

Technique for Measuring Air Flow and Carbon Dioxide Flux in Large, Open-Top Chambers

Jay M. Ham,* C. E. Owensby, and P. I. Coyne

ABSTRACT

Open-Top Chambers (OTCs) are commonly used to evaluate the effect of CO₂, O₃, and other trace gases on vegetation. A study was conducted to develop and test a new technique for measuring forced air flow and net CO₂ flux from OTCs. Experiments were performed with a 4.5-m diam. OTC that had a sealed floor and a specialized air delivery system. Air flow through the chamber was computed with the Bernoulli equation using measurements of the pressure differential between the air delivery ducts and the chamber interior. An independent measurement of air flow was made simultaneously to calibrate and verify the accuracy of the Bernoulli relationship. The CO₂ flux density was calculated as the product of chamber air flow and the difference in CO₂ concentration between the air entering and exhausting from the OTC ($C_{in} - C_{out}$). Accuracy of the system was evaluated by releasing CO₂ within the OTC at known rates to emulate respiration from the field surface. Data were collected with OTCs at ambient and elevated CO₂ ($\approx 700 \mu\text{mol mol}^{-1}$). Results showed that the Bernoulli equation, with a flow coefficient of 0.7, accurately measured air flow in the OTC to within $\pm 5\%$ regardless of flow rate and air duct geometry. Experiments in ambient OTCs showed that CO₂ flux density ($\mu\text{mol m}^{-2} \text{ s}^{-1}$), computed from 2-min averages of air flow and $C_{in} - C_{out}$, was typically within $\pm 10\%$ of actual flux, provided that the exit air velocity at the top of the OTC was greater than 0.6 m s^{-1} . Obtaining the same level of accuracy in CO₂-enriched OTCs, however, required a critical exit velocity near 1.2 m s^{-1} to minimize the incursion of ambient air and prevent contamination of the exit gas sample. When flux data were integrated over time to estimate daily CO₂ flux ($\mu\text{mol m}^{-2} \text{ d}^{-1}$), actual and measured values agreed to within $\pm 2\%$ for both ambient and CO₂-enriched chambers, suggesting that accurate measurements of daily net C exchange are possible with this technique.

OPEN-TOP CHAMBERS (OTCs) have been used since the early 1970s to evaluate the effects of trace gases on vegetation (Heagle et al., 1973; Mandle et al., 1973). The OTC was developed to provide a method for modifying aerial gas concentrations, while minimizing the effect of the chamber on plant microclimate. A typical OTC is composed of a cylindrical metal frame covered with transparent plastic film. Chambers are usually 1.5 to 4.5 m in diameter and have a large opening in the top of the chamber that is 50 to 100% of the chamber's basal area. This opening allows a portion of the natural rainfall and solar radiation to reach the surface. Additionally, the large opening allows for rapid forced exchange of air (2–4 chamber volumes per minute), which minimizes the effect of the chamber on air temperature and humidity. A variety of chamber styles have been employed to evaluate the effect of O₃ (Heagle et al., 1973; Mandle et al., 1973; Kats et al., 1985; Jetten, 1982), CO₂ (Rogers et al., 1983; Drake et al., 1989), and SO₂ (Roberts et al., 1983).

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Open-top chambers are well suited for studying the effect of elevated CO₂ on natural and agricultural ecosystems. These experiments often require long-term CO₂ enrichment as plants grow in their native soil and experience normal fluctuations in climate (Rogers et al., 1984; Drake and Leadley, 1991; Owensby et al., 1993). The effect of elevated CO₂ is often quantified by comparing growth dynamics inside CO₂-enriched chambers to those in chambers aspirated with ambient (non-enriched) air. Although biomass measurements provide an integrated assessment of treatment effects, more explicit measurements of CO₂ exchange are needed to evaluate the effect of elevated CO₂ on photosynthesis, respiration, and the ecosystem C budget. Researchers often measure single-leaf photosynthesis inside OTCs using a portable gas exchange system (Wullschlegel et al., 1992). However, such techniques only provide information on leaf fluxes at a given point and time and do not measure the integrated response of the ecosystem to long-term CO₂ enrichment.

One possible method for measuring net carbon exchange (NCE) within OTCs involves operating the chamber as an "open" gas exchange system. In the open-system approach, NCE is simply a function of the air flow rate through the system and the differences in CO₂ concentration between the air entering and exhausting from the chamber. Unfortunately, the large opening in the top of OTCs makes it difficult to accurately sample the exhaust gas concentration. During periods of high wind, incursion of outside air down through the top opening can contaminate the gas concentrations inside the OTC (Davis et al., 1983; Schmitt and Ruck, 1987; Jetten, 1992). This problem is more pronounced in CO₂-enriched chambers, in which large differences in CO₂ concentrations exist between the chamber and outside air. Another problem with the open-system approach is quantifying the air flow rate through the chamber. This measurement is often difficult and expensive in OTCs because of the complex nature of the air handling systems. Leadley and Drake (1993) overcame the problem of turbulent incursion by temporarily adding a top or "chimney" to their 1.5-m diam. OTCs that restricted the opening to 0.2 m in diameter. This procedure eliminated incursions and allowed accurate CO₂ sampling required for the NCE measurements in both ambient and CO₂-enriched chambers. However, the logistics of the method coupled with microclimate effects required that the supplemental tops be removed after about 4 d of continuous measurement. Grimm and Fuhrer (1992) also added temporary tops to their OTCs to measure CO₂ fluxes during an O₃ exposure experiment.

Previous measurements of NCE in OTCs have been conducted in small (1.5-m diam.), modified chambers over relatively short periods of time (<7 d). Although these data are informative, uninterrupted measurements

Abbreviations: OTC, open-top chamber; NCE, net carbon exchange; IRGA, infrared gas analyzer; RMSE, root mean square error.

of NCE from the surface are needed over the entire growing season to accurately quantify terrestrial C budgets. Unfortunately, techniques are not available for obtaining continuous measurements of CO₂ flux during long-term CO₂ enrichment experiments, even though this methodology is crucial for determining if ecosystems are sequestering or outgassing C in response to elevated CO₂ and climate change.

