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Fluctuation-enhanced scent sensing using a single gas sensor

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Abstract: Scent or aroma sensing during aromatherapy can be carried out by applying only a single resistance gas sensor (TGS – Taguchi Gas Sensors). This paper considers the efficiency of detection of essential oils by DC resistance and its fluctuations observed in TGS sensors. A detailed study has been conducted for scents emitted by five popular essential oils using three sensor types (TGS 2600, TGS 2602, TGS 823). The research was focused on the practical use in aromatherapy to assure the same intensity of scents which are sprayed by a glass nebulizer. The prepared system for scent emission and control of its intensity was presented as well.

Keywords: gas sensing; noise measurements; gas sensors; aromatherapy

1. Introduction

Nowadays aromatherapy, which affects human senses and feelings, becomes more and more popular. It is believed that essential oil scents are helpful to people with dementia. In particular that therapy can reduce agitation, anxiety and insomnia as a result of relatively inexpensive treatment [1]. Another good example of aromatherapy application is reduction of appetite at the presence of peppermint scent that may lead to weight reduction [2]. It has been also shown that perception and learning skills of human beings can be improved by selected scents of essential oils. The experiments indicate that lavender or lemon aromas could be used during lessons and examinations to increase learning performance and student achievements, as well as reducing agitation during breaks [3]. Finally, scents are successfully used for increasing sales by influencing customer behavior. For example, a geranium scent improved brand evaluations and lavender affected both length of time and the amount of money spent in restaurants [4].

The mentioned examples show clearly that aromatherapy is a very influential factor for human behavior and feelings. Unfortunately, the effectiveness of aromatherapy is often not well recognized due to weak repeatability of scent emission and its individual reception by human beings. Therefore there is a demand for techniques that could monitor aroma intensity and control more precisely the process of scent emission. This paper presents briefly the prepared scent emitting device and explores possibilities of scents detection by two techniques that can be easily utilized in practice.

2. Techniques of Essential Oil Diffusion

There are two popular types of scent emission systems that are currently available on the market. The first one is based on spraying aromas, by hand or by an electronic device, in the given instants. This method uses a nebulizer to produce a mist of scent. The nebulizer produces tiny drops of essential oils by utilizing ultrasound vibrations or compressed air as the driving force. This solution is popular due to fast scent emission and low energy consumption.

Another commonly-used method is based on heating (e.g. by flame of a candle) water with a few drops of essential oil. The scent vaporizes by a diffusion process. This method is very cheap but much more slower than the previous one. Additionally, higher temperature can lead to some disadvantageous chemical reactions within the essential oils that could destruct the final effect.

The first-mentioned method can be easily modified to be used in aromatherapy when repeatability of the emitted scent intensity is important. This result could be achieved by applying a selected resistance gas sensor to measure its response to the changes of ambient atmosphere and by a control unit that affects the scent emission intensity, e.g. by altering the air pressure or fan speed (Fig. 1). However, DC resistance measurements of the TGS sensor

can be insufficient to detect low concentrations of the emitted scents. Therefore, we propose additional method to improve the efficiency of aroma detection. The proposed method is called fluctuation enhanced sensing (FES) and utilizes resistance fluctuations of gas sensor which give additional information about their ambient atmosphere.

2.1. Scent Emitting Device

A new device was applied to emit essential oil scents. The device comprises four independent nebulizers powered by the same pump and electronics. The method of scent emission bases on mechanically spreading small oil drops by applying specially formed tiny glass pipes (Fig. 1) and an air pump. This setup produces low pressure, over the pipe filled with aroma oil stored at the flask bottom. The pressure produced by the applied air pump will affect the speed of aroma emission. The same effect is obtained by changing the speed of the fan used to spread aroma within the whole room. Both elements can be easily controlled by a cheap electronic circuit.

Another advantage of the proposed solution is that sprayed odor drops have very small dimensions (~1 μm) which means fast and efficient smell spreading. Additionally, the smaller molecules combine more easily with air molecules what results in longer aroma presence.

2.2. Resistance Gas Sensors

Measurements of scent intensity were carried out by applying Taguchi gas sensors (TGS) that are reliable and popular gas sensors available on the market. Such sensors (Fig. 2) change their DC resistance in the presence of different gases in their ambient atmosphere. The gas-sensitive layer (e.g. SnO_2) of these sensors is preheated to an elevated temperature. Such conditions increase the probability of gas molecule adsorption on the gas-sensitive layer surface. The layer comprises grains of different size. The adsorption processes change potential barriers between the grains; that results in a decrease of DC resistance. The same processes are responsible for fluctuations of potential barriers between the grains that are observed as sensor resistance fluctuations.

The applied gas sensors were optimized to detect air pollutants or hazardous and explosive gases but we can expect their reaction to various scents (e.g. aroma oil fragrance). It was assumed that during aromatherapy various air pollutants (e.g. cigarette smoke, fungus odours) are diminished by ventilating air in the therapy room. Otherwise, aromatherapy wouldn't be effective due to unpredictable and often adverse effects caused by the mentioned pollutants.

