Sensor System with Multi-point Sampling Applied to IAQ Measurements

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Abstract: Quality of indoor air (IAQ) is one of considerable concerns of today. Its evaluation through measurement is highly requested, but difficult. The reason is the numerosity of influencing factors involved as well as significant temporal and spatial variability of IAQ. In this work, we proposed a sensor system with multi-point sampling for this purpose. It is based on semiconductor gas sensor. The measurements were performed in a concert hall. The measurement procedure included sensor exposure to gas samples delivered from four sampling points, interchangeably with purified air for sensor regeneration. The obtained results show that the sensor system with multi-point sampling is a promising concept for indoor air monitoring. It was demonstrated that the system is applicable to determine the influence of occupants on IAQ. It is possible, because human beings release VOCs, which are measurable by semiconductor gas sensors. Sensor regeneration plays crucial role in the system operation. For achieving valuable results it is necessary to apply sensor signal pre-processing, which consist in baseline correction.

1 INTRODUCTION

Poor indoor air quality (IAQ) can lead to a number of physical symptoms and complaints (**?**; **?**). Hence, it is the subject of much attention these days (**?**).

The problem of inappropriate chemical quality of air inside buildings is difficult to diagnose and solve without the expert assistance, supported by the appropriate information (**?**). The most reliable source of such information are measurements.

The ideal analytical instrument dedicated to IAQ assessment should be able to identify and quantify a broad spectrum of chemical compounds with the minimal cross-interferences. It has to exhibit an appropriate detection limit, sensitivity and dynamic range. In real life, indoor environment is a dynamic system. The qualitative and quantitative composition of air inside buildings can undergo complex changes in time (**?**). Thus, it is important to use instruments designed for real-time, continuous measurements, with fast response time. Only such devices may be able to detect various circumstances, when concentrations of contaminants display characteristic behavior. The set of chemicals present in air inside building, as well as their concentrations, vary greatly across indoor space. The need to recognize this variation implies on-line or *in situ* mode of operation of measuring instruments. In addition, the selection of representative sampling points is a key issue. It is also important to consider if the analyzer can be used in the chosen (specific) location. Analytical equipment has to be prepared to work, with the declared accuracy, in different environments . The cost of regular maintenance of the analyzer is sometimes high and therefore it has to be taken into account, as well. The fundamental stage of the measurement process is calibration. Instruments for indoor air analysis should be easily calibrated without the support from the supplier.

Today, there are a number of analytical methods and techniques which allow to characterize indoor air quality (**?**). The available measuring instruments vary in their cost, advantages and limitations. Gas Chromatography and Mass Spectrometry, Photoacoustic Spectroscopy and Fourier Transform Spectroscopy offer good accuracy, sensitivity, selectivity and repeatability (**?**; **?**). They are mainly dedicated for quantitative and qualitative analysis of indoor air. Unfortunately, chromatographs and spectrometers are very often unattractive, because of their setting-up time, size, ruggedness, cost and serious difficulties with conducting measurements in field conditions. The available analytical equipment very often requires sample preparation, so that on-line, real-time, continuous analysis is difficult in these circumstances. Additionally, the cost and size of these instruments limit the number of monitoring sites. The

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shortcomings of traditional analytical equipment are partially reduced in instruments based on gas sensors (?; ?). These devices present numerous advantages, like small size, low weight, simplicity of use, high sensitivity in detecting low concentrations (at the level of ppm or even ppb) of a wide range of gaseous chemical compounds, fast response (it gives the possibility of on-line operation) and low cost, due to the possibility of batch production. The gas sensors have also several weak points. First of all, their responses can be often influenced by humidity and temperature. They also suffer from limited measurement accuracy, problems of long-time stability (drift) and poor selectivity.

The requirements of IAQ monitoring and limitations of gas sensor technology caused that we developed the measurement system equipped with a single semiconductor gas sensor and a multi-point sampler. The aim of this work is to show that the proposed measurement system can be used for automatic, real-time, determination of the influence of occupancy on IAQ. This indicator plays a significant role in the control and diagnostics of IAQ. The developed instrument is not dedicated for quantitative and qualitative analysis of indoor air. It can be applied in public utility buildings where air exchange rate and humidity levels are relatively constant. Additionally, it provides data that allows to determine spatial and temporal variability of the occupancy influence on air quality. Unlike in case of the wireless sensor networks, the problem of energy consumption is significantly reduced in this equipment. The indication of the occupancy influence on IAQ and the determination of its spatial and temporal variability, as a result of sensor signal baseline manipulation, are the main elements of novelty.

