

Novel design of an enclosed CO₂/H₂O gas analyser for eddy covariance flux measurements

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ABSTRACT

This study describes design and field performance of a new enclosed CO₂/H₂O gas analyser, LI-7200. Unlike present closed-path analysers, this new instrument is designed for operation with short intake tubes, with the intention to maximize strengths and to minimize weaknesses of both traditional open-path and closed-path approaches. The study provides description of the instrument, shows the principles of its operation, and explains advantages of a new design. Field results are provided from three field experiments with the prototypes, and cover such parameters as high frequency air temperature and pressure fluctuations inside the sampling cell versus ambient conditions, instantaneous concentrations and cospectra for CO₂ and H₂O in comparison with open-path instrument, and eddy covariance hourly CO₂ and H₂O fluxes in comparison with both open-path and closed-path instruments. Field data loss inventory is also provided in comparison with open-path and closed-path gas analysers. The new enclosed design results in little data loss during precipitation and icing, similar to the closed-path design, but with a low power consumption and high field stability comparable to open-path instruments.

1. Introduction

Open-path and closed-path designs of the fast CO₂/H₂O gas analysers are well-established and widely used to measure concentrations and fluxes of carbon dioxide and water vapour (Lee et al., 2004). Both designs have their advantages and deficiencies. Open-path analysers have excellent frequency response, long-term stability, and low sensitivity to window contamination. They are pump-free, have low power demand and require infrequent calibrations. Yet they are susceptible to data loss during precipitation and icing, and may need instrument surface heat flux correction when used in cold conditions (Burba et al., 2008). Closed-path analysers can collect data during precipitation, can be climate-controlled, and are not susceptible to surface heating issues. Yet they experience significant frequency loss in long intake tubes, especially problematic when computing water vapour flux, due to sorption and desorption of water molecules at the interior walls and other related processes (Massman and Ibrom, 2008). They may require frequent calibrations, need a powerful pump, and have high power consumption. Here we present preliminary data from a third kind of design: an enclosed analyser, LI-7200 (LI-COR Biosciences, Lincoln, NE, USA), developed for operation with short intake tubes, and in-

tended to maximize strengths and to minimize weaknesses of both traditional open-path and closed-path designs.

2. Materials and methods

LI-7200 is designed as a compact enclosed CO₂/H₂O analyser enabled for using short intake tube. The intake tube can be as short as few centimetres or as long as many metres (similar to LI-7000 and LI-6262, LI-COR Biosciences). However, optimum tube length for most eddy covariance applications would be in the approximate range of 0.4–1.7 m (Clement et al., 2009; this study). Shorter tube will result in less temperature attenuation and increased Webb–Pearman–Leuning sensible heat term (Webb et al., 1980) and would be difficult to mount near a sonic anemometer without generating flow disturbance. Longer tube may result in excessive attenuation of water vapour flux, and in increased pump power requirements.

The LI-7200 is based on the absolute Non-Dispersive Infrared (NDIR) design of the LI-7500 (LI-COR Biosciences). However, it uses a closed-path sampling cell, similar to the closed-path gas analysers. Unlike any previous closed-path instrument, the LI-7200 can be used with a short intake tube because the analyser is weatherproof and can be mounted at the top of the tower, and because high frequency air temperature and pressure fluctuations of the gas stream are measured in the sampling cell. High frequency air temperature fluctuations are measured in two places: just before gas entry into the cell and just after the gas

