Gas sensor network for air-pollution monitoring

Wataru Tsujita [a,*], Akihito Yoshino [a], Hiroshi Ishida [b], Toyosaka Moriizumi [a]

[a] *Department of Physical Electronics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan*
[b] *Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho,
Koganei, Tokyo 184-8588, Japan*

Abstract

This paper describes the development of a gas sensor system to be used as a sensing node to form a dense real-time environmental monitoring network. Moreover, a new auto-calibration method is proposed to achieve the maintenance-free operation of the sensor network. The network connectivity can be used not only for data collection but also for the calibration and diagnosis of the sensors since the measured pollutant concentrations can be easily compared through the network with nearby sensors and governmental monitoring stations. Different pollutant concentrations are usually monitored at different sites. However, a case study on local NO_2 distribution has shown that there exists a special condition under which pollutant concentrations become low and uniform in a certain local area. The baseline of the gas sensor response can be adjusted in this special occasion using the pollutant concentration values reported from the neighboring environmental monitoring stations. The experimental result has shown that NO_2 concentration can be measured with sufficient accuracy by incorporating appropriate temperature and humidity compensation into calibration curves. Moreover, a case study on auto-calibration demonstrates its effectiveness in keeping the measurement accuracy of the sensor system in long-term operation.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Environmental monitoring; Nitrogen dioxide (NO_2); Metal oxide gas sensor; Sensing network; Auto-calibration

1. Introduction

Air pollution emerged in Japan in the late 1960s as a result of explosive industrial growth. Since then, efforts were made to control and reduce the emission of pollutants from vehicles and industrial facilities. The technological advances in the emission control had a successful impact on the levels of sulfur dioxide and carbon monoxide that were increasing in the 1960s. Nowadays, their levels in the atmosphere are kept below the environmental quality standards in Tokyo [1]. However, dramatic improvements in the overall air quality have not yet been achieved. For example, the levels of nitrogen dioxide (NO_2) and ozone (O_3) in Tokyo often exceed the environmental quality standards. Similar problems are also found in other major cities in the world although the scales and the severeness of the pollution are different from one another [2–4].

Formation and transport of pollutants are governed not only by the distributions of their sources but also by the dynamics of the atmosphere. Pollutant clouds are sometimes observed traveling along the wind directions [2]. To understand the involved processes in more detail, we need more thorough data on the spreads of pollutants and their variations with time. Although reliable networks of environmental monitoring stations have already been established in Japan, they lack temporal and spatial resolution. Since the operation of those stations relies on expensive and cumbersome analytical instruments, the number of stations each local government can have is severely limited by the cost to build the stations and to manage them. The spacing between the stations often exceeds 10 km although local but heavy pollution may occur in smaller scales depending on geographical and climatological conditions. For example, severe air pollution often occurs along roads weaving through high rise buildings.

* Corresponding author. Tel.: +81 3 57343049; fax: +81 3 57342828.
E-mail address: wtsujita@mn.ee.titech.ac.jp (W. Tsujita).

Since the buildings act as shields against the wind, vehicle exhaust is accumulated in the street canyon with the width of typically several tens of meters. The data obtained from the environmental monitoring stations are undoubtedly a collection of reliable measurements at representative locations, but may not reflect the details of the real spatial distributions of pollutants.

The authors have been proposing a gas distribution analyzing system (GASDAS) to achieve air quality monitoring with improved spatial resolution [5]. Various types of gas sensors have been developed for the detection of air pollutants although they have not been used frequently for monitoring low level gases in the atmosphere [6–8]. We believe that the use of those sensors combined with appropriate signal processing techniques enables us to develop compact and inexpensive sensing systems. A dense network of gas sensor system will help in obtaining detailed data on local air pollution.

To develop a sensor-based environmental monitoring system, there are some problems to be solved. The lack of the long-term stability, for example, is an inevitable problem of the gas sensors, which causes the deterioration of the measurement accuracy over time. Frequent recalibration of a number of individual sensors in the network is a time-consuming and laborious task. Therefore, a new auto-calibration method is proposed in this paper to achieve maintenance-free operation of the sensing network. The network connectivity can be used not only for collecting the sensor data but also for the calibration and diagnosis of the sensors since the measured pollutant concentrations can be easily compared through the network with those measured with nearby sensors and at governmental monitoring stations. Different concentrations are usually monitored at different sites. If the pollutant concentration in the whole local area becomes uniform in a certain weather condition, however, the sensor output can be calibrated on such occasions. The proposed auto-calibration method utilizes such special occasions.

