An Experimental and Numerical Study of the Humidity Effect on the Stability of a Capacitive Ceramic Pressure Sensor

Marina SANTO ZARNIK[1,2,3], *Darko BELAVIC*[1,2,3]

[1]HIPOT-RR, Šentpeter 18, 8222 Otočec, Slovenia
[2]IN.Medica, Levičnikova 34, 8310 Šentjernej, Slovenia
[3]Centre of Excellence NAMASTE, Jamova 39, 1000 Ljubljana, Slovenia

marina.santo@ijs.si, darko.belavic@ijs.si

Abstract. *The effect of the humidity of the surrounding atmosphere on the characteristics of capacitive structures is a known problem for capacitive gas-pressure sensors. However, the use of a differential mode of operation can provide a good solution – only the manufacturing of the ceramic structures with the appropriate pairs of capacitive sensing elements remains a major challenge. In order to find a compromise solution, the effect of the humid atmosphere and the moisture on the exterior of an LTCC-based capacitive pressure sensor was inspected closely through experimental and numerical analyses of various situations.*

Keywords

Capacitive pressure sensor, LTCC, fringe electric field, stray capacitances, finite-element analysis.

1. Introduction

Changes in environmental factors and particularly the humidity of the surrounding atmosphere can affect the stability of any capacitive structure and are particularly critical for capacitive sensors. Generally, in order to avoid the influence of the humidity of the air on the sensors' characteristics, the differential mode of operation can be considered as an appropriate solution. This requires the realization of a sensor module with two capacitive sensing structures on a pair, with one of them to be used as a reference. However, in the case of a capacitive ceramic pressure sensor (CCPS), manufacturing the appropriate pair of capacitive sensing/reference elements (ceramic structures with an air-gap between the thick-film electrodes on the thin membrane and the rigid substrate) was found to be technologically very demanding. However, our previous investigations [1]–[5] showed that capacitive gas-pressure sensors made by using low-temperature cofired ceramic (LTCC) materials have a good sensitivity and temperature stability. The characteristics were improved by placing readout electronics realized with an Analog Devices AD7746 capacitance-to-digital converter (CDC) directly on the sensor body, close to the sensing-capacitor electrodes. The optimized design of a single-ended CCPS with a guard-ring electrode showed a reduced rms output reading noise (< 100 aF) and the overall resolution of the sensor was better than 0.5 mbar in the pressure range 0 – 1 bar. However, the effect of the atmospheric humidity was found to be a drawback for the application and remained as the subject of further investigations [4]. Recently, there has been a report on the impact of a humid atmosphere on a CDC. In [6] the authors found that the AD7746 can be significantly affected by humidity variations and, to a lesser extent, by temperature changes, and introduced a measurement of the RH of the air with the intention of compensating for its effect in order to obtain a stable operation of the sensor system. In order to avoid increasing the complexity of the system we instead proceeded with our investigation of a CCPS using some tests of the elementary ceramic structure and tried to find another effective solution for wet/wet applications.

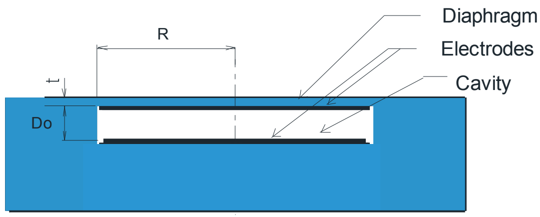
This paper presents the results of our recent study of the humidity and moisture effects on the stability of an air-capacitor in an LTCC structure. Our observations were focused on an unloaded sensor and the influence of the parasitic stray capacitances on its zero capacitance, C_0 (the capacitance of the unloaded sensor). In order to avoid the effect of the humidity on the readout electronics a measurement set-up with a dislocated AD7746 evaluation board was used. The effects of the humid atmosphere around and inside the sensor's structure as well as the effect of the moisture on the external surface of its ceramic body were also analyzed numerically and the simulation results were compared to the measured characteristics.

2. Background

One important question arising in connection with the considered problem is what we understand about the measured sensor's capacitance in terms of the metrology.

