Section: Energy for Buildings

Determine a methodology for calculating the needed fresh air

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Abstract

By improving thermal properties and air tightness of buildings, there is a change of indoor air quality in buildings – without any ventilation (natural or mechanical) there is a significant deterioration of indoor air quality. In low-energy and passive houses about 80% of total energy consumed for heating is used to heat the fresh air needed for occupants.

The aim of the paper is to determine a methodology for calculating the needed airflow rate (including fresh air) in an occupied room, based on carbon dioxide measurement and calculation, in order to maintain a comfortable level of indoor air quality. The calculated airflow rate should optimize the investment and the operating costs of HVAC equipment. In the work calculation methods used to determine the ventilation airflow rate are analyzed. A methodology for calculating the ventilation airflow rate for a room with people inside by using the measured values of carbon dioxide concentration is presented. The connection between carbon dioxide concentration and ventilation airflow rate is verified by experimental measurements.

This methodology is applicable in Slovakia because it complies with all current standards. The result obtained by using this calculation method is almost the same with the results achieved from experimental measurements. To confirm the results, we present a case study of an office with occupants, in which the ventilation airflow rate calculation method is applied.

Keywords: ventilation; airflow rate; legislative; carbon dioxide (CO_2), concentration.

Nomenclature	
w	velocity (m/s)
h	height (m)
l	length of the joints (m)
V	volumetric airflow rate (m^3/s)
i	air permeability through window joints ($m^3/s \cdot m \cdot Pa^{2/3}$)
n	exponent that characterizes the airflow through joints
p	pressure (Pa)
C	carbon dioxide concentration (g/m^3)
q_H	carbon dioxide emissions (g/s)
q_V	airflow rate (m^3/s)
V_M	room volume (m^3)
t	time (s)
n	ventilation rate (1/h)
Greek symbols	
Δ	difference
θ	temperature (°C)
ρ	air density (kg/m^3)
Subscripts	
i	indoor
e	outdoor
IDA	indoor air
SUP	supply air

Abbreviations
CO_2 carbon dioxide
HVAC   heating, ventilation and air conditioning
C-AQ-0001R sensor unit for CO_2
S-3541   thermo-hydrometer

1. Introduction

In recent years, the standard of living in Europe increased significantly. The direct consequences are increases in energy consumption of buildings and a negative impact on the environment. Larger number of home appliances cause greater energy consumption. In some European countries, approximately 40% of energy is consumed in buildings. In construction industry increasing pressure to construct low energy buildings is exerted. Energy effective houses do not present the new definition of projection but it is more improving of attested processes and adaptation to new requests [1]. According to EuroACE [2], 57% of consumed energy in a building is used for heating, 25% for heating hot water, 11% for lighting and electrical appliances and 7% for cooking.

Nowadays, the priority is to build-up low energy buildings with controlled ventilation. Importance of ventilation in heated and tight building is documented by questionnaires, where the respondents had the opportunity to comment on the issue of office buildings indoor environment. 177 persons filled out a questionnaire, 43% of them were women and 57% men, with the age of 20 – 30 years (73%), 30 – 40 (20%), 40 – 50 (3%) and over 50 years (4%) [3].

The respondents also expressed their opinion on the indoor air quality by giving evaluation marks from 1 to 10 (1 for the poorest and 10 for the best indoor air quality). Most of the respondents considered indoor air quality as very good as they gave marks from 8 to10 (Fig. 1).
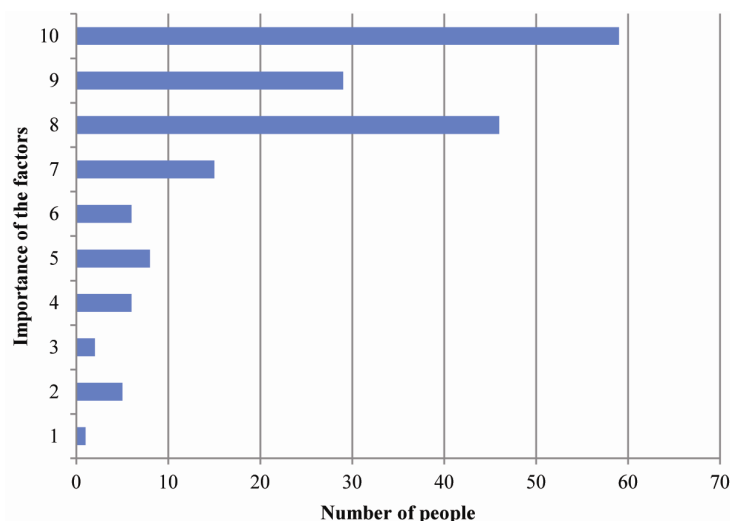