2 EXPERIMENTAL

2.1 Sensor System with Multi-point Sampling

There was applied a gas sensor system with multi-point sampling. Major elements of the system are: 1) sensor chamber, 2) inlet ports for gas samples, 3) unit for the inlet ports switching, 4) pump, 5) electrical circuits, 6) power supply, 7) control mechanisms (sensor heaters and the pump), 8) data acquisition unit, 9) software. The construction was developed in the Laboratory of Sensor Techniques and Indoor Air Quality Studies at Wroclaw University of Science and Technology, Poland. The photo of the system is shown in Figure ??.

Figure 1: Sensor System with Multi-point Sampling in Technical Space.

The system utilizes semiconductor gas sensors. In this work there was considered the performance of TGS2600. According to the data sheet (?) this sensor is dedicated to the detection of air contaminants. Its measuring range, in terms of ethanol concentration, is 1-100 ppm. Sensor power consumption is 210 mW.

In the device, an individual sensor is mounted in one flow-through chamber. The inlet of the chamber is connected with inlet ports for gas sampling via the switching mechanism. One inlet port a time can be connected to the sensor chamber. There are 8 gas inlet ports available in total. The operation of the instrument is controlled by the software. The user defines the following working parameters: sequence of inlet ports connection to sensor chamber, intensity of sensors' heating (as the percentage of maximum power applied to heaters), gas flow (as the percentage of the maximum throughput of the pump).

In order to realize the automatic mode of operation, the software code is loaded from the memory card. Once loading is completed, sensor system operates continuously by repeating in cycle the sequence of actions and by applying the predefined settings, as described in the operation program. The measurement data is recorded on the memory card. The data may be easily downloaded to the computer as the *.txt file.

2.2 Concert Hall

The instrument was applied for carrying out indoor air measurements in a concert hall. The investigated object is quite new. It was built in 2012. The hall is heavily loaded with numerous cultural events. Big concerts (several hundred listeners) are held nearly each Friday, Saturday and Sunday, frequently, two concerts per day. Sometimes, musicians perform on working days (e.g. for schools). Numerous rehearsals take place in course of entire week. Their time span and the number of participants are highly variant and neither predefined nor controlled. Allover, the space is very unevenly occupied in time.

The volume of the concert hall is 10 800 m^3. In the auditorium there are 526 seats and the stage can host up to 300 performers. The hall has amphitheatric layout (4.5 m height difference at the distance of about 18 m), as shown in Figure **??**.

Figure 2: Concert hall.

The hall is fitted with the displacement ventilation. Fresh air is delivered through diffusers located under seats. Exhaust air is removed via numerous ventilation grills located in the technical ceiling (about 17 m above the stage level). The ventilation rate is constant. The technical space above the ceiling hosts multiple installations, including ventilation ducts and their inlets (see, Figure **??**). Between the technical ceiling and the auditorium as well as over the stage there are mounted elements of suspended ceiling which serve achieving proper acoustics (see, Figure **??**). They restrict the area through which the indoor air is removed from the hall.

2.3 Measurements

For the purpose of measurements there were chosen four sampling points. They were located in ventilation grills, mounted in the technical ceiling, as shown in Figure **??**. The points were arranged centrally, along the auditorium. Sampling point 1 was located over the balcony at the back of auditorium. Sampling point 4 was located at the border between the auditorium and stage. Points 2 and 3 were located between points 1 and 4, at approximately equal distances. It is important to note that sampling points 1, 2 and 3 were over gaps between the elements of the acoustic ceiling. Therefore, they were on the way of air flowing upwards, from the auditorium towards the ceiling. Contrarily, sampling point 4 was quite shielded (about 5 m from the nearest gap).

