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Demand Controlled Ventilation - Evaluation of commercially available sensors

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Synopsis

A test programme has been designed to evaluate the performance characteristics of sensors for the automatic control of ventilation rates. The test programme consists of two main parts, one being the evaluation of sensor performance in laboratory tests and the other referring to long term characteristics of sensors in actual buildings. Included in the present evaluation are eight different types of humidity sensors, two carbon dioxide sensors and five mixed gas sensors.

The test results indicate that capacitive humidity sensors are well suited for the control of humidity levels in buildings. The combined error of linearity, hysteresis and repeatability is normally below 5% RH at 20 °C. The cross-sensitivity to variations in the ambient temperature and power supply (voltage and frequency) are acceptable and the cross sensitivity to hydrocarbons, carbon dioxide and tobacco smoke is negligible. A plastic stripe humidity sensor on the other hand proved unsuitable due to excessive hysteresis and linearity errors.

Carbon dioxide sensors show acceptable performance for control purposes but sensor calibration and/or adjustment is a time consuming process. These sensors are sensitive to humidity below a threshold value. The mixed gas sensors show a mixed behaviour. Some react strongly to tobacco smoke, some slightly and one hardly at all. The characteristic curve was determined using a gas cocktail consiting of equal parts of one alifatic HC, one aromatic HC and one aldehyde. Tests were also made with one component at a time but there was little difference in the response to the individual components.

All sensors endured the climatic tests reasonably well. Mechanical vibration on the other hand caused some of the sensors to break. Radiated electromagnetic fields affected all sensors and electric shocks, due to a simulated strike of lightning, proved too much for most of the sensors.

List of symbols and abbreviations

AQ	Air quality
ASD	Acceleration spectral density
DPT	Dew point temperature
f	frequency
HC	Hydrocarbon
IEA	International Energy Agency
RH	Relative humidity
RMS	Root mean square
SP	The Swedish National Testing & Research Institute
U	Voltage
VOC	Volatile organic compounds
WBT	Wet bulb temperature

1 Background

A fundamental prerequisite for demand controlled ventilation systems is the possibility to find a measurable "indicator" of the air quality. Another important factor is the existence of commercially available sensors for the measurand, which have acceptable sensitivity, accuracy, long term characteristica and price level.

Different types of "indicators" can provide different types of information concerning the ventilation requirements of a specific building. Furthermore, different types of sensors for the same "indicator" can give different results. Such sensors must be sensitive enough to detect changes in the air quality requiring increased or decreased supplies of outdoor air and simultaneously be stable enough to function satisfactorily over long periods in varying environments.

Hence it is of great value to increase our knowledge concerning questions such as

1) which "indicators" are suitable
2) which sensors are possible for the planned "indicators"
3) how do the different "indicators" read relative to each other
4) how do different sensors for one particular "indicator" read in the short term as well as in the long term.

2 Project description

Sensors for the following types of indicators (in accordance with the scope of IEA Annex 18) were included in a laboratory performance test:

* Water vapour (RH, WBT, DPT)
* Carbon dioxide
* Non-oxidized gases (VOC, e.g. C_mH_n, CO, etc).

The tests consist of two main parts. In the first part one specimen of each sensor type is extensively laboratory tested and in the second part one specimen of each sensor type is exposed to normal indoor climatic conditions (e g in an office building).

Thus two specimens of each sensor type are included. To limit the size and cost of the project, testing was planned for a maximum of fifteen sensors (seven for water vapour, three for carbon dioxide and five for non-oxidized gases). In the actual test it was not possible to include more than two carbon dioxide sensors due to time considerations. Several suppliers expressed an interest to participate in the test but only two actually delivered any sensors. Instead another humidity sensor was included to give the same total number of sensors.

This presentation pertains only to the laboratory part of the test program. The experience in using this test procedure has been reasonably good and thus a continuation of the project with other types of sensors is possible. Feed back from the tests however indicate a need to revise some of the procedures.

The laboratory tests consist of four main parts (see separate detailed description in chapter 3).

* Checking of the manufacturers' data sheets and instructions

* Determination of the performance of new sensors including comparisons with data sheets

* Determination of the cross-sensitivity of sensors exposed to various combinations of the three chosen indicators as well as variations in the power supply, atmospheric pressure, temperature and air velocity

* Environmental tests concerning exposure to dry heat, dry cold, humidity, temperature change, vibration, electromagnetic radiation and electrostatic discharge.

