Experimental setup for calibration of wide scope of sensors for IoT applications

Jiří Jurík*[1], Martin Doubek[1], Václav Vacek [1,2]

[1] *Department of Physics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Czech Republic*
[2] *supervisor*

Abstract

We have built the experimental setup that allows for testing of sensors and electronics in environment with specific humidity, temperature and even with specific air composition. The tested devices are placed in a chamber while two streams of air at defined humidity are supplied to allow for simultaneous test at different conditions. The setup contains temperature, flow and humidity sensors as well as hydrogen and oxygen sensors. This paper describes the process of construction and commissioning of the measurement setup, sensors calibrations and outlines the measurement procedure. Data acquisition system based on SIEMENS WinCC software was used for monitoring, visualisation and archiving of the measured data, whereas further data processing was performed in Microsoft EXCEL and Python. The measurement setup is able to provide stable level of humidity at different temperatures and allows for self-calibration of the sensors. One possible use of the setup is to test and calibrate combined temperature and humidity sensors or sensors that allow for monitoring of air quality or detection of combustible gases in air. Such sensor are nowadays popular in internet of things (IoT) applications dealing with remote sensing and data acquisition.

Key words: Measurement of humidity; sensor; internet of things, data acquisition; Siemens WinCC

1 Introduction

The measurement setup was built at the Department of Physics, its main purpose is to precisely control following conditions in the test chamber:

- Relative Humidity
- Temperature
- Air flow

The setup is intended for test of digital or analog environmental sensors that can monitor temperature, relative humidity or air quality. Although it can be used for many other applications such are test of electronic components or to test devices for active control of humidity such are various dryers or humidifier. Following quantities can be analysed during test of instrument for active control of humidity which employ processes similar to electrolysis:

- Rate of change of relative Humidity
- Oxygen generation rate
- Hydrogen generation rate

High relative humidity (RH) will be generated by passing air stream through water bubblers. Low humidity can be reached by drying room air with silica gel. The treated air at certain humidity can be subsequent cooled or warmed up. In many case the treatment itself (humidification/drying) of the airstreams has to take place at certain temperature in order to achieve specific conditions. Following conditions can be achieved:

- High humidity at increased temperature (>30°C and >80% RH)
- High humidity at low temperature (<5°C and >80% RH)
- Two streams at different humidity at specified temperature, for instance 50% RH and 80% RH at 33°C or at 5°C

Generation of air streams with low humidity at low temperature will be the most difficult. The inlet room air will require precision drying before it is cooled down. The resulting humidity will be very sensitive to the actual humidity level before the cooling. The required precision will be achieved by using specific amount of silica gel and aby by precise mixing of airstreams with different humilities.

The measurement setup is divided into two sectors, so-called inner sector and outer sector, Figure1. The arrangement with the water bubblers for measurement at high relative humidity at increased temperatures (>26°C) is shown. For measurements at low relative humidity levels the silica gel driers will be used instead of the bubblers.

The outer sector, shown in Figure 2, includes the bubbler, ELMB data acquisition system, solenoid valves for handling of calibration gases, flow and pressure measurement, reference humidity measurement, oil-less air compressor and power supplies. The air from the compressor is split into two stream each for one half-chamber. The airflow is regulated by needle valve located after the compressor. Pressure and temperature are measured at the outlet of the compressor. The arrangement is modular so that multiple bubbler/driers

* Corresponding author : jirka.jurik@gmail.com

can be used in series if needed. Each bubbler/drier is bypassed by needle valve for precise humidity control.