In this paper, we describe two achievements toward the development of a sensing node to be used in GASDAS for NO_2 monitoring. Firstly, a commercially available gas sensor was tested to evaluate their capabilities and to identify the potential interferences the sensor would encounter in the field use. Secondly, a case study was performed on the auto-calibration of the NO_2 sensor system placed at our university. Statistical analysis of NO_2 concentrations reported from the surrounding environmental monitoring stations are presented together with experimental results using a real gas sensor system to show the validity of the proposed calibration method of the sensor system.

2. Method

2.1. Sensor system for NO_2 measurement

A commercially available metal oxide gas sensor (TGS2106, Figaro Engineering) was used for measuring
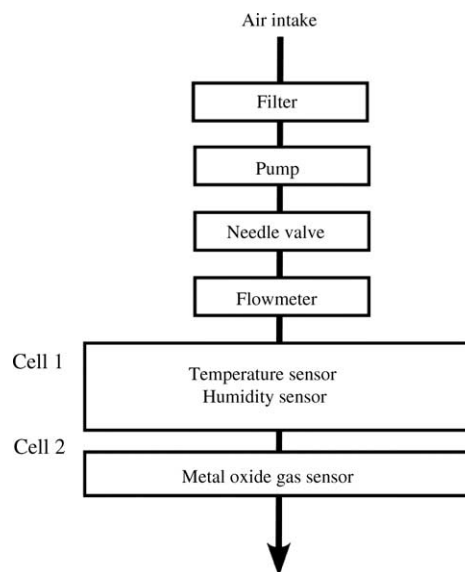

Fig. 1. Schematic diagram of the NO_2 measurement system.

NO_2. Fig. 1 shows the schematic diagram of the measurement system. Ambient air is taken through a membrane filter (SSWP01300, Millipore) with the diameter of 13 mm and the pore size of 3 μm. The flow rate is regulated to be 500 ml/min using a needle vale, and is monitored with a digital flow meter (SEF-21A, STEC). The gas sensor is installed in cell 2. A temperature sensor (LM35DZ, National Semiconductor) and a humidity sensor (CHS-GSS, TDK) are placed in cell 1. The two sensor cells are connected in series so that all sensors are exposed to the same air sample with the equal flow rate.

2.2. Location of the case study

The case study was performed in the area shown in Fig. 2. The sensor system and a chemiluminescence-based NO_x analyzer (Model 42C, Thermo Environmental Instruments) were
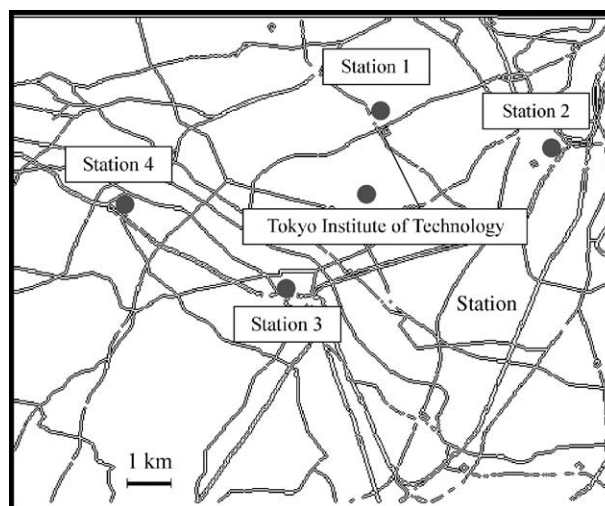

Fig. 2. Road map around the university.

placed in the laboratory room of our university. The NO_x analyzer is the same type of instrument as those used in the environmental monitoring stations, and was used in the experiments as a reference for the sensor system.

As shown in Fig. 2, there are four governmental environmental monitoring stations around the university. The concentration of sulfur dioxide, nitrogen dioxide, photochemical oxidant, suspended particulate matter (SPM) and carbon monoxide are measured by using atmospheric monitoring instruments at the stations. Meteorological variables (temperature, humidity, wind direction and wind speed) are also measured at the stations. Hourly mean values of those measured data are available at the web site on the Internet [9]. NO_2 mainly comes from vehicle exhaust, and therefore, the major roads around the monitoring site are also shown in Fig. 2.

2.3. Auto-calibration method for a sensor system in monitoring network

The evaluation of the sensor system was first performed in terms of the long-term stability of the gas sensor. Among the various factors that influence the gas sensor response (e.g., interference gases and aging problems), the baseline drift was found to be the major cause of the errors in the measured gas concentrations. The sensor system has to be occasionally recalibrated to keep the measurement accuracy at high levels.