Ignoring the end effects of the environmental media and assuming the electrodes are ideal conductors (flat, smooth and parallel), it is straightforward to calculate the capacitance of the air capacitor. However, the geometry of the real ceramic structure with an air-gap between the sensing capacitor electrodes is not as simple as in the case of the "ideal" capacitor. The geometry and the permittivity of the ceramic body normally influence the capacitance of the sensor, not only the dielectric medium between the electrodes of the sensing capacitor.

The basic structure of the relative air-gap capacitive pressure sensor considered in this study (Fig. 1), and the governing relations defining the sensitivity to the applied pressure in terms of the geometry, dimensions, and the material's elastic properties, were already discussed in [1]-[5]. All those analytical relations were derived for ideal capacitors, with the permittivity of the air considered as a constant. However, because the permittivity of the air depends on its relative humidity (RH) and temperature, the air-gap capacitive sensors are very sensitive to the ambient conditions. This is why, in practice, the condition of the atmosphere and the media in the air gap should be considered more carefully.



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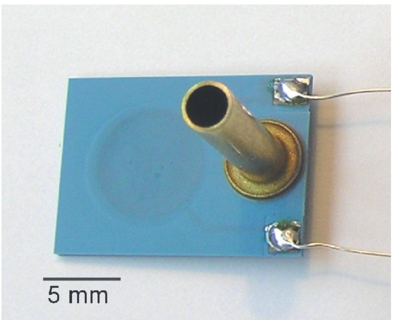


b)

Fig. 1. a) Schematic cross-section of the air-gap capacitor in the LTCC structure (not to scale) and b) The CCPS prototype.

The permittivity of the air as a function of the relative humidity can be calculated from the empirical relation (1), [7],

$$\varepsilon_{air} = \varepsilon_0 \cdot \left[1 + \frac{211}{T} \cdot \left(P + \frac{48 \cdot P_S}{T} \cdot RH \right) \cdot 10^{-6} \right] \tag{1}$$

where ε_0 is the permittivity of vacuum, T is the absolute temperature (K), RH is the relative humidity (%), P (mm Hg) is the pressure of the air, and P_S (mm Hg) is the pressure of saturated water vapor at the temperature T.

The effect of the changes in ε_{air} on the sensors' characteristics can be roughly assessed by substituting (1) into the relation for the capacitance of a parallel-plate capacitor. However, in practice this can result in a wrong assessment, since the total capacitance of the structure is not considered. The stray capacitances resulting from the effect of the humidity of the surrounding atmosphere on the exterior of the ceramic structure may even surpass the sensor's functional parameters. Furthermore, the problem is not only the change in the capacitance due to the humidity of the atmosphere but also the relatively large hysteresis in the sensor's characteristics after a reduction of the humidity. A typical dependence of the zero capacitance, C_0, of the unloaded sensor on the RH of the surrounding atmosphere is presented in Fig. 2. It is obvious that only low RH (< 30 %) conditions of the surrounding atmosphere can be appropriate for very accurate measurements. The conditions with a higher RH (> 50 %) and particularly any direct contact with the moisture are particularly problematic for capacitive-based measurements.

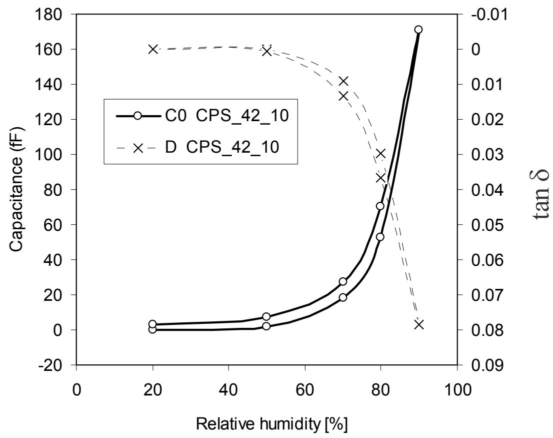


Fig. 2. Typical hysteresis of the capacitance (C_0) and the dielectric losses (tan δ) versus RH characteristics measured in the temperature/humidity chamber (stabilization of the conditions for 1 hour).

