High Energy Physics Applications on Fiber Optic Sensors in Relative Humidity

Erat Krishnankutty Jishore[1], Rajendrakumar Ramadass[2]
[1]Lecturer, Mechanical Section, Engineering Department, College of Engineering & Technology, University of Technology and Applied Sciences - Shinas, Sultanate of Oman.
[2]Lecturer, Electrical Section, Engineering Department, College of Engineering & Technology, University of Technology and Applied Sciences - Shinas, Sultanate of Oman.

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ABSTRACT

Our multidisciplinary research group has been conducting studies in recent years on the use of fiber grating-based sensors for relative humidity measurement in the Compact Muon Solenoid (CMS) instrument at CERN in Geneva. In order to monitor low relative humidity (RH) values even in cold temperatures, our multidisciplinary research group has been working to develop near-field fibre optic sensors based on tin dioxide particle layers, in light of the extensive research conducted in the past few years to evaluate the radiation hardness capability of fibre optic technology in high-energy physics settings. Compared to other sensor types, optical fiber sensors provide several advantages. These benefits mostly stem from the characteristics of optical fibers, which include their tiny size, inexpensive, electromagnetic passivity, resistance to high pressure, and resistance to high temperatures. Sensing is the process of measuring variables like temperatures, stress, or angular velocity by examining the characteristics of light. To evaluate the sensors' performance under the circumstances needed for CERN experiments, untried tests in the [0-65] %RH range at various temperatures were conducted. There were other campaigns of progressive irradiation using γ-ionizing radiations. The results obtained show that the suggested technologies have great potential for usage in High Energy Physics (HEP) activities as a reliable and acceptable replacement for commercial hygrometers in the future.

Corresponding Author:

Mr Erat Krishnankutty Jishore,
Lecturer, Mechanical Section, Engineering Department,
College of Engineering & Technology, University of Technology and Applied Sciences - Shinas,
Sultanate of Oman.
Email: Erat.Jishor@utas.edu.om

1. INTRODUCTION

Many different application domains have found great benefit from the monitoring of relative humidity (RH), and numerous sensor systems and solutions have been put forth. Here, we concentrate on the use of fibre optic sensors (FOS) as the CMS (Compact Muon Solenoid), one of the CERN accelerator's sensors, for relative humidity (RH) monitoring under high energy particle (HEP) circumstances. The semiconductor micro-strip and pixel detectors, which are in charge of particle detection, may experience significant performance degradation as a result of the high radiation level brought on by the accelerator operating at maximum brightness [1]. The fluids' temperature must be maintained at or below -30 °C to prolong the life of the silicon sensors. Any moisture risk must be eliminated at very low temperatures, precise control of the temperature and humidity of the air entering the cold compartments of the sensor is therefore necessary.

Any humidity gauge positioned within the detector chamber must meet certain specifications, including being compacted, resistant to radioactivity (up to 1 MGy), insensitive to magnetic forces, able to provide accurate readings over long distances, and using fewer cables overall. The experience gained from developing and manufacturing the first batch of tracking sensors at CERN has made it abundantly evident that there aren't

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enough tiny sensors for monitoring relative humidity under challenging conditions. With its insensitivity to magnetic fields, optical fiber transmission is ideal for long-distance readout. Our interdisciplinary research team began working on the creation of new FOS layers for RH measurement at CERN in 2011.

