Electrochemical Sensors for the Measurement of Relative Humidity and Their Signal Processing

Ivan Krejci, Michal Hedl
Dept. of Technical Studies
College of Polytechnics Jihlava, VSPJ,
Jihlava, Czech Republic
e-mail: krejci19@vspj.cz hedl@student.vspj.cz

***Abstract*— Highly sensitive and accurate determination of relative humidity of technical gases is required in many branches of human activities (health care, food packing, etc.). In this paper, we introduce a new series of sensors manufactured by BVT Technologies taking advantage of the hygroscopic material conductivity change with the water vapor content. The main topics of the contribution focus on sensor signal processing and electronic equipment architecture and its design.**

Keywords-relative humidity; hygroscopic material; synchronous detection; microcontroller.

I. INTRODUCTION

The amount of water vapor in a gas mixture is at any time less than that required to saturate the gas at a given temperature. The actual-to-saturated water vapor content ratio is called the relative humidity. It is usually expressed in % as

$$RH = (m/M).100, \quad (1)$$

where m is the actual vapor mass in the unit volume of the gas and M is the water vapor mass of the same volume of the saturated gas.

There are several methods to measure the relative humidity. For precise measurements, where high accuracy and resolution are required, the methods taking advantage of the impedance or resistance change of materials that absorb the tested gas humidity are used. These water absorbing materials are called hygroscopic.

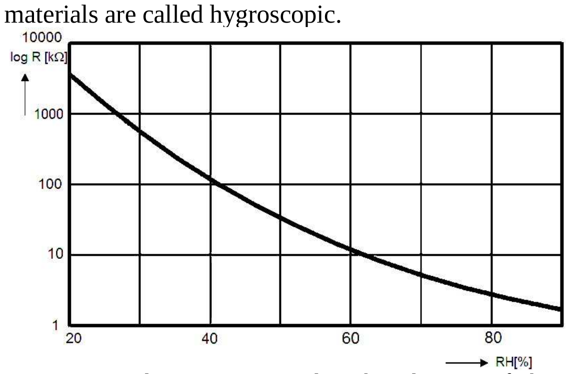

Figure 1. Typical resistance versus relative humidity curve of a hygroscopic material [1].

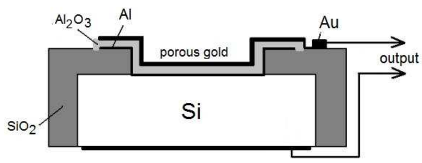

Figure 2. The resistive relative humidity sensor placed on the silicon substrate.

Figure 1 shows a typical plot of the electrical resistance change of a hygroscopic material as a function of increasing relative humidity. As can be seen, the measuring apparatus should be able to measure the resistance within the range of 1 kΩ to 10 MΩ.

This measuring method has been selected because it enables the use of electrochemical sensors that have been specifically developed for this purpose by the local company BVT Technologies (www.bvt.cz) [3]. As BVT Technologies has no electronic development department, VSPJ (Vysoka Skola Polytechnicka Jihlava, www.vspj.cz) was approached to propose an electronic design of the sensor signal processing unit.

II. SENSOR PERFORMANCE

Usually, the sensor taking advantage of the hygroscopic material resistance measurement is placed on a silicon substrate, on which the electrode system composed of the substrate itself and the porous gold electrode is placed. It is capable of directing the measured gas to the active hygroscopic layer. This layer consists of an aluminum base on which the active hygroscopic layer of alumina is applied, as shown in Figure 2 [2].

In our case, a different sensor arrangement has been used. The sensor, provided by the local manufacturer of the electrochemical sensors, BVT Technologies, uses a corundum ceramic base on which the electrode system is applied. The electrodes are made of platinum – gold alloy and are shaped as two combs, inserted into each other (Figure 3) [3]. The electrodes are connected with a sensor connector by silver paths, covered by an insulating protective layer.

The electrodes are covered by a hygroscopic alumina layer. The sensor dimensions are 25.4 x 7.62 mm and the active electrode system takes up a space of 2 x 2 mm.

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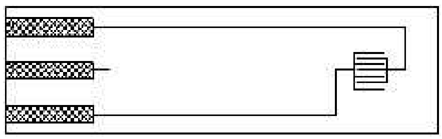

Figure 3. The BVT Technologies CC1 conductometric sensor.

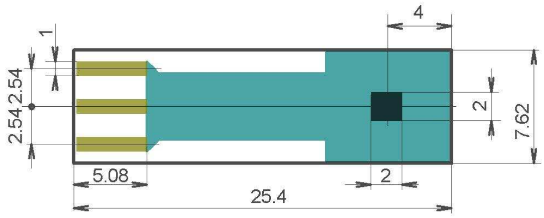

Figure 4. Real electrochemical sensor, including its dimensions.

