"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.262
DOI: https://doi.org/10.3846/enviro.2017.262

Determining the Ventilation Rate inside an Apartment House on the Basis of Measured Carbon Dioxide Concentrations – Case Study

Peter Kapalo[1], Silvia Vilčeková[2], Florin Domnita[3], Ciprian Bacotiu[4], Orest Voznyak[5]

[1, 2]Faculty of Civil Engineering, Technical University of Kosice, Slovakia
[3, 4]Faculty of Building Services Engineering, Technical University of Cluj-Napoca, Romania
[5]Department of Heat and Gas Supply and Ventilation, Lviv Polytechnic – National University, Lviv, Ukraine
E-mails: [1]peter.kapalo@tuke.sk; [2]silvia.vilcekova@tuke.sk (corresponding author);
[3]florin.domnita@insta.utcluj.ro; [4]ciprian.bacotiu@insta.utcluj.ro; [5]orest.voznyak@i.ua

Abstract. In the construction process of modern residential buildings the aim is to achieve maximum comfort within minimum energy consumption. One of the ways to achieve this requirement is the accurate determination of the volumetric air flow rate necessary to ensure the required indoor air quality. The aim of the paper is to present a methodology for determination the volumetric air flow rate on the basis of the results obtained from experimental measurements of carbon dioxide concentrations, which were carried out inside an apartment house lived by a standard family. Based on the measured values, the mass flow rate release of carbon dioxide was calculated. Consequently, the volumetric air flow rate was calculated in two situations, during the day and during the night. The main goal of the paper is to determine the required fresh air flow rate in an occupied room, based on carbon dioxide concentration measurement, in order to maintain a comfortable level of indoor air quality. The calculated air flow rate should optimize a future investment in ventilation equipment in order to choose the proper air handling unit with low operating costs. The aim is not only to improve the energy efficiency of the ventilation system, but also to ensure a healthy indoor environment. Based on the presented research it can be stated that during the sleeping of four family members there is necessary to ensure the fresh air flow rate of 104 m^3 per hour.

Keywords: apartment, carbon dioxide, experimental measurement, mass air flow, ventilation, volumetric air flow.

Conference topic: Energy for buildings. Indoor air quality.

Introduction

The trend in the whole world is to decrease as much as possible the energy consumption of buildings, having as a consequence the reduction of pollutants release into atmosphere. For these purposes, the buildings are more and more thermally insulated and thereby their air tightness increase. This tendency requires an adequate design of ventilation system that provides fresh air inside these buildings.

Although sealing/tightening buildings can save energy and reduce the penetration of outdoor pollutants, an adverse outcome can be the increasing build-up of pollutants with indoor sources. In one study (Coombs *et al.* 2016), it was fundamented that indoor pollutants concentration is 3.5 times higher after the renovation of a building. The outbreak of a highly contagious disease, SARS, in Asia in 2003 has revealed the health risk of living in a high-density environment. The connection between human health and indoor air quality is indisputable. Another study (Wong *et al.* 2009) surveys the prevalence of sick building syndrome (SBS) among apartment residents and makes evaluation of indoor environmental quality (IEQ). Statistical analysis showed that residents with SBS symptoms were less satisfied with their IEQ than those without.

Indoor air quality is an important predictor of health, especially in low-income populations (Colton *et al.* 2014; Du *et al.* 2015). People who pay their energy bills individually based on meter readings tend to spend less energy than people who pay collectively, e.g. based on floor areas. It has been hypothesised that these savings are an effect of lower indoor temperatures and lower ventilation rates during heating seasons (Andersen *et al*. 2016).

According to a study about the impact of outdoor and indoor air pollution on indoor air quality, performed for various urban indoor environments (Niu *et al.* 2015), the office environment was affected mainly by outdoor sources and the apartment environment pollution was caused mainly by human activities. According to another study (Park *et al.* 2014), the mechanical ventilation can significantly reduce the exposure to outdoor particles in residential buildings.

The article is focused mainly on monitoring the carbon dioxide concentration, because is the main pollutant produced by humans. The experimental measurements took place in a three-room apartment. Based on the measured carbon dioxide concentration, the mass flow rate of carbon dioxide and, subsequently, the fresh air flow rate needed to ensure a proper indoor environment were calculated.

