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Air exchange rates from atmospheric CO₂ daily cycle

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Abstract

We propose a new approach for measuring ventilation air exchange rates (AERs). The method belongs to the class of tracer gas techniques, but is formulated in the light of systems theory and signal processing. Unlike conventional CO₂ based methods that assume the outdoor ambient CO₂ concentration is constant, the proposed method recognizes that photosynthesis and respiration cycle of plants and processes associated with fuel combustion produce daily, quasi-periodic, variations in the ambient CO₂ concentrations. These daily variations, which are within the detection range of existing monitoring equipment, are utilized for estimating ventilation rates without the need of a source of CO₂ in the building. Using a naturally-ventilated residential apartment, AERs obtained using the new method compared favorably (within 10%) to those obtained using the conventional CO₂ decay fitting technique. The new method has the advantages that no tracer gas injection is needed, and high time resolution results are obtained.

Keywords

Tracer gas; Air exchange rate; Air infiltration; Atmospheric CO₂; Hilbert transform; Time varying

1. Introduction

With the need to save energy in the buildings sector, e.g., as articulated in the 2020 and the 2030 energy policy objectives of the European Union [1,2], energy losses by conduction through the building envelope are being minimized. As a result, energy exchanges associated with ventilation and air infiltration are gaining an increased importance in the energy balance of new and retrofitted buildings.

Most of the assessment tools developed for characterizing the relation between ventilation rates and energy consumption, e.g., [3,4], rely on estimates of the average air exchange rate (AER). Such tools provide a valuable indication of energy losses associated with air infiltration rates on a large trans-national scale and over long time periods. However, these methodologies are ineffective for detailed assessments of single buildings at normal operational time scales because infiltration rates vary with local weather conditions and with

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the operation of the heating and cooling systems of the building [5]. In addition, the use of estimates for AERs and the lack of accuracy in modeling the dynamics of air infiltration remain major sources of uncertainty in building energy dynamic simulation models [6,7]. Measurement and analysis methods are needed that allow researchers and practitioners to infer detailed information, including temporal data, on air infiltration in buildings. Such information would improve simulation models, allow for more detailed and accurate assessments of energy consumption, and provide real-time assessment of indoor conditions that could be utilized, for instance, to efficiently control the indoor climate [8].

Although the physical principles of natural ventilation are well understood, both from the deterministic [9] and the probabilistic [10] point of view, it has been generally recognized that it is difficult, if not impossible, to obtain detailed information on the continuous time evolution of AERs in buildings [11]. Instead, established methods determine time-averaged AERs by processing the concentration time series of a tracer gas over a period of time [12]. One such tracer gas that has been widely used is CO₂, produced by the building occupants [13–15], which decays exponentially towards atmospheric concentration levels after the occupants leave the building. An average AER over the decay period can be easily determined by fitting the step response of a first order system to the decay portion of the concentration time series.

Since the 1980s, automated and continuous measurements of AERs have been obtained by maintaining a constant concentration of a tracer gas using a PID controller, and calculating AERs from the quantity of tracer gas injected that is needed maintain the concentration [16,17]. This method has the advantage of being applicable during the normal operation of the building, whether occupied or not, but it has significant disadvantages, including the need to inject a tracer gas not normally present, and the complexity of both the experimental setup and data processing [18].

Recently, a method has been published that can provide continuous measurements of AERs in buildings [19] and, to our knowledge, is the first such method proposed in the literature. The method used state-space dynamic modeling techniques and Kalman filtering to estimate the radon entry rate into an unoccupied house. The AER was measured as a necessary but secondary time-varying parameter, using CO as the tracer gas and injections at a constant rate. While not the focus of the study, the method demonstrated that it is possible and practical to measure continuous time series of AERs in buildings.

