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IR Absorbance as a Criterion for Temperature Compensation in Nondispersive Infrared Gas Sensor †

Jin-Ho Kim, Han-Gil Park and Seung-Hwan Yi *

Department of Mechanical Eng., Korea National University of Transportation, Chungju 27469, Korea; wlsgh0614@naver.com (J.-H.K.); hangil121000@naver.com (H.-G.P.)

* Correspondence: isaac_yi@ut.ac.kr; Tel.: +82-43-841-5129

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Abstract: Nondispersive infrared (NDIR) CO_2 gas sensor was developed by using White-cell structure and tried to compensate the temperature effects in order to monitor CO_2 concentrations without hindering the temperature variations. However, the absorptions of infrared light depend on not only the temperatures but also CO_2 concentrations. Thus, a single Beer-Lambert law couldn't properly describe the tendency of voltage decrements within full scale input (FSI, 0 to 5000 ppm) because it was affected by both parameters. In this article, the absorbance of infrared light is defined according to the concentrations of CO_2 gas. Then, a new temperature compensation algorithm has been implemented into micro-controller unit (MCU), the measurement errors were within ±3.6% as the temperature-dependent absorbance was chosen at 1450 ppm CO_2 concentrations.

Keywords: nondispersive infrared gas sensor; infrared absorbance; temperature compensation; carbon dioxide; White-cell

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1. Introduction

TOC (total organic carbon) measurement systems need CO_2 gas sensor to estimate the organic carbon concentrations in water because byproducts of livestock and other contamination sources pollute the rivers and streams. So, many developed countries are using TOC systems to manage the quality of water now, and TOC systems currently use two sensor types for assuring the quality of water: NDIR and permeable membrane types [1–3]. In terms of autonomous systems and ubiquitous society, compact size and convenient sensor systems are more user-friendly than the bulky one. This might be one of the reasons to choose NDIR CO_2 gas sensor for TOC system so far. However, TOC system generates the toxic gases (mainly acids) and water vapors during the ultraviolet or thermal combustion processes in TOC systems. Therefore, the above-mentioned molecules should not affect NDIR gas sensors and they should have high sensitivity in order to reduce the quantity of sampled water and have a long-term stability, adequate temperature compensation methods and enhance the efficiency of TOC systems. However, the absorption coefficient of carbon dioxide gas is dependent upon the ambient temperatures and also the concentrations of CO_2 gas. So, it is desirable to propose a criterion for the temperature compensation methods and their effects on the accuracies of the measurements. In this article, the authors tried to suggest the criterion for the temperature compensation methods in NDIR CO_2 gas sensor.

2. Theoretical Consideration and Experiments

2.1. Theoretical Considerations

The basic components of NDIR gas sensor are IR source, optical waveguide (or gas cell/chamber denoted in previous articles), and IR detector with a narrow band-pass filter at the end of optical waveguide structure. The Lambert-Beer law as described in Equation (1) explains the attenuation of IR energy after transmitting the optical waveguide that contains IR absorbing gas molecules and the transmitted energy generates the voltage at the IR detector ($V_d(T, x)$) as shown in Equation (2) [4]:

$$I_d(T,x) = I_o(T,x) \cdot \exp(-\beta(T) \cdot x), \quad (1)$$

$$V_d(T,x) = V_o(T) + \alpha(T) \cdot \exp(-\beta(T) \cdot x), \quad (2)$$

These equations explain the relationship between transmitted IR intensity and output voltage after traveling the optical waveguide structure characterized by the product($\beta(T)$) of absorption coefficient (σ) of target gas and optical path length (l), initial IR intensity (I_0) and target gas concentrations (x). Because the optical filter has a passband of light (which is around 180 nm), there are non-absorbing wavelengths of light by the target gas. It causes the generation of output voltages ($V_o(T)$), which is not affected by the concentration of target gas. Also, the IR source and filter properties can be affected by the ambient temperature, furthermore, the movement of gas molecules also shows temperature dependency, these cause the changes of output voltages ($\alpha(T)$), which is affected by temperature dependent absorption property of gas molecules and filter in Equation (2).

