

*Full Research Paper*

## **Use of a Dynamic Enclosure Approach to Test the Accuracy of the NDIR Sensor: Evaluation Based on the CO<sub>2</sub> Equilibration Pattern**

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**Abstract:** As part of a quality assurance (QA) study for sensor systems, an enclosure approach is applied to assess the accuracy of non-dispersive infrared (NDIR)-based CO<sub>2</sub> sensors. To examine the performance of the sensor system, an enclosure chamber containing six sensor units of the two model types (B-530 and H-500) was equilibrated with calibrated CO<sub>2</sub> standards at varying concentration levels. Initially, the equilibration pattern was analyzed by CO<sub>2</sub>-free gas (0 ppm) at varying flow rates (i.e., 100, 200, 500, and 1000 mL min<sup>-1</sup>). Results of the test yielded a highly predictable and quantifiable empirical relationship as a function of such parameters as CO<sub>2</sub> concentration, flow rate, and equilibration time for the enclosure system. Hence, when the performance of the NDIR-method was evaluated at other concentrations (i.e., 500 and 1000 ppm), all the sensor units showed an excellent compatibility, at least in terms of the correlation coefficients ( $r > 0.999$ ,  $p = 0.01$ ). According to our analysis, the NDIR sensor system seems to attain an overall accuracy near the 5% level. The relative performance of the NDIR sensor for CO<sub>2</sub> analysis is hence comparable with (or superior to) other methods previously investigated. The overall results of this study indicate that NDIR sensors can be used to provide highly accurate and precise analyses of CO<sub>2</sub> both in absolute and relative terms.

**Keywords:** NDIR; accuracy; CO<sub>2</sub>- equilibration; sensor

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## 1. Introduction

It is widely understood that carbon dioxide plays an important role as a greenhouse gas for its ability to absorb a wide range of the infrared light along with a long residence time in the Earth's atmosphere [1]. Because of increasing anthropogenic activities (such as the combustion of fossil fuels and deforestation), the concentration of atmospheric carbon dioxide has been gradually raised to reach a global mean of 380 ppm, which is about 35% higher than that seen at the beginning of the industrialization age [2]. It is hence estimated that atmospheric CO<sub>2</sub> is currently responsible for up to 63% of radiative forcing with a prominent rise in its concentration level [3].

Because of the unique physicochemical properties of CO<sub>2</sub>, its distribution in the atmosphere is found to maintain a consistent but dynamic variation on both spatial and temporal scales. The concentration of CO<sub>2</sub>, while experiencing a gradual increase through the years, tends to be subject to a strong seasonality. CO<sub>2</sub> levels, when compared on a spatial scale, also exhibit a unique pattern in which enhanced values are prevalent in urban areas relative to rural areas [4]. Likewise, CO<sub>2</sub> levels in indoors are commonly found to be several times higher than those in the outdoor atmosphere [5]. Because of the environmental significance of CO<sub>2</sub> pollution under both outdoor and indoor conditions, it is highly desirable to acquire accurate information concerning the real concentration levels of CO<sub>2</sub>.

The non-dispersive infrared (NDIR) sensors have been used widely in the real time monitoring of CO<sub>2</sub> in air [6, 7]. In a recent study, we investigated the relative performance of these sensors for the real-time analysis of CO<sub>2</sub> under open air conditions in the laboratory [8]. Based on the concurrent analysis of several sensors, we were able to demonstrate that these sensors can be employed to yield fairly unbiased data between different sensor units. In the present study, we intended to examine the accuracy of the NDIR-based sensor method as a continuation of our efforts to validate the application of such a sensor system. To this end, a series of experiments were conducted by equilibrating an enclosure system with calibrated CO<sub>2</sub> gaseous standards at known concentrations. The results of these calibration experiments were then used to explore the basic properties of the NDIR-based sensor method.