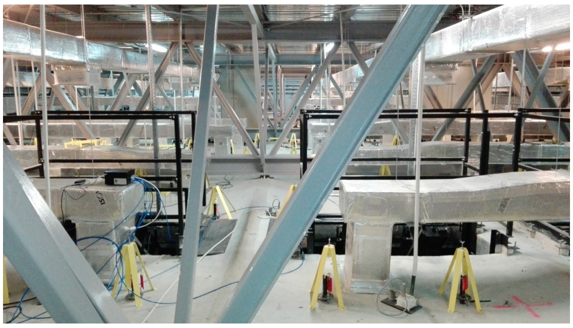

Figure 3: Sensor system with multi-point sampling in technical space.

The sensor system was placed in the technical space (see, Figure **??**). The possibility of locating the device in technical space is very advantageous. First of all, the users of the indoor space are totally unaffected by the measurements. It is particularly important when gas flow through sensor device is enforced with a pump, which may cause noise. This possibility is also critical in respect of realization of multi-point sampling, which requires a system of tubing for gas sample transportation. This, at best, should be out of reach of the average room user. Usually, the instrument located in technical space may be easily connected to power supply, which gives some flexibility of its placement with respect to the investigated space. The device operator may be granted relatively unconstrained access in respect of installation, control and maintenance of the instrument, as well as data download.

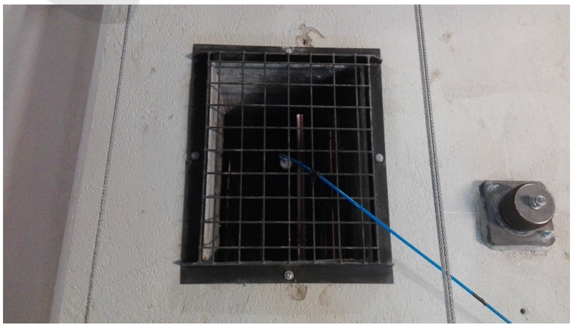

Figure 4: Sampling point.

Sampling points were connected with sampling ports of the sensor device by tubing. There was applied polyamide tubing. The pieces of 17 m length were used, the same for each pair sampling point - instrument port. Anti-dust filter was mounted at the inlet of tubing in order to protect sensors from the particulate matter contained in the air. There was also created one reference sampling point. The air delivered from there was used for the sensor system regeneration. For this purpose there was applied 17 m long Teflon tubing fitted at the end with a filter module. The module included activated charcoal, molecular sieves and soda lime. The indoor air which passed through this filter could be considered void of volatile organic compounds (with reference to sensors detection range) and, to a large extent, dehumidified.

The sensor system operated in four-point sampling schema. The single measurement cycle was composed of 8 steps. During each step, the gas sample was drawn from one sampling point for the predefined period of time (30 s), as shown in Table **??**. The complete cycle lasted 4 min. The measurement data was recorded continuously with the temporal resolution of 1 s.

Table 1: Cycle of operation for the gas sensor system with multi-point sampling.

Cycle stage	Sampling point	Sampling time [s]
1	reference	30
2	1	30
3	reference	30
4	2	30
5	reference	30
6	3	30
7	reference	30
8	4	30

Table 2: Concert beginning hours and the number of attendees. Each concert was held on different day.

Beginning	Audience
19:00	400
16:00	455
11:00	310
19:00	700
17:30	50
15:00	600
19:00	320
16:00	210
19:00	300
19:00	400

In this work tehre was examined the measurement data collected during 10 selected days in the spring 2017. We were particularly interested in the conditions during concerts. They were held at different times of the day (from 11:00 to 19:00) and the audience was of various size (form 50 to 700 listeners). The details of concerts involved in the analysis are provided in Table **??**. The number of listeners is rounded to tens.

3 DATA PROCESSING METHODS

The sensor system with multi-point sampling was proposed to determine the influence of occupants on IAQ in the concert hall during a symphonic concert. Problems with poor air quality could result first of from the elevated concentrations of CO_2 and VOCs, which are emitted by people who stay in the room. In this study we focused on VOCs, because they are responsible for olfactory sensation. The concentrations of individual gases emitted by human beings are relatively low, but their sum is high and it can be measured by semiconductor gas sensors. The key point in our analysis was to demonstrate that their responses could be quantitatively related to the number of occupants. Such relationship means that sensor response is mainly affected by occupants and not other VOCs sources. It was assumed that during the concert thermal conditions indoors are stable. Therefore, the influence of temperature and humidity on sensor response was constant.