The present paper proposes a new method for continuous measurements of AERs in buildings that are temporarily unoccupied during the assessment period. While also based on dynamic modeling, the proposed method differs substantially from Ref. [19] in that a formula is derived for the time varying AER in terms of the outdoor and indoor tracer gas concentration time series. It also differs in using atmospheric CO₂ as the tracer, and in using its natural daily variation as the forcing function applied to the dynamic system. This is possible since the atmospheric CO₂ concentration varies on most days on the order of 100 ppm, a result of photosynthesis and respiration cycle of plants, emissions associated with fuel combustion, and other processes [20–22]. We take advantage of this periodic daily variation to estimate AERs when there is no source of CO₂ in the building, e.g., during

extended unoccupied periods, and during the commissioning of new and renovated buildings when the building is ready for operation but has not yet been occupied.

The paper is organized as follows: We start with a brief summary of the theoretical formulation of the conventional metabolic CO₂ decay methodology, followed by the formulation of the new proposed method. Next, we describe two phases of AER measurements in a residential building: the first acquired CO₂ time series simultaneously indoors and outdoors to apply the proposed method; the second used the conventional metabolic CO₂ decay method to obtain the average AER. Lastly, results from the two methods are compared and discussed.

2. Theoretical formulation

Consider a single zone with volume V (m³) such that air is exchanged with the outdoor environment through one or more of its boundaries at a volume flow rate $q(t)$ m³h⁻¹. Assuming complete mixing, and in the absence of filtering mechanisms, deposition and absorption processes, the time evolution of the CO₂ concentration within the enclosure, $C_{\text{int}}(t)$, is described by the mass balance equation ([23], pp. 277)

$$VC'_{\text{int}}(t) + q(t)[C_{\text{int}}(t) - C_{\text{ext}}] = g(t), \quad (1)$$

where the prime denotes differentiation with respect to time, C_{ext} is the CO₂ concentration in the exterior environment and $g(t)$ is the rate of CO₂ generation within the enclosure.

2.1. Conventional tracer gas decay technique

If the volumetric flow rate is assumed to be constant, i.e., $q(t) = Q$ (m³ h⁻¹), and the CO₂ generation rate has the functional form of a step function, i.e., $g(t) = 0$ (mg h⁻¹) for $t < t_0$ and $g(t) = G$ (mg h⁻¹) for $t > t_0$, then Eq. (1) has the solution

$$C_{\text{int}}(t) = C_{\text{equi}} + [C_{\text{int}}(t_0) - C_{\text{equi}}]e^{-\lambda(t-t_0)}, \quad (2)$$

where $\lambda = Q/V$ h⁻¹ is the AER and C_{equi} is the concentration that occurs when equilibrium is achieved between the rate of generation and the net outflow of CO₂:

$$C_{\text{equi}} = C_{\text{ext}} + \frac{G}{\lambda V} \quad (3)$$

In a concentration decay situation, $g(t) = G$ (mg h⁻¹) for $t < t_0$, $g(t) = 0$ (mg h⁻¹) for $t > t_0$, and $C_{\text{equi}} = C_{\text{ext}}$. As long as C_{ext} is known, (2) can be used with regression techniques to estimate the AER. Moving the first term on the right-hand side of (2) to the left-hand side and taking the natural logarithm of both sides of the equation gives

$$\log_e [C_{\text{int}}(t) - C_{\text{ext}}] = \log_e [C_{\text{int}}(t_0) - C_{\text{ext}}] - \lambda(t - t_0), \quad (4)$$

which is the equation of a straight line with slope $-\lambda$. Thus, the slope of a straight line fit to the decay data, transformed according to the left-hand side of (4), gives an estimate of the AER during that time period. In practice, it is common to assume a nominal constant value for C_{ext} , e.g., 385 ppm, but no single value has been universally adopted. The use of a specific value for C_{ext} also requires zero offset calibration of the measuring equipment, which is not always possible or accurate. A way to circumvent this issue is to use a non-linear solver to find C_{ext} such that, given a known initial concentration $C_{\text{int}}(t_0)$ and an AER λ found from linear least squares, satisfies both sides of (4).