The ambient atmosphere changes affect resistance fluctuations as well and can be utilized as a source of useful information, which can strongly improve the sensitivity and selectivity of gas detection [5–8]. Usually, the resistance fluctuations within a gas sensor can be observed as voltage fluctuations across the polarized sensor [5]. The observed fluctuations can be analyzed by the estimated power spectral density $S(f)$ using the fast Fourier transform (FFT algorithm) [9, 10]. This algorithm can be implemented in a computer that controls the device.

Other statistical functions or parameters of the observed fluctuations that could improve aroma detection are kurtosis, skewness or probability distribution.

2.3 Measurement Setup

During measurements the gas sensor was placed inside a gas chamber which was filled through a pipe with air sucked in the vicinity of the scent-emitting device. Voltage fluctuations across the gas sensor, which was polarized by an adjustable DC voltage, were amplified by a low-noise voltage preamplifier. A cheap JFET transistor (2SK170) was used to provide such a preamplifier with a voltage gain in the range of $K = 200 \div 800$ V/V [11, 12]. Batteries were used to polarize the applied sensor and to supply voltage to the mentioned low-noise preamplifier. The DC voltage component across the gas sensor was measured at the output of a low-pass RC filter that comprised a capacitor C and a resistor R being a few orders greater than the sensor resistance R_s. Polarization of the gas sensor was adjusted by a potentiometer, connected to the sensor by a resistor $R_1 = 11$ kΩ of a value similar to the sensor resistance (Fig. 3). An additional capacitor at the potentiometer output was used to reduce outside interference and the noise component from the applied DC voltage source. The amplified AC voltage component $U(t)$ was measured by a Stanford SR760 spectrum analyzer and a parallel National Instruments PCI-4474 data acquisition card. The spectrum analyzer was used to estimate power spectrum and data acquisition card was used to record voltage samples for kurtosis estimation. The DC voltage across the sensor was measured by the precise voltmeter, Keithley model 199 System DMM Scanner.

3. Experimental Results

The gas sensors DC resistance and its fluctuations were observed when the sensors were exposed to an ambient atmosphere of various scents. Measurements were performed for popular essential oils of lemon, musk, melissa (lemon balm), cinnamon and pine. The selected sensors (TGS 2600, TGS 2602 and TGS 823) are optimized to detect hazardous gases or air pollutants. Nevertheless, all the selected sensors exhibited changes of their DC resistance in the presence of the used scents.

Power spectral density of voltage fluctuations across the sensor was proportional to the square of sensor DC voltage U_{DC} (Fig. 4). That result proves that the applied measurement system recorded noise generated by fluctuations of sensor resistance in the low-frequency range [5, 13]. The observations were conducted at frequencies up to 12.5 kHz and for $U_{DC} \geq 1$ V. The prepared measurement setup can be easily implemented on a PC computer, using a cheap data acquisition card, or in a handheld system with a microcontroller.

All measurements were carried out in the same way. The scent was evenly emitted within the first ten minutes. The measurements were continued during the next ten minutes when the emitted aroma diffused in the whole room and disappeared almost completely. The DC voltage across the sensor was measured every minute to calculate the DC resistance of the sensor. At the same time voltage fluctuations across the sensor $U(t)$ were sampled by

spectrum analyzer to estimate their power spectral density within frequency span 12.5 kHz. The random signal was acquired within an interval of 3.2 s only. We can assume that during such short time the recorded random signal was stationary. The random error of the estimated power spectrum was about 10% due to limited averaging (over 100 spectra) within the measurement time and resolution of the spectra in the frequency domain [14].

The estimated power spectra exhibited 1/f noise in the low-frequency range, at least up to 12.5 kHz (Fig. 5), as was reported previously for these sensor types [15]. Therefore, we proposed another parameter that characterizes the intensity of the observed fluctuations and has a lower random error than the estimated function of the power spectrum. Because we observed a 1/f noise component only, the values of $S(f)$ were multiplied by the corresponding frequency f and summed up by starting from the frequency $f_1 = 250$ Hz up to $f_2 = 12.5$ kHz with a frequency resolution $\Delta f = 31.25$ Hz :

$$I = \frac{\sum_{f_1=0.25kHz}^{f_2=12.5kHz} S(f) \cdot f}{U_{DC}^2}. \tag{1}$$

Additionally, the product was normalized to the squared DC voltage across the sensor which ensured independence from the sensor polarization conditions.

3.1 Measurements of Sensor TGS 2600

The first sensor used to detect the presence of the applied scents was a TGS 2600. This type is commonly used for air-quality monitoring in ventilation systems. The sensor exhibits high sensitivity to low concentrations of gaseous air contaminants such as hydrogen or carbon monoxide which exist within cigarette smoke [16].

Figure 6 shows measurement results of noise parameter I and DC resistance R_S in an ambient atmosphere of lemon, musk, pine and melissa scents. We can conclude that relative changes of the parameter I are even a few times greater than those of the DC resistance. Thus, a combination of both parameters I and R_S would be sufficient to control scent emission process even at low scent intensities.