In IAQ measurements, temporal and spatial aspect are important. When using one sensor device and multi-point sampling option, the information about the individual sampling locations is refreshed on a periodic basis. The length of the period imposes a constraint on the length of the measurement cycle which includes a full sequence of exposures to all sampling points. It also implies time constraint on the duration of measurement done at single point. Obviously, the shorter they are, the better temporal resolution of information delivery. In this work, the measurement cycle lasted 4 min and the individual exposure lasted 30 s.

In respect of the properties of semiconductor gas sensors, mainly the memory effect, it was assumed that gas samples from different sampling points should not enter the sensor system directly one after another. There was introduced exposure to purified air, delivered to the sensor system from reference sampling point after completing exposure to the gas sample from each real sampling point. This solution allows for achieving partial regeneration of gas sensor. The degree of regeneration is dependent on many factors, including the composition of the earlier delivered gas sample and the time which may be dedicated to sensor regeneration. This operation has to be included in the measurement cycle, further limiting the time which is available for an individual exposure. In this work, there was considered the measurement procedure, in which the purified air was delivered for 30 s between subsequent exposures to gas samples from different sampling points. One of the major objectives in this work was to examine the importance of sensor regeneration stage for acquiring the target measurement information from sensor system with multi-point sampling.

The analysis of measurement data was focused on identifying the feature of sensor signal, which is linearly related to the number of people in the concert hall. In the study, the following issues were taken into consideration:

- sampling points, numbered with $k \in \{1,2,3,4\}$.
- advancement of the exposure phase for k^{th} sampling point (time which elapsed since it started), $i \in \{1,2,\ldots...,30\}$ s;
- advancement of the concert (time which elapsed since it started; We limited the period to 1 h), $j \in \{1,2,\ldots...,60\}$ min;

There were considered two kinds of features, raw sensor response, R and corrected sensor response, $R - R_0$. Once properly indexed, they have the following meaning:

- $R_{i,j,k}$ is the value of sensor signal recorded at time i of sensor exposure to gas sample delivered from sampling point k, while the exposure started a time j since the beginning of the concert;
- $R_{0\,j,k}$ is the last value of sensor signal recorded during sensor exposure to purified air, prior to switching to sampling point k, while the switching takes place at time j since the beginning of the concert.

For each sampling point, k there were considered the following relationships:

$$N = a_1 + a_2 R_{i,j,k} + \varepsilon \tag{1}$$

$$N = b_1 + b_2 \left(R_{i,j,k} - R_{0\,j,k} \right) + \varepsilon \tag{2}$$

where N stands for the number of people in the concert hall. The data utilized for regression fitting was collected during 10 concerts, as listed in Table **??**. The performance of fitting was examined using coefficient of determination (R^2) and root mean squared error (RMSE).

4 RESULTS

In Figure **??** there is shown the raw signal of TGS2600 sensor, recorded during a single measurement cycle.

As indicated by the orange line in Figure **??**, the sensor system was first exposed to purified air (regeneration), followed by exposure to gas delivered from sampling points 1, 2, 3 and 4 in turn, interchangeably with exposure to purified air. As shown in Figure **??**, the exposure to gas from any sampling point caused increase of sensor signal and the exposure to purified air resulted in signal decrease. Changes of sensor signal at individual measurement points were different. Also, the degree of sensor regeneration achieved after the subsequent exposures was not the same. This fact was responsible for the overall shift of sensor signal in time.