2.2. Time-varying Infiltration rates from atmospheric CO₂

Eq. (2) implicitly assumed that the outdoor CO₂ concentration, C_{ext} , does not vary in time. Allowing for $C_{\text{ext}}(t)$ to be now an explicit function of time, substituting $y = C_{\text{int}}(t) - C_{\text{ext}}(t)$, and setting the rate of generation of CO₂ to zero, (1) becomes

$$y'(t) + \lambda(t)y(t) = x(t), \quad (5)$$

where $x(t) = -C'_{\text{ext}}(t)$.

Eq. (5) is a first order linear time varying (LTV) system with input $x(t)$ being the negative time rate of change of the outdoor CO₂ concentration, and output $y(t)$ being the difference between the indoor and outdoor concentrations.

If $X(t) = x(t) + i\xi(t)$ and $Y(t) = y(t) + i\upsilon(t)$ are the analytic extensions of $x(t)$ and $y(t)$ to the complex plane, respectively, then $Y(t)$ is the complex response of the LTV system described by (5) to the complex input $X(t)$. $\xi(t)$ and $\upsilon(t)$ are the harmonic conjugates of $x(t)$ and $y(t)$, respectively, and can be computed from

$$\xi(t) = \mathcal{H}[x(t)], \quad (6)$$

and

$$\upsilon(t) = \mathcal{H}[y(t)], \quad (7)$$

where $\zeta = \mathcal{H}(z)$, is the Hilbert transform of z , formally defined by the improper integrals (p.v. stands for Cauchy principal value)

$$\zeta(t) = \mathcal{H}[z(t)] = \frac{1}{\pi} \text{p.v.} \int_{-\infty}^{\infty} \frac{z(\tau)}{\tau - t} d\tau \quad (8)$$

$$z(t) = \mathcal{H}^{-1}[\zeta(t)] = -\frac{1}{\pi} \text{p.v.} \int_{-\infty}^{\infty} \frac{\zeta(\tau)}{\tau - t} d\tau. \quad (9)$$

In practice, the Hilbert transform generates a signal that is in phase quadrature with its argument. The transformed signal is usually approximated by computing the complex fast

Fourier transform (FFT) of the real signal, equating to zero all the negative frequency components, and taking the inverse FFT of the resulting data.

Expressing $X(t)$ and $Y(t)$ in the general polar forms

$$X(t) = A_x e^{i\phi_x} \quad (10)$$

and

$$Y(t) = A_y e^{i\phi_y}, \quad (11)$$

substituting back in (5) and equating real and imaginary parts leads to the pair of equations

$$(A'_y + \lambda A_y) \cos \phi_y - A_y \phi'_y \sin \phi_y = A_x \cos \phi_x \quad (12)$$

$$(A'_y + \lambda A_y) \sin \phi_y - A_y \phi'_y \cos \phi_y = A_x \sin \phi_x. \quad (13)$$

Making use of the trigonometric identity $a \cos \theta + b \sin \theta = c \cos(\theta + \alpha)$ to aggregate the terms of the left-hand side in (12), with $c = \sqrt{a^2 + b^2}$ and $\alpha = -\tan^{-1}(b/a)$, gives

$$\sqrt{(A'_y + \lambda A_y)^2 + (A_y \phi'_y)^2} \cos \left[\phi_y + \tan^{-1} \left(\frac{A_y \phi'_y}{A'_y + \lambda A_y} \right) \right] = A_x \cos \phi_x. \quad (14)$$

Similarly, using the identity $a \sin \theta + b \cos \theta = c \sin(\theta + \alpha)$ in Eq. (13), with $c = \sqrt{a^2 + b^2}$ and $\alpha = \tan^{-1}(b/a)$, gives

$$\sqrt{(A'_y + \lambda A_y)^2 + (A_y \phi'_y)^2} \sin \left[\phi_y + \tan^{-1} \left(\frac{A_y \phi'_y}{A'_y + \lambda A_y} \right) \right] = A_x \sin \phi_x. \quad (15)$$

