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USE AND CALIBRATION OF CAPACITIVE RH SENSORS FOR THE HYGROMETRIC CONTROL OF THE CMS TRACKER

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Abstract.

The CMS Tracker needs careful thermal and hygrometric control during steady state operations as well as during cool down processes. In order to avoid undesirable dew formation, it is mandatory to control the relative humidity of the air filling the tracker cold volumes (working temperature about –10°C, with local peaks at –20°C). Few sensors are suitable candidates to this aim, due to the need for sensor miniaturisation, response reliability and radiation hardness characteristics.

Among the commercial devices, capacitive sensors have many of the required features and are extensively used in the phases of preparation and commissioning of several Tracker components. Therefore, some Honeywell HIH series devices have been experimentally tested in order to ascertain the real response to relative humidity variations and to check the influence of the voltage supply. In particular saturated salt solutions have been employed to create reference humidity environments for the calibration of the sensors. The experimental results show that the real sensor response can be sensibly different from the one provided by the manufacturer and that distinct behaviours occur in the considered sample. Even though these sensors are not candidate for use inside CMS, the experience gained points to an important problematic to be taken into account for the selection and validation of the final sensor to be used inside the Experiment.

The preliminary tests shown in this note are useful towards the definition of rules to be identified in order to perform an overall calibration procedure devoted to the selection of proper instrumentation able to assure long period operations under well-established measurement uncertainty.

1.Introduction

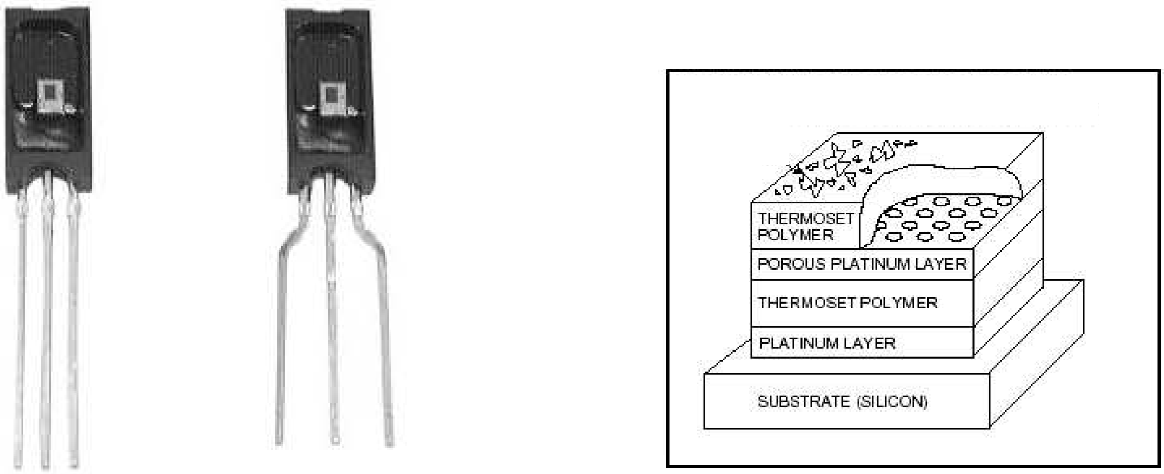
The Silicon Tracker detector of the CMS experiment at LHC will require a temperature and humidity controlled environment during its operational life. The high radiation levels to which silicon sensors will be exposed, require their operation at temperatures below 0°C and consequently in a dry atmosphere to avoid condensation.

Recently, an experimental set-up for a thermal and environmental simulation of a portion of the CMS Tracker has been completed at CERN and is now under commissioning. The purpose of the set-up is to study the technical implications in preserving a cold and dry condition inside the Tracker volume during operation. Humidity and temperature measurements will be taken and analysed for the duration of a whole year in several configurations and operational modes. Honeywell HIH series devices have been selected for relative humidity (Rh) measurement in this mock-up due to their reduced size and low cost.