Assume that a sensor network is placed in a certain local area and consider the calibration procedure for each sensor system. The outputs of sensors in the area can be calibrated by comparing measured NO_2 concentrations and the true concentration values at individual sensor locations. However, reliable data are available only at a small number of governmental monitoring stations. Accurate estimate of NO_2 concentration at the place where each system is located has to be obtained using the values measured at the surrounding stations.

If the level of pollutant gas concentration in the whole local area under study is almost uniform, similar values are reported from the surrounding stations, and the sensor output in that area can be adjusted to their average. Fig. 3(a and b) shows conceptual diagrams of NO_2 distribution in the local area. In normal circumstances, the NO_2 level in this urban area is high and, as shown in Fig. 3(a), the NO_2 distribution is not uniform. Therefore, it is difficult to estimate the concentration at the university from those reported at the four monitoring stations. If unusually low concentration is reported at the monitoring stations, it would be reasonable to consider this low concentration as a sign showing unusually small emission of NO_2 (due to small traffic in national holidays for example) and/or extremely large dilution of NO_2 achieved by a special weather condition (in a stormy day, for example). In either case, the pollutant level becomes low not only at the location of the environmental monitoring stations but also in the whole surrounding area. Therefore, it would be reasonable to hypothesize the existence of uniformly low
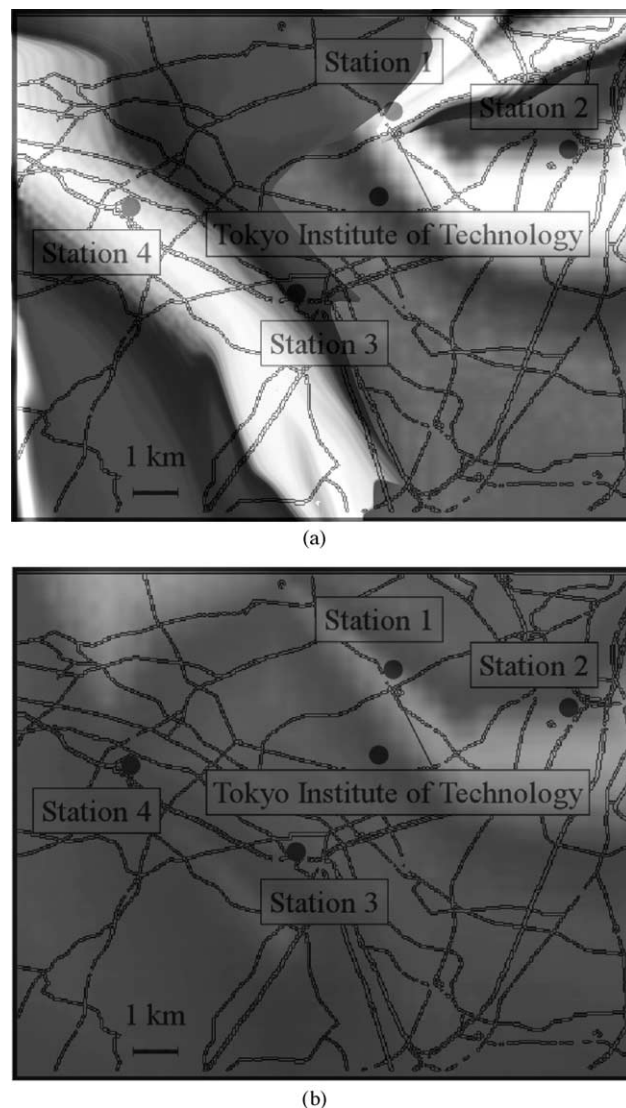

(a)

(b)

Fig. 3. Conceptual diagrams showing distributions of (a) high level NO_2 and (b) low level NO_2. Bright region indicates the area of high NO_2 concentration.

NO_2 distribution as shown in Fig. 3(b). The gas sensor output around the baseline can be calibrated in this special case by assuming the uniformity of the concentration. The calibration procedure tested in the case study is to adjust the sensor output to the average NO_2 concentration values at the four environmental monitoring stations when the values at all stations become less than 10 ppb. A sensor system equipped with the network connectivity can perform the calibration autonomously in the field, and there is no need to prepare standard gases for each system as in the conventional calibration.

3. Initial calibration of gas sensor

The calibration curves of the NO_2 sensor were first obtained under various temperature and humidity conditions.

The environmental quality standard for NO_2 in Japan is currently set that the daily average for hourly mean values shall be within the 0.04–0.06 zone or below that zone [1]. Different concentrations of NO_2 ranging from 0.03 to 0.09 ppm were prepared by diluting 5 ppm NO_2 with clean air. Different temperature conditions were created by placing the sensor cells in the water bath. Different humidity conditions were created by adding moistened air.