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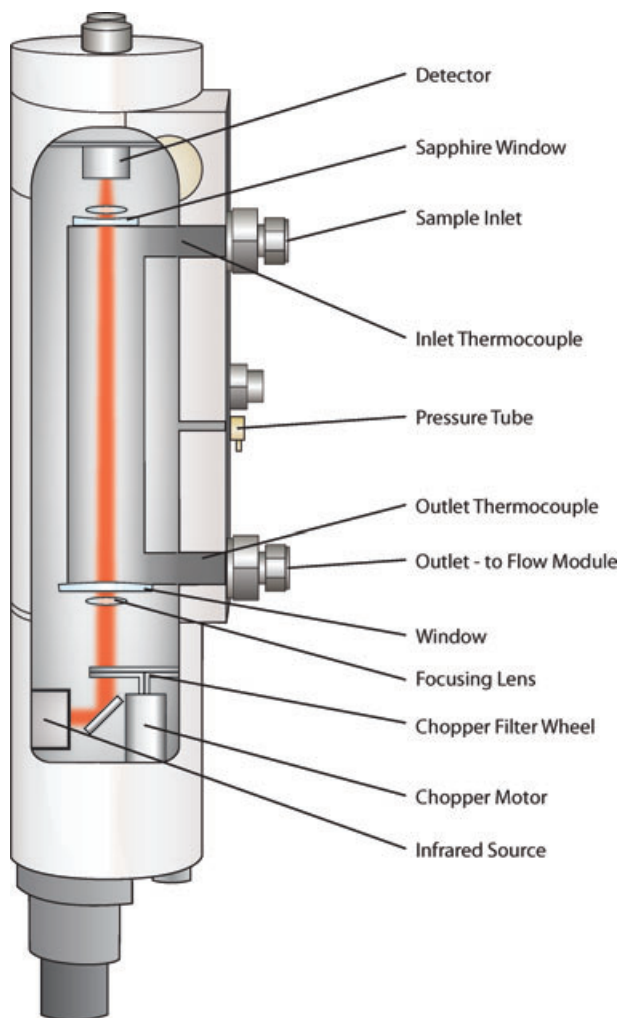


Fig. 1. Schematics of the key elements in the new enclosed design of high frequency $\text{CO}_2/\text{H}_2\text{O}$ gas analyser, LI-7200.

exits from the cell. High frequency pressure fluctuations are measured in the middle of the sampling cell. These and other key elements of the new design are shown in a schematic in Fig. 1.

Use of a short intake tube and high frequency temperature and pressure measurements inside the cell allow the LI-7200 to use the strengths of both open-path and closed-path designs at the same time. The practical benefits of such design include minimal data loss due to precipitation and icing (similar to closed-path analysers); good frequency response for both CO_2 and H_2O fluxes and low power consumption (comparable to open-path analysers); infrequent calibration and minimum maintenance requirements (similar to open-path analysers); no surface heating issues (Burba et al., 2008) and minimal-to-negligible Webb–Pearman–Leuning sensible heat term (similar to closed-path analysers), and possibility of automated calibrations on the tower (similar to closed-path analysers).

Data presented in this study cover the field deployments of three prototypes of LI-7200, which were extensively tested in 2006–2009 to assess performance and power requirements of the instrument, and to determine its optimal configuration. The data were collected in May of 2006, in January, March, April and May of 2007, and from August of 2008 to January of 2009. The experiments were conducted at LI-COR test facility (Lincoln, NE, USA) over ryegrass, at the measurements height of 2.5 m, and covered a wide range of weather conditions with ambient temperature ranging from -24 to $+37^\circ\text{C}$, relative humidity ranging from 12 to 100%, and wind speeds from 0 to 12 m s^{-1} . All flux data were collected at a 10 Hz rate, and processed using FluxNet methodology described in detail in Aubinet et al. (2000). The open-path LI-7500 was used as a standard for mean concentrations of carbon dioxide and water, for frequency response and for water vapour flux. The closed-path LI-7000 was used as a standard for carbon dioxide flux. The LI-7000 was not used as a standard for frequency response and for water vapour flux because of relatively large spectral attenuation due to the long intake tube (Massman and Ibrom, 2008). Table 1 provides a description of further details from the three experiments.

3. Results and discussion

3.1. Environmental parameters, high-frequency attenuation and fluxes

Daytime air temperature inside the LI-7200 sampling cell (Fig. 2a) was several degrees warmer than ambient air due to solar load and internal electronics, purposely coupled to the cell to prevent condensation. Instantaneous fluctuations were attenuated, on average, by about 85–90% with 0.5 m intake tube (Fig. 2a), and by about 90–95% with 1 m intake tube (not shown). The remainder was measured directly, eliminating open-path heating issues.