Results relating to the specific makes of sensors will be published when the entire project has been terminated. Before publication of the test results, the supplier/manufacturer of a sensor shall however be permitted to study the results and express his opinion.

3 Laboratory testing of DCV sensors

The test procedure consisted of four main parts as described in 2.1. In this chapter the detailed test procedure is described including presentation of some results. Sensors for the following indicators were tested:

* Water vapour (8 types)
* Carbon dioxide (2 types)
* Non-oxidized gases (5 types)

3.1 Sampling and preparation

Sensors were selected and tested by the respective manufacturer prior to delivery to SP. Special care was asked for regarding packaging and handling of the selected sensors in order to avoid unrepresentative test results due to delivery mishaps. All necessary instructions concerning general descriptions, installation, operation and maintenance were to be included in the delivery of the sensors. The sensors were installed in the laboratory as described by the manufacturer's instructions. The reference ambient testing conditions were considered to be (unless other values were specified in the individual test procedures):

Temperature: 20 ± 2 °C
Relative humidity: 40 ± 10 %
Pressure: 101 ± 1 kPa(a)
Air velocity: < 0.5 m/s
Supply voltage: Nominal ± 5 %
Supply frequency: Nominal ± 5 %
Air quality: Normal indoor air (CO_2 = 350 ± 50 ppm, VOC < 0.4 mg/m^3)

The test room was kept free of strong electric or magnetic fields and the input power to the sensors was supplied via magnetic stabilizers (except during tests with electromagnetic radiation).

The reference gas for testing VOC-sensors was composed of the following constituents:

1 aldehyde (Octanal, $C_7H_{15}CHO$):
1 aromatic HC (Toluene, C_7H_8)
1 aliphatic HC (Nonane, C_9H_{20})

These substances were intended to represent organic compounds that are frequently found in the analysis of air from e.g. office buildings.

3.2 Data sheets and general information

A standardized data sheet for the presentation of sensor characteristica was proposed. Prior to the test the manufacturers were asked to fill in the data asked for in this data sheet. This information was noted as background information to be compared with the test results.

3.3 Determination of the performance of new sensors

The sensor performance has been defined in terms of the following parameters,

* Warming up time
* Zero drift
* Linearity
* Repeatability
* Hysteresis
* Stability
* Accuracy
* Sensitivity
* Rise time
* Sensitivity to influence factors (cross-sensitivity).

3.3.1 Warming up time

The intention was to measure the warming up time by inserting the sensor into a test chamber with all parameters, except for the primary measurand, at the reference conditions (see 3.1). The measurand (e.g. humidity) was held constant at a value corresponding to an output signal of 40-60 % of the measuring range of the sensor. The sensor was then left 24 h with the power switched off. The power was then switched on and the sensor output was measured. The time from switching on the power supply until the output was stable within the claimed uncertainty of measurement was recorded as the warming up time.

One half of the humidity sensors had negligible warming up times (less than 30 s). The other half of the humidity sensors had sizeable warming up times, e.g. no. S9 (2000 s), S12 (4000 s), S14 (1800 s) and S15 (4000 s). The VOC-sensors on the other hand have two different warming up times, one after a short interruption of the power supply and one after the heated sensing element has been permitted to cool down. These were not determined in this investigation but the long term warming up time may be as long as a fortnight or even up to a month according to the manufacturer.

3.3.2 Determination of the sensor characteristic curve

The output from the tested sensors were recorded for values of the measurand according to table 3.1.

Table 3.1. Values for determination of the sensor characteristic curve

Measurand	1	2	3	4	5	6	7	8	9
Relative humidity (%)	-	20	40	60	80	60	40	20	-
Carbon dioxide (ppm)	200	500	1000	1500	2000	1500	1000	500	200
VOC (mg/m^3)	0	0.5	1.0	1.5	2.0	1.5	1.0	0.5	0

The VOC-cocktail is normally composed of equal parts of the three constituents. At test point 3 (1.0 mg/m^3) tests were also performed with the total concentration consisting of only one of the reference gases at a time. It was found that for this particular cocktail, and with these particular sensor types, changing the composition had no significant influence on the result.