The shift may be observed in Figure **??**. It shows the behavior of the raw sensor signal recorded during an exemplary day. Four subplots display measurement data which refer to individual sampling points. More precisely, the data plotted in a single subplot comes from 30 s of exposure to the air delivered from a measurement point, once every 4 minutes. The remaining 3 min 30 s of measurement cycle are void of data for the particular location. As shown, for each considered location, the raw sensor signal varied in time. Considerable part of the variation was caused by the properties of sampled air. The hall was not occupied during the night. However, around 9:00 a.m. there started numerous activities, namely rehearsals and later, preparations immediately preceding concerts. In the afternoon, at 15:00 and in the evening, at 19:00 there were concerts. All these events were associated with considerable variations of room occupancy in terms of the number of people, their activities and distribution in the hall. This was reflected in the variation of sensor's responses. However, some part of the senor signal change has to be attributed to the memory effect. If there was no memory effect, the sensor signal would have approximately the same value at the beginning of each subsequent exposure. The incomplete regeneration results in baseline shift.

In Figure **??**, there is shown the time series of raw responses, R recorded during exposure of TGS2600 sensor to the gas delivered sequentially from four sampling points, in the period of one day. However, there was displayed just the data recorded during a single second of each exposure. The middle, 15^{th} second of exposure was chosen. Figure **??** was prepared as a reference to Figure **??**.

In Figure **??** there is shown the time series of corrected responses of sensor TGS2600, recorded during 15^{th} second of exposure. The correction $R - R_0$ consisted in subtracting the last response of sensor recorded upon regeneration, prior to exposure, from the raw sensor response recorded in 15^{th} s of exposure. The value of R_0 was not constant for all expo-

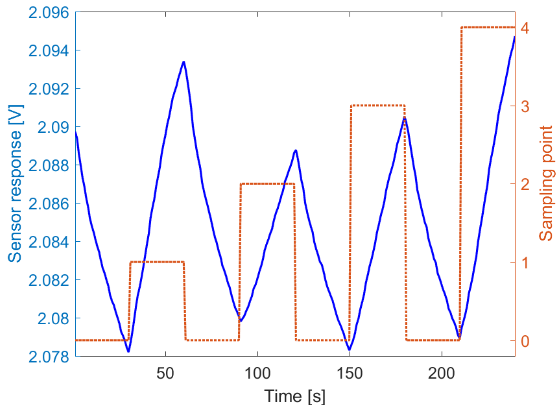

Figure 5: Raw signal of TGS2600 sensor, recorded during single measurement cycle. Sampling point switching is indicated by the *orange* line. Measurement data was collected during a concert, i.e. when there was an impact on indoor air, from the audience.

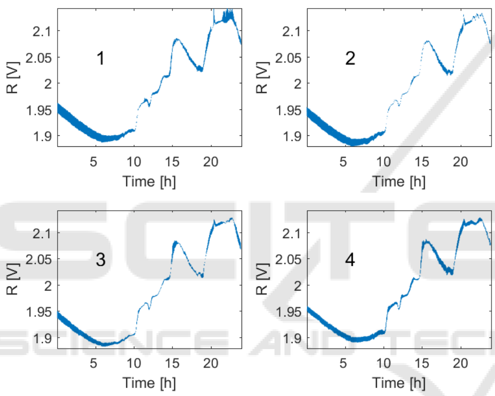

Figure 6: Raw signal recorded during exposure of TGS2600 sensor to the gas delivered sequentially from four sampling points during one day. Subplots are labeled with sampling point numbers.

sures. It changed in time, because of the inefficiency of sensor regeneration process.

As shown in Figure **??**, raw sensor response displayed similar temporal variation in all subplots. Also, the corresponding values of the responses were similar in four sampling points. It implies that the information about four monitored locations was similar, if based on raw sensor response, R.

The situation was different when applying the corrected response $R - R_0$ as the source of information. As shown in Figure **??**, the temporal variation of the variable $R - R_0$ was quite different at individual subplots. Also the ranges of values were different. The information about conditions at sampling points based on the corrected sensor response, $R - R_0$ was different from the information based on the raw response, R.

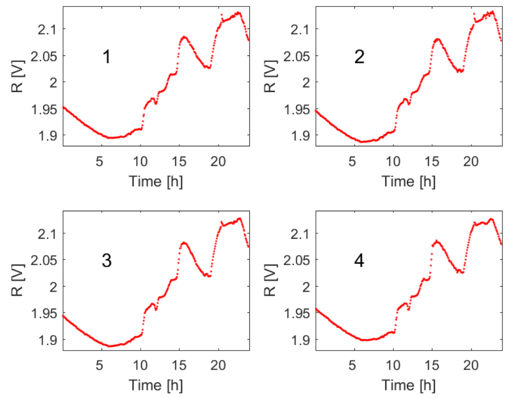

Figure 7: Raw responses, R recorded during exposure of TGS2600 sensor to the gas delivered sequentially from four sampling points, during one day. The 15^{th} second of exposure was used. Subplots are labeled with sampling point numbers.