The purpose of our research was to develop and test a technique for obtaining continuous, long-term measurements of NCE from surfaces encompassed by OTCs. The research had two distinct objectives. First, we wanted to evaluate the feasibility of estimating air flow through an OTC using measurements of pressure differentials within the air delivery system. This approach would eliminate the need for sophisticated and expensive air straighteners, anemometer arrays, and Pitot tubes normally used to estimate chamber aspiration rates. Our second objective was to evaluate the utility of combining pressure-based flow data with measurements of CO₂ to estimate NCE using an open- (flow-through) system approach. The accuracy of both the air flow and CO₂ flux measurements were evaluated by comparing results with independent measurements under a range of environmental conditions in the field. Results document the feasibility and potential accuracy for measuring gas exchange within OTCs when conducting experiments on CO₂ enrichment and pollutant exposure.

THEORY

Carbon dioxide flux in an OTC can be expressed as

$$J_{\text{CO}_2} = \frac{F_v}{A}(C_{\text{in}} - C_{\text{out}}) \quad [1]$$

where J_{CO_2} is CO₂ flux density ($\mu\text{mol m}^{-2} \text{s}^{-1}$), F_v is air exchange rate ($\text{m}^3 \text{s}^{-1}$), A is the ground area encompassed by the OTC (m^2), and $(C_{\text{in}} - C_{\text{out}})$ represents the difference in CO₂ concentration between air entering and exhausting from the chamber ($\mu\text{mol m}^{-3}$). Because A is constant, only measurements of F_v and $C_{\text{in}} - C_{\text{out}}$ are required to calculate J_{CO_2} .

Evaluating techniques for determining F_v requires knowledge of the chamber's air handling system. Air usually is forced into an OTC using an axial fan positioned outside the chamber. A duct directs air from the fan into the OTC, where it is distributed within the chamber using a perforated plenum. The plenum is a large plastic tube connected to the sides of the chamber that has hundreds of circular orifices to direct air flow toward the vegetation (Fig. 1). Traditionally, F_v has been determined by measuring the velocity profile in the duct that connects the fan to the chamber. However, vortices generated by the fan often require that air straighteners be used to condition the flow stream before the velocities can be measured accurately (Jetten, 1992). An array of velocity sensors must then be positioned across the flow stream to estimate the average cross-sectional velocity in the duct. The expense and logistics of operating air straighteners and arrays of velocity sensors in a large number of chambers would be prohibitive.

An alternative hypothesis for measuring F_v can be developed by utilizing an approach analogous to that used in orifice flowmeters (i.e., obstruction flowmeters). This flow-metering principle is often used in pipes, and involves placing an orifice inside the pipe that has an area of flow less than that of the unobstructed pipe. The restriction causes a drop in pressure to develop across the orifice that varies with flow rate (Doebelin, 1990). The plastic plenum used to distribute air inside the OTC offers an opportunity to exploit the orifice flow-metering con-

cept. The plenum represents the greatest restriction to forced air flow in most OTCs and, thus, becomes highly pressurized. Air flow out of the plenum occurs through hundreds of small circular orifices of known geometry. Therefore, each of the orifices in the plenum could be treated as an orifice flowmeter, and the sum of their flows would represent the air flow rate through the whole chamber, F_v . This suggests that flow through an OTC could be determined by simply measuring the pressure difference between the plenum and the chamber interior. Air flow through orifice flowmeters is normally calculated with the Bernoulli equation, where flow is proportional to the square root of pressure drop across the restriction (Doebelin, 1990). With the assumption that F_v can be modeled as the sum of the flow through all orifices in the plenum, a Bernoulli equation for an OTC would take the form

$$F_v = KA_o \sqrt{\frac{2(P_1 - P_2)}{\rho}} \quad [2]$$

where K is an empirical flow coefficient (dimensionless), A_o is the total area of orifices in the plenum (m^2), P_1 is the average pressure inside the plenum (Pa), P_2 is the pressure in the chamber interior (Pa), and ρ is air density (kg m^{-3}). The flow coefficient is usually determined by experiment and is dependent on the size of the orifices, the geometry of the air supply duct, and the Reynolds number (Fox and McDonald, 1985). Air density, ρ , in kilograms per cubic meter can be computed as

$$\rho = \frac{P}{287.04T} \left(1 - \frac{0.378e_a}{P} \right) \quad [3]$$

where P is atmospheric pressure (Pa), T is air temperature (K), e_a is the vapor pressure of water (Pa), and 287.04 represents the ratio of the gas constant and the molecular weight of air ($\text{J kg}^{-1} \text{K}^{-1}$).

Equation [2] suggests that continuous measurements of air flow through OTCs can be accomplished using a single, differential, pressure transducer to measure $(P_1 - P_2)$. These data could be used in Eq. [1] to calculate J_{CO_2} , provided that accurate measurements of $C_{\text{in}} - C_{\text{out}}$ are attainable. The specific objective of our experiment was to test the accuracy of using Eq. [1] and [2] to estimate CO₂ flux and air flow, respectively.

MATERIALS AND METHODS

Experiments were conducted at an established CO₂-enrichment site approximately 2 km north of Manhattan, KS (39.12°N, 96.35°W). The OTCs are used at this location to study the effects of elevated CO₂ on a tallgrass prairie (Owensby et al., 1993). chambers are 4.5 m in diam. and 4 m tall, with cone-shaped baffles that reduce the diameter of the top opening to 3 m (Rogers et al., 1983). In 1992, one of the OTCs at the site was converted into a specialized engineering chamber in which F_v and J_{CO_2} could be accurately controlled by the user. The pressure-based air flow measurements (Eq. [2]) and the open-system CO₂ flux measurements (Eq. [1]) were evaluated by comparing their performance to those of known standards within the engineering OTC.

