Measuring Air Exchanges Rates Using Continuous CO_2 Sensors

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SUMMARY

Measuring AERs in an effective, real-time, easy and low-cost way is still a challenge, especially in China where rooms were usually naturally ventilated but not with the Heating, Ventilating and Air Conditioning (HVAC) system. A new AER monitoring method using continuous CO_2 sensor was validated through both laboratory experiments and field studies. Controlled laboratory simulation tests were conducted in a 1 m³ environmental chamber at different AERs (0.1~10.0 hr^{-1}). AERs were determined using steady-state method and decay method based on box model assumptions. Field tests were conducted in apartments, offices, classrooms, dormitories and meeting rooms in during 3-5 weekdays with four sets of sensors coupled with data loggers. Statistic results indicated that good laboratory performance was achieved. In spite of limitations, this new method, along with mini-sized and easily operational instrumentations which provide sufficient continuous data, demonstrated an effective way to measure AERs in various indoor environments.

INTRODUCTION

Ventilation (Air exchange rates, AERs) is a critical ventilation parameter that affects thermal comfort and air contaminant exposure in civil buildings and other indoor environments. The concentrations of indoor pollutants mainly depend on the ventilation rates, source strength, and the emission rates. For many indoor-generated air pollutants, ventilation with outside air is usually the dominant removal process.

Many methods have been established to measure air exchange rates. Some studies reported AERs using perfluorocarbon tracer (PFT) compounds [1-4]. The most commonly used method is sulfur hexafluoride (SF6) decay tests which has been reported in many studies [5, 6] when commercial availability of instruments for SF6 tests has also made possible AER measurements. However, the instrumentation for these methods are usually big sized and expensive.

Although the Chinese national Indoor Air Quality Standard (GB18883 - 2002) regulates that the new air quantity for occupants is 30 m³ per hour per person, the requirement of new air is not strictly meet based on experiences. The ventilation rate or the air exchange rate was not measured at all when indoor air quality was investigated because of limits of measurement equipment available and convenient for tracer gas such as CO_2, CO, CH4, SF6 and so on. Because the cost of conventional PFT technique in China is high (at least $1,500 only for a bottle of SF6 gas), and its analysis equipment, the GC-ECD is not so popular in China, a convenient, accurate, and low-cost measurement method for ventilation or AERs needs to be set up and employed.

Carbon dioxide (CO_2), although a ubiquitous compound in air, is one of the bioeffluents. Occupants are usually the main indoor source of CO_2, resulting in an increase of indoor CO_2 concentrations compared with outdoor levels. In this study, CO_2 was employed as a tracer gas for determining AERs under certain circumstances satisfied for a box model (described in details in the method part). Commercially available CO_2 sensor have the ability to measure real-time CO_2 concentrations, and therefore semi real-time AERs can be determined using both steady-state and decay methods. The instruments are usually small sized, quiet, easy to use and relatively cheap.

The objective of this study is to validate a method for measuring AERs using continuous CO_2 sensor in both controlled environmental chamber and real settings.

METHOD

Box model for determining AERs

A compartment can be simplified as a box with a specified volume V (m^3) and a box model can be established assuming that the inside air is fully mixed (Figure 1). The carbon dioxide in a compartment results from outdoor concentration and exhaled carbon dioxide.

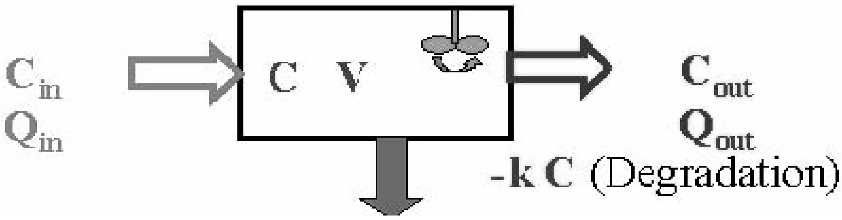

Figure 1. Schematic diagram of a fully mixed box model

The rate of change in concentration of the monitored gas depends on the concentration of the in-flowing air, the concentration of the out-flowing air and the internal generation rate of the gas in question. The time derivative of the monitored concentration is given by:

