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The Relative Performance of NDIR-based Sensors in the Near Real-time Analysis of CO_2 in Air

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Abstract: In this study, the reliability of NDIR-based sensors was explored by evaluating the comparability between measurement systems in the near real-time analysis of CO_2. For this purpose, replicate analyses were performed using sensors of two different model types (H-550 and B-530, ELT Company, Korea). Three replicate data of each sensor type collected continuously by side-by-side analysis in three second intervals (a duration of 304 hour) were evaluated for the relative performance of NDIR sensors. The reproducibility of sensors, when assessed by relative standard error (RSE %) values of all sensor units, showed moderate changes with time with the overall mean of 2.33%. When CO_2 measurements from all NDIR sensor units were evaluated by correlation analysis, the results showed strong comparability, regardless of the model type. The overall results of this study suggest that NDIR sensors are reliable enough to produce highly comparable data at least in a relative sense.

Keywords: NDIR sensor; CO_2 monitoring; side-by-side analysis; performance evaluation

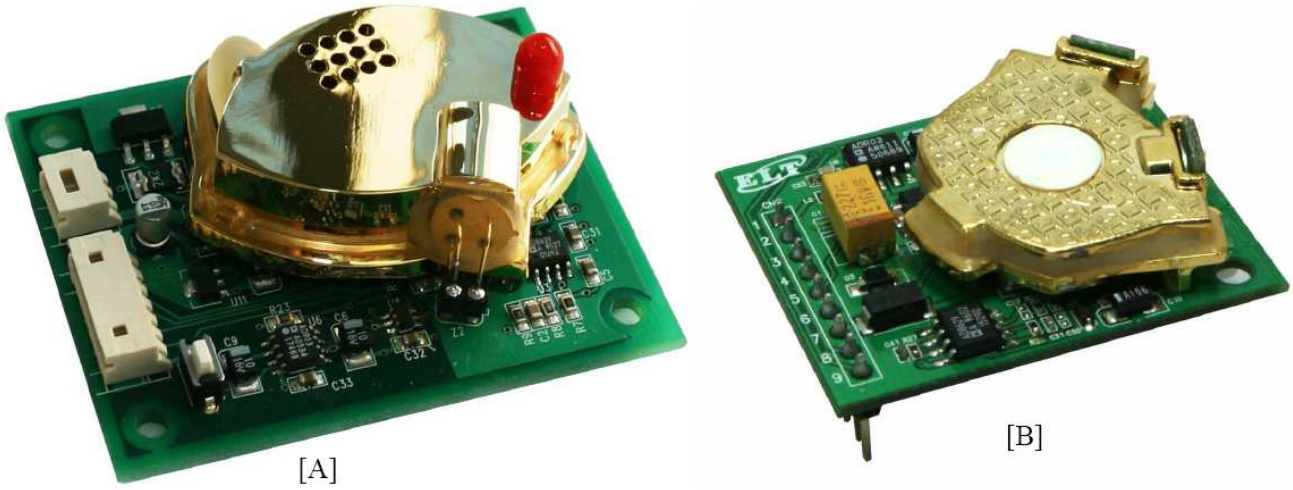
1. Introduction

Carbon dioxide (CO_2) is the fourth most common gas present in the earth's atmosphere with an average ambient concentration (in fresh air) of about 380 ppm [1]. Being the most important anthropogenic green house gas, carbon dioxide contributes to changes in the climate, as it is responsible for alterations in the chemistry of the ocean through the trapping of infrared radiation. This in turn can lead to a warming of the climate and changes in ecological systems [2].

Carbon dioxide is one of the most common by-products of living organisms [3], as humans release it into the atmosphere with every exhaled breath (with an average concentration of about 3.8%) [4]. According to a study conducted by the United States Department of Agriculture (USDA), a daily production rate of CO_2 for the average person corresponds to 450 liters (900 grams) [5]. Carbon dioxide is an insidious gas so that changes in its concentration are difficult for humans to recognize. The gas is safe in low concentrations but life-threatening in excessively large quantities (e.g., more than 30,000 ppm for a short term exposure of 15 minutes and more than 5000 ppm for 8 hour time-weighted average) [6].

