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Using Experimental Measurements of the Concentrations of Carbon Dioxide for Determining the Intensity of Ventilation in the Rooms

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Considering the fact that in operating costs of the new building the important place take expenses on heating, mainly, on air heating in systems of ventilation, the measures directed on optimization of the intensity of ventilation at maintaining comfort of consumers, are of high importance and have national character.
To reduce electricity consumption it is possible to use air-conditioning equipment providing heat recovery from exhaust air. When choosing the ventilating equipment it is necessary to consider the correct boundary conditions that the ventilating equipment wasn't the overestimated or underestimated power with the aim of optimizing investment and operating costs of ventilation equipment in compliance with sanitary requirements with regard to air quality in the internal environment of buildings. This paper is aimed to develop a methodology for determining the intensity of ventilation of indoor premises based on the experimental measurements of the concentration of carbon dioxide (CO_2).
Using experimental measurements and the knowledge gained in the study of this issue, in the work the method for intensity ventilation determining of the indoor premises was developed on the basis of the measured values of carbon dioxide which was verified also by another experimental measurements. The resulting values of ventilation intensity rate obtained by calculation from the measured values of carbon dioxide were compared with the results of calculations executed according to the laws and standards, current in Slovakia. Based on comparison of the results one of the methods for calculation of the ventilation intensity was developed that is valid in Slovakia, the results of which were close to the results obtained by the method of determining the intensity of ventilation rate in the room on the basis of the measured values of carbon dioxide. The above mentioned method is determined by the method of calculating intensity of ventilation rate in the rooms intended for offices.

1. Analysis for calculating the intensity of ventilation rate in the buildings

Analysis for calculating the intensity of ventilation rate in the buildings is carried out according to regulations and standards valid in Slovakia. In Slovakia the estimated ventilation intensity is regulated by several law regulations and instructions: (Resolution No 364/2012, 2012 - used for energy certificates of buildings - Slovak law, (Resolution No 391/2006, 2006 - used for dimensioning of ventilation rate - Slovak law - the most used in Slovakia), (Standard STN 73 0540-2, 2012 - used for calculated energy performance of building), (Standard STN EN 13779, 2005 - used for dimensioning of ventilation rate - accepted from Euronorm) and (Standard STN EN 15251, 2007 - accepted from Euronorm).
Intensity of air exchange in the tested room generally can be defined by calculations and measurements. In this work the room with natural ventilation is examined. In the most part of the room there is an uncontrollable air infiltration and ex-filtration. Natural ventilation can be considered as air exchange of the

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internal environment due to the pressure difference, which is caused by the effects of natural forces arising from temperature difference or the dynamic action of wind.

2. Determination of the intensity of ventilation rate based on the values of concentration CO_2, obtained by experimental measurements

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

2.1 Features of the tested room

The tested room is an office located in five-story building on the second floor.
Considered room is the office in the five-story building on the second floor. The office has the following measurements: length 5.63 m, width 3.4 m and height 2.72 m.
In the room there is one window with the measurements: height 1.75 m and width 1.1 m. The internal volume of the room is 52.07 m^3 and the floor area of the room is 19.14 m^2. In outdoor environment there was the concentration of CO_2 C_{SUP} = 380 ppm. During the measurement one adult person was present in the room.

2.2 Measurement of indoor air parameters

Measurement of the parameters of internal air: temperature of air, relative humidity and concentration of CO_2 was conducted in winter on 04.02.2013. To measure the carbon dioxide concentration there was used sensor of CO_2 concentration C-AQ-0001R. For measurement of the temperature and relative humidity there was used thermo-humidity meter S3541.
It was very important to provide ideal conditions during the measurement for mathematic definition of process of CO_2 concentration from measured data. In addition to the measured internal parameters of air there was clock data of parameters of outdoor air like temperature of outdoor air and also the wind speed. The data are manipulating on intensity ventilation by infiltration.
The first increase in the concentration of CO_2 is slower. In the room a person producing CO_2, performs administrative work in a sitting position. Once the CO_2 concentration reached 900 ppm, the room was aired by opening windows.
The second increase in the concentration of CO_2 is much faster. Increase in concentration was caused by intense production of CO_2, produced by the person doing exercises - squats and exercises with hands. For significantly less time CO_2 concentration was more than in the first case.

