

## An Improved Humidity Sensor\*

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### ABSTRACT

A common feature of all capacitance humidity sensors is their undesirable hysteresis effect due to the unequal adsorption and desorption of water vapor on the surfaces of their dielectric porous materials. To eliminate this error, an improved humidity sensor has been used composed of a commercial capacitive polymer sensor chip and an infrared (IR) radiation corrector emitting at a wavelength of 0.93  $\mu\text{m}$ . The IR photons excite water molecule vibrations and destroy the bonds between water vapor and the material surface molecules, thus reducing residual hysteresis. Linearity is also improved, drift at high humidity is diminished, and response time is decreased.

### 1. Introduction

Capacitance and resistance humidity sensors that utilize certain porous substances as a dielectric, such as a thin polymer film (e.g., polyimide film), aluminum dioxide, or porous ceramic, are widely used. The porous material adsorbs water vapor from the air. Therefore, the capacitance of the porous material varies with humidity, usually relative humidity (RH). For example, a capacitive sensor's capacitance changes from 107 to 122 pF when relative humidity varies from 0% to 100% (Ward 1983).

Most of these sensors are relatively cheap, small, and easy to use, particularly polymer sensors. However, they suffer from hysteresis due to unequal moisture adsorption and desorption (Coantic and Friehe 1980), which significantly limits their application for meteorological purposes (Muller and Beekman 1987). It is, therefore, necessary to reduce this hysteresis.

Ideally, the variation of the capacitance or resistance of the sensor with humidity should be an un-

ambiguous value (Nelson and Amdur 1965). The amount of water vapor adsorbed by porous material is related to both the porosity and the attractive force between water molecules and the surface of the dielectric. To obtain a wide variation of the electrical parameter to be measured, a high degree of porosity and a moderate polarity of the dielectric are needed, since water molecules are strong dipoles. Although the interaction between molecules is complex, the bonding is treated here simply by hydrogen bonds, and breaking the bonds requires energy. This causes the hysteresis effect, which cannot be avoided completely, and which is found particularly at high humidities.

From many observations, the hysteresis effect and the slow response are well known. For instance, they were reported from the intercomparison of the Vaisala humicap (with a polymer capacitive sensor) and VIZ carbon hygistor sensors under operational conditions by Klein and Hilton (1987). Two problems with the Vaisala humicap occur systematically:

1) The humicap responds more slowly than the carbon hygistor and cannot completely follow the humidity variation; therefore, it often fails to indicate humidities in excess of 90% when passing through thin non-precipitating clouds.

2) The humicap tends to report a moisture increase (about +10%, and occasionally up to +40%) after emerging from a cloud.

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We start with a description of the residual hysteresis and a possible mechanism causing the hysteresis, then we propose a photodissociation method to eliminate the residual hysteresis, that is, the secondary time constant. After providing two versions of an infrared (IR) corrector, initial experimental results are shown. Then we have a further discussion on the performance of the IR corrector.

## 2. Laboratory measurements of the hysteresis effect

In Fig. 1, curves 1 and 2 show the hysteresis of a Vaisala Oy 6061 HM capacitive polymer sensor (also refer to the data of sensor 1 in Table 1). The measurements were carried out in a climate chamber (System WEISS, Unterdruck- und Überdruckprüfanlagen Vakuumklimaprüfanlagen). The reference humidity values were measured by an electrical Assmann aspiration psychrometer (AAP), which was assembled together with the tested humidity sensor and a temperature sensor into a plastic pipe. They were ventilated to ensure uniform temperature and humidity inside the pipe and to blow off the moisture arising from the wet bulb of the AAP.

During the measurements, we have taken only the stable values and also waited at every stable value for a few (up to 10) minutes to make sure whether there was really no further drift, particularly in the dry-down process and at low temperature.

The step response times of the polymer sensors were found to be between 1 and 2 s depending on humidity and temperature. A faster response corresponds to a thinner sensor chip.