The VOC-sensors were not possible to test in a closed system as planned originally. The sensors were encased in plastic housings with emissions substantial enough to cause a continuous increase in the VOC-level if left in a closed tank. Instead outdoor air was supplied continually to the tank and a specified amount of the VOC-cocktail was evaporated into this air flow. As can be seen from examples of the characteristic curves for VOC-sensors in diagram 3.1 the behaviour of different sensors may be markedly different even though the sensing elements come from the same manufacturer.

Linearity is calculated as the maximum deviation between any measured value and a straight line between points 2 and 5 in table 3.1. Hysteresis is calculated as the maximum deviation between points 2 and 8, 3 and 7, 4 and 6. Finally the sensitivity is calculated as the change in output between points 3 and 4 in table 3.1, divided by the corresponding change in input (e.g. V/% RH). The results obtained are presented in table 3.2 below. Sensor no. S14 is equipped with two sensing elements, one for humidity and one for VOC.

Table 3.2. Results from determinations of the sensor characteristic curve.

Sensor no.	Linearity	Hysteresis	Sensitivity
S1 VOC	1 (%AQ)	0.9 (%AQ)	0.28 (V/ mg/ m^3)
S2 VOC	-*	-*	-*
S3 VOC	-*	-*	-*
S4 VOC	3.5 (%AQ)	0.3 (%AQ)	0.046 (V/ mg/ m^3)
S5 CO2	98 (ppm CO_2)	18 (ppm CO_2)	0.0038 (V/ ppm CO_2)
S6 CO2	26 (ppm CO_2)	21 (ppm CO_2)	0.0047 (V/ ppm CO_2)
S7 RH	0.9 (%RH)	0.8 (%RH)	0.15 (mA/ %RH)
S8 RH	0.6 (%RH)	0.8 (%RH)	0.0097 (V/ %RH)
S9 RH	0.1 (%RH)	3 (%RH)	0.084 (V/ %RH)
S10 RH	11 (%RH)	15 (%RH)	0.071 (V/ %RH)
S11 RH	0.4 (%RH)	1 (%RH)	0.15 (mA/ %RH)
S12 RH	0.3 (%RH)	0.9 (%RH)	0.16 (mA/ %RH)
S13 RH	0.4 (%RH)	0.8 (%RH)	0.15 (mA/ %RH)
S14 RH/ VOC	3.5 / 2.2 (%RH / ppm CO_2)	0.3 / 1.4 (%RH / ppm CO_2)	0.0073 (V/ %RH)/ 0.098 (V/mg/m^3)
S15 RH	2.4 (%RH)	2.3 (%RH)	0.098 (V/ %RH)

* The response of the sensor was too small to be significant or the results were inconclusive.

A special problem with the use of an open system is that the the quality of the outdoor air is beyond the control of the experimenter. Figure 3.2 illustrates this problem clearly. The supply air to the test set up is being fed with a constant level of 3.5 mg/m^3 of toluene. Initially the output of the sensor is constant but at a specific time, which corresponds to the end of the working day, the indicated air quality deteriorates. This is the result of people starting their cars to go home. This is also an illustration of one of the problems in controlling ventilation flowrates using a VOC-sensor. In this case the sensor would have signalled to the ventilation system to increase the outdoor air flow even though the outdoor air was the source of the decreased air quality.

