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Optimizing the Materials Response in Humidity Capacitive Sensors

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The number of humidity outputs on the cap of a cylindrical capacitance sensor is optimized by designing three different probes with direct and indirect windows. The time interval is measured within which 30-70 % humidity can influence the dielectric constant and conductivity of the capacitance when exposed to a range of relative humidity. It is then compared with a simple set-up including a simplified equivalent circuit. The direct probes had four and double outputs on the window of the cylindrical capacitive sensor while the indirect probe had a thin plastic layer only. We observed that the dielectric constant and its conductivity depend closely to the humidity outgoing pathway and also to the increasing rate of humidity between the capacitance plates. The final variation in the materials properties alters the capacitance of the sensor which is measured simply by a LCR. This technique presents a simple method for tracking the recovery and reliability of the humidity sensors over time and assists in optimizing and controlling the materials response to the relative environment humidity. As a result, by controlling the environment humidity rate (0.02 %/s.), we could measure the increment rate of capacitance with accuracy of 0.01 pf/%.

Keywords: Humidity sensor, Capacitance, Output, Dielectric constant.

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1. INTRODUCTION

Capacitive sensors have been widely used in various measurement systems such as for the environment humidity control [1]. This system is quite simple consisting of a probe and the measuring module for capacitance monitoring. A cylindrical capacitive sensor was already used for probing the effect of temperature on electrical properties of the water liquids [2, 3]. With an slightly improvement in dielectric materials, the probe geometry and a few analytical calculations, one can extend the proposed instrument for measuring the physical and chemical parameters of the environment. The refractive index is an important parameter for the atmospheric optic that can be obtained within this approach [4, 5]. In this work we investigate a new technique for evaluating the direct and indirect ingress of the relative humidity into the sensor and its effects on the materials properties over time which finally leads to the recovery / degradation of the sensor.

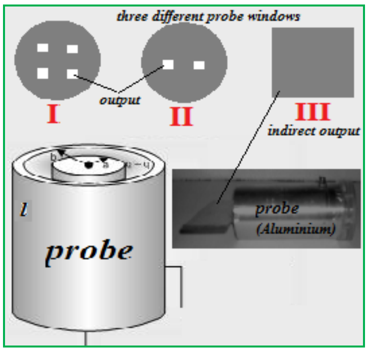

Fig. 1 – The geometry of capacitance probe and three different multi-output windows. Probe I, II are direct and probe III is indirect as a thin plastic layer

The theoretical and experimental investigations suggest that a simple cylindrical capacitance sensor can be widely used and replaced for measuring the environment humidity by monitoring the variation in its capacitance over time. This technique does not require one to calculate the materials refractive index and it's variation by humidity outgoing. The device consists of a very simple electric circuit which leads to a lower production cost. The structure of the sensor is mechanically strong with a high reliability, sensitivity in materials responsiveness to the humidity ingress [6]. We proposed a novel procedure for measuring the humidity where there is no need for probing the wide range of neither frequencies nor temperature. The technique and procedure reported here is also applicable to the high humid environments like humid air condition at sea low-level altitudes [6].

2. THEORY

There are three methods to model the Capacitance, C, of a cylindrical cell; solving Laplacian with the boundary conditions, Gauss law, and Coulomb law [7]. The latter is applied here since it takes into account the edge effects and height of the cylinder, l. Considering Fig. 1, the total capacitance of the cylinder is given by,

$$c = \frac{Q}{\varphi_{ab}} = \frac{2\pi l \in^{*}}{(A-B)} \tag{1}$$

where Q, φ_{ab}, and $\in^{*}$ are the induced charge on the plates, potential di_erence between the plates and complex permittivity constant of the material sandwiched between the capacitance plates with the radius a and b, respectively.