In this paper, the gas sensor response (r) is defined as the ratio of the sensor resistance and its baseline, which is given by:

$$r = \frac{R_{gas}}{R_{air}}, \qquad (1)$$

where R_{gas} (kΩ) is the resistance of the sensor in the presence of NO_2. The baseline resistance (R_{air} (kΩ)) is the resistance of the sensor in clean air. Although R_{gas} and R_{air} change with the variations of temperature and humidity, r is generally known to be more robust against those variations.

Fig. 4 shows the temperature dependence of the sensor resistance in dry clean air. The gas sensor has a heater and operates at a high temperature. The change in ambient temperature varies the operating temperature of the sensor and, thus, causes the variation of the resistance. The behavior of the sensor against temperature variation is complicated and a theoretical equation that can predict the sensor resistance at various operating temperature is not yet available [10]. Therefore, an empirical model has to be used to describe the resistance variation in the given temperature range. In Fig. 4, an exponential curve was fitted to the sensor resistance for the temperature range from 10 to 40 °C. The relationship between the ambient temperature and the resistance of the gas sensor is, thus, approximated in our sensor system by:

$$R_T = R_a \exp(bT), \qquad (2)$$

where R_T (kΩ) is the resistance in dry clean air, T (°C) the ambient temperature and R_a and b are constants.
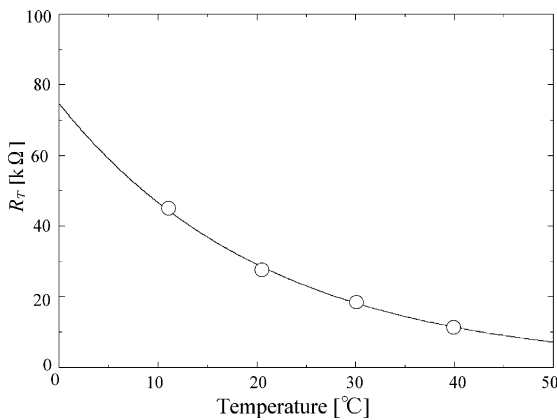

Fig. 4. Relationship between temperature and gas-sensor resistance in dry clean air.
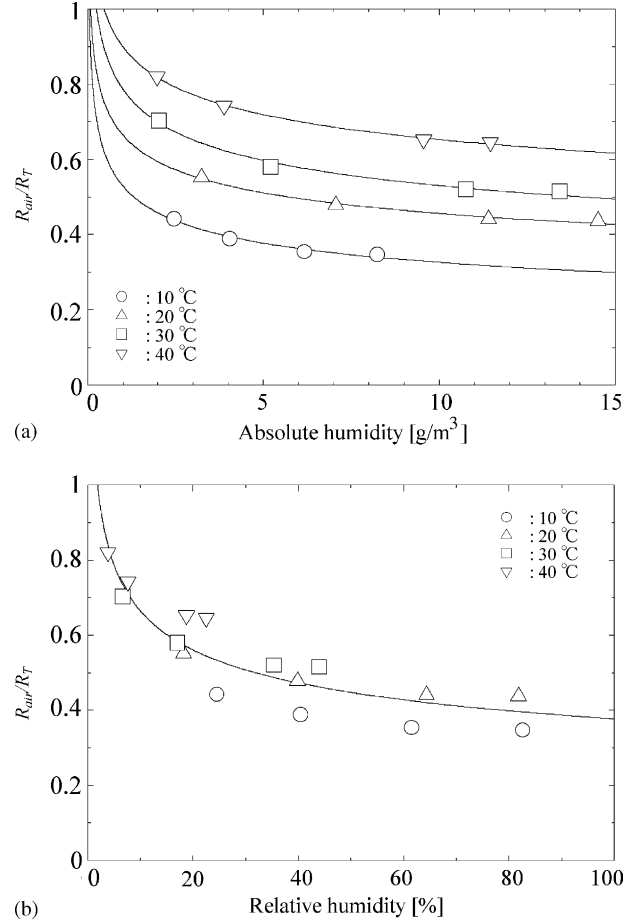

Fig. 5. (a) Relationship between absolute humidity and gas sensor resistance in clean air. (b) Relationship between relative humidity and the resistance in clean air.