Dividing Eq. (15) by (14) leads to

$$\tan \left[\phi_y + \tan^{-1} \left(\frac{A_y \phi'_y}{A'_y + \lambda A_y} \right) \right] = \tan \phi_x \quad (16)$$

and equating the tangents arguments and rearranging, gives the following formula:

$$\lambda = \frac{\phi'_y}{\tan \Delta \phi} - \frac{A'_y}{A_y} \quad (17)$$

where $\phi = \phi_x - \phi_y = \arg \{XY^*\}$, Y^* being the complex conjugate of Y , is the phase difference between the input and the output signals.

Eq. (17) is the main result of this paper. It expresses the time-varying parameter of a first order LTV system in terms of the phase difference between the system's input and the resulting system's response, the instantaneous frequency ϕ'_y the amplitude envelope A_y , and its time rate of change A'_y . If one removes the dependence of λ on time and sets $\tau = (1/\lambda)$ to be the time constant of a first order linear time invariant system, then, for a single frequency input $x(t) = A \cos(\omega t)$, one recovers the well known relation

$$\frac{1}{\tau} = \frac{\omega}{\tan \Delta \phi} \quad (18)$$

where ϕ is a time-invariant phase difference between the input and output signals which, in this case, depends only on the frequency of excitation ω . In ventilation studies, the time constant τ has the physical interpretation of the mean age of air in the compartment.

3. Materials and methods

Two Extech SD800 measuring devices were used to record temperature, relative humidity and CO₂ concentration, at a rate of one sample every 5 s, in a two bedroom flat located in a rural village near Oliveira do Bairro, Portugal. The flat has an interior floor area of 88 m² and height 2.5 m, and is one floor above ground. This three level building was constructed in the 1990s. The exterior device was placed in the east-facing balcony, shielded from direct solar radiation; the interior device was placed in the living-room, leading to the same balcony. Fig. 1 shows a floor plan of the flat and the locations of both measuring devices.

During the measurement period, all windows and exterior doors were fully closed, and all interior doors were fully open, so that the space can be considered a uni-zone enclosure. There were no occupants or other sources of CO₂ inside the flat, and there was no heating, cooling or mechanical ventilation during the entire measurement period.

Interior and exterior continuous CO₂ concentration time series were obtained simultaneously from 01:49 on August 26, 2013 to 07:49 on September 1, 2013. Prior to analysis, both time series were processed by subtracting the respective means and removing high frequency noise with a second order low pass Butterworth filter, with cutoff approximately at 4.78×10^{-5} Hz (corresponding to a period of ~ 6 h).

To compare the new proposed method with the conventional CO₂ decay method, a second measurement phase using the CO₂ decay to estimate AERs was conducted the following week, and data for this purpose were obtained from 17:47 on September 5 to 23:22 on September 10, 2013. All conditions remained the same as described previously except for the presence of one occupant from approximately 20:00 in the evening to the following morning.

To compare weather conditions in the two measurement phases, outdoor temperature, wind speed and wind direction were recorded. Indoor temperature was also acquired, in order to calculate indoor/outdoor temperature differences. Temperatures were recorded at 5 s intervals and subsequently downsampled to 5 min intervals. Wind speed and direction were obtained at 5 min intervals from a weather station sited at approximately 3 km distance.

4. Results and discussion

Fig. 2(a) shows the raw data obtained from the interior and the exterior devices, with an artificial vertical offset for better visualization. Fig. 2(b) shows the same time series noise filtered and with mean removed. The shaded areas indicate the night time periods (20:00 to 07:00). Fig. 3 shows the input signal $x(t) = -C'_{ext}(t)$ and the output signal $y = C_{int}(t) - C_{ext}(t)$ computed from the noise-filtered data in Fig. 2(b). All time derivatives were estimated using central differences.