The measurements showed clearly that the changes of I and R_S are observed at the relevant moments of the scent emission process that proves the correctness of the applied methods. Only the measurements in the presence of melissa scent showed some discrepancy from the results obtained for other scents. This could result from air movement in the laboratory and faster achievement of maximal scent intensity during the measurement time than in the presence of other scents. Nevertheless, even in this case the recorded changes of I and R_S occurred parallel in time, which also confirms the correctness of both applied methods.

The voltage fluctuations $U(t)$ across the sensor were acquired within the same intervals when their power spectra were estimated. The recorded voltage fluctuation sequences allowed to estimate other statistical parameters like skewness or kurtosis. Skewness is a measure of asymmetry of probability distribution of the analyzed random signal. Kurtosis is a measure of the “peakedness” of probability of the analyzed noise. The results obtained for both

parameters confirmed that only kurtosis showed significant changes during the process of scent emission and could be useful for detection improvement (Fig. 7). Kurtosis k was estimated by the function *kurtosis* that is available in a matlab software and is defined by formula [17]:

$$k = \frac{N\sum_{i=1}^{N}\left(U(t_i)-\overline{U}\right)^4}{\left(\sum_{i=1}^{N}\left(U(t_i)-\overline{U}\right)^2\right)^2} \tag{2}$$

where $N = 75000$ is the number of the analyzed samples of voltage fluctuations $U(t)$; $\overline{U}$ means the averaged value of $U(t)$; the consecutive noise samples were used to estimate k at the sampling frequency $f_s = 25$ kHz performed by data acquisition board. According to definition (2) the k value for normal distribution equals 3. We suppose that also other methods of non-Gaussian components detection could be used [18].

3.2 Measurements of Sensor TGS 2602

Another sensor type used for aroma detection was TGS 2602 which is commonly used to detect air contaminants. This sensor exhibits high sensitivity to low concentrations of odorous gases such as ammonia and hydrogen sulphide which are common products of putrefaction. Additionally, this sensor demonstrates high sensitivity to volatile organic compounds, like toluene that is present in paint thinners [16].

The measurements were carried out for the same scents as for the sensor TGS 2600 including additionally scent of cinnamon. This sensor was very sensitive to scents of musk, melissa and cinnamon (Fig. 8). Nevertheless, the sensor exhibited also changes of the measured parameters for the other applied fragrances. The measurement results show that this time the relative changes of DC resistance were slightly greater than the relevant changes of the noise parameter I. Thus, again a combination of DC resistance and parameter I can determine intensity of scents, even at their low concentrations.

3.3 Measurements of sensor TGS 823

The last investigated sensor was a TGS 823 which is optimized to detect vapors of organic solvents as well as other volatile chemicals. It is also sensitive to a variety of combustible gases what makes it a general purpose sensor [17]. The measurements show that this sensor can be also used to detect all the applied scents (Fig. 9).

We can conclude that the DC resistance as well as the noise parameter I have changed much stronger for the sensor TGS 823 than for the previously investigated sensor types. In case of essential oils of musk and cinnamon the I values have increased seriously in the first phase of measurements, during stable scent emission. Then, after some period of saturation, I started to return to a level observed at the beginning of observations (Fig. 9). Changes of DC resistance happened at the same moments of scent emission as in case of the parameter I. The DC resistance decreased at the beginning of observations and came back to the beginning

value after ending the scent emission. It is worth to underline that the greatest relative changes of both parameters I and R_S were observed for the same scents: cinnamon and musk.

4. Scent Detection Method

The main aim of the presented measurements was to identify whether the resistance gas sensors available on the market can detect the intensity of essential oils aroma and then can be applied in a suitable controlling circuit. We proved that both proposed methods can be used for this aim but at low scent intensity the methods appear to have too limited accuracy. The observed relative changes of DC resistance or I did not exceed a factor of a few separately and can be too low to control intensity of the emitted scents. Therefore we decided to propose another parameter that combines the results of both methods.

At higher scent intensities the DC resistance R_S decreases but the value of I increases. Thus, we propose an indicator G which is a quotient of the mentioned parameters normalized to its value observed at the beginning of measurements (time of 0 min.):

$$G = \frac{R_S / I}{(R_S / I)_0}. \tag{3}$$

Figure 10 presents the values of the proposed indicator G as a new measure of scent intensity obtained for the investigated types of resistance gas sensors. The estimated curves of G during the experiments in the presence of the selected scents are different for TGS 2600 and TGS 2602 sensors than for TGS 823.

When the emitted aroma saturated the air in the laboratory (usually within a period of 3–10 min. of the performed experiment) the estimated parameter G reached a different level, characteristic for the applied scents. Such a result was observed for the gas sensors TGS 2600 and TGS 2602 only. This means that the proposed parameter can be used to improve the detection of the scents as well as their intensity. The mentioned differences between G values were evident (e.g. musk – 0.25, melissa – 0.35 and cinnamon – 0.55 for TGS 2602 at Fig. 10b). The sensor TGS 823 did not demonstrate such clear variation of G values between all the applied essence oils for scent emission (Fig. 10c).

It has to be underlined that for aromatherapy reasons the most important in practice is to control scent intensity only. Usually, a single essential oil scent is emitted in a given period but possibility of various scents detection could be used in other applications that are not discussed here.

