Effects of Outdoor Environment on Air Exchange Rate

Maria Marrero*[1], Manuel Gameiro da Silva[2], Leslie Norford[3]

1 ADAI LAETA, University of Coimbra
R. Luis Reis dos Santos
3030-788 Coimbra, Portugal
**Corresponding author:*
uc2016248508@student.uc.pt

2 ADAI LAETA, University of Coimbra
R. Luis Reis dos Santos
3030-788 Coimbra, Portugal

3 Department of Architecture, Massachusetts
Institute of Technology,
77 Massachusetts Avenue,
02139, Cambridge, MA, United States

ABSTRACT

Indoor air quality is the chemical, physical and biological properties that indoor air must have to not cause any negative impact on occupants' health and provide comfort: feel fresh, pleasant and stimulating.
The indoor air quality is mainly determined by the indoor pollution sources and the outdoor air imported to the building. The indoor pollution sources are related to occupants, the building and their activities. The effect of the outdoor air in the indoor environment depends on its level of pollution and the amount entering the building through different ventilation systems and infiltrations. Ventilation and infiltrations are essential to ensure an optimal level of indoor air quality by refreshing the air. However, this can mean extra energy consumption because it can affect thermal comfort. Therefore, it is important to evaluate the efficiency of ventilation.
One way to characterize the ventilation rate, and the amount of air entering or leaving the indoor environment, is by the air exchange rate. The air exchange rate indicates the number of times that air in a fixed space is replaced by outdoor air in one hour. This study aims to determine the changes in the air exchange rate throughout the day depending on the weather conditions in the Mechanical Engineering Department building within the university campus located in the south of Coimbra city, Portugal. In line with this purpose, the air exchange rate determined using the metabolic CO_2 decay tracer gas technique, by measuring the CO_2 concentration inside and outside the building during a 3-month period. Meteorological observations were obtained from a weather station set in the car park. The variations and correlations of the air exchange rate against various outdoor meteorological factors, namely temperature, dew point, barometric pressure, wind speed and direction, precipitation and solar irradiation were tested using statistical regression techniques.
This paper concludes that the air exchange rate measured by the CO_2 tracer gas technique in an unoccupied building depends on meteorological conditions. Almost 80% of the variation in the air exchange rate can be explained by meteorological variables such as temperature, dew point, humidity, and wind speed and direction. Other parameters that affect air exchange rate are wind direction and precipitation. In these cases, the effects are conditioned to the situation. For example, only the wind coming from the direction in which the building is exposed has a noticeable effect. The precipitation episodes have different effects. Generally, it rains in cloudy skies, which reduces the amount of solar radiation that reaches the surface of the earth and the building. Thus, it can increase photosynthesis and the production of environmental CO_2 thanks to the extra contribution of water, an essential component in the respiration-photosynthesis process. All these parameters indirectly affect the air exchange rate.

KEYWORDS

Tracer gas method, air infiltration, atmospheric CO_2, Meteorological conditions

1 INTRODUCTION

We breathe air continuously, and the pollutants present in it can affect the respiratory system and accumulate in our body. Some symptoms related to poor indoor air quality are irritation in the eyes, nose, throat or bronchial tubes, or the appearance of rhinitis or asthma. The poor indoor air quality can produce mood swings, difficulties in concentration and a decrease in work performance (Mahbob N. S. et al., 2011, Satish U. et al., 2012). Therefore, air quality is not only a health problem but also an economic one.

Indoor air quality is the result of indoor emissions and the entry of outside air, through infiltration and ventilation. In general, the indoor air is more polluted than the outside, which makes the existence of infiltration and ventilation in the building necessary. Nevertheless, this can mean an additional energy consumption because it can affect thermal comfort. Therefore, it is important to evaluate the efficiency of ventilation.

A way of monitoring the rate in which air exchange occurs is the tracer gas method. This technique consists of releasing an inert gas in the room to be studied. When the gas is uniformly distributed in the room, its concentration is sampled to find a relationship with infiltration rates. A widely used tracer gas is CO_2, as it is safe (non-flammable, non-toxic, non-allergic ...), non-reactive, measurable and mixes well with the air. The presence of CO_2 in the air in small amounts is not a problem in the sampling if a large amount of CO_2 is injected during the test (Sherman, 1990). In addition, it has the advantage of its low cost, since the CO_2 generated naturally by the occupants of the building can be used as a source (Hänninnen, 2012). Although the use of metabolic CO_2 is simple and inexpensive, it has drawbacks that must be taken into account for good performance.