Even though these sensors are not foreseen for use inside the Tracker, and the ultimate decision about the Rh sensor to be effectively employed is not already taken, some general considerations can be drawn. In order to assure reliable operations, Rh sensors should be carefully calibrated in order to define the uncertainty in the measurements with respect to the theoretical response as provided by the manufacturer. In consideration of the large range of temperature through which humidity measurements will be taken inside the Tracker, from room temperature to -20^{o}C, these reference sensors should be calibrated against different temperature conditions.

Furthermore, humidity sensors are expected to operate in the Tracker for several years without maintenance and further calibrations, still providing enough reliable and uniform information to allow an automated feedback control system for keeping safe operational conditions. Anyway, humidity sensors often exhibit response drift due to the humidity cycles, to which they are subjected. A long-period procedure, based on repeated exposure to humidity cycles alternated with measurements in a reference environment, should define the drift properties of the selected sensors and provide guidance for their long-term implementation. The above considerations require the definition of a calibration procedure able to provide the technical knowledge on Rh sensor behaviour, in order to reduce the measurement uncertainty down to an engineering reasonable and safe value, needed for an efficient feed-back control of cooling and ventilation devices.

This work describes the first steps towards the study of these problems and towards a full characterisation of a few sensors for mock-up measurement purposes: preliminary tests have been performed on a sample of HIH devices in order to evaluate the real response to relative humidity variations and to check the influence of other parameters



(a) (b)

Figure 1. HIH 3610 sensor view (a) and a scheme of the elements (b).

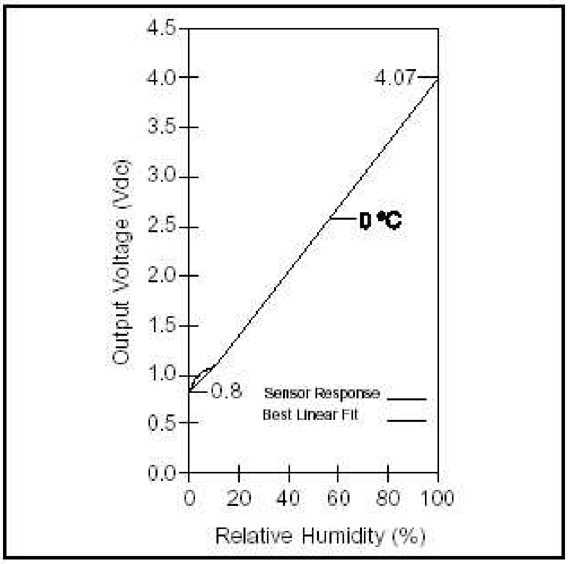


Figure 2. Manufacturer sensor response to Rh variations for a Voltage supply of 5 V at 0°C.

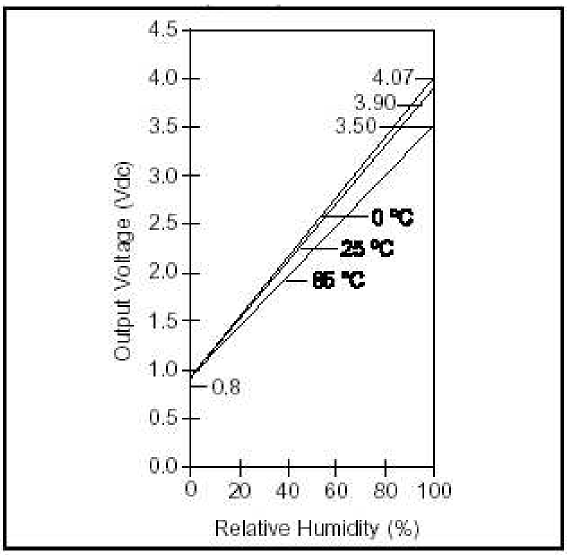


Figure 3. Manufacturer sensor response to Rh variations for different working temperatures.

(e.g. voltage supply, temperature, time drift). In particular saturated salt solutions have been employed to create reference humidity environments at controlled temperature.

2. Sensor characteristics and calibration procedure

The Honeywell HIH-3610 Series humidity sensors are devices based on a thermoset polymer capacitive sensing element with on-chip integrated signal conditioning (Figures 1(a) and 1(b)). The manufacturer data sheet is reported in Table 1 in the Appendix and shows a linear sensor response with respect to the relative humidity (Figure 2). The output voltage V_{out} at 25°C depends on the supply voltage V_{supply} as:

$$V_{out}=V_{supply}\,(0.0062\ Rh + 0.16), \qquad (1)$$

the relative humidity Rh being expressed in percentage.

