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Evaluation of Indoor Air Quality in a Library Using Natural CO_2 as Tracer Gas: A Case Study

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Abstract

The indoor air quality was studied in the library of the Faculty of Civil Engineering in Bratislava, where people are considered to be the main source of pollution, expressed as the number of air changes per hour. The results refer to the period of several weeks in December 2014, when the room occupancy was high due to the end of the winter semester. The collected data show similar course of CO_2 concentration every work day throughout the measurement period, when the concentration was increasing in the morning, peaking in the afternoon and slowly decaying during the night. The gradual CO_2 decay during the nights allowed for calculation of the air change rate using natural CO_2 as the tracer gas. The air change rate was calculated to be $0.11 \pm 0.04\ h^{-1}$, indicating a good air-tightness of the envelope and thus the heat loss by infiltration reasonably low. The calculated value was compared with the ventilation criteria as defined in various documents. Although the ventilation requirements vary largely in the range of 0.4 to 3.3 h^{-1}, depending on the occupancy level and the document used, the measured air change rate in the library does not comply with any of these criteria. Whereas at low occupancy levels the remedy to this problem could be opening windows, mechanical ventilation needs to be installed to achieve sufficient indoor air quality at high occupancy.

Keywords - indoor air quality; CO_2 decay; air change rate; library; tracer gas measurements

1. Introduction

The concentration of CO_2, which is the product of human metabolism, has been traditionally used as an indicator of the indoor air quality (IAQ) since the 19th century [1]. Several relationships exist between the IAQ and the CO_2 concentration, including the effect of increased CO_2 concentration on health, the influence of CO_2 on the perceived air quality, the relationship between the CO_2 concentration and the concentration of other pollutants, and the relationship between the CO_2 concentration and the ventilation intensity. The CO_2 itself is not considered harmful at concentrations that typically occur indoors [2]. Thus, the indoor CO_2 can be used as the indicator of certain limited aspects of the IAQ, but not as the overall indicator of the IAQ. The CO_2 can be a good IAQ indicator in cases, when the pollution generated depends on the measure of human occupancy in the space. The standard EN 15251:2007 [3] recommends maximum CO_2 concentrations as shown in Table 1, where category I corresponds to the IAQ requirements recommended for sensitive persons, such as children or elderly people, category II represents a level of expectations typical for new and refurbished buildings, category III represents the acceptable level, used for existing buildings, category IV is not acceptable and should be tolerated for only a limited amount of time.

Tab. 1: Recommended CO_2 concentrations above outdoors for demand controlled ventilation and energy calculations [3]

Category	Corresponding CO_2 above outdoors in ppm for energy calculations
I	350
II	500
III	800
IV	< 800

However, only some of the pollution types are the function of people´s presence, and many of the pollution types are not associated with the presence of humans at all. Therefore, the CO_2, although a good indicator of the pollution by human, it is often a poor indicator of the overall perceived air quality, because it does not consider a number of pollution sources, such as building materials, tobacco smoke and cleaners.

Besides of using the natural CO_2 produced by people directly to evaluate the IAQ, CO_2 can also be used as a tracer gas in tracer gas ventilation measurements, providing that certain criteria are met. When the air change is to be calculated from the CO_2 concentration increase (step up method) or decline (decay method), these criteria include [2, 4, 5]:

- The fluid properties (i.e. density, and tracer gas concentration) are assumed to be the same at every point within the zone.
- The zone only communicates with the “outside”, and area whose concentration of tracer gas is unaffected by the zone. Thus, there is neither reintrainment of tracer (from exfiltrating air to infiltrating air) nor is there any buffer zone.
- Distribution of the tracer gas is uniform throughout the zone.
- The occupancy density should not exceed one person per 1000 m^2 in the tracer gas decay method.

- Precision better than 5 % applied to the difference between the indoor and outdoor CO_2 concentrations.
- The indoor tracer gas concentrations at multiple points within the building should differ by less than 10 % of the average concentration in the building. This requirement should be applied to the difference between the indoor and outdoor concentrations.

The values of supply air flow obtained from the calculation can be subsequently compared with the ventilation requirements expressed as the number of air changes per hour, air flow per person and air flow per square meter of floor area. Table 2 shows the recommended ventilation rates as defined in EN 15251:2007 [3] for class room, which is the space type that can be considered similar to library (requirements for libraries are not defined in [3]). It is recommended to ventilate the pollution associated with occupants, as well as the pollution associated with building materials.