Cell air pressure was typically about 0.35 kPa below the ambient (Fig. 2b). This pressure drop was observed at 14 L min^{-1} flow, with both 0.5 and 1 m intake tubes without intake filters. Fluctuations in instantaneous cell air pressure were about 0.1 kPa without buffer volume, and were reduced to 0.02 kPa, with use of 20 l buffer downstream from the cell (Fig. 2c).

Frequency losses for CO_2 and H_2O fluxes were small (Figs 3a and b), yet slightly higher than that by LI-7500 (on average, 12% versus 8% for 0.5 intake, 13% versus 9% for 1 m intake) as expected due to some high frequency attenuation by a short intake tube. For comparison, frequency losses for LI-7000 with 4.5 m intake tube were between 15 and 30%. Instantaneous 10 Hz CO_2 concentration values were within 1 ppm of standard LI-7500 (Fig. 3c), resulting in mean concentrations being within a fraction of 1% of the standard LI-7500.

Hourly carbon dioxide and water vapour fluxes were within 2.5% of the standards, LI-7000 and LI-7500, respectively

Table 1. Details of the setup for the three presented experiments: May 2006, January–May, 2007 and August, 2008–January, 2009

Experiment duration	May 5–19, 2006	January, March–May, 2007	August, 2008–January, 2009
Standard			
Instrument	LI-7500	LI-7000 and LI-7500	LI-7000 and LI-7500
Intake length	–	4.5 m	4.5 m
Tube diameter	–	0.0064 m	0.0064 m
Tube material	–	Dekabon ^a	Dekabon
Buffer	–	20 L	20 L
Intake filter	–	Gelman ^b	Gelman
Flow rate	–	9 L min ^{−1}	9 L min ^{−1}
LI-7200			
Instrument	Enclosed LI-7500	Early prototype LI-7200	Alpha LI-7200
Intake length	0.5 m	0.5 m/1.0 m/1.5 m	1.0 m
Tube diameter	0.0064 m	0.0064 m	0.0064 m and 0.0096 m
Tube material	Copper	Stainless steel/Teflon	Stainless steel/Parflex ^c
Buffer	No buffer/20 L	20 L	None: LI-7200–101 ^d is used
Intake filter	None	15 µm NuPro ^e	None
Flow rate	14 L min ^{−1}	16 L min ^{−1}	14 L min ^{−1}

^aMegaflex Ltd, Southwell, Nottinghamshire, UK.

^bGelman Sciences, Ann Harbor, MI, USA.

^cParker Inc., Cleveland, OH, USA.

^dLI-7200–101 is a pump blower flow module (LI-COR Biosciences, Lincoln, NE, USA) optimized for LI-7200, and rendering buffer unneeded.

^eNuPro Co., Willoughby, OH, USA.

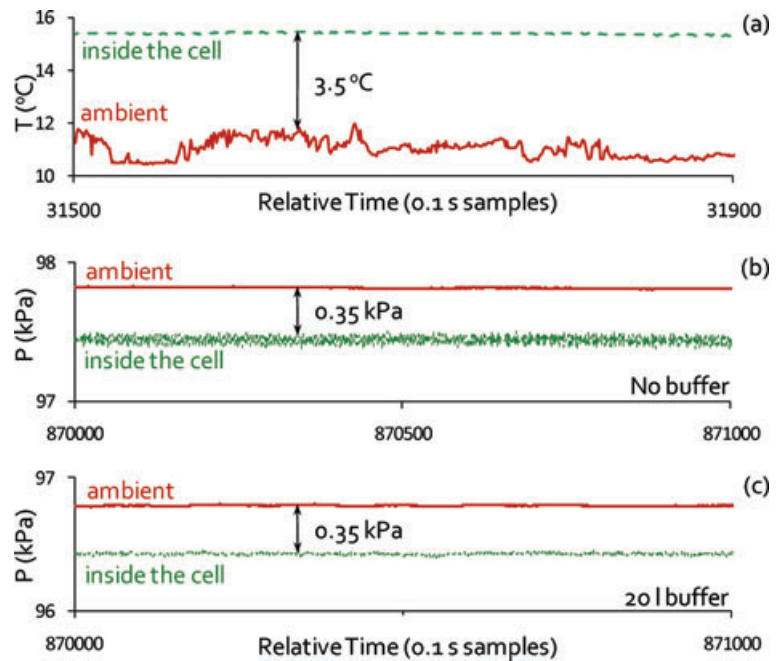


Fig. 2. Typical examples of instantaneous temperature and pressure fluctuations outside (ambient) and inside the cell of LI-7200. (a) air temperature measured with fine-wire thermocouples in May 2006 deployment with 0.5 m long tube of 0.0064 m internal diameter; (b) air pressure using industrial pump with 14 L min^{−1} flow without buffer and (c) with 20 l buffer.