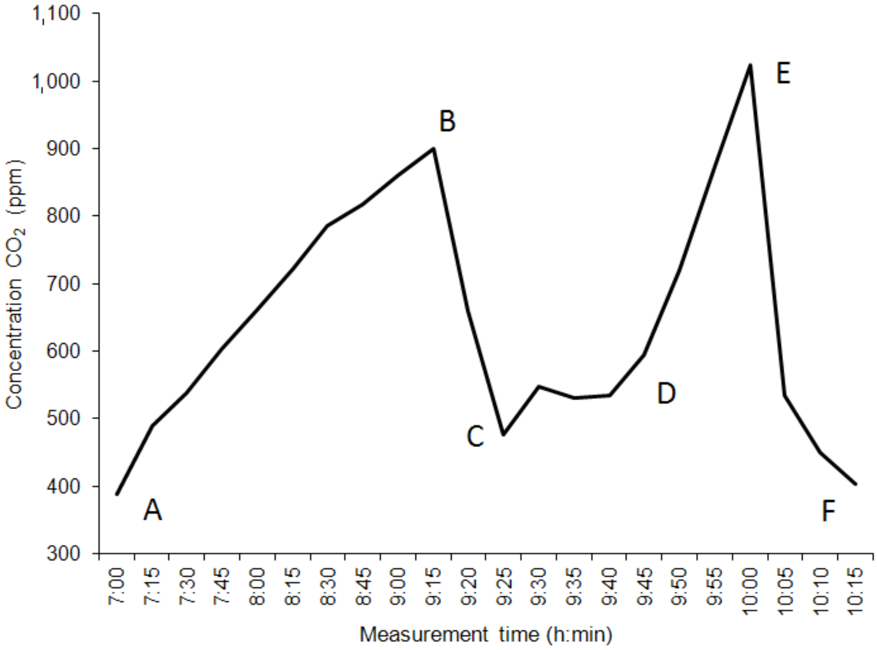

Figure1: Changes in CO_2 concentration - division into sections

In section A - B (Figure 1) observed increase in CO_2 concentration, when the main source of pollutants is the person. The increase in the concentration of CO_2 can be mathematically represented by the equation:

$$C_{IDA} = C_{SUP} + \frac{q_{ms}}{q_V} \cdot \left\{1 - \exp\left[\left(\frac{-q_V}{V_M}\right) \cdot t\right]\right\} \quad (1)$$

Where: C_{IDA} is concentration of CO_2 in the air in a room for time t (mg/m^3); C_{SUP} is concentration of CO_2 in the supply air for time t (mg/m^3); q_{ms} is mass flow rate of CO_2 in the room, which comes from the source of pollutants (mg/s); q_V is the volume of airflow required for the ventilation of the room (m^3/s); V_M is volume of the room (m^3); t is time (s).

Mentioned values indicate the volume of the room, time of CO_2 concentration, given in ppm, to be recalculated in units of mg/m^3. Unknown quantities are our mass flow of pollutants and flow rate of fresh air that penetrates into the room due to infiltration.

2.3 Calculation of the intensity of ventilation rate by infiltration from the measured decrease in the concentration of CO_2

In determining the air exchange rate in result of infiltration in the room it is possible to use indirect chemical mixing method. This method analyses the decrease in the concentration of pollutants in the air (Rusli et al., 2014). CO_2 is considered as a pollutant. CO_2 is diffused in the room and monitors time in decrease the concentration. The measurement is terminated with decreasing CO_2 concentration to the concentration of CO_2 outdoors. For a given phenomenon the Eq.2 is valid (Persily, 2005).

$$n = \frac{1}{t} \cdot \ln \frac{C_{IDA,S}}{C_{IDA,E}} \quad (2)$$

Where: n is ventilation intensity as a result of infiltration (1/s); $C_{IDA,S}$ is concentration of CO_2 in the room at the beginning of decrease of the concentration (mg/m^3); $C_{IDA,E}$ is concentration of CO_2 in the room at the end of decrease of the concentration (mg/m^3); t is time of decrease of CO_2 concentration (s).

In our case, in the premises carbon dioxide was produced by a person. Increase in CO_2 concentration was caused by the presence of the person (section A - B). During all the time room ventilation was provided due to infiltration.

In sector B - C there is no person in the room so we can consider with zero production CO_2. Enhanced concentration CO_2, which was caused by presence of a person (sector A - B), is gradually reduced in sector B - C by influence of uncontrolled ventilation through infiltration.

When reducing CO_2 concentration (due to infiltration in a room) the metrics impacting on infiltration process were changing (temperature of outdoor air and wind velocity).

Since the CO_2 concentration in the room at the end of measurements was different from the CO_2 concentration in the outdoor air, then the ventilation intensity in the considered room is determined through the S function of CO_2 concentration against time. When calculating we shall use the measured values of CO_2 concentration.