5. Conclusions

In this exploratory study the changes of DC resistance and intensity of resistance fluctuations in TGS sensors in the ambient atmosphere of essence oils scents were observed. The measurements confirmed that the applied commercial gas sensors TGS 2600, TGS 2602 and TGS 823 can be effectively used to control the intensity of scent emission. We propose to use both methods of aroma detection: measurements of DC resistance and resistance fluctuations as well. The biggest relative changes during the consecutive phases of scent

emission were observed for the proposed parameter *G*. Then, we can presume that even emission of slight aromas could be performed during aromatherapy sessions by estimating the propose parameter *G*.

Additionally, we suppose that the combined parameter *G* measured in the presence of intensive scents can be used to detect the type of the applied essential oil. It is worth to underline that values of *G* can be estimated by applying a cheap electronic circuit that does not require high computational complexity. Moreover, the proposed noise measurements can be done within a short time window of a few seconds only.

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References

1. E.J. Bowles, P. Cheras, J. Stevens, S. Myers, A survey of aromatherapy practices in aged care facilities in northern NSW, Australia. The Int. J. of Aromatherapy 15 (2005) 42–50.
2. J.A. Reed, J. Alemida, B. Wershing, B. Raudenbush, Effects of peppermint scent on appetite control and caloric intake. T.H. Moran / Appetite 51 (2008) 350–412.
3. A.K. Kutlu, E. Yılmaz, C. Çeçen, Effects of aroma inhalation on examination anxiety. Teaching and Learning in Nursing 3 (2008) 125–130.
4. N. Guéguen, Ch. Petr, Odors and consumer behavior in a restaurant. Hospitality Management 25 (2006) 335–339.
5. L.B. Kish, R. Vajtai, C.G. Granqvist, Extracting information from noise spectra of chemical sensors: single sensor electronic noses and tongues, Sens. & Act. B 71 (2000) 55–59.
6. B. Weisz, Effect of electronic charge transfer between adsorbate and solid on chemisorption and catalysis. J. Chem. Phys. 21 (1953) 1531–1539.
7. M.J. Madou, S.R. Morrison, Chemical Sensing with Solid State Devices. Academic Press (1989).
8. V. Aroutiounian, Z. Mkhitaryan, A. Adamian, C.G. Granqvist, L. Kish, Fluctuation-enhanced gas sensing. Procedia Chemistry 1 (2009) 216–219.
9. M.J. Beeson, Fluctuations and Noise: The Ultimate Key to Understand Physics. Springer, Berlin (1985).
10. K.L. Clark Flicker Noise Data Base. Eds. H. Gallaire and J. Winker, Plenum Press, New York (1973) 293–306**.**

11. M. Joliat, Total elimination of 1/f noise from conventional MOS transistors. IEEE Trans. Electr. Dev. 45 (1976) 753–764.
12. J. Smulko, The measurement setup for gas detection by resistance fluctuations of gas sensors. IMTC Instr. and Meas. Technology Conf., Sorrento, Italy, 24–27 April, (2006) 2028–2031.
13. J. Smulko, C.G. Granqvist, L. Kish, On the statistical analysis of noise in chemical sensors and its application for sensing. Fluctuation and Noise Letters. 1 (2001) 147–153.
14. J.S Bendat, A.G. Piersol, Random Data Analysis and Measurement Procedures. Wiley, New York 2000.
15. M. Kotarski, J. Smulko, Hazardous gases detection by fluctuation-enhanced gas sensing. Fluctuation and Noise Letters 9 (2010) 359–371.
16. Taguchi gas sensors data sheets (e.g. http://www.figarosensor.com/).
17. Definition of kurtosis (e.g. http://www.mathworks.com/help/toolbox/stats/kurtosis.html).
18. S. Melkonyan, Non-Gaussian conductivity fluctuations in semiconductors. Physica B: Condensed Matter. 405 (2010) 379–385.

Vitae

Mateusz Kotarski was born in Olsztyn, Poland. He received the M.Sc. degree in electronics from the Gdansk University of Technology in 2008. Currently, he is with the Faculty of Electronics Telecommunication and Informatics, Gdansk University of Technology, working on enhanced gas and scent sensing and preparing Ph.D. thesis. His main research activity is concentrated on applications of 1/f noise measurements in resistance gas sensors.

Janusz M. Smulko was born in Kolno, Poland. He received his M.Sc., Ph.D. and D.Sc. degrees in electronics from Gdansk University of Technology, Poland, in 1989, 1996 and 2007, respectively. His doctoral research was in 1/f noise measurements in high-frequency bipolar transistors. Presently, he is working in Faculty of Electronics Telecommunication and Informatics, Gdansk University of Technology on problems of low frequency noise measurements and analysis. His main research activity is concentrated on the application of 1/f noise measurements for gas sensing and Raman spectroscopy in portable applications. He is a member of the board of the Polish Society of Theoretical and Applied Electrotechnics in Gdansk, a member of the Microsystems and Sensors Section of the Metrology Committee of the Polish Academy of Science and a member of the IEEE.