The manufacturer claims that the sensor accuracy is within ±2% Rh and that the sensor interchangeability is ± 5% Rh in the 0 to 60% Rh range. The effects due to the operating temperature are given by the graph reproduced in Figure 3.

A quite common technique to obtain constant humidity environments is based on the use of saturated salt solutions in closed containers filled by air. Saturated salt solution can provide stable humidity conditions, provided that several constraints are fulfilled, the most important being the temperature stability of the bath containing the solution.

The problem of maintaining relative humidity fixed points have been discussed quite extensively in literature (Greenspan 1977, Cretinon 1991, Carotenuto et al. 1994), even if some uncertainties still exist in the Rh values to be ascribed to each salt solution, as can be observed in the Appendix, Table 2. Another debated issue is related to the influence of solution temperature, since available data are limited and they are usually referred to temperatures above zero Celsius (see Appendix, Table 3).

Another way to obtain stable Rh air volumes concerns the use of non-saturated solutions. The advantage of this technique is that one can employ a single salt to create many Rh fixed points simply by changing the salt concentration in water. Furthermore, if the salt is Lithium Chloride, Rh values ranging from about 10% to 100% can be achieved in short transient times, due to the capability of this salt to produce fast diffusing solutions. Sealed ampoules of non-saturated solutions are commercially available.

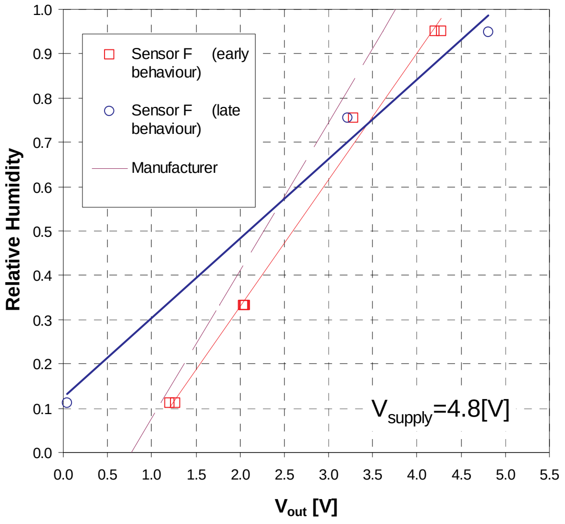


Figure 4. Probe F response in early and late behaviours.

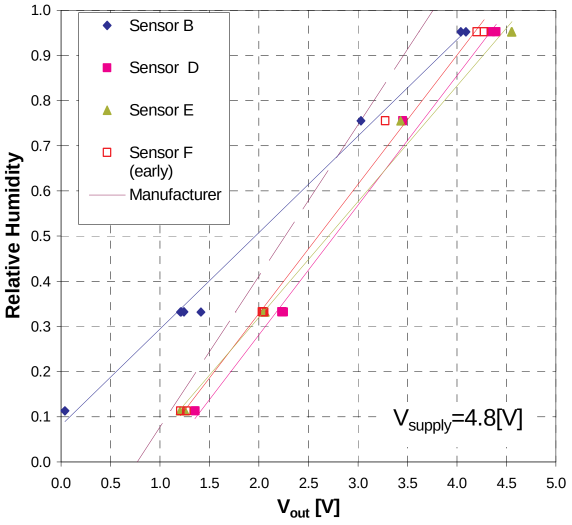


Figure 5. Probe responses to Humidity variations. Reference temperature 18°C.

The drawbacks are mainly two. One is the uncertainty on the relationship between concentration and equilibrium relative humidity, in addition to the difficulties in preparing solutions at prescribed concentrations. The other is the diffusive process between air and solution, which, in principle, changes the solution concentration and hence the final Rh equilibrium value. In order to avoid the latter problem, it is advisable to employ small containers (i.e. small air volumes) so that the amount of water vapour diffusing from (to) air is small enough to allow an almost constant concentration to be maintained. On the other hand, small containers cannot host several sensors, have to be accurately sealed, may undergo temperature variations due to the reduced heat capacity.

