Dynamic Temperature Modulation Sensing Technique of Electronic Nose: A Review

Huaisheng Cao
College of Westa
Southwest University
Chongqing, China
e-mail: 937091690@qq.com

Pengfei Jia
College of Electronic and Information Engineering
Southwest University
Chongqing, China
e-mail:jiapengfei200609@126.com

Abstract— Electronic nose (E-nose) is a simulation of human nose, which consists of a gas sensor array and an artificial intelligent algorithm. The gas sensing properties of semiconductor sensors are affected by the heating temperature. For most gases, there exists the optimum oxidation temperature. If sensor response is recorded, we can obtain the data with abundant information at different working temperatures. The selectivity and sensitivity of a gas sensor array are the bottleneck of its development. Dynamic temperature modulation sensing technique is a use of semiconductor sensor temperature modulation characteristics by modulating its heating voltage to realize the heating temperature in a range of changes, people can record the corresponding response. The temperature modulation sensing technique can effectively improve the sensitivity of E-nose and realize the detection of low concentration gas, so it is of great practical significance to development technique of E-nose, which is based on temperature modulated sensing system for promoting the detection speed. But so far, the technique is only used for the detection of several common gases (such as methanol, ethanol, carbon monoxide, et al). The aim of this review is to supply a summary of the development and significant achievements of dynamic temperature modulation sensing technique used in E-nose in recent years. We are also looking forward to seeing dynamic temperature modulation sensing technique to accomplish more breakthroughs and get more achievements.

Keywords- *Review; Electronic nose; Dynamic temperature modulation sensing technique.*

*****

I. INTRODUCTION

An electronic nose (E-nose) is a device,which comprises a gas sensor array with partial specificity and an appropriate pattern-recognition system mimicking the mammalian sensory system to recognize simple and complex odors. The sensor is equivalent to 'the olfactory cells', which transforms the odors into electrical signals. Intelligent algorithm is equivalent to 'the brain', which is responsible for making judgments. E-nose is effective in dealing with odor analysis problems [1-4], which is expected to become a fast, efficient and convenient way. During the past decades, the E-nose technique has been applied to many fields such as wood detection [5-10], quality control of food industry [11-16], environment protection [17-19], public health [20-25], explosives detection [26]. The main hardware component of an E-nose is the sensor array system. For each kind of gas, sensor array will be output with the corresponding spectrum, which is the key to distinguish a variety of gases for E-nose. Semiconductor gas sensor is the most widely used electronic nose sensor, which has the advantages of good stability, long service life and low cost. This kind of sensor makes use of semiconductor gas sensing material to contact with gas, which causes the change of the semiconductor material property, so as to detect the specific gas component. For most gases, there exists the optimum oxidation temperature. Figure 1 depicts the sensitivity of metal oxide sensor simulation curve with the heating temperature. The gas sensing properties of semiconductor sensors are affected by the heating temperature. If sensor response are recorded, we can obtain the data with abundant information at different working temperatures.

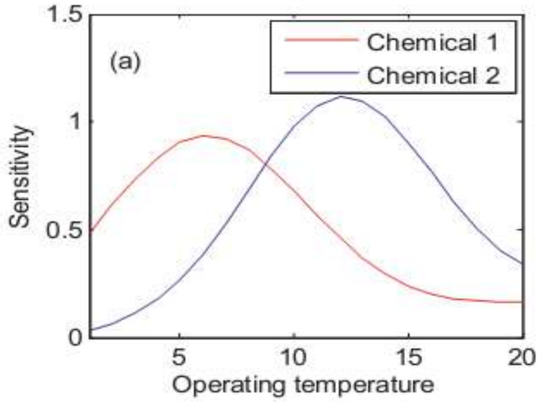


Figure 1. Relationship between sensitivity and working temperature of metal oxide sensors