Air Flow and Pressure Measurements

The engineering OTC was identical to other chambers at the site except for specialized air-handling and CO₂-augmentation systems (Fig. 1). The fan normally used to aspirate the chamber was replaced with a variable-flow, air-handling unit composed of an elevated air intake, an axial fan, a honeycomb air

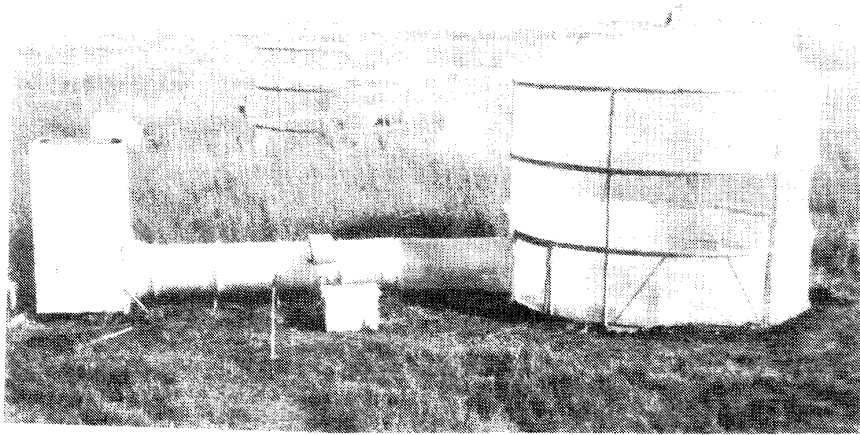


Fig. 1. Photograph of the open-top chamber (OTC) used in the study. The chamber was 4.5 m in diameter and 4.0 m in height. The system had an adjustable air-handling system that could provide flows from 1 to 4 m³ s⁻¹. Air was forced through a honeycomb air straightener and passed over an array of 10 anemometers before entering the chamber. A section of the chamber wall has been removed to reveal the perforated plenum used to discharge air into the OTC.

straightener, an anemometer array, and associated ducts (Fig. 2). Air was drawn into the unit with an adjustable-pitch axial fan that was 0.9 m in diam. and powered by a 3.7-kW motor (Powermate Panel Fan, Chicago Blower Corp., Glendale Heights, IL). The air intake was positioned 2 m above the ground to avoid large temporal variations in CO₂ that occur near the surface (Garcia et al., 1990). After exiting the fan, air traveled 1 m through a 0.76-m diam. metal duct before reaching the air control section, which consisted of two nylon

screens and a honeycomb straightener. The straightener was made from rectangular cells 0.1-m square and 0.71 m long in accordance with the recommendations of Pope (1984). Nylon screens were placed upstream and downstream of the honeycomb to reduce variation in velocity vectors parallel to the flow stream. Air velocity inside the duct was measured 1.2-m downstream of the air straightener using an array of 10 heat-balance anemometers similar to the design of Kanemasu and Tanner (1968). Sensors were positioned inside the duct to mea-

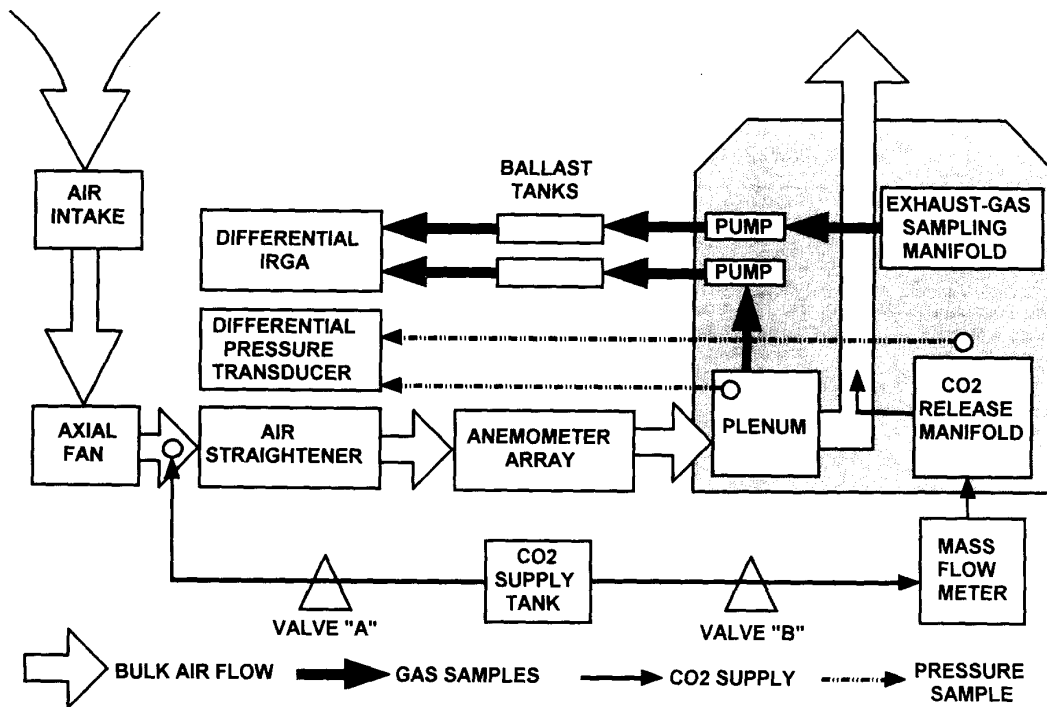


Fig. 2. Schematic diagram of the chamber, air and CO₂ management systems, and supporting instrumentation. Measurements of pressure, CO₂, and air flow are depicted.

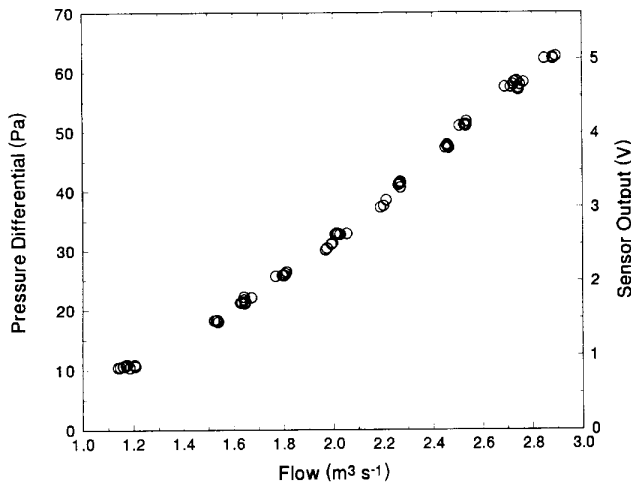


Fig. 4. Relationship between the average gauge pressure inside the plenum and air flow rate through the OTC. Also shown on the right y-axis is the corresponding output from the pressure transducer.