L. Jun et al. [5] suggested the absorbance F_a, to estimate the concentration of target gas, is as described in Equation (3)

$$F_a = 1 - \frac{V_o}{Z \times V_r}, \quad (3)$$

where, V_o is the output voltage of gas sensor at certain temperature and gas concentrations, V_r is the output voltage of reference sensor at the same condition, and Z is the voltage ratio of V_o and V_r at zero ppm and a specific temperature.

However, the absorbance defined in Equation (3) should be properly selected to estimate the correct concentrations of target gas because it is dependent on the ambient temperature and gas concentrations as previously reported [6]. As the gas concentration gets higher, the absorbance increases and it shows a temperature dependency at each gas concentration.

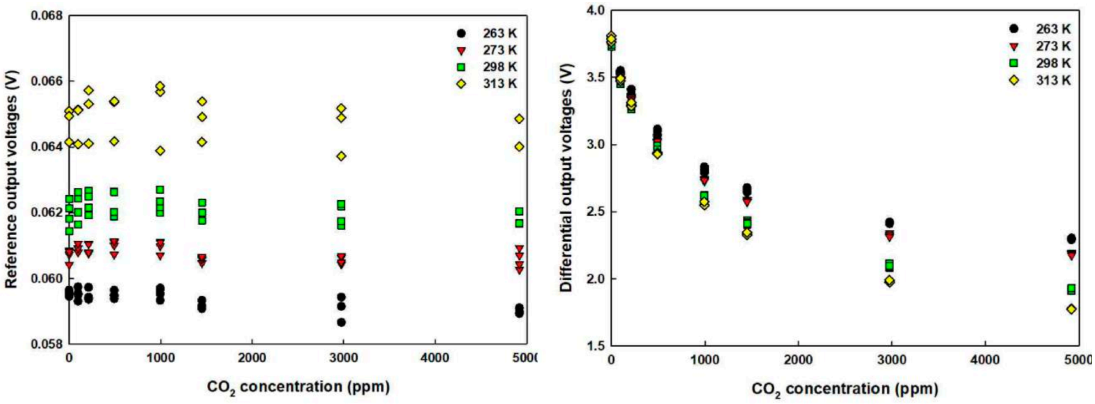
2.2. Experiments

The experiments were performed according to the designed procedures; the four ambient temperatures were chosen to calibrate the temperature effects and the full-scale inputs of gas ranged from 0 to 5000 ppm. The seven standard CO_2 gases are used to measure the output voltages of sensor: 100, 200, 500, 1000, 1500, 3000, 5000 ppm. The experimental procedures are similar to the previous report [7]. After analyzing the output voltages and implementing the temperature compensation methods based on the above mentioned criteria, the measurement errors were revealed in order to quantify the performance of developed CO_2 sensor.

3. Experimental Results and Summaries

Figure 1 shows output voltages of IR detectors as a function of CO_2 concentrations. The output voltages of reference detector show almost constant around 63 mV from 263 to 313 K. The differential output voltages between CO_2 detector and reference detector decreased as the CO_2 concentrations increased as shown in Figure 1b. When the regression analyses were conducted with one exponential function, however, the derived functions for each experimental set showed large discrepancies compared to the experimental results for each ambient temperature.

Based upon the results and also regression analyses, the authors tried to propose the accurate criterion for temperature compensation methods within FSI range. As previously reported [5,7], the absorbance of IR light could be a possible criterion for dividing the range of concentrations and estimating the accurate concentrations of target gas because it is affected by temperatures and gas concentrations. Furthermore, it could roughly reveal a coordinate where the measured value might be positioned in the plot of output voltages vs. gas concentration domain shown in Figure 1b.