(Fig. 4a), after all appropriate corrections were applied (Aubinet et al., 2000). The observed 2.5% difference was not statistically significant for P -value < 0.05 (Figs 4b and c).

Flux data loss over duration of all experiments (Table 2) was at about 8% for open-path analyser mostly due to precipitation

(75% loss during precipitation events). For the same period, losses from closed-path analyser were less than 1%. In all cases, only periods with functioning sonic anemometer and $u^* > 0.1$ were considered. Data loss from LI-7200 was close to that of closed-path analyser.

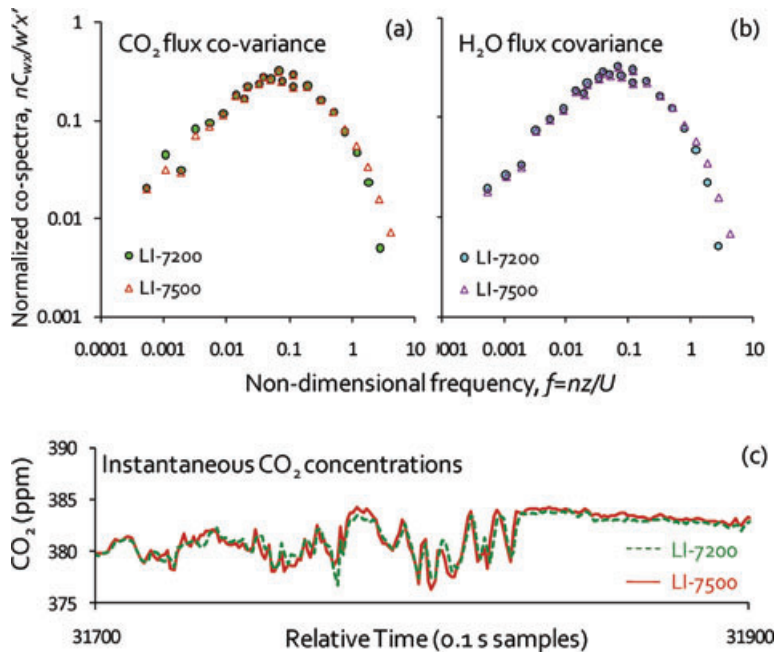


Fig. 3. Ensemble averaged non-dimensionalized flux cospectra for (a) CO₂ flux and (b) H₂O flux, plotted versus non-dimensional frequency during all three deployments (May 2006, January–May, 2007 and August, 2008–January, 2009). (c) Example of instantaneous CO₂ readings from LI-7200 and LI-7500 during May 2006 deployment.