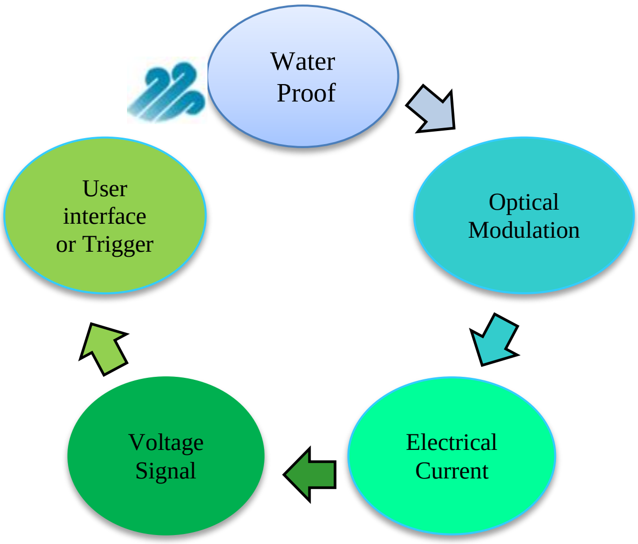

Figure 1.1 An Example of an Optical Humidity Sensor's Flow Diagram

The ratio of water vapour to saturation value in a mixture of water and air at a particular temperature is known as humidity ratio, or RH. Therefore, fewer water molecules are needed to reach 100% RH at a lower temperature [2]. The regular occurrence of condensate on colder surfaces allows one to witness this effect. Rather than varying the temperature, the quantity of water molecules is changed while testing a humidity sensor simply. This is due to the possibility that adjusting the setting could have unintended temperature-related consequences, such as thermal contraction, stress-optic, and thermo-optic effects. According to Figure 1.1 a humidity sensor is an object that measures the RH and either directly displays the data to the user or functions as an actuator to propel the subsequent system step.

Humidity is essential to human life. Due to the fact that the highly reactive dipolar molecules that make up these vapours condense on surfaces or evaporate off them even with very small temperature changes in the surrounding air (the high polarity resulting from the different electron-negativity of the oxygen and hydrogen atoms), humidity has become incredibly important [3]. Thus, it becomes essential to gauge and manage the humidity. Transducers known as humidity sensors use the amount of water vapor (H2O) to create a measurable variable. One of the quantities that measurement scientists measure the most often is humidity. Humidity measurement is not just difficult, but it has long been a challenge. Today's humidity sensors can be found in everything from home air conditioners to nuclear power reactors, thanks to recent advancements in sensor manufacturing. For human survival, humidity is crucial. Humidity has become crucial because these vapours are composed of highly reactive dipolar molecules that condense on surfaces or evaporate when nearby temperatures slightly change. The high polarity of these molecules is caused by the different electron-negativity of both oxygen and hydrogen atoms. Thus, measuring and regulating the humidity becomes essential.

The remaining portions of this study are broken down into the following categories. In Section 2, the many definitions of the optical humidity sensor and avatar are arranged chronologically. Section 4 finishes with a discussion of the experiment's results, our perspective, and suggested areas for future research. Section 3 lists and offers the procedures and supplies needed. Section 5 has the solution.

2. LITERATURE REVIEW

Montero, A., et.al [4] The impact of humidity on five distinct FBG sensors will be measured in this experimental program. Temperature was held constant while RH levels were adjusted in increments of 10% from 30% to 90%. Steps of 10°C were used to repeat these RH series at various temperatures between 10°C and 70°C. Notably, we have adjusted the climate room to 22℘C instead of 20∘C to match the temperature at which each FBG's standard frequency is used as a standard. However, not every feasible combination of temperature and relative humidity could be reached because of the climate chamber's operational constraints.

Gupta, B. D., et.al [5] An optical fiber's end gets struck by the light coming from a polychromatic emitter. At the metal-dielectric sensor layer contact, the directed rays' evanescent field activates the surface plasmons. The wavelength, fiber parameters, probe shape, and characteristics of the metal layer all have a

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significant impact on how well the faint field and surface plasmons couple. In SPR-based fiber optic sensor geometries, as opposed to prism-based SPR sensors, the majority of directed rays have more reflections than one. In the fiber, there are more echoes per unit length depending on the angle of incident at the contact.

Pelino, M., et.al [6] Humidity is a constant environmental component, thus controlling and measuring it is crucial for many sectors and innovations as well as for human pleasure. Humidity sensors have been widely used in homes recently to regulate cooking in microwaves and humidity management in air conditioners. Accurate and quick humidity management is vital in the food and chemical sectors as well as in the manufacturing of electrical gadgets. The extensive expansion of greenhouse agriculture, which needs precise sensors for concurrent temperature and humidity control, merits citation. The most popular humidity metric is RH in percentage, which is the proportion of the saturated level to the actual water's pressure.