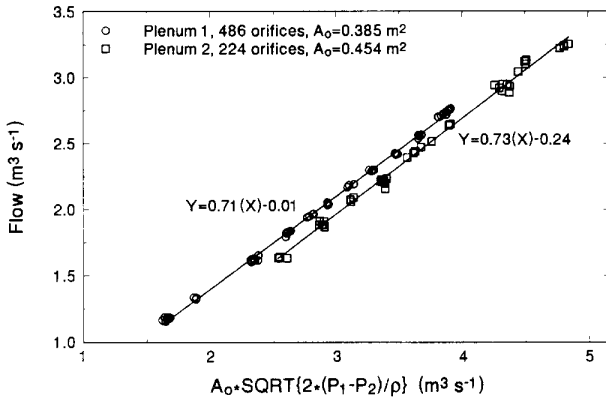


Fig. 5. Regression analysis used to determine the flow coefficients for two different plenum designs. The slope for the lines represent empirical estimates of K for the Bernoulli equation (Eq. [2]) as applied to an open-top chamber system. The R^2 values for both regression lines were greater than 0.99.

agreed to within 5 to 10%. Because the square root of $(P_1 - P_2)$ is used to calculate F_v , the relative effect of errors in P_1 were reduced.

Figure 4 shows $(P_1 - P_2)$ and the voltage output from the pressure transducer as chamber flow was varied between 1 and 3 $m^3 s^{-1}$, using the plenum with 486 orifices. Air flow was measured with the anemometer array. A strong relationship between F_v and $P_1 - P_2$ was observed, with a near-linear response at higher flow rates. The Sentra pressure transducer provided a large and sensitive output (1.72 V $m^{-3} s^{-1}$). Similar data were collected using the plenum having 286 orifices.

Anemometer-based measurements of F_v were combined with corresponding pressure data, $P_1 - P_2$, to calculate the flow coefficient, K , using Eq. [2]. Linear regression analysis was employed, where F_v was the dependent variable and all terms on the right hand side of Eq. [2], excluding K , were the independent variable. The resulting slope represented an empirical estimate of the flow coefficient. Figure 5 shows the excellent fit obtained

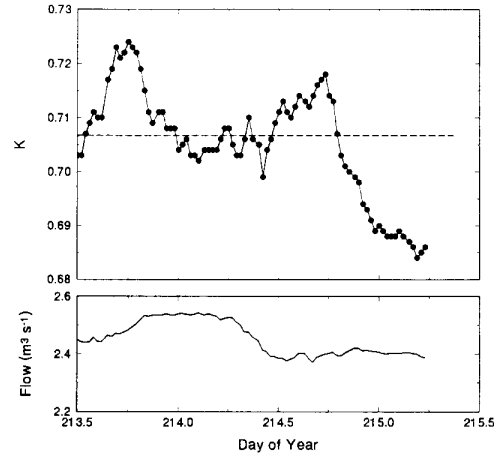


Fig. 6. Plot of the flow coefficient, K , and chamber air flow over a 2-d period for a plenum with 486 orifices. Coefficients were computed with Eq. [2] using continuous measurements of pressure and air flow. The dashed horizontal line is the average value of K over the entire test period.

using the Bernoulli model. The strong linear relationship and near-zero intercept suggest that the Bernoulli equation and orifice flow-metering concept adequately described air flow into the chamber. Flow coefficients of 0.71 and 0.73 were computed for the 486- and 224-orifice plenums, respectively. These K values are within the range expected for sharp-edged circular orifices (Fox and McDonald, 1985). A slightly better fit (lower mean square error) and almost perfect zero intercept were obtained with the 486-orifice plenum. This may indicate that plenums should be fabricated with a large number of smaller orifices instead of a few large ones.

One concern with the orifice flow-metering principle was that the flow coefficient could be influenced by vegetation growing inside the chamber. To evaluate this effect, pressure data were collected while a nylon screen was used to tightly cover 80% of the orifices on the 486-orifice plenum. Under these conditions, the Bernoulli model continued to provide a good fit to the data, but the flow coefficient dropped from 0.71 to 0.65. The screen caused only an 8.5% reduction in K , despite severe obstruction at the orifices. Thus, the growth of vegetation probably would not cause significant changes in K during the growing season.

The stability or drift in the measurement system was evaluated by monitoring fluctuations in K over a 48-h period. Fan blades were set to produce flow near 2.4 $m^3 s^{-1}$ at the start of the study, and F_v was continuously measured with the anemometer array. The flow coefficient was calculated every 2 min by simply rearranging Eq. [2] to solve for K . Flow coefficients varied between 0.725 and 0.685 over the study period (Fig. 6). These small variations in K were within $\pm 3.5\%$ of the K value determined by regression. Additionally, the mean value of K over 48 h was 0.708, which was almost identical to the regression results in Fig. 5. These data indicate that K was reasonably stable over time, even though large variations in wind speed and temperature occurred at the site.

sure the average cross-sectional velocity using standard engineering guidelines (Fan Application Manual, Air Motion and Control Assoc., Arlington Heights, IL). The air flow rate through the system, F_v , was computed as the product of the air velocity and the cross-sectional area of the duct.

Air was distributed within the chamber interior with a plenum made from 0.76-m diam. plastic tubing (Fig. 1). The plenum used for most of the study had 486 orifices that were 3.175 cm in diam. ($A_o = 0.385 \text{ m}^2$). During certain portions of the research, a different plenum was installed that had 224 orifices that were 5.08 cm in diam. ($A_o = 0.454 \text{ m}^2$). The pressure difference between the plenum and the chamber interior ($P_1 - P_2$) was measured with a differential pressure transducer (Model 264, 0–62 Pa, Sentra Systems, Acton, MA). The low pressure sample (P_2) was monitored 1 m above the floor in the center of the chamber. The average pressure inside the plenum (P_1) was sampled with a nine-port manifold. The sampling ports were equally spaced throughout the length of the plenum to obtain an areally averaged pressure. Additional detail on the design of the pressure manifold is provided in the results section.