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A and B are given by the following

$$A = \int \ln \left(\frac{z - \frac{l}{2} + \sqrt{a^2 + \left(z - \frac{l}{2}\right)^2 - 2a^2 \cos\varphi' + a^2}}{z + \frac{l}{2} + \sqrt{a^2 + \left(z + \frac{l}{2}\right)^2 - 2a^2 \cos\varphi' + a^2}} \right) d\varphi' \quad (2)$$

$$B = \int \ln \left(\frac{z - \frac{l}{2} + \sqrt{b^2 + \left(z - \frac{l}{2}\right)^2 - 2b^2 \cos\varphi' + a^2}}{z + \frac{l}{2} + \sqrt{b^2 + \left(z + \frac{l}{2}\right)^2 - 2b^2 \cos\varphi' + a^2}} \right) d\varphi' \quad (3)$$

For a conductive material with $\sigma \neq 0$, the relative complex permittivity can be written as,

$$\in_r^* = \in_r - j\frac{\sigma}{w \in_0} \quad (4)$$

where $\in_r$ is the real component of the relative permittivity of the material, and $\in_0 = 8.854 \times 10^{-12}$ F/m, is the vacuum permittivity. The imaginary component, $\sigma / \omega\in_0$, includes $\omega = 2\pi\nu$ where ν is the frequency of the measurement. The parameter σ is electric conductivity $(1 / \Omega{\cdot}m)$ which is different for any liquid and thus also depend on the environment humidity. As a relevant example, conductivity of water is greater than the vapor [8]. Using the relation of dielectric constant, K to the permittivity $\in$as $\in = k\in_0$, a practical equation can be obtained for the dielectric constant of the humidity in the environment air as,

$$K_{moist \quad air} = 1 + \frac{211}{T}\left[P + \frac{48}{T} P_S(RH)\right] 10^{-6} \quad (5)$$

where RH is the relative humidity of the environment in percentage, P_S is the saturated pressure of the vapor in millimeter Hg at a certain temperature and P is the pressure of the humid air.

3. EXPERIMENT DESIGN & MEASUREMENT PROCEDURE

The cylindrical probe used in this experiment was designed from Al with $a = 18$ mm, $b = 24$ mm, and $l = 110$ mm and the distance between the electrodes was 3 mm [9]. As has been schematically drawn in Fig. 1, we designed three different probes with different number of windows or outputs: Probe I with 4 outputs, Probe II with 2 outputs, and Probe III with an open window. The latter probe is capped by a thin plastic layer with the area of 3 × 50 mm². The set up has been schematically drawn in Fig. 2 and the different probes with various numbers of outputs and indirect input window have been illustrated. A LCR-816 was used to measure the capacitance which employs an auto balancing bridge method, a Konor-SPS-808 was used emit a uniform humidity under the tank and conducting the humidity to The chamber through a pipe with 3 mm diameter. The humidity is supposed to be with a constant room temperature ($T = 300$ K). Probes I & II let the humidity to enter the cylinder through a pipe with 9 mm diameter. Both of them are over capped with an ordinary paper having respectively 4 and 2 outputs (aperture) for the output of the humidity from the cylinder. In contrast, Probe III uses an indirect output of the humidity Fig. 3 represents the equivalent circuit used for capacitance measurements by LCR [2]. When there is a connection between the metal and liquid (e.g. humidity or water vapor), the equivalent circuit of the contact cylindrical probe considered as a sample dielectric capacitance C_x in parallel with a sample resistance R_x which result in the reactance capacitance of the water liquids [10].

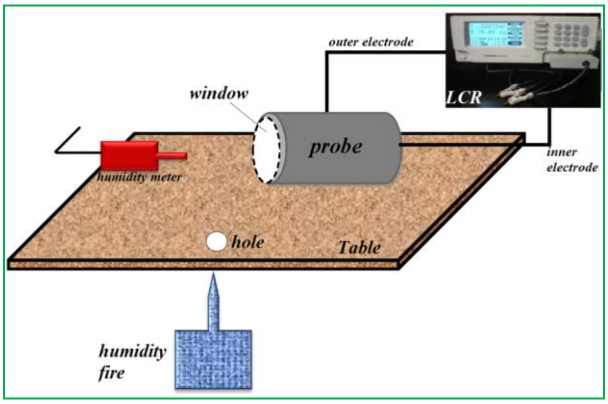

Fig. 2 – Schematic of the humidity sensor measuring set-up, the different probes and the humidity meter and humidity

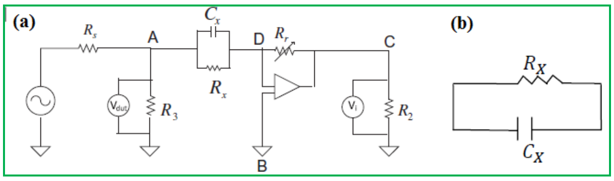

Fig. 3 – a) Equivalent circuit used in the LCR for measuring the sensor capacitance using an auto balancing bridge method, b) equivalent circuit of the probe. A, B, C, and D are nodes

4. RESULTS AND DISCUSSION

The experiment is started by turning on the humidity creator and measurement tools and placing the sensor. The results of measuring the relative humidity over time and the variation of capacity vs. relative humidity using probe I have been indicated in Fig. 4.