Tab. 2: Recommended ventilation rates for class rooms as defined in EN 15251 [3]

		Airflow for building emissions pollutions (l/s/m^2)		
Category	Airflow per person l/s/person	Very low polluting building	Low polluting building	Non low polluting building
I	10	0.5	1	2
II	7	0.35	0.7	1.4
III	4	0.2	0.4	0.8

The requirements set in the American standard ASHRAE 62.1 [6] (Table 3) are more relaxed than those imposed by the European standard [3]. The difference is in the adaptation of the people to pollution; while the European criteria apply to people who are not adapted on the pollution in the room, the American criteria apply to people who have already had time to adapt on the room air.

Tab. 3: Recommended ventilation rates for libraries as defined in ASHRAE 62.1 [6]

Occupancy category	People Outdoor Air Rate l/(s.person)	Area Outdoor Air Rate l/(s.person)
Libraries	2.5	0.6

In Slovakia, the mandatory regulation regarding the IAQ is the Act of the Ministry of Health of the Slovak Republic no. 259/2008 Coll. [7], which defines the required ventilation rates in rooms without harmful pollutants and with smoking restriction, with long-term occupation by people with the metabolic activity within the classes 0 to 1a (relaxed lying or sitting, or standing with minimum activity). The minimum ventilation rate is determined from Fig. 1, where *V* is the room volume and *G*v is the ventilation rate.

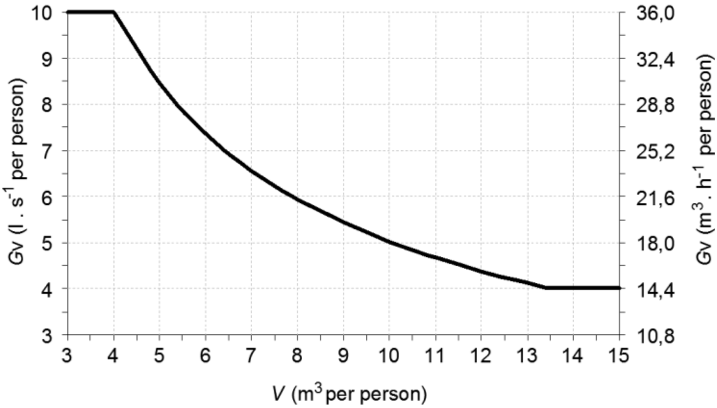

Fig. 1: Requirements on ventilation rate per one person as defined in the Act no. 259/2008 [7]

The present case study focused on the IAQ in the library of the Faculty of Civil Engineering in Bratislava, Slovakia. The regular increase in the CO_2 concentration during days and its subsequent gradual decay during nights allowed for calculation of the air change rate using natural CO_2 as the tracer gas. The results are compared with required ventilation rates as defined in international and national documents, assuming two different occupancy levels of 30 % and 100 %.

2. Methods

2.1 The Library

The library presents a room 5.8 m tall, of a relatively large volume 2073 m^3, divided into two height levels. The second level is a gallery accessed by a staircase (Fig. 2). The library has a total capacity of 190 seats and registers more than 35 000 official entries annually. Heating is provided by radiators located beneath the windows. The room is ventilated by natural infiltration through leaks in the building envelope, and manually by opening windows.

2.2 Monitoring of CO_2 concentration

The measurements were performed in the period from 2 to 18 December 2014. The library was densely occupied due to the end of the winter semester, and even with the windows open the CO_2 concentration during the day peaked at more than 2000 ppm. Five data loggers were placed all over the library to detect the potential imperfections in room air distribution, whereas one data logger recorded the CO_2 concentration in the exterior (Fig. 2).