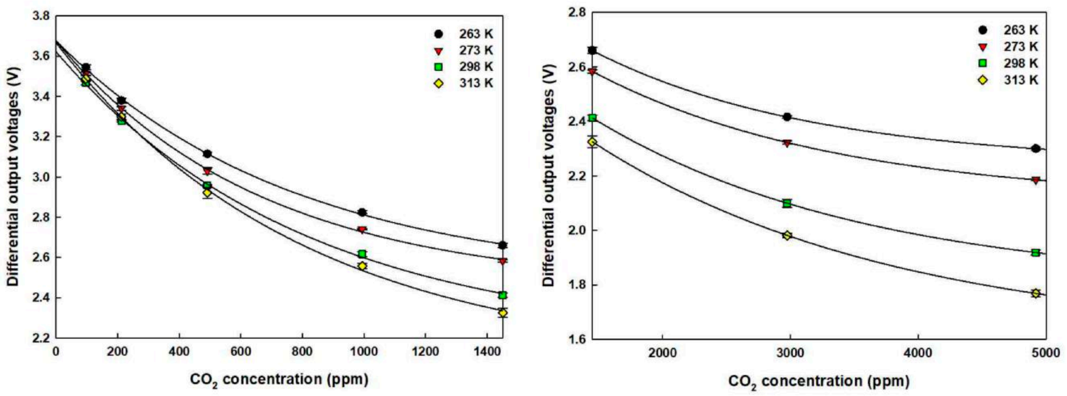
(**a**) (**b**)

Figure 1. Output voltages of IR detectors as a function of CO_2 concentrations and ambient temperatures: (**a**) reference output voltages; (**b**) amplified differential output voltages between CO_2 and reference detector.

Table 1 shows the estimation errors of CO_2 concentrations as a function of ambient temperatures according to absorbance criteria at a specific gas concentration. As can be inferred from Table 1, when the absorbance criterion was chosen at 1450 ppm of CO_2 concentrations, the accuracy could be enhanced and the experimental data matched well to the regression analyses as shown in Figure 2.

Table 1. Estimation errors of CO_2 concentrations as a function of ambient temperatures according to the criteria of IR absorbance.

Absorbance Criteria @	263 K	273 K	298 K	313 K
491 ppm	−8.5 ~ −5.1%	−7.6 ~ −6.4%	−11 ~ −3.4%	−7.2 ~ −0.5%
994 ppm	-4.8 ~ −1.4%	−2.9 ~ −1.7%	−6.8 ~ +1.0%	−3.3 ~ +0.6%
1450 ppm	−2.0 ~ +1.5%	−1.0 ~ +1.5%	−3.9 ~ +4.2%	−2.0 ~ +1.6%



(a) **(b)**

Figure 2. Regression analysis of the differential output voltages of IR detectors according to the IR absorption criteria at 1450 ppm: (**a**) below 1450 ppm; (**b**) above 1450 ppm CO_2 concentrations.

Table 2 presents the measurement results of CO_2 concentrations at the random temperatures and standard CO_2 concentrations. The errors of random measurement showed within ±3.6%. So, the proposed criterion for temperature compensation methods could improve the accuracy of developed CO_2 gas sensor.

Table 2. Measurement results of CO_2 concentrations at random temperatures and standard CO_2 concentrations.

Standard Concentration (ppm)	272 K	282 K	293 K	304 K
491	−3.4%	1.2%	3.2%	12.8%
1450	−3.6%	2.4%	3.5%	3.6%
4832	−0.9%	0.3%	3.2%	3.2%

The decrements of output voltages of developed CO_2 sensor showed two distinct features according to the concentrations of CO_2 gas. To enhance the accuracies, the absorbance of IR light as a new criterion for estimating gas concentrations was adopted in this research. Because the errors of CO_2 measurement were affected by the absorbance of IR light, the absorbance should be carefully selected to enhance the performance of temperature compensations in NDIR gas sensors.

Author Contributions: S.-H.Y. and J.-H.K. designed the experiments; J.-H.K. performed the experiments; H.-G.P. systematically summarized and reported the experimental data and participated in the discussions of experiments with them; they discussed the whole experimental results and prepared the reports to the company which supported these research activities; S.-H.Y. wrote the paper which was originally written in Korean language.

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