

Analysis of ventilation air exchange rate and indoor air quality in the office room using metabolically generated CO₂.

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Abstract. The article presents measurements carried out in an office room using metabolically generated carbon dioxide. The measurements were conducted using concentration decay gas tracer method. Increase of the concentration of CO₂ in the room occupied by workers allowed for evaluation of internal air quality and thermal work conditions. Analysis of the CO₂ concentration decay conditions after leaving the space by users was used to determine the efficiency of ventilation system and room envelope airtightness. The obtained results were used to calculate specific airflow rate of natural ventilation system being used in the analysed room.

1. Introduction

Due to the increasing concerns regarding building energy demand reduction of energy for ventilation is one of the main targets in the designing process. Ventilation cannot be analyzed without influence of infiltration (uncontrolled and unintentional airflows) which also affects total energy losses. On the other hand, ventilation system provides the fresh and removes contaminated and humid air to and from the interior environment which is crucial for the internal air quality. Indoor air quality is significantly associated with ventilation. Low ventilation air exchange can affect the inside air quality and going further the people's health negatively.

The efficiency of ventilation system can be evaluated using gas tracing method. One of the gases which may be used in those measurements is carbon dioxide. The CO₂ generated by users can be treated as the tracer gas. It makes the tests cheaper as no mechanical gas emitters are required. Gas tracing measurement with CO₂ allows for simultaneous evaluation of ventilation efficiency, building airtightness and air quality. This approach to the problem was suggested by Persily [1] who presented some techniques to evaluate the building ventilation efficiency and indoor air quality analyzing carbon dioxide concentration within the internal space. Similar problems were described by Bulinska [2] who used metabolically generated carbon dioxide to determined efficiency of ventilation systems in the buildings. Zhang [3] has used the same method testing the ventilation rates of dormitories and offices. Analysis of increasing concentration of CO₂ when buildings are occupied by users allow for evaluation of indoor air quality. Such measurements were described by Benedettelli [4] and Cichowicz [5]. In both cases quality of internal air in the university facilities were analyzed.

2. Carbon dioxide in the air – level adjustments and restrictions

Polish legal acts do not specify admissible concentrations of carbon dioxide in atmospheric air and in rooms intended for permanent residence, for example for dwellings. Because of that, the standards and recommendations of other European countries and the United States (ASHRAE) [6], [7] are most commonly used to determine acceptable concentrations. Per those requirements the upper level of carbon dioxide concentration for permanent residence of people should not exceed 1000 ppm. To keep



this requirement about 27 m³/h of fresh air per person should be supplied per hour to the internal leaving space.

Polish regulations define the permissible concentrations and intensities of harmful factors in the working environment [8]:

- Permissible exposure limit (NDS) – the weighted mean value of concentration, the impact on an employee of 8 hours per day and the average weekly working time during his/her working activity should not result in negative changes in his/her health and health of his/her future generations;
- Short term permissible exposure limit (NDSCh) – mean value of concentration which should not cause negative changes in the worker's health if it is present in the work environment for not more than 15 minutes and not more than 2 times during the work shift, with the a time interval not shorter than 1 hour.
- Ceiling exposure limit (NDSP) – value of concentration which due to health or life threat of the worker, cannot be exceeded in the work environment at any time.

According to this regulation NDS of carbon dioxide is 5000 ppm (9000 mg/m³), and NDSCh cannot exceed 15 000 ppm (27 000 mg/m³).

3. Air quality of the working and leaving internal environment

In every enclosed spaces where a human resides, the concentration of carbon dioxide increases because of depletion of the oxygen due to process of breathing. The carbon dioxide concentration in exhaled air is about 40 000 ppm [7]. The amount of CO₂ produced by human may differ depending on the body weight and level of its metabolic activity [6][7].

The CO₂ exhaled stream is related to the amount of oxygen consumed. The amount of oxygen consumed by one person in m³/h can be determined from the equation [7]:

$$V_{O_2} = 3.6 \frac{0.00276 \cdot A_D \cdot M}{0.23R_q + 0.7}$$

Where: A_D is DuBois surface (surface of human body) in m², M is a metabolic rate, met (1 met is equal to 58.2 W/m², R_q is a respiratory quotient which can be assumed depending on the intensity of activity performed by the human, from 0.83-1. The DuBois surface area can be taken as 1.8 m² for an average adult.