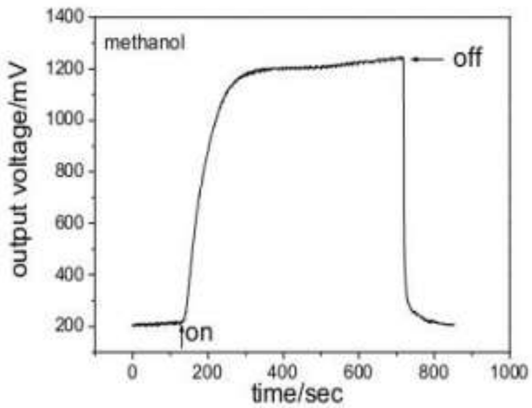
The selectivity and sensitivity of a gas sensor array are the bottleneck of its development. Dynamic temperature modulation sensing technique is a use of semiconductor sensor temperature modulation characteristics by modulating its heating voltage to realize the heating temperature in a range of changes, people can record the corresponding response and obtain more useful information which can help E-nose to make right judgments. The temperature modulation sensing technique can effectively improve the sensitivity of E-nose and realize the detection of low concentration gas, so it is of great practical significance to development technique of E-nose, which is based on temperature modulated sensing system for promoting the detection speed.

The review provides a summary of the development and achievements of dynamic temperature modulation sensing technique in recently years, which is conducive to analyze and study E-nose technique by describing significant achievements of dynamic temperature modulation sensing technique used in E-nose. What's more, we believe that the future of dynamic temperature modulation technique will get more results. We are also looking forward to seeing dynamic temperature modulation sensing technique to accomplish more breakthroughs and get more achievements.

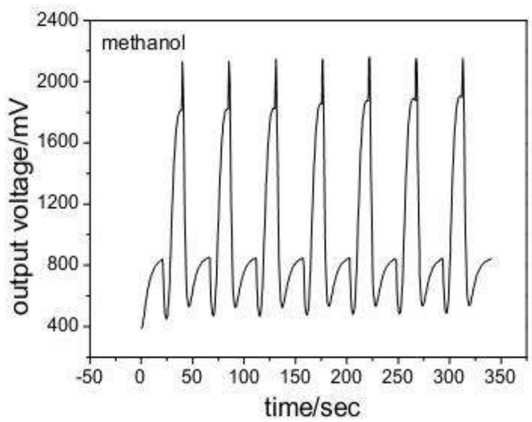
The rest of the paper is structured as follows: development and significant achievements of dynamic temperature modulation sensing technique in recently years in Section 2. Then, the conclusions and outlook of this paper are drawn in Section 3.

II. MATERIALS AND METHODS

In 2004, the Hefei Institute of intelligent mechanics, Chinese Academy of Sciences, studied the response characteristics of the sensor under different heating voltages waveforms and frequencies. The results were compared with the fixed heating voltage. They reported the advantages of the dynamic measurement, and discussed the influencing factors, such as modulated temperature, waveformand frequency of heater voltageon the dynamic responses. The heating waveforms that had been studied were rectangular, sinusoidal, triangular, saw-tooth, pulse, trapezoidal and etc. They found that the optimum modulation temperature was 250 – 300 ◦C at a heating frequency of 20mHz for acetone detection. Response curves of methanol to methanol in different working modes have been given in their paper. But the modulated temperature itself was the most essential factor, because any change in heating waveform and frequency wound affect the changes in surface temperature of the sensor element. The dynamic measurements indicated that it was a possibility to discriminate the organic species in air environment from the characteristic response curves, even if sometimesthe discrimination wasobscure. To improve the discrimination, further studies they made were carried out in which different modulation waveforms were employed. Figure 2 shows the response curve of the sensor under different operating modes which are fixed heating voltage mode and dynamic temperature modulation (rectangular voltage). Obviously, the responses were different from each other.The heating waveform which was an alternative parameter made the discrimination of target gases more precise [27]. And Institute of Intelligent Machines, Chinese Academy of Sciences used the combination of temperature modulation and the discrete wavelet transform (DWT) artificial neural network to improve the selectivity of the sensor to carbon monoxide in 2006. By applying artificial neural networks to the features extracted from the sensor signals, the selectivity of SnO_2 sensors for CO detection was sufficiently improved. 100% classification of two gases and a sufficiently good prediction of the CO concentration can be given by the artificial neural network. To be comforting, the results showed that even if the environment contained high concentrations of methane, the carbon monoxide concentration prediction was still satisfactory [28]. Xi'an Jiao Tong University of China, in 2005, presented a new strategy to extract features from the response of a thermally modulated semiconductor sensor for gas identification. This strategy consists of two steps. Firstly, under temperature modulation, made the sensor work and pre-processed the sensor's response signal. The presented pre-processing method was useful to suppress the influence of environmental temperature or humidity on sensor response. Secondly, wavelet decomposition was been applied to extract features of the pre-processed sensor's response curves. The temperature modulation technique was used by them to modulate the TGS821 for qualitative analysis. Experiments results showed that between gases studied (hydrogen, carbon monoxide and their binary mixture) the strategy proposed allowed accurate discrimination over a wide concentration range, from 10 to 1000 ppm, by using only one commercial metal oxide gas sensor.Meanwhile, it owned good ability of restraining the influence of gas concentration variation, sensor's cross sensitivity and sensor drift on the identification result[29].