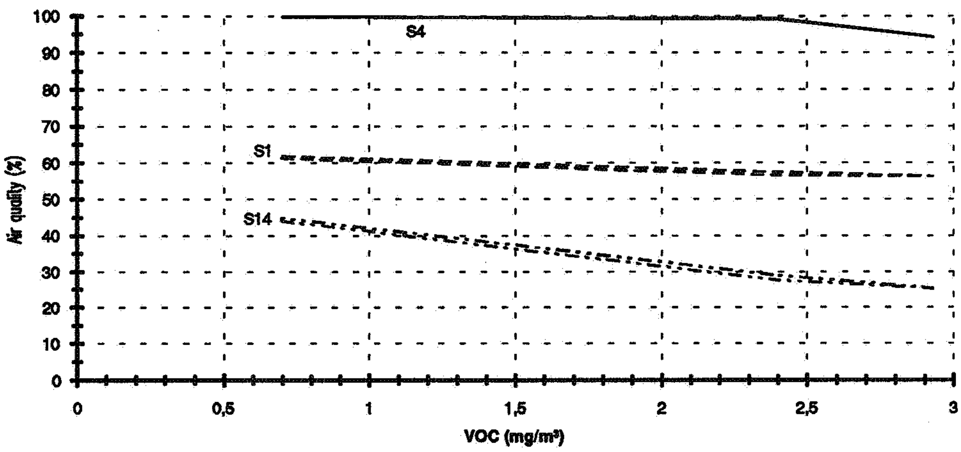

Figure 3.1. One example of output signals in terms of "percentage air quality" for sensors S1 , S4 and S14 as a function of the VOC-level in mg/m^3.

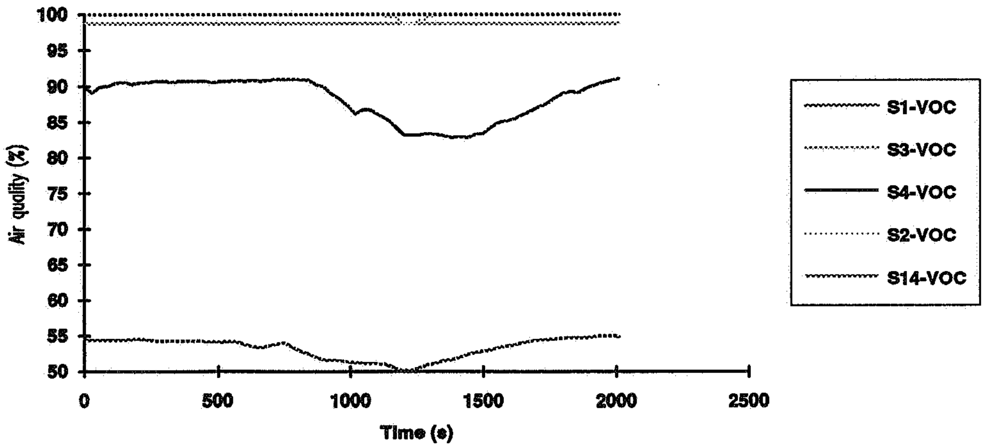

Figure 3.2. Output signals in terms of "percentage air quality" for sensors S1-S4 and S14 as a function of time. The VOC-level was aimed at 3.5 mg/m^3 but the background level changes after 800 s.

VOC-sensors were also tested with tobacco smoke corresponding to two levels of smoke concentration at each of three different flowrates (minimum flow for a non-smoking environment, minimum flow for a smoking environment and the maximum flowrate of the system). Cigarettes were smoked by an "artificial smoker" to achieve a reproducible test. In figure 3.3 the response of CO_2-sensors (S0, S5 and S6) and VOC-sensors (S1, S2, S3, and S4) are shown for the case of 1 0 cigarettes smoked simultaneously at a condition of minimum ventilation rate for a non-smoking environment. The diagram indicates that although this is a case of extreme smoke pollution one of the VOC-sensors does not react at all and one only reacts to a very small extent.