Fig. 1. Indoor air quality [3]

To establish the necessary ventilation rate the theoretical knowledge can be used, based on the theory of determining volumetric airflow rate based on the quantity of gaseous pollutants and CO_2 released inside a room. Experimental measurements of the concentration of CO_2 were carried out in winter in several selected rooms. On the basis of measured concentration of CO_2 the needed fresh air ventilation rate that meets sanitary requirements, as well as the intensity of ventilation rate in the room can be calculated.

Intensity of air exchange in the tested room generally can be defined by calculations and measurements. In this work a room with natural ventilation is examined.

2. Data/Methods

2.1. Carbon dioxide as a result of respiration

The human body of an adult contains approximately 12.6 kg of carbon. Carbon is an element with a content of about 18% in the human organisms. Redundancy of carbon atoms is removed from organism in the process of respiration in the form of carbon dioxide. Energy released in such way is spent to maintain the vital processes in human organism.

The carbon dioxide is a gas without color and odor and it is also contained in the atmospheric air. The exhaled air contains (Table 1) approximately 4% carbon dioxide [4]. Such concentration is non-toxic for humans. However, in case of higher concentrations there are typical syndromes like hyperventilation, higher blood pressure and pulse. Even more increased concentration of carbon dioxide causes serious damages to the organism. At 10% concentration a blackout occurs and it comes to death caused by suffocation.

Table 1. Composition of inhaled and exhaled air for healthy adult humans [4]

Breathing substance	Inhaled air (%)	Exhaled air (%)
Oxygen	20.96	15.4 –17
Carbon dioxide	0.04	4 – 5.6
Nitrogen	78	78
Other gases	1	1

At a normal rate of breath, an adult can inhale 2.5 liters of air or even more. After the exhalation approximately 0.5 liters of air remains in lungs and bronchi. This volume is called the residual lung volume. Respiratory rate is the number of breaths per minute and is depending on age. The respiratory rate for a newborn is from 40 up to 45 inhalations/exhalations per minute, for a child 25 up to 30 inhalations/exhalations per minute and for an adult from 16 up to 20 inhalations/exhalations per minute. Accelerated breathing is more than 20 inhalations/exhalations per minute for an adult person and it can increase up to 100 in the case of a high demand of oxygen (i.e. during intense physical or psychical loading). Reduced respiration is less than 12 breaths per minute (Table 2).

Table 2. Calculated carbon dioxide flow rate for different degrees of breathing

Volume of inhalation/exhalation	Intensity of respiration	Airflow rate inhalation/exhalation		Carbon dioxide flow rate		
[l]	[1/min]	[l/s]	[m³/h]	[m³/h]	[kg/h]	[mg/s]
0.5	12	0.10	0.36	0.014	0.028	7.86
0.5	13	0.11	0.39	0.016	0.031	8.51
0.5	14	0.12	0.42	0.017	0.033	9.17
0.5	15	0.13	0.45	0.018	0.035	9.82
0.5	16	0.13	0.48	0.019	0.038	10.47
0.5	17	0.14	0.51	0.020	0.040	11.13
0.5	18	0.15	0.54	0.022	0.042	11.78
0.5	19	0.16	0.57	0.023	0.045	12.44
0.5	20	0.17	0.60	0.024	0.047	13.09

A healthy adult has a respiratory flow rate from 7.5 to 8 litres of air per minute at approximately 15 breathings per minute. The breathing frequency will increase during physical effort, when a large volume of oxygen is needed [4].

According to the CO_2 parameters, lung volume and intensity of breathing, there are calculated the CO_2 mass flow rates for different degrees of breathing (Table 3).

Table 3. Calculated CO_2 mass flow rates for different degrees of intensity of breathing and for 0.5 l of inhalation-exhalation

Intensity of breathing, [1/min]	12	13	14	15	16	17	18	19	20
Mass flow rate of CO_2 [mg/s]	7.86	8.51	9.17	9.82	10.47	11.13	11.78	12.44	13.09

It can be seen that the CO_2 mass flow rate increases linearly with breathing intensity.