## 3. Adsorption-desorption mechanism

### a. Causes for hysteresis

Following Anderson's model (Anderson 1995) the porous material is coated by a thin surface film of water a few molecules thick, which are adsorbed by hydrogen bonding. However, we assume here that only a monomolecular layer in direct contact with the material surface may be considered as bound by hydrogen bonding. This is justified by the very short bonding action range (about  $10^{-8}$  cm), which is roughly the scale of one molecule. Additional water molecule layers in the water film may be bound by some much weaker Van der Waals force. Some of them may probably be unbound inside the material (Diamant et al. 1981).

When ambient air is drying down diffusion of moisture along a water vapor density gradient may easily destroy the physical bonds and desorption takes place. But this is not the case for the water molecules in direct contact with the porous material bound by the hydrogen bonding, since for their desorption more energy than supplied by the kinetic energy of air molecules is needed for a rapid desorption. In other words, a much larger water vapor density gradient will be needed for

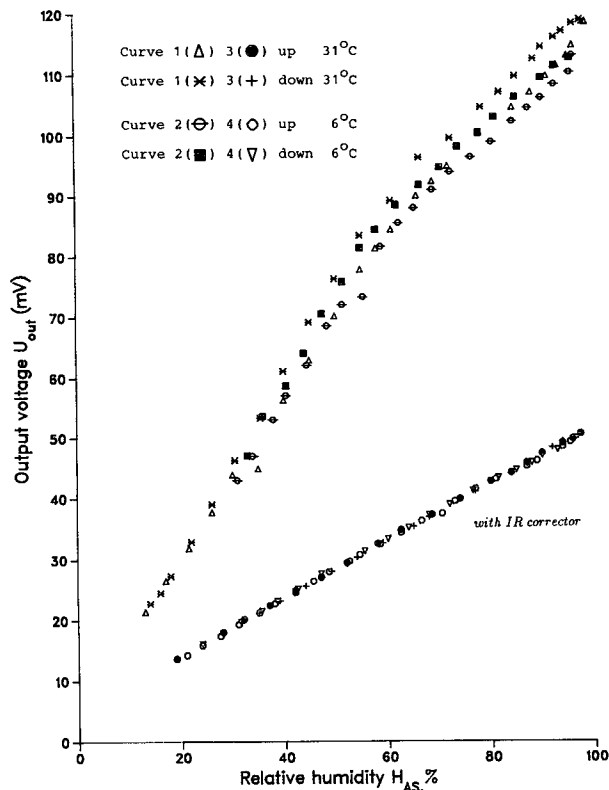


FIG. 1. Measured output of a Vaisala sensor chip. Curves 1 and 2 show the original characteristics without IR corrector. Curves 3 and 4 are for an open loop system with an IR corrector.

further desorption. Consequently, the humidity sensors show residual hysteresis.

According to the investigation by Muller and Beekman (1987) complete recovery may be possible if the adjustment time is long, approximately one week after saturating the sensor for about one day. This is because some molecules still exist with large enough momentum to occasionally rupture these hydrogen bonds. This causes a very long relaxation time, which corresponds to the residual hysteresis.

We may assume that the desorption mechanism involves two energy states: the bonding between the polymer and directly bound water molecules with a comparably large energy barrier and the bonding between water molecules in layers above the contact layer, however, with smaller energy needed for vaporization. The so-called step response time constant arises from the latter. We may refer to it as the *first time constant* having a value of some seconds. Whereas the former bonding causes the residual hysteresis. We may consider it as a *secondary time constant* with values even reaching several hours to several days.

From the point of view of manufacturing a sensor chip, we conclude that thinning the polymer dielectric film may reduce the first time constant rather than the

TABLE 1. Variation of humidity measurements due to an IR corrector.

Sample at RH% = 85%	Original sensor 1	Original sensor 2	Sensor 1 with IR corrector	Sensor 2 with IR corrector
Hysteresis effect at 6°C	≤4%	≤5%	≤0.5%	≤0.5%
Hysteresis effect at 31°C	≤4%	≤4%	≤0.5%	≤0.5%
Effect of temperature variation of 6°–31°C	≤4%	≤5%	≤0.5%	≤0.5%
Output drift	yes	yes	no	no

secondary time constant. A partial reduction of the inherent residual hysteresis of a polymer sensor chip can—without an IR diode—probably be carried out only through an improvement of the polymer material by diminishing the energy barrier of adsorption bonding of water molecules. But this also reduces sensitivity to changes in relative humidity.