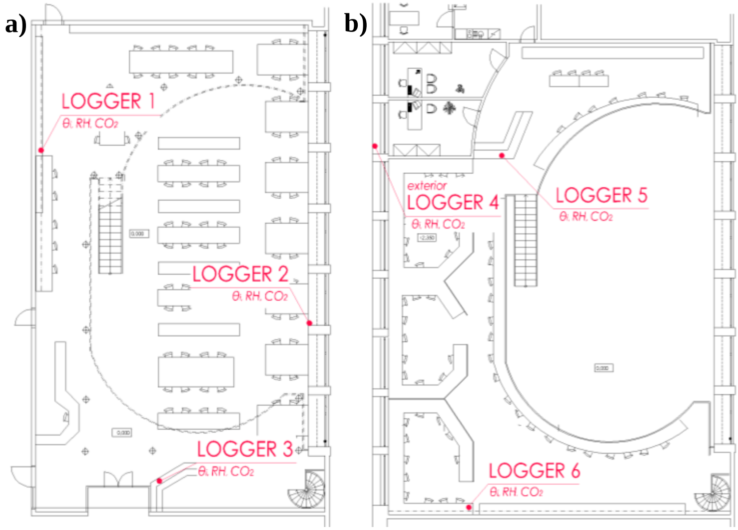

Fig. 2 Plan of the library and the measurement positions: a) 1st level and b) gallery

2.3 Calculation of air change rate

The calculation of air change rate was based on the methodology as described in ASTM E741 [4]. During a typical work day, the CO_2 concentration started increasing in the morning, peaked in the afternoon and started decreasing towards evenings when the visitors were gradually leaving. After the closing time at 18:00 the library was empty and with all windows to the exterior and doors to adjacent rooms closed. Thus, the air change rate was calculated from the CO_2 concentration decay from 19:00 to 6:00 next morning (Fig. 3). The exchange of air between adjacent rooms and the library was considered negligible and the change in the CO_2 mass balance was attributed entirely to the exchange of air between the library and the outdoor environment through leaks in the building envelope.

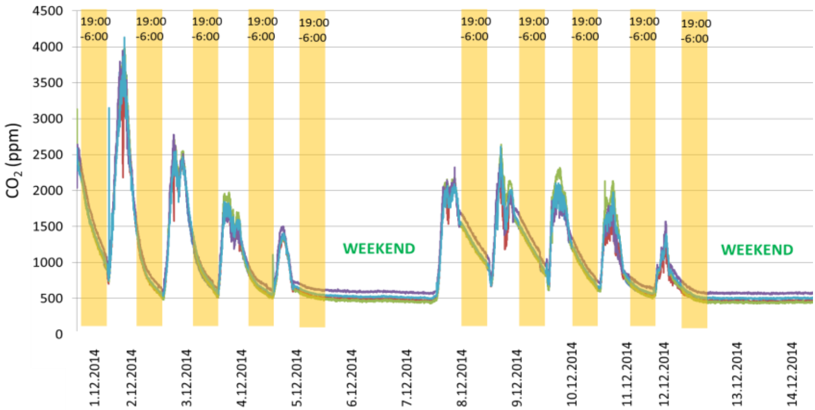

Fig. 3 Time course of CO_2 concentration during two weeks. The vertical colored strips indicate CO_2 concentrations used in air change rate calculations.

The air change rate λ can be calculated iteratively using the CO_2 mass balance equation:

$$C(\mathrm{t}) = (C_0 - C_\mathrm{a}) \,.\, \mathrm{e}^{(-\lambda\,.\,t)} + C_\mathrm{a} \qquad \text{(ppm)} \qquad (1)$$

where C is the tracer gas concentration inside (ppm); C_0 is the tracer gas concentration at the beginning of the measurement (ppm); C_a is the tracer gas concentration outside (ppm); λ is the air change rate (1/h); t is the time (h).

However, linear form of eq. (1) was used to calculate the air change rate directly as recommended by [4]:

$$\ln(C(\mathrm{t}) - C_\mathrm{a}) = \ln(C_0 - C_\mathrm{a}) - \lambda \,.\, t \qquad \text{(ppm)} \qquad (2)$$

This relationship corresponds to a regression on Y against X:

$$Y = a \,.\, X + b \qquad (3)$$

where λ corresponds to a, $\ln(C_0 - C_\mathrm{a})$ corresponds to b, $\ln(C(\mathrm{t}) - C_\mathrm{a})$ corresponds to Y, and t corresponds to X. An example of such linear form is shown in Fig. 4 with the least square equation and the goodness of fit, expressed by the coefficient of determination R^2.

