# Characterisation of capacitive humidity sensors under Martian pressure and temperatures down to -120 °C

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**KURZFASSUNG:** Für ein Raumfahrtprojekt wurden unter anderem kommerziell erhältliche, kapazitive Sensoren im Bereich von -73 °C bis -20 °C bei einem Druck von 800 Pa mit Luft als Trägergas getestet. Im Ergebnis konnte sowohl eine Abnahme des Sensorsignals mit der Temperatur als auch eine Temperaturunabhängigkeit der Kennlinie im Bereich von 0 %r.F. bis 30 %r.F. festgestellt werden. Zudem wurde in Thermalzyklentests zwischen -120 °C und -10 °C festgestellt, dass es im Bezug auf die Kennlinie keine Veränderungen gab.

**ABSTRACT:** Extensive measurements of commercial capacitive polymeric humidity sensors were made at temperatures ranging from -73 °C to -20 °C and at a pressure of 800 Pa in order to test and validate their performance for future space missions. We found the sensor signal decreases when temperature decreases as well as a temperature independent sensor characteristic in the range from 0 %RH to 30 %RH. In addition the sensor has shown stable characteristics during thermal cycling in the range from -120 °C to -20 °C under vacuum conditions.

*Schlagwörter: capacitive, humidity sensor, low temperature, sensor characteristics*

## 1 Introduction

As part of the of the scientific payload of the former ESA ExoMars mission, the institute of Planetary Research at the German Aerospace Centre (DLR) and the SMB dr.wernecke Feuchtemesstechnik GmbH have jointly developed a humidity sensor system to perform in-situ measurements of the near-surface atmospheric water content on Mars. The water content of soils significantly influences their chemical and physical properties and is also needed for biological processes to proceed. Since pressure and temperature are too low on Mars, bulk water can not exist in a stable form [1, 2]. Measurements at DLR show that adsorbed water, adhered to solid surfaces, could remain in liquid like state even under conditions present on Mars in the equatorial region [1, 3]. The amount of adsorbed water in the soil is a function of water vapour density in the near-surface atmosphere, the temperature, specific area per mass, and the mineralogy. In respect of Mars the thin layer of the upper millimetres of the Martian surface is of particular interest since the soil interacts directly with the diurnally varying atmospheric humidity, which can reach saturation during night and early morning [4, 5, 6, 7]. Therefore, near-surface measurements of the atmospheric water vapour content will allow to investigate the interaction between the atmosphere and the adsorbed water, which is deposited in the upper soil-layer.

The instrument, denominated as “MiniHUM” uses three different sensors for measuring in the expected humidity content at -75 °C frost point to -50 °C frost point [5,8,9]. These sensors are based on three different measurement principles which help not only to widen the working range, increase the accuracy and sensitivity of the instrument but also provides redundancy and a cross reference for each sensor. To measure the humidity on Mars during night and early morning hours it was intended to use inter alia off-the-shelf capacitive, polymeric humidity sensors.

The capacitive humidity sensor uses the humidity dependence of some polymeric dielectrics to measure the relative humidity content of environmental gas from 3 %RH to 98 %RH Relative humidity changes the dielectric constant of the hydrophilic polymer which is placed between capacitor electrodes. This in turn is converted to a measurable signal. Thereby the oscillator frequency varies inversely with the partial pressure of the moisture.

To validate the sensor performance as well as for calibration purposes different capacitive sensors has been tested within a temperature range from -73 °C to -20 °C. The carrier gas used during the experiment was air at 800 Pa. Furthermore thermal cycling vacuum tests have been carried out in the range from -120 °C to -10 °C to verify if the sensors maintain a stable sensor characteristic.

## 2 Experimental

### 2.1 Sensors

We have studied two different commercial capacitive humidity sensors manufactured by Sensirion and Rotronic. For the experiments we tested the Sensirion SHT75 a digital humidity and temperature sensor used mainly in the automotive industry. According to technical data sheet the measurement range is between 0 %RH and 100% with an accuracy of ±4 %RH in maximum at 0 %RH and 100 %RH. The mean accuracy is given as ±1,8 %RH. The maximum operating temperature range for the sensor is between -40 °C to 125 °C [10].