In order to estimate the effect of the moisture on the characteristic of the CCPS, a series of experiments was performed as described below.

3. Experimental

A representative prototype of the CCPS manufactured for the experiments in this case study is presented in Fig. 1b. The experimental set-up used for the evaluation of the effect of the humidity and moisture on the capacitance of the CCPSs involved an AD7746 evaluation board placed in a box completely shielded with an aluminum foil is shown in Fig. 3. The measurements were performed under ambient room conditions (the effect of the temperature changes was avoided by using differential mode measurements) and in a temperature/humidity chamber for a more precise assessment of the humidity. For the measurements in contact with water the sensors were mounted in plastic pots in such a way that the electrical contacts and the inlet for the gas pressure were outside the reservoir (Fig. 4). This simple construction allowed relatively good control over the level of water in the reservoir and a visual observation of the situation during the measurements.

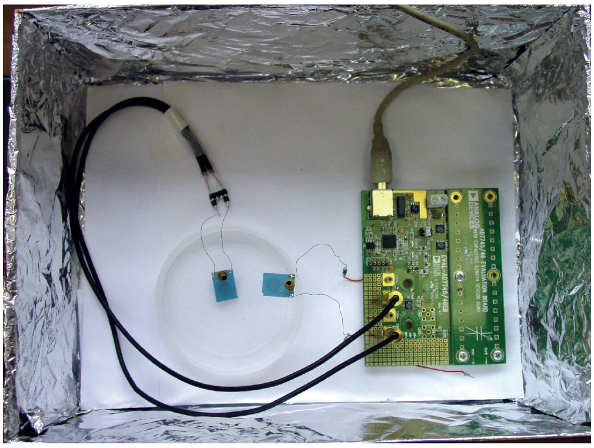


Fig. 3. Experimental set-up with AD7746 evaluation board used for evaluation of the effect of the humidity and moisture on the CCPS.

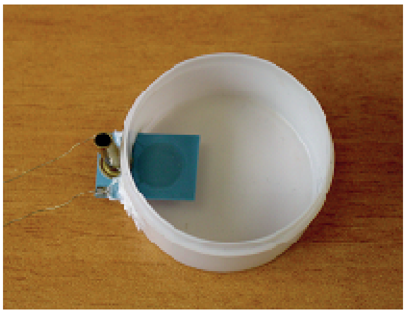
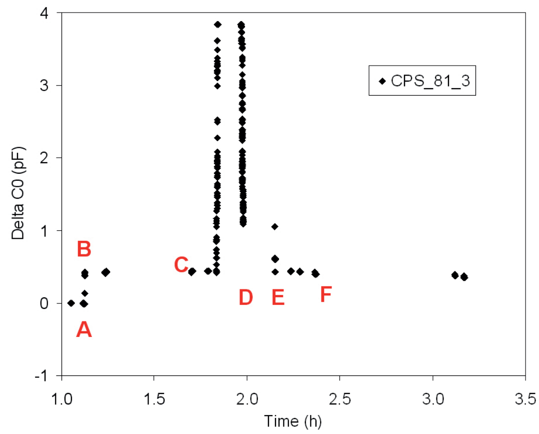


Fig. 4. The CCPS mounted in the plastic pot to prevent contact of the electrical contacts with water during the experimentation.

The zero capacitance of the prototypes (Fig 1b) with the100-µm diaphragm and the diameter of 7.8 mm, the diameter of the electrodes of 6.0 mm and the air gap between the electrodes of 50-80 µm was about 5 pF. The change in the capacitance for the full-scale pressure range (0-300 mbar) was typically up to 500 fF. The sensors measured in this case study were selected from three different lots (i.e., CPS_12, _42 and _81). In the following, each sensor is denoted CPS_xx_yy, where xx is the lot number and yy is the sample number.