Information concerning CO_2 concentration levels often becomes an essential element in air quality investigations. The popularization of the airtight envelope system in the design of buildings and in Heating Ventilating and Air Conditioning (HVAC) systems have resulted in the deterioration of indoor air quality [7, 8, 9]. The poor quality of indoor air in houses and workplaces due to a high concentration of CO_2 can result in several health-related problems such as: sick building syndrome (SBS) or tight building syndrome (TBS), building related illnesses (e.g., nausea, skin irritation, lethargy, etc), and sick house syndrome (SHS) [10,11]. For this reason, there is a growing demand for real-time continuous monitoring of indoor CO_2 concentration levels such as affordable and portable CO_2 gas sensors. In the present study, the analytical performance of NDIR sensors was investigated in terms of reproducibility and compatibility in the continuous long-term measurement of CO_2.

Figure 1. A picture of two different sensor types tested in this study: [A] B-530 and [B] H-550.



2. Materials and methods

2.1 Background of CO_2 analysis

The analysis of CO_2 gas comprises a long history of 180 years with the development of several chemical and physical methods such as: gas chromatography [12, 13], infrared analysis [14], C^{14} isotope measurement [15], mass spectrometry [16], FT-IR spectroscopy [17], gas diffusion-flow injection (GD-FIA) [18] or continuous flow systems based on photometric detection with various pH

indicator systems [19, 20, 21, 22], conductimetric sensors [23, 24, 25] thermistors [26], and acoustic detectors [27, 28].

At present, there are two types of gas sensors that are commonly available for monitoring CO_2 concentrations in air, i.e., non-dispersive infrared (NDIR) [29] and solid electrolyte sensor types [30]. Non-dispersive infrared sensors have more technical advantages in terms of long-term stability, accuracy, and power consumption rate during CO_2 measurement [31]. Hence, NDIR sensors are the most widely used for the real-time measurement of carbon dioxide. Because the NDIR method uses the physical sensing principle such as gas absorption at a particular wavelength, it has a high selectivity and sensitivity in open air conditions. It can be employed to measure CO_2 as a function of the absorbance of infrared (IR) light at a specific wavelength (4.26 μm) [32]. It is well-known that CO_2 has a strong absorbance at that band that is selective with negligible interference [33].

NDIR sensors are simple spectroscopic devices that can be applied to gas analysis. The main components of NDIR are infrared sources (lamps), sample chambers (or light tubes), wavelength filters, and infrared detectors [34]. The gas is pumped (or diffused) into the sample chamber, and the concentration of target gas is measured electro-optically by its absorption of a specific wavelength in the infrared (IR) range. The IR light is directed through the sample chamber towards the detector. An optical filter in front of the detector can eliminate all light except the wavelength of the selected gas molecules. The term non-dispersive refers to all the light that passes through the gas sample while being filtered immediately before entering the detector. (In the case of dispersive IR detectors, the use of grating (or prism) is useful to pre-select the desired wavelength of light.) Ideally, other gas molecules do not absorb light at this wavelength so as not to affect the amount of light reaching the detector.

2.2 Experimental methodology

In this study, the relative performance of CO_2 sensors was tested using two different NDIR-based sensor types produced by ELT Company in Korea. These sensors models (H-550 and B-530) are different in terms of their detection ranges, i.e., B-530 has detection range of 0-10,000 ppm, while H-550 can measure CO_2 in the range of 0-50,000 ppm (refer to Table 1 for their specifications). These two models were examined for their feasibility in the real-time analysis of CO_2 gas. For this purpose, we designed a system to concurrently retrieve data from six CO_2 sensors (i.e., three identical sensor units of each model introduced above). A computer installed with data acquisition software for NDIR sensors was operated to collect near real-time measurement data for CO_2 from each system at 3 second intervals. For all the sensor units, calibration was made prior to the study, and the performance of each sensor unit was basically found well within the specifications mentioned.

During this study, all six sensors were operated to record CO_2 concentrations concurrently for a 304 hour duration (~13 day: 21 May to 1 June, 2007) at 3 second intervals. This side-by-side analysis of CO_2 sensors was conducted under the same environmental conditions at the Atmospheric Environment Laboratory, Sejong University, Korea. All data sets primarily recorded at 3 second intervals were utilized as raw data after being converted into hourly (or daily) mean values. The results obtained from this study were then evaluated to examine the relative performance for real-time CO_2 measurements in air. To properly apply this sensing system to the analysis of CO_2 in ambient air, more experiments are

currently underway to describe analytical properties of this sensor including its absolute reliability; the results of our continuing efforts will be described subsequently in our future publications.