The second sensor used in the test is the HC2-S3 made by Rotronic. In contrast to the SHT75 the Rotronic is using a capacitive film sensor and a separate temperature element. The measurement range is given by 0 %RH to 100 %RH with the absolute accuracy less than 0,8 %RH The operating temperature range is stated with -100 °C to 200 °C. Beside a digital interface the HC2-S3 provides also a free scalable analogue output from 0 V to 1 V which was used for the tests [11].

### 2.2 Experimental Setup

The experiments were performed in the mars simulation laboratory “Humilab” located at DLR. The lab provides the possibility to test sensors under simulated martian conditions as well as under controlled terrestrial environment. Martian conditions can be simulated in terms of pressure, continuously down to 2 Pa, temperature, continuously from -75 °C to 120 °C, gas composition and humidity. The latter ones are being controlled by a gas mixing facility which is able to control humidity continuously in the range from -73 °C frost point to +10 °C dew point (ambient pressure) as well as to produce atmospheres composed from up to five different constituents.

Figure 1 show a schematic diagram of the experimental setup which has been used to determine the sensor characteristics. Initially, dry air produced by a membrane dryer was flowing into the gas mixing facility were moist air is added, such that a dedicated absolute humidity or frost point was reached.

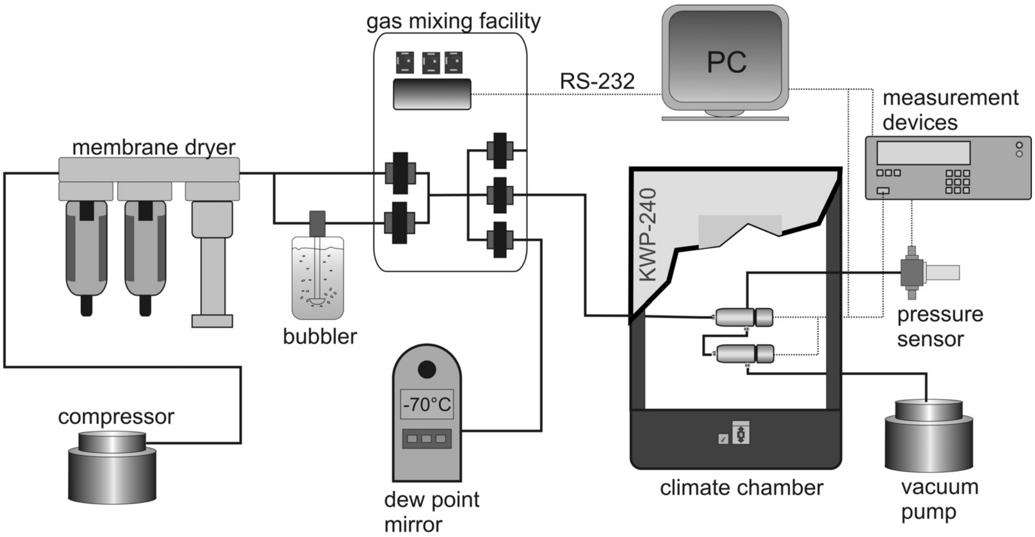


**Figure 1:** Experimental set-up used to determine the sensor characteristics at 800 Pa and between -73 °C and -23 °C

The humidity was controlled by a dew point mirror which was connected to one of the three outlets of the mixing facility. All gas pipes used in the laboratory are made of steel to prevent any diffusion into the gas and therefore a change in humidity. The second outlet was connected to cylindrical measurement cells located inside the climate chamber. For assessing the behaviour, drift and repeatability of the Sensirions, three sensors were mounted equally spaced around the circumference of the cylinder as shown in Figure 2. Additionally an extra resistance temperature element was placed in between, since the lower measurement range of Sensirions is restricted to -40 °C. Further, additional Pt-elements were glued on the surface of the cells in order to get reliable temperature information's even at low pressures expected for this experiment.