Carbon Dioxide Measurement and Control Systems

In order to control J_{CO_2} in the engineering chamber, natural sources and sinks of CO_2 had to be eliminated. Therefore, vegetation inside the chamber was removed, and a multilayer plastic floor installed to seal the chamber from the soil surface. The CO_2 flux density was controlled artificially within the OTC by releasing CO_2 at floor level through a precision mass flowmeter (Model UFM-1100, Unit Instruments, Yorba Linda, CA). The rate of CO_2 delivery was adjusted manually using a needle valve in the supply line (see Valve B, Fig. 2). Once the pure CO_2 entered the chamber, it was mixed with resident chamber air and then distributed on the floor using a manifold made from 0.1-m diam. pipe. Releasing CO_2 in this manner emulated respiration from the field surface. For our OTC, releasing pure CO_2 at 1 L min^{-1} corresponded to a CO_2 flux density of $46.8 \mu\text{mol m}^{-2} \text{ s}^{-1}$. During certain portions of the study, air used to aspirate the chamber was augmented with CO_2 by injecting gas into the air supply duct (Fig. 2). When elevated CO_2 was desired, CO_2 concentrations were enriched to approximately $700 \mu\text{mol mol}^{-1}$ by manually adjusting Valve A depicted in Fig. 2.

The difference in CO_2 concentration between air entering and exhausting from the chamber ($C_{\text{in}} - C_{\text{out}}$) was measured with an infrared gas analyzer (IRGA) (Model 6262, Li-Cor, Lincoln, NE) operating in differential mode. Inlet gas concentration, C_{in} , was sampled in the plenum, whereas air for the determination of C_{out} was sampled with a three-port manifold positioned 2.5 m above the chamber floor. Air was pumped from the sampling location to the IRGA at 6 L min^{-1} and passed through 5-L ballast tanks to reduce temporal variability at the analyzer (Fig. 2).

A thermocouple was positioned inside the air delivery duct to measure air temperature, and an anemometer was placed 0.5 m above the top of the chamber to measure wind speed. Analog signals from all instruments were sampled at 1 Hz using dataloggers (Campbell Scientific, Logan, UT), and 2-min averages computed for final storage.

Evaluation Procedures

The restriction flowmeter concept for measuring air flow was evaluated by measuring F_v with the anemometer array, while concurrently monitoring the pressure differential ($P_1 - P_2$) with the pressure transducer. Flow and pressure data were collected over a range of flow rates ($1\text{--}3.5 \text{ m}^3 \text{ s}^{-1}$) by adjusting the pitch of the fan blades. Data were collected using the plenums with 486 and 224 orifices. These data were combined with measurements of A_o and ρ to solve for the flow coefficient, K , in Eq. [2] using regression analysis.

The CO_2 flux measurement technique was evaluated by releasing CO_2 near the floor of the chamber through the mass flowmeter, while simultaneously monitoring $C_{\text{in}} - C_{\text{out}}$ with the IRGA and F_v with the pressure transducer (Eq. [2]). The accuracy of the measurement system was quantified by comparing flux through the mass flowmeter to J_{CO_2} calculated with Eq. [1]. During a typical test cycle, flux densities were varied between 0 and $80 \mu\text{mol m}^{-2} \text{ s}^{-1}$ over an 8-h period using a pyramid pattern. Experiments were conducted over a range of environmental conditions, while the OTC was aspirated with ambient or CO_2 -enriched air.

RESULTS AND DISCUSSION

Air Flow Experiments

Air flow determination with the Bernoulli equation required accurate measurement of the average pressure within the plenum (P_1). Preliminary experiments were conducted to map the positional variation of pressure inside the plenum and determine the number of pressure sampling ports needed. Point measurements of gauge pressure (i.e., pressure relative to atmospheric pressure) were obtained every 0.25 m inside the plenum, while air flow through the chamber was maintained at $1.8 \text{ m}^3 \text{ s}^{-1}$ (Fig. 3). Results showed that gauge pressure varied from 10 to 50 Pa and was especially variable where air first entered the plenum. Kinks in the plenum are formed where the plastic tube attaches to the chamber wall, and strong pressure gradients developed across each restriction (Fig. 3). To obtain an areally averaged pressure, a manifold was constructed from nylon tubing that had nine sampling ports equally spaced along the length of the plenum. Ports were not positioned near kinks to avoid pressure extremes. The manifold was connected to the high pressure side of the pressure transducer, so only one sensor was required to measure P_2 . The manifold pressure and the arithmetic average of the point samples

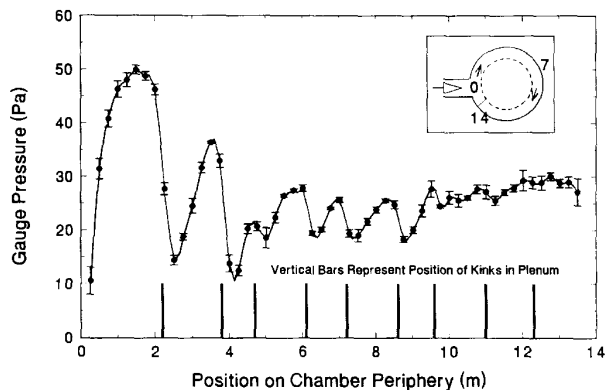


Fig. 3. Pressure distribution within the perforated plenum used to discharge air inside the chamber. The plenum was attached to the wall of the chamber at ground level and surrounded the circumference of the OTC (Fig. 1). The inset depicts a top view of the chamber and plenum and shows the notation used to label the x-axis with respect to position in the plenum. Data points are means ± 1 SD. Vertical bars on the baseline represent the location of kinks in the plenum caused by bending it around the circular chamber.