3. Results and discussions

3.1 The overall pattern of CO_2 analysis

To make a diverse comparison of the CO_2 data sets, all data obtained initially at 3 second intervals were used as raw data after being converted into hourly intervals. All of these data were used to derive a statistical summary (Table 2). When the raw CO_2 data (3 second interval) were compared against the ones converted at hourly intervals (Table 2A and 2B), the latter data exhibited the same mean values as the former but at slightly reduced standard deviation (SD) values. Hence, for the sake of simplicity, interpretation of our CO_2 data was conducted using hourly data unless otherwise specified. As shown in Table 1A, the overall mean values of CO_2 measured by each sensor unit ranged from 396 ± 30.9 ppm (B1) to 448 ± 29 ppm (B2). When the results were compared in terms of mean values, each sensor unit generally showed strong comparability (Fig 2).

Figure 2. A comparison of relative performance of six sensor units for CO_2 analysis (All results compared in overall mean concentration levels of CO_2 (ppm) at hourly intervals) Dotted line represents the grand mean concentration derived from all six sensor units and whiskers represent the standard deviation values from the mean.

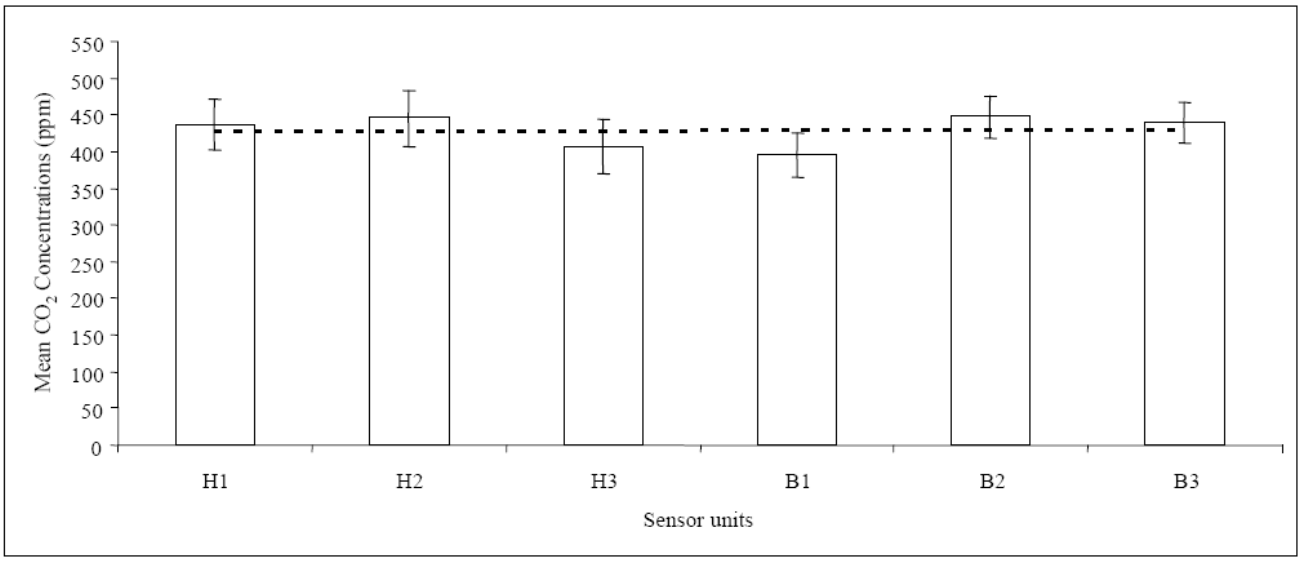


Table 1. A brief description of general properties and specifications pertaining to two types of NDIR-based CO_2 sensors used in this study.