Permissible levels of carbon dioxide in non-residential spaces are regulated by the standard PN-EN13779 [9]. It introduces four acceptable levels of carbon dioxide concentration depending on the selected level of indoor air quality. The table 1 shows the permissible values for the carbon dioxide concentration according to the air quality category.

Table 1. Permissible values for carbon dioxide concentration to the air quality category per standard PN-EN 13799 [9]

Category of fair quality in the room	Increment of CO ₂ concentration, above CO ₂ level in external air, ppm
High quality of indoor air	350
Medium quality of indoor air	500
Moderate quality of indoor air	800
Low quality of indoor air	1200

4. Experimental method

The measurements were conducted using gas tracer concentration decay method. The methodology of measurements is described in standard [10]. Method was also described by Sherman [11]. This method is based on the analysis of decay of concentration of a tracer gas mixed with the air. Metabolically generated carbon dioxide was used as the tracer gas in the measurements. Carbon dioxide is one of the natural compound of atmospheric air. It is an odourless, colourless non-flammable gas, heavier than the air. The density of carbon dioxide is almost 1.5 higher than that of air [7]. Emission of gas to the atmosphere is usually caused because of combustion of chemical compounds containing carbon atoms. Carbon dioxide is also released into the atmosphere as a result of human and animal activity.

Measurements with the gas tracing method were conducted using 3 sensors Rotronic CP11 allowing the continuous measurements of CO₂ concentration, temperature changes and relative humidity (fig.1).



Figure 1. Sensor Rotronic CP11 used for measurements

5. Measurements

The analysed office room is located in the five-storey office building in Cracow at Oleandry street (figure 2). Office room is located at second story of the building and does not have direct contact with outside corridor. The room is designated to perform light computer office work for four working people at the same time. The measuring zone (figure 3) has one wall with direct contact with the external environment with two 1.95m width on 1.90m height windows. Three other walls have contact with other rooms. Door 2.00m height and 0.85 width dividing two office rooms are located on the south wall of the room. There is natural ventilation system with one ventilation duct 18cm on 18cm located 2.35m above floor level shown in figure 2b.

Considered zone is constantly occupied by four people working from 8 am to 4 pm with one half an hour break at 12 am. Volume of the office room is about 58m³.



Figure 2. a) office building at Oleandry street, b) ventilation duct in the office room



Figure 3. View of measuring zone

Detectors were located in three different places of the zone in a 2 meters distance from workers to avoid direct contact of the exhaled air with the sensors. Such arrangement ensured appropriate results of measurements, because high concentration of air exhaled gas by people. Standards [6] suggest to keep at least distance of 2m from the occupant. Per standard [10] the concentration of carbon dioxide in a representative measurement place should not differ by more than 10% from the mean concentration value in the measurement zone. Before performing the test all sensor were calibrated in accordance with the manufacturer's instructions.

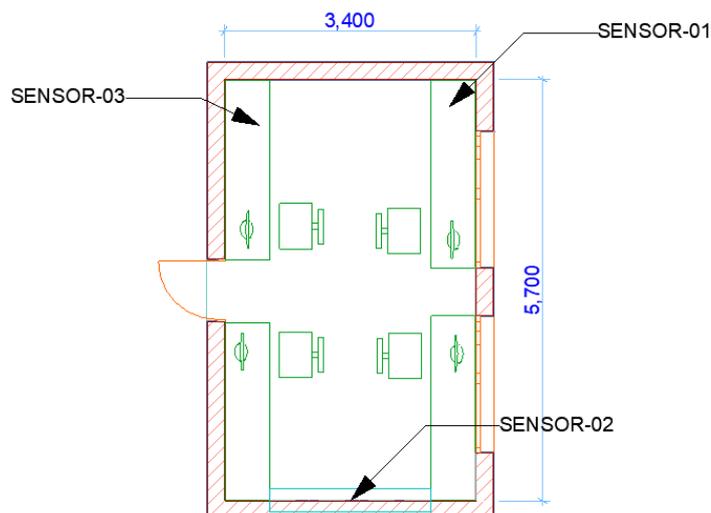


Figure 4. Location of sensors in the measuring zone

All measuring devices were located inside considered room. Sensors 1 and 3 were placed on desks 0.75 m above floor level, sensor 2 was placed on a shelf mounted along the wall located 1.75 m above floor level (figure 3).