The intensity of air through infiltration in the considered room we determinate from function drop of concentration CO_2 with independence of time – Eq.3.

$$\frac{C_{IDA,B} - C_{SUP}}{C_{IDA,C} - C_{SUP}} = e^{-nt} \quad (3)$$

By editing the Eq.3 we expressed intensity of ventilation by infiltration – Eq.4.

$$n = \frac{1}{t} \cdot ln \frac{C_{IDA,B} - C_{SUP}}{C_{IDA,C} - C_{SUP}} \quad (4)$$

Where: n is intensity of ventilation by infiltration (1/s); $C_{IDA,B}$ is concentration of CO_2 in the room on the start reduction concentration (mg/m^3); $C_{IDA,C}$ is concentration of CO_2 in a room at the end of reduction concentration (mg/m^3); C_{SUP} is concentration of CO_2 supply air in the time (mg/m^3); t is time of reduction of CO_2 concentration (s).

If during CO_2 concentration decrease the boundary conditions are changing (air temperature outdoors and wind speed) that affect infiltration, the intensity of ventilation should be defined on the basis of measured concentrations of CO_2.
The experimental measurements are based on the actual production of CO_2, produced by a person that was in the room. Ventilation intensity n = 0.5 1/h was calculated mathematically on the basis of measured decrease in CO_2 concentration. Calculated intensity of ventilation corresponds to the values obtained due to experimental measurements that were executed only for intensity of ventilation determination.

Table 1: Office on the second floor

Volume of the room (m^3)	Calculated ventilation rate infiltration (1/h)	Indoor Temperature (°C)	Outdoor Temperature (°C)	Measured ventilation rate infiltration (1/h)	Window material	Type of weather-strip
50.5	0.25	23.0	3.5	0.41	Wood	Sheet Steel
50.5	0.25	22.0	5.0	0.63	Wood	Sheet Steel
50.5	0.25	24.9	6.0	0.59	Wood	Sheet Steel

2.4 Determination of the intensity of ventilation - when working in a sitting position
In the office there was conducted some work by one person being in a sitting position and producing CO_2 by breathing. There was calculated mass flow carbon dioxide for the expected average 0.5 L volume of breath / exhale and for intensity of breathing from 12 to 20 breaths/min.

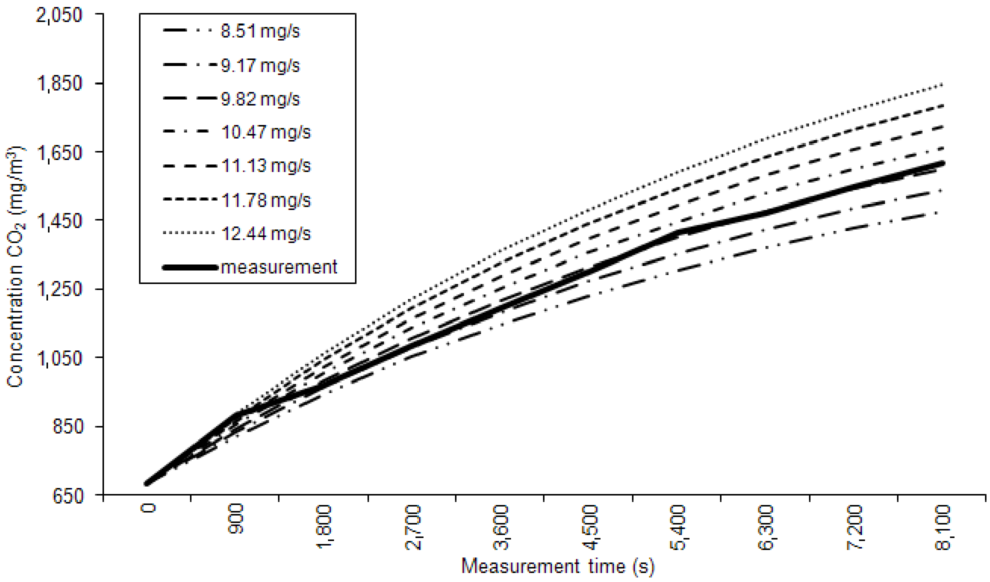

Figure 2: Changes in the concentration of CO_2, associated with the intensity of breathing - administrative work in a sitting position