2.2. The calculation of needed fresh airflow rate in a populated room

During the research, in the selected room (office with one occupant), the following indoor environment parameters were measured: air temperature, relative humidity and carbon dioxide concentration.

The dimensions of the office, where the experimental measurements were carried out, are:
– length: 5.63 m
– width: 3.40 m
– height: 2.72 m

The office window has the following dimensions:
– height: 1.75 m
– width: 1.10 m

2.3. Infiltration airflow rate

Volumetric airflow rate through window joints can be determined [5] from the Eqn (1):

$$V = i \cdot l \cdot \Delta p^n \ \ [\text{m}^3/\text{s}] \tag{1}$$

where: V – volumetric airflow rate, m^3/s; i – air permeability through window joints, $\text{m}^3/\text{s} \cdot \text{m} \cdot \text{Pa}^{2/3}$; l – length of the joints, m; n – exponent that characterizes the airflow through joints, commonly $n = 2/3$; Δp – differential pressure due to the air temperature difference between indoor and outdoor and the external wind pressure, Pa.

Differential pressure due to air temperature difference between indoor and outdoor and the external wind pressure [5], is given by the Eqn (2):

$$\Delta p = h \cdot g \cdot (\rho_e - \rho_i) + 0.5 \cdot w^2 \cdot \rho_e \ \ [\text{Pa}] \tag{2}$$

where: θ_i – indoor air temperature, °C, $\theta_i = 23$ °C; θ_e – outdoor air temperature °C, $\theta_e = 7$ °C; ρ_i – indoor air density, kg/m^3, $\rho_i = 1.153 \ \text{kg/m}^3$; ρ_e – outdoor air density, kg/m^3, $\rho_e = 1.219 \ \text{kg/m}^3$; h – window height, m; w – medium wind velocity m/s, $w = 4.16$ m/s.

This calculation provides the boundary conditions needed for measuring the carbon dioxide concentration. The result for infiltration airflow rate in the tested office is 0.205 1iters per hour.

3. Results and discussion

3.1. Carbon dioxide concentration

Carbon dioxide concentration in the room air [6], [7], [8] is calculated according the Eqn (3):

$$C_{IDA} = C_{SUP} + \frac{q_H}{q_V} \cdot \left\{ 1 - \exp\left[\left(\frac{-q_V}{V_M} \right) \cdot t \right] \right\} \ \ [\text{g/m}^3] \tag{3}$$

where: C_{IDA} – carbon dioxide concentration in indoor air at the time t, g/m^3; C_{SUP} – carbon dioxide concentration in supply air at a time t, g/m^3; q_H – carbon dioxide emissions inside the room from the human source, g/s; q_V – airflow rate required for room ventilation, m^3/s; V_M – room volume, m^3; t – time, s.

Eqn (3) provides values for carbon dioxide concentration in the room air by means of Table 2 and for carbon dioxide concentration in supply air, $C_{SUP} = 420$ ppm, measured outdoor. For different values of respiration intensity the results of the calculations together with measurements (bold line) are shown in Figure 2. By comparing the measured to the calculated values, the most accurate carbon dioxide production is determined.
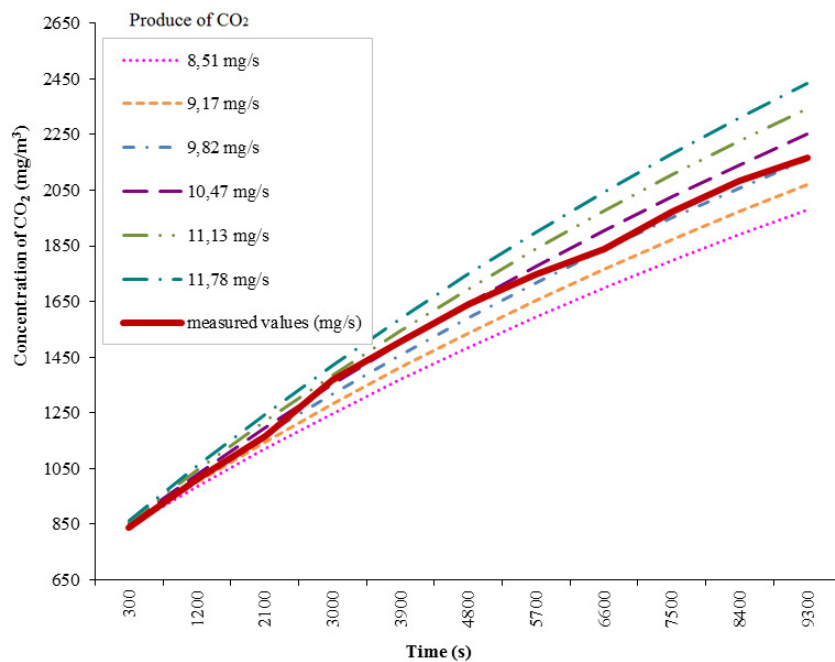