Andrzej Czyzewski is Head of the Multimedia Systems Department of the Technical University of Gdańsk; He acts also as a Director of the Center for Advanced Technologies "Pomerania". He received his M.Sc. degree in Sound Engineering from the Gdansk University of Technology in 1982, his Ph.D. degree in 1987 and his D.Sc. degree in 1992 from the Cracov Academy of Mining and Metallurgy. In December 1999 Mr. President of Poland granted him the title of Professor. In 2002 the Senate of his University approved him to the position of Full Professor. He is a member of the IEEE and AES. As a researcher, he and his team of research engineers designed a number of digital devices; several of which are produced commercially in Poland. The subjects of the mentioned projects concern multimodal interfaces, digital communication systems, environmental noise monitoring solutions and advanced video monitoring systems.

Slavik V. Melkonyan was born in Yerevan, Armenia, in 1959. For his research in semiconductor physics he received his first Ph.D. (Candidate of Phys.-Math. Sciences) from the Institute of Radiophysics and Electronics (Armenia) in 1990, and the second Ph.D. (Doctor of Sciences – Physics) from Yerevan State University (Armenia) in 2007. Both of his doctoral investigations were in noise theory in semiconductors. Presently, he is working in the Faculty of Radiophysics, Department of Physics of Semiconductors and Microelectronics, Yerevan State University, on problems of mobility equilibrium fluctuation theory. His main research activity is concentrated on the fluctuation phenomena in semiconductor materials and devices.

Captions to figures

Figure 1. Nebulizer for oil essential scents emission powered by compressed air (left) and the prepared prototype device (right) that can emit four different aromas.

Figure 2. Taguchi gas sensor (TGS) produced by Figaro company: (a) the purchased sensor type TGS 826, (b) uncovered gas sensitive layer covering a tube with an inside heater and outside contacts.

Figure 3. Measurement setup used for measurements of gas sensor DC resistance and its fluctuations.

Figure 4. Power spectral densities of voltage fluctuations $S(f)$ across the gas sensors TGS 2602, TGS 2600 and TGS 823 versus squared polarization DC voltage U^2_{DC} of the sensor at frequency f =2.5 kHz in ambient atmosphere of synthetic air.

Figure 5. Power spectral densities of voltage fluctuations $S(f)$ across the gas sensors TGS 2600 normalized to its squared DC voltage U^2_{DC} at ambient atmosphere of pine essential oil and different instants of scent emission: without scent emission (0 min.) and after 5, 10 and 15 minutes of scent emission.

Figure 6. Noise parameter I (top) and sensor DC resistance (bottom) observed in a resistance gas sensor type TGS 2600 at ambient atmosphere of various scents during time of their emission.

Figure 7. Kurtosis of voltage fluctuations observed across the sensor TGS 2600 at ambient atmosphere of various scents during time of their emission.

Figure 8. Noise parameter I (top) and sensor DC resistance (bottom) observed in a resistance gas sensor type TGS 2602 at ambient atmosphere of various scents during time of their emission.

Figure 9. Noise parameter I (top) and sensor DC resistance (bottom) observed in a resistance gas sensor type TGS 823 at ambient atmosphere of various scents during time of their emission.

Figure 10. Changes of parameter G during scent emission of various essential oils for the resistance gas sensors: (a) TGS 2600, (b) TGS 2602 and (c) TGS 823.