The actual production of carbon dioxide by breathing of a person in the office is determined graphically in Figure 2, where the intensity of each breath acc. to the formula 1 changes of CO_2 concentration is calculated. To Figure 2, with calculated changes of CO_2 concentration changes of the actual measured CO_2 concentration are described. On the basis of curves it can be observed that the actual production of pollutants is matching the intensity of breathing – 15 breaths/min, which corresponds to the mass flow produced carbon dioxide 9.82 mg/s.
The intensity of ventilation rate is determined similarly by the graph on the basis of changes in the concentration of CO_2. When calculating changes in CO_2 concentration formula 1 is used, in which we take a mass flow of CO_2, the volume of the room and measured initial concentration of CO_2. The calculations are performed for each hour and for different intensity of ventilation. The overall result should be arranged in such a way that the initial value of CO_2 concentration was specified in ppm. For our case, results are shown in Figure 3.

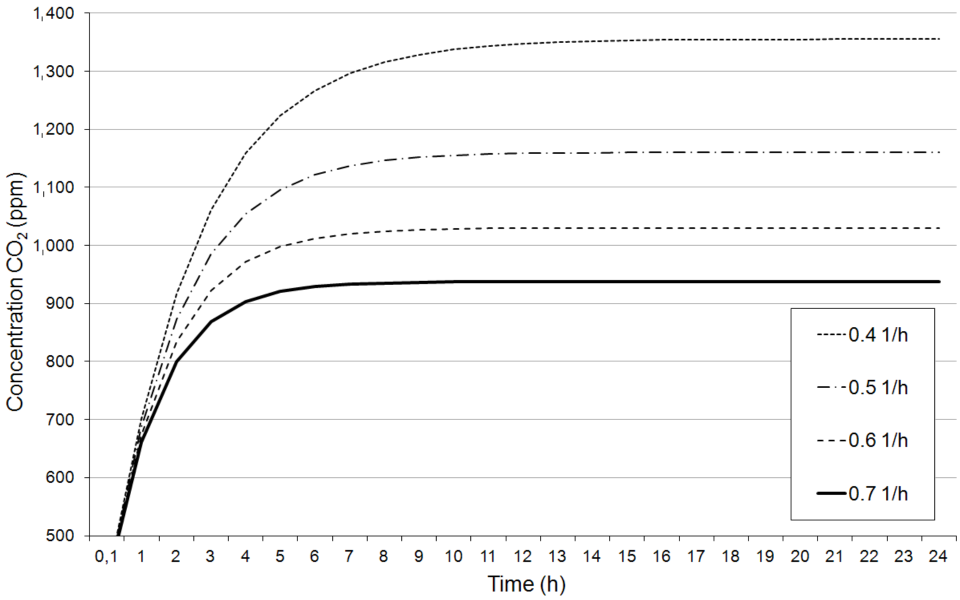

Figure 3: Changes in the concentration of CO_2 at different intensity of ventilation - work in a sitting position

In Figure 3 one can observe the increase of the concentration of CO_2 at different intensity of ventilation. Second from the top curve defines the changes in the concentration of CO_2 in the intensity of ventilation n = 0.5 1/h, which corresponds to the obtained ventilation intensity due to infiltration in the office. Calculated changes of CO_2 concentration correspond to the actual measured value.

The concentration of CO_2 outdoor air in our case amounted to 380 ppm. The initial concentration of CO_2 in the beginning of measurements was 380 ppm. If the desired level of CO_2 will be 1,000 ppm, then in Figure 3 we are looking for the value of the concentration of CO_2, which does not exceed the limit value of 1,000 ppm. The required intensity of ventilation is determined graphically on the basis of changes in the concentration of CO_2, described in Figure 3. In our case, changes in the concentration are described by the solid line indicating the intensity of ventilation 0.7 1/h.

2.5 Determination of the intensity of ventilation - during physical activity

If the person was doing physical exercises, he/she produced much more CO_2 during respiration. The actual value of the produced CO_2 in the breathing process of the person in the office during physical exercises performance is determined graphically similarly as it was in the previous case. The actual production corresponds to the production of CO_2 54.99 mg/s. This value corresponds to the intensity of breathing 20 breaths per minute with volume inhale/exhale 2.1 L.