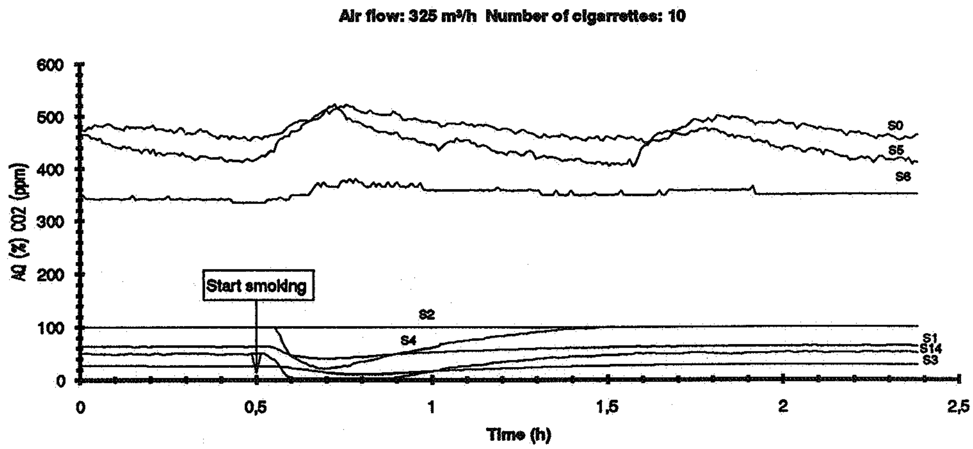

Figure 3.3. Response of CO_2-sensors (S0, S5 and S6) and VOC-sensors (S1, S2, S3, and S4) when 10 cigarettes are smoked simultaneously at a condition of minimum ventilation rate for a non-smoking environment.

In figure 3.4 the characteristic curve for the two CO_2-sensors are shown and in figure 3.5 results for three of the humidity sensors are presented. As can be seen in figure 3.5 there is a considerable difference in linearity and hysteresis between sensors S7 and S8 (capacitive) on the one hand and sensor S10 (plastic stripe) on the other hand.

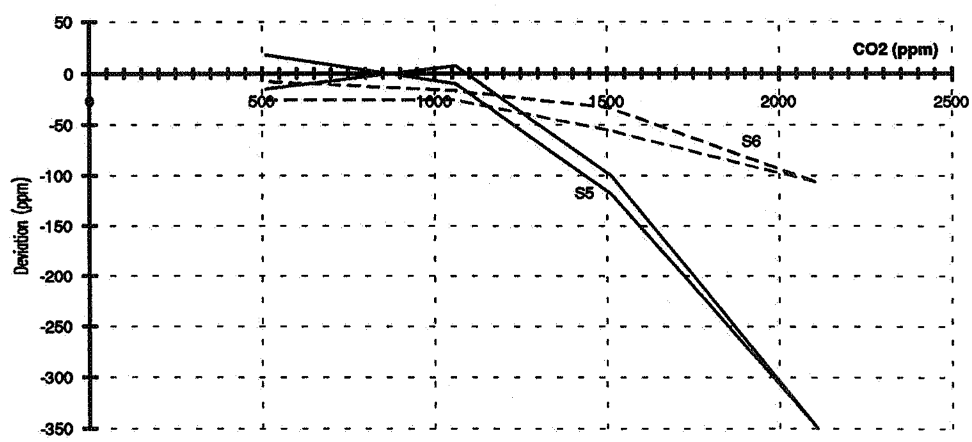

Figure 3.4. Characteristic curves for the two CO_2-sensors S5 and S6.

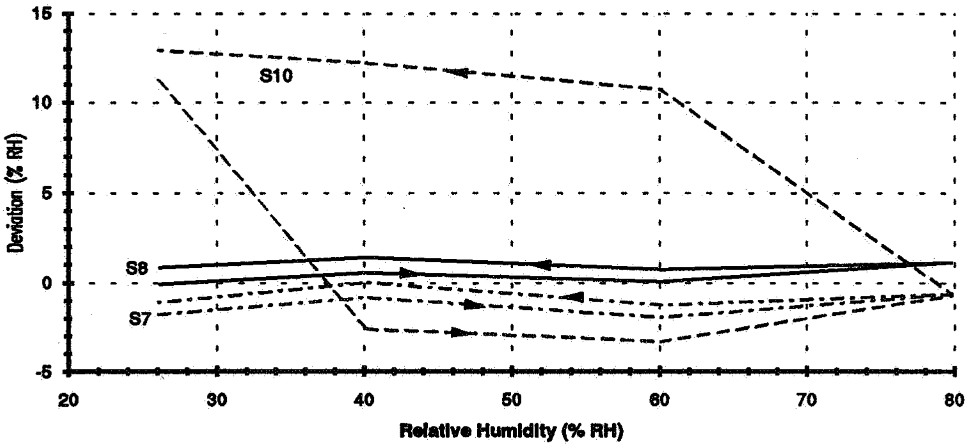

Figure 3.5. Characteristic curves for three humidity sensors (S7, S8 and S10).

3.3.3 Repeatability and stability

The sensors were tested at points 2 and 5 in table 3.1 alternatively 5 times. The repeatability is the maximum deviation between any measured value and the corresponding measured value in 3.3.2. To evaluate the stability of the sensors they were kept at point 4 in table 3.1 for 24 hours. The stability is the maximum deviation between any measured value and the initial value. Results from determinations of repeatability and stability for humidity sensors are presented in table 3.3.