(a) Fixed heating voltage mode

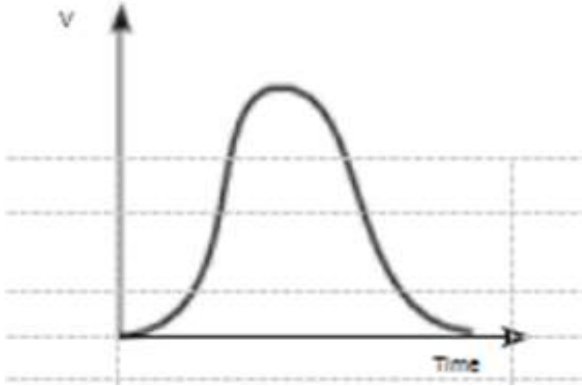


(b) Dynamic temperature modulation (rectangular voltage)

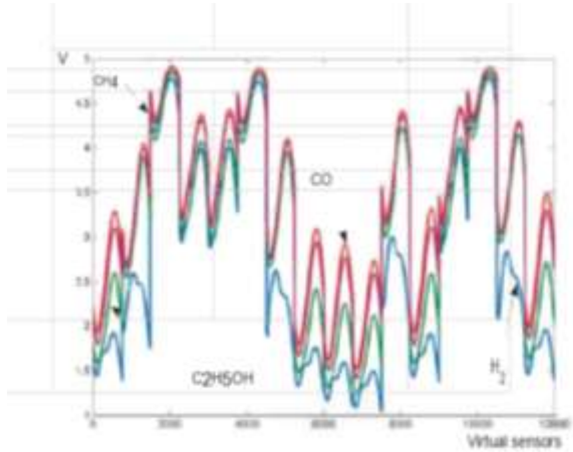
Figure.2. Response of selected sensors to methanol

Then in 2007, in order to measure the concentration of different vapors in air, T. Iwaki et al, from University of Warwick, proposed a novel temperature modulation technique for carbon black polymer composite sensors to enhance their selectivity. Applying a square wave voltage to a resistive microhotplate to modulate the sensor temperature and measure the transient sensor conductance in the presence of different vapors. They modulated the composite sensor heating voltage and detected water, ethanol and methanol vapor by using temperature modulation technique. They found that the shape of the fractional difference of transient conductance curve depended only on vapor type, so it can be used for vapor identification. Besides, it was possible to detect different vapors using a single carbon black polymer/composite sensor [30]. A novel thermodynamic response was obtained from the sensor response using a rectangular heating voltage to modulate the four polymer sensors by Yong Shin Kim et al. So as to the ability to distinguish methanol, acetone and benzene was significantly improved. The resultant outcome clearly demonstrated that the use of the additional thermodynamic feature improved the classification capability in VOC classes because of the correction of the deteriorations originated from the temperature-dependent response variations [31]. Kieu An Ngo etc, from France, compared the sensor array work fixed and dynamic heating voltage. A temperature modulation method was applied to a sensor array and compared with experiments with different constant temperatures. The former showed stronger gas discrimination ability than the latter. In the dynamic heating voltage on 25-100 ppm carbon monoxide concentration, the recognition effect of acetylene and hydrogen sulfide were obviously better than the fixed heating voltage. Their study showed that temperature modulation of gas sensors gathered in the matrix was a simple and powerful strategy to distinguish individual gases. By using a neural network classifier, this device was reliable and easy to adapt for on-line and real-time analysis [32].