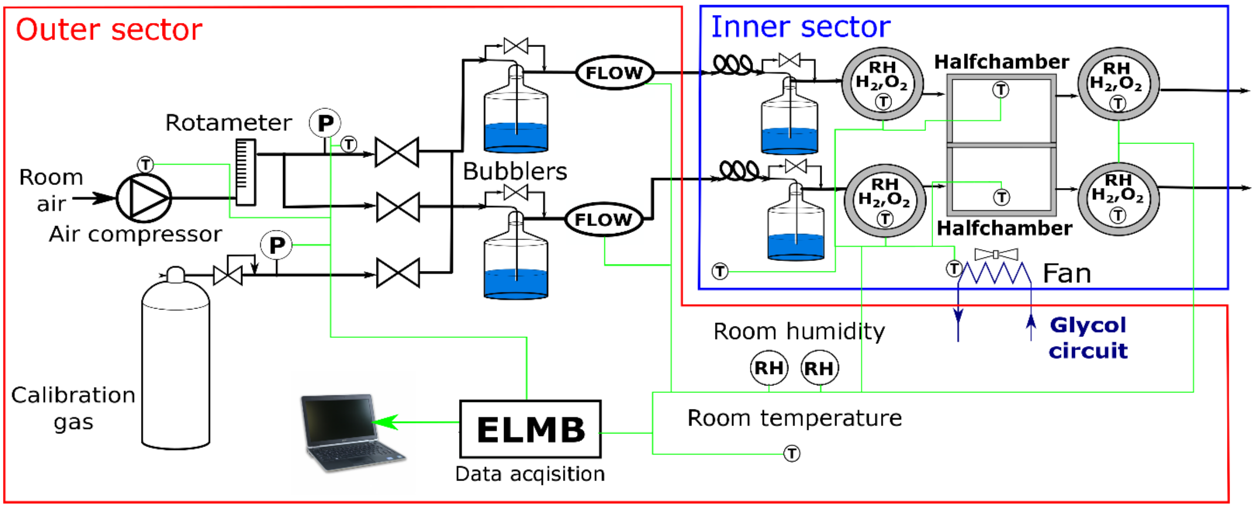

Figure 1. *Setup scheme*

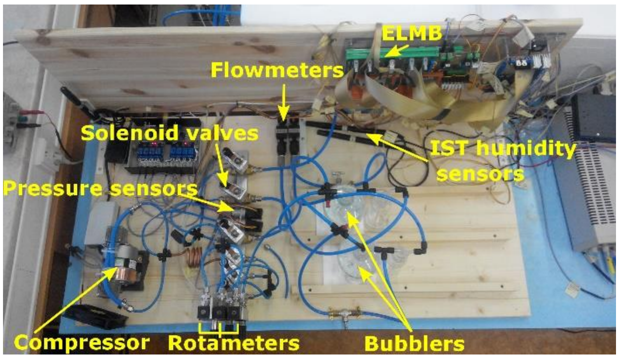

Figure 2. *Outer sector of the setup*

2 Description of setup principle

Since setup allow for testing at various temperatures the second half of the setup is placed in a styrene thermo boxes, shown in Figure 3 and 4. Stable temperature inside the boxes is important because the relative humidity is dependent on temperature. The temperature in the boxes is maintained using a glycol-air heat exchanger.

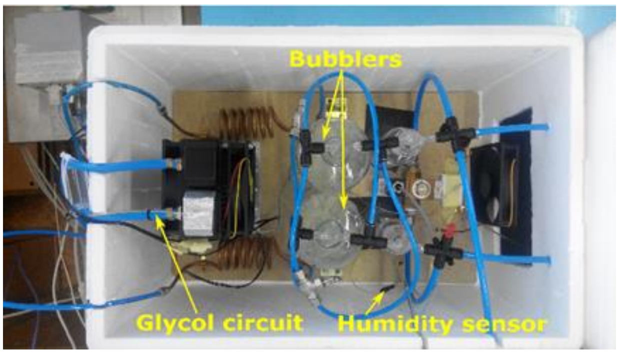

Figure 3. *First styrene thermo box with bubblers and heat exchanger*

First box contains another set of bubbler which are in series with the bubblers from the outer sector. The advantage is that these bubblers are maintained at the same temperature as the tested devices. Second thermo box contains the test chamber and all the main sensors (relative humidity, hydrogen and oxygen). The test chamber itself is equipped with multiple temperature sensors.

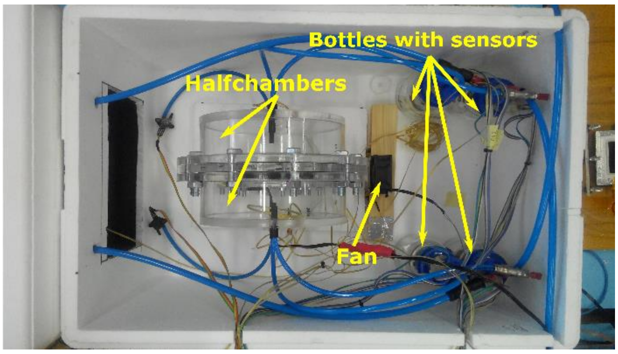

Figure 4. *Second styrene thermo box with test chamber*

2.1 Setup build for warm temperatures

A room air is drawn by a piston compressor (20 RND Vacuum Bohemia) at the beginning of the measurement setup. The air passes through a rotameter flowmeter with a regulation needle valve before it splits into two equal streams. The streams pass through first set of bubblers and flowmeters. The streams than enter the thermo box where they pass through cooper tube coils in order to warm to the temperature inside the box. After the coils the streams go through second set of bubblers, see Figure 5. This second set of bubblers was installed after the initial test phase where we discovered that only one set of bubblers was struggling to achieve humidity above >65%. The best solution is two use two set of bubblers connected in series. The resulting air streams at defined humidity and temperature pass through inlet sensors of the test chamber. The sensors measure temperature, humidity and levels of oxygen and hydrogen. Each stream continues into one of the half-chamber before passing through the outlet sensors which are the same as the inlet ones, Figure 5.

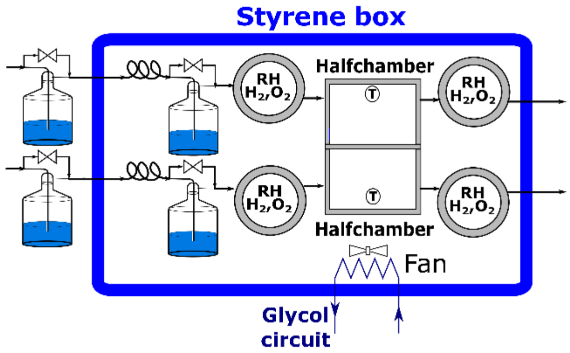

Figure 5. *Styrene box – warm temperatures modification*

Desired temperature in the box is controlled by a glycol bath chiller. Chiller heats up or cools down the glycol which circulates through an air heat exchanger equipped with fans that distribute the air inside the thermo box. Initially, the distribution of the temperature inside the two thermo-boxes was uneven. This was solved by adding two additional fans that allows for better circulation of air.