Using probe I with four outputs (as is indicated in Fig. 1) the relative humidity increases from 29.37 % to 86.66 % within 65 s. Thus the rate of humidity increment is about 0.95%/s. Within the first 15 seconds, this rate is higher representing that the humidity is outgoing from the four outputs on the window of the probe I. However, in the second 45 seconds, this rate is smaller because a part of the humidity is already deposited on the capacitance plates and outgoing of the humidity will be rather slow. In Fig. 4, the variation of capacitance vs. relative humidity was shown when probe I was used with four outputs. By increase in relative humidity from about 30 % to 86.88 %, the capacitance of the probe rise from 27.0 to 27.20 pf. In the first

20 seconds, the humidity increases significantly from 29.9 % to 72.2 % which cause an increase in capacitance from 27.09 pf to 27.12 pf. In contrast, within the second 45 seconds, for an increase in humidity from 72.2 % to 86.88 %, the capacitance rise from 27.12 pf to 27.20 pf. Thus in the first time interval a rather effective increase in dielectric constant of the capacitance was occurred. However, its value is still close to air dielectric constant of about 1.0005. Thus a small perturbation and increase is observed in the capacitance of probe I. In Fig. 5, the rate of humidity increase and capacitance vs. relative humidity has been drawn using probe II.

As indicated in Fig. 1, in this case we put only two outputs on the window. When the cylinder is capped with a double output window, the measurements show a change in the rate of humidity increase from 31.15 % to 68.35 % within 9.5 minutes. Therefore, the humidity increment rate is about 0.06 %/s in this case which is an order of magnitude less than the one of probe I. Such a significant reduction is attributed to the fewer number of outgoing apertures on the window of probe II (only two outputs). Clearly, a fewer number of outputs on the probe window reduce the rate of humidity outgoing from the cylinder [9]. Fig. 5 also shows the increase in capacitance of probe II from 26.44 pf to 29.1 pf when the relative humidity increases from 31.15 % to 68.35 %. It is seen that within 30 seconds, when the relative humidity increase from 31.15 % to 45.16%, the probe capacitance increases from 26.44 pf to 26.7 pf. Thus from the measurement starting time the capacitance increment (or dielectric increase) is more than the one of probe I. This is because, for the