- Temperature, humidity and pressure can affect CO_2 sensors.
- The generation of CO_2 is rarely measured. The generation of CO_2 by the occupants is generally estimated through generic tables based on the activity and weight of the people.
- Outdoor CO_2 concentration varies daily and diurnal depending on traffic and weather (ECA, 2003, Batterman, 2017). In the tracer gas method, the outdoor concentration of CO_2 is considered as constant of 350-600 ppm depending on the site and year (Seppänen, 1999, Roulet et al., 2002, Xiaoshu Lu, 2011).
- Air exchange is generated by wind effect and stack effect and therefore depends on heating-cooling loads and weather: (Batterman, 2017, Roulet, 2002).

Previous research has addressed several aspects of the effects of meteorology conditions (air temperature, relative humidity, and wind speed and direction) on CO_2 concentration (Strong, 2011; Sreenivas, 2016) and on air exchange rate (Laschober and Healy, 1964, Shaw, 1981, Almeida, 2017). High temperature enhances the photosynthesis (Sreenivas, 2016) and the convection (Parazoo, 2008). Both processes decrease the atmospheric CO_2. Moisture in the soil greens the vegetation enhancing the photosynthesis and limiting the soil respiration. Both processes reduce the CO_2 concentration in the atmosphere (Sreenivas, 2016). Strong winds imply higher shear and more turbulence diluting the CO_2 in the atmosphere (Parazoo, 2008).

On the other hand, most of the studies have determined a linear relation between air change rate and both variables, indoor-outdoor temperature difference and wind speed. Malik (1978) went further and studied the relation with wind direction. He concluded that wind perpendicular to the wall is highly related to high air change rates. Montoya (2011) studied the relation in different conditions and determined the predominance of each variable. For example, in calm days the temperature difference dominates the change of the air change rate.

This paper proposes to determine the rate of air exchange from the instantaneous concentration of CO_2 in the environment. In addition, the relationship between the air exchange rate with different meteorological parameters is exposed. The meteorological parameters considered were air temperature, dew point, barometric pressure, relative humidity, precipitation, wind speed, wind direction, and solar irradiation.

2 MATERIALS AND METHOD

2.1 Theoretical formulation

The type of tracer gas test most widely used is the tracer decay. In a tracer gas decay test, the test space is initially loaded to a concentration of tracer gas appropriate for the instrumentation and then the injection is turned off. During the decay, the concentration is monitored. Since there are no sources or sinks of CO_2, the change in the concentration of CO_2 inside the zone is related to the airflow into and out of the zone:

$$\frac{dC_i}{dt} = -C_i\lambda + C_a\lambda \tag{1}$$

where C_i is CO_2 concentration in the room (ppm), λ is the air exchange rate (h^{-1}); C_a is the outdoor CO_2 concentration (ppm). In the decay case, the evolution of the indoor CO_2 concentration has an exponential behaviour described by the Eq. 2.

$$C(t) - C_{equi} = (C_0 - C_{equi})e^{-\lambda t} \tag{2}$$

where C(t) is the instant concentration in the room (ppm); C_{equi} is the equilibrium concentration that in the CO_2 decay tracer method equals to the outdoor concentration (ppm); C_0 is the initial concentration (ppm); λ is the air change rate (h^{-1}); t is the sample time (h). The indoor and outdoor CO_2 concentrations vary throughout the day and we measure them every 1 minute. The previous equation is discretized as indicated in Eq. 3.

$$C_{in_{n+1}} - C_{out_n} = (C_{in_n} - C_{out_n})e^{-\lambda\Delta t} \tag{3}$$

This equation can be fit to the measured data using regression methods.

2.2 Experimental site description

The study site is the office of the PhD students in the building of the Mechanical Engineering Department located on the university campus at the southern end of the city of Coimbra, Portugal (40º11'4.31''N 8º24'46.5''W, elevation 37m). It is an educational building surrounded by large trees and isolated from the influence of the city by a hill (Fig. 1). The only existing traffic is from the department's faculty and students. The climate is Mediterranean with oceanic influence. Mediterranean climates (Cs) receive rain primarily during winter season from the mid-latitude cyclone. The average annual temperature is 16.5ºC. Over the course of the year, the temperature typically varies from 10ºC to 22ºC and is rarely below -5ºC or above 30ºC. Average monthly temperatures vary by 11.8ºC. Average annual rainfall amounts to 922 mm and the least amount of rain occurs in July when the average of this month is 10 mm. With an average of 129 mm, the most precipitation falls in January.