Property / specification	Sensor model	
	B-530	H-550
Sensing Method	(Non dispersive Infrared)	
Measurement Range	0~10,000 ppm	0~50,000 ppm
Storage Temperature	-20 ~ +60℃	-20 ~ +60℃
Operating Temperature	0 ~ +50℃	0 ~ +50℃
Sensitivity	±20 ppm ± 1%	±20 ppm ± 1%
Accuracy	±30 ppm ± 5%	±30 ppm ± 5%
Response time (90%)	Within 120 sec	Within 30 sec
Operating Humidity (RH: (%)	0~95% RH	0~95% RH
Input Power	DC12 V	DC12 V
Size	50(L)X65(W)X25.5(H) mm	38(L)X32(W)X12(H) mm
Output Signal	Analog (0.5 V ~4.5 V,2~10 V)	Digital (UART Rx,,Tx)

Table 2. A statistical summary of CO_2 concentration data measured using two different sensor types (H-500 and B-530 model) (21May to 01June 2007: 304 hour duration): Results derived using [A] 3 second raw data and [B] hourly data are compared (All concentrations in ppm unit).

		Sensor units					
		H1[1]	H2[1]	H3[1]	B1[2]	B2[2]	B3[2]
[A] 3 second data	Mean ± SD (Median)	438 ± 36.3 (436)	445 ± 40 (442)	407 ± 39.8 (396)	396 ± 34.2 (391)	448 ± 31.7 (442)	439 ± 30.2 (433)
(raw data)	Range	333-668	335-678	307-666	323-557	317-678	335-668
	N	383,662	383,660	383,581	383,406	383,469	383,555
[B] After conversion into hourly intervals	Mean ± SD (Median)	438 ± 33.8 (437)	445 ± 37.2 (445)	407 ± 37 (401)	396 ± 30.9 (392)	448 ± 29 (442)	439 ± 27.4 (433)
	Range	372-586	368-601	330-572	336-522	391-595	386-582
	N	304	304	304	304	304	304

[1] and [2] denote the model No H-500 and B-530 series of sensor units for CO_2 measurements used in this study, respectively

Table 3. A statistical summary of percent deviation (PD) values for each sensor unit calculated from the raw data and hourly mean values of all 6 sensor units.

		Sensor units					
		H1[1]	H2[1]	H3[1]	B1[2]	B2[2]	B3[2]
[A] 3 second raw data (N = 359,919)	Mean ± SD (Median)	2.25 ± 2.93 (1.95)	2.21 ± 4.96 (2.85)	-5.15 ± 5.74 (-5.58)	-5.60 ± 6.51 (-7.47)	4.15 ± 2.77 (4.16)	2.49 ± 2.52 (2.51)
	Range	-9.87-15.2	-17.2-17.7	-24.6-10.8	-20.1-21.6	-18.9-23.5	-10.5-18.6
[B] Hourly data (N = 304)	Mean ± SD (Median)	2.03 ± 2.52 (1.54)	3.73 ± 2.76 (3.46)	-5.11 ± 5.35 (-5.42)	-7.68 ± 3.98 (-8.12)	4.63 ± 2.05 (4.75)	2.40 ± 2.00 (2.55)
	Range	-2.76-10.7	-2.46-11.0	-15.2-7.86	-16.6-2.64	-0.23-9.74	-3.49-6.98

[1] and [2] denote the model no H-500 and B-530 of sensor units for CO_2 measurements used in this study, respectively

The temporal patterns of CO_2 measured during the entire study period were also plotted in Fig 3. When the results of CO_2 analysis were plotted at hourly intervals (Fig 3a), each individual sensor unit fell in close range regardless of sensor type. The raw data sets obtained at 3 second intervals were segregated and used directly to compute day-to-day variabilities in CO_2 concentration values. As all measurements were collected in open air in a laboratory, the CO_2 concentrations seemed to exhibit slight variations in relation to the day-to-day activities of the laboratory.

3.2 Performance evaluation of NDIR sensors

As a simple means to assess the relative performance of NDIR sensors in CO_2 measurement, relative standard error (RSE in %) was computed for the data sets from 6 sensor units.

$$RSE = \frac{SE}{Mean} \times 100 \quad (1)$$

$$\text{Where } SE = \frac{SD}{\sqrt{N}}$$

The hourly RSE values were calculated using the CO_2 data measured by all six sensor units and plotted for the entire study period (304 hour duration) (Figure 4). RSE values when checked at hourly intervals, exhibited a moderate changes that ranged from 1.33 to 3.56%. However, this trend was consistent throughout the study period. The overall mean for RSE during the entire period was 2.33%.