In 2008, Smart Sensory Integrated Systems Lab of Hong Kong University of Science and technique studied the temperature modulation of the tin oxide gas sensor. The main purpose of their work was to perform a temperature modulation experimental setup for a tin oxide gas sensor so as to improve the selectivity of the sensor array and increase the number of sensors. The sensor response under each temperature modulation was considered as a virtual sensor. A large population of virtual sensors was obtained by modulating the operating temperature of a sensor. Temperature modulation was shown to increase the number of their sensors from 16 physical sensors (integrated on-chip) up to 12000 virtual sensors. And they got analyses of hydrogen, carbon monoxide, methane and ethanol. Figure 3 shows temperature modulation for tin oxide gas sensors. A sinusoidal voltage (a) was applied to the heater element. The response of a given sensor at a particular temperature can be treated as a separate virtual sensor (b), and used to simulate a large population of ORNs [33]. Then, they detected indoor gas (hydrogen, carbon monoxide, methane and ethanol) at different concentrations (1-4000ppm) [34].



(a) Sinusoidal voltage V



(b) Temperature modulated response of 16 tin-oxide sensors to 4 gases

Figure. 3. Temperature modulation for tin oxide gas sensors. A sinusoidal voltage (a) is applied to the heater element. The response of a given sensor at a particular temperature can be treated as a separate virtual sensor (b), and used to simulate a large population of ORNs.

Amir Amin team of Iran studied the relationship between the heating voltage of the sensor and the temperature of the tray. In an analyte-exposed gas sensor, sharp operating temperature fluctuations resulted in temporal responses containing quite a lot of extracting information of analytes. However, applying step heating voltages failed to provide step temperature variations in generic metal oxide gas sensors because of their high thermal capacity, In order to induce the sharp pallet temperature rises required and obtain selective responses in commonly used bulk tin oxide gas sensors, a new technique was proposed. Surpassing the nominal heating voltage of the device, a voltage spike was applied prior to a voltage step in this technique. Each in a wide concentration range, the temporal responses recorded for 12 different airborne analytes, appear different enough to identify contaminants with minimal computational cost. This technique was used to improve the selectivity of the gas sensor which can distinguish the different concentrations of methanol and 1-propanol gas better. Analyte examination and recognition took only 4s[35]. Amir Amin team used a staircase waveform to modulate the heating voltage of a single sensor, and the patterns were generated for air contaminated with different concentrations of various volatile organic compounds by applying a staircase heating voltage waveform to the microheater of a tin oxide-based sensor that modulated its operating temperature in the 50 – 400 ◦C range. Figure 4 shows the response curve of the sensor to different concentrations of methanol when the heating voltage is modulated by a staircase[36]. Then, they used a rectangular waveform to modulate the heating voltage. The experimental database was developed by recording the temporal responses obtained at different conditions and different concentration (100-2000ppm) to methanol, ethanol and 1-butanol vapors. Figure.5 shows Six rectangular voltage pulses (dotted line) used for the thermal modulation of the gas sensor along with the responses recorded for methanol at different concentrations in the 100 – 2000 ppm range in air. The inset shows the response recording circuit; (b) and (c) similar responses recorded for ethanol and 1-butanol, respectively [37]. I. Montoliu et al used self-modelling curve resolution techniques, in particular multivariate curve resolution-alternating least squares (MCR-ALS) in order to enhance the extraction of useful information from temperature modulation of gas sensors. The performance of MCR, which has been evaluated, showed good results both in the resolution of gas mixtures and in the determination of concentration/sensitivity profiles, in a synthetic dataset generated from temperature-modulated gas sensor response models. They used a sawtooth wave to modulate the heating voltage of the sensor to analyze carbon monoxide and methane gas mixtures in dry air. As was described, the use of temperature modulation techniques in MOX sensors can provide changes in its specificity which allowed a differentiation in the response of these devices towards different gas species [38].

