tai'an Grain Depot of Shandong Province, China. A major set of experimental measurements, taken over a 4-month period, show that the data obtained through an innovative quasi-distributed fiber optic sensor system are consistent with what is obtained with current sensors, using conventional technology, in the granary. However. the quasi-distributed measurement of temperature and humidity with a single fiber optic network used across the longitudinal section of grain has allowed the system developed to be installed by relatively unskilled technicians, reflect the variation of temperature and humidity at different depths of the grain in the presence of dust and localized temperature rises and thus offer a practical fiber optic sensor solution. This greatly improves the real-time monitoring performance achievable, allowing better management of granaries, together with improved safety from using a non-electrical monitoring system and thus overall reduced spoilage and consequent cost.

Future plans are to extend the work to develop a fiber optic distributed temperature and humidity sensor and monitoring system. Combining such a distributed monitoring system with

3D visual technology designed for use in granaries allows the possibility of a multi-parameter stereoscopic graphical display of the granary environment. Data from this system would further improve the potential for automated management of grain storage silos of this type.

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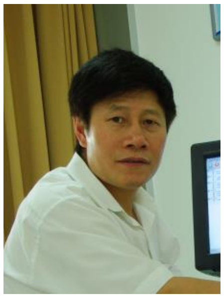

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