To make a more meaningful evaluation of the comparability between different sensor units, the hourly percent deviation (PD) values were calculated for each unit by subtracting CO_2 values of individual units from the mean from all 6 units. The results of PD computation are summarized in Table 3. As shown in Table 3, sensor units H3 and B1 showed negative deviation (~ -6% range), whereas H1, H2, B2, and B3 units showed positive deviation (~ 4%) from the mean. The results shown in Fig. 5 reconfirm that the trends for hourly PD values were similar between H3 and B1 units. The two units showed negative deviation from the mean as a general trend. Although B-530 units are supposed to experience delayed response relative to H-500, the results obtained from concurrent measurements were not sufficient to detect such a trend in a systematic manner (refer to Table 1).

Figure 3a. A comparison of variations in mean hourly concentration values of CO_2 measured simultaneously by 6 CO_2 senor units for a continuous duration of 304.

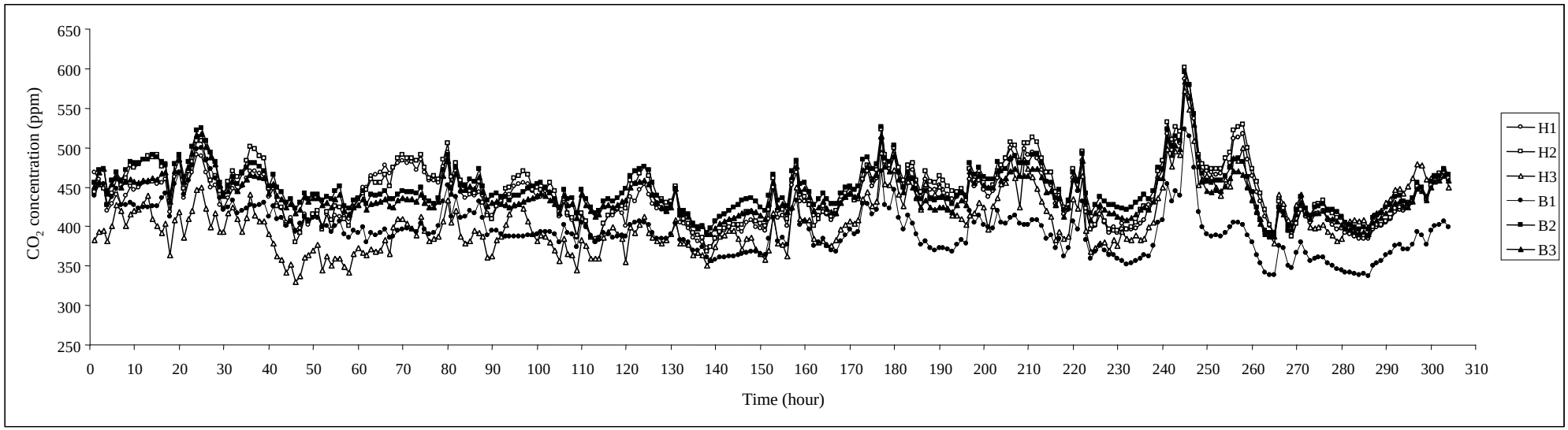
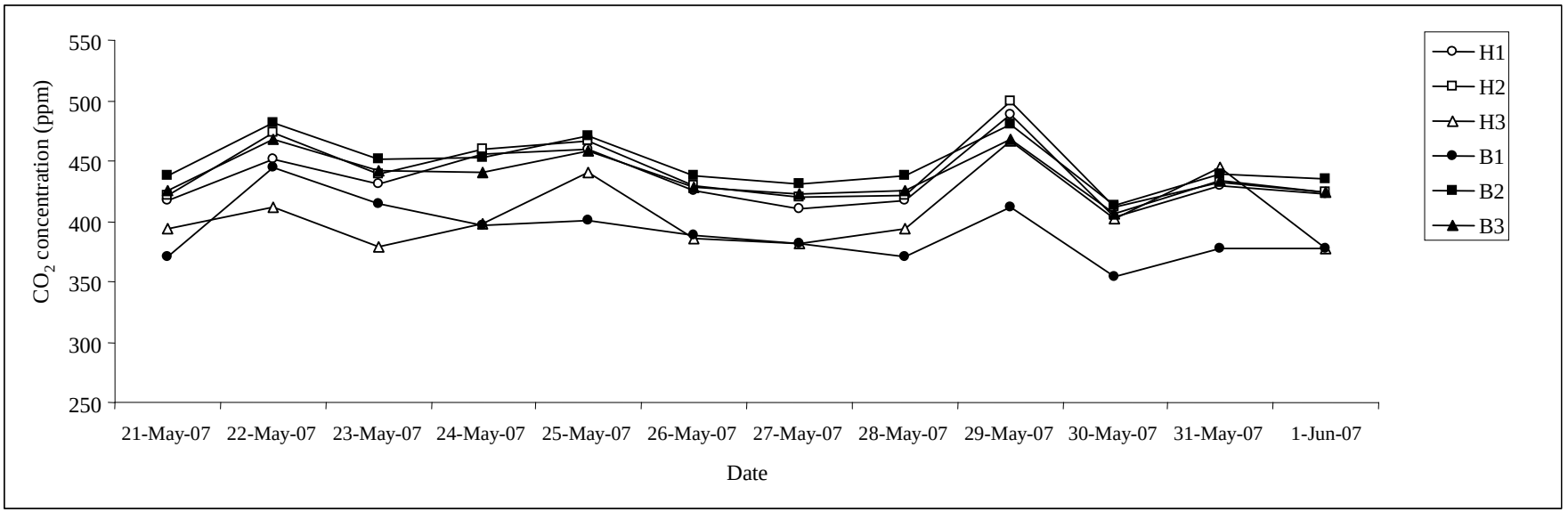