The air flow is regulated by two air rotameters with integrated needle valve, two rotameters with ranges 0 - 250 l/hour and 0-1000 l/hour are used in parallel. Nominal flow in the setup is 6 Nl/min through each half-chamber (10 Nl/min in total).

2.2 Setup build for low temperatures

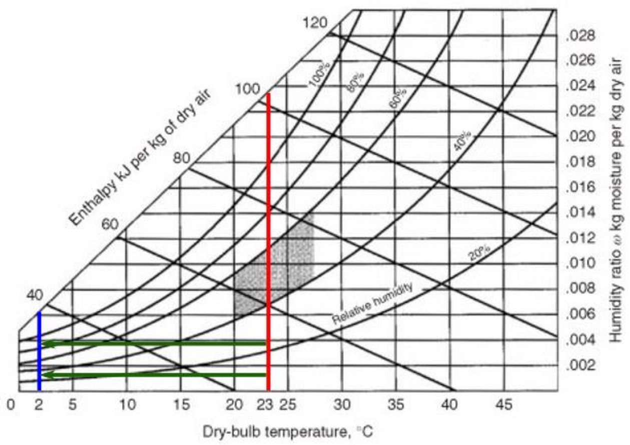

Figure 6. *Mollier diagram of humid air*

The setup has to be slightly modified for measurements at low temperatures due to the fact that the relative humidity increases with decreasing temperature. The relation between the temperature and relative humidity is shown in the Figure 6. According to the Mollier diagram a „room“ air at 23°C with common humidity of 20% to 40% has to be dried to ~23% or ~5% in order to obtain relative humidity of 85% or 30% at 2°C [1 and 2]. In our setup, the air at room temperature passes through driers before entering the thermo box where it is cooled down. In this arrangement the sensors are located outside the thermo box to avoid difficulties with measurement of relative humidity at low temperatures, Figure 7.

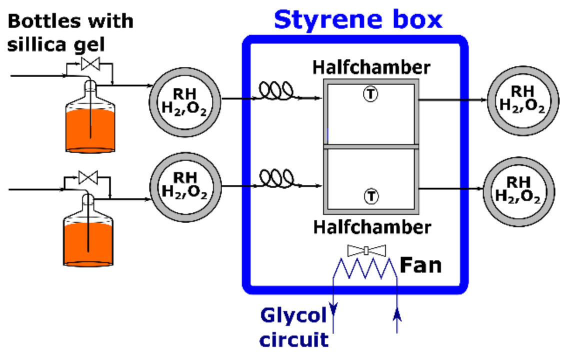

Figure 7. *Styrene box - low temperatures modification*

3 Sensors used in setup

3.1 Pressure sensors

Figure 8. *JSP DMP331 [3]*

Three pressure sensors JSP DMP331 [3] were calibrated and are used for the setup, Figure 8.

- JSP DMP331, 0-250 kPa – bubblers/driers inlet
- JSP DMP331, 0-10 bar – compressor outlet
- JSP DMP331, 0-1.6 MP_a – calibration gas bottle

The absolute sensor with range of 16 bar is used to monitor pressured in a bottle containing gas mixtures for calibration of the oxygen and hydrogen sensors. The 10 bar relative sensor is connected at the output of the compressor while the 2.5 bar relative sensor monitors the pressure after needle valve used for a flow regulation

3.2 Temperature sensors

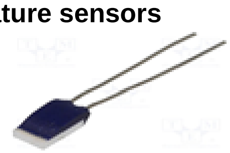

Figure 9. *Pt1000*

Thirteen PT1000 temperature sensors are used in the measurement setup, Figure 9. They are standard Pt1000 sensor with nominal resistance of 1kΩ at 0°C, the class B sensors with precision of 0.12 % were used [4]. Although, the accuracy of the sensor is sufficient for our purpose a calibration was carried out against precision Tinsley reference sensor to account for the resistance of wires and connectors that would otherwise could cause an offset of up to two degrees Celsius in the measured temperature.

The sensors measure following temperatures: room air, compressor motor, compressor outlet, chiller glycol outlet, air inside the thermo box on multiple locations, temperature of the air passing through the sensors, inside the half-chambers.

3.3 Flowmeters

Figure 10. *Honeywell flowmeter [5]*

Two Honeywell AWM5104VN flowmeters [5] are used in the measurement setup, Figure 10. These devices allow for measurement of gas flows from 0-20 Nl/min and are factory calibrated for pure nitrogen. A calibration with air was carried out to check the flowmeter operation. Further parameters from the datasheet are summarized in Table 1. The manufacturer specifies the repeatability and linearity error but not the overall accuracy of the measurement, for example in percent of full scale range.