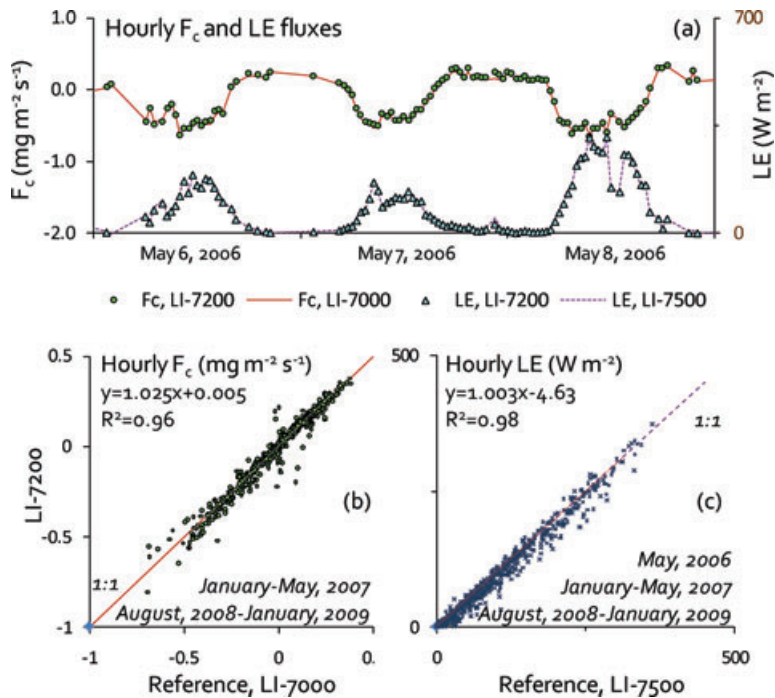


Fig. 4. (a) Example of hourly CO₂ and H₂O fluxes from LI-7200 compared to LI-7500 and LI-7000 in May 2006 deployment. (b) Hourly CO₂ fluxes from LI-7200 plotted versus LI-7000 during deployments in January–May, 2007 and August, 2008–January, 2009. (c) Hourly H₂O fluxes from LI-7200 plotted versus LI-7500 during all three deployments (May 2006, January–May, 2007 and August, 2008–January, 2009).

3.2. Optimal intake tube length

Examination of the attenuation of high frequency signal by the intake tube (such as those shown in Figs 2a and 3a,b) could also be used to establish the optimal range for the intake length for a specific instrument or setup. The theory and modelling behind such optimization in relation to tube diameter, flow rate, power requirements, ambient conditions, and other key factors was de-

scribed in detail in Clement et al. (2009). In the present study, the scope was narrower, and one of the goals for the LI-7200 intake design was to maximize the attenuation of instantaneous fluctuations of temperature and to minimize the attenuation of instantaneous fluctuations of water at the same time. This would help to significantly reduce WPL term (Webb et al., 1980) and associated uncertainties, without requiring excessive frequency response corrections for water vapour flux and its associated

Table 2. Summary of hourly data loss inventory from LI-7200, LI-7500 and LI-7000 during all three deployments (May 2006, January–May, 2007 and August, 2008–January, 2009)

	LI-7500	LI-7000	LI-7200
CO ₂ flux			
Total for all experiments	8%	<1%	<1%
During precipitation	75%	0%	0%
H ₂ O flux			
Total for all experiments	7%	<1%	<1%
During precipitation	75%	0%	0%

uncertainties. The instantaneous fluctuations of CO₂ are attenuated considerably less than those of water vapour (Massman and Ibrom, 2008), and are not a critical factor for such optimization.

Figure 5 shows the range of water and temperature attenuation at each available intake length, as observed in the field during the periods with no fine-particle intake filters, with new or newly cleaned intake tubes, over the entire duration of all experiments. The optimal intake length suggested by these data ranges from about 0.4 m, attenuating 90% of high frequency temperature fluctuations and less than 5% of the water fluctuations, and to about 1.7 m, attenuating 99% of the temperature fluctuations and less than 10% of the water fluctuations. Similar results were also observed and modelled theoretically in Clement et al. (2009) for similar tube diameters for a much wider range of conditions.

The crossing of the two fitted lines in Fig. 5 suggests that overall, the best intake length is about 0.7 m. However, the single length is too restrictive to apply to all studies because the specific focus of a particular study may require a specific tube length. For example, hydrological studies may benefit from shorter tubes (e.g. 0.4–1.0 m, or less) to reduce uncertainties associated with the effects of long intakes on high frequency water vapour fluctu-

ations. Meanwhile research groups focused solely on ecosystem CO₂ exchange would likely benefit from using longer tubes (e.g. 1.0–1.7 m, or more) to further reduce or eliminate temperature fluctuations and associated uncertainties in measured CO₂ covariance. In the latter case, especially with intake tubes longer than 1.7 m, the water attenuation could still be corrected by frequency response corrections, so no actual water vapour flux would be lost. However, with larger frequency response corrections, more uncertainty will be built into the final estimate of the water vapour flux. This uncertainty is also expected to increase with tube wall contaminations, relative humidity and sharp turns or uneven joints in the intake tube (Massman and Ibrom, 2008).