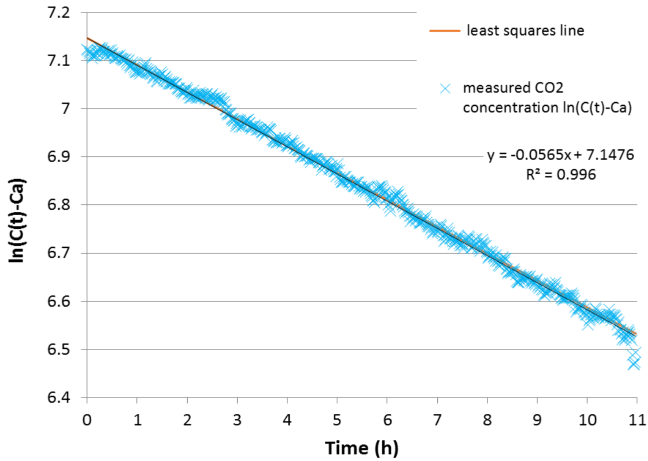

Fig. 4 Linear form of the CO_2 decay

The total uncertainty of the air change rate measurements was estimated by combining the errors due to imperfect mixing of the room air and due to the variation in the recorded values of CO_2 concentration.

The uncertainty due to imperfect mixing of the room air was estimated by comparing the values recorded by the two data loggers with the biggest discrepancy between the measured data.

The uncertainty due to the variation in recorded values of CO_2 concentration was estimated for two sided probability α of 0.05.

2.4 Evaluation criteria

The calculated values of air change rate were compared with the ventilation criteria as defined in various documents, for different levels of occupancy. The ventilation criteria in this study are based on the European standard EN 15251 [3], the American standard ASHRAE 62.1 [6] and the Act of the Ministry of Health No. 259/2008 Coll [7]. Two occupancy levels were considered, 30 % (57 people) and 100 % (190 people) occupancy.

The first criterion is based on the maximum level of CO_2 concentration as shown in Table 1. Here the pollution from materials is not taken into account. The required ventilation level is calculated by:

$$Q = E/(C_i - C_a) \qquad (m^3/s) \qquad (4)$$

where Q is the exchange air flow between room and outside (m^3/s); E is the amount of CO_2 produced by occupants (m^3/s), E = 18 l/h = 5.10^{-6} m^3/s for a person engaged in sedentary activity [8]; C_i is the concentration of CO_2 inside (m^3 CO_2/m^3 air); C_a is the concentration of CO_2 outside (m^3 CO_2/m^3

air). The difference (C_i – C_a) is 500 ppm (500.10^{-6} m^3 CO_2/m^3 air), which corresponds to category II in Table 2. Substituting these values to eq. (4) for 100 % occupancy (190 people):

$$Q = 190 \,.\, 5.10^{-6} / 500.10^{-6} = 1.9\ m^3/s = 6840\ m^3/h$$

The corresponding air change rate (ACR_{100}) is:

$$ACR_{100} = 6840\ m^3/h / 2073\ m^3 = 3.3\ h^{-1}$$

The criterion for 30 % occupancy (ACR_{30}) was calculated analogically.

The ventilation rates as defined in various documents, expressed as air change rate in h^{-1}, at the room occupancy of 30 % (ACR_{30}) and 100 % (ACR_{100}), are shown in Table 4.

The requirements in the first two rows assume that the occupants are not adapted on the room air, and that people are the only pollution source, i.e. the pollution associated with building materials is not taken into account.

The requirement in the third row assumes that the occupants are not adapted on the room air, and it takes both the pollution associated with people and the pollution associated with building materials into account.

Tab. 4: Recommended ventilation rates for the Library in h^{-1}

Calculation method	Requirement	ACR_{30}	ACR_{100}
EN 15251 (2007) • pollution associated with occupants, • unadapted people	**Category II (20 % dissatisfied)** CO_2 concentration indoors less than 500 ppm above the outdoor CO_2 concentration level	0.99	3.30
EN 15251 (2007) • pollution associated with occupants, • unadapted people	**Category II (20 % dissatisfied)** ventilation rate of 7 l/(s.person)	0.69	2.31
EN 15251 (2007) • total pollution load, • low polluting building, • unadapted people	**Category II (20 % dissatisfied)** ventilation rate of 7 l/(s.person) and 0.7 l/(s.m^2_{floor})	1.54	3.16
ASHRAE 62.1 (2013) • total pollution load, • adapted people	**20 % dissatisfied** ventilation rate of 2.5 l/(s.person) and 0.6 l/(s.m^2_{floor})	0.98	1.55
Act of the Ministry of Health no. 259/2008 Coll. • total pollution load	**Minimum ventilation** ventilation rate of 4 l/s for 30 % occupancy and 4.8 l/s for 100 % occupancy	0.40	1.58