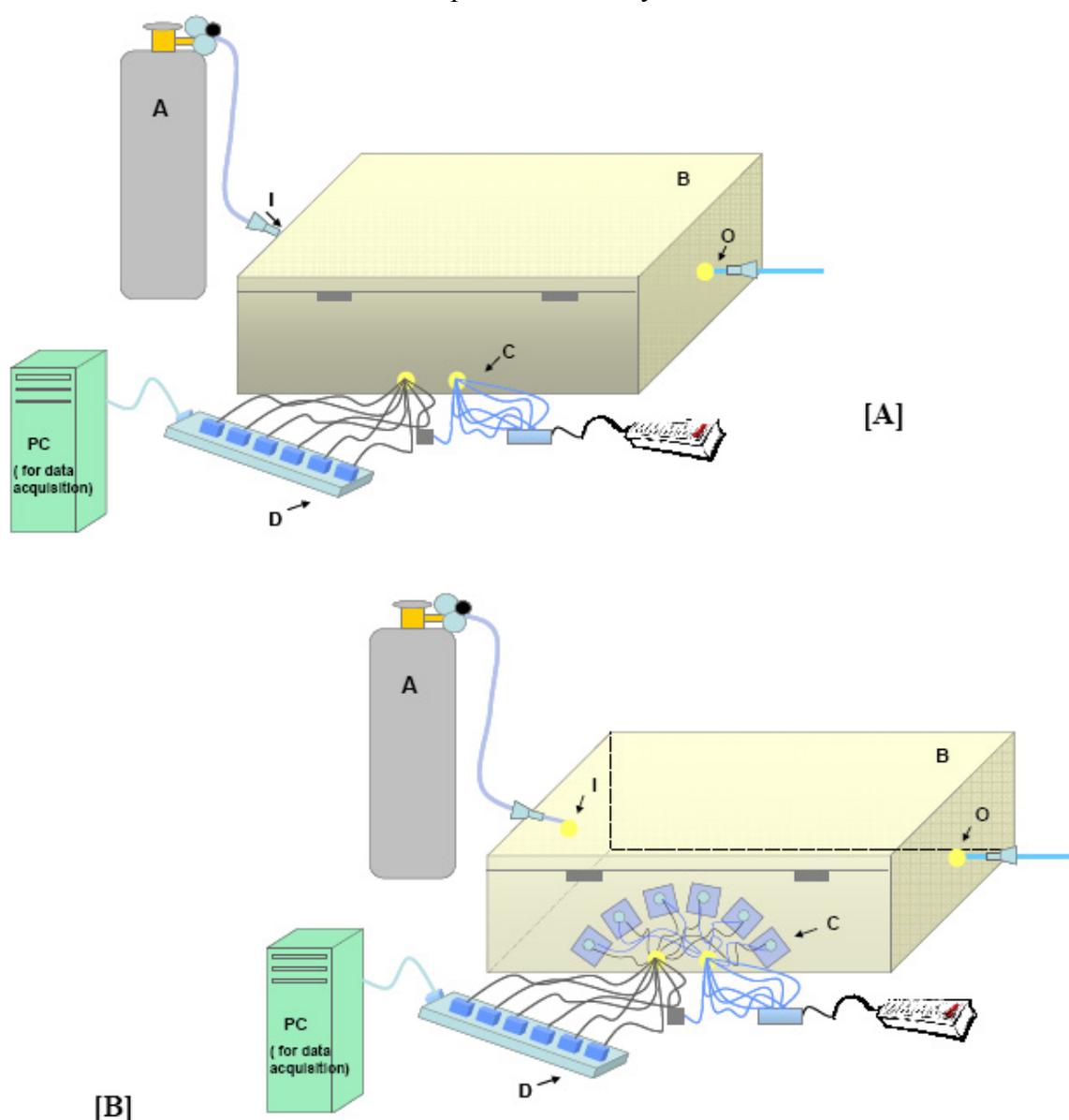
## 2. Materials and methods

### 2.1. Schematic of the analytical setup

In this study, the analytical performance of CO<sub>2</sub> sensors was evaluated using two types of the NDIR sensor model (B-530 and H-550: ELT Co., Korea). Each model is distinguished in terms of their detection range and response time. The maximum detection ranges are 10,000 and 50,000 ppm, respectively. In addition, their initial response times are less than 120 and 30 sec, respectively. More details concerning the sensor types, instrumental set-up, and quality control procedures have been described elsewhere [8]. As a simple means to examine the performance of the sensor units, an enclosure system was developed in which NDIR sensors were exposed to constant levels of CO<sub>2</sub> standards prepared at varying concentration ranges (0, 500, and 1000 ppm) (refer to Fig 1). The CO<sub>2</sub> gaseous standards used in this study were purchased at three concentration levels of 0, 497.9, and 999.9  $\mu\text{mol mol}^{-1}$  (Deok Yang Energen Co., Korea). As a platform to conduct the accuracy test, a

vacuum enclosure built to serve as a sensor repository system was used to concurrently retrieve CO<sub>2</sub> data from six individual sensors (i.e., three identical sensor units of each model introduced above) (Fig 1). The enclosure box inhabiting all the sensor units was built with nearly 35 L capacity (a dimension of 47.8×38.0 ×19.4 cm) and connected to the standard gas cylinder to supply CO<sub>2</sub> gases at a constant flow rate. Once the sensor units are connected to the data acquisition system, the punched holes in the enclosure were completely sealed with silicon adhesives. To provide the constant flow of CO<sub>2</sub> gases into this enclosure box, flow rates of standard gases were regulated by the union valve system in the inlet.

**Figure 1.** A schematic diagram of the enclosure system for the evaluation of CO<sub>2</sub> equilibration pattern based on the NDIR. sensor method: [A] closed view and [B] transparent view showing the sensor components of the system.



A = Cylinder with CO<sub>2</sub> gas standard, B = Container box (~ 35 L), C = NDIR-CO<sub>2</sub> sensor units, D = Data transferring port, I = Inlet valve, and O = Outlet valve.

## 2.2. Experimental scheme

After establishing all the experimental set-up for the enclosure system, the basic performance of this system was tested by supplying pure air (CO<sub>2</sub>-free air) contained in a cylinder to the inlet of the enclosure box at four different flow rates (i.e., 100, 200, 500 and 1000 mL min<sup>-1</sup>). By flushing the container (initially equilibrated with the laboratory air at CO<sub>2</sub> concentrations of approx. 400-450 ppm) with CO<sub>2</sub>-free air, the general circulation cycle to attain equilibrium was assessed as a function of flow rate and time (Table 1). The concentration of CO<sub>2</sub> in the container decreased gradually with the mixing of the CO<sub>2</sub>-free air until the 0 ppm was recorded (Fig 2). Based on our initial experiment with CO<sub>2</sub>-free air, the time required for the system equilibration was quantified at each individual flow rate.