Figure 3b. The variation patterns in the mean CO_2 levels (ppm) measured in side-by-side analysis with 6 sensor units for the entire study (Results are compared in terms of the daily mean values).



As another means to check for the comparability of NDIR performance, a correlation analysis was conducted between hourly CO_2 data sets retrieved from all the sensor units (Table 4). The results of correlation analysis indicate that there are many matching cases of strong correlation such as: B2 and B3 ($r = 0.99$, $p < 0.01$), H1 and H2 ($r = 0.98$, $p < 0.01$), B1 and B2 ($r = 0.97$, $p < 0.01$), and B1 and B3 pairs ($r = 0.92$, $p < 0.01$. A strong positive and significant correlation (e.g., $r > 0.80$ and $p < 0.01$) was observed from most of the matching pairs, while there were also a few exceptions from such general trend (e.g., B1 and H3 pair). To account for the differences in the correlation patterns between different combinations of sensor units, three different types of matching cases are compared in Fig 6. It shows that H1 vs. H2 pair maintain an excellent correlation with the slope value approaching the unity. In contrast, the matching pair of B2vs.H3 shows a moderately strong correlation, while B1 vs. H3 combinations the lowest of all matching pairs ($r=0.39$, $p < 0.01$). Considering that all correlation pairs with the H3 unit maintain the weakest correlations among all matching cases, the individual H3 unit is suspected to suffer from certain problems such as the possible variations in calibrations [e.g., 35].

Table 4. Results of a correlation analysis between hourly CO_2 concentration data in side-by-side measurement with different sensor units (All results are expressed in terms of correlation coefficient values).

	H1	H2	H3	B1	B2	B3
H1	1					
H2	0.98**	1				
H3	0.75**	0.75**	1			
B1	0.70**	0.72**	0.39**	1		
B2	0.85**	0.88**	0.66**	0.88**	1	
B3	0.85**	0.86**	0.66**	0.92**	0.99**	1

** Correlations is significant at the level of 0.01 (two-tailed)

3.3 Comparison with previous studies

In an attempt to understand the fundamental features of NDIR performance examined in this study, we explored available data concerning comparative measurements of CO_2 between different techniques. In a previous study conducted by Satienperakul et al. [18], performance of diffusion-flow injection (GD-FIA) method was evaluated with respect to gas chromatography with thermal conductivity detector (GC-TCD) and to CO_2/Temperature meter. These authors collected and analyzed air samples from various environmental conditions (e.g., laboratory, an undercover park, the headspace of pasteurized-milk containers, and soil). The report highlighted that the results obtained with the three methods (GD-FIA, GC-TCD, and CO_2/Temperature meter) were statistically indistinguishable at 95% confidence level (based on a *t*-statistics).