Table 3.3. Results from determinations of repeatability and stability.

Sensor no.	Repeatability (%RH)	Stability (%RH)
S7 RH	0.3	0.3
S8 RH	0.3	0.2
S9 RH	1.9	0.2
S10 RH	0.8	0.2
S11 RH	0.9	0.6
S12 RH	0.6	0.3
S13 RH	0.3	0.3
S14 RH/ VOC	0.3 / -	0.4 / -
S15 RH	0.2	0.1

3.3.4 Rise time

The sensor input was changed from point 2 to point 4 and then from point 4 to point 2. The rise time and fall time respectively were calculated as the time between a change of input until the output has changed to 90 % of the steady state value. The air flowrate passing the sensor during the test was to be specified by the manufacturer. If no specification was made, the flowrate used was 3 m/s for sensors mounted in ducts and less than 0.15 m/s for wall mounted units.

The rise times of most humidity sensors were quite short. Therefore the test will have to be repeated with a measuring system using a higher time resolution. Rise times for carbon dioxide and VOC-sensors have not yet been evaluated.

3.3.6 Cross-sensitivity

The sensitivity of the sensor to various influence quantities is tested by varying each influence quantity, one at a time, according to table 3.4.

Table 3.4. Variation of influence factors.

Influence factor	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Temp., (°C)	20	30	10	20	20	20	20	20	20	20	20	20	20	20
RH, (%)	40	40	40	80	20	40	40	40	40	40	40	40	40	40
Voltage, (U/Un)	1.0	1.0	1.0	1.0	1.0	1.2	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Freq., (f/fn)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	0.9	1.0	1.0	1.0	1.0	1.0
Pressure, (kPa)	101	101	101	101	101	101	101	101	101	105	97	101	101	101
CO_2, (ppm)	500	500	500	500	500	500	500	500	500	500	500	1000	500	500
VOC, (mg/m^3)	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Tobacco smoke	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes

The cross-sensitivity is given for each influence factor as the ratio between total change in output and total change in input. Test results are indicated in table 3.5 expressed as the change in output relative to the nominal operating point. The response to tobacco smoke is only indicated qualitatively by "yes" or "no".

Table 3.5. Results from the cross-sensitivity test.

Sensor no.	**Vol-tage (unit/ V)**	**Fre-quen-cy (unit/ Hz)**	**Tem-pera-ture (unit/ K)**	**Rel. humi-dity (unit/ % RH)**	**Air pres-sure (unit/ hPa)**	**CO_2 (unit/ ppm CO2)**	**VOC (unit/ mg/ m^3)**	**Cig. smo-ke (yes or no)**
S1 VOC (%AQ)	0.2	0.1	0.1	0.2	-*	-*	-	yes
S2 VOC (%AQ)	-*	-*	-*	-*	-*	-*	-	yes?
S3 VOC (%AQ)	-*	-*	-*	-*	-*	-*	-	yes
S4 VOC (%AQ)	0.7	0.3	1.5	0.6	-*	-*	-	yes
S5 CO2 (ppm)	3.2	-18	7.1	2.6	0.0	-	-*	yes
S6 CO2 (ppm)	-57	-0.2	4.7	0.1	0.4	-	-*	yes
S7 RH (%RH)	0.0	0.0	0.1	-	0.0	0.0	0.0	no
S8 RH (%RH)	0.0	0.0	0.1	-	0.0	0.0	0.0	no
S9 RH (%RH)	0.1	0.0	0.2	-	0.0	0.0	0.1	no
S10 RH (%RH)	0.0	0.0	0.4	-	0.0	0.0	0.0	no
S11 RH (%RH)	0.1	0.0	0.1	-	0.0	0.0	0.1	no
S12 RH (%RH)	0.0	0.0	0.0	-	0.0	0.0	0.0	no
S13 RH (%RH)	0.0	0.0	-0.1	-	0.0	0.0	0.0	no
S14 (%RH) /(%AQ)	0.0 /0.0	0 /0.3	0.1 /0.0	- /0.0	0 /-	0.0 /-	0.1 /-	no / yes
S15 RH	4.9	0.0	0.3	-	0.0	0.0	0.1	no

* The response of the sensor was too small to be significant or the results were inconclusive.