Measurements were conducted for four working days between 19.09.2017 and 22.09.2017. Data were collected continuously and recorded every 60 seconds. Analysis below will be divided on two parts, first one while room was occupied by workers and the second part after leaving the room by workers (analysis of CO₂ concentration decay).

5.1. Office room occupied by workers, 8 am to 4 pm

While the office room was occupied by workers the measurements allowed to analyze the internal changes of metabolically generated CO₂ concentration, temperature and relative humidity.

Figure 5 presents changes of CO₂ concentration during one working day from three sensors. The external CO₂ concentration at 8 am, measured by separate sensor was equal to 389 ppm. The initial concentration inside at this time is at the level around 1000 ppm due to the presence of people in the room before the beginning of measurements.

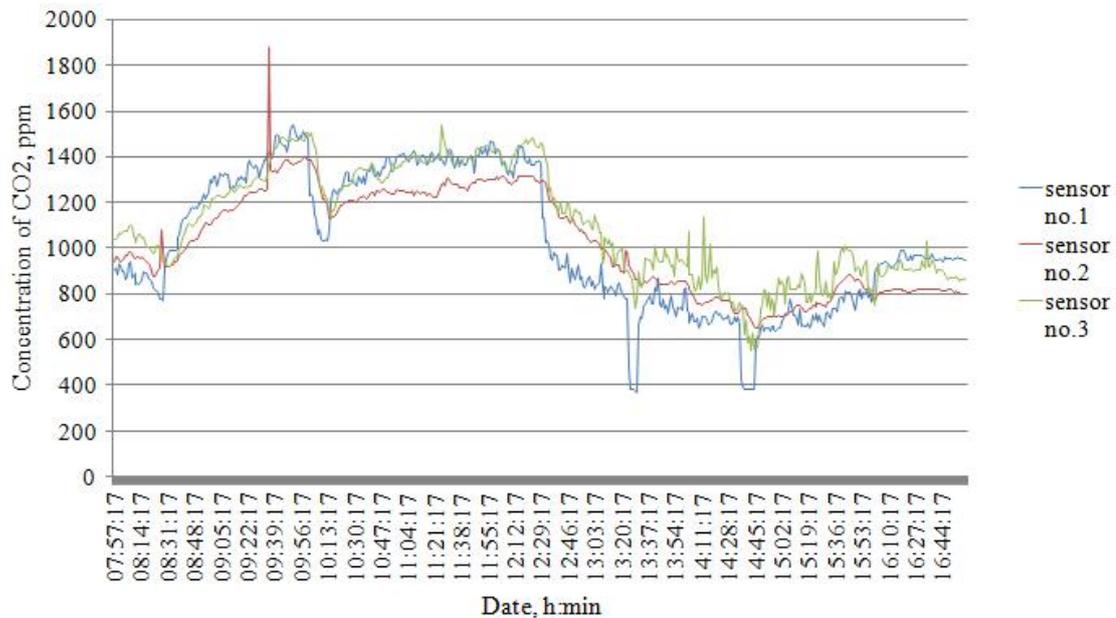


Figure. 5. Carbon dioxide concentration inside the room – 19.09.2017

The sharp increase of carbon dioxide concentration can be observed up to 10 am can be observed. Around 10 am workers opened the window as they started to feel uncomfortable. The CO₂ concentration was at level of 1500 ppm. After opening the window the concentration drop can be observed to about 1200 ppm. At 12 am the workers left the office on lunch break and it caused the decrease of CO₂ concentration. After the break till the end of working day windows inside were partially open so level of CO₂ is between 600 and 1000 ppm. Values recorded by sensor 1 are much lower comparing to other two as this sensor is located closest to the window. When the workers left the room due to the end of the working day the window was completely closed.

Based on the received data the quality of internal air was classified. The external concentration of CO₂ during entire measurement time was assumed at the level of 400 ppm. The result of the internal concentration of carbon dioxide was taken as the average value of all three sensors at 10:03 when the level of CO₂ was the highest. Results were compared with the referenced values found in the table 1, showing the increase in carbon dioxide concentration above the CO₂ level in the outdoor air.

Per the classification of standard [9] the indoor air can be qualified between moderate and low quality, which is very unsatisfactory result. The employees spent about 40% of their working time in conditions qualified by the standard as moderate quality of indoor air. Taking into account the ASHRAE standard [6], the concentration level determining conditions as comfortable are exceeded for more than 50% of the working time.