For a contaminant of interest, the governing equation for this model is:

$$V\,dC/dt = Q_{in}C_{in} - Q_{out}C_{out} + S - kC \qquad (1)$$

i.e. dC/dt = inflows -outflows + sources - degradation where C_{in}, C and C_{out} are concentrations of the contaminant in the inflow, indoor air and outflow (mg/m^3), $Q_{in} = Q_{out} = Q$ are air flows into/out of the building (m^3/h), S is the indoor emission source of the contaminant (mg/h) and k is the first-order degradation constant (m^3/h). Solving (1) by integration yields the final equation, which describes the generation and decay of CO_2 as a function of time:

$$C(t) = W/(ß\,V)[1 - \exp(-ß\,t)] + C0\exp(-ß\,t) \qquad (2)$$

Where:
C_o = concentration at t = 0, $W = Q_{in}C_{in} + S$ and ß = AER + k.
C(t) = internal concentration of carbon dioxide at time t (ppm)
For a conservative contaminant, i.e. k = 0, AER can be determined in two ways:

(1) Steady-state method
When t -> infinity:

$$AER = W/(CV) \qquad (3)$$

(2) Decay method
When there is no source, i.e. S = 0, AER can be resolved from the equation:

$$C = QCin/(ß\ V)[1-\exp (-ß\ t)] + C0\exp (-ß\ t) \qquad (4)$$

Environmental chamber simulation

The laboratory simulation is evaluated in a simplified model chamber using a tracer gas technique of CO_2 gas injected into a supply duct. Ventilation systems, which consist of a air supply pump, a CO_2 gas generator, a CO_2 gas analyzer and a small stainless steel environmental simulating chamber (1m×1m×1m, 1.5 mm thick), are set up to evaluate the performance of this box model for determining AER using CO_2 concentrations at steady-state and decay processes. A fan is installed inside the chamber to provide the fully mixing condition. The CO_2 level in the environmental chamber was measured at a height of 3 ft above the floor level using a Vaisala GMW20 series CO_2 sensor (Vaisala Oyj, Helsinki, Finland). This sensor has an accuracy better than ±1% full scale ±1.5% of the reading with a repeatability better than ±1% of full scale and temperature dependence of , 0.1% full scale/°C. An air pump (Yinhu Company, China) is installed inside the chamber and emits CO_2 at a constant rate. One-channel data loggers equipped with temperature and relative humidity sensors Hobo sensors (Hobo H08004-02, Onset Computer Corporation, USA) are used in conjunction with the CO_2 sensor to capture the CO_2 concentration every 10 seconds. Three are placed inside and one outside of the chamber to record ambient temperature and relative humidity simultaneously. Data from the data acquisition system were periodically downloaded via a cable to a PC for processing.

An air pump ((Xinma Electronic Enterprise Co., Ltd., China)) is installed at the downstream of the chamber to control the AER. Dupliate simulations are performed at 10 AERs, i.e. 0.1, 0.6, 1.0, 2.0, 3.2, 4.0, 5.2, 6.0, 7.2 and 10.0 hr^{-1}, respectively. In each test, the chamber temperature and relative humidity are equilibrated with the room temperature at 20 0C and 50%, respectively. The CO_2 pump is running for few minutes. Then the CO_2 pump is shut down but the AER is kept unchanged for about 10 hr.

Calibration of the carbon dioxide sensors was weekly accomplished using zero gas (N2, purity=99.999%) and a series of carbon dioxide standard gas (297, 632, 914, 1212, and 1501 ppm CO_2). Instruments were also cross-compared during short-term (about 15 min) outdoor air CO_2 measurements at each outdoor location distant from potential CO_2 sources. Calibration of the temperature and humidity sensors had been performed by the manufacturer immediately prior to this research.

Field study

The field study will be conducted in 2 residential apartments, 1 office building, and 1 school. In each apartment, CO_2 sensors are placed in each room for 3-5 weekdays. In the office building and school building, CO_2 sensors are placed in selected offices or classrooms. There sets of equipment were placed in different indoor environments for at least 12 hours, approximately 1.5 m high from the floor and away from windows, doors and fans, and at least 1 m from occupants. One set of equipment was also placed out of the windows about 1.5 m high from the indoor floor. A questionnaire and walkthrough survey is completed for each location examining basic building characteristics, occupancy and other information potentially related to AERs.