Fig. 2. Determination of carbon dioxide production by comparing measured and calculated values

It can be concluded that the releases of carbon dioxide from human occupants with a breathing intensity of 15 1/min are almost the same according to the calculated and measured values (Fig. 2). This value corresponding to the carbon dioxide produce $q_H = 9.82$ mg/s.

$$q_V = \frac{q_H}{C_{IDA} - C_{SUP}} \quad [M^3/S] \tag{4}$$

By using the Eqn (4) to calculate the needed indoor airflow rate, the result is $n = 0.68$ 1/hour, almost similar to that obtained by graphical method.

3.2. Measurement of carbon dioxide production

In order to determine the values of carbon dioxide concentration, a CO_2 sensor unit C-AQ-0001R was used. To measure the air temperature and relative humidity a thermo-hydrometer measuring device S-3541 was used.

Figure 3 shows the graphic variation (depending on time) of the following measured parameters: CO_2 concentration, indoor air temperature and relative humidity.
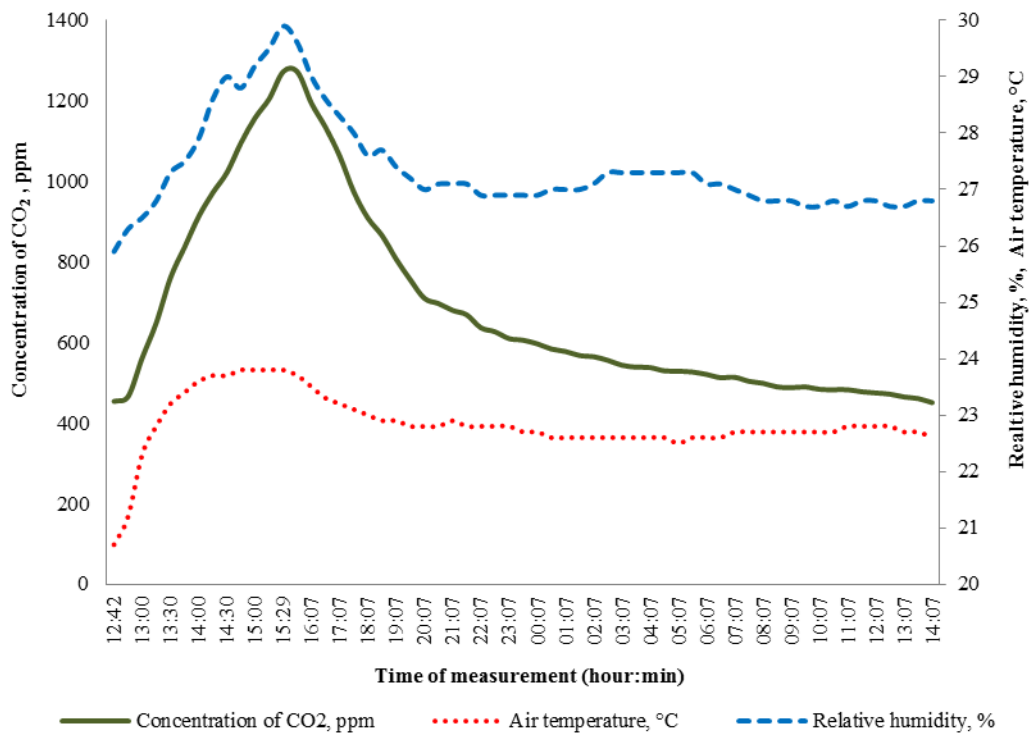

Fig. 3. Measured CO_2 concentration, indoor air temperature and relative humidity

The waveforms of measured values of CO_2 concentration and indoor air relative humidity are increasing significantly until 16 o'clock and after that are slowly decreasing. The increasing and decreasing of indoor air temperature is not similar to the relative humidity. After reaching a maximum CO_2 concentration at 16 o'clock, the room was abandoned and the releases of CO_2 stopped. The decreasing of CO_2 concentration is caused by infiltration and natural ventilation.