Fig. 5(a and b) shows the variation of the baseline resistance with humidity. The baseline resistance was normalized by R_T under each temperature condition. The humidity dependence of the metal oxide sensor resistance is usually discussed in terms of absolute humidity, i.e., the concentration of water vapor in the air [11]. However, the sensitivity of the TGS2106 sensor to water vapor was found to vary with temperature. The different curves were obtained for different temperatures as shown in Fig. 5(a). On the other hand, the variation of the sensitivity was almost cancelled out when the graph was redrawn by taking the relative humidity for the abscissa as shown in Fig. 5(b). The normalized sensor resistance under various temperatures gathered around a single calibration curve. The power law is often used to represent the gas sensor response to high concentration gas [10]. Therefore, the relationship between the baseline resistance and the relative humidity, H (%), was modeled in Fig. 5(b) using the power law:

$$R_{air} = cR_T H^d, \qquad (3)$$
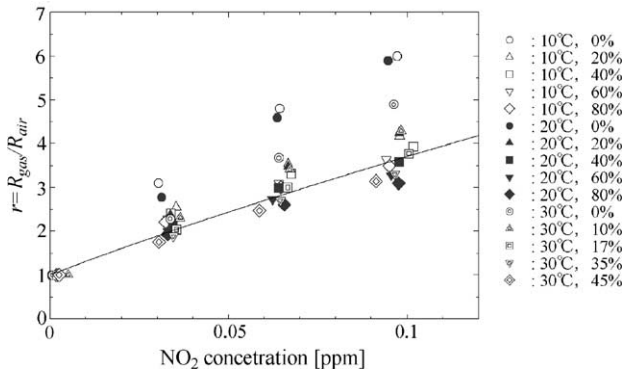
where c and d are constants.

Fig. 6. Relationship between NO_2 concentration and gas sensor response.

Fig. 6 shows the sensor response to NO_2. Even under different temperature and humidity conditions, the sensor responses were collapsed to one calibration curve. The only exceptions are the sensor responses under the dry air conditions (0% relative humidity at 10, 20 and 30 °C), which are rarely encountered in the field use. The relationship between r and NO_2 concentration in Fig. 6 is given in the form of a typical calibration curve used to represent the gas sensor response to a low level gas [12]:

$$r = \frac{R_{\text{gas}}}{R_{\text{air}}} = (1 + eC_{NO_2})^f \qquad (4)$$

where C_{NO_2} (ppm) is concentration of NO_2, and e and f are constants.

In the following part of the paper, the experimental data are presented after converting the sensor response into NO_2 concentration using Eqs. (2)–(4). NO_2 concentration measured with the sensor system and the NO_x analyzer are compared in Fig. 7. The error in the measured NO_2 concentration was relatively small immediately after starting to use the calibrated gas senor. The cross-sensitivity of the sensor to other gases, e.g., O_3 and NO, were found negligible. The measurement
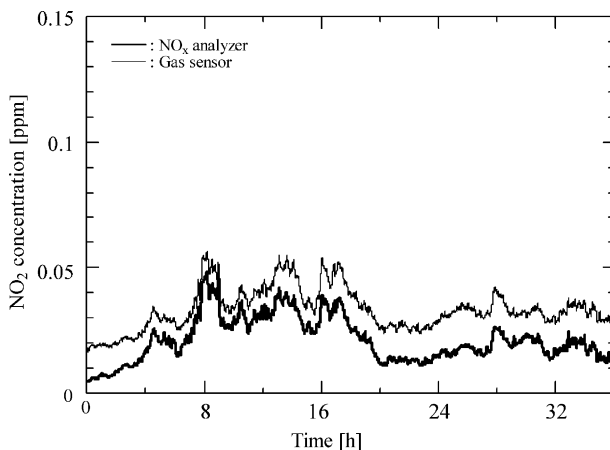

Fig. 7. Comparison of NO_2 concentration measured with gas sensor and NO_x analyzer immediately after starting to use a calibrated gas sensor on August 7, 2003.

error of the system was 8.1 ppb for this 2-week measurement.

## 4. Case study on auto-calibration of sensor system

A case study on the auto-calibration of the sensor system was performed in two stages. In the first stage, NO_2 concentrations measured at the four environmental monitoring stations were obtained from the governmental web site, and analyzed to validate the concept underlying the auto-calibration (Section 4.1). In the second stage, a field test was performed using a real sensor system to evaluate the effect of the new auto-calibration method (Section 4.2).