The present investigation is based on the use of saturated salt solutions in order to calibrate a sample of sensors and to ascertain the difficulties related to this kind of practice.

The ASTM 104 (1985) recommendations have been strictly followed. In particular, at least 100 cm^3 of saturated solutions (obtained by mixing the salt with demineralised water) have been always employed, the container has been accurately sealed, the ratio between the trapped air volume and the solution interface was maintained always less that 25 cm^3/cm^2.

Two different experiments have been carried out. The first one was a complete calibration on a limited set of sensors (four probes) with reference to different values of Rh and supply voltages.

The second experiment was carried out on a larger sample of 22 sensors in order to ascertain the scatter of output signals when the sensors are exposed to a stable humidity and temperature condition. In this case, the related operations were performed by means of a new facility, which allows for fitting inside all the 22 sensors at the same time and for a more precise temperature control.

2.1 Probe response curves and supply voltage influence

As briefly discussed above, extensive experimentation was performed on a limited set of four sensors that were exposed to different air humidity values in order to build their specific characteristic curve also in terms of supply voltage variations.

Temperature was maintained at 18°C ±0.9°C. The experimental facility available for this test did not allow more stable temperature to be achieved: mainly due to this fact, the overall calibration uncertainty was around ±1.5% Rh.

Four sensors (identified as sensor B, D, E, F) have been calibrated according the above-described procedures. The effect of sensor voltage supply was also investigated.

Solutions have been prepared and left interacting with the trapped air up to 96 hours prior to collect the sensor output. Temperature (as given by Pt100 RTDs) and sensor signal have been recorded at constant time intervals in order to ascertain when the thermo-chemical equilibrium is reached.

Four salts have been considered, namely lithium chloride, magnesium chloride, sodium chloride and potassium nitrate. As can be observed from Tables 2 and 3 in the Appendix, the corresponding relative humidity values are respectively around 11%, 33%, 75%, 95%, so covering the expected operating condition range.

2.2 Probe response scatter

In order to establish the real degree of probe interchangeability, measurements were performed on a set of 22 sensors (referred to as sensors S1 to S22). The procedure adopted consisted in confining all the probes in a stable humidity environment as achieved by the air contact with a LiCl saturated solution (Rh=11.3%). A new sealed container was employed, which is able to host up to 40 sensors and can control the bath temperature by means of the circulation of a thermal fluid around five walls of the calibration box. In such a way it was possible to reduce the temperature oscillations (during 48 hours runs) both in frequency and in amplitude (down to the range ± 0.2°C). Type-K thermocouples were employed to record the temperature variations. In this case the uncertainty in the measurement can be evaluated around ± 0.5%Rh

3.Results and discussion.

3.1 Probe calibration curves and influence of the supply voltage

According to the procedure previously described, a calibration was performed on four sensors by fixing four constant humidity conditions in the 11 to 95% range. The first series of measurements ("early") was conducted at a constant supply voltage (V_{supply}=4.8 V), while in a following series ("late") the supply voltage was also varied.

During these experiments, probe F showed a peculiar behaviour, since, without any apparent reason, it changed its response dramatically. The response of probe F is plotted in Figure 4, as a function of relative humidity for both its early and late behaviours. It can be noticed that "early" and "late" responses are characterised by very different slopes, even if a linear behaviour still seems to exist.

Furthermore it can be observed that, after the change, the output of sensor F at Rh close to 11% is around 0.04 V against an expected output of about 1.2 V. This kind of response is very similar to that of sensor B. It seems possible to conclude that the above sensors underwent a degradation, whose causes should be investigated in order to assure the reliability of a measurement procedure based on this type of sensors. Indeed the same behaviour was later observed in two other sensors, belonging to the sample of 22 elements.

The comparison among the four sensors is plotted in Figure 5: sensor responses are different and the ones given by the manufacturer is not able to efficiently describe the individual sensor response. Indeed, using the nominal response can produce errors up to 20% Rh at humidity values higher than 75%. Only at low humidity values (around 10%) the nominal curve is able to fit the real responses (of sensors D and E) within the expected measurement accuracy.