**Table 1.** Experiment schedule in this study for the analysis of CO<sub>2</sub> equilibrium using a dynamic enclosure system

[A] Initial test to evaluate the equilibrium pattern of the enclosure system using CO <sub>2</sub> -free air					
Experiment	CO <sub>2</sub> concentration (ppm)	Flow rate (mL min <sup>-1</sup> )	Exp date	Total duration (min)	Predicted duration for equilibration (min) <sup>1]</sup>
1	0	1000	07. Sep 07	120	1283
2	0	500	07. Sep 07	300	710
3	0	200	08. Sep 07	650	303
4	0	100	09. Sep 07	1140	155
[B] Comparison with the calibrated CO <sub>2</sub> standards at two concent:					
5	500	500	13. Sep 07	360	303
6	1000	500	14. Sep 07	360	303

1] Calculation based on empirical equation by considering total volume of the box (i.e., approx. 35 L) containing all the sensors.

Upon completing the initial test with CO<sub>2</sub>-free air, the experiments proceeded to the next stage with two known concentrations of CO<sub>2</sub> standards (500 and 1000 ppm). For all experiments in the second stage, the NDIR sensors were tested at a single flow rate of 500 mL min<sup>-1</sup> (Table 1). The moderate flow rate of 500 mL min<sup>-1</sup> was selected because it was plausible to attain the system equilibration under reasonably long durations (Fig 3). The measurements for each of the two CO<sub>2</sub> standards (500 and 1000 ppm levels) were initiated immediately after equilibrating the container with the CO<sub>2</sub>-free air (To make a parallel comparison between different experiments, CO<sub>2</sub> values for each experiment were forced to rise from the zero ppm level). Knowing that the duration for equilibration at a flow rate 500 mL min<sup>-1</sup> requires approx. 300 min, the experiments for those two concentration levels were conducted well above the predicted equilibration time (i.e., up to 360 min duration). This was intended to ensure the complete equilibration of the enclosure system at given CO<sub>2</sub> concentration levels.

The CO<sub>2</sub> data sets for each experiment were initially retrieved at each 3-second interval but analyzed after being converted into 10-min averaged values (by pooling them together for each 10-min interval). This 10-min conversion was made to optimize the handling of CO<sub>2</sub> data with the Excel program from raw data sets with enormously large number. To examine the reliability of this 10-min conversion, the variabilities of two different data sets (primary 3-sec vs. converted 10-min data) were compared using the results of a 1000-ppm CO<sub>2</sub> analysis. The data sets with two different intervals, taken after the equilibration (i.e., after 300 min), were compared in terms of the relative standard error (RSE %) values of all the six sensor units, the results were highly comparable between the raw (3.02 ±

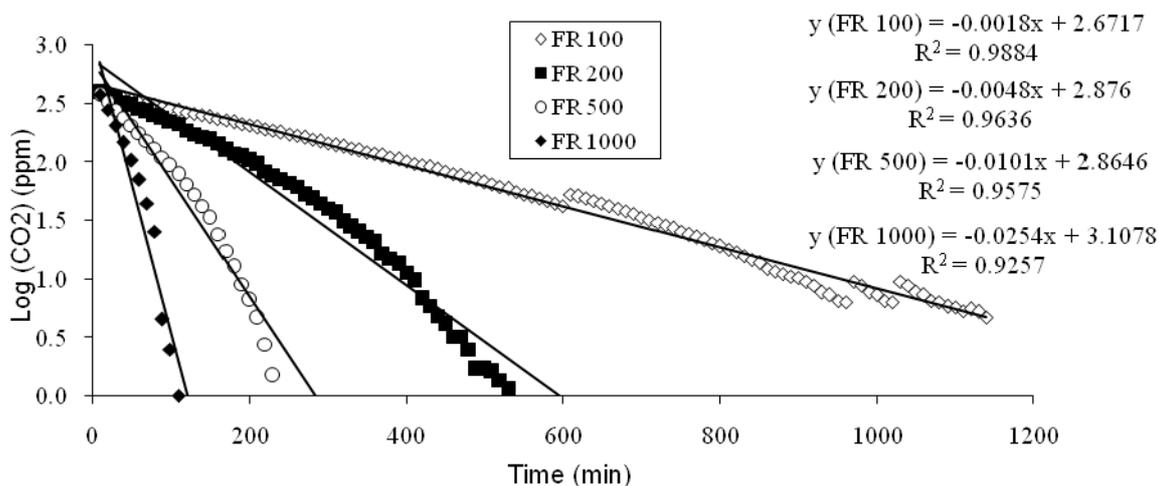
0.10%) and the converted data sets ( $2.68 \pm 0.02\%$ ). When the reproducibility of our individual sensor model is assessed based on the repetitive measurement of an equilibrated CO<sub>2</sub> sample, it ranged from 0.08 (H1) to 0.17% (H3) for H-500 and 0.10 (B1) to 0.13% (B3) for the B-530 model. Hence, all of our analysis of these sensor systems was mainly made using these 10-min converted data sets.