Table 1. *Flowmeter parameters [5]*

	Min	Typ.	Max.
Excitation VDC	8	10±0.01	15
Power Consump-tion (mW)	--	--	100
Response time (msec)	--	--	60
Null output shift -20 to 70°C	0.95	1	1.05
Full scale output shift	--	±0.05VDC	±200VDC
Full scale output shift -20 to 70°C	±7.0% Reading		
Linearity error	±3.0% Reading		
Repeatability and Hysteresis	±0.5% Reading		
Leak rate, max	0.1 psi/min. at static con-dition		

3.4 Hydrogen sensors

Figure 11. *Figaro TGS6812 [6]*

Five Figaro TGS6812 hydrogen sensor, Figure 11, are used to monitor the hydrogen that can be generated on the from decomposition of the water molecules on humidification/dehumidification devices. This sensor detect combustion of gases on temperature sensitive heating element and compare this signal with reference element in Wheatstone bridge [6]. Combustion of hydrogen changes the temperature and subsequently the resistance of the sensing element which causes change of output voltage. The sensor operates up to 3% of hydrogen in the air. This particular model of the sensor was selected thanks to its linear response.

3.5 Oxygen sensors

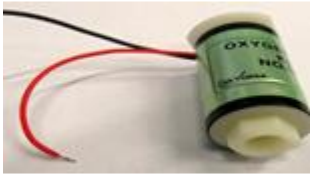

Figure 12. *Oxygen sensors Figaro KE series [7]*

The Figaro KE series sensor, shown in Figure 12, is a lead-oxygen battery which incorporates a lead anode, an oxygen cathode made of gold and a weak acid electrolyte. Oxygen molecules enter the electrochemical cell through a non-porous fluorine resin membrane and are reduced at the gold electrode with the acid electrolyte. The current which flows between the electrodes is proportional to the oxygen concentration in the gas mixture being measured. The terminal voltages across the thermistor (for temperature compensation) and resistor are read as a signal, with the change in output voltages representing the change in oxygen [7]. The response of the sensor is linear and the range is up to 30% of oxygen in air.

3.6 Relative humidity sensors

Figure 13. *Honeywell HIH-4000 [8]*

Honeywell HIH-4000 relative humidity sensors, Figure 13, are placed before and after each half-chamber. Two additional sensor are placed inside the thermo box to detect leaks from the chambers. The sensors have linearity of ±3.5% RH and accuracy of 5% RH or 8% RH for relative humidity above 60% [8]. For this reason the calibration of the sensors had to be carried out.

3.7 Relative humidity sensors (reference)

Figure 14. *IST humidity reference sensor*

Three IST humidity reference sensors, shown in Figure 14 were used for calibration of the Honeywell sensors. The sensors are based on IST P-14 (MK 33) capacitive elements coupled to an electronic circuit that provides linear output 0-10V corrected for temperature. The sensor parameter can be found in Table 1.

Table 2. *IST P14 (MK 33) parameters*

Parameter	Typical	Unit	Note
Accuracy	<1.5	%RH	At 23°C after one point calibration
Sensitivity	0.25	pF/%RH	
Response time	<5	s	(50%RH to 0%RH)
Operating temperature	-50 to 100	°C	
Range	0 to 100	%RH	

4 Data acquisition and visualisation

4.1 ELMB data acquisition system

Given the number of various sensors, a sophisticated DAQ system is needed. A combination of Embedded Local Monitoring Board and SIEMENS WinCC software is used, as it integrates all necessary features of SCADA system such is the data archiving in database or visualisation panels with plots. The ELMB, shown in Figure 15, provides 64 analog channels which can be configured for measurement of resistance (Pt1000 temperature sensors) or volt and millivolt level signals.

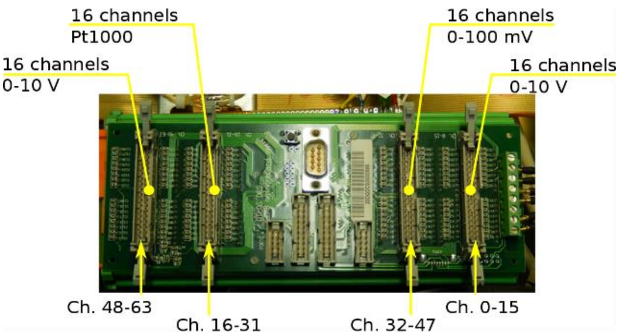

Figure 15. *ELMBs channels*

The ELMB was calibrated in two steps: inner and outer calibration. During the inner calibration all adapters that act as voltage dividers or current sources for the Pt1000 sensors were dismounted and their resistance was measured with high accuracy. The outer calibration of the Pt1000 channels with precise reference resistor. The calibration of the volt and millivolt channels was carried out with a precise Keithley multimeter. Both, inner and outer calibrations constants were embedded in the WinCC software.

4.2 Visualisation

Graphical user interface was developed in the WinCC environment and visualisation graphics were prepared for better orientation in the ongoing measurements, see Figure 16.