The intensity of ventilation is determined graphically based on changes in the concentration of CO_2. When determining the concentration of CO_2 we use the formula 1, in which we apply the obtained mass flow of CO_2, the volume of the room and measured initial concentration of CO_2. The concentration of CO_2 of outdoor air is 380 ppm. If the desired level of CO_2 will be 1,000 ppm, then in Figure 4 we are looking for the value of the concentration of CO_2, which does not exceed the limit value of 1,000 ppm. When intensity of ventilation that takes place due to infiltration n = 0.5 1/h after 8 h of stay of the person, doing physical exercises, indoor concentration would have reached CO_2 4,531 ppm. After 20 min according to the calculation of the concentration of CO_2 will rise from initial concentration of CO_2 380 ppm up to the value of 1,851 ppm at the intensity of ventilation due to infiltration n = 0.5 1/h. According to the measured data, the concentration of CO_2 after 20 min increased from the initial 534 ppm up to 1,842 ppm when the concentration of CO_2 in the supply air was 380 ppm.

In Figure 4 one can observe the increase of the concentration of CO_2 at different intensity of ventilation. The second curve from the top contains changes in the concentration of CO_2 at the intensity of ventilation n = 0.5 1/h, which corresponds to the received ventilation intensity as a result of infiltration in the office. The concentration of CO_2 outdoor air in our case is 380 ppm. The initial concentration of CO_2 in the beginning of measurements amounted to 534 ppm. To simplify the calculations, it takes the initial concentration of 380 ppm. If the desired level of CO_2 together would amount to 1,000 ppm, on Figure 4 we will find the concentration of CO_2, which will not exceed the limit value of 1,000 ppm. In our case these are changes in concentration that are described by the solid line indicating intensity of ventilation 3.4 1/h.

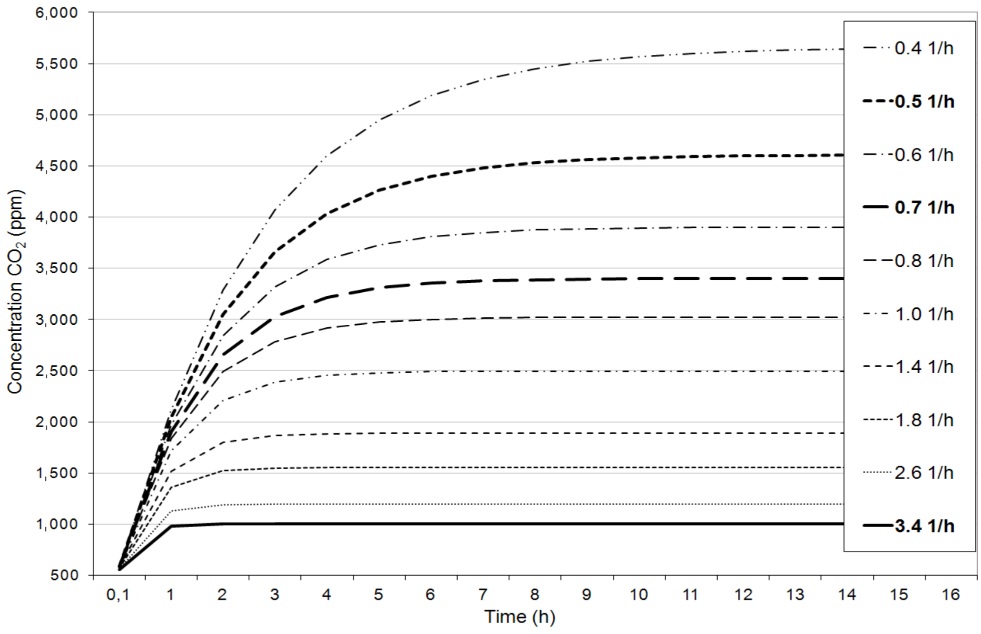

Figure 4: Changes in the concentration of CO_2, at different intensity of ventilation - exercises

3. Conclusions

According to the Regulation 259/2008 recommended intensity of ventilation is n = 5 1/h for premises, where people are doing physical exercises. According to the measured concentration of CO_2 calculated intensity of ventilation in the tested room is n = 3.4 1/h with initial concentration of CO_2 C_{IDA} = 380 ppm. If the initial concentration is higher (in our example, C_{IDA} = 534 ppm), while the concentration of CO_2 in the supply air is lower (in our case C_{SUP} = 380 ppm), higher intensity of ventilation is needed where n = 4.6 1/h (in a simplified calculation). When producing CO_2 q_{ms} = 54.99 mg/s, the concentration of CO_2 in the supply air C_{SUP} = 380 ppm and maximum permitted concentration of CO_2 C_{IDA} = 1,000 ppm according to STN EN 13 779 the ventilation intensity should be n = 4.6 1/h. In the result of measurements it was confirmed that the required intensity of ventilation n = 5 1/h, provided by Regulation 259/2008 (2008).

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