4.1. Statistical analysis of NO_2 concentration measured at nearby environmental monitoring stations

To validate the concept of the proposed auto-calibration method, NO_2 concentrations measured at the four environmental monitoring stations for about 1 year (from June 1, 2002 to May 31, 2003) was statistically analyzed. The results are shown in Fig. 8(a and b). Fig. 8(a) shows the frequency distributions of NO_2 concentrations at stations 2–4 when hourly average values of NO_2 concentration at station 1 was at a relatively high level (50–60 ppb). The concentra-
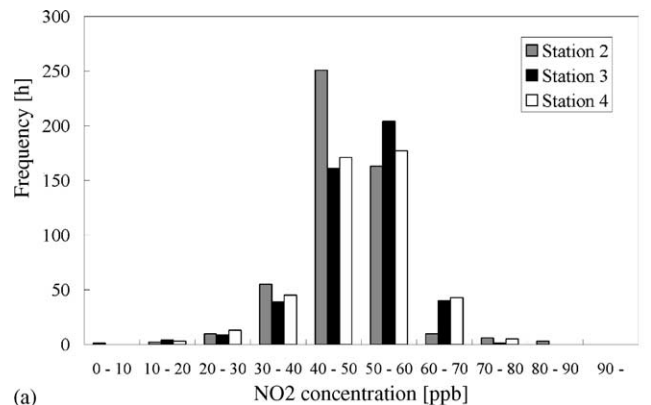
(a)
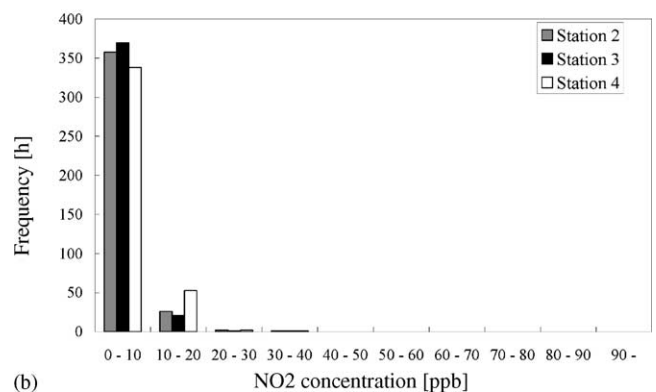
(b)

Fig. 8. Frequency distributions of NO_2 concentrations at stations 2–4 when the concentration at station 1 was (a) 50–60 ppb and (b) 0–10 ppb.

tions at stations 2–4 ranged from 30 to 80 ppb. The sensors placed at different locations would be exposed to different concentrations, and the sensor network would serve for its original purpose, i.e., to monitor a detailed pollutant distribution.

Fig. 8(b) shows the frequency distributions of NO_2 concentration at stations 2–4 when hourly average value of NO_2 concentration at station 1 was low (0–10 ppb). The narrow distributions of NO_2 concentration indicate that NO_2 concentrations were less than 10 ppb at all stations in most of the time. Therefore, the uniform distribution can be assumed as discussed in Section 2.3 when low NO_2 concentration is reported at one monitoring station. This assumption will be further supported when the NO_2 concentrations reported at the four stations all become less than 10 ppb. The concentration uniformity in the whole local area can be assumed with high confidence, and the baseline of the sensor at the university can be calibrated.

The above discussion has led to the calibration procedure as follows: to adjust the gas sensor output in the sensor system to the average of the values measured at surrounding stations when all stations in the area simultaneously report concentrations less than 10 ppb. The value, 10 ppb, was chosen taking the stability of the gas-sensor output into account. It was shown experimentally that the sensor has enough stability for drift-free operation for 2–4 weeks. To keep the measurement accuracy described in Section 3 for longer time periods, the sensor system has to be calibrated every 2–4 weeks. During the 1-year period, the above criterion was met at the total of 307 h. Fig. 9 shows that the calibration criterion was met at least once per month except February 2003. This result suggests that the auto-calibration can be performed at least once per month using the proposed procedure.

The data reported at the monitoring stations were further analyzed to investigate the weather conditions in which NO_2 concentration became less than 10 ppb at all stations. The frequency distributions of wind speed and wind direction at station 1 when the calibration criterion was met are shown in Fig. 10(a and b). Such low levels of NO_2 concentrations were reported in south wind condition as shown in Fig. 10(a) and in strong wind condition as shown in Fig. 10(b).
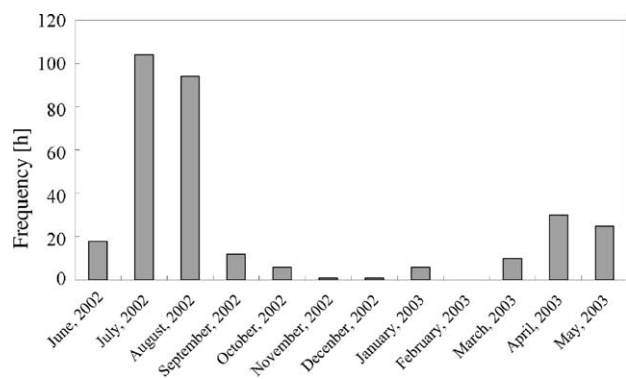