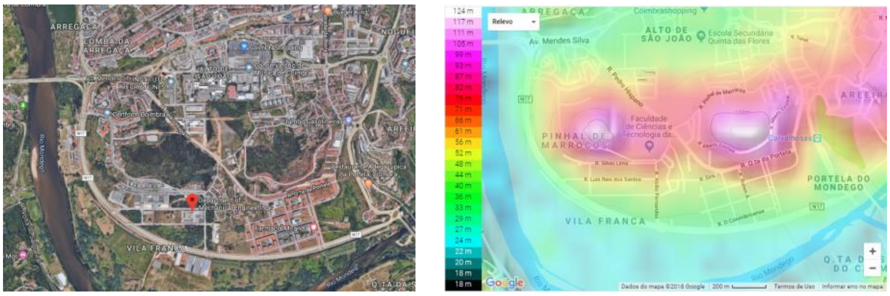

Figure 1: (a) Satellite image of the south of Coimbra. (b) Relief map of south of Coimbra, Portugal.

2.3 Measurements and Data Processing

The weather station measures the following parameters: air temperature, relative humidity, barometric pressure, wind speed and direction, solar irradiance. The anemometer and the pyrometer are mounted on poles at 5m over ground level. The sensors produce raw data each 0.1s, from which a 5 min average is calculated. The CO_2 concentrations were sampled with two Carbon Dioxide - Temp - RH Data Loggers, one place outdoor and the other in the PhD student office. The sampling time of the carbon dioxide sensors is 1 minute. For reducing random noise, the signal of the CO_2 concentrations were filtered using a Savitzky-Golay FIR filter with frame length of 6 hours.

Three months of data used, from February 27, 2019 to June 7, 2019. Multiple linear regression was performed to estimate relationships between the air exchange rate and the different meteorological parameters. In the section that follows, the results obtained will be discussed.

3 RESULTS AND DISCUSSION

This study focuses on the decay trace gas method. The metabolic CO_2 released by the occupants of the office is used as a tracer gas. Since the objective is the study of the influence of the external environment, the calculations are made at times when the office is unoccupied and approximately 3 hours immediately after the departure of all occupants. Figure 2 shows the indoor and outdoor CO_2 concentration for a 16 days period.

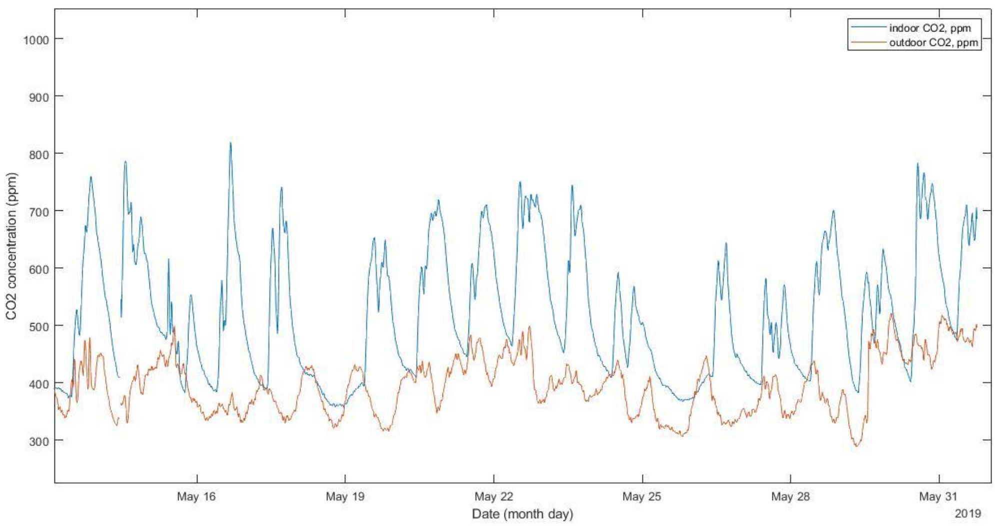

Figure 2: Indoor and outdoor CO2 concentration.

The air exchange rate (AER) from Equation 3 is determined by applying a linear regression to every period in which the office is unoccupied. The different values obtained in each period are shown in Figure 3. The average of results is 0.1965 ± 0.1206 h^{-1}. Applying the same process to the whole sample the air exchange rate is 0.1977 ± 0.0167 h^{-1}. Although both values are very close, the dispersion of the data with respect to the mean indicates that there are factors that affect the estimate.