A daily journal was kept to record activities that might affect the air change rate, for example, when windows were open or closed, and how much the actual width/area of each opening was. The normal practice of the occupants for indoor ventilation was to open windows/doors and fans.

RESULTS

Laboratory simulation

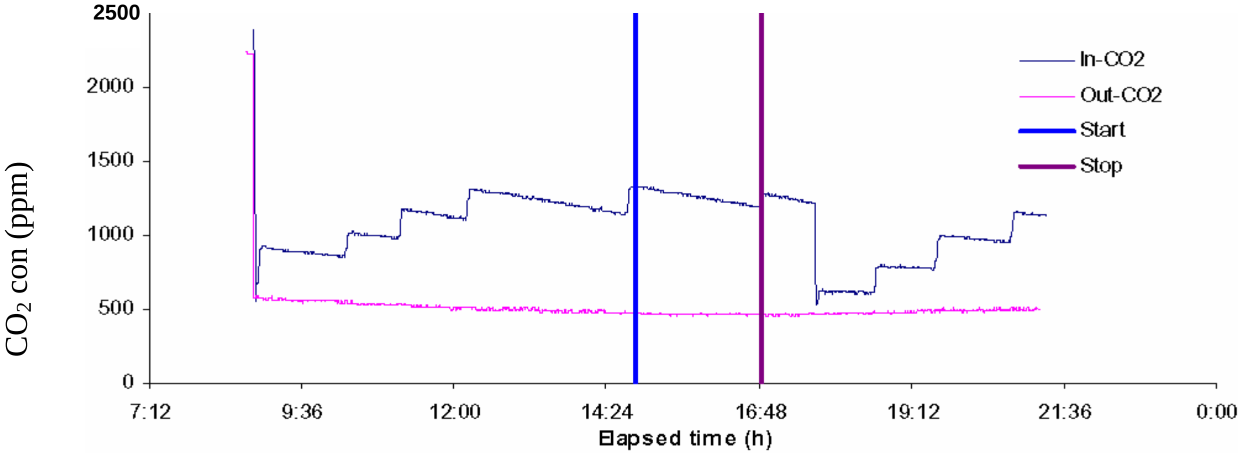

Figure 2a Decay curves of CO_2 under AER=0.1 conditions in chamber

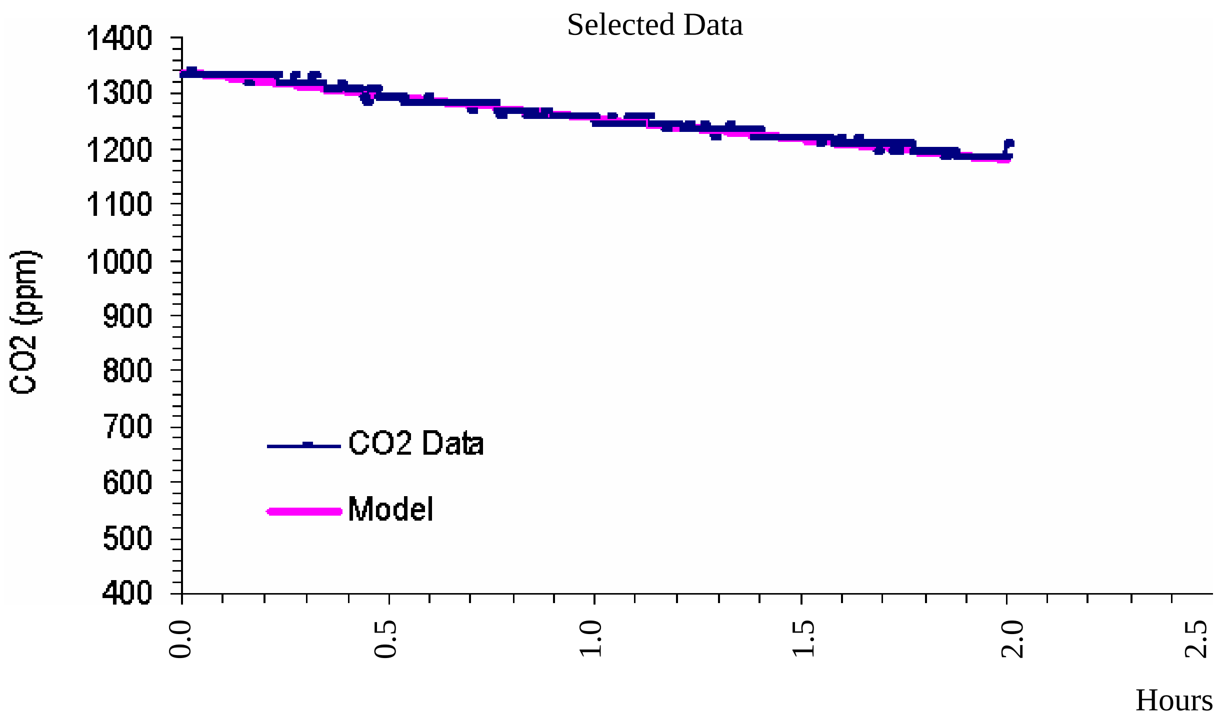

Figure 2b Data simulation, $AER_{nominal}$=0.1, $AER_{simulation}$=0.1 (slope).