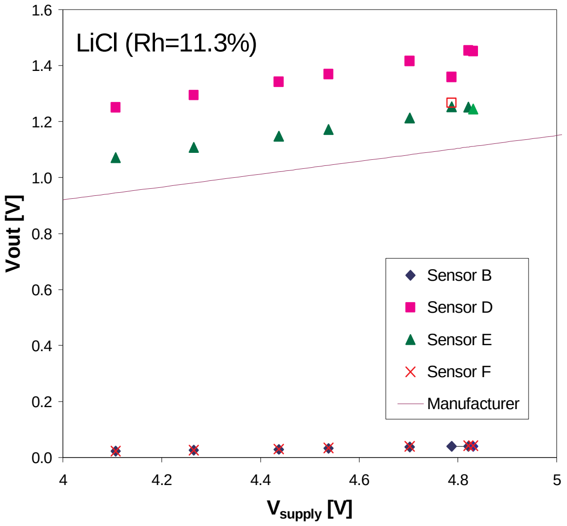


Figure 6. Probe responses to supply voltage variations. Reference humidity 11.3%

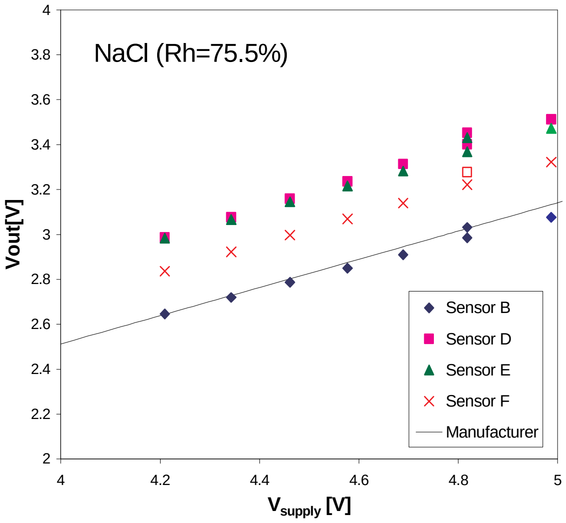


Figure 7. Probe responses to supply voltage variations. Reference humidity 75.5%

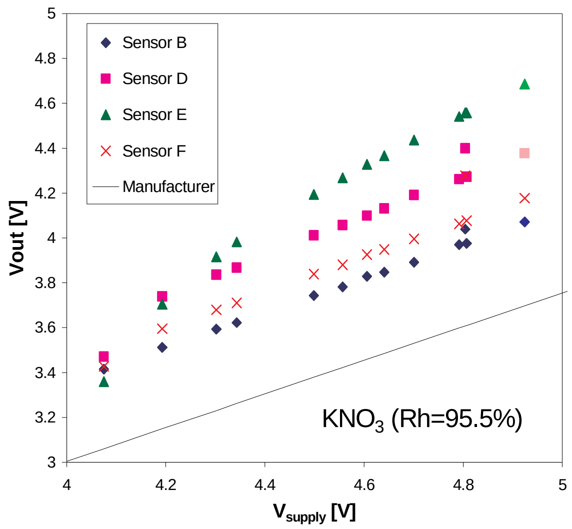


Figure 8. Probe responses to supply voltage variations. Reference humidity 95.5%.

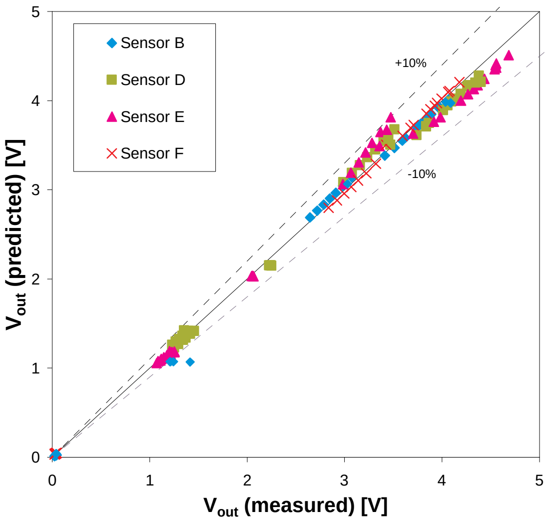


Figure 9. Correlation reliability in terms of sensor output for different humidity and supply conditions.