A more detailed drawing of the sensor is given in Figure 4. It provides information about sensor dimensions and electrode and protective cover arrangements.

The main advantages of the resistive humidity sensors are the short response time 30 – 50 s as declared by the sensor producer [5] and high resolution which can be improved by using signal amplification.

III. SIGNAL PROCESSING UNIT

The electronic design and construction of the signal evaluating unit were the main goals of our work. The design rules have been determined by assigned parameters.

A. Required system parameters

The essential parameter is the range of measured resistances which is from 100 Ω to 10 MΩ. Further, if the hygroscopic material absorbs water, the polarization of electrodes occurs. To prevent it, the sensor must be supplied by AC (alternating current), the frequency of which is above Warburg frequencies [4], i.e., above 5 kHz. For our purposes, the frequency of the supplying signal was 10 kHz. To achieve both high precision and high resolution of the measured resistance, the use of highly precise analog to digital converters (AD converter) was necessary. The requirement of the resistance measurement over five decades with the precision at least 1%, asks for the use of the 24 bit AD converter (the required resolution is 10^{-}5 x 10^{-2}, it is 10^{-7}, the 24 bit AD converter resolution is 5.9 x 10^{-8}). As the effective number of bits is less than the AD converter's resolution, an additional digital filtering has to be done.

As for the mechanical arrangement, minimized electronic unit dimensions have been required, comparable to a common plug-in flash disc unit.

For the resistance measurement, the Ohm's method has been selected [6], based on the measurements of the voltage drop on the sensor, and current flowing in it.

Another problem of the applied method of measurement is the strain capacity of the sensor. To avoid this problem, the synchronous detection must be applied, to separate the real resistance from the imaginary reactance.

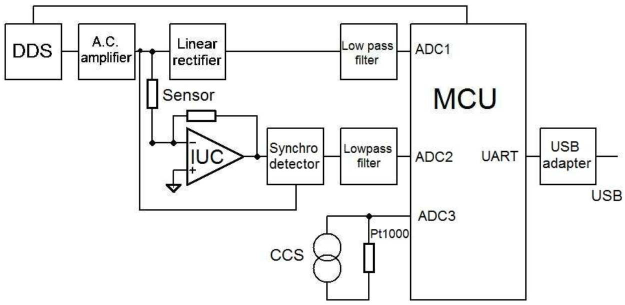

Figure 5. Hygrometer block diagram. DDS – direct digital synthesizer, IUC – current/voltage converter, CCS / constant current source, MCU – microcontroller.

The relative humidity magnitude depends on the temperature. This means, the system must be equipped with a precise thermometer capable of the measuring of the nearest 0.1 °C.

The transport of measured results to a host computer is provided by a USB 2.0 standard interface (Universal Serial Bus).

The equipment is designed so that it will create a small plug - in unit, which can be directly plugged into a computer USB connector (Figure 5).

B. Electronic design – analog signal processing

The analog part of the system involves three basic building blocks, the Direct Digital Synthesizer (DDS) with an amplifier of the AC signal supplying the sensor, and two signal traces measuring the voltage drop on the sensor and the current flowing through it. The voltage trace consists of a linear full-wave rectifier and a low pass filter that rejects residual AC signal components.

The current trace arrangement begins with the current to voltage converter (IUC), the output signal of which is detected in the full-wave synchronous detector. The sense of this detection type is to gain the real part of the measured current. After the detection, the output detector signal contains a useful DC (Direct Current) component and a residual AC component, which is filtered out in the low pass filter. The cut-off frequency of the second order low pass filters in both traces is 10 Hz. This frequency ensures sufficient 126 dB rejection of the residual 20 kHz components of the full/wave detected signals. Besides, the filters serve as anti-aliasing filters for AD converters (AD converter sampling frequency is 250 Hz – see the next paragraph).

The resistance thermometer using a platinum Pt1000 sensor is the last analog element of the circuit. The sensor is supplied from a constant current source (CCS).

From the technological point of view, high precision operational amplifiers have been used for the analog signal processing at the operating frequency, and the chopper stabilized amplifiers for the detected signal filtering and for the constant current source for supplying the Pt1000 thermometer.

C. Digital signal processing

The digital part of the equipment is controlled by the TI microcontroller unit (MCU) MSP430AFE253, which has small power consumption and contains three independent 24 bit analog to digital converters needed for the system realization. The AD converters of the microcontroller can be synchronized, and thus they offer their results simultanously. As the built-in converters are very fast Σ–Δ converters having a low effective number of bits, it was necessary to correct it using oversampling and additional digital filtering. The conversion results are obtained by an averaging filter taking advantage of the sum of 256 AD converter samples, shifted 8 bits right. The AD converter sampling period is 4 ms, thus the measurement itself takes about 1 s.