During our experiments in the climate chamber, we could never clearly observe a recovery, even when waiting up to 10 min at every measured stable unsaturated humidity value, because the secondary time constant is much longer than 10 min.

We should mention here that the company Vaisala OY (Finland) developed a modified humidity sensor with a heater at the back of the sensor chip, named humidity probe HMP21V. The heater maintains the temperature of the chip above ambient temperature equivalent to about 25% relative humidity. Although the well-known output drift at high humidity may be reduced because the water vapor inside the polymer has never been saturated, the total response time is significantly increased due to the higher thermal capacity of sensor plus heater. However, this results only in a small hysteresis reduction according to our observations, and the hysteresis, for example, of about 4% at RH = 85% still remains.

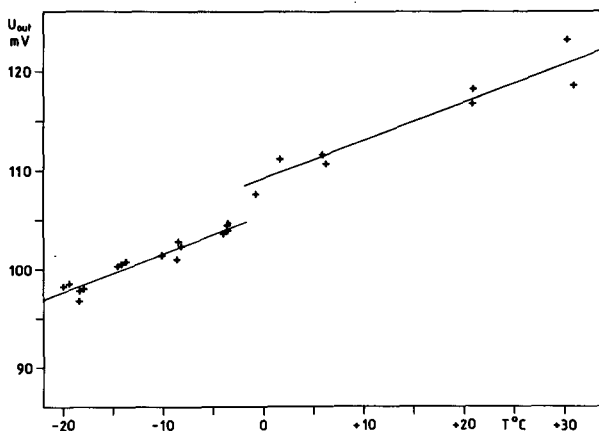


FIG. 2. Output of a capacitive hygrometer versus temperature at a relative humidity RH = 97%.

### b. Temperature effects

The adsorbed water molecules in a capacitive humidity sensor should behave similarly to liquid water. With a large dielectric constant they align freely to an applied electrical field, which should be unimpaired by their bonding to the material. The adsorbed water molecules do not experience a sudden phase change at temperatures below 0°C and remain as a quasi-liquid noncrystalline phase. If this were the case, a large jump in sensor output due to a phase change should be detected, since the dielectric constant of crystal ice is much smaller than that of liquid water. During our measurements we found, however, a small signal jump of slightly more than 3% at high humidity, as shown in Fig. 2 for a Vaisala hygrometer at RH = 97%. This measurement was repeated twice. We used also an electrical Assman aspiration psychrometer and a hair hygrometer as an additional indicator in order to keep the humidity constant at RH = 97% inside the climate chamber. It is seen that the jump appears at about -2°C to -3°C probably owing to a phase change of a small portion of the water molecules inside the porous polymer.

In fact, some studies show that unbound water molecules exist inside polymer media (e.g., Diamant et al. 1981; Adamson 1980). These unbound molecules may be contained in the free volume of porous media, with probably electrical forces helping to form water clusters inside polymers (Yoshimitsu et al. 1983). At temperatures below 0°C, small ice crystals form causing an output reduction of about 3%–4%. However, the question still remains as to whether this is a general phenomenon and how this jump may be avoided. When developing new porous materials and improving the structure of the sensor chip, this jump has to be avoided.

As also seen in Fig. 2, a rather constant output drift of about 0.3% K<sup>-1</sup> occurs. It is well known that the capacitance of a sensor is proportional directly to the area of the electrodes but inversely to the thickness of the polymer film. In a first approximation, the temperature coefficient of thermal expansion can be considered to be the same in all three dimensions. Since the area increases with the square of the linear expansion, it is apparent that the capacitance of the sensor will increase linearly with the temperature. Reducing the film thickness and improving on the structure of the