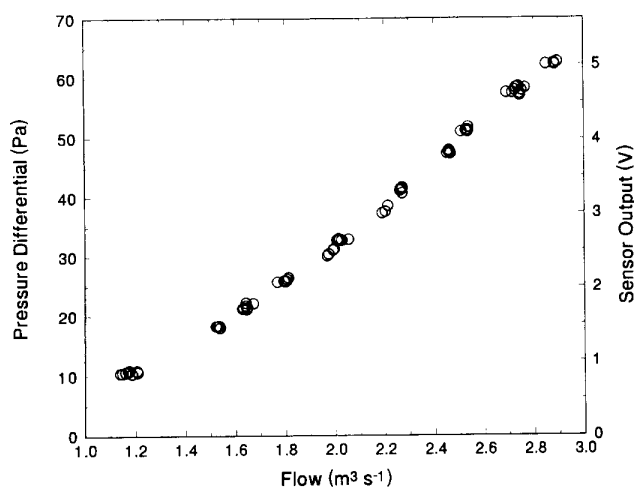


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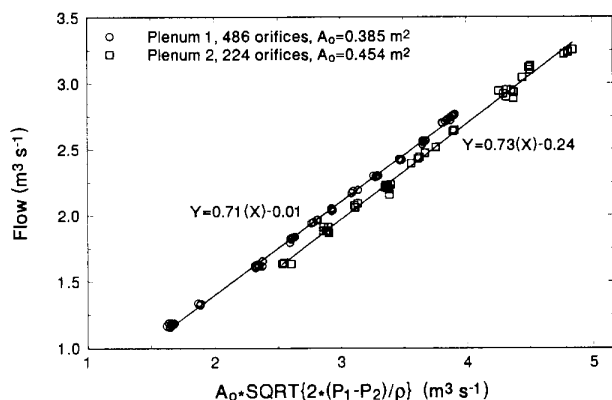


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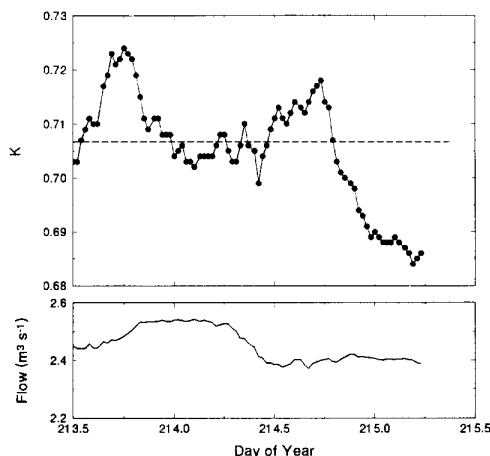


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Carbon Dioxide Flux Experiments

Measuring CO_2 flux using an open-system approach (Eq. [1]) required accurate measurement of the CO_2 differential between air entering and exhausting from the OTC ($C_{\text{in}} - C_{\text{out}}$). Previous research suggested that incursion of outside air through the top opening might contaminate measurements of C_{out} (Unsworth et al., 1984; Davis et al., 1983). Flow visualization studies were performed by releasing smoke near the top of the engineering chamber and observing the extent of turbulent incursion. Air flow through the chamber was set at $1.8 \text{ m}^3 \text{ s}^{-1}$, which provided an exit velocity out the top of the chamber of 0.25 m s^{-1} . When outside wind speeds were approximately 1 m s^{-1} or greater, plumes of smoke were freely transported down into the chamber in large eddies. Smoke typically moved downward along the chamber wall until reaching the plenum and then was thoroughly mixed with incoming air. These results indicated that the chamber would require modification to prevent turbulent incursion and allow accurate sampling of C_{out} .

Wind tunnel studies of Schmitt and Ruck (1987) and the modeling work of Jetten (1992) suggested that the extent of incursion within OTCs is dependent on the relationship between outside wind speeds and the exit velocity out the top of the chamber (hereafter called V_e). Their work indicated that a V_e of approximately 0.6 m s^{-1} would virtually eliminate incursion for outside wind speeds less than 10 m s^{-1} . Therefore, the area of the top opening on the engineering OTC was reduced to 3.14 m^2 and the flow rate set at $1.9 \text{ m}^3 \text{ s}^{-1}$, in order to produce an V_e of 0.61 m s^{-1} . Smoke tests were repeated over the modified chamber, and no visual evidence of turbulent incursion was observed.

After modifying the OTC to minimize incursion, trials were performed to test the validity of measuring CO_2 flux in a chamber aspirated with ambient air (Valve A in Fig. 2 was closed). Air flow was measured with the Bernoulli equation (Eq.[2]), and $C_{\text{in}} - C_{\text{out}}$ was measured with the IRGA. Figure 7 shows a comparison of

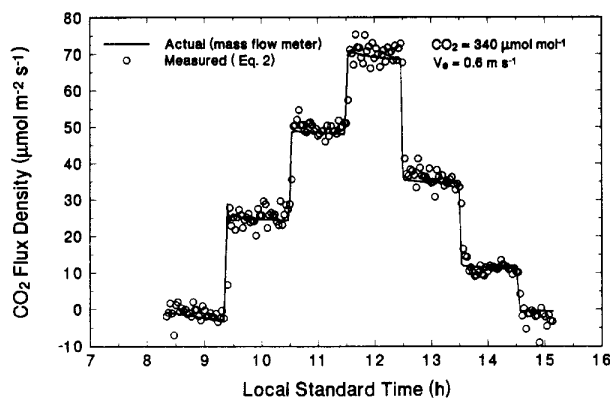


Fig. 7. Comparison of actual and measured CO_2 flux density from an OTC aspirated with ambient air. The chamber had a 3.14-m^2 nozzle (top opening) and an air flow rate of $2 \text{ m}^3 \text{ s}^{-1}$ to provide an exit air velocity of 0.6 m s^{-1} . Actual CO_2 flux was controlled by releasing CO_2 on the chamber floor at known rates through a mass flow meter. Measured CO_2 flux was estimated from measurements of air flow and differences in CO_2 concentration (Eq. [1]).