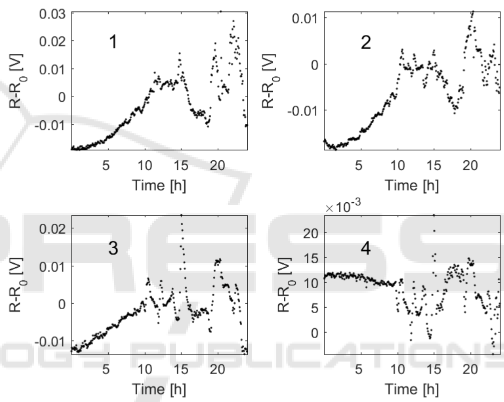

Figure 8: Corrected responses, $R - R_0$ recorded during exposure of TGS2600 sensor to the gas delivered sequentially from four sampling points during one day. 15^{th} second of exposure was used. Subplots are labeled with sampling point numbers.

In Figure **??** there is displayed the coefficient of determination, R^2 for the regression models described by eq. **??**. They are linear models of the relationship between raw sensor response, R and the number of concert hall occupants. The indicator of the adequacy of the model is displayed as a function of the advancement of the concert and the advancement of the individual exposure of the sensor. In Figure **??** there are shown the results obtained when assuming linear relationship between the corrected sensor response, $R - R_0$ and the number of concert hall occupants, see eq. **??**.

The results presented in Figure **??** allow to conclude that there may not be established a linear relationship between the raw sensor response, R and the number of people in the concert hall. It is shown that the coefficient of determination, R^2 increased with the

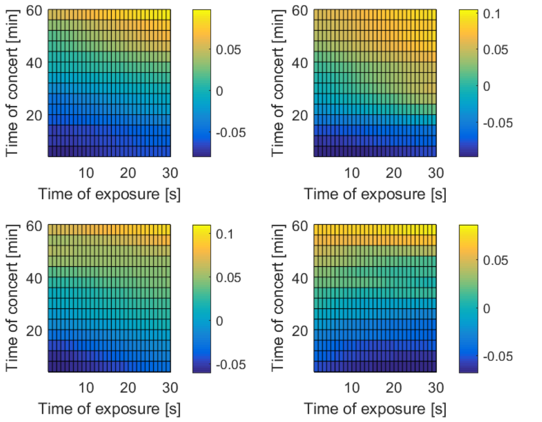

Figure 9: Coefficient of determination R^2 for linear regression models linking TGS2600 sensor response $R_{i,j,k}$ with the number of people in the concert hall. Subplots refer to individual sampling points, as shown in Figure ??.

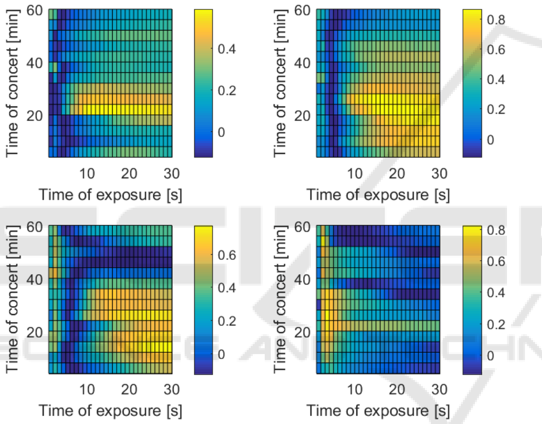

Figure 10: Coefficient of determination R^2 for linear regression models linking TGS2600 sensor response $R_{i,j,k} - R0_{j,k}$ with the number of people in the concert hall. Subplots refer to sampling point, as shown in Figure ??.

progress of the concert. However, after one hour it still remained smaller than $R^2 = 0.1$, which indicates total inadequacy of linear regression model. Typical concerts do not last longer than 1.5 h so the considerable improvement would not be achieved by extending the time of the analysis. Based on our results, the sensor response in its raw form, R is not suitable for quantifying the occupancy impact on indoor air using the sensor system with multi-point-sampling and the measurement arrangement considered in this work.