Materials and methods

It was assessed a three-room apartment, located in an eight-storey block of flats in a housing estate, with a floor area of about 72 m^2. The block of flats was build 35 years ago. Recently, the old wooden windows have been replaced with new plastic double glazing windows. The apartment was inhabited by two adults and two teenagers. Experimental measurements of the most important parameters of indoor air quality, namely carbon dioxide concentration, air temperature and relative humidity in the apartment were conducted. Measurements were carried out in the following spaces of the standard three-room apartment: living room (22 m^2), children bedroom (15 m^2), kitchen (9 m^2), bathroom (3 m^2), adult bedroom (12 m^2) and hallway (10 m^2). The indoor air parameters were recorded 24 hours a day, over an entire week in February. During measurements, the family activities were carried out normally, the parents went to work during the day and the children went to school.

For monitoring the indoor air parameters, a carbon dioxide sensor and a thermo-hygrometer were used. The principle of the measurement of carbon dioxide sensor C-AQ-0001R is based on the variation of infrared radiation with the carbon dioxide concentration. The carbon dioxide concentration measurement range is from 0 to 5000 ppm and the measurement accuracy is ±75 ppm. The thermo-hygrometer S-3541 is designed for recording the air temperature and relative humidity. The measurement range of temperature is from –30 °C to +70 °C and the accuracy is ±0.4 °C. The measurement range of relative humidity is from 5% to 95% and the accuracy is ±2.5% RH at 25 °C. The recorded values are stored on a non-volatile electronic memory. During the measurements, the thermo-hygrometer was interconnected and used simultaneously with the carbon dioxide sensor. Both devices have calibration certificate with declared metrological requirements. For downloading data into a computer, it was used the Datalogger 2.240.0 software developed by Comet System.

Measurement of indoor air parameters

The measurements were carried out during a whole week, from Monday to Sunday, separately for each apartment room. The aim of measurements was to find out in each day the variation of indoor air parameters, while the apartment was occupied by a standard family. Figure 1 presents the measured parameters of indoor air in children room.

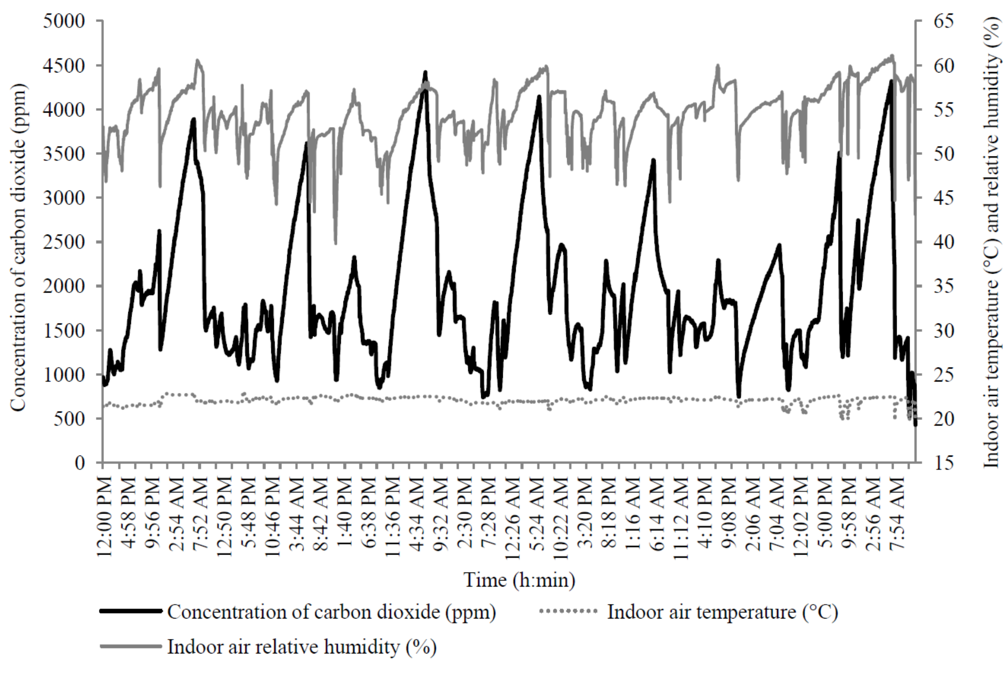

Fig. 1. Variation of indoor air parameters in children room

From Figure 1 it can be seen that in the children room, the maximum values of carbon dioxide concentration and relative humidity were reached during the night. The reason was because over the night hours, when the occupants were asleep, the door and the window were closed and, as a consequence, the ventilation was poor, provided only by infiltration. According to a study (Langer *et al.* 2016), the average air exchange rate during the night for all examined dwellings was 0.44 h^{-1}, as confirmed by the experimental measurements presented in this paper. It follows a rapidly decrease of carbon dioxide concentration in the morning, caused by opening the door and the window. For a better illustration, the carbon dioxide concentrations are presented in Figure 2, as measured day by day during a whole week.