The microcontroller also controls the direct digital synthesizer producing the AC signal 10 kHz used for the sensor supplying. Further on, the microcontroller evaluates the measured resistance and calculates the relative humidity taking advantage of the polynomial approximation of the diagram in Figure 1. The calculated data is sent to a host computer via the standard USB link.

D. Metrological aspects

The accuracy of the measurement is determined by both the sensor calibration and the signal processing. As the signal processing has been discussed in the previous paragraphs, the calibration of the sensor represents the last obstacle in achieving the required parameters. To get the best results, the Agilent 34410A – the 6.5 digit multimeter - has been used to prepare the resistance standards. The basic measurement procedure measures the sensor conductivity, so that the calibration curve is linear, G =I/V (the conductance G is given by the current I, divided by the voltage V), if the voltage is kept constant. In this case, it is necessary to get two points of the line. These points were determined by the zero and maximum required conductivities of 10.0012 mS (nominal resistance value 100 Ω).

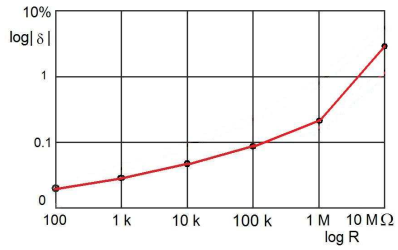

Figure 6. The absolute value of relative error as a function of the measured resistance.

The calibration was checked using the standards, the conventional true values of them were given by the Agilent multimeter measurements, and covered all decades of the required conductivity range (10 mS – 0.1μS). The results of the series of twenty measurements are given in Figure 6. The errors in the graph represent the worst results of the series. The obtained results show the error dramatically increases when high resistances are measured. It is caused by lower value of AD converter data, which is influenced by the digital noise of the AD converter. A possible improvement can be achieved by using an internal programmable gain amplifier built in the AD converter. This adaptation does not require any changes of the system hardware.

IV. CONCLUSIONS

The electronic system has been designed and its firmware created. The firmware also includes the system calibration procedure, described above, together with the calibration constants store in the microcontroller internal electrically erasable programmable read only memory (EEPROM). The system performance, the assembled printed circuit board (PCB), is shown in Figure 7a and Figure 7b. The PCB dimensions are 59 x 25 mm. If the achieved results are compared with the required parameters, the results are a little worse than it is required and the design needs some improvements, namely as for the calibration stability. At present, to get introduced results, it is necessary to do the re-calibration of the instrument whenever it is switched on. Although this procedure is simple and does not require much time, it is a complication of the measuring procedure. One possibility of the system accuracy improvement is the software adaptation of the sensitivity mentioned in the previous paragraph. For further improvement, it is necessary to re-design the hardware, which would involve the use of a better voltage reference and a possibility to divide the current range into several subranges.

V. ACKNOWLEDGMENT

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REFERENCES

[1] A. Brodgesell and B. Liptak, “Instrument Engineers’ Handbook: Process Measurement and Analysis”, 4th edition. J. Wiley & Sons, N.Y. 2003, pp. 1426.
[2] J. Fraden, “Handbook of modern sensors: physics, designs and applications”. Springer science + business media, Inc., 2004, pp. 400.
[3] Electronic publication http://www.bvt.cz/ftp/Senzory/CC1.pdf : “Conductometric Sensor Substrates – CC1”, Sensor Data Sheet, BVT Technologies, 2016, pp. 1, last access April 2017.
[4] I. Krejci, M. Musil, and P. Smetana, “Impedance Spectrometer for Application in Biology and Food Quality Control”, Proceedings of XXI IMEKO World Congress, Prague 2015, pp. 2222.
[5] Electronic mail information - BVT Technologies proposals.

 ISBN: 978-1-61208-580-7

[6] V. Krejci and J. Stupka, "Electrical Measurements" (in Czech), Statni Nakladatelstvi Technicke literatury (SNTL), Prague 1973, pp.232.

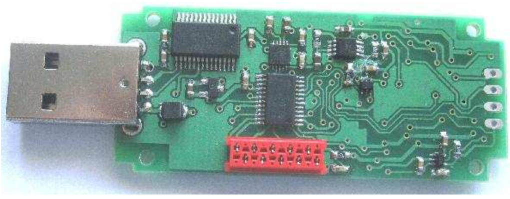

Figure 7a. Upper view on the PCB of the electronic unit, the digital signal processing part.

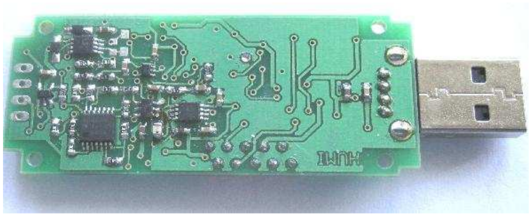

Figure 7b. Bottom view on the PCB, the analog signal processing part.