Different situations for the sensor in contact with water were analyzed using the following experiments. In the first experiment the water was applied on the external surface of the sample presented in Fig. 2b and the response (C_0) was measured continuously in several steps. The results are presented in Fig. 5, where each particular step is denoted with a capital letter A to F. Point A shows the initial state, i.e., the changes in C_0 for the dry sensor. Then the water was slowly added to the plastic pot (Fig. 4) by using the stactometer. Point B indicates the moment when the level of the water was in contact with the bottom wall of the sensor. In the moment when the water was poured all over the sensor (point C) the change in C_0 increased by more than 4 pF (out of range for a differential measurement with the AD7746). The sensor was then left in the water for some time and after that the moisture was removed by the stactometer. Even when the outer surface of the sensor seemed to be dry (point E), the capacitance of the structure remained different from the initial value because of the effect of the moisture on the ceramic surface. Measurements during further drying in room conditions (from point E to F) showed $C_0 > C_0$ initial by 400 fF. Only after drying the sensor for several hours did C_0 return to its initial value (Fig. 5b).



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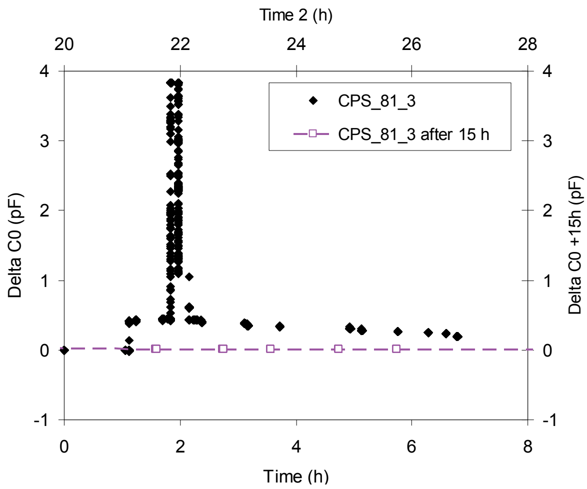
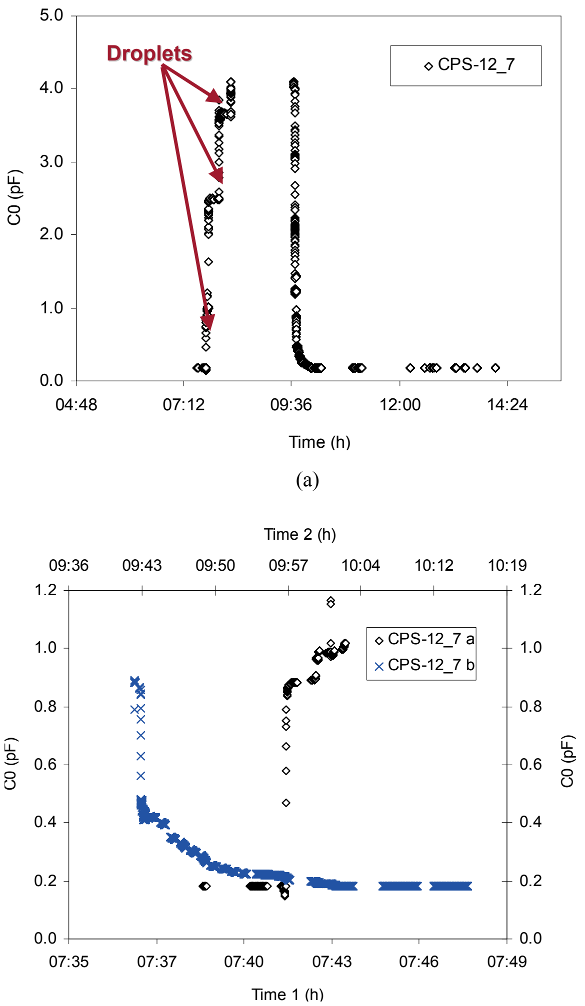


(b)

Fig. 5. a) Changes in C_0 of the sample CPS_81_3 measured during the experiment with the water applied on the external walls of the sensor body. Point A shows the initial C_0, B points at the change in C_0 after adding the water to the vessel (the level of the water is in contact with the bottom wall of the sensor), C: the water touches the lateral walls of the sensor, D: the whole sensor is plunged into the water, E: the water was poured away, F: the walls of the sensor are dried in air and b) Changes in C_0 after drying the sensor for about 15 hours (second x axis, Time 2).