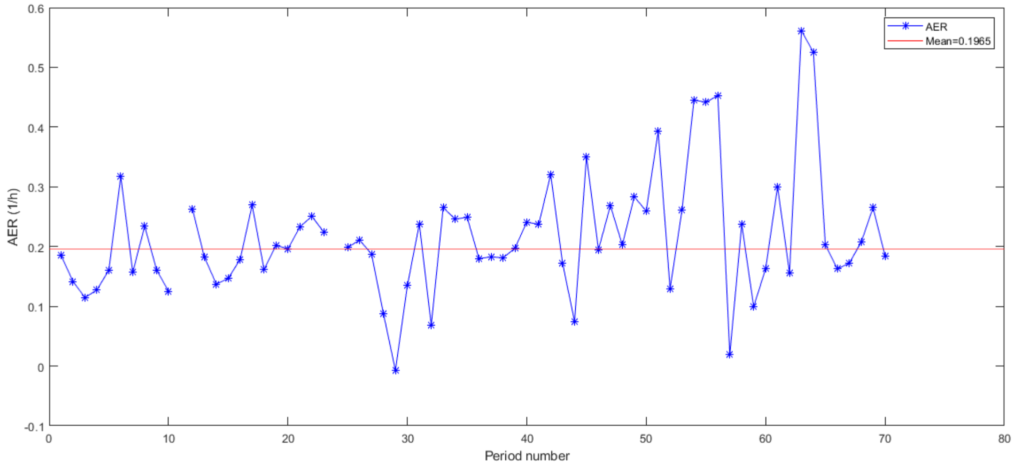

Figure 3: Estimated air exchange rate in different periods when the office is unoccupied.

3.1 Correlation between AER and different meteorological factors

The study of the correlation between AER and the different factors was carried out using multiple linear regression. By adding all the factors that describe different processes, we can explain 80% of the AER variation with a highly significant p-value = 4.4e-05. The statistics of this multiple regression are shown in Table 1. The most significant factors are the outdoor temperature, the outdoor relative humidity, and the difference between indoor and outdoor dew point. However, they are not the ones with high effect on AER prediction. The factors with highest effect on the estimation of AER are the difference between indoor temperature and the indoor dew point (iS in Table 1), the indoor relative humidity (iRH in Table 1) and outdoor temperature (oT in Table 1). Wind direction is not statically significant nor does it have a large effect on the AER estimate but it improves the model by 17%. The average value of the AER estimated by this model is 0.1592 ± 0.0675 h^{-1}, very close to values obtained by the mass balance.

The fact that wind direction has an effect on the amount of information provided by the model but is not statistically significant, is due to the lack of data. The building is located to the south of two hills, protected from the north and north-easterly winds. Many nights the winds are very gentle and there are no records.

On the other hand, this analysis is in agreement with the results of the aforementioned studies. The AER depends above all on temperature and humidity. In our analysis, the outdoor temperature plays a more important role than the indoor temperature. This is because the outdoor temperature varies more widely. In addition, it is a factor closely correlated with variations in ambient CO_2 concentrations.

Table 1: Statistics of correlation between AER and meteorological parameters: Indoor Temperature (iT), indoor Relative Humidity (iRH), outdoor Temperature (oT), outdoor Relative Humidity (oRH), difference between indoor and outdoor Dew Point (ΔDP), Wind Direction (WD), Wind Speed (WS), Daily Rain (Rain), Solar Radiation (SOL), and difference between indoor Temperature and Dew Point (iS).

Variables	Estimated Coef.	SE	t-Stat	pValue
Intercept	- 25.045	6.233	-4.0181	0.00067434
iT	+0.1123	0.03491	3.2168	0.0043268
iRH	+0.3395	0.07823	4.3392	0.00031834
oT	-0.1808	0.03088	-5.8559	9.9498e-06
oRH	-0.0310	0.00585	-5.2995	3.4663e-05
ΔDP	-0.1439	0.02864	-5.0246	6.4956e-05
WD	+0.0004	0.00032	1.1848	0.24997
WS	+0.0099	0.00445	2.2253	0.03773
Rain	-0.0688	0.02284	-3.0102	0.0069158
SOL	-0.0002	7.155e-05	-2.5701	0.01827
iS	+1.0179	0.25687	3.9627	0.00076769

In terms of humidity, the indoor humidity has a greater contribution to the prediction of AER due to the possibility of saturation inside the office.

4 CONCLUSIONS

The AER in the office is 0.1977 ± 0.0167 h^{-1}. It can be estimated from a model based on meteorological factors, particularly temperature and humidity. The temperature has different effects, direct and indirect, also affecting the concentration of CO_2. The effects of humidity are shown in different variables, from the relative humidity, the difference in the dew temperature and even in the rain. The wind also contributes to the variation of the AER, both its direction and its speed. Solar radiation contributes to a lesser extent, especially affecting the concentration of environmental CO_2.