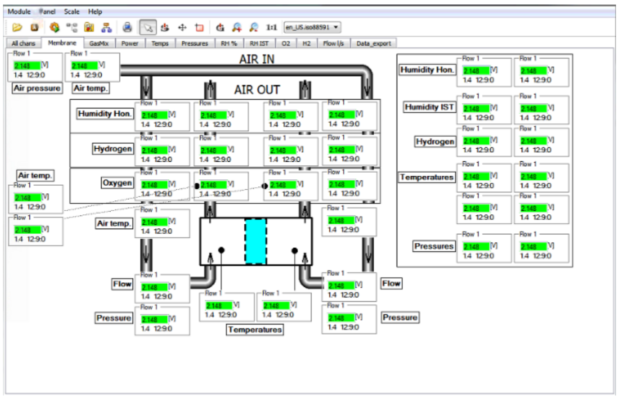

Figure 16. *Values visualisation*

WinCC software also provided real-time graphs that can also display measured values form history stored in a database, see Figure 17. This is practical for comparing and checking values against previous measurements. The measured data can be exported into CSV (comma separated data) for further processing in excel, Matlab or Python.

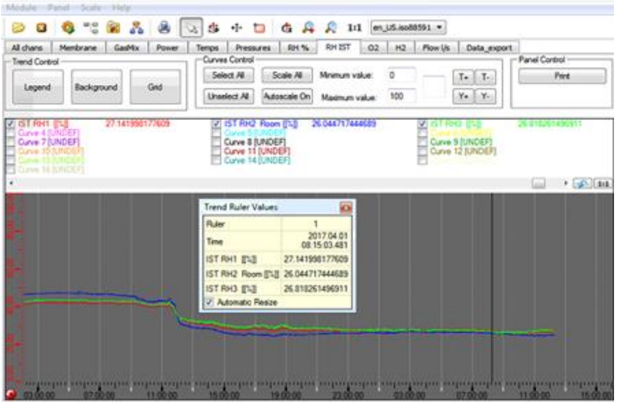

Figure 17. *Graph of humidities in the WinCC software*

5 Sensor calibrations

5.1 Calibration box

The humidity, hydrogen and oxygen sensors were calibrated in a hermetically closed calibration box. This arrangement guaranteed the same conditions for all the sensors, see in Figure 18.

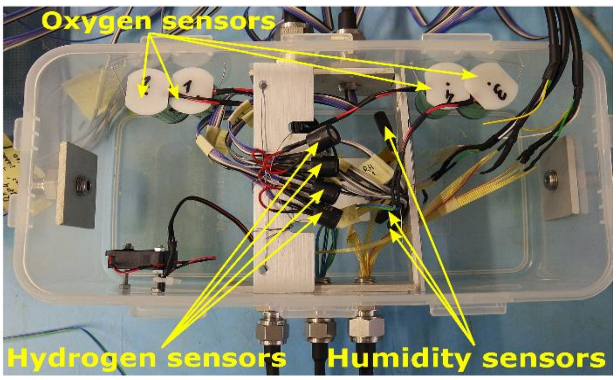

Figure 18. *Calibration box*

The calibration box was flushed with gases composed of dry air with added nitrogen or hydrogen in a different proportions. The gas mixtures were either dry or humidified by passing through a bubbler, Figure 19.

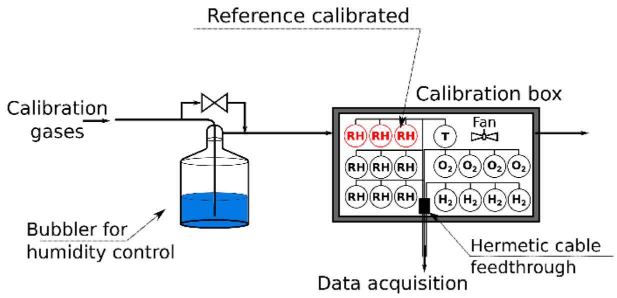

Figure 19. *Calibration box scheme*

A fan was located in the top right corner of the box for to ensure even flow around the sensors. This is crucial for the hydrogen sensors because they burin small amount of hydrogen and require therefore supply of fresh gas mixture.

5.2 Gas mixture preparation

Different ratios of dry air, hydrogen and nitrogen were mixed in a bottle for the calibration, see Figure 20. Only small amount of hydrogen (<2%), well below the low explosion limit, were mixed with air.

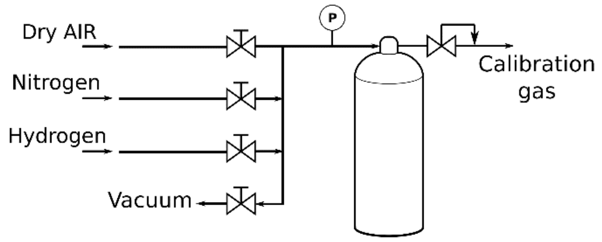

Figure 20. *Gas mix scheme*

Following procedure was used to prepare the calibration gas mixture: firstly the bottle was evacuated. Then it was filled with small amount of hydrogen gas to different pressure between 0.01 bar_a – 0.3 bar_a. The bottle was then pressurized with dry air to 16 bar_a. The procedure is graphically outlined in Figure 21.