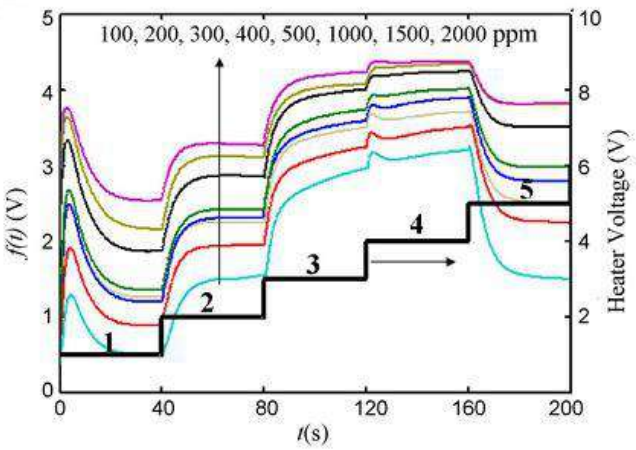
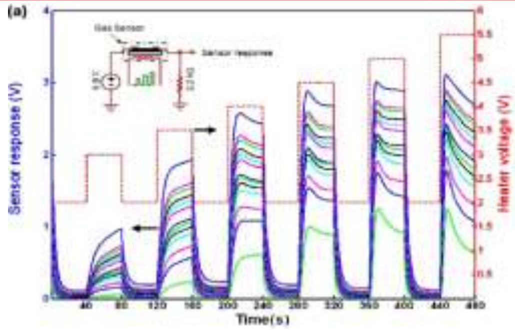
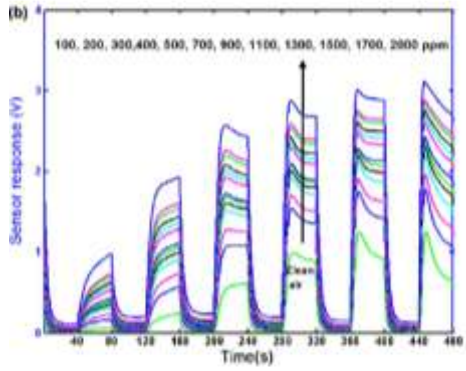


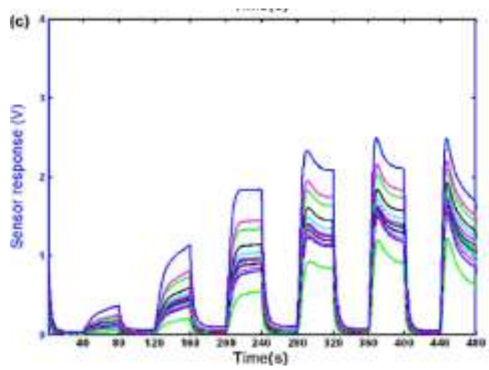
Figure. 4 Response of the sensor to methanol



(a) Response of the sensor to methanol



(b) Response of the sensor to ethanol



(c) Response of the sensor to1-butanol vapors

Figure. 5. Response of the sensor to methanol (a). The inset shows the response recording circuit; (b) and (c) similar responses recorded for ethanol and 1-butanol, respectively.