### 3. Results and discussions

#### 3.1. The general pattern of CO<sub>2</sub> circulation in the container

In order to investigate the dynamic equilibration pattern of the enclosure system investigated in this study, a series of preliminary tests were conducted initially using CO<sub>2</sub>-free air. As shown in Table 1, the results of this test conducted at four different flow rates (i.e., 100, 200, 500, and 1000 mL min<sup>-1</sup>) demonstrated that all the sensor units exhibited highly systematic patterns at each individual flow rate (Fig 2). As shown in Fig 2, log (CO<sub>2</sub>) values tend to maintain strong inverse correlations with time. Hence, to learn more about the fundamental features of CO<sub>2</sub> circulation in an enclosure system, these experimental results were utilized to derive the empirical relationship between all the experimental variables.

**Figure 2.** A plot for CO<sub>2</sub> equilibration pattern derived by an enclosure system investigated in this study: tests were conducted at four different flow rates (FR (mL min<sup>-1</sup>)) of CO<sub>2</sub>-free air shown in the legend box. Results are drawn as log (CO<sub>2</sub>) concentration vs. time (linear regression equations derived at each flow rate).



In order to describe the exchange dynamics of CO<sub>2</sub> gas in a quantitative manner, the experimental data acquired from the CO<sub>2</sub>-free gas were used to fit the non-linear equations via a trial and error. As a result, the equation (1) was derived to equally consider the major parameters involved in this exchange process:

$$C = [\text{CO}_2(t)/\text{CO}_2(i)] = \{1 - 0.00015 \cdot t - 0.00000629 \cdot t \cdot \text{FR}\}^{3.5724}, \quad (1)$$

where [1] the concentration of CO<sub>2</sub> expressed as the ratio between a given time (CO<sub>2</sub>(t)) and the initial time (CO<sub>2</sub>(i)) (unitless), [2] flow rate (FR) of CO<sub>2</sub>-free gas (mL min<sup>-1</sup>), and [3] time (t) for the equilibration (min).

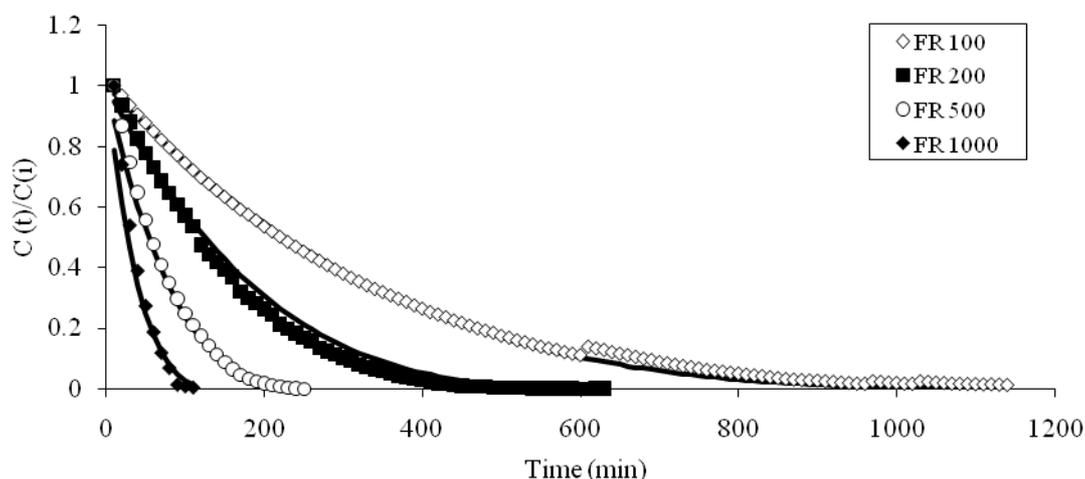
From this equation, the equilibration time to reach the CO<sub>2</sub> concentration (of zero or any other concentration values) at a given flow rate (mL min<sup>-1</sup>) can be computed by the following equation:

$$t = 1 / (0.00015 + 0.00000629 \text{FR}) \quad (2)$$

According to the above formula, the equilibration times for all four flow rates (100, 200, 500, and 1000 mL min<sup>-1</sup>) are computed as 1283, 710, 303, and 155 minutes, respectively (Table 2).

To evaluate the efficacy of these model-fit equations, a parallel comparison was made between observed and predicted values of CO<sub>2</sub> ratio (Fig 3). As seen in the Fig 3, the observed route of CO<sub>2</sub> equilibration in the enclosure system shows an excellent agreement with the predicted pattern at each of all flow rates.

**Figure 3.** A parallel comparison of the observed and predicted equilibration pattern of CO<sub>2</sub> concentration ratio; results are shown as the concentration ratio for the derivation of empirical formula. The predicted CO<sub>2</sub> values are shown as lines.



**Table 2.** Comparison of analytical bias of the NDIR sensor system: Results are shown in terms of both [A] CO<sub>2</sub> concentration level and [B] percent deviation (PD) values derived by all 6 sensor units employed in the analysis of CO<sub>2</sub>.