Fig. 9. Number of times the auto-calibration criterion was met in each month.
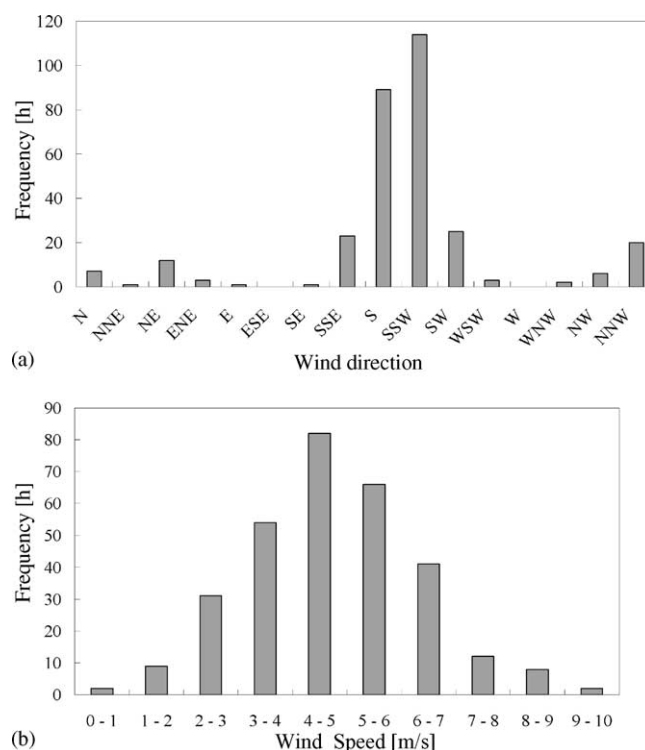

Fig. 10. (a) Frequency distribution of wind direction when the criterion was met. (b) Frequency distribution of wind speed when the criterion was met.

Those results suggest the following scenario in which the pollutant concentration in the whole local area becomes uniformly low. The strong wind permits immediate mixing and dispersion of the generated pollutant gas in the local area. Tokyo bay is located about 10 km south from the area under study. South wind blowing from Tokyo bay does not contain high levels of NO_2 since there is no source.

4.2. Auto-calibration of gas sensor

The raw sensor data and the data reported at the environmental monitoring stations were collected for several months, and were reviewed to investigate the effect of the proposed auto-calibration method. The initial calibration of the gas sensor was performed immediately before starting the long-term measurement. The data shown in Fig. 7 were obtained during the first 40 h of the long-term monitoring campaign.

Two months after the gas sensor was calibrated, the measurement error in the same sensor system increased to 40 ppb. Fig. 11 shows an occasion when the calibration criterion was met. Adjusting the gas sensor baseline to the average values of the four environmental monitoring stations decreased the measurement error from 40 to 10 ppb or less. The sensor output curve after the baseline adjustment agreed well with the NO_2 concentration recorded using the NO_x analyzer, which was placed side by side with the gas sensor system. The new calibration method was shown effective to keep the accuracy of the sensor system at a sufficient
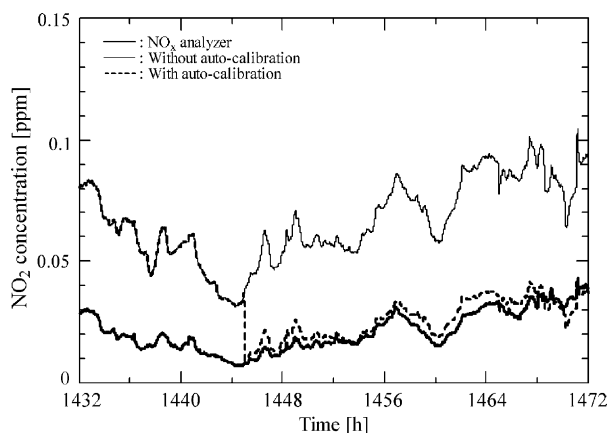
Fig. 11. Comparison of NO_2 concentration measured with gas sensor and NO_x analyzer. Thin line depicts the NO_2 concentration measured with gas sensor without applying the auto-calibration procedure. Dashed line shows the recalculated sensor value after adjusting the sensor baseline at 1445 h to the average of the concentrations reported from the surrounding stations.

level for the use in an atmospheric environmental monitoring network.

5. Conclusion

The NO_2 measurement system was developed. Its performance was evaluated by comparing the measured pollutant concentration with the output of the chemical analyzer. The metal oxide NO_2 sensor combined with the temperature and humidity compensation set was found to have fair stability and sufficient sensitivity for the use in an atmospheric environmental monitoring system.