The results presented in Figure ?? allow to draw the conclusion that the relationship between the corrected sensor response, $R - R_0$ and the number of people in the concert hall may be described by the linear model. As shown, the coefficient of determination R^2 reached values exceeding $R^2 = 0.8$, which indicates high adequacy of linear regression. The relationship

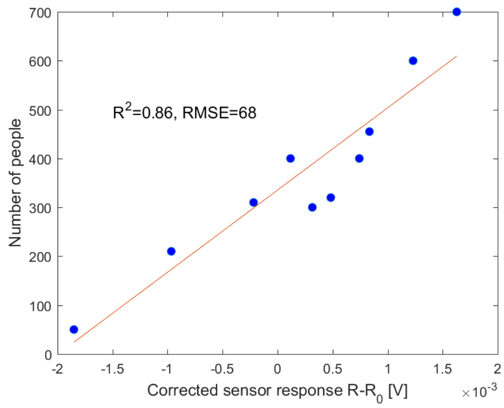

Figure 11: Best linear fit of the relationship between the corrected response of TGS2600 sensor and the number of people. Sampling point 2, sensor signal recorded during 19^{t}h minute of the concert and 20^{t}h second of exposure.

was not equally strong at each measurement point. As shown in Figure ??, it was most vivid in locations 2 and 4. The strength of the relationship was also dependent on the time of the measurement. More precisely it was dependent on the time which elapsed from the beginning of the concert as well as on the advancement of the individual exposure of the sensor. In case of measurement point 2, the best fitting was achieved between 16 and 28 min of the concert and between 15 and 25 s of sensor exposure, although later points of exposure could also be used. Regarding measurement point 4, high linearity was observed during almost entire concert. However, only the beginning of each individual sensor exposure, between 2 and 6 second, provided useful data.

The best relationship between sensor response and the number of people in the concert hall was obtained for measurement point 2, provided the assessment was based on 19th minute of the concert and 20th second of sensor exposure. The relationship is shown in Figure ??. In this case the coefficient of determination was $R^2 = 0.86$ and the root mean square error was RMSE=68, which is less than 10% of the range. Based on our results, the corrected sensor response, $R - R_0$ is suitable for quantifying the occupancy impact on indoor air using sensor system with multi-point sampling and the measurement arrangement considered in this work.

The analysis presented in this work leads to a crucial conclusion concerning measurements using the sensor system with multi-point sampling. It shows that it is essential to perform the measurement according to the procedure which includes the stage of sensor regeneration between subsequent exposures to air delivered from individual sampling points. Thanks to this stage, it is possible to correct the baseline of sensor signal. This correction is necessary to achieve high correlation of sensor response with the number of people in the indoor space in short term perspective.

5 CONCLUSIONS

This work examines the selected aspects of sensor system with multi-point sampling applied for indoor air monitoring.

The main idea of the system is to perform measurements at several locations using one, stationary sensor unit. This solution involves a number of technical and data processing problems. One of them is the regeneration of semiconductor gas sensors between exposures to gas samples delivered from different locations.

In this work we focused on the role of sensor regeneration stage in acquiring the information from the measurement system. The measurement was aimed at capturing the impact of the audience on indoor air.

The analysis was based on the data collected during measurement session in a concert hall. Four measurement points were served by the sensor system, one point every 4 minutes.

It was shown that raw sensor signal remained uncorrelated with the number of people who occupied the indoor space. Negative results were obtained at all sampling points.

However, the raw sensor signal corrected with reference to the value achieved after the regeneration phase, well correlated with room occupancy. The strength of the relationship was dependent on the location of the measurement point and the timing of measurement. The best regression model was highly adequate (R^2=0.86).

The obtained results show that sensor system with multi-point sampling is a promising concept for indoor air monitoring. In this kind of measurements sensor regeneration plays crucial role. For achieving target information it is necessary to apply sensor signal preprocessing, which consist in baseline correction.

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