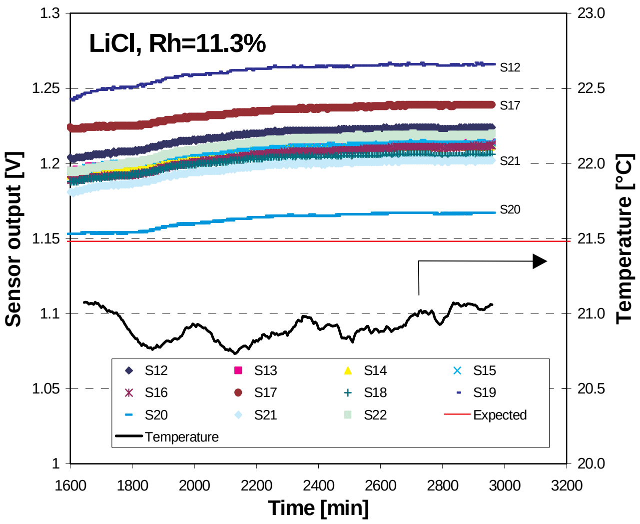


Figure 10. Time-evolution of probe responses. Reference humidity 11.3%.

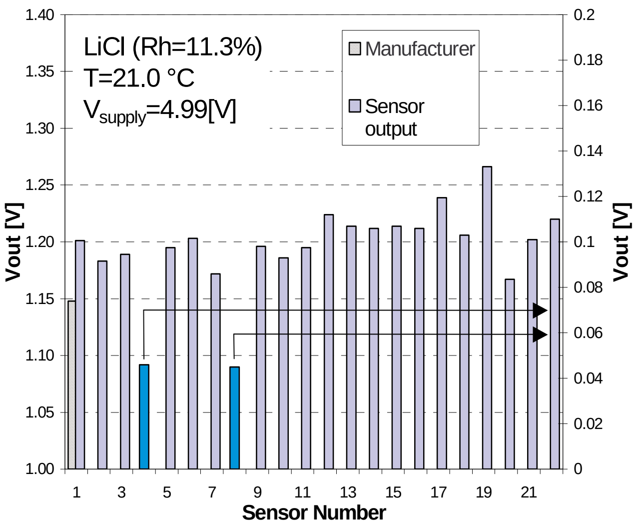


Figure 11. Steady state sensor response and comparison with expected behaviour. Reference humidity 11.3%.

The effect of supply voltage on probe responses is shown in Figures 6, 7 and 8 where the probe output is plotted for different supply voltages and different humidity conditions. Note that in these figures probe F shows its “late” behaviour.

The analysis of Figures 6, 7 and 8 shows that the effect of the supply voltage is different from the expected one. Furthermore, it is worth noticing that the linear behaviour does not tend to zero, at least by extrapolating the profile obtained in the nominal working range (4 to 5.8 V).

In order to fit all the experimental data and to account for the real sensor behaviour, a four constant expression (eq. 2) has been introduced and multiple regression fit has been performed. On the contrary, the expression proposed by the manufacturer contains only two constants.

$$V_{out} = (C_1+C_2V_{supply})\,(C_3+C_4Rh). \qquad (2)$$

For the sake of brevity, details on data reduction are omitted and individual constant values are reported in Appendix, Table 4. The results of the data fit are shown in Figure 9, where the measured output voltages are compared with predicted ones according to empirical equations having the form of eq.2. After reduction, the typical uncertainty is well within ±10% of the actual reading.