[A] CO<sub>2</sub> concentration data acquired after the equilibration time (300-360 min duration)<sup>1]</sup>

Concentration level		Sensor units						Grand mean
		B1 <sup>2]</sup>	B2	B3	H1 <sup>3]</sup>	H2	H3	
[A] 500 ppm (N=6)	Mean ± SD (Median)	453 ± 1.11 (453)	441 ± 1.41 (441)	427 ± 1.90 (427)	536 ± 1.23 (536)	524 ± 1.00 (524)	483 ± 2.16 (483)	477 ± 44.9 (468)
	Range	451-454	439-443	424-430	534-537	522-525	481-486	427-536
[B] 1000 ppm (N=6)	Mean ± SD (Median)	919 ± 2.42 (920)	903 ± 2.59 (903)	885 ± 2.87 (885)	1031 ± 2.07 (1031)	1025 ± 3.22 (1025)	963 ± 3.98 (964)	954 ± 62.7 (941)
	Range	915-921	900-906	880-888	1028-1034	1020-1029	958-969	885-1031

[B] PD values derived after the equilibration time (300-360 min duration)<sup>1]</sup>

Concentration level		Sensor units						Grand mean <sup>4]</sup>
		B1 <sup>2]</sup>	B2	B3	H1 <sup>3]</sup>	H2	H3	
[A] 500 ppm (N=6)	Mean ± SD (Median)	-9.39 ± 0.22 (-9.33)	-11.7 ± 0.28 (-11.7)	-14.6 ± 0.38 (-14.6)	7.30 ± 0.10 (7.33)	4.83 ± 0.08 (4.85)	-3.30 ± 0.18 (-3.38)	8.52 ± 4.25 (8.34)
	Range	-9.78 ~ -9.17	-12.2 ~ -11.4	-15.1 ~ -13.9	6.93-7.55	4.50-5.06	-3.69 ~ -2.66	3.30-14.6
[B] 1000 ppm (N=6)	Mean ± SD (Median)	-8.03 ± 0.24 (-7.91)	-9.65 ± 0.26 (-9.65)	-11.5 ± 0.29 (-11.5)	3.15 ± 0.21 (3.15)	2.53 ± 0.32 (2.59)	-3.62 ± 0.40 (-3.58)	6.41 ± 3.81 (5.83)
	Range	-8.46 ~ -7.85	-10.0 ~ -9.35	-11.9 ~ -11.2	2.88-3.46	2.03-2.89	-4.15 ~ -3.05	2.53-11.5

### 3.2. The accuracy of NDIR-CO<sub>2</sub> analysis

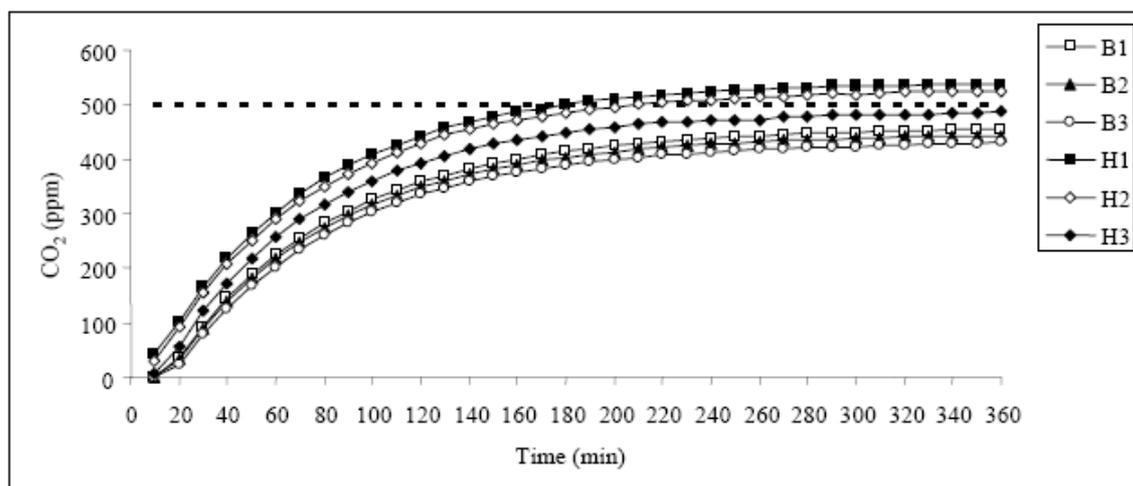
In an attempt to investigate the analytical bias arising from the application of the NDIR-system, the accuracy of the NDIR method was assessed using CO<sub>2</sub> standards prepared at the two concentration levels of 500 and 1000 ppm. Based on our initial equilibration experiments using CO<sub>2</sub>-free air, all experiments representing CO<sub>2</sub> levels of 500 and 1000 ppm were conducted at a moderate flow rate of 500 mL min<sup>-1</sup>. As shown in Fig 4, the concentration of CO<sub>2</sub> increased systematically with time to reach their respective equilibration concentrations (i.e., near 500 and 1000 ppm) after the equilibration point (approx. 300 min). The observed pattern suggests that the NDIR sensors behave systematically to detect the changes in the CO<sub>2</sub> concentrations. As summarized in Table 2A, the results taken from the 500 ppm CO<sub>2</sub> standard gas showed an average CO<sub>2</sub> concentration of 477 ± 44.9 ppm with a range of 427-536 ppm after the equilibration time (using the data taken between 300 and 360 min). Likewise, the experimental data for the 1000 ppm CO<sub>2</sub> standard, taken for the similar duration, averaged 954 ± 62.7 ppm with a range of 885-1031 ppm.