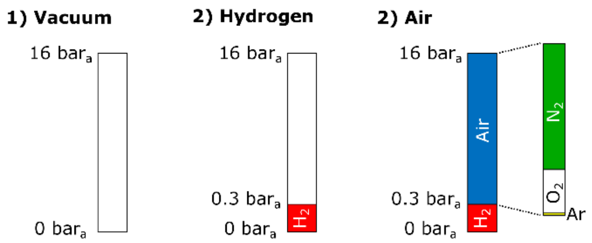

Figure 21. *Preparation of mixtures with air and small amount of hydrogen*

The same process was used to prepare mixtures with various oxygen fractions. Nitrogen was mixed with air to effectively decrease the oxygen content in the resulting mixture, shown in Figure 22.

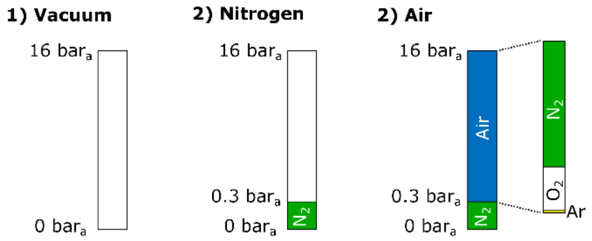

Figure 22. *Preparation of mixtures with varying oxygen content*

Thankfully, behaviour of all the components (oxygen, nitrogen and hydrogen) is close to ideal gas i.e. their compressibility factors are closed to one for the pressures used during the mixing. The molar fraction of the mixture components were therefore obtained directly from the partial pressures that were recorded during the mixture preparation.

5.3 Pressure sensors

The pressure sensors for the setup were calibrated against digitally read Keller 33X absolute sensor with measurement range of 0-10 bar and accuracy of 0.05 %FS. The calibration was split into two parts. Firstly, all of the sensor were calibrated in a range from atmospheric pressure to 2.4 bar. Than the 250 kPa relative pressure sensor was removed and the calibration continued up to 9.3 bar. The calibration confirmed linear behaviour of the sensors. Example of one of the resulting linear fit is shown in figure 23.

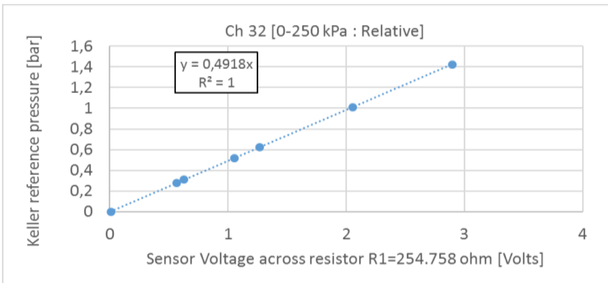

Figure 23. *Pressure sensors calibrations*

5.4 Temperature sensors

The Pt1000 sensors were calibrated in a range from -2°C to 25°C. Thanks to the linear nature of these sensors they can be safely used outside the range of this calibration. A Tinsley Pt100 sensor was used as a reference sensor, its accuracy is better than 0.1°C. Since the measurement setup is relatively large, seven of the Pt1000 sensors were attached to two-meter long wires while the other six were attached to one-meter long wires. The calibration fits takes into account the resistance of these wires therefore the length of the wires will not affect the accuracy of our measurements. Example of the linear relationship obtained for one of the sensors is in Figure 24.

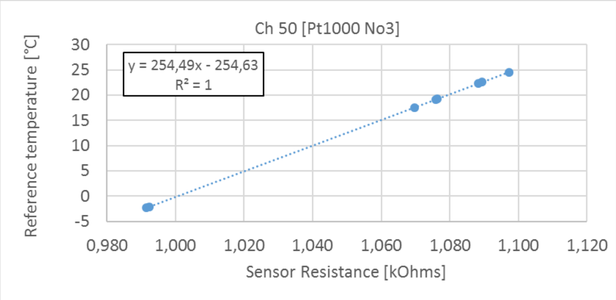

Figure 24. *Temperature sensor calibration*

5.5 Flowmeters

The Honeywell AWM5104VN flowmeters were calibrated against to Voegtlin rotameters specified for air at 20°C and 1.21 bar. Two rotameters with the same accuracy of ±4% full scale but with different ranges: 900 Nl/hour and 250 Nl/hour were used in order to increase the overall accuracy of the calibration. The calibration setup was equipped with pressure sensor at the rotameter outputs so that flow values could be corrected for the difference between the nominal pressure (1.21 bar) and actual pressure. Following correction was used:

$$Q_{air} = K_{gas} \times Q_{gas} \tag{1}$$

$$K_{gas} = \sqrt{(G \times T_{act} / T_o \times P_o / P_{act})} \tag{2}$$

Where Q_{air} is the normalized air flow, Q_{gas} is the measured air flow, G is the specific density (G=1 for air), T_{act} is the temperature of the gas during the measurement, T_o is the normalized temperature, P_{act} is gas the pressure and P_o is the normalized pressure. Output voltage of the flowmeters was found to be linearly proportional to the flow, Figure 25.