What is very important those unsatisfactory conditions were noticed despite of the fact that windows were opened during the measurements. Conditions would be much worse if the windows would be closed during entire working day.

Sensor used in the measurements allow for measuring of temperature and humidity changes. Results are presented in figure 6 and 7.

No sensor was used to measure the outdoor temperature, so the data concerning average external temperature were taken from measuring station Vaisala WXT520 located at the roof of Faculty of Physics and Applied Computer Science belonging to AGH University [12].

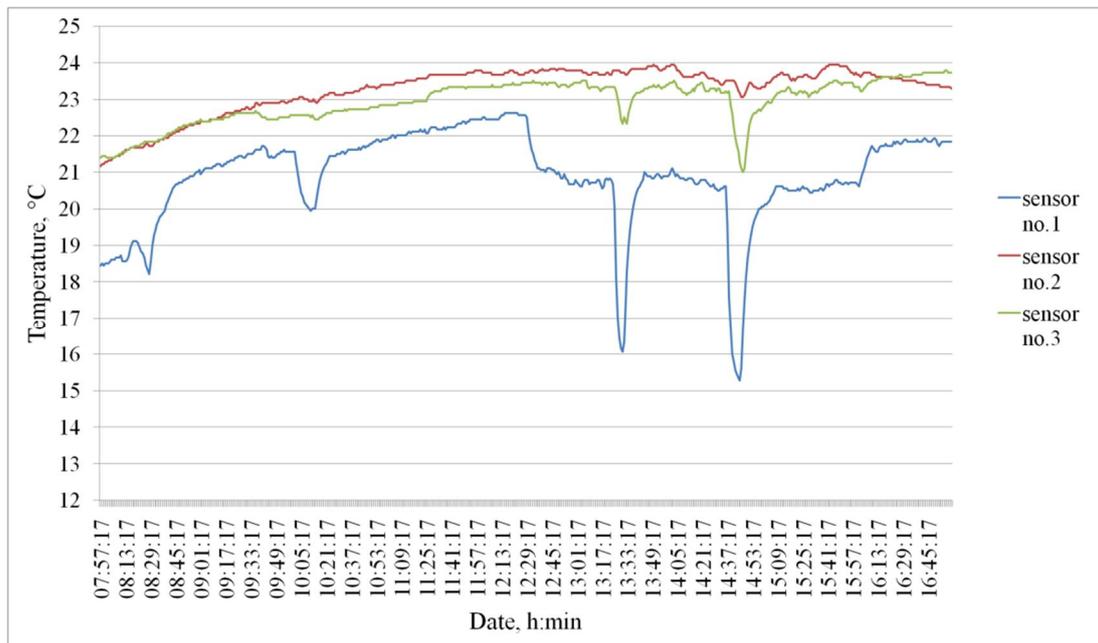


Figure 6. Indoor temperature recorded during measurements in the zone during first day of measurements

Figure 6 presents temperature readings from 3 sensors. The highest values of internal temperature have been indicated throughout the course of the tests by the sensor number 3 located farthest from the windows. Similar values were indicated by sensor number 2 which is located in the corner of the room, but some small temperature drops may already be noticed. Sudden drops of temperature are connected with opening of windows and local movements of cold outside air.