The CO<sub>2</sub> data obtained from these comparative experiments were used to compute the percent deviation (PD) values of each sensor unit. The PD values were calculated by subtracting the CO<sub>2</sub> concentration value for a given unit by the known value of CO<sub>2</sub> for the respective gaseous standard:

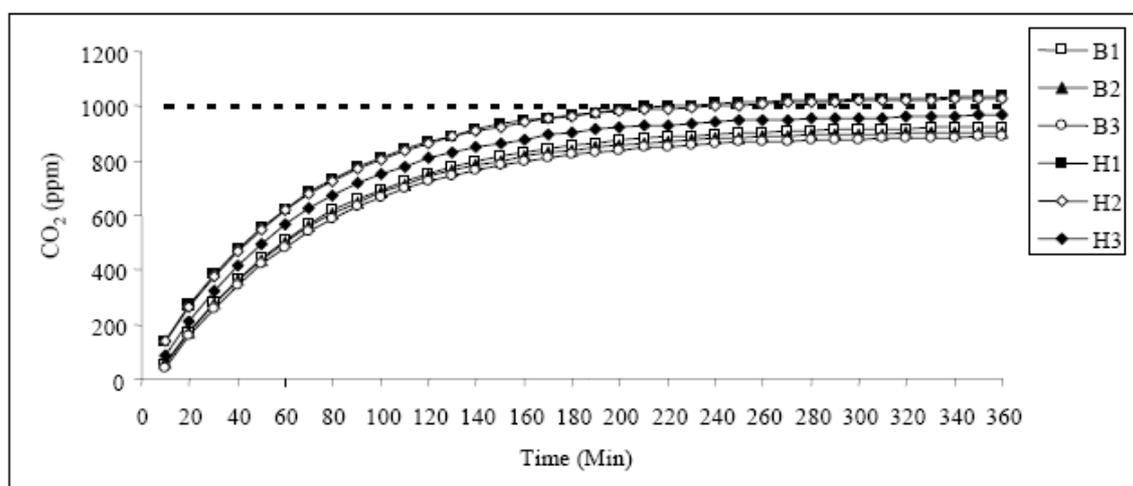
$$PD = \frac{[(CO_2(\text{obs}) - CO_2(\text{known}))]}{[CO_2(\text{known})]} \times 100 \quad (3)$$

where CO<sub>2</sub>(obs) is the mean CO<sub>2</sub> value observed by all sensor units, and CO<sub>2</sub>(known) is the actual CO<sub>2</sub> concentration of standard (i.e., 500 and 1000 ppm). The PD values obtained using the CO<sub>2</sub> values in the equilibrium stage (during the 300 to 360 min of the study duration) are summarized in Table 2.

**Figure 4.** The performance of the CO<sub>2</sub> sensors between different sensor units; tests were made with two known concentrations of CO<sub>2</sub> gaseous standards at [A] 500 and [B] 1000 ppm. All dotted lines show the absolute concentration values of calibrated CO<sub>2</sub> standard for the given test.



[A] 500 ppm



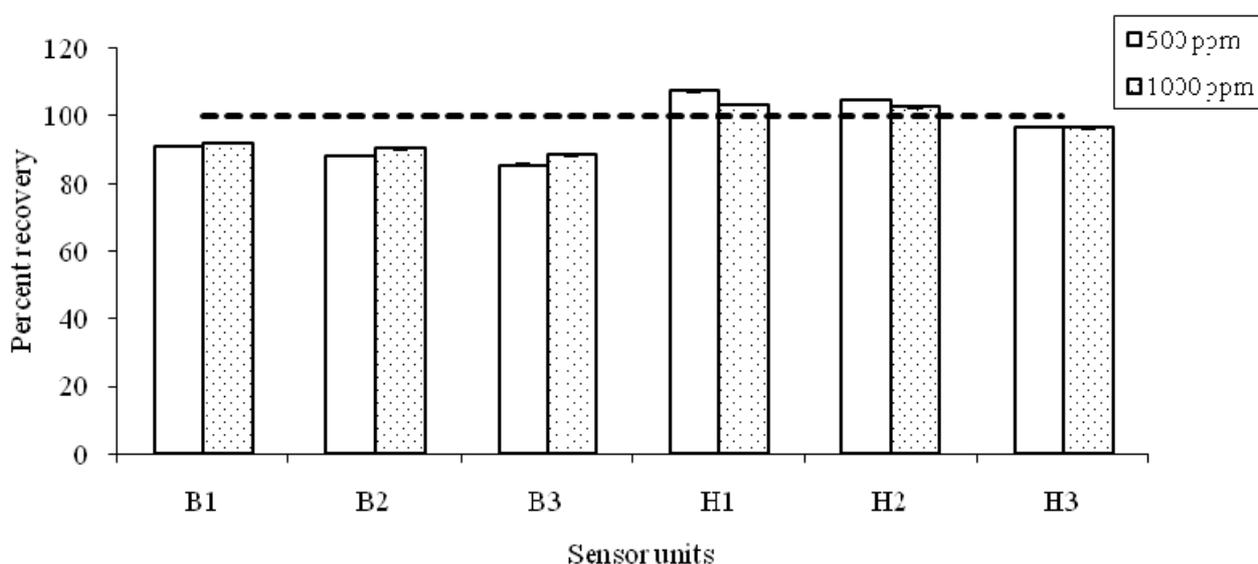
[B] 1000 ppm

As shown in Table 2B, the sensor units of the model type B-530 showed a negative bias for the 500 ppm CO<sub>2</sub> measurement in terms of their PD values (ranging from -14.6 % (B3) to -9.39 % (B1)). In contrast, H-500 units generally exhibited a positive bias, with PD values of +7.30 (H1) and +4.83% (H2) (with the exception of the H3 unit). The results of 1000 ppm experiment in fact showed patterns that are highly analogous to the 500 ppm experiment.