J_{CO_2} "measured" using Eq. [1] and the actual CO_2 flux determined by the CO_2 release rate through the mass flowmeter. Results show that the gas exchange measurements were in excellent agreement with data from the mass flow meter. This suggests that both F_v and $C_{\text{in}} - C_{\text{out}}$ were measured accurately, and that C_{out} was sampled without being significantly affected by incursion. Additionally, the resolution of the IRGA measurements must have been adequate to measure the small values of $C_{\text{in}} - C_{\text{out}}$. For example, a J_{CO_2} of $40 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$ corresponded to a $C_{\text{in}} - C_{\text{out}}$ value of only $8.4 \text{ } \mu\text{mol mol}^{-1}$. When data were integrated over the 7-h test period to calculate cumulative flux, the measured daily flux was within 2% of the actual value. Other trials conducted over a range of environmental conditions produced similar results.

A second set of trials was performed to evaluate the accuracy of the gas exchange measurements in a CO_2 -enriched OTC. Tests were performed using the same protocol shown in Fig. 7, except Valve A depicted in Fig. 2 was opened so that the CO_2 concentration of air forced into the chamber was approximately $700 \text{ } \mu\text{mol mol}^{-1}$. Initial comparisons of actual and measured CO_2 fluxes indicated that J_{CO_2} was being underestimated by Eq. [1] (Fig. 8a). Data showed that $C_{\text{in}} - C_{\text{out}}$ was less than expected, because C_{out} was being diluted by the incursion of outside air. Because the CO_2 concentration

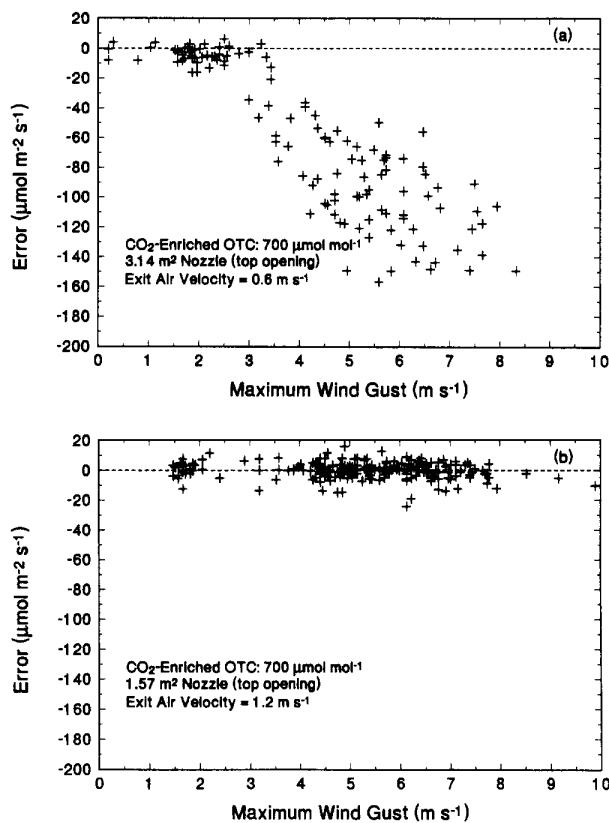


Fig. 8. Measurement errors in CO_2 flux density within a CO_2 -enriched OTC as a function of maximum wind gusts at the top of the chamber: (a) represents a chamber with a 3.14-m^2 nozzle having a critical exit velocity of 0.6 m s^{-1} , and (b) represents a chamber with a 1.57-m^2 nozzle and a 1.2 m s^{-1} exit air velocity.

in the chamber was double the ambient value, the incursion of only a small volume of air could cause a large dilution error in $C_{in} - C_{out}$. Errors in J_{CO_2} increased dramatically when maximum wind gusts near the top of the OTC exceeded about 3.5 m s^{-1} (Fig. 8a). These data indicated that turbulent incursion was sufficient to cause large errors in a CO_2 -enriched OTC when V_e was 0.6 m s^{-1} .

The height of the exhaust-gas sampling manifold was lowered from 2.5 to 1.5 m in an attempt to reduce the effect of incursion on the measurement of C_{out} . However, the accuracy of the gas flux measurements did not improve. Smoke tests and point measurements of CO_2 at different locations within the OTC indicated that air mixing was sufficient to eliminate positional variations in gas concentration. These observations are consistent with Davis et al. (1983) and Heagle et al. (1973), who also found very small variations in gas concentrations within OTCs. Smoke tests in the engineering OTC showed that, once an outside eddy penetrated and became entrained within the chamber, it was quickly mixed throughout the entire chamber volume. Thus, incursion caused errors in the determination of C_{out} regardless of where the sampling manifold was positioned. Smoke tests did indicate that samples should not be taken within about 1 m of the top opening, because occasionally an eddy would penetrate to that depth and then move back out on the top without becoming trapped within the chamber.

In an attempt to eliminate incursion into the chamber, the area of the top opening was reduced to 1.57 m^2 to obtain an exit velocity of 1.2 m s^{-1} . The exit velocity also could have been modified by increasing F_v ; however, that would have had the undesirable side effects of reducing the magnitude of $C_{in} - C_{out}$ and increasing CO_2 demand in enriched chambers. Reducing the diameter of the top opening also may help reduce incursion by filtering out incoming eddies with length scales greater than the size of the opening (Baldocchi et al., 1989). After the OTC had been modified, comparisons of actual and measured fluxes in the CO_2 -enriched OTC showed that

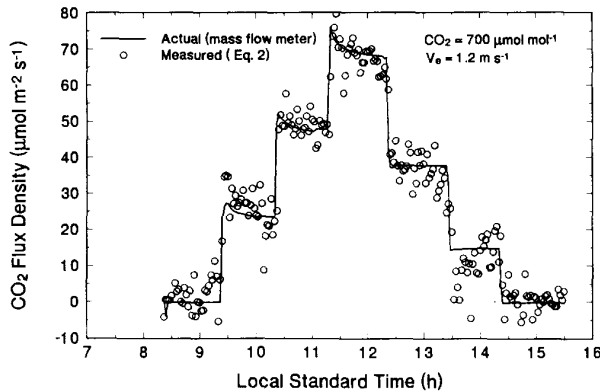


Fig. 9. Comparison of actual and measured CO_2 flux density from an OTC aspirated with CO_2 -enriched air (700 ppm). The chamber had a 1.57-m^2 nozzle (top opening) and an air flow rate of $1.9 \text{ m}^3 \text{ s}^{-1}$ to provide an exit air velocity of 1.2 m s^{-1} . Actual CO_2 flux was controlled by releasing CO_2 on the chamber floor at known rates through a mass flow meter. Measured CO_2 flux was estimated by measuring air flow and differences in CO_2 concentration (Eq. (1)). Wind gusts at the top of the chamber ranged from 5 to 8 m s^{-1} for most of the test period.