Table 1 Simulated AERs and actual AERs using steady-state and decay methods.

	Steady State Method		Decay Method	
Nominal AERs (hr^{-1})	Simulated AER(hr^{-1})	Duplicate precision (%)	Simulated AER(hr^{-1})	Duplicate precision (%)
0.10	0.12	9.2	0.11	9.2
0.60	0.65	8.8	0.63	7.5
1.0	1.2	4.7	1.1	3.3
2.0	2.2	4.2	2.0	3.4
3.2	3.5	3.9	3.3	3.1
4.0	4.6	3.8	4.3	3.0
5.2	5.6	2.8	5.7	2.0
6.0	6.3	2.7	6.0	2.5
7.2	7.9	2.5	7.6	2.5
10.0	11.2	2.5	10.4	2.4

Field study

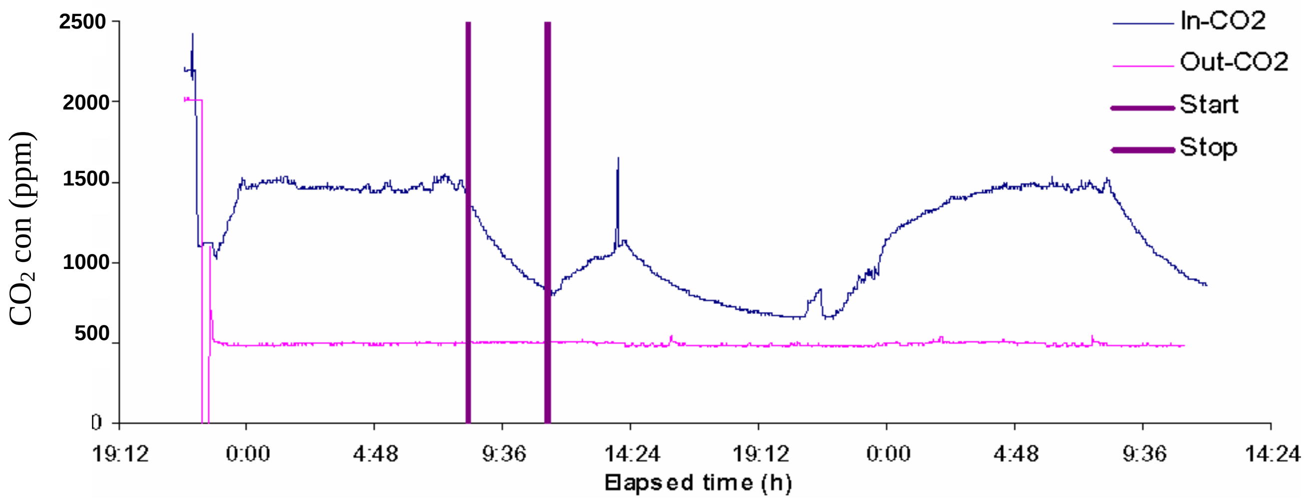

Figure 3a Decay curves of CO_2 in a apartment.