The requirement in the fourth row assumes that the occupants are adapted on the room air, and it takes both the pollution associated with people and the pollution associated with building materials into account.

The requirement in the last row considers both the pollution associated with people and the pollution associated with building materials. It represents the minimum amount of fresh outdoor air that shall be supplied.

3. Results

The calculated values of CO_2 concentration are presented in Fig. 5. The average air change rate obtained from the measurements was 0.11 ± 0.04 h^{-1}. The ventilation criteria as defined in different documents [5, 6, 7], and for the two occupancy levels, are represented by the horizontal lines. In the legend the ventilation criteria are listed in the order from the strictest one (uppermost line) down to the most benevolent one (undermost line).

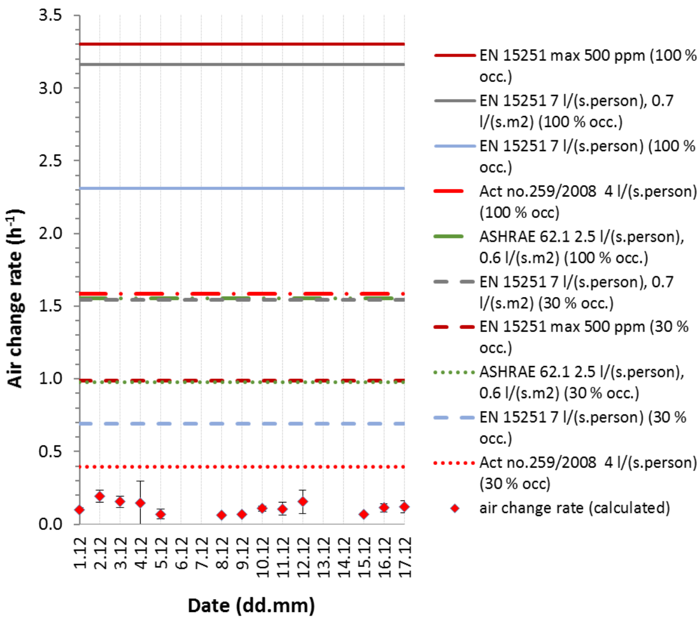

Fig. 5 Comparison of the calculated air change rate with ventilation criteria as defined in different documents, and for two levels od occupancy.

4. Discussion and Conclusion

The values of air change rate obtained from the measurements (Fig. 5) refer to conditions with windows and doors closed, and are lower than required for ventilation of office spaces.

The required air change rates shown in Table 4 vary largely from 0.40 h^{-1} as defined in the Act no. 259/2008 Coll., at 30 % occupancy level, up to 3.30 h^{-1} as defined in EN 15251, at 100 % occupancy level. The requirements increase when the pollution associated with building materials is taken into account, at higher occupancy levels, and when criteria apply to people not adapted on the room air. One exception is the requirement on the maximum CO_2, which is the strictest of all the criteria. Substituting a lower value of CO_2 production of 17 l/h, and a less strict requirement of 660 ppm (as recommended by CR 1752 [9]) to eq. (4) would have resulted in the required ventilation rate of 7 l/s/person, corresponding to the ventilation criteria as defined in EN 15251 (Table 2, category II).

Regardless of the ventilation criteria applied, the values of air change rate obtained from the measurements do not comply with the current requirements on the perceived IAQ. Opening windows to improve the IAQ may cause thermal discomfort to people sitting nearby, and in the whole room by increasing the room thermal losses. Moreover, even with the windows open the CO_2 concentration in the library peaked at more than 2000 ppm at full occupancy. Thus, in similar types of spaces, mechanical ventilation could be a solution to achieve sufficient IAQ, thermal comfort and energy efficiency by heat recovery in the winter period.

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