Moreover, a new auto-calibration procedure to be used in a gas sensor network was proposed. A case study showed that there exists a special weather condition under which the NO_2 concentration becomes low and uniform in the whole local area. The long-term stability of the sensor system was improved by the baseline calibration using the values reported from neighboring stations in such special occasions. In future work, extension of this calibration method to more general cases will be investigated.

Acknowledgment

References

[1] White paper on the Environment of Tokyo Metropolis, Environmental Management Division, Bureau of Environmental Protection, Tokyo Metropolis, 2000 (in Japanese).

[2] J.C. St. John, W.L. Chameides, Climatology of ozone exceedences in the Atlanta metropolitan area: 1-h vs. 8-h standard and the role of plume recirculation air pollution episodes, Environ. Sci. Technol. 31 (1997) 2797–2804.

[3] J.C. St. John, W.L. Chameides, R. Saylor, Role of anthropogenic NO_x and VOC as ozone precursors: a case study from the SOS Nashville/Middle Tennessee Ozone Study, J. Geophys. Res. 103 (1998) 22415–22423.

[4] J. Plaza, M. Pujadas, B. Artíñno, Formation and transport of the Madrid ozone plume, J. Air Waste Manag. Assoc. 47 (1997) 766–774.

[5] W. Tsujita, S. Kaneko, T. Ueda, H. Ishida, T. Moriizumi, Sensor-based air-pollution measurement system for environmental monitoring network, in: Technical Digest of the 12th International Conference on Solid State Sensors, Actuators and Microsystems, vol. 1, June 2003, pp. 544–547.

[6] S. Chang, J.R. Stetter, Electrochemical NO_2 gas sensors: model and mechanism for the electroreduction of NO_2, Electroanalysis 2 (1990) 359–365.

[7] T. Inoue, K. Ohtsuka, Y. Yoshida, Y. Matsuura, Y. Kajiyama, Metal oxide semiconductor NO_2 sensor, Sens. Actuators B 24–25 (1995) 388–391.

[8] T. Ohyama, Y.Y. Maruo, T. Tanaka, T. Hayashi, A ppb-level NO_2 detection system using coloration reactions in porous glass and its humidity dependence, Sens. Actuators B 64 (2000) 142–146.

[9] http://w-soramame.nies.go.jp/.

[10] K. Ihokura, J. Watson, The Stannic Oxide Gas Sensor: Principles and Application, CRC Press Inc., Boca Raton, FL, 1994.

[11] T. Takada, T. Fukunaga, Long-term monitoring of natural O_3 using In_2O_3-based semiconductor sensor comparing with ultraviolet method, Ozone Sci. Eng. 20 (1998) 499–505.

[12] H. Ishida, T. Nakamoto, T. Moriizumi, Remote sensing of gas/odor source location and concentration distribution using mobile system, Sens. Actuators B 49 (1998) 52–57.

Biographies

Wataru Tsujita was born in Osaka Prefecture, Japan, in 1977. He received his BE and ME degrees in physical electronics from the Tokyo Institute of Technology, Tokyo, Japan, in 2000 and 2002, respectively. He has been a PhD candidate in physical electronics since 2002 and was awarded a 2-year fellowship by the Japan Society for the Promotion of Science in 2003. His research interests include gas sensor, and gas sensing system.

Akihito Yoshino was born in Kanagawa Prefecture, Japan, in 1981. He received the BE degree in physical electronics from the Tokyo Institute of Technology, Tokyo, Japan, in 2003. He is currently pursuing the ME degree in physical electronics. His research topic is atmospheric environmental monitoring using gas sensor systems.

Hiroshi Ishida was born in Morgantown, WV, in 1970. He received the ME and PhD degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1994 and 1997, respectively. From 1997 to 2004, he was a research associate of the Tokyo Institute of Technology. From 1998 to 2000, he visited the School of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA, as a Postdoctoral Fellow. In 2004, he joined the Department of Mechanical Systems Engineering at the Tokyo University of Agriculture and Technology, Tokyo, Japan, where he is currently an associate professor. His research interests are in biomimetic electronics with emphasis on chemical sensors and their applications in robotics.

Toyosaka Moriizumi was born in Gumma Prefecture, Japan, in 1942. He received the BE, ME and PhD degrees in electronics from the Tokyo Insti-

tute of Technology, Tokyo, Japan, in 1964, 1966 and 1969, respectively. From 1973 to 1985, he was an associate professor of the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, and is now a professor with the Department of Physical Electronics. From 1978 to 1979, he was with Carnegie Mellon University, Pittsburgh, PA, as a visiting associate professor. He has been engaged in research in the fields of semiconductor thin films, heterojunctions and SAW devices. His present interest is bioelectronics and biomimetics, i.e., electronics noses and gas/odor plume-tracking systems.