A similar experiment with water droplets applied to the external surface of the diaphragm showed that immediately after the moisture was removed the capacitance C_0 remained about 200 fF higher than it was initially. The changes in C_0 measured after applying a few droplets of water on the external side of the sensor's membrane and then after removing the water from the sensor surface are presented in Fig. 6. For a better illustration, Fig. 6b shows the details of the characteristics of C_0 from Fig. 6a, measured while dripping the water on the sensor's surface and during drying in the graph with two different x axes (Time 1 and Time 2, respectively). It is clear that the effect of the humidity diminished after drying the sensor for approximately one hour under normal ambient conditions (24°C, 40 % RH). These results explained, to some extent, the hysteresis of the characteristic in Fig. 2.



(a)

(b)

Fig. 6. a) Changes in C_0 of the sample CPS-12_7 after applying a few droplets of water on the external side of the sensor's membrane and then after removing the water from the sensor surface, b) The characteristics CPS-12_7_a (Time 1) represent C_0 measured during dripping the water on the sensor's surface and CPS-12_7_b (Time 2) shows C_0 during draying.

4. Modeling

For this case study the numerical model was built in the FlexPDE finite-element (FE) code. The analysis was based on a calculation of the capacitance from the electrostatic field energy stored in the capacitive LTCC structure and the surrounding media. Initially, an analysis was made of the influence of the geometry/dimensions of the ceramic structure on the capacitance. The results were compared to the calculations by using the known analytical relation for a parallel-plate capacitor. The initial FEA results (Tab. 1) obtained for different dimensions of the top and bottom electrodes at the same diameter of the diaphragm showed the important influence of the stray capacitances on the actual capacitance of the structure. It was shown that in the case of the actual dimensions of the CCPS considered, the difference between the capacitances C_{0_Wtot}, $C_{0\_Wair\_gap}$, C_{ideal} (the values obtained from the total energy stored in the structure and the surrounding media, the energy stored within the air gap and from the analytical equation for the ideal parallel plate capacitors, respectively) can be as high as 13 % of the ideal value. This rough assessment also showed the important influence of the surrounding media.

	Bottom/top electrode d = 6mm C (pF)	Bottom el. d = 6mm Top el. d = 7.8 mm C (pF)	Bottom el. d = 7.8 mm Top el. d = 6 mm C (pF)
C_{0_Wtot}	4.056	4.642	4.216
$C_{0\_Wair\_gap}$	3.563	3.507	3.765
C_{ideal}	3.579	4.812	4.812
C_{0_Wtot} - C_{ideal}	0.477 (13.3%)	-0.170 (-3.5%)	-0.596 (-12.4%)
C_{0_Wtot} - $C_{0\_Wair\_gap}$	0.493 (12.2%)	1.136 (24.5%)	0.451 (10.7%)

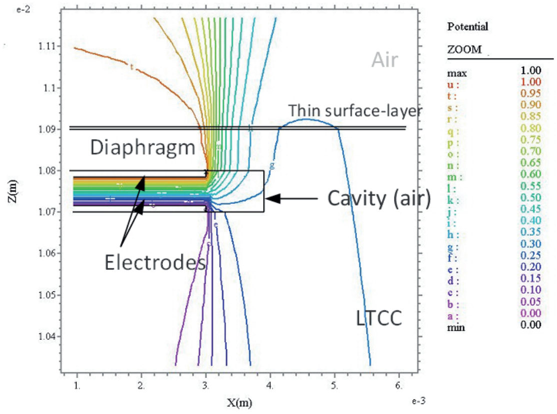
Tab. 1. FEA results obtained for the sensor with the diaphragm of diameter d equal to 7.8 mm and the air gap of 70 μm, and the top and bottom electrodes with diameters of 7.8 mm and 6 mm. Capacitances C_{0_Wtot}, $C_{0\_Wair\_gap}$, C_{ideal} are the values obtained from the total energy in the structure and the surroundings, the energy stored between the electrodes and from the analytical equation for the ideal parallel plate capacitors, respectively.