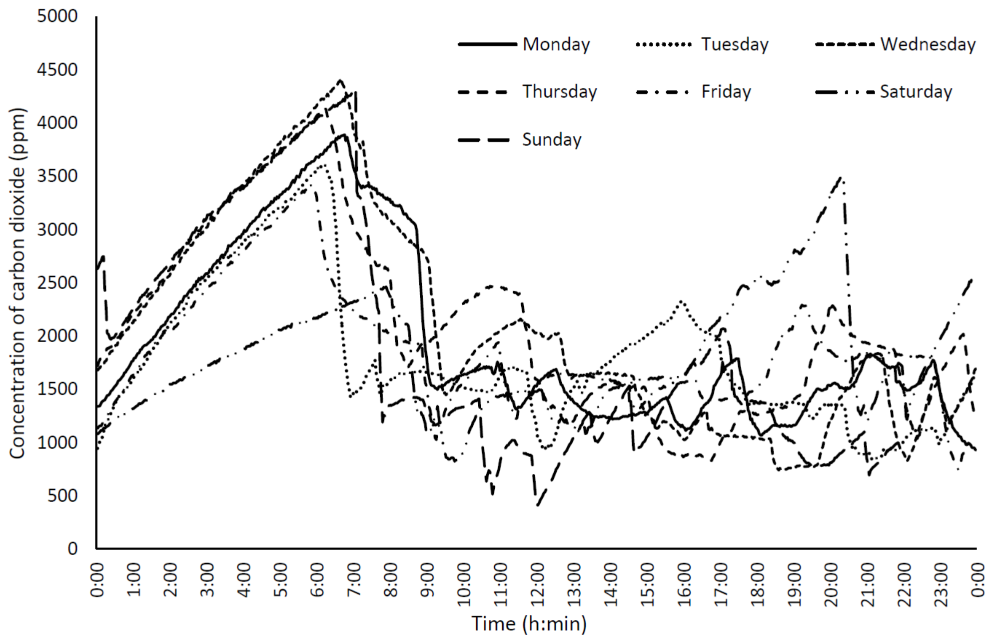

Fig. 2. Daily measurement of carbon dioxide concentration in the children room

During the week, in the children room was found approximately the same trend of carbon dioxide concentration. Particularly at night, the variation in time of carbon dioxide concentration was very similar in every day. The values of CO_2 concentration were significantly higher over the night.

In all other rooms, similar experimental measurements of carbon dioxide concentration were performed in every day of the week, as presented in Table 1 (on Wednesday).

Table 1. Maximum and minimum values of carbon dioxide concentration in the apartment rooms (on Wednesday)

	Maximum value of carbon dioxide concentration (ppm)	Minimum value of carbon dioxide concentration (ppm)
Living room	1348	656
Adult bedroom	3787	725
Children room	4420	739
Kitchen	2534	558
Bathroom	1675	560
Hallway	1978	705

It should be further noted that the outdoor carbon dioxide concentration fluctuated during the measurements from 388 ppm to 469 ppm.

Determining ventilation rate on the basis of measured values of carbon dioxide concentration

The aim of this paper is to determine the required ventilation rate inside each room of the apartment on the basis of measured carbon dioxide concentration.

The natural ventilation rate through infiltration was determined based on the decrease of carbon dioxide concentration in time (Persily 1997, 2005) in all the unoccupied monitored rooms (1).

$$n = \frac{1}{t} \cdot \frac{C_{IDA,S} - C_{SUP}}{C_{IDA,E} - C_{SUP}}, \quad (1)$$

where: n – air change rate caused by infiltration (s^{-1}); t – time of carbon dioxide concentration decrease (s); $C_{IDA,S}$ – carbon dioxide concentration at the beginning of its decrease (mg/m^3); $C_{IDA,E}$ – carbon dioxide concentration at the end of its decrease (mg/m^3); C_{SUP} – outdoor carbon dioxide concentration (mg/m^3).