Figures

Figure 1

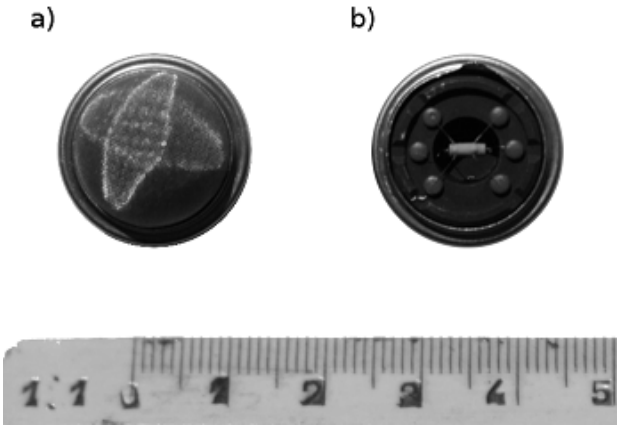


Figure 2

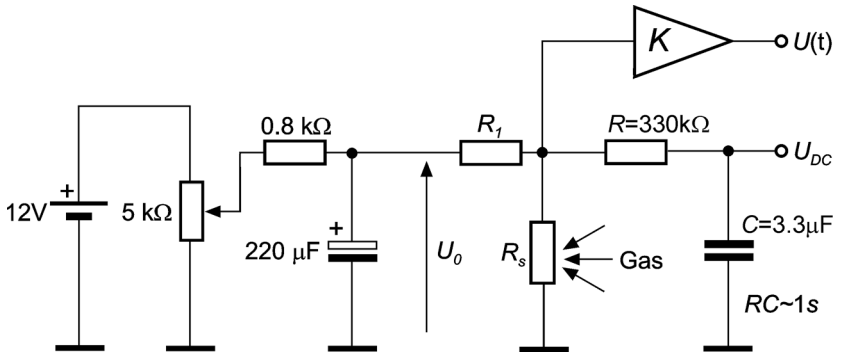


Figure 3

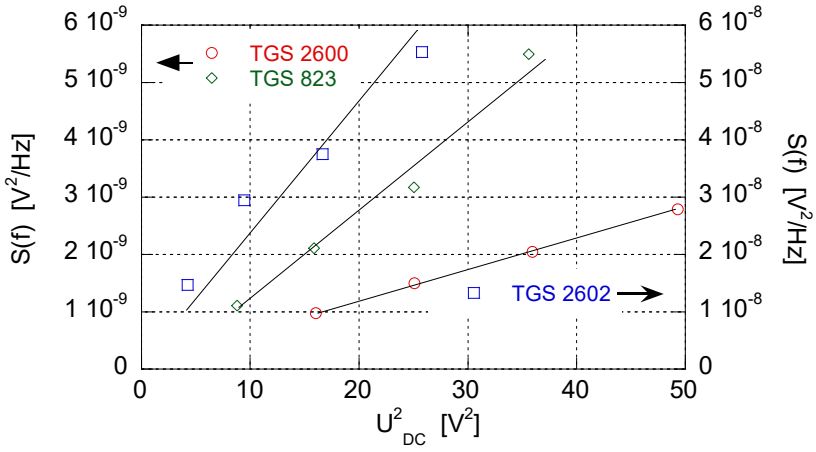


Figure 4

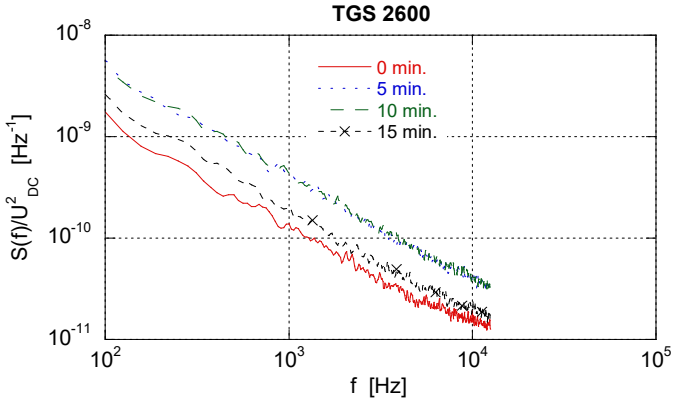
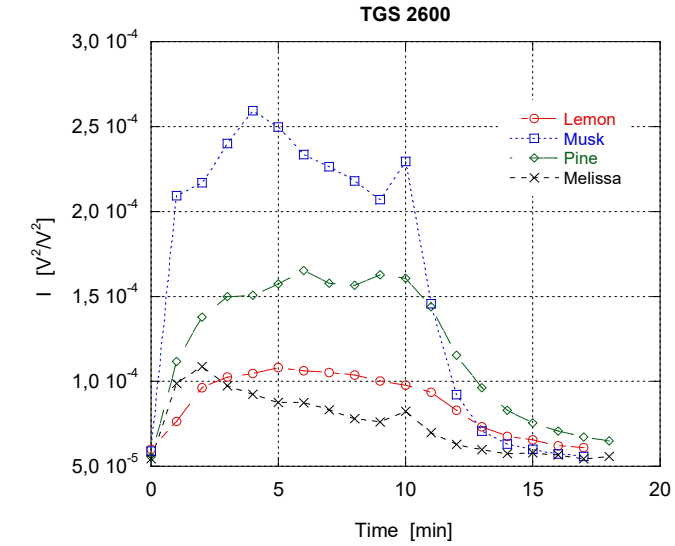