In 2011, Christian Bur et al of Sweden studied the influence of dynamic temperature modulation on the selectivity of the gas sensor. The effect of dynamic temperature modulation on the selectivity of gas analysis sensors FETs, which was based on a diode coupled silicon carbide field effect transistor (FET) as catalytic gate material with platinum, has been investigated in their study. This operating mode, in-depth study of the semiconductor gas sensor, has only recently been applied to field effect transistor. Suitable temperature cycles combined with appropriate signal processing for typical exhaust gas detection was developed. When the oxygen content in the background was not the same, the tested gas (carbon monoxide, nitric oxide, hydrogen, ammonia and propylene) can be detected [39]. In 2012, a self-adaptive temperature modulation was proposed and a closed-loop circuit connecting the sensor resistance to the sensor heater was designed by Eugenio Martinelli et al of Rome Italy University. In this case, the resistance change of the sensor reflected the variation of the operating temperature. An oscillating circuit was implemented by this method. So, the signal that had a steady resistance value drove the temperature modulation converges to a periodic pattern of pulses of specific for the sensor state. Under this technique, they modulated the heating voltage of TGS2600 and analyzed nitrobenzene, carbon monoxide, nitric oxide and mixed gas of nitric oxide and nitrobenzene. The results showed that the gas with different concentration and different types can be separated [40]. Then in 2013, Rakesh Gosangi et al of U.S.A proposed a combination of probabilistic model optimization algorithm to select the heating value of TGS2620 temperature sensor. To be specific, using metal-oxide (MOX) chemical sensor, an active sensing method which allowed a MOX sensor to adapt its operating temperature in real time so as to sequentially reduce uncertainty in the concentration estimates for quantitative analysis of gas mixtures was presented, the problem was formulated as one of probabilistic state estimation coupled with a myopic optimization algorithm. On the basis of this, they analyzed the two gases of p-xylene and ethanol [41].

III. CONCLUSION AND OUTLOOK

E-nose is effective in dealing with odor analysis problems, which is expected to become a fast, efficient and convenient way. E-nose is a device, which comprises a gas sensor array with partial specificity and an appropriate pattern-recognition system. The gas sensing properties of semiconductor sensors are affected by the heating temperature. For most gases, there exists the optimum oxidation temperature. Dynamic temperature modulation sensing technique is a use of semiconductor sensor temperature modulation characteristics, by modulating its heating voltage to realize the heating temperature in a range of changes, people can record the corresponding response and obtain more useful information which can help E-nose to make right judgments. This paper provides a summary of the development and significant achievements of dynamic temperature modulation sensing technique used in E-nose in recently years. So we can't cover all achievements in this paper also because of the space constraints. The above research results have shown the potential of dynamic temperature modulation in odor analysis, in the past several decades. The working temperature of the semiconductor sensor can be controlled by adjusting the heating voltage, and different waveforms, amplitudes and frequencies of the heating voltage corresponding to different gas response curves. Temperature modulation sensor technique can obtain a response from the different temperature and more useful information. But so far, temperature modulation is mainly used to reduce the dimension of the sensor array, and many researches focus more on how to use single sensor instead of sensor array. The technique is only used for the detection of several common gases (such as methanol, ethanol and carbon monoxide etc, the detection of gas concentrations are generally higher, ppm magnitude or even up to thousands of ppm). However, we believe that the future of dynamic temperature modulation technique will get more results. Come very naturally, we are also looking forward to seeing dynamic temperature modulation sensing technique to accomplish more breakthroughs and achieve more achievements.

ACKNOWLEDGMENT

The work is supported by Program for New Century Excellent Talents in University (No. [2013] 47), National Natural Science Foundation of China (Nos. 61372139, 61101233, 60972155), China Postdoctoral Science Foundation (No. 2016M602630) and Fundamental Research Funds for the Central Universities (No. XDJK2015C073).