The validated model was then used for simulations of the sensor in different media and in various physical situations that were previously analyzed experimentally. The aim was to assess the parasitic capacitances resulting from the fringe fields at the edge of the air-capacitor electrodes in the ceramic structure and the surrounding field lines within the whole chosen problem domain. A subsequent analysis was performed for the same geometries of the capacitive structure as in Tab. 1 and the different humidity of the atmosphere at a constant temperature. The dielectric constant of the humid air was modeled with relation (1).

The initial simulations of the sensor in the humid air modeled in this way showed smaller changes in C_0 than were obtained experimentally. The discrepancy between the numerical and experimental results was particularly noticeable at the higher RH values. For RH > 80 % the measured changes in C_0 (the experimental results in Fig. 2) were even several percent higher than the numerical results. In the updated model we assumed for the physical situation at higher RH (> 80 %) that the surface of the ceramic is covered with a film of condensed water. For a rough estimation, such a situation was modeled with 5-15 µm thick films of water ($\varepsilon_{r\ water}$ = 80). Alternatively, the model of the sensor structure with a thin layer of the ceramic (on the external surface of the sensor body) with the dielectric properties changed due to the effect of the humidity can also be considered. Due to a lack of experimental data for the dielectric properties of the ceramic for such situations and since an in-depth study of the effect of the humidity on the surface of the LTCC ceramic was beyond the scope of our project, we could only assume that this layer should have a several times higher dielectric constant in comparison to the LTCC ($\varepsilon_{r\ LTCC}$ = 7.8). Being aware of the inexactness of the assumptions that were made, we could only use the proposed numerical models to predict the trends.

Some representative numerical results showing the fringe field at the edge of the air-capacitor are presented in Fig. 7. Fig. 7a shows the detail of the cross-section of the sensor cowered with a thin film of moisture (on the top surface of the diaphragm). The simulated equi-potential lines are parallel in the air-gap between the electrodes and submitted to the structure geometry around in accordance with the material properties specified in these regions. Fig.7b shows the electric field vector in this situation. By integrating over the whole problem domain the energy stored in the structure was evaluated, from which the actual capacitance of the sensor was obtained. A summary of the FE analyses performed for two different dimensions of the electrodes and different situations for the sensor's environment (the humid air and the thin layers of moisture on the external surface of the ceramic structure) are presented in Fig 8. This figure shows the simulated changes in the capacitance C_0 of the CCPSs for two geometry cases with different diameters of the capacitor electrodes, and for different humidity/moisture situations: the humid atmosphere in the cavity and around the sensor (four categories on the left part of the graph corresponding to 20 %, 50 % 89 % and 100 % of RH), and the condensed water on the external walls of the sensor structure (the last three categories on the right of the graph, for 5 µm, 7.5 µm and 15 µm thick film of water).

These results show that the influence of RH (in the idealized case when ε_{air} is described with (1)) is almost negligible and that the actual problem comes from the effect of the humidity on the surface of the ceramic structure (arising noticeably for the increased RH). Comparing the numerical results with the measured characteristics (Fig. 8b) shows that for a RH > 60 %, the humid air affects the surface of the ceramic or a thin film



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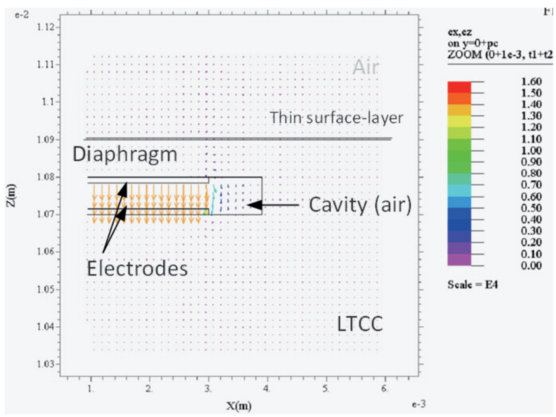