From the calculated values of the intensity of natural ventilation through infiltration, the volumetric air flow rate produced by infiltration can be determined (2). This result will subsequently be employed for carbon dioxide mass flow rate calculation.

$$q_V = n \cdot V_R \,, \tag{2}$$

where: q_V – volumetric air flow rate produced by infiltration (m^3/s); n – air change rate caused by infiltration (s^{-1}); V_R – room volume (m^3).

A methodology for calculating the ventilation air flow rate for an occupied room, by using the measured values of carbon dioxide concentration, was presented in a research study (Kapalo *et al.* 2014). Based on the measured values of carbon dioxide concentration, it was calculated the carbon dioxide mass flow rate, released in each monitored room, by using Eq. (3):

$$q_{ms} = \frac{q_V \cdot \left(C_{SUP} - \left(C_{IDA,B} - C_{IDA,A}\right)\right)}{1 - e^{\left(\frac{-q_V}{V_R} \cdot t\right)}} \,, \tag{3}$$

where: q_{ms} – carbon dioxide mass flow rate (mg/s); q_V – volumetric air flow rate produced by infiltration (m^3/s); $C_{IDA,A}$ – carbon dioxide concentration at the beginning of its increase (mg/m^3); $C_{IDA,B}$ – carbon dioxide concentration at the end of its increase (mg/m^3); C_{SUP} – outdoor carbon dioxide concentration (mg/m^3); t – time of carbon dioxide concentration increase (s); V_R – room volume (m^3).

According to European standard (STN EN 13779: 2007), the ventilation rate was calculated, by using Eq. (4):

$$n_n = \frac{q_{ms}}{\left(C_{IDA,N} - C_{SUP}\right) \cdot V_R} \,, \tag{4}$$

where: n_n – needed room air change rate (s^{-1}); q_{ms} – carbon dioxide mass flow rate (mg/s); $C_{IDA,N}$ – required level of carbon dioxide concentration in the room (mg/m^3); C_{SUP} – outdoor carbon dioxide concentration (mg/m^3); V_R – room volume (m^3).

The obtained values for carbon dioxide mass flow rate and for the required ventilation rate corresponding to each analyzed room are presented in Table 2.

Table 2. The calculated values of carbon dioxide mass flow rate and required ventilation rate

	Carbon dioxide mass flow rate (mg/s)	Required ventilation rate $(h \cdot pers)^{-1}$
Living room	11	38
Children room	15	53
Kitchen	26	89
Bathroom	15	50
Hallway	18	61

Based on both carbon dioxide mass flow rate and calculated volumetric air flow rate required per person, it can be determined the volumetric air flow rate needed for a proper ventilation in the entire apartment. Combining the calculated volumetric air flow rates can be obtained the required volumetric air flow rate for given activity. For example, during sleep in the home is required to provide the fresh air flow rate of 104 m^3 per hour. If one person cook, 2 persons read the book and one sleep, than the volumetric air flow rate is 191 m^3 per hour.

Discussion

According to calculated values of ventilation rate produced by natural infiltration, it can be stated that, in the apartment rooms, the air exchange between indoor and outdoor was not the same. The calculated carbon dioxide mass flow rates were very different from one room to another. The difference was caused by the various activities carried out by the persons inside each room. In the living room, where the carbon dioxide mass flow rate was 11 mg/s, the activities were mainly sedentary. In the children room, where the mass flow rate was 15 mg/s, there were more intensive physical activities. In the kitchen, besides the carbon dioxide released from the occupants, it was added the carbon dioxide produced during the burning process of natural gas for cooking, therefore the carbon dioxide mass flow rate reached 26 mg/s.

For the common activities developed in each room, it was calculated the required volumetric fresh air flow rate in order to ensure a healthy indoor environment. It was assumed that carbon dioxide concentration would not exceed a limit of 1000 ppm. In order to achieve an entirely healthy indoor environment, the level of carbon dioxide concentration should be as close as possible to that of fresh air from outdoor. For a better understanding, a graphical representation of required volumetric air flow rate was made, for different values of carbon dioxide mass flows rate (Fig. 3).