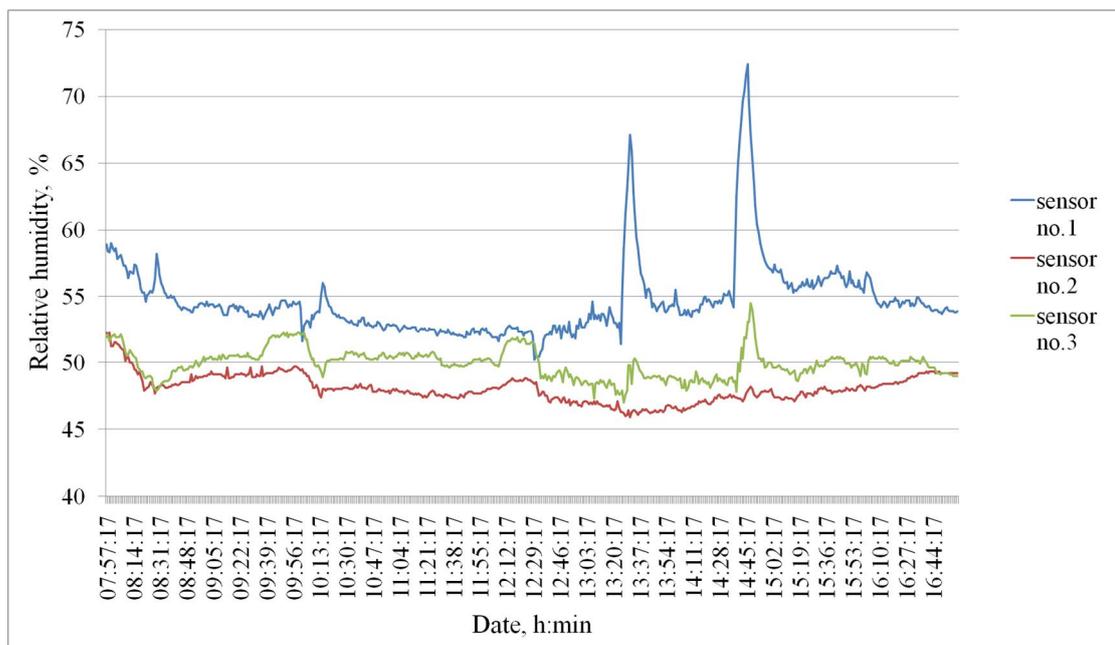


Figure 7. Indoor relative humidity recorded during measurements in the zone during first day of measurements

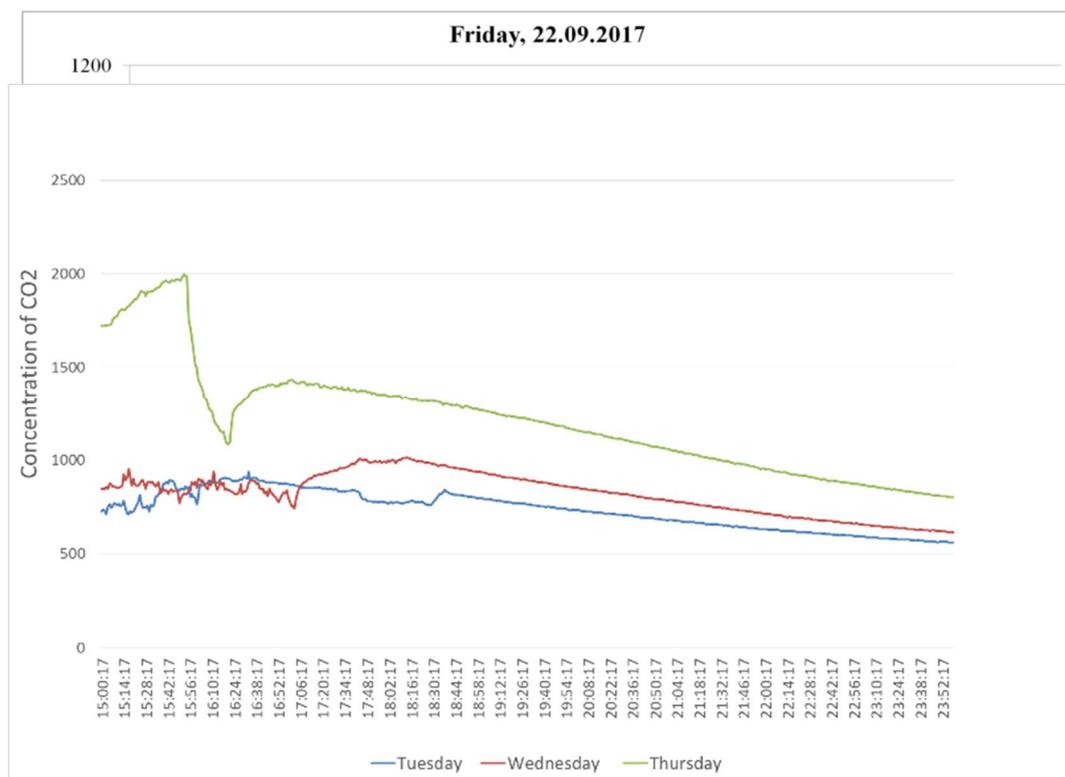
There are big