Pinet, É. et.al [7] The same measurement problems would arise if you were a chemist trying to control critical variables like pressure or temperature during the microwave chemistry process, an engineer supervising radiofrequency (RF) wood drying, a physician monitoring the temperature of a critical care patient during an MRI, or even a surgeon burning particular tissues with RF examined minimally invasive catheters. If you don't have an optical sensor, you may experience severe issues. Optical sensors offer an appealing substitute for traditional methods, even in harsh conditions like those seen in nuclear reactors where intense radiation is prevalent.

Mitrica, B., et.al [8] A wide range of contemporary study topics, including astrophysics, cosmic radiation, neutrino fluctuations, black holes, and cosmology, are covered within the field of high energy physics. Numerous contemporary experiments are situated underground at various locations across the globe to silence experiences: The USA's Fermilab, Japan's Kamioka, Italy's Gran Sasso, and other locations. Several contemporary experiments are in underway, including MINOS (USA), T2 K (Japan), Super-Kamiokande, and others. Additional ones like LBNE, LAGUNA, Hyper-Kamiokande, INO, and so on are under development.

Berruti, G., et.al [9] One of the two main general-purpose detectors for particle physics built on the Large Hadron Collider (LHC) accelerator is located at the European Organisation for Nuclear Research (CERN) in Geneva. It is called the Compact Muon Solenoid (CMS). Due to the significant radiation exposure from running the LHC at maximum brightness, silicon sensors may operate less well, which could lead to an increase in leakage current—a source of heat production and detector noise. Because of this exponential drop in current leakage with inverse temperatures, the CMS tracker can only function when the surface temperatures of each semiconductor sensor are less than or equal to 10 ~C. Because of this, flowing fluids that range in temperature from 20 to 25 degrees Celsius cool all tracker sub-detectors.

Pellegrini, G., et.al [10] The idea presented here is to develop p-type pad sensors that, based on their reactions to pre-irradiation, have a moderate gain. With regard to standard structures, we predict that the gain used in the non-irradiated electronics would still have some impact after radiation, but at a higher multiplication factor. The output signal is the same for typical thick substrate; slimmer devices can be fabricated thanks to the mild multiplication value. To minimize crosstalk and keep the signal within the readout electronics' dynamic limit, the signal gain should be controlled. In addition, variations in bias voltage and heat should not affect the yield.

3. METHODS AND MATERIALS

3.1 Humidity Sensing Material Based on Nafion®

A unique substance known as Nafion® has many uses in the fields of chemical sensors, nanomaterials, and electrochemistry analysis. Nafion® is a material in which certain gases, like water molecules, alcohol vapor, and ammonia gas, can reversibly alter their optical properties (refractive indices, thickness, etc). Because of this, it has a lot of potential for use in fiber-optic gas sensors as an optochemical sensing material. As a detecting film for the RH sensor in this work, Nafion® was selected. The cation Nafion® is excellent converter in addition strong mechanical strength, excellent transparency to polar analytes, excellent chemical resistance (apart from polar compounds like alcohols and ammonia gas), and strong thermal stability are just a few of the material's many benefits.

PEM fuel cells and commercial gas dryers are common applications for Nafion® because of these factors. With Nafion®, three structural elements are easily recognized and differentiated: an interfacial region, hydrophobic ionic clusters of Sulphur dioxide groups, and the hydrophilic portion of the fluorocarbon backbone. Polar water molecules are capable of being physisorbed by these ionic clusters.

3.2 Sensing Concept

Fibre Fabry-Pérot interferometers (FPIs) have been used as chemical gas sensors, temperature sensors, strain sensors, and ultrasonic pressure sensors in composite materials. The basis for extensive development and research as well as marketing was established by these early efforts. When there are changes that impact the optical route length between the two mirrors, fiber FPIs becomes very sensitive. The sensing zone may be

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several hundred nanometers in size. There are numerous ways to monitor optical signals and probe an FP sensor cavity. Low-coherence interferometry methods are the most robust and dependable approach.