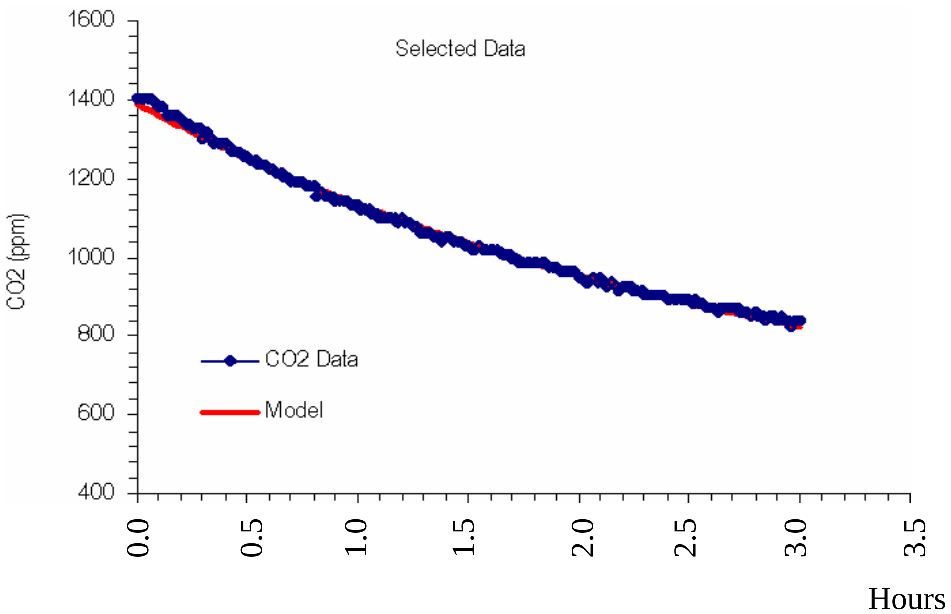

Figure 3b Simulation for selected data, $AER_{simulation}$=0.34.

DISCUSSION

Advantages and applications

CO_2 can act as an indicator of ventilation efficiency, showing whether the supply of outside air is sufficient to dilute air contaminants. As examples, to maintain odor-free environments acceptable contaminant levels, China ventilation standards specify a CO_2 ceiling of 800 ppm higher than outdoor levels. Besides bioeffluents, CO_2 has been used or suggested as a surrogate for carbon monoxide (CO) and other combustion products, and radon.

In former researches, it was always found that obtaining the required mixing of CO_2 and air is often difficult. Multipoint injection of tracer gas into the airstream is frequently necessary and multipoint measurements from different locations within the airstream are essential to confirm mixing7. In our study, because of high occupancy, indoor activities/movement of occupants, as well as the full application of ceiling fans, adequate full-mixing was obtained. The AER in each was constant during the sampling period in the light of small variation (COVs < 20%). CO_2 levels were similar within the same building (COVs < 20%), indicating good mixing conditions.

Statistic results indicated that good laboratory performance was achieved: duplicate precision was within 10%, differences between the two methods were within 10%, and the measured AERs were 90 -120% of the real AERs. Fully mixing conditions were observed in most indoor environments with fan operation.

The AERs measured in selected indoor environments were comparable to those reported in literature. Average AERs were 1.4, 1.7, 1.1, 1.0 and 0.6 hr^{-1} in apartments, offices, classrooms, dormitories and meeting rooms, respectively. Two day-long experiments, although air exchange rates higher than 2 h^{-1} were achieved for a brief time, the average over 12 h was never more than $1h^{-1}$

Figure 3 shows that the CO_2 level returned to about 800 ppm in about 3 hours from the time the occupants left the house while the initial indoor level was 1, 400 ppm. This defines the complete air change cycle of the apartment. Thus, a building that takes a longer time for the CO_2 to decay is tighter than that which takes a shorter time.

Limitations

Although CO_2 emission rates have been very well characterized and average 18 L/hr-person or 35.3 g/hr-person for people engaged in typical office work, the main problem with the method is that it can not be well employed when the spaces were occupied or it requires accurate information about the rate of CO_2 production within the space. This is not a problem during the unoccupied period, when the production rate will be zero.

ACHNOWLEDGEMENT

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