Table 5. A comparison of relative performance between different methods in the analysis of CO_2 .

Method	Measurement condition	Mean	SD	N	CV	RSE (%)
NDIR-sensor [1]	Laboratory	429	33	6	7.69	2.33[4]
GD-FIA [2]	In open air (Laboratory)	338	35	3	10.4	5.98
GC-TCD [2]	In open air (Laboratory)	335	36	3	10.7	6.2
CO_2 monitor [2]	In open air (Laboratory)	320	3	3	0.94	0.54
GD-FIA[2]	Undercover car parking	565	9	3	1.59	0.92
GC-TCD[2]	Undercover car parking	554	15	3	2.71	1.56
CO_2 monitor[2]	Undercover car parking	541	18	3	3.33	1.92
GD-FIA[2]	Soil atmosphere	5770	340	3	5.89	3.4
GC-TCD[2]	Soil atmosphere	5820	340	3	5.84	3.37
GD-FIA[2]	Headspace in milk container	6020	80	3	1.33	0.77
GC-TCD[2]	Headspace in milk container	5750	190	3	3.3	1.91
Detector tube anlysis[3]	Indoor air	800-1000	-[5]	-[5]	-[5]	5-7

1] This study

2] Satierperakul et al., 2004

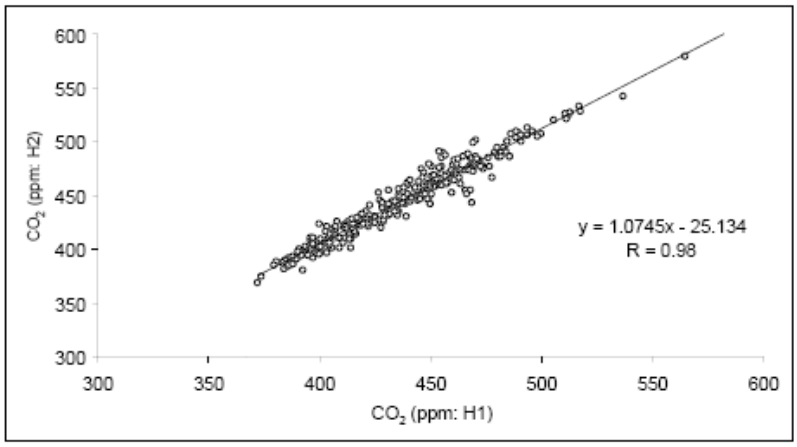
3] Norback et al., 1992

4] Shows mean RSE value for entire study, calculated from hourly RSE data

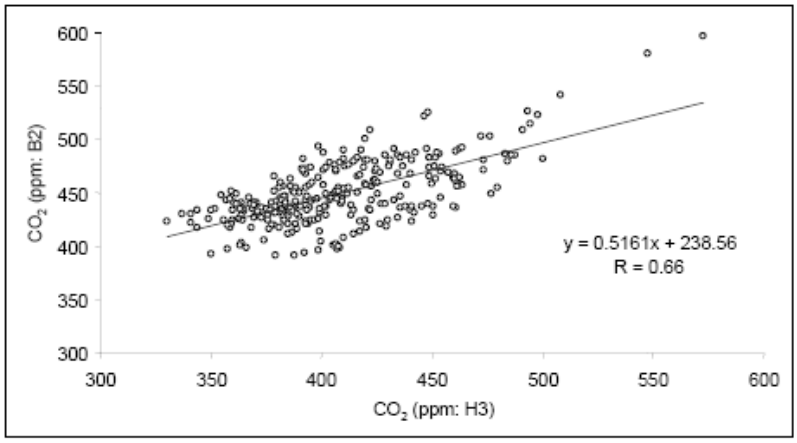
5] Data not available

To indirectly assess the relative performance of the NDIR method in CO_2 analysis, we compared the RSE values of CO_2 data acquired using different methodologies as a measure of reproducibility. Table 5 presents a summary of RSE computations between different methods under various environmental conditions. Although the RSE value determined by the NDIR method was moderately low at 2.33%, those determined by the repetitive CO_2 measurement at a constant concentration level (~340 ppm) were 6.20% (GC-TCD) and 5.98% (GC-FIA). According to another report by Esler et al (2000), CO_2 analysis by Fourier transform infrared (FT-IR) spectroscopy yielded short-term precision at a level of 0.15%. The relative error in CO_2 measurement was reported as -3.0% by the continuous-flow method using a conductimetric detector [24]. As per NIOSH manual of analytical methods (1994), the GC-TCD method has an accuracy of ± 5.3% and a bias of -2.5% in the 2270-10000 ppm range of CO_2 analysis. A comparative study of CO_2 analysis (in the 800-1000 ppm range) conducted between three brands of detector tubes (Draeger CH 30801, Kitagawa 126, and Gastec 2LL) yielded relative standard error values in the 5-7% range [36]. The mean RSE (2.33%) observed in the present study was derived from 6 different sensor units which were operated concurrently. Hence, our results can be distinguished from those of other studies made by repetitive measurements of an individual unit. Based on the above comparison, it can be concluded that the method applied in the present study (NDIR-based CO_2 sensor) may fall into a reliable range of reproducibility in terms of RSE.