3.4 Environmental tests

Environmental tests were performed to check the resistance of a sensor to possible extreme situations in the environment within the field of application of the sensor. Tests were carried out concerning

* Climatic parameters
* Mechanical parameters
* Electrical parameters.

3.4.1 Climatic parameters

Climatic tests were performed in accordance with IEC standards on low temperature, dry heat, damp heat and change of temperature. **IEC 68-2-1, Test Ad**, was used for the low temperature test. The sensors were exposed to a temperature of +5 °C for a duration of 16 hours.

This test seemed to have little effect on the sensors and all survived. Concerning the sensitivity of the actual output signal reference is made to table 3.5 regarding temperature as an influence parameter.

The next step was to expose the sensors to a temperature of 55 °C for a duration of 72 hours as specified in **IEC 68-2-2, Test Bd**, dry heat. Functional tests were carried out at an intermediate temperature of 40 °C. This test also seemed to have little effect on the sensors and all were still functioning after the test. Concerning the sensitivity of the actual output signal reference is again made to table 3.5, this time regarding temperature as an influence parameter.

Damp heat was tested as prescribed by **IEC 68-2, steady state, Test Ca**. The temperature selected was 40 °C at a humidity level of 93 %. The duration of the test was 21 days. None of the sensors showed any signs of significant deterioration due to this test. Concerning the sensitivity of the actual output signal reference is made to table 3.5 regarding humidity as an influence parameter.

The effect of a cyclic change in temperature was investigated according to **IEC 68-2-14, Test Nb**. The temperature was cycled between a low level of +5 °C and a high level of + 40 °C. The rate of change of temperature was 5 °C/min, the number of cycles was 5 and the exposure time was 3 h. Results show that all sensors pulled through also during this test.

In addition humidity sensors will be checked functionally after storing the sensors at -10 °C with the power switched off for 24 h. The ambient conditions will then be changed to +20 °C with a relative humidity of 80 % in less than 10 minutes. This test is yet to be carried out.

3.4.2 Mechanical parameters

Mechanical tests were performed in accordance with the IEC standard on random vibration, **IEC 68-2-36, Test Fdb**. The equipment was mounted on the vibrator using its normal means of mounting, e.g. flanges and screws. Tests were repeated for each of the three perpendicular axes of the equipment and a functional check was performed after exposure to:

ASD 10-20 Hz: 0.5 g^2/Hz
ASD 20-500 Hz: -3 dB/octave.

The total rms acceleration was 1.9 g for a duration per axis of 90 minutes. One CO_2-sensor (S5) and two humidity sensors (S12 and S14) broke during this test.

3.4.3 Electrical parameters

Electrical tests were performed in accordance with IEC standards on conducted bursts, electrostatic discharge, electromagnetic radiation and surge voltage immunity. Conducted transient bursts were tested according to **IEC 801-4**. In this test each group of signal cables was exposed to transients using capacitive coupling boxes for each group. At least 2 minutes of both polarities were used for testing of each group. All exposures were repeated for each specified functional mode of the equipment with a voltage amplitude of 4 kV.

Most sensors were greatly affected during the actual transient burst. The output of one humidity sensor (S15) changed from 1 V to -10 V and another (S13) changed from 3.8 V to 25 V. The remaining CO_2-sensor changed its output from 10.3 V to 40 V and then slowly died altogether. Humidity sensor no S10 was also irretrievably damaged by this test.

Electrostatic discharges were applied as described by **IEC 801-2**. The test generator, charged to a voltage of 8 kV, was approached to points on the test object normally accessible to the operator. Ten discharges were applied on each preselected point and the test was repeated for each functional mode of the equipment. During the electrostatic discharge there was little change in the output signals of the sensors. However three further sensors (S3, S9 and S13) did not pass this test and thus only seven of the fifteen sensors remained for the test with radiated interference.