REFERENCES

[1] P. Ciosek, W. Wróblewski, The analysis of sensor array data with various pattern recognition techniques, Sensors and Actuators B: Chemical, 114 (2006): 85-93.
[2] Q. Liu, H. Wang, H. Li, J. Zhang, S. Zhang, F. Zhang, K. J. Hsia, P. Wang, Impedance sensing and molecular modeling of an olfactory biosensor based on chemosensory proteins of honeybee, Biosensors and Bioelectronics, 40 (2013): 174-179.
[3] J.H.Sohn,N.Hudson, E.Gallagher,M.Dunlop, L.Zeller,M.Atzeni, Implementation of an electronic nose for continuous odour monitoring in a poultry shed, Sensors and Actuators B: Chemical, 133(2008): 60-69.
[4] Q. Chen, A.Liu, J. Zhao, Q.Ouyang, Classification of tea category using a portable electronic nose based on an odor imaging sensor array, Journal of Pharmaceutical & Biomedical Analysis, 84C(2013): 77-83.
[5] http://europa.eu/rapid/press-release_IP-10-1050_en.htm#PR_metaPressRelease_bottom.
[6] ALPS Bailey, A.M. Pisanelli, K. Persaud, Development of conducting polymer sensor arrays for wound monitoring , Sensors and Actuators B, 131 (2008): 5-9.
[7] M.E. Şahin, H.M. Saraoğlu, Investigation of Escherichia coli bacteria growth process using electronic nose, Biomedical Engineering Meeting, 2010, 1-4.
[8] M. Trincavelli, S. Coradeschi, A. Loutfi, P. Thunberg, Direct identification of bacteria in blood culture samples using an electronic nose, IEEE transactions on biomedical engineering, 57 (2010): 2884-2890.
[9] G.C. Green, A.D.C. Chan, H. Dan, M. Lin, Using a metal oxide sensor (MOS)-based electronic nose for Discrimination of bacteria based on individual colonies in suspension, Sensors and Actuators B, 152 (2011): 21-28.
[10] C.H. Shih, Y.J. Lin,K.F. Lee, Philip Drake, Real-time electronic nose based pathogen detection for respiratory intensive care patients, Sensors and Actuators B, 148 (2010): 153-157.
[11] T. Konduru, G.C.Rains, C. Li, Detecting sour skin infected onions using a customized gas sensor array, Journal of Food Engineering, 160(2015): 19-27
[12] Y.Dai, R.Zhi,L.Zhao, H.Gao, B.Shi, H.Wang,Longjing tea quality classification by fusion of features collected from E-

nose, Chemometrics &Intelligent Laboratory Systems, 144(2015): 63-70.

[13] M.Längkvist, S.Coradeschi, A.Loutfi,Fast Classification of meat spoilage markers using nanostructured ZnO thin films and unsupervised feature learning, Sensors, 13(2013): 1578-1592.

[14] V.Y.Musatov, V.V.Sysoev, M.Sommer, I. Kiselev, Assessment of meat freshness with metal oxide sensor microarray electronic nose: A practical approach, Sensors & Actuators B Chemical, 144(2010): 99-103.

[15] P. Hartyani, I.Dalmadi, D. Knorr, Electronic nose investigation of Alicyclobacillus acidoterrestris inoculated apple and orange juice treated by high hydrostatic pressure, Food Control, 32(2013)262-269.

[16] L.Pan, W.Zhang, N.Zhu, S. Mao, K.Tu, Early detection and classification of pathogenic fungal disease in post-harvest strawberry fruit by electronic nose and gas chromatography—Mass spectrometry, Food Research International, 62(2014): 162-168.

[17] A.C.Romain, J. Nicolas, Long term stability of metal oxide-based gas sensors for E-nose environmental applications: An overview, Olfaction & Electronic Nose,(2009): 502-506.

[18] F.D.Cesare, S. Pantalei, E.Zampetti, A. Macagnano, Electronic nose and SPME techniques to monitor phenanthrene biodegradation insoil, Sensors & Actuators B Chemical, 131(2008): 63-70.

[19] C.Becherb, P. Kaulb, J.Mitrovicsa, J. Warmerb, The detection of evaporating hazardous materialreleased from moving sources using a gas sensor network, Sensors & Actuators B Chemical, 146(2010): 513-520.

[20] D.Li, T.Lei, S.Zhang, X.Shao, C. Xie, A novel headspace integrated E-nose and its application in discrimination of Chinese medical herbs,Sensors & Actuators B Chemical, 221(2015): 556-563.

[21] A.D.Wilson, Review of Electronic-nose Technologies and algorithms to detect hazardous chemicals in the environment, Procedia Technology, 1(2012): 453–463.

[22] Q. He, J. Yan, Y. Shen, Y. Bi, G. Ye, F. Tian, Z. Wang, Classification of electronic nose data in wound infection detection based on PSO-SVM combined with wavelet transform, Intelligent Automation & Soft Computing, 18(2012): 967-979.

[23] Y.Adiguzel, H. Kulah, Breath sensors for lung cancer diagnosis, Biosensors & Bioelectronics, 65(2014): 121-138.