3.2 Probe response scatter

For the second experiment, a larger sample of 22 HIH sensors was exposed to a reference humidity condition given by Rh=11.3% and T=21.0°C for more than 48 hours. As an example, Figure 10 shows the time history concerning the output of 11 sensors during the last 24 hours. Stable temperature conditions as well as a steady state response were achieved. The response dispersion is around 10% of the average output voltage, which, at this low humidity value, corresponds to an error within 4% Rh at room temperature. Figure 11 shows the steady state output values given by the 22 sensors when the supply voltage is 4.99 V. Sensors S4 and S8 show a peculiar response, their output being very low (about 0.04 V) compared to that given by all the other sensors (about 1.2 V). This behaviour is very similar to that of sensors B and F described in Section 3.1 and it can be ascribed to a performance degradation that can occur to certain sensors. Finally, it is confirmed that at low humidity values the theoretical curve fits reasonably well the real sensor response: its bad accuracy at humidity values higher than 50% Rh, observed with the limited set of sensors B, D, E, and F, will be investigated through further measurements on the larger sample of 22 sensors.

5.Conclusions

The use of saturated salt solutions appears a suitable procedure to characterise the humidity sensors to be employed inside the CMS tracker and in the experimental set-up used to simulate its thermal and environmental behaviour. In this first work, the Honeywell HIH series sensors have been considered and their theoretical response was compared with experimental data. The experimental results show that the real sensor response can be quite different from the expected behaviour and a scatter of responses can occur. The main results can be summarised as follows:

- during operations, some sensors can undergo a degradation, which produces remarkable shift from original response and a change of the slope. The causes of such behaviour should be investigated in order to assure the reliability of a measurement procedure based on this type of sensors;
- the nominal response curve does not describe efficiently the individual sensor response to Rh variations. In particular, errors around 3 to 4% Rh have been observed at low humidity and errors up to 20% Rh at humidity values higher than 75%;
- the effect of the supply voltage is different from the expected one. Furthermore, when extrapolating the linear profile obtained in the nominal working range (4 to 5.8V), the predicted sensor output does not tend to zero at zero voltage supply;
- it is anyway possible to achieve the expected interchangeability, within ±10% of the actual readout. However this requires the reduction of the overall calibration data in terms of both humidity and supply voltage by means of a four parameters equation, as opposed to the nominal one, based on two only;
- measurements on a sample of 22 sensors confirmed that at low humidity values the nominal curve always underestimates the real probe response, even if the differences, in this situation, are within 4% Rh.

Although these sensors are not candidate for use inside CMS, these points should be carefully taken into account for the selection and validation of the final sensor to be used inside the Experiment.

Finally these preliminary tests allow general rules to be identified in order to perform an overall calibration procedure devoted to the selection of proper instrumentation able to assure long period operations under well-established measurement uncertainty.

6.Further developments

The work presented is a first step towards a deeper comprehension of the issues related to a reliable, long-term Rh measurement inside the CMS Tracker.

In consideration of the large range of temperature through which humidity measurements will be taken inside the Tracker, in the next step the sensors will be calibrated and tested against different temperature conditions.

Also, the probe response scatter at humidity values higher than 50% Rh will be evaluated on a large sample of sensors.

In the future, a long-period procedure, based on repeated exposure to humidity cycles alternated with measurements in a reference environment, should define the drift properties of the selected sensors and provide guidance for their long-term implementation.

Furthermore, once the radiation/magnetic hardness of sensor families of affordable cost and dimensions will be demonstrated, saturated salt solutions should be employed to thoroughly characterize the behaviour of the different candidates. This would provide a clear guideline for the ultimate selection of the Rh sensor to be effectively employed in the Tracker and would allow for its safe and reliable use to monitor the humidity level in the experiment.