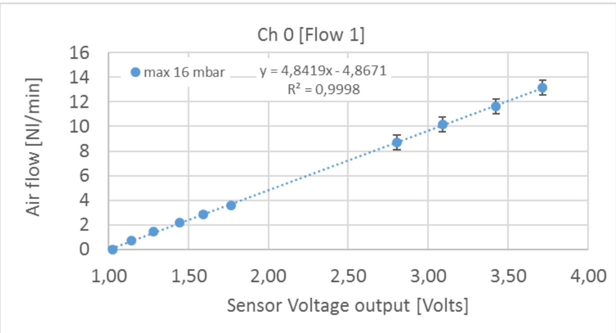

Figure 25. *Flowmeter calibration*

5.6 Hydrogen and oxygen sensors

The Figaro TGS6812 hydrogen sensors as well as the Figaro KE series oxygen sensors were calibrated using the gas mixtures described in section 5.2. The calibration was based on precise knowledge of the composition of the calibration mixtures. Responses of the sensors to changes in oxygen or hydrogen content in the air are shown in Figure 26 for one hydrogen senor and in Figure 27 for one oxygen sensor.

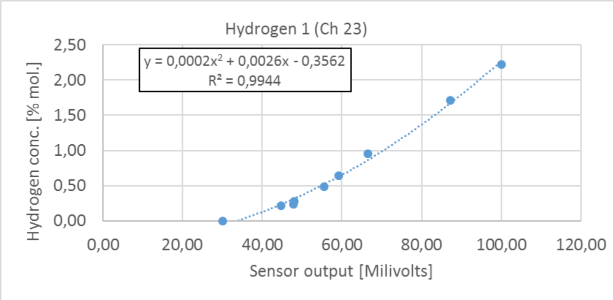

Figure 26. *Hydrogen sensor calibration*

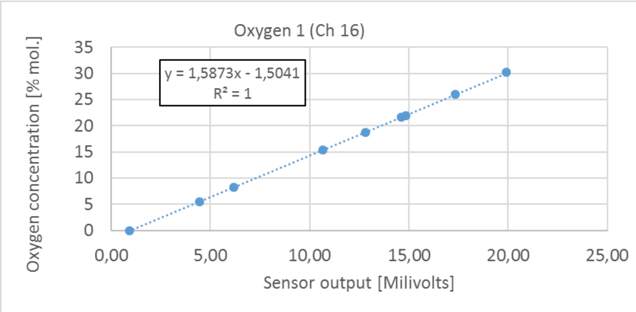

Figure 27. *Oxygen sensor calibration*

5.7 Reference relative humidity sensors

Saturated and unsaturated salt solutions were used to calibrate three IST reference humidity sensors. Solutions of certain pure salts in distilled water have the ability to maintain constant relative humidity in a closed container, see Figure 28. Calibration of humidity sensors with salt solutions is the most common method. We have used the Rotronic humidity standards which are pre-prepared high quality salt solutions. Following standards were used for the calibration:

- 5% RH - Calcium bromide + Zinc bromide
- 10% RH - Lithium bromide sol.
- 35% RH - Lithium chloride sol.
- 80% RH - Lithium chloride sol.

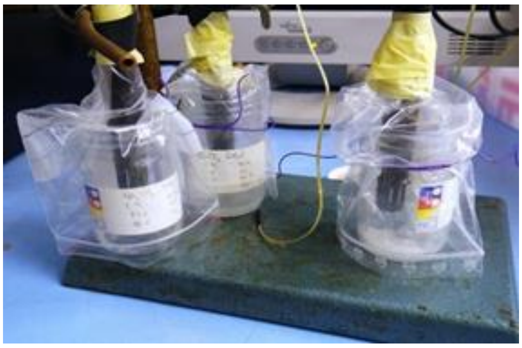

Figure 28. *Calibration of reference humidity sensors with saturated and unsaturated salt solution*

The humidity above the salt solutions vary somewhat with temperature and for this reason the calibration can be carried out only in stable environment. It takes relatively long time to achieve equilibrium with stable relative humidity. Figure 29 shows the calibration with different humidity standards in time. The whole procedure with five different standards took three days.

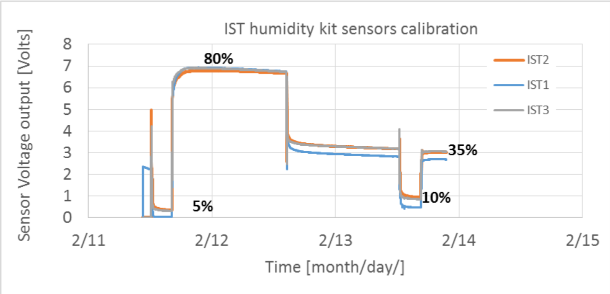

Figure 29. *IST humidity kit sensors calibration*

5.8 Relative humidity sensors

Six Honeywell HIH-4000 sensors were calibrated against the reference IST humidity sensors. The arrangement with hermetic calibration box from Figure 19 was used. The relative humidity was adjusted by a needle valve bypassing the bubbler and several stable values in the range from 5% RH to 80% RH were used. Relationship between relative humidity reported by the reference IST sensors and the voltage output of the Honeywell HIH-4000 is shown in figure 30. It is apparent that the response of the HIH-4000 sensors is linear. The calibration was carried out at 26°C. Although all the sensors are temperature compensated, the setup for the was designed so that the sensors are operate in relatively narrow range of temperatures between 23°C to 30°C even when the test requires temperatures below 5°C.