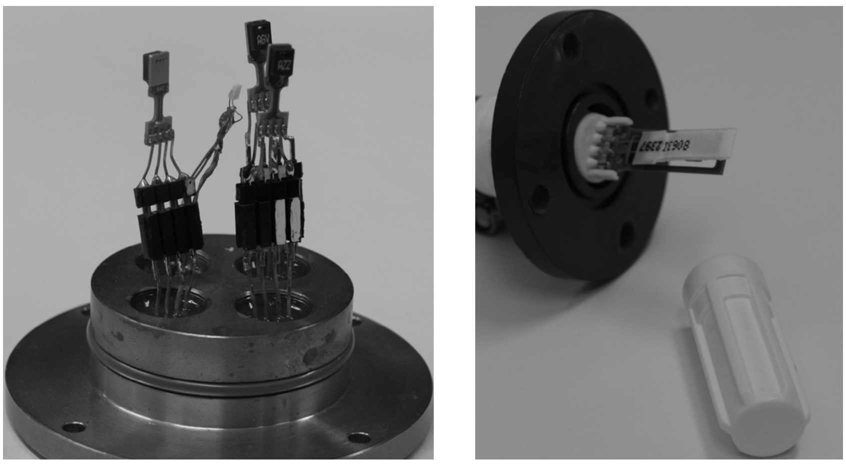

**Figure 2:** Configuration of the Sensirion sensors (l.) and Rotronic (r.) inside the measurement cell

For measuring the pressure a provision has been used which is located at the Sensirion cell. Both the Sensirion as well as the Rotronic were connected in series.

The thermal cycling and the long duration tests were done at the DLR institute of system conditioning, Berlin. For these tests the solar simulation chamber was used which is capable to simulate pressure and temperatures present at low earth orbit. In total 8 cycles between -120 °C and -10 °C have been conducted at $8 \cdot 10^{-4}$ Pa (cf. Figure 3).

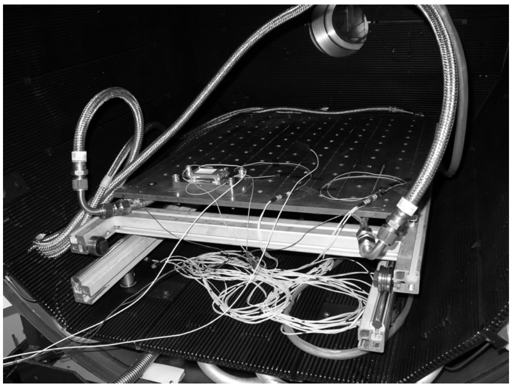

**Figure 3:** Test setup of the thermal cycling test at DLR, Berlin

### 2.3 Measurement strategy

All sensors were calibrated in a DKD accredited laboratory[1] right before and after the experiment. For calibrating the capacitive sensors the humidity calibrator HUMOR 20 was used while the Pt-elements were calibrated to a reference element available at the DLR.

For the experiment the temperature of the climate chamber was decreased stepwise by 10 °C down to -73 °C. After each step when equilibrium was reached, the relative humidity was set by gas mixing facility and measured by the dew point mirror. For every temperature set point, the moisture of the gas has been varied from 10 %RH to 95 %RH.

## 3 Analysis

The actual relative humidity can be derived from the measured dew and frost points. The equation used to calculate the saturation pressure is given by Sonntag [12] as:

$$\begin{aligned}\ln e_w(T) = \frac{-6096{,}985}{T} + 21{,}2409642 - 2{,}711193 \cdot 10^{-2} \cdot T + \\ + 1{,}673952 \cdot 10^{-5} \cdot T^2 + 2{,}433502 \cdot \ln(T)\end{aligned} \tag{1}$$

and,

$$\begin{aligned}\ln e_i(T) = \frac{-6024{,}5282}{T} + 29{,}32707 + 1{,}0613868 \cdot 10^{-2} \cdot T - \\ - 1{,}3198825 \cdot 10^{-5} \cdot T^2 - 0{,}49382577 \cdot \ln(T)\end{aligned} , \tag{2}$$