5 ACKNOWLEDGEMENTS

The presented work was framed under two projects:
• The Energy for Sustainability Initiative of the University of Coimbra and LAETA (Associated Laboratory for Energy, Transports and Aeronautics) Project “SusCity: Modelação de sistemas urbanos para a promoção de transições criativas e sustentáveis”. The first author wishes to acknowledge the Portuguese funding institution FCT – Fundação para a Ciência e Tecnologia, for supporting her research through the Ph.D. grant MITP-TB/CS/0026/2013
• The project TRAPHIC-“Traffic related air pollution impacts on historic city centres: an integrated approach” Supported by the Portuguese Foundation for Science and Technology (FCT) through national funds (PTDC/ECM-URB/3329/2014), and the co-funding of the European Regional Development Fund (POCI01-0145-FEDER-016729) and COMPETE2020.

6 REFERENCES

Almeida, M.S.F, Barreira, E., Moreira, P., (2017): *Assessing the variability of the air change rate through tracer gas measurements*, Energy Procedia 132 (2017) 831–836.

Batterman, S., (2017), *Review and Extension of CO2-Based Methods to Determine Ventilation Rates with Application to School Classrooms*, Int J Environ Res Public Health. Feb; 14(2): 145, 2017.

ECA (European Collaborative Action), (2003), *Urban Air, Indoor Environment and Human Exposure, Environment and Quality of Life* Report No 23 Ventilation, Good Indoor Air Quality and Rational Use of Energy, 2003.

Hänninen, O., 2012, *Combining CO2 data from ventilation phases improves estimation of air exchange rates*, Proceedings of Healthy Buildings Conference, Brisbane, July 8–12, 2012.

Laschober, R.R., Healy, J.H., *Statistical analyses of air leakage in split-level residences*, ASHRAE Trans (1964) 70: 364–374

Mahbob N. S. et al. (2011), *A Correlation Studies of Indoor Environmental Quality (IEQ) Towards Productive Workplace*, 2nd International Conference on Environmental Science and Technology IPCBEE vol.6 (2011) IACSIT Press, Singapore.

Malik N., (1978), *Field studies of dependence of air infiltration on outside temperature and wind*, Energy Build (1978) 1: 281–292.

Montoya, M. I., Pastor, E., Planas, E., (2011), *Air infiltration in Catalan dwellings and sealed rooms: An experimental study*, Building and Environment Volume 46, Issue 10, October 2011, Pages 2003-2011.

Parazoo N.C. et al., (2008): *Mechanisms for synoptic variations of atmospheric CO2 in North America, South America and Europe*, Copernicus Publications, Atmos. Chem. Phys., 8, 7239–7254, 2008.

Roulet Claude-Alain & Flavio Foradini (2002), *Simple and Cheap Air Change Rate Measurement Using* CO_2 *Concentration Decays*, International Journal of Ventilation, 1:1, 39-44, DOI: 10.1080/14733315.2002.11683620

Satish U. et al. (2012), *Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance*: Environ Health Perspect 120: pp 1671–1677.

Shaw, C.Y., (1981): *A Correlation between Air Infiltration and Air Tightness for Houses in a Developed Residential Area*; National Research Council Canada: Ottawa, OT, Canada, 1981, 87, 333 –341.

Sherman, M. H. (1990), *Tracer-gas techniques for measuring ventilation in a single zone*. Building and Environment, 25, pp 365-374.

Seppänen, O. A. et al. (1999), *Association of Ventilation Rates and CO2Concentrations with Health and Other Responses in Commercial and Institutional Buildings*, Indoor Air 1999; 9: 226–252

Sreenivas, G. et al. (2016), *Influence of Meteorology and interrelationship with greenhouse gases*, Copernicus Publications, Atmos. Chem. Phys., 16, pp 3953–3967.

Strong, C. et al. (2011), *Urban carbon dioxide cycles within the Salt Lake Valley: A multiple-box model validated by observations*, J. Geophys. Res., 116, D15307.

Xiaoshu Lu, Tao Lu and Martti Viljanen (2011), *Estimation of Space Air Change Rates and CO2 Generation Rates for Mechanically-Ventilated Buildings*, Advances in Computer Science and Engineering, Dr. Matthias Schmidt (Ed.), ISBN: 978-953-307-173-2, InTech