3.3. Power demands

In addition to optimizing the length of an intake tube to reduce flux uncertainties, another important practical aspect of the new enclosed design is minimizing the system power requirements. With sufficiently low power demands, the enclosed analyser could be used in remote unattended locations in a similar manner to an open-path analyser, using solar power or a small generator, but without data loss incurred due to precipitation, fog, sea spray, and other types of window contaminations (such as insects, nests, birds, etc.). This would expand the geographical applicability and a number of ecosystems that could be successfully studied in a continuous long-term manner, and may help to better construct their carbon and water budgets. The power requirements were addressed in LI-7200 design in two ways: (i) by employing high frequency temperature and pressure measurements inside the cell in conjunction with cell's low sensitivity to window contamination and (ii) by designing the optimized flow module specifically for LI-7200. The former allowed for the use of the short intake tube with and without an intake filter, and the latter allowed air to be drawn through the tube at 15 L min⁻¹ at

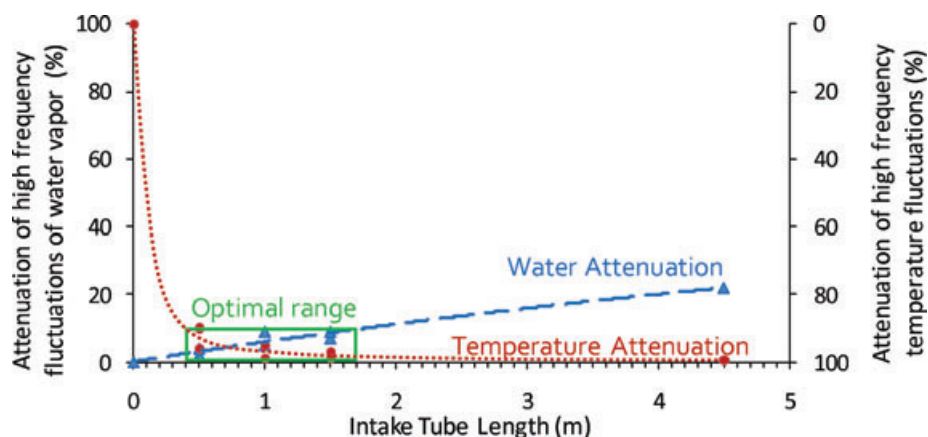


Fig. 5. Upper and lower limits (symbols) of the attenuation of high frequency fluctuations in water vapour and air temperature plotted versus the length of an intake tube, as observed in the field experiments described in Table 1, during daytime periods with no fine-particle intake filters and with new or newly cleaned intake tubes.

about 15 W of power (including pump blower, flow control and output circuitry). The power demand could be reduced further, to about 7–10 W, by using a fan without flow control (Clement et al., 2009). As a result, the total system power demands for LI-7200 would be 19–27 W, making it comparable to open-path analysers, and considerably less than power required by traditional closed-path systems (about 60–100 W).

4. Summary and conclusions

Three field experiments with LI-7200 prototypes demonstrated that the design of an enclosed short-tube-enabled CO₂/H₂O gas analyser, with high frequency air stream temperature and pressure fluctuations measured inside the sampling cell, utilizes strengths of both closed-path and open-path designs at the same time. The enclosed design provides following advantages, similar to closed-path analysers: minimal data loss due to precipitation and icing, no surface heating issues, and improved water specifications due to the absence of a filter eliminating sunlight interference in open-path instruments. The enclosed design also provides advantages similar to those of open-path analysers: low power configuration, small flux attenuation loss in short intake tube, infrequent calibration requirements, minimum maintenance requirements, small size, light weight and weather-proof construction.

The enclosed design of the LI-7200 also allowed it to operate equally well in broad range of environmental conditions during the three experiments, from cold (below –20 °C) to hot (above +35 °C), and from humid (above 99%) to dry (below 15%). Low sensitivity to contamination allowed measurements without an intake filter for months at a time before cleaning was needed. Although LI-7200 is specifically designed for low-power eddy covariance measurements, it also could be used with any other flux measurement techniques, such as for flux storage profile measurements, relaxed eddy accumulation, gradient flux techniques, canopy and soil chamber measurements, airborne and ship-borne measurements.

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