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where $e_w$ and $e_i$ is the saturation vapour pressure in Pa with respect to water and ice, respectively, and T is the temperature in kelvins. Since the reference measurements were made at normal pressure it is also needed to calculate the water vapour pressure at 800 Pa. At low densities, ideal gas law and Daltons-law are applicable and therefore,

$$\frac{p_{tot_1}}{p_{tot_2}} = \frac{e_{w_1}}{e_{w_2}} \text{ or } \frac{p_{tot_1}}{p_{tot_2}} = \frac{e_{i_1}}{e_{i_2}}, \tag{3}$$

where $p_{tot1}$ and $p_{tot2}$ are the total pressures at 800 Pa and 101325 Pa, respectively. Thus the reference relative humidity derived from dew point mirror measurements could be obtained accordingly by using,

$$RH = \frac{e_{w_1}}{e_{i_t}} \cdot 100 \text{ or } RH = \frac{e_{i_1}}{e_{i_t}} \cdot 100, \tag{4}$$

where $e_{w1}$ and $e_{i1}$ is the calculated water vapour pressure at 800 Pa and $e_{it}$ is referred as the maximum water vapour pressure at the equilibrium temperature measured at each step

The humidity read out of the Sensirion's ($SO_{RH}$) are converted to %RH values using the following relation,

$$RH_{lin} = c_1 + c_2\, SO_{RH} + c_3\, SO_{RH}, \tag{5}$$

where $c_1$, $c_2$ and $c_3$ are equal to -2,0468; 0,0367 and $1{,}5955 \cdot 10^{-5}$, respectively. For temperatures different than 25 °C, the following correction equation is used,

$$RH_{true} = (T - 25) \cdot (t_1 + t_2\, SO_{RH}) + RH_{lin}, \tag{6}$$

where $t_1$ and $t_2$ are 0,01 and $8 \cdot 10^{-5}$, respectively [10].

## 4 Results and discussion

Two different polymeric capacitive Sensors were tested under Martian pressure and temperatures similar to those on Mars. As result it was found that the sensor signal is decreasing with decreasing temperature as shown in Figure 4.