3.3. Indoor airflow rate calculation

Required indoor air quality is given by standards STN EN 13779 [6]. Processed data are presented in Table 4.

Table 4. CO_2 concentration level in occupied rooms and outdoor airflow according to STN EN 13779 [6].

Category	CO_2 concentration above outdoors level (ppm)		Outdoor airflow per person (non smoker) (l/(s·person))	Outdoor airflow per one m² of floor area (l/(s·m²))
	Current range	Standard value	Standard value	Standard value
IDA 1	≤ 400	350	20	
IDA 2	$400 \div 600$	500	12.5	0.83
IDA 3	$600 \div 1000$	800	8	0.55
IDA 4	> 1000	1200	8	0.28

It can be seen that the required value for indoor airflow rate must be chosen in such a way, that the concentration of CO_2 never surpasses 1000 ppm.

From the values obtained by calculation we calculated the required intensity of ventilation for a room with a given number of persons located in it. The requirement which was necessary to meet was the maximum concentration of CO_2 in the room C_{IDA} = 1000 ppm – see Figure 4.
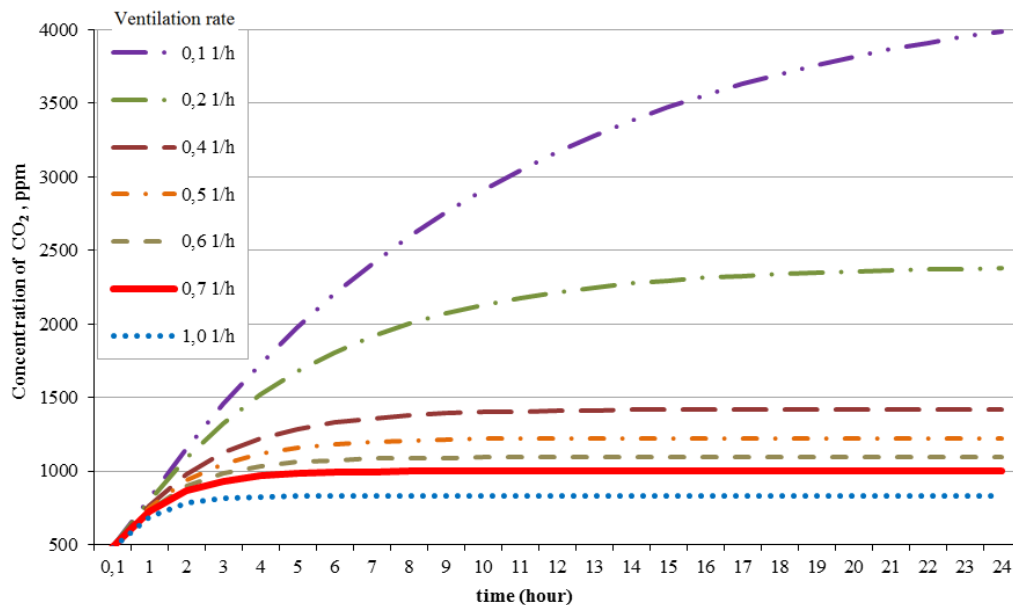

Fig. 4. Graphic method to determine indoor airflow rate

In our case it is the curve of concentrations marked in bold (second from the bottom) with an intensity of ventilation of n = 0.7 1/h.

4. Conclusions

The aim of the research is to determine the needed exchange of indoor air on the basis of combined calculation and experimental method (measurement of the release of carbon dioxide from room occupants). During the experiment, the studied room was occupied with persons who produced 9.82 mg/s of carbon dioxide, based on measurement results.

In order to ensure a healthy indoor climate, by calculation method, an indoor airflow rate of 0.68 l/hour is required. According to standard EN 13779 [6], the needed indoor airflow rate can be determined according to the production of pollutants inside the tested room, in our case study the release of carbon dioxide from room occupants. On the basis of measured concentration from CO_2 (Fig. 4) the result value for indoor airflow rate is 0.7 1/hour (bold line), accordingly the experimental CO_2 results have shown good congruence of air change rate with the calculated valid standards.

The standard EN 13779 [6] is satisfactory according to research for determination ventilation rate.

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