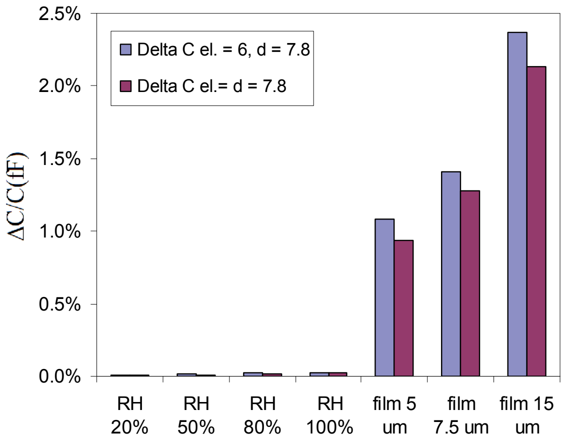
(b)

Fig. 7. Numerical results shown in the detail of the cross-section of the sensor: a) Equi-potential lines representing the fringe field at the edges of the air-capacitor electrodes, b) Electric field vector

of moisture is condensed on the ceramic surface, which changes the stray capacitances in the CCPS structure.

5. Conclusions

The effect of the humid atmosphere and the moisture applied on the external surface of the CCPS was analyzed both numerically and experimentally. It was shown that the characteristics can be strongly affected by the parasitic stray capacitances resulting from the humidity of the surrounding atmosphere and the condensed water on the outer walls of the sensor, particularly for the structure with a relatively low capacitance C_0. Showing the same trends as the experimental observations, the simulations also revealed that the effect of the humidity can be slightly reduced for an optimized design and for higher capacitances. However, the problem of changing the dielectric properties of the ceramic on its surface (even temporarily) cannot be avoided for a direct contact with the humid atmosphere without additional filters and appropriate packages.



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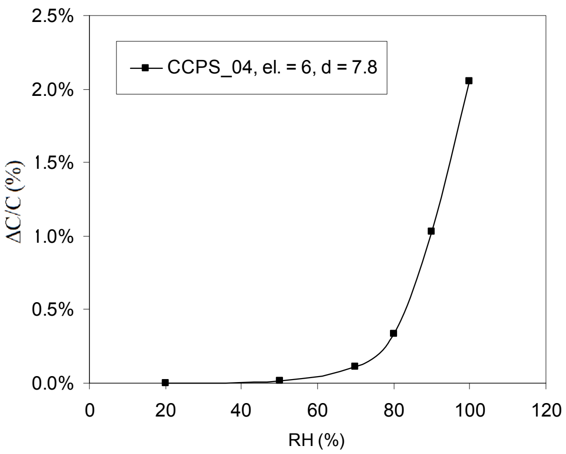

(b)

Fig. 8. a) Simulated changes in the capacitance of the CCPSs for two geometries (with different diameters of the capacitor electrodes) and for different humidity/moisture situations: Influence of the RH and the condensed water on the external walls of the sensor structure, b) Measured capacitance changes due to the effect of RH (stabilization of the conditions before each measurements for 2 hours)

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About the Authors …

Marina SANTO ZARNIK received an M.Sc. degree in computer science and a Ph.D. in electrical engineering from the University of Ljubljana, Slovenia in 1993 and 1998, respectively. Her research covers different areas of interconnection and electronic packaging, testing and fault diagnosis of analog- and mixed-signal circuits and electromechanical sensors. Recently, her main research interests include the characterization and finite-element modeling of ceramic electromechanical systems and thick-film sensor structures.

Darko BELAVIC graduated in electrical engineering in 1977 from the University of Ljubljana, Slovenia. Since 1978 he has been working in the field of thick-film hybrid microelectronics in a research and development team at HIPOT-R&D and at the Jožef Stefan Institute, Ljubljana. In 1996 he became head of the HIPOT Research and Development Group. His research interests are thick-film and LTCC technology, hybrid-microcircuit and ceramic-microsystem design, and pressure sensors.