As another means to assess the analytical bias of NDIR sensor units, the percent recovery (PR) rates of each sensor unit were computed and plotted for CO<sub>2</sub> standards at both concentration levels (500 and 1000 ppm) (Fig 5). The PR is calculated by dividing the mean CO<sub>2</sub> concentration (after the equilibration time) with the known standard concentration (i.e., after approx. 300 min onwards for 60 min; refer to Table 2 for details). The PR value of the 500 ppm CO<sub>2</sub> standard averaged  $95.4 \pm 8.95$  % with a range of about 86 to 107 %. Similarly, the PR values for the 1000 ppm test averaged  $95.4 \pm 6.27$  % with a range of about 88 to 103 %. As such, the accuracy of NDIR sensor investigated in this

study seems to approach the 5% level, if the accuracy is expressed as the difference between the unity and the recovery ratio. Although the absolute accuracy of the NDIR-based CO<sub>2</sub> sensors seemed to improve slightly at the 1000 ppm level, their variabilities do not appear to be significant with increasing concentration levels. The results of the present study thus indicate that the performance of the NDIR method is fairly stable and reproducible in the tested concentration ranges in terms of its precision and accuracy.

**Figure 5.** Percent recovery (PR) computed for each sensor unit based on the NDIR-based analysis of CO<sub>2</sub>. Dotted line denotes the theoretical recovery rate (100%). The standard error bars for the repetitive measurement of CO<sub>2</sub> are shown for each individual sensor unit.



To evaluate the compatibility of each sensor unit in the CO<sub>2</sub> measurement, a correlation analysis was performed using the CO<sub>2</sub> concentration data acquired by all sensor units at each flow rate. The results of the correlation analyses for three different concentration levels (i.e., 0, 500, and 1000 ppm) are summarized in Table 3. As shown in Table 3, all the sensor units showed highly significant correlations with each other in terms of their correlation strengths (i.e.,  $R^2 > 0.99$ ,  $p = 0.01$ ). Although the correlation results of the CO<sub>2</sub>-free air were the strongest of all, the results of high CO<sub>2</sub> levels (500 or 1000 ppm) were also indistinguishable in that respect; all sensor units showed correlation coefficients approaching the unity ( $> 0.999$ ), irrespective of the model types. Hence, as seen in our earlier study based on side-by-side monitoring of ambient CO<sub>2</sub> levels under the laboratory conditions [8], we were able to obtain highly comparable patterns between different sensor units. The findings of relatively enhanced compatibility between different sensor units or with CO<sub>2</sub> standard gases may be ascribable to the use of a stable equilibrium system developed for the comparative test.

**Table 3.** Results of correlation analysis between CO<sub>2</sub> concentration data (10-min converted data) derived at 3 concentration ranges: [A] 0, [B] 500, and [C] 1000 ppm.

[A] Results of CO<sub>2</sub>- free air (CO<sub>2</sub> = 0 ppm)

	B1	B2	B3	H1	H2	H3
B1	1.000					
B2	1.000	1.000				
B3	1.000	1.000	1.000			
H1	0.997	0.998	0.998	1.000		
H2	0.997	0.998	0.998	1.000	1.000	
H3	0.995	0.996	0.997	1.000	1.000	1.000

All correlations are significant at 0.01 level (N= 30)

[B] Results of the intermediate range (CO<sub>2</sub> = 500 ppm)

	B1	B2	B3	H1	H2	H3
B1	1.000					
B2	1.000	1.000				
B3	1.000	1.000	1.000			
H1	0.999	0.999	0.999	1.000		
H2	0.999	0.999	0.999	1.000	1.000	
H3	0.999	0.999	0.999	1.000	1.000	1.000

All correlations are significant at 0.01 level (N= 36)

[C] Results of the highest range (CO<sub>2</sub> = 1000 ppm)

	B1	B2	B3	H1	H2	H3
B1	1.000					
B2	1.000	1.000				
B3	1.000	1.000	1.000			
H1	1.000	1.000	1.000	1.000		
H2	1.000	1.000	1.000	1.000	1.000	
H3	1.000	1.000	1.000	1.000	1.000	1.000

All correlations are significant at 0.01 level (N= 36)

### 3.3 Comparison between different detection techniques

As a simple means to assess the analytical reliability of our sensor method in the CO<sub>2</sub> analysis, the previous records of diverse measurement techniques involved in CO<sub>2</sub> analysis were explored in terms of accuracy and precision (Table 4). According to this analysis, it is found that many scientists relied on the Gas chromatographic (GC) method for the CO<sub>2</sub> analysis. For instance, Ekeberg et al (2004) attempted to quantify the precision and accuracy of certified CO<sub>2</sub> standards by GC with mass spectrometry (GC-MS) [9]. The results of their GC-MS analysis revealed accuracy near  $\pm 4\%$  for a 977  $\mu\text{L/L}$  certified CO<sub>2</sub> standard; their results appear to be highly comparable to the overall mean accuracy observed in this study (i.e., 4.60%), which was in fact determined from a comparable CO<sub>2</sub> concentration range (i.e., 1000 ppm) using all six sensor units (Table 2B). It is also found that the overall mean precision of the repetitive analysis made by GC-MS (2.30%) is highly comparable with

those derived by our sensor method (2.68%). In comparison, the GC-TCD method for CO<sub>2</sub> analysis has shown an accuracy of  $\pm 5.3\%$  in the range of 2270-10000 ppm [10]. The precision of the GC-TCD and GC-FIA techniques was also estimated by the repetitive measurement of CO<sub>2</sub> at a constant concentration level (approx. 340 ppm), and the results were found to be 6.20% and 5.98%, respectively [11].