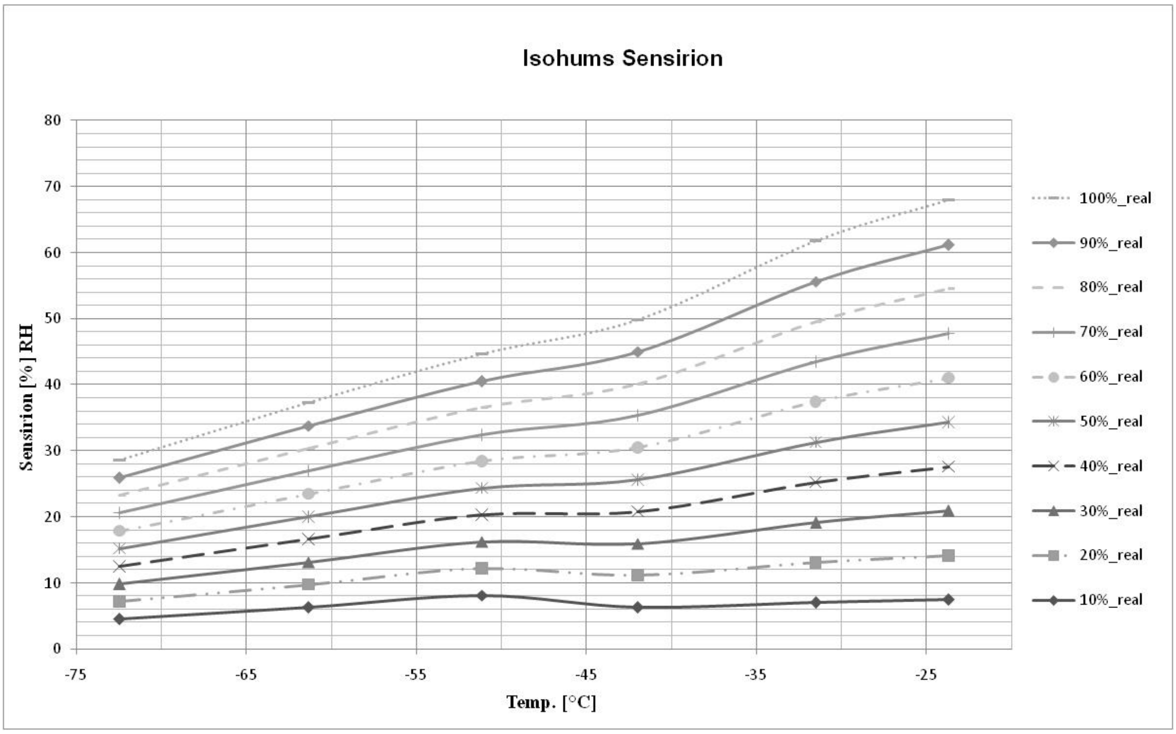


**Figure 4:** Sensor characteristics of Sensirion no. 1 at 800 Pa and -73 °C and -23 °C. The sensor characteristics of the other sensors differ not significantly from that shown here.

Further it is seen that the gradient of the sensor signal increases as the relative humidity increases, e.g. the difference of the 90 %RH signal between -25 °C and -70 °C is higher than for the 20%° RH signal. Thus, the sensor characteristic is nearly temperature independent at humidities lower than 30 %RH. This temperature independence could be a consequence of high binding energies between the polymer surface and the water molecules caused mainly by van der Waals forces. Thus, water molecules are so strongly adhered to the surface, that especially at low humidities their orientation within the electrical field is not being effected by the change in temperature [13]. As the humidity and the amount of water adsorbed increases, the influence of van der Waals interactions between polymer and water molecule decreases. Thus, an increasing temperature effect could be a consequence.

In a second test the sensors should verify if they maintain stable sensor characteristics when exposed to extreme environmental conditions as those on Mars. Therefore the sensors were tested by thermal cycling vacuum tests in the range from -120 °C to -10 °C as well as by a long duration test at -105 °C. The results obtained by the thermal cycling test are shown in Figure 5. It can be seen that both sensors, the Sensirion as well as the Rotronic maintain the stable sensor characteristic. The reference measurements were made by the humidity calibration tool HUMOR 20.

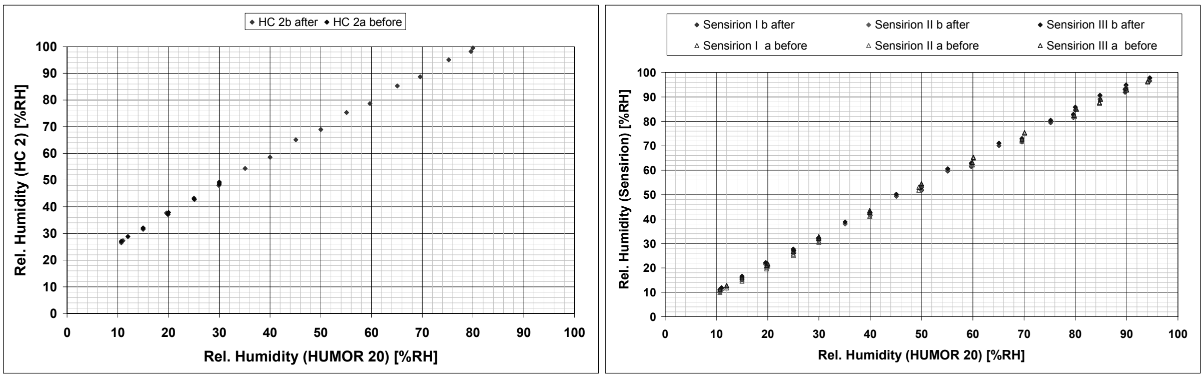


**Figure 5:** Sensor characteristics of the Rotronic (l.) and Sensirion (r.) before and after a 5-days-long duration test. During the test all sensors were operational.

## 5 Conclusions

From the experiments carried out, we can conclude that modern polymeric capacitive sensors are being capable to withstand extreme conditions. In short term tests it was shown that the sensors could be used at low pressures and temperatures even though they needed to be calibrated. Additionally they maintain a stable sensor characteristic.

The results found in this study show only the short term behaviour of the sensors being exposed to such an environment. Therefore future long term experiments should be conducted to analyse aging processes taking place at the polymer.

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