Figure 5



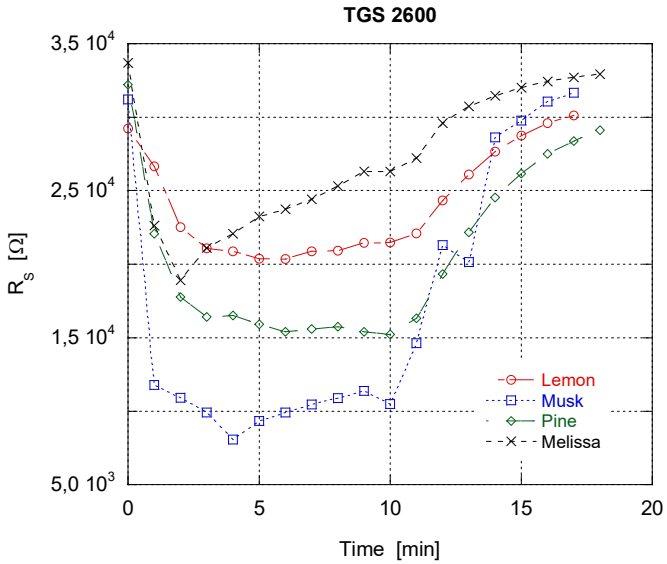


Figure 6

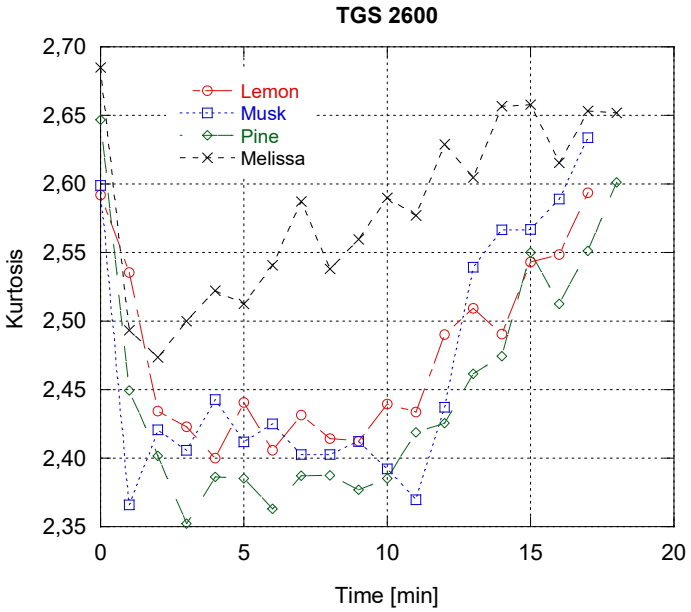


Figure 7