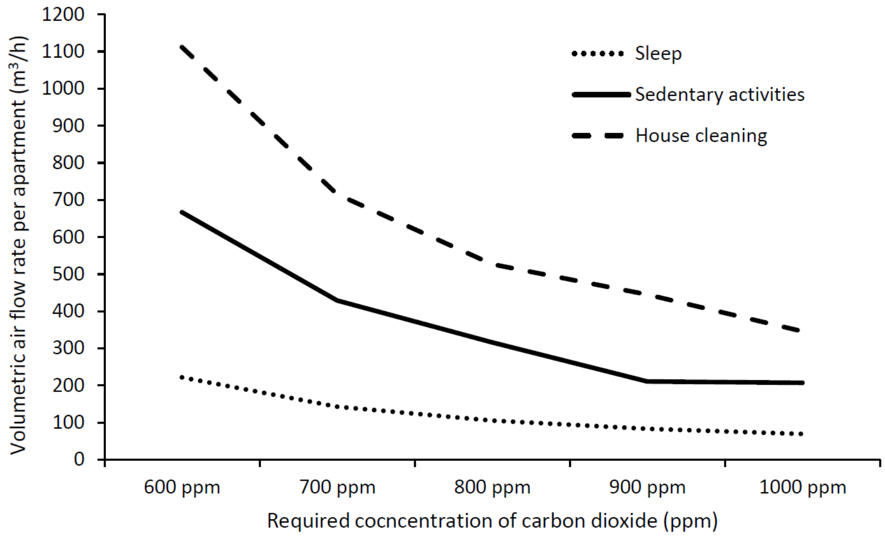

Fig. 3. Required volumetric air flow rate per apartment

According to the graphical representation as presented in Figure 3, for the assessed apartment (occupied by four people, for three type of activities), the required volumetric air flow rate can be read. The volumetric air flow rate increases logarithmically with the decrease of carbon dioxide concentration. For a normal way of living inside an apartment, it is needed to maintain the carbon dioxide concentration to maximum 1000 ppm.

Results

For reasons of maximum energy efficiency, we simulated a limit of 1000 ppm of carbon dioxide concentration in the apartment, which led to calculation of the lowest volumetric fresh air flow rate (104 m^3/h), required during the night. Throughout the day, as normal, sedentary activities were carried out in the apartment, so we obtained a medium volumetric fresh air flow rate of 220 m^3/h. In the case of more physically demanding activities, such a house cleaning, the value of 350 m^3/h were found.

In order to achieve a higher quality of indoor air, with a carbon dioxide concentration of 600 ppm, is needed a volumetric fresh air flow rate of approximately 230 m^3/h throughout the night. Similarly, over the day, for more intensive physically activities, the needed fresh air flow rate is considerably higher. The medium value that results in the case of sedentary activities is 670 m^3/h and the maximum value that results if the whole family is doing the household cleaning is 1120 m^3/h.

From the calculated simulation of required volumetric air flow rate it can be seen that, for the case study presented above, in order to ensure a proper indoor air quality, it is required a ventilation equipment with an air flow rate of 350 m^3/h. This value ensures the required quatity of fresh air inside the apartment and also provides a healthy environment, even for activities that involve physical effort. The air handling unit will exceed the sound power limit of 45 dB only during physically demanding activities, when the fan speed is maximum. During the less demanding activities, when the fan speed is lower, the sound power limit of 45 dB will not be reached.

Conclusions

The major source of pollutants inside an apartment are occupants. By using the experimental measurements, the carbon dioxide concentration in the standard apartment was evaluated and, based on the collected data, the intensity of natural ventilation through infiltration was calculated. Subsequently, based on the methodology for determining the ventilation air flow rate for a room with people inside, the mass flow rate of carbon dioxide released by the occupants in each monitored room was calculated by using measured values of CO_2 concentration. Finally, implementing the real values of the carbon dioxide mass flow rate, was calculated the required volumetric air flow rate in order to reach the required level of indoor air quality.

The results obtained from this study lead us to the conclusion that, by quantifying the volumetric fresh air flow rate on the basis of monitored concentration of carbon dioxide, we can acquire exact input data in order to make a proper air handling unit selection. This will provide the required air quality inside an apartment, allowing us in the same time to maintain lower levels of energy consumption for HVAC systems.

Acknowledgements

This article was elaborated within the framework of the project VEGA 1/0307/16.

Funding

This paper was financially supported by the Slovak Grant [VEGA No. 1/0307/16].

Disclosure statement

As authors of this paper, we declare that we have not any competing financial, professional, or personal interests from other parties.

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