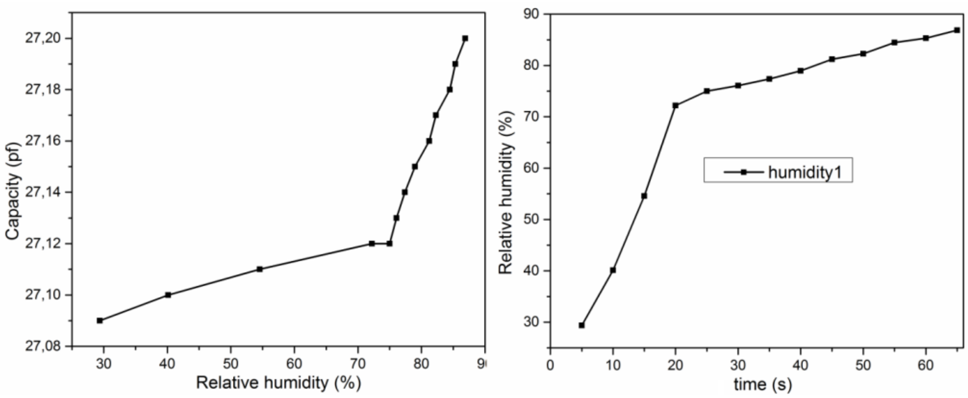

Fig. 4 – Relative humidity vs. time measured using probes I

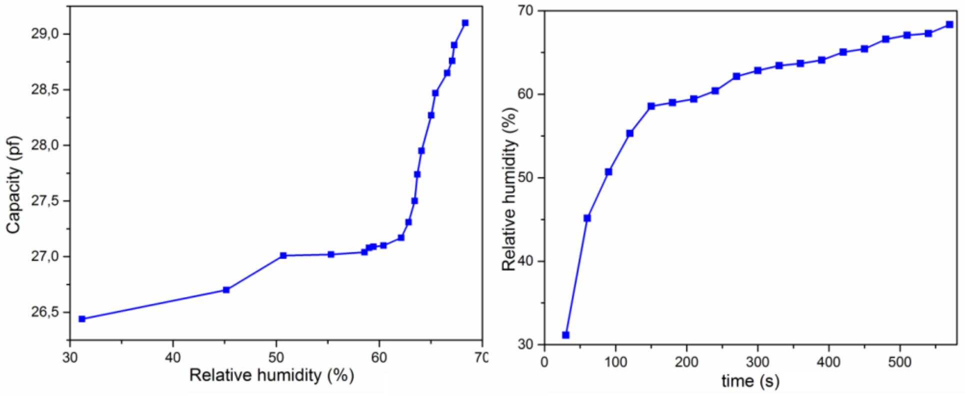

Fig. 5 – Relative humidity vs. time measured using probes II

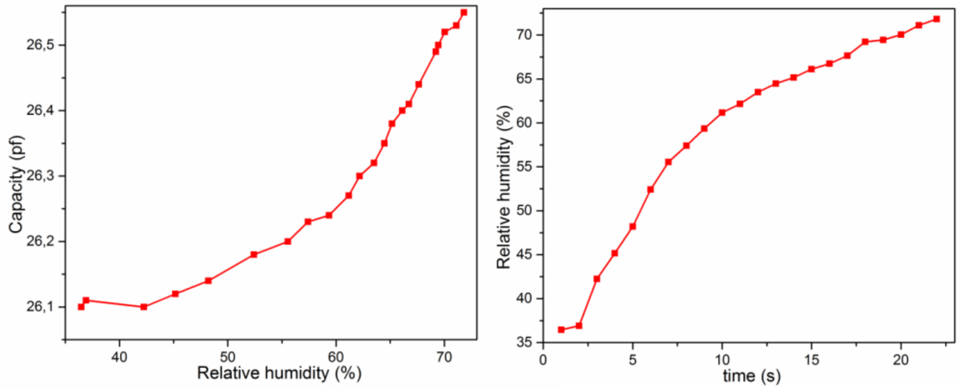

Fig. 6 – Relative humidity vs. time measured using probes III

probe II with only two outputs, the rate of humidity outgoing is lower and thus in this time some more humidity or water vapor is accumulated in the probe. In Fig. 6, the humidity increment rate and capacitance variation vs. relative humidity has been indicated when the cylinder is capped indirectly with a thin plastic layer as indicated in Fig. 1. In this case the humidity increment rate is quite lower than the one of the other two probes. This is attributed to the indirect path of the humidity to the cylinder and a uniformly output of the humidity to the sensor. Thus an indirect window without any aperture will be a barrier for the precise measurement of the humidity and a small variation is obtained for the capacitance representing that the sensor is not receiving a significant amount of change in its materials [11]. As shown in Fig. 6 when the humidity increase from 42.25 % to 69.22 %, the capacitance of probe III increases from 26.11 pf to 26.49 pf almost uniformly. This almost uniform and slow increment is because of the shape of the window which is indirect and thus the humidity will enter the probe very slowly. For this case, we intentionally limited the humidity penetration to the probe. It is seen that the measured humidity and the capacitance are more appropriate and responsive to each other. We note that the variation in capacitance is due to variation in dielectric constant by the environment humidity [12-14].

In Fig. 7, the rate of the variation (e.g. increment) in relative humidity, ΔRH in units of %/s, and the capacitance increment per relative humidity increment, $\Delta C / \Delta RH$ was compared for three different probes.