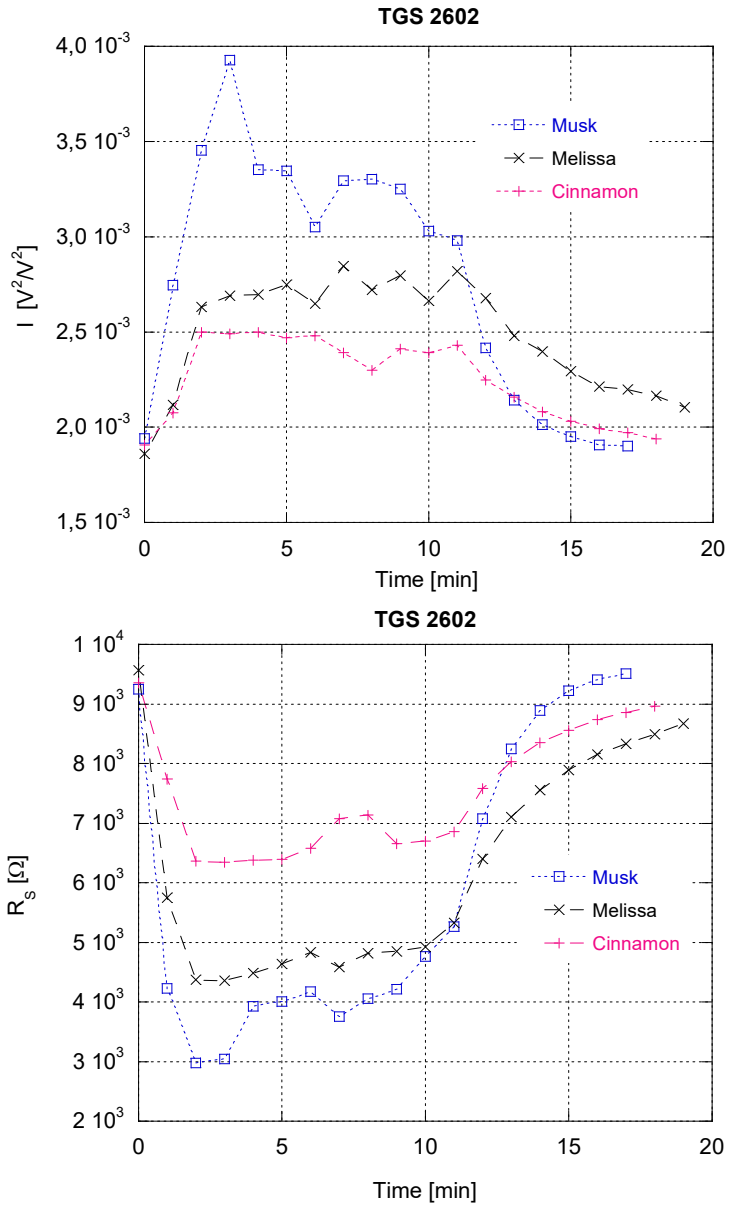


Figure 8

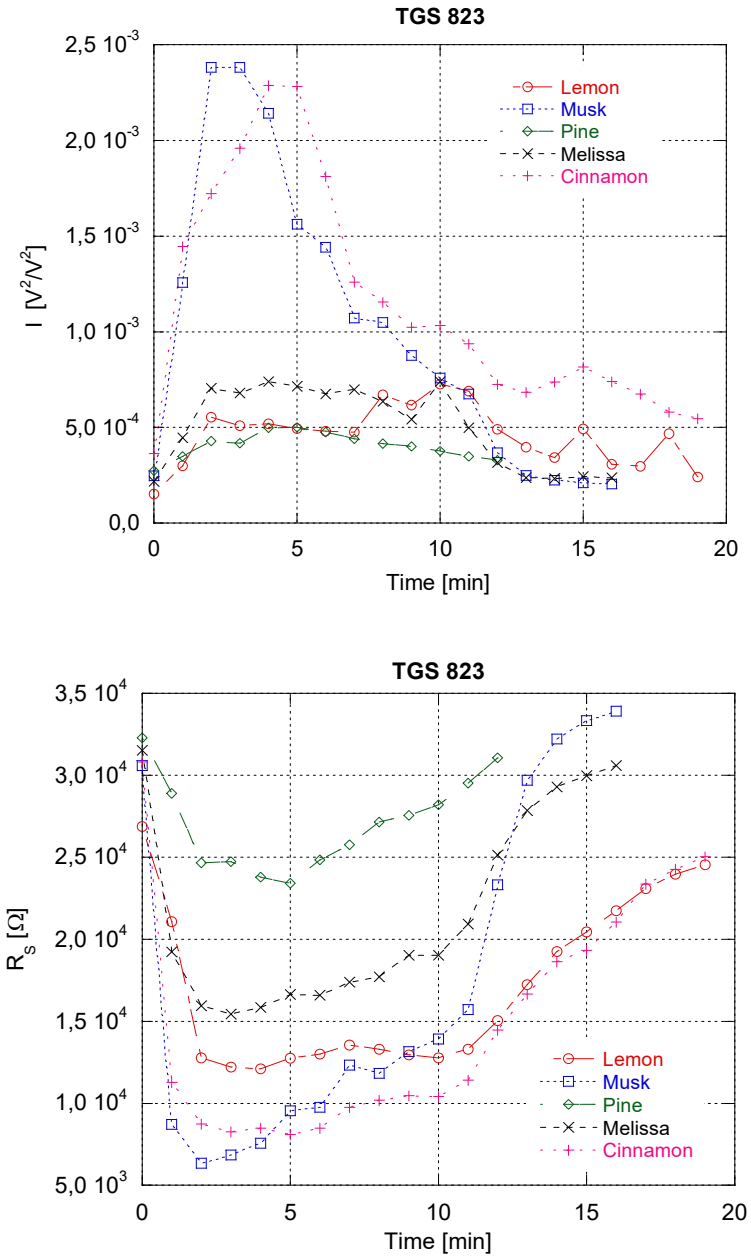


Figure 9

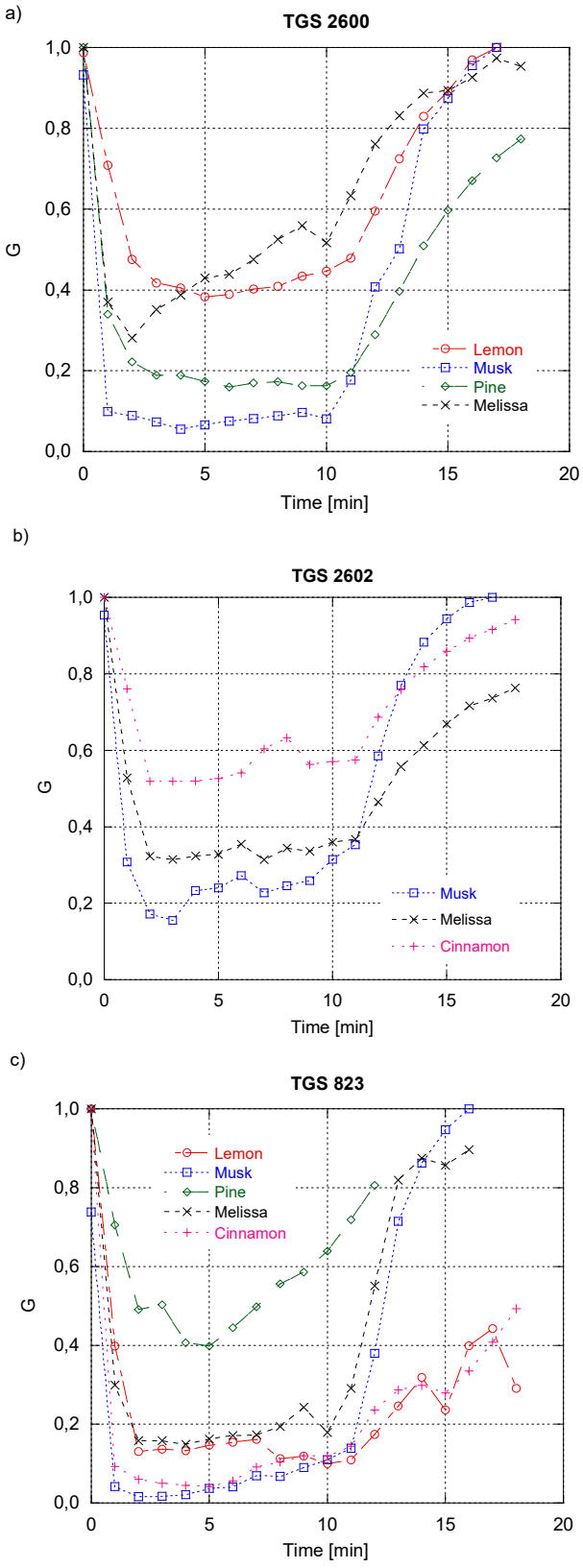


Figure 10