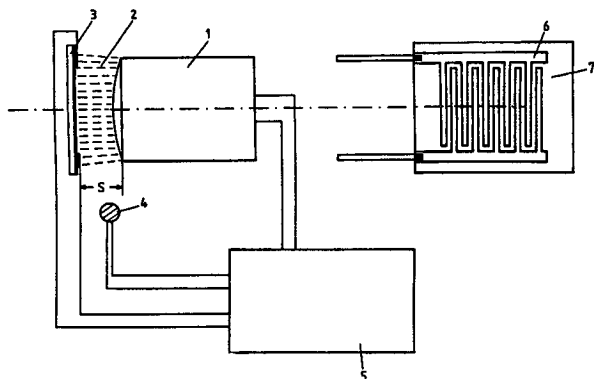


FIG. 3. Block diagram of the new humidity sensor with an IR corrector: 1)—the IR diode with 5-mm diameter and 5-mm thickness, 2)—gap between diode and humidity sensor varying from  $s = 0.3$  mm to 0.6 mm with an indication of the IR radiation field, 3)—humidity sensor chip with dimensions of 4 mm  $\times$  6 mm as for the Vaisala chip, 4)—temperature sensor, 5)—electronics and temperature compensation circuits, 6)—electrodes on the humidity sensor chip, 7)—thin polymer film as the dielectric of the sensor; 3 also indicates the substrate glass.

sensor chip will reduce the temperature dependence of the humidity measurements.

**4. Elimination of the hysteresis through photodissociation**

Experimental studies of the infrared photodissociation of molecular bonds have shown that the photodissociation reaction is a sequence starting with infrared excitation of one molecule within a cluster of molecules, followed by an energy transfer to a stretching vibration and the final bond cleavage (Bomse et al. 1983). Similarly, if we try to excite the vibration-rotation state of water molecules by infrared radiation it may dissociate the bonds between water and polymer molecules. It is clear that IR radiation will loosen the bonding between water and porous material molecules not only during dry-down but also wetting conditions. Therefore, the originally strongly unequal adsorption and desorption will become less pronounced. Hysteresis should thus be significantly reduced.

The response time of the sensor is mainly governed by the diffusion rate of water vapor and also depends on the thickness of the water film on the material surface. Presumably, the diffusion may proceed layer by layer for the original sensor chip, whereas this may not be the case with the IR corrector. The IR photons may simultaneously reach all water molecules bound and rupture their bonds, therefore, the diffusion may start for all the liberated water molecules. The response will thereby be accelerated and will no longer be related to the thickness of the water film bound by the material.

There are several strong absorption bands in the infrared vibration-rotation spectrum of water vapor, with central wavelengths at 0.72, 0.82, 0.937, 1.13,

1.38, 1.86, 2.7, and 6.7  $\mu\text{m}$ . When the sensor chip is irradiated by IR photons, the following process will take place: at first, water molecules bound by the polymer molecules are excited by absorption of IR photons, then energy is transferred to vibrations inducing also stretching vibrations, finally rupturing the bonds if the energy is sufficient.

*a. Design of the IR corrector*

We have developed a combined humidity sensor composed of a commercial capacitive polymer sensor chip and an IR corrector, which consists of an IR diode radiating at a wavelength of 0.93  $\mu\text{m}$  ( $\Delta\lambda \approx 0.05 \mu\text{m}$ ) and its electronic control circuits. The IR wavelength is chosen such that it is strongly absorbed by water vapor and not so much by the polymer. Therefore, IR radiation penetrates into the polymer medium and reaches all water molecules. The block diagram of this humidity sensor is shown in Fig. 3.

Humidity can be measured with this new sensor in two ways: with the open loop system and the closed loop system, the latter with negative IR radiation feedback. Both are shown schematically in Fig. 4. The electronic circuits of the capacitance to voltage converter (C/V) consist of basic electronic pulse width multi-vibrators. The IR diode current  $I_{\text{IR}}$  is also controlled by an ambient air temperature sensor, to compensate for temperature effects.

With a linear sensor chip, the open loop system is better (see also Fig. 1). Otherwise, the closed loop may have advantages, because—according to negative feedback theory—the effects of instability will be reduced to  $(1 + K_{\Sigma})^{-1}$  in comparison with the open loop case (the total system transfer coefficient  $K_{\Sigma}$  is equal