This test consisted of exposing the sensors to radiated electromagnetic fields as specified in **IEC 801-3**. The sensors were submitted to electromagnetic radiation with a field strength of 10 V/m with the frequency changing from 27 to 500 MHz while the correct function was checked continuously. When disturbances occured the frequency was recorded. The test was repeated for each functional mode. The results clearly indicate that this type of interference is a potential source of trouble. Even though the behaviour of individual sensors was quite different in detail all of them changed their outputs by several orders of magnitude at specific frequencies or frequency ranges.

For the final electrical test, i.e. surge voltage immunity ("thunder"), seven sensors (S1, S2, S4, S7, S8, S11 and S15) remained. The test was carried out as outlined in the draft proposal **IEC 801-5 DP** and the voltage used was 2 kV.

As a result of this final test three more sensors (S2, S4 and S15) were irrevocably damaged. Thus as a final result of all the environmental testing there was a total of four surviving sensors.

3.5 Final test

The sensor outputs of the surviving four sensors were checked in accordance with table 1 in chapter 3. The results for two of the sensors are shown in figure 3.6 . Sensor no. S8 has endured all tests extremely well whereas sensor no. S7 has survived but changed its output at low humidities considerably. This is probably due to a change in off-set voltage.

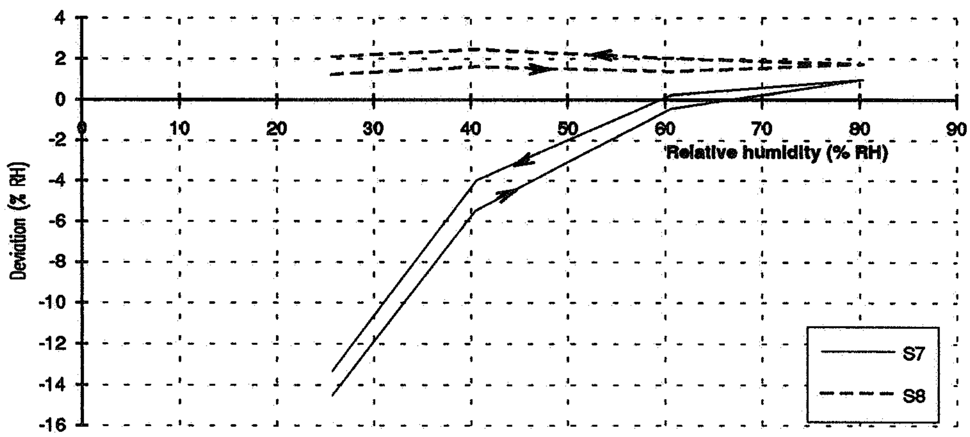

Figure 3.6. The characteristic curves of humidity sensors S7 and S8 after the environmental testing. These curves can be compared with the corresponding curves in figure 3.5.

4 Conclusion

The test results indicate that capacitive humidity sensors are well suited for the control of humidity levels in buildings. The combined error of linearity, hysteresis and repeatability is normally below 5% RH at 20 °C. The cross-sensitivity to variations in the ambient temperature and power supply (voltage and frequency) are acceptable and the cross-sensitivity to hydrocarbons, carbon dioxide and tobacco smoke is negligible. A plastic stripe humidity sensor on the other hand proved less suitable due to excessive hysteresis and linearity errors.

Carbon dioxide sensors show acceptable performance for control purposes with a deviation of less than 30 ppm at a level of 1000 ppm. Sensor calibration and/or adjustment is however a time consuming process. These sensors are also sensitive to humidity below a threshold carbon dioxide level. The mixed gas sensors show a mixed behaviour. Some react strongly to tobacco smoke, some slightly and one hardly at all. On the other hand all of them seem quite sensitive to humidity. Tests with varying compositions of the chosen VOC-cocktail indicated little difference in the response to the individual components.

All sensors endured the climatic tests reasonably well. Mechanical vibration on the other hand caused some of the sensors to break. Radiated electromagnetic fields affected all sensors and the electric shock due to a simulated strike of lightning proved too much for most of the sensors.

The environmental tests were decisive in the respect that only four out of fifteen sensors survived all of the tests. These results notwithstanding the test conditions were chosen to represent favourable operating situations that e.g. household electronics may encounter. It must however be born in mind that laboratory tests are one thing and the facts of real world situations may be quite a different cup of tea. Future in situ evaluations will hopefully provide further useful information in this respect.

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