Acknowledgements

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APPENDIX

HIH 3610 sensor Technical Documentation
RH Accuracy(1) ±2% RH, 0-100% RH non-condensing, 25 °C, $V_{supply} = 5$ Vdc
RH Interchangeability ±5% RH, 0-60% RH; ±8% @ 90% RH typical
RH Linearity ±0.5% RH typical
RH Hysteresis ±1.2% RH span maximum
RH Repeatability ±0.5% RH
RH Response Time, 1/e 15 sec in slowly moving air at 25 °C
RH Stability ±1% RH typical at 50% RH in 5 years
Power Requirements
Voltage Supply 4 Vdc to 5.8 Vdc, sensor calibrated at 5 Vdc
Current Supply 200 A at 5 Vdc
Voltage Output ($V_{supply} = 5$ Vdc)
$V_{out} = V_{supply}$ (0.0062(Sensor RH) + 0.16), typical @ 25 C
Drive Limits
0.8 Vdc to 3.9 Vdc output @ 25 C typical
Push/pull symmetric; 50 A typical, 20 A minimum, 100 A maximum
Turn-on 0.1 sec
Temperature Compensation True RH = (Sensor RH)/(1.093-0.0021T), T in °F True RH = (Sensor RH)/(1.0546-0.00216T), T in C
Effect @ 0% RH: ±0.007 %RH/°C (negligible)
Effect @ 100% RH: -0.22% RH/°C (<1% RH effect typical in occupied space systems above 15 °C (59 F))
Humidity Range
Operating: 0 to 100% RH, non-condensing(1)
Storage: 0 to 90% RH, non-condensing
Temperature Range
Operating: -40 °C to 85 °C (-40 F to 185 F)
Storage: -51 °C to 125 °C (-60 F to 257 F)
Package(2) Three pin, solderable SIP in molded thermoset plastic housing with thermoplastic
cover
Handling Static sensitive diode protected to 15 kV maximum
Notes: 1. Extended exposure to 90% RH causes a reversible shift of 3% RH. 2. This sensor is light sensitive. For best results, shield the sensor from bright light.

Table 1. HIH sensor data sheet

Salt	Rh % Buonanno et al. (1995)	Rh % Greenspan (1977)	Rh % Wyzykowska (1979)	Rh % Cretinon (1991)
LiBr	6.83	6.61±0.58	-	-
LiCl	10.95	11.31±0.31	12.6±1.0	10.9±0.6
KCH_3CO_2	23.52	23.11±0.25	-	-
$MgCl_2$	32.64	33.07±0.18	33.6±1.2	-
K_2CO_3	43.45	43.16±0.33	-	43.9±0.5
$Mg(NO_3)_2$	54.25	54.38±0.23	56.2±2.2	-
KI	69.56	69.90±0.26	-	-
NaCl	75.76	75.47±0.14	76.2±1.7	75.2±0.3
$(NH_4)_2SO_4$	80.64	81.34±0.31	81.3±1.0	-
KNO_3	93.89	94.62±0.66	95.0±1.7	-
K_2SO_4	98.33	97.59±0.53	98.9±1.3	-

Table 2 Comparison among literature data on saturated salt humidities at 20 °C.

Temperature [°C]	Relative humidity [%]			
	Lithium chloride LiCl	Magnesium chloride $MgCl_2$	Sodium Chloride NaCl	Potassium nitrate KNO_3
0	11.23±0.54	33.66±0.33	75.51±0.34	96.33±2.9
5	11.26±0.47	33.60±0.28	75.65±0.27	96.27±2.1
10	11.29±0.41	33.47±0.24	75.67±0.22	95.96±1.4
15	11.30±0.35	33.30±0.21	75.61±0.18	95.41±0.96
20	11.31±0.31	33.07±0.18	75.47±0.14	94.62±0.66
23	11.30±0.28	32.90±0.17	75.36±0.13	94.00±0.60
25	11.30±0.27	32.78±0.16	75.29±0.12	93.58±0.55
30	11.28±0.24	32.44±0.14	75.09±0.11	92.31±0.60
35	11.25±0.22	32.05±0.13	74.87±0.12	90.79±0.83
40	11.21±0.21	31.60±0.13	74.68±0.13	89.03±1.2
45	11.16±0.21	31.10±0.13	74.52±0.15	87.03±1.8
50	11.10±0.22	30.54±0.14	74.43±0.19	84.78±2.5

Table 3 Relative humidity of saturated salt solutions as a function of temperature (from Greenspan, 1977)

Probe	C_1	C_2	C_3	C_4
B	0.1187	0.0778	0.493	0.876
D	0.1976	0.1765	-0.423	0.7801
E	0.5954	0.0328	-2.1337	1.2448
F	-0.0957	-0.082	0.2589	0.9641

Table 4 Experimental constants for equation (2)