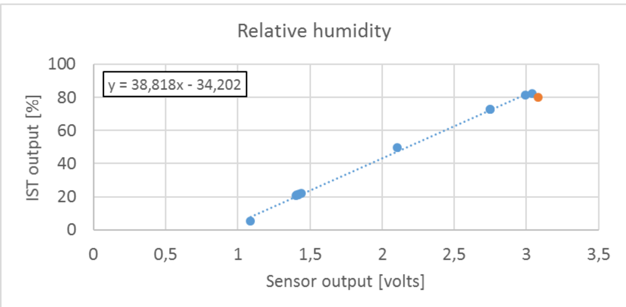

Figure 30. *Honeywell calibration sensor calibration*

6 Summary

We have designed an experimental setup for testing f sensors, electronic components and devices for humidification or drying. The setup is equipped with two test chambers (half-chambers). The relative humidity in each of the half-chambers can be controlled independently while the test can take place at temperatures from 0°C to 40°C. Additional hydrogen and oxygen sensors will enable test at various air compositions, test of sensors for combustible gases or to detect possible water decomposition on humidifiers or dehumidifiers. The setup is ideal for or for evaluation of cross sensitivity of sensors, for instance for testing sensitivity of oxygen sensors to temperature and humidity.

In the recent phase of the setup construction we have calibrated all the sensors that will be used in the setup. This includes the temperature, pressure, flow, humidity, hydrogen and oxygen sensors. All of the sensors except for the hydrogen sensors have linear response. The hydrogen sensors can be fitted with second order polynomial. Even though the salt solution for humidity sensors calibration often do not provide satisfactory results the high quality pre-prepared solutions we have used delivered excellent results.

As a demonstration we have tested cheap-widely used sensors that combined temperature and humidity measurement with digital (I^2C) output. This kind of sensor are often provided by online resellers for internet of things (IoT) applications with Arduino or Raspberry PI modules. The results are shown in Table 3. It is apparent that cheap sensors provide dismal "out of the box" accuracy for both temperature and humidity measurement. The sensors must be calibrated before they can be used in even simple applications.

Table 3. *Test of cheap combined sensors (temperature + relative humidity) with digital output*

	Temperature		Relative humidity	
	°C	°C	%	%
reference values	31	27	11	23
Sensor 1	33	29	9	11
Sensor 2	33	29	12	15
Sensor 3	32	29	9	11
Sensor 4	28	24	17	19
Sensor 5	30	24	12	16
Sensor 6	32	27	34	32
Sensor 7	31	27	18	27

Nomenclature

G Specific density ($kg.m^{-3}$)
P_0 Normalized pressure (bar_a)
P_{act} Pressure of measured gas (bar_a)
Q_{air} Normalized air flow ($Nl.min^{-1}$)
Q_{gas} Measured air flow ($Nl.min^{-1}$)
RH Relative humidity (%)
T_0 Normalized temperature (°C)
T_{act} Temperature of measured gas (°C)

References

[1] NOŽICKA, J. Základy termomechaniky. Vyd. 1. Praha: Vydavatelství CVUT, 2001, 187 s. ISBN 80-01-02409-1.

[2] ŠAFAŘÍK, P. , VESTFÁLOVÁ, M.: *Termodynamika vlhkého vzduchu*. Praha: České vysoké učení technické v Praze, 2016. ISBN 9788001060209.

[3] *JSP měření a regulace* [online]. [cit 06.04.2017]. Dostupné z: http://www.jsp.cz/files/d0028kpcz.pdf

[4] *Konsberg* [online]. [cit 06.04.2017]. Dostupné z: https://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/A707D00EE0F558D6C12574E1002C2D1C/$file/tsiec751_ce.pdf

[5] *Honeywell Sensing and Internet of Things* [online]. [cit 06.04.2017]. Dostupné z: https://sensing.honeywell.com/honeywell-sensing-airflow-awm50000-series-catalog-pages.pdf

[6] *Figaro sensors* [online]. [cit 06.04.2017]. Dostupné z: http://www.figarosensor.com/products/docs/TGS%206812D00(1014).pdf

[7] *Figaro sensors* [online] [cit 06.04.2017]. Dostupné z: http://www.figaro.co.jp/en/product/docs/KE_Product%20Infomation_rev02.pdf

[8] *Honeywell Sensing and Internet of Things* [online]. [cit 06.04.2017]. Dostupné z: https://sensing.honeywell.com/honeywell-sensing-hih4000-series-product-sheet-009017-5-en.pdf