The results are interesting to interpret. RH is taken within 30-70 %/s. In probe I, the increment rate for 30-70 % relative humidity is about 2.8 %/s. This rate is lower in probe II and within 9.5 minutes increases from 31.5 % to 68.3 % with a variation rate of 0.06 %/s. As we discussed about this before, the latte lower rate is because of a fewer outputs embedded for probe I. Nevertheless, this rate is still rather slow about probe III since this probe has an indirect output [15, 16]. About probes I. In probe I and II, we obtained $\Delta C / \Delta RH = 0.0004$ and 0.07 pf /%, respectively. Therefore, a faster variation is attributed to probe II which is because of a relative effect on the dielectric constant and conductivity of the sensor materials. In probe II, the increment in conductivity is because of the increase in humidity on the plates which is significant in probe II due to fewer numbers of apertures on the window of this probe than the one of four-outputs in probe I. Since the humidity creator was a tap water with 368 μs/cm, the probe III has a uniform variation in its humidity input and output as an indirect sensor. Therefore, an almost linear increase is observed for the measured parameters in Fig. 6. The deviation from the linear behavior is likely due to the casual variation in humidity percentage in water vapor and a weaker influence of relative humidity on the conductivity of the dielectric. The latter casual effects lead to a $\Delta C / \Delta RH = 0.01$ pf /%. The nonlinear increase in capacitance vs. relative humidity is due to the conductivity term in the theory. This non-linearly is observed in Fig. 4, 5, and 6. In Fig. 6, the variation in capacitance is mostly due to the change in real part of Eq. (4) which reminds the direct dependency of dielectric constant to the capacitance and it's variation by relative humidity of the environment. Consequently, probe III increases almost linear due to the indirect design of its window where the humidity evacuates slowly from the thin plastic layer. According to Eq. (4), this slow variation is due to a negligible variation in the imaginary part of Eq. (4) i.e. the imaginary conductivity and dielectric terms. The introduced approach can further be developed for the materials response optimization and / or device degradation / recovery issues [17, 18]. Note that the data and experiment was reproducible in the different places and different times.

5. SUMMARY

In this work, we basically calibrated cylindrical aluminum capacitors according to humidity in a chamber. We measured the change in capacitance as a function of the humidity. There were 3 capacitors with different number of holes on their caps, to exchange humidity with the chamber. The relative humidity vs. time of the environment was measured by cylinder capacitance sensor using three probes with the different caps (windows). Probe I and II were directly capped with a four and double outputs and probe III was an indirect window as a thin plate. The first two probes indicate a higher humidity increment rate comparing with the indirect probe. A simple set-up and circuit was drawn for these measurements. The obtained results were then interpreted using the proposed theory and the fact that the humidity will change on the materials

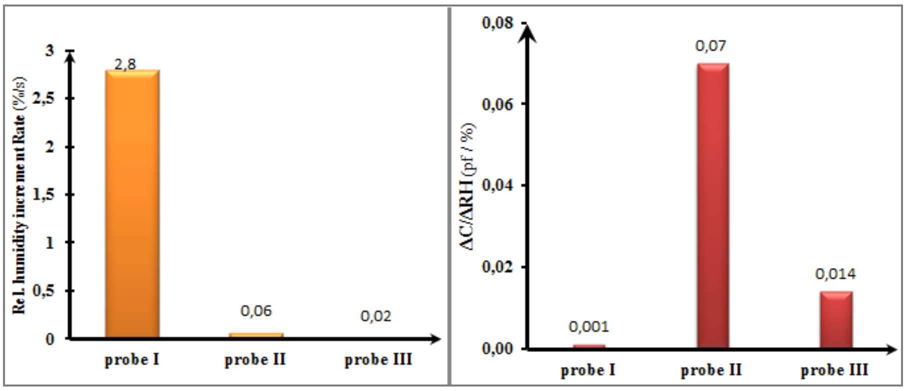

Fig. 7 – The rate of relative humidity increment for the three different probes with direct (I,II) and indirect (III) window outputs

electrical properties and finally on the capacitance of the sensor which is measurable afterwards. Comparing the rate of increase in relative humidity for probe I and III, we obtain $\Delta RH = 28$ %/s, and 0.02 %/s, respectively. Thus, probe III better shows the variation of capacitance with relative humidity. It is concluded that the optimized output window of a sensor is indirect. A non-linear increase in capacitance observed in Fig. 4, 5, and 6 is due to the dependency of dielectric constant to the conductivity according to Eq. (4).

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