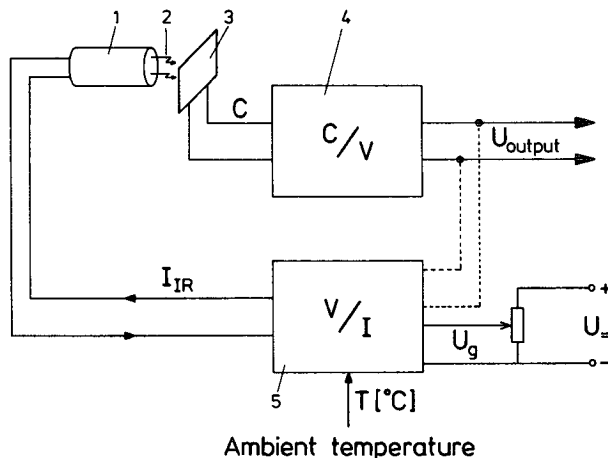


FIG. 4. The configuration of the new humidity sensor. The dashed line connections are for the closed loop system. Items 1, 2, 3 correspond to Fig. 3; 4)—Capacitance to voltage converter. 5)—Voltage to current converter. Here  $U_g$  is the voltage to adjust IR intensity to a given value.

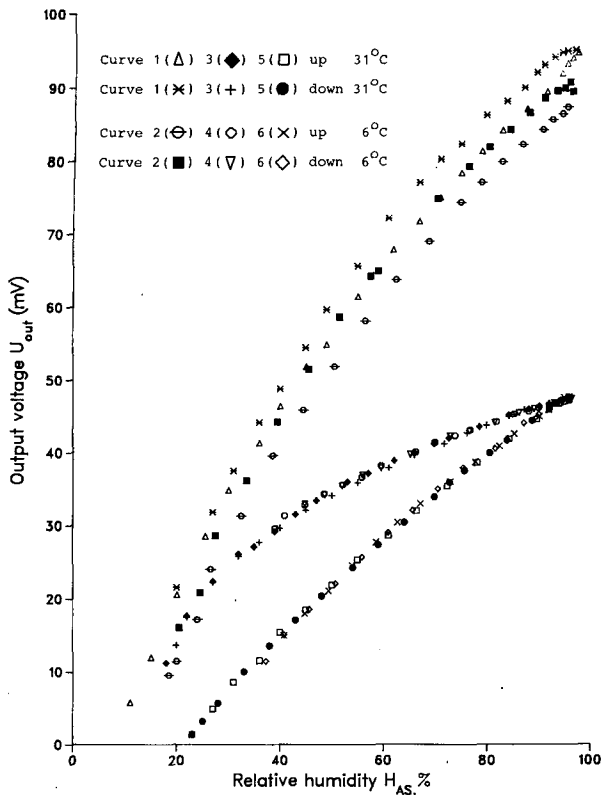


FIG. 5. The measured output characteristics for sensor chip 2. Curves 1 and 2 show the original characteristics without the IR corrector. Curves 3 and 4 are closed loop system outputs with negative IR feedback. Curves 5 and 6 are for an open loop system.

to the product of transfer coefficients of all system parts). However, the additional nonlinearity of the closed loop is a considerable disadvantage (see Fig. 5 curves 3 and 4 and section 5).

A further very attractive point for practical applications is the low cost of the IR corrector.

*b. Performance of the new IR corrector*

The output of the new humidity sensor with an open loop is portrayed by curves 3 and 4 in Fig. 1, where the sensor 1 (see Table 1) is used. Clearly, the hysteresis is eliminated, the linearity is improved, and only a negligible drift occurs at high humidity. The response time is also reduced to less than 0.5 s.

Table 1 shows humidity variations caused by hysteresis and temperature changes. All experiments with an IR corrector in the open loop system were carried out in the climate chamber mentioned above.

A new humidity sensor including a Vaisala 6061 HM has been running from May to August 1985 under field conditions. Its output values have been compared to Assmann aspiration psychrometer readings three times a day (0730, 1130, and 1530 LST). The correlation

coefficient was 0.997, and the output drift was negligible.

Measurements with the sensor chip 2 (see Table 1) produced by Endress+Hauser GmbH+Co. are displayed in Fig. 5 without IR corrector (curves 1 and 2), and both with a closed loop (curves 3 and 4) and open loop IR correctors (curves 5 and 6). Both systems were with different gain factors and were adjusted to show the same output value at RH% = 97%.

Owing to a different chip structure and also a thicker polymer film employed in chip 2, this chip is inferior because of its greater nonlinearity, slightly larger hysteresis and larger step response time greater than 2 s.