The AER time series computed from (17) using the indoor and outdoor concentration time series acquired in the first measurement phase is shown in Fig. 4. The AER varies randomly about a mean value of 0.20 h^{-1} , a typical value for Portuguese residential buildings constructed over the last 20 years [24]. The median is 0.21 h^{-1} and the standard deviation is 0.08 h^{-1} . The reconstructed AER time series resembles a random walk, as observed in Ref. [19], although our results look smoother due to noise filtering of the input data.

Fig. 5 shows the indoor CO_2 concentration time series recorded during the second phase. The decay sections of the natural logarithm of the excess CO_2 concentration, i.e., $\log_e[C_{int}(t) - C_{ext}(t)]$, were fitted using linear regression. The slope of each regression line corresponds to an average AER for that period of time. For the purpose of defining homologous measurement periods for a meaningful comparison with the proposed method, AERs were estimated from decays occurring between 13:07 and 19:47 of each day, which was the largest period without occupancy common to all days. The mean AER derived from the five afternoon decays is 0.23 h^{-1} ; the median AER is 0.19 h^{-1} and the standard deviation is 0.06 h^{-1} .

Table 1 shows weather statistics for both measurement phases and the period used to determine the decay rate-based AERs (13:07 to 19:47). Average weather conditions in the two phases were similar, although mean exterior temperatures decreased from 28.8°C in the first phase to 22.9°C in the second phase. The dominant wind direction and mean wind speed were unchanged.

Table 2 compares AERs derived using the two methods for the homologous measurement periods. AERs determined using the two methods did not differ statistically ($t = 0.32$, $n = 9$, two-tail $p = 0.75$) although the proposed method obtained slightly (10%) lower results.

Several factors can account for the small (but statistically insignificant) difference observed. First, although an attempt was made at conducting the measurements on both phases in as similar conditions as possible, the comparison is done with data obtained in different weeks, and differences in weather conditions will affect AERs. However, the mean values of wind speed and direction did not differ statistically and, despite the drop in the outdoor

temperature, the absolute value of the mean indoor–outdoor temperature differences did not differ. Thus, changes in weather appear unlikely to explain the higher AER observed in the second measurement phase.

Second, we assumed that indoor and outdoor measurements were representative of the air exchange through the building envelope. This issue may be less critical for the AERs derived using the conventional method, since the effect of the CO₂ generation by the apartment occupant is far greater than that due to variation in outdoor CO₂ levels or from CO₂ generation in other parts of the building. For the first measurement phase, however, the ingress of CO₂ generated in other parts of the building, i.e., not from the building envelope, might introduce a bias in the measured indoor concentration.

Third, both methods assumed that the interior space was fully mixed. This assumption may be more likely to be satisfied for the proposed method since CO₂ is well mixed in the atmosphere. However, incomplete mixing in both methods could account for errors. For example, CO₂ generated by the occupant may not be uniformly distributed throughout the space, e.g., the initial concentration $C_{\text{int}}(t_0)$ estimated as the concentration at the time the occupant left the apartment, might not be representative of the true initial concentration had the space been fully mixed. Additional monitoring indoors could be performed to quantify the extent of mixing.

Fourth, we did not account for measurement issues, e.g., limits to resolution, accuracy and response time of the measuring equipment, or data processing issues such as the effect of noise filtering and windowing on the spectral resolution of the AER time series. A full scale validation would address these issues in detail, possibly using long term and controlled experiments involving a range of environmental conditions, and using tests with tracer gases such as SF₆ that are not normally present in the atmosphere.

Despite several possible sources of error, the proposed method gave results that were reasonable and potentially as accurate (not statistically different) as decay-based methods, based on the limited experiments performed. Since a tracer gas present in the atmosphere is used, the new method may be particularly suitable for use in larger buildings, where it can be difficult to ensure uniform mixing with tracer gas injection techniques. The method can be easily extended to the study of inter-zonal airflows by considering each zone as a multiple input single output (MISO) system and monitoring the time evolution of tracer gas in each zone, in addition to the exterior concentration.