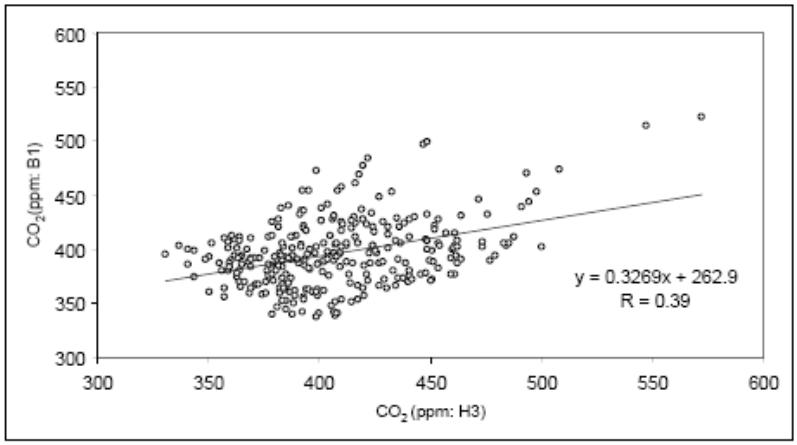
Figure 6. Comparison of correlation analysis patterns between different matching pairs of sensor units: the results of three extreme cases are plotted for comparative purpose.



[A] The most significantly correlated case: H1*vs.*H2



[B] An Intermediate case: B2 *vs.*H3



[C] The weakest correlated case: B1 vs. H3

4. Summary

This study was undertaken in order to assess the relative performance of NDIR sensors in the continuous real-time analysis of CO_2. For this purpose, 3 replicate sensors from each of two NDIR sensor models (H-550 and B-530, ELT Company, Korea) were operated to monitor the CO_2 concentration in open air condition in a laboratory. During the comparative experiment conducted in a laboratory environment, the CO_2 concentration data were obtained at three second interval as a side-by-side analysis with six sensor units for a continuous duration of 304 hours. The temporal patterns

(hourly and daily) of CO_2 measured during the entire study showed that performance of each individual sensor unit showed a good correlation in terms of CO_2 concentration regardless of the sensor type. The results of the CO_2 analysis were compared in terms of RSE (%) values using the data measured concurrently at hourly intervals throughout the study period. According to this analysis, a moderate change in RSE values was observed throughout a 304 hour period with a mean RSE of 2.33%. The results of the correlation analysis further indicated that all 6 sensor units used in this study yielded fairly good correlation with each other. A comparative analysis with other methods suggests that the NDIR method can be used to produce stable data in terms of reproducibility.

In the present study, the relative performance of the NDIR CO_2 sensor was evaluated in a range of the concentrations which is comparable to that of the ambient air (i.e., ~400 ppm range); results of routine monitoring task on CO_2 levels are commonly made from the various authentic agencies such as WMO and IPCC. Based on the results of present study, we are currently testing the possibility for the application of this sensing system to the routine analysis of CO_2 in ambient air with simultaneous measurement of relevant meteorological parameters.

Acknowledgements

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