Generally speaking, a fiber optic track with an X or Y-shaped coupler as the main component, an optical sensing component, a camera with a recording device, and a light source are the components of any fiber FPI transducer/sensor design. Making the right choosing a different spectral range and modifying the interferometry detecting structure's optical configuration will allow you to customize the sensor's selectivity, sensitivity, and temporal response. Optical sensing occurs when alterations in the optical qualities coincide with physical modifications in the sensor structure.

An optical response can be immediately produced, as in this instance, by spectral or brightness signal processing as a result of changes in the optical properties of the sensor layer or layers [11]. If the OPD between the several beams is significantly smaller than the light's coherence length, the FP cavity can produce a signal that is very disruptive. It is not possible for the reflected beams to adequately interfere with one another and create fringes if the interferometer's OPD is greater than the light's coherence length. The Nafion® layer, which serves as the interferometer's resonance cavity, should thus have a thickness of several hundred millimeters or less. Equation (1) applies to express the OPD between the two reflectors:

$$OPD = 3nl \tag{1}$$

The Nafion®'s refractive index, m, and thickness film, Q at a specific wavelength are the respective values.

$$J(\partial) = J_0(\partial)[S_1 + S_2 + \sqrt[2]{S_1 S_2 cos(\nabla\partial)}] \tag{2}$$

where $J(\partial)$ is the wavelength-averaged reflected light energy; $J_0(\partial)$ is the wavelength-averaged light source power; s1, s2 is the wavelength-averaged reflector reflectance; Equation (4) can be used to express $\Delta\varphi$, which refers to the phase difference between the two light rays that the detecting interferometer's mirrors reflect.

$$\nabla\partial = \frac{2\pi OPD}{\partial} = \frac{2\pi nQ}{\partial} \tag{3}$$

Consequently, the disrupted signal follows the effective cavity size as a function. OPD variations and modulation of the optical reflected signal are caused by air humidity. The applied moisture can be determined by observing the sensor's output.

$$\nabla OPD = 2(-\nabla mq + m\Delta Q) = OPD(-\frac{\Delta n}{m} + \frac{\nabla L}{Q}) \tag{4}$$

3.3 Manufacturing of Sensors

The fiber sensor probe is composed of gradient index (GI) fibers that are multi-mode (MM). A comparatively easy method for applying uniform thin layers from the liquid phase to glass and plastic surfaces is a dip (or absorption) coating. To provide a homogeneous sensing coating on the end of the fiber optic substrate, this technique uses dip coating. The following methodology was used to produce the Nafion®-based sensor devices. The Nafion® perfluorinated ion-exchange resin solutions, it was purchased from Sigma Aldrich (Poznańn, Poland) and used without further purification. It is 6 weight percent in a lower aliphatic alcohol and water mixture with 55% water content. It was immediately immobilised by dip coating for 10 seconds at room temperature onto the end of a perfectly split MM fibre optic (63.5/135 µm).

After coating, the coated fiber optics were dried at 4 °C for 120 minutes and cured for fifteen minutes at 110 °C. The interface Nafion® thin film has a thickness of several hundred millimeters following solvent evaporation [12]. The fiber optic substrate gets stickier after the first layer, which has a depth of about 100 nanometers, is deposited, and subsequent layers that are formed during the immersion stage will be thicker than the first. A Nafion®-based detecting structure will then be constructed by depositing single layers one after the other. An estimated 260 nm (±20 nm) thick Nafion® layer was formed as the outcome of the single process application. The deposition process needs to be done multiple times to produce thicker layers. About 10% of the layer's depth is accurately determined using a single process application. Sensing structures made of two layers of Nafion® have been used in this work.