The current method requires that the building be unoccupied during the assessment period since occupants introduce a source term which is not accounted for in the theoretical formulation. However, the method is not limited to the use of atmospheric CO₂. In fact, the method can potentially have broad applicability to other gases that have the required cyclic variation, few if any sinks or sources within the building, and low reactivity. For example, NO_x and CO produced by road traffic at buildings near major roads or in large urban areas can show significant diurnal changes in concentration, and many buildings do not have indoor sources of these pollutants (residences with gas stoves being an exception).

In principle, the method is applicable to buildings of any size and it should work for all major types of ventilation systems: natural, exhaust, balanced and hybrid systems. In addition, the method has the advantage that it measures ventilation and air infiltration rates during natural conditions, as opposed to Blower Door methods that estimate air leakage, but in unnatural conditions.

5. Conclusion

A new method to determine AERs in buildings has been proposed. The method belongs to the class of tracer gas techniques, but contrary to established methods, uses the variation in ambient CO₂ concentrations to derive continuous estimates of AERs. This novel approach has several advantages: it does not rely on the injection of a tracer gas or the use of metabolic CO₂ generated by the building occupants; it produces continuous time series of AERs with the time resolution dictated only by the noise level of the sensing equipment; and it may be less sensitive to mixing assumptions compared to methods which require the injection or generation of a tracer gas. The new method may provide a very useful tool for studying the dynamic behavior of ventilation in buildings, which remains a main source of uncertainty in modeling building systems and, consequently, in the assessment of energy balance in buildings as well as the indoor environment.

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Fig. 1.

Sketch of the residential flat where the measurements took place. Locations of the interior (living room) and exterior (balcony) measuring devices are shown with crosses.

Fig. 2.

Time series, recorded over one week, of exterior and interior CO₂ concentrations: (a) raw data are shown with an artificial vertical offset for better visualization. Ticks on the vertical axis are 50 ppm apart. Shaded areas identify night periods (20:00 to 07:00). (b) The same time series low-pass filtered to remove noise and with the mean removed.

Fig. 3.

Input and output signals computed from the noise filtered data shown in Fig. 2(b).

Fig. 4. The infiltration AER obtained with the proposed method from the data acquired during the first measurement phase. Shaded areas identify night periods (20:00 to 07:00).

Fig. 5. Interior CO₂ time series obtained in the second measurement phase. Pattern results largely from nighttime occupancy and metabolic CO₂ emissions. Shaded areas identify night periods (20:00 to 07:00).

Table 1

Comparison of weather statistics of both measurement phases, for the homologous measurement periods from 13:07 to 19:47 of each day.

Measurement phase	Quantity	Mean of sample mean	Standard deviation of sample mean
1(proposed method)	Interior temperature (°C)	26.1	0.11
	Exterior temperature (°C)	28.8	0.99
	Wind speed (ms ⁻¹)	4.8	0.55
	Wind direction (deg)	281	17
2 (conventional method)	Interior temperature (°C)	25.8	0.5
	Exterior temperature (°C)	22.9	1.74
	Wind speed (ms ⁻¹)	4.7	0.63
	Wind direction (deg)	285	9.4

Table 2

Summary of results for both measurement phases: Phase 1 corresponds to the proposed time-varying method; Phase 2 corresponds to the conventional decay fitting method.

Sample	Phase 1 AER(1/h)		Sample	Phase 2 AER(1/h)		Standard deviation of regression residuals	
	Sample mean	Sample standard deviation		Decay regression	Standard deviation of regression residuals		
1	0.24	0.03	7	0.19	0.05		
2	0.12	0.03	8	0.31	0.08		
3	0.18	0.02	9	0.16	0.04		
4	0.12	0.02	10	0.28	0.13		
5	0.28	0.05	11	0.19	0.08		
6	0.33	0.04		–	–		
Mean of sample mean	0.21	–		0.23			
Standard deviation of sample mean	0.08	–		0.06			