errors due to incursion had been significantly reduced at high wind speeds (Fig. 8b). Figure 9 shows a comparison of the measured and actual CO_2 flux densities over a 7-h period when wind gusts at the top of the chamber were 5 to 8 m s^{-1} for most of the day. Measurements of J_{CO_2} were more scattered in the CO_2 -enriched chamber than those in the ambient OTC (Fig. 7). This response could have resulted from several factors, including random fluctuations in C_{in} , differences in hydraulic capacitance between the C_{in} and C_{out} sampling systems, or mild turbulent incursion.

Summary statistics for three trials in CO_2 -enriched and ambient OTC are given in Table 1. Root Mean Square Errors (RMSE), computed from differences between actual and measured CO_2 fluxes on a 2-min basis, were almost twice as large in the CO_2 -enriched cases. This statistic confirms the observation that more random variation in J_{CO_2} is expected in CO_2 -enriched OTCs. However, comparison of daily CO_2 flux densities showed that measurements in both enriched and ambient chambers, on average, were within 2.5% of actual fluxes. No signs of systematic errors or biases were evident.

System Response

The engineering chamber provided an opportunity to evaluate the response time of the CO_2 flux measurement system. The chamber was operated using the 1.57-m^2 open top and air flow was set at $1.9 \text{ m}^3 \text{ s}^{-1}$. Response of the system was evaluated by first releasing CO_2 through the mass flowmeter to establish a steady flux density of $70 \mu\text{mol m}^{-2} \text{ s}^{-1}$. The supply of CO_2 was then suddenly stopped to create a step change in flux to $0 \mu\text{mol m}^{-2} \text{ s}^{-1}$. The rate change in $C_{in} - C_{out}$ at the IRGA was recorded every 1 s for analysis. Results show that the IRGA did not begin to detect changes in CO_2 until 38 s after the step change (Fig. 10). This "dead time" was caused by the buffering effect of the OTC air volume and the time required for gas to travel through the tubing and ballast tanks. Flux measurements changed slowly at

Table 1. Comparison of actual and measured CO_2 flux density from ambient and CO_2 -enriched open-top chambers. Root mean square errors (RMSE) were calculated from differences in actual and measured fluxes determined every 2 min. Daily fluxes were computed by integrating 2-min flux measurements over the whole test period. Data were collected in chambers with a 1.57-m^2 top opening using a pyramid-style measurement protocol demonstrated in Figs. 7 and 9.

Replication	RMSE	Daily CO_2 flux density		
		Measured	Actual†	Error
		mol $\text{m}^{-2} \text{ d}^{-1}$		
		%		
Ambient chambers ($340 \mu\text{mol mol}^{-1}$)				
1	3.97	0.698	0.683	2.2
2	3.81	0.698	0.705	-1.0
3	3.29	0.743	0.730	1.8
CO_2 -enriched chambers ($700 \mu\text{mol mol}^{-1}$)				
1	6.91	0.744	0.726	-2.5
2	5.49	0.701	0.706	0.7
3	5.48	0.752	0.720	4.4

† Actual fluxes were obtained by releasing CO_2 near the floor of the chamber at known rates through a mass flow meter.

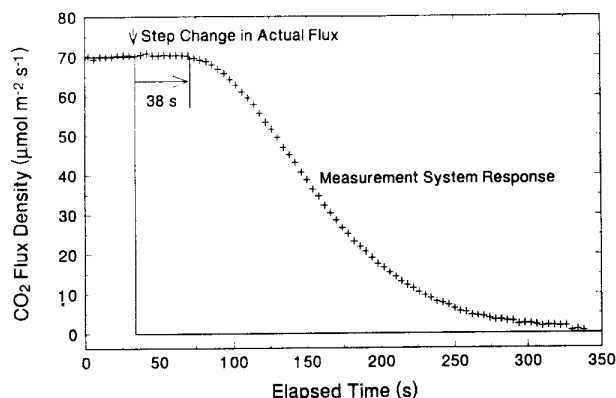


Fig. 10. Response of the CO₂ flux measurement system. Data show how the system responded to a step change in flux density from 70 to 0 $\mu\text{mole m}^{-2} \text{s}^{-1}$. The dead time between the step change in flux and initial detection by the gas analyzer was dependent on the volume of the gas sampling system.

first and then declined in an exponential manner after about 1 min. Attempts to model the time constant using a single first-order model were unsuccessful, because the system responded like a series of first-order instruments rather than an individual sensor. Results indicate that modeling the dynamic response of this system will require a separate time constant analysis of each component in the system (e.g., chamber, ballast tanks, IRGA). The settling time was approximately 300 s.

CONCLUSIONS

Air flow through large OTCs can be accurately metered using measurements of pressure inside the chamber's air delivery system. The Bernoulli equation, with a flow coefficient of 0.71, proved an accurate model of air flow into the chamber. Flow coefficients were stable over time and were not strongly affected by plenum design or restrictions over the orifices. Results suggest that accurate and cost-effective measurements of air flow can be obtained using a single pressure transducer. This measurement technique may be viable in many types of chambers and air-handling systems, provided that pressure data are compared to independent air flow measurements to validate the approach.

Carbon dioxide flux from an OTC was successfully quantified by combining the pressure-based measurements of air flow with measurements of CO₂. However, the size of the chamber's top opening had to be reduced to prevent turbulent incursion from disrupting the measurements. Thus, some of the climatological advantages of having an open-top chamber may be compromised when it is modified for gas exchange measurement. However, very accurate measurements of daily C flux were obtained in both ambient and CO₂-enriched OTCs. Results suggest that small differences in daily NCE between experimental treatments should be detectable with these techniques. This method also could be used to measure the flux of water vapor, CH₄, and other trace gases provided that an analyzer of adequate resolution was utilized.

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