**5. Discussion of the IR corrector**

*a. Output reduction*

Besides the desirable elimination of the hysteresis, the IR corrector causes a reduction of the output as seen in Figs. 1 and 5, which is proportional to the IR intensity, that is, to the IR diode current  $I_{IR}$  as also demonstrated by Fig. 6. Here  $\Delta U_{out}$  is the output reduction due to IR radiation.

For the closed loop system, the intensity of IR radiation is also proportional to the output voltage, namely, is proportional to RH. The output change  $\Delta U_{out}$ , therefore, becomes proportional to  $(RH)^2$ , causing a nonlinear relation between  $U_{out}$  and RH even for a linear chip at an open loop IR corrector.

The measured outputs of both the open and closed loop system with the humidity sensor chip 2 (see Table 1) are shown in Fig. 5. Clearly, a good agreement between the measured and the theoretical characteristics is obtained. However, in contrast to Fig. 1 where the corrected sensor shows linearity, we should note that

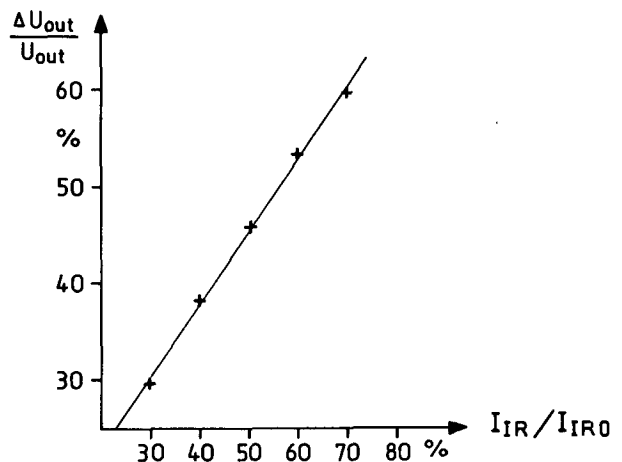


FIG. 6. The output reduction versus the IR intensity for a gap  $s = 0.3$  mm. The relative output change is proportional to the current  $I_{IR}$  of the IR diode. The slope of the curve depends on the gap  $s$  between the IR diode and the chip. Here  $I_{IR0}$  is the nominal current of the IR diode.

the remaining nonlinearity in Fig. 5 is due to the inherent nonlinear characteristics of the sensor chip 2.

### b. Wavelength selection

A crucial point is the correct selection of an IR wavelength, because breaking the bonds between the molecules of water and a polymer in order to eliminate the hysteresis is the core of this technique. The adoption of the IR wavelength  $0.93 \mu\text{m}$  is firstly due to strong water vapor absorption at this wavelength, secondly due to the availability of sufficiently high photon energy to break the hydrogen bonds of water molecules to the polymer, and thirdly also due to the low price of a commercial IR diode available at this wavelength.

The output of this humidity sensor was unaffected when we used other wavelengths outside strong water vapor absorption. For instance, we tried to use the same type of diodes also in the visible at green, yellow, and red wavelengths but  $\Delta U_{\text{out}} = 0$  occurred for any value of  $I_{\text{IR}}$ .

## 6. Conclusions

Five sensor chips from Vaisala Oy (6061 HM), two from Endress+Hauser GmbH+Co. and two from CO-RECT GmbH (CCH) were used in our investigation (in this paper the data provided were only for two sensors from two companies). The observed effects of the IR corrector are similar and agree with expected effects in all cases.

Through the introduction of two energy levels for the desorption mechanism we may consider the residual hysteresis as a secondary time constant of several hours to several days. The IR photodissociation reaction can be successfully used to reduce this hysteresis to negligible magnitude, that is, to eliminate the secondary time constant in polymer humidity sensors. The application of the IR corrector also shortens the first time constant of the humidity sensor, brings it nearer to linearity and the output drift at high relative humidity is negligible. Owing to the low price of the commercial

IR diode the additional cost of an improved humidity sensor is rather low. It could be widely used in routine humidity measurement and also in radiosondes.

The complete theoretical analyses is beyond the scope of this paper. We will discuss it in a separate paper in the near future.

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