**Table 4.** A comparative evaluation of various detection methods in the CO<sub>2</sub> analysis; all data compared in terms of precision and accuracy.

Method	Measurement condition	Mean (ppm)	SD	N	Accuracy	Precision RSE (%)	Reference
NDIR-sensor	Enclosure system	954	62.7	6	4.60	2.68	This study
NDIR-sensor	Enclosure system	477	44.9	6	4.60	3.84	This study
NDIR-sensor	Laboratory	429	33	6	NA	2.33	Pandey and Kim [8]
GC-MS	Certified CO <sub>2</sub> standard	1016	74	10	3.99	2.30	Ekeberg et al.[9]
CF-GC/IRMS	Test cylinders	328-603	0.33-0.61	10	0.18-0.38	0.33-0.61	Schauer et al.[12]
GC-TCD	CO <sub>2</sub> gas sampling bags	2270-10,000	NA	NA	5.3	0.014	NIOSH [10]
GD-FIA	In open air (Laboratory)	338	35	3	NA	5.98	Satierperakul [11]
GC-TCD	In open air (Laboratory)	335	36	3	NA	6.2	Satierperakul [11]
GD-FIA	Undercover car parking	565	9	3	NA	0.92	Satierperakul [11]
GC-TCD	Undercover car parking	554	15	3	NA	1.56	Satierperakul [11]
Detector tube analysis	Indoor air	800-1000	NA	NA	NA	5-7	Norback [13]

1] Accuracy is expressed as the difference between the unity and recovery ratio.

2] Data not available.

3] Accuracy is expressed in terms of the differences between the means of two systems, i.e., DI-IRMS/NDIR and CF-IRMS.

4] Precision is expressed as the standard deviation of the samples analyzed on the automated systems.

In a continuous-flow isotope ratio mass spectrometric (CF-IRMS) analysis of CO<sub>2</sub>, the accuracy was estimated in the 0.18-0.38 range as differences between the means of two systems, i.e., dual-inlet isotope ratio mass spectrometry/nondispersive infrared gas analysis system (DI-IRMS/NDIR) and automated system of CF-IRMS in the analysis of five CO<sub>2</sub> test gases covering a concentration range of 328 to 603  $\mu\text{mol mol}^{-1}$  [12]. The overall precision of CF-IRMS was estimated at 0.04% for the five CO<sub>2</sub> test gases covering a concentration range of 328 to 603  $\mu\text{mol mol}^{-1}$  [12]. A comparative study of a CO<sub>2</sub> 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 [13]. In comparison, the relative error in the CO<sub>2</sub> measurement was reported at -3.0% by the continuous-flow method using a conductimetric detector [14].

Considering the performance of various measurement techniques introduced in the previous studies, the NDIR method investigated in the present study appears to be fairly reliable and capable of the near real-time analysis of CO<sub>2</sub> in terms of its accuracy and precision. In view of the fact that other techniques (such as GC-TCD, GC-MS, and CF-IRMS, etc.) should consider the delicate arrangement for instrumental management (complicated operating procedures, high cost, duration for the data acquisition, etc), the simple, economic NDIR sensor technique can be comparatively advantageous from a number of aspects (e.g., affordability, handling, and rapid measurement time).

#### 4. Conclusions

In the present study, an effort was made to evaluate the accuracy of the NDIR sensor by equilibrating an enclosure system with CO<sub>2</sub> gases at known concentration levels. As the basic tool for such a purpose, a dynamic enclosure system was built to attain CO<sub>2</sub> equilibrium at different CO<sub>2</sub> concentration levels. The status of the equilibrium was measured by 6 sensor units with two different model types. By acquiring the equilibrium concentration data of CO<sub>2</sub> by the enclosure system, we were able to derive empirical equations in which the CO<sub>2</sub> concentration can be predicted at a given time and flow rate. The accuracy of the NDIR-sensor was hence assessed by comparing the observed and calibrated CO<sub>2</sub> concentration levels derived based on our experimental design.

According to the analysis of calibrated CO<sub>2</sub> gases at 500 and 1000 ppm, the NDIR system was found to maintain approx. 5% accuracy. Moreover, when the CO<sub>2</sub> data obtained by all the sensor units were compared, an excellent compatibility was maintained throughout the entire side-by-side analysis. The results of correlation analysis indicated that all sensor units had a correlation coefficient approaching the unity (> 0.999 at 0.01 level), regardless of model type or concentration range. The overall results of this study thus suggest that NDIR sensors can be used to produce highly reliable data sets for CO<sub>2</sub> analysis in both absolute and relative senses. It should also be pointed out that the concentration range examined in this study (0 to 1000 ppm) covers the current atmospheric CO<sub>2</sub> levels (approx. 380 ppm), as reported by the WMO and the IPCC. Hence, one can explore the possibility of utilizing these sensors in the real time monitoring of atmospheric CO<sub>2</sub>, as they have been proven to be competent in terms of experimental performance, like other instrumental methods with proven reliability.

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