[24] M. Bruins, Z. Rahim, A. Bos, W. Sande, H. Endtz, A. Belkum, Diagnosis of active tuberculosis by E-nose analysis of exhaled air, Tuberculosis, 93(2013)232-238.

[25] O.Burfeind, M.Bruins, A.Bos, I.Sannmann, R.Voigtsberger, W. Heuwieser, Diagnosis of acute puerperal metritis by electronic nose device analysis of vaginal discharge in dairy cows, Theriogenology, 82(2014)64-70.

[26] A.Norman, F.Stam, A.Morrissey, M.Hirschfelder, D. Enderlein, Packaging effects of a novel explosion-proof gas sensor, Sensors & Actuators B Chemical, 95(2003)287-290.

[27] X. Huang,F. Meng, Z. Pi, W. Xu, J. Liu, Gas sensing behavior of a single tin dioxide sensor under dynamic temperature modulation, Sensors and Actuators B, 99 (2004): 444-450.

[28] J.R. Huang,G.Y. Li, Z.Y. Huang, X.J. Huang, J.H. Liu, Temperature modulation and artificial neural network evaluation for improving the CO selectivity of SnO2 gas sensor, Sensors and Actuators B, 114 (2006): 1059-1063.

[29] H. Ding,H.F. Ge, J.H. Liu,High performance of gas identification by wavelet transform-based fast feature extraction from temperature modulated semiconductor gas sensors, Sensors and Actuators B, 107 (2005): 749-755.

[30] T. Iwaki, J.A. Covington, J.W. Gardner, Identification of vapours using a single carbon black/polymer composite sensor and a novel temperature modulation technique, IEEE SENSORS 2007 Conference.

[31] Y.S. Kim, Y.S. Yang, Additional thermodynamic feature extraction from chemoresistive carbon black-polymer composite sensors by temperature modulation, Sensors and Actuators B, 121 (2007): 507-514.

[32] K.A. Ngo,P. Lauque, K. Aguir, High performance of a gas identification system using sensor array and temperature modulation, Sensors and Actuators B, 124 (2007): 209-216.

[33] A. Far, B. Guo,F. Flitti, A. Bermaket, Temperature Modulation for Tin-Oxide Gas Sensors. 4th IEEE International Symposium on Electronic Design, Test & Application, 2008, 378-391.

[34] A. Far, F. Flitti, B. Guo, A. Bermaket al, Gas Identification System based on Temperature Modulation tin-oxide sensors and bio-inspired processing, IEEE, 2008, 1010-1013.

[35] F. Hossein-Babaei, Amir Amini, A breakthrough in gas diagnosis with a temperature-modulated generic metal oxide gas sensor, Sensors and Actuators B, 166-167 (2012): 419-425.

[36] F. Hossein-Babaei,S.M. Hosseini-Golgoo, Amir Amini, Extracting discriminative information from the Padé-Z-transformedresponsesof a temperature-modulated chemoresistive sensor for gas recognition, Sensors and Actuators B, 142 (2009): 19-27A.

[37] Amini,M.A. Bagheri, G.A. Montazer, Improving gas identification accuracy of a temperature-modulated gas sensor using an ensemble of classifiers, Sensors and Actuators B:, 187 (2013): 241-246.

[38] I. Montoliu, R.Tauler , M. Padilla, A. Pardo, S. Marco, Multivariate curve resolution applied to temperature-modulated metal oxide gas sensors, Sensors and Actuators B, 145 (2010): 464-473.

[39] C. Bur,P. Reimann, M. Andersson,A. Schütze, A.L. Spetz, Increasing the Selectivity of Pt-Gate SiC Field Effect Gas Sensors by Dynamic Temperature Modulation, IEEE SENSORS JOURNAL, 12 (2011): 1906-1913.

[40] E. Martinelli, D. Polese, A. Catini, A. D'Amico, C.D. Natale, Self-adapted temperature modulation in metal-oxide semiconductor gas sensors, Sensors and Actuators B, 161 (2012): 534-541.

[41] R. Gosangi, R. Gutierrez-Osuna, Active temperature modulation of metal-oxide sensors for quantitative analysis of gas mixtures, Sensors and Actuators B, 185 (2013): 201-210.