Nafion®, an amorphous fluoropolymer with slightly higher refractive index values than water, is particularly interesting because, as previously mentioned; both at the synoptic and molecular levels of observation, these materials are transparent because they can be manufactured into thin, translucent membranes that are ideal for an optical sensor. The Nafion® film's refractive index (n = 2.37 RIU at λ = 589.3 nm, after a dry hardening process) is less than the fibre optic core's, causing some light to be bounced from the SiO2/Nafion® contact. Nafion® has superior optical transmission even when the material is divided into several layers. However, when the hydrated film's refractive index decreases and it grows even more comparable to water, as seen in a schematic picture of the fiber optic RH sensor based on Nation® thin film. Multi-mode (MM) gradient index (GI) fibres are used to make the fibre sensor probe. Dip coating, also known as immersion coating, is a reasonably easy method for applying homogeneous thin coatings of liquid phase on substrates made of glass and plastic. In order to apply a homogeneous sensing coating to the end of the fibre optic substrate, this work uses dip coating to deposit a Nafion® layer. It was directly immobilised onto the end of a perfectly split MM fibre optic (62.5/125 µm) by dip coating, which took 10 seconds at room temperature (Figure 3.1).

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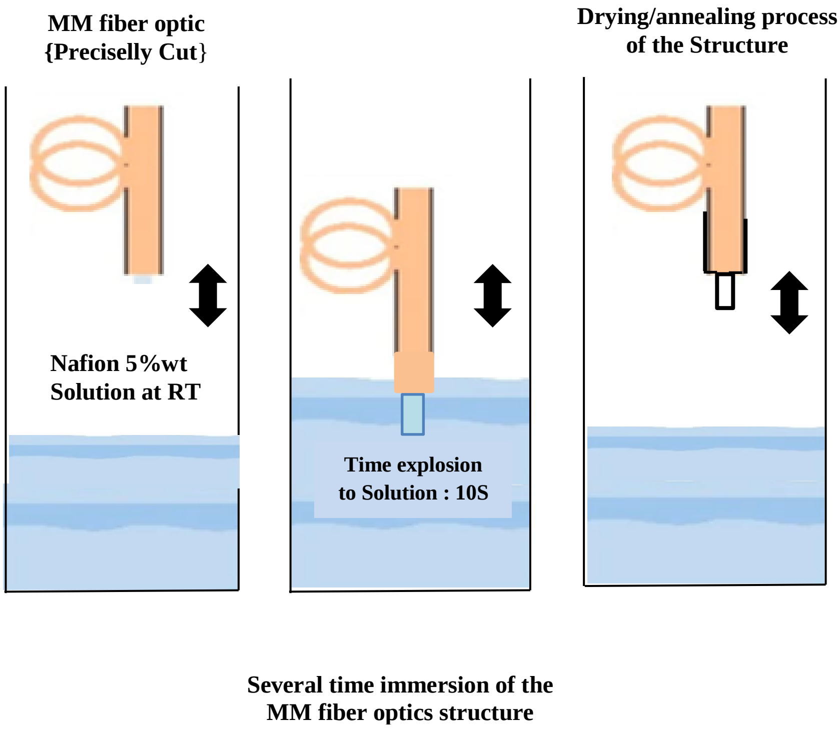

Figure 3.1. Mechanism of Nafion® sensing thin film deposition innovation

3.4 Description of the Fibre Optic Sensing Circuit of the Nafion®

Multiple methods of measurement were used to characterize the produced Nafion® thin films on fibers. In addition to confocal microscopes and a force microscope (Spectral Musical Instruments, Moscow, Russia, AFM, NT-MDT), reflection spectroscopy was used to assess the layer's thickness and quality. An AFM Raman Confocal system (NT-MDT Spectrum Instruments, Moscow, Russia) from Ntegra Spectra was used in an upright posture to analyze sensor structures based on Nafion®. An optical confocal microscope was used to investigate the shape and surface optical homogeneity of these Nafion® formations. A laser-scanning module with two lasers made up the confocal laser scanning system. The size of the pinhole was changed to 100 µm. Photomultiplier tubes were employed as binocular optical signal detectors.

The semi-contact topography mode was used to analyse morphology and roughness using an AFM technique. The metrics surface average roughness and root means square (Sq, RMS) were used to define the surface roughness, which was calculated by dividing the integral of the topmost layer of the pore/islands by the total surface area acquired by AFM. Optical microscopy was also utilized to characterize the produced Nafion® thin films. Before the optical test, the samples were put in a specific holder so that the Nation® surface and the Newtonian fringes could be seen more clearly. The entire Nation® structure was deposited onto the end of an MM fiber optic, particularly in the fibred core area. NOVA software was used to acquire digital images and analyze the laser and AFM sections.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

A SnO2-based fiber optic sensor's typical output signal fluctuations are displayed in Figure 4.1 during step characterization conducted at 0 ◦C and 20 ◦C, with RH varying roughly between 4 and 18.5 and 3.8 to 26%, respectively. Additionally reported is the manufacturer's hygrometer's answer for reference.

As the humidity inside the climate chamber increases, more water molecules are clearly deposited on the SnO2 overlay surface. Following their interaction with the optical near-field that appears at the fibre tip, these molecules raise the optical probe reflection. When the relative humidity began to decrease, the molecules in the sensor also exhibited well desorption characteristics, desorbing rapidly. Even at cold temperatures, there was a very excellent agreement between the commercial (and now in use) sensor and the humidity values supplied by the optical fiber sensor.

SnO2-based sensors, however, seemed to respond more sharply to low RH readings than to high humidity levels; this suggests that the sensor's feature is not quite linear. The resulting signal's steady-state value, which is obtained at equilibrium for every step, has been displayed in this instance against the matching RH

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value supplied by the company's sensor. The sensor responsiveness curve of Figure 4.1 (red circles) generated at 20 ◦C can be piecewise divided into two parts, according to an initial estimate: the first half corresponds to low RH (<5%), while the second half corresponds to medium RH (about 5 < RH < 35%). This implies that two different values for the fibre optic sensor sensitivities—which are found by figuring out the slope of the reaction curve in the specific range (S = ∂I/∂RH) [13]—can be considered for each temperature. These values are summarized in Table 1.

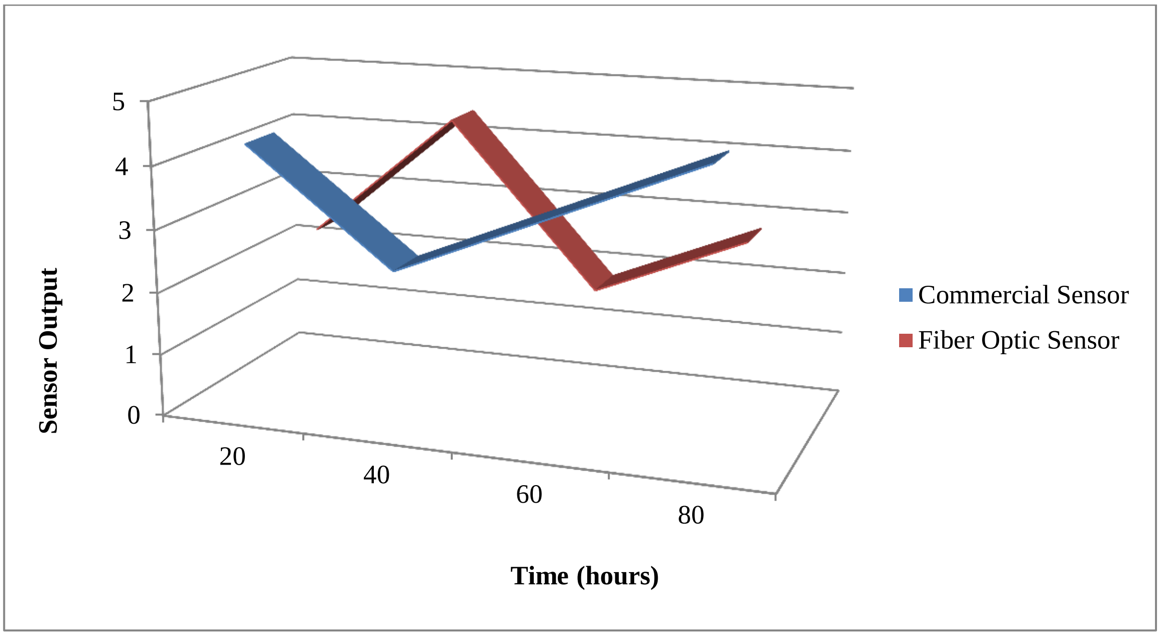

Figure 4.1 RH fluctuations at a temperature measured by a commercial capacitive sensor and a realised fibre Optic Sensor

One that is roughly 5 < RH < 35%, or medium relative humidity. This means that, for each humidity, two distinct values for the fibre optic sensor sensitivities—which are determined by calculating the slope of the reaction curve in a specific range (S = ∂I/∂RH) can be taken into consideration. Table 1 summarizes these parameters. Regarding the sensor curve response measured at 0 °C, the same cannot be said wherein insufficient values (actions) have been recorded (executed) in this range to enable the correct calibration of the sensor, making it impossible to establish SL 0. Only the threshold for medium RH levels (about 8 < RH < 20%) can be calculated in this situation, and the result is roughly equal to that of SM 20 (5 × 10−4).

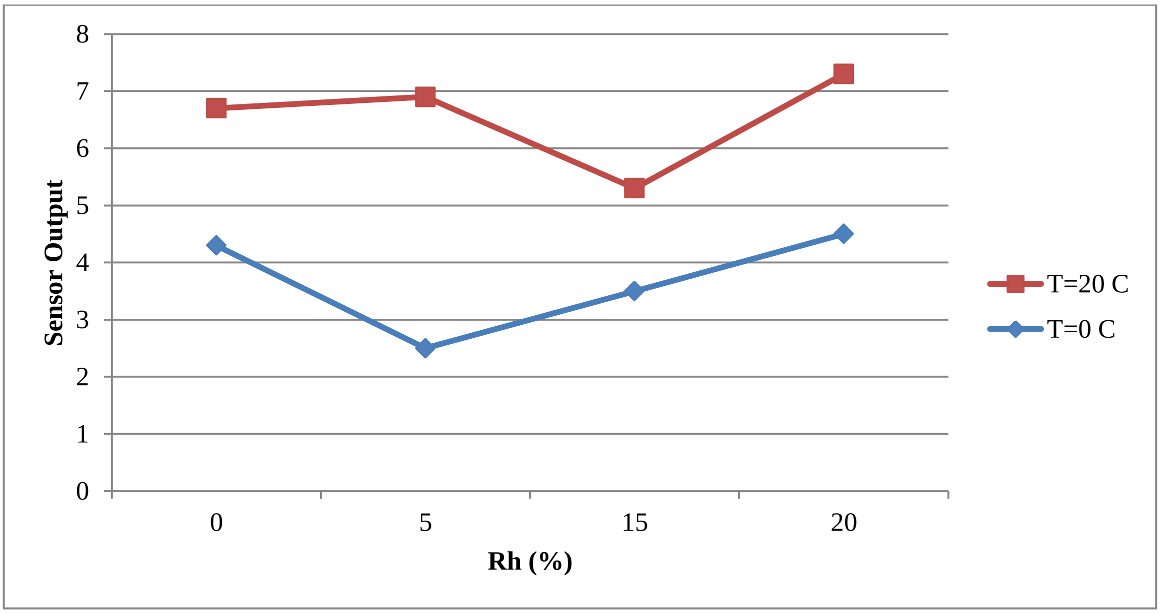

Figure 4.2 Response of the sensor to different relative humidity levels at 20 ◦C

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However, the experiments that have been conducted show that the SnO2 sensor can function effectively even at 0 °C. Further experiments are now being carried out in order to completely characterize the sensor reaction curve for low RH values at that temperature and at levels below it (down to −20 ◦C or −30 ◦C).

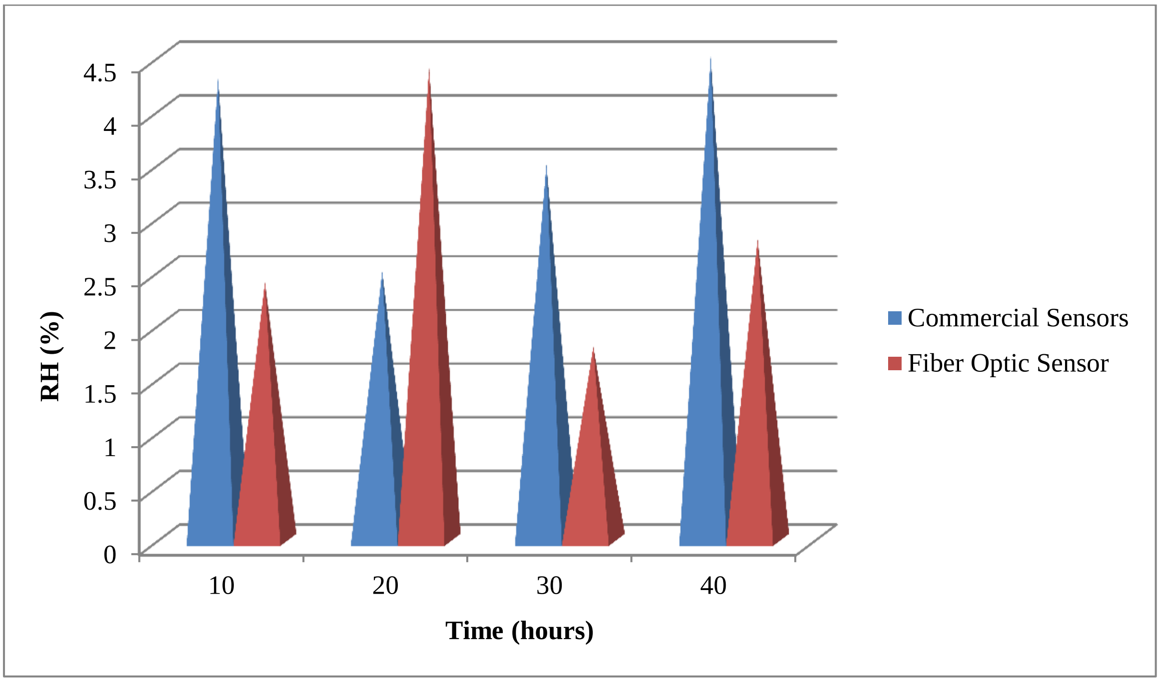

Figure 4.2 Response of a SnO2-based sensor to quick changes in relative humidity between 2 and 40% at Temperatures

4.1 Dynamic Evaluations

At 20 ◦C, the dynamic characteristics of the SnO2-based sensor were also examined by quickly and successively altering the relative humidity (RH) between approximately 2% and 40% and between 40% and 2% inside the climate chamber. The obtained results are displayed in Figure 4.2 and are compared with the findings of the commercial electrical sensors, which are recognized for having a relatively quick reaction time.

The optical fibre sensor output has been translated in RH using the calibration in this instance graph made during static observations in order to compare the reactions of both systems. Specifically, a best fitting approach was used, where a Sigmoidal Weibull operation, type 2, was fitted to the sensor reaction curve.

The reactions of commercial and fiber optic sensors are found to be in excellent agreement in Figure 4.3, despite the former's slightly slower response time, as evidenced by its highest RH values being slightly lower than the ones of the electrical equivalent.

5. CONCLUSION

This paper highlights our study on the use of fiber optic grating-based sensors for relative humidity monitoring in HEP environments, developed in collaboration with CERN of Geneva. The R detection performances of TiO-coated LPGs and polyimide-coated FBGs were specifically examined in the range of [0-65] % at various temperatures and following strong radiation exposures. The gathered data clearly indicates that Compared to the electronic hygrometers based on polymers currently employed in the CMS investigation at CERN, this novel technology offers a reliable and viable substitute.

The efficacy of manufactured sensors in detecting relative humidity has been examined at both 30 ◦C and 0 ◦C in a comprehensive experimental campaign conducted at CERN's facilities in Genève. The results show that, in both static and dynamic tests, the responses from the fiber optic sensor are remarkably similar to those from commercial polymer-based thermometers. The fiber optic sensor has very high sensitivity, with limits of identification less than 0.2% for low RH ranges (<20%).

However, our findings show that fiber optic probes may already be able to take the place of some currently used hygrometers in areas with low enough radiation doses. This would allow for the advantage of some significant features of fiber optic technological advances, such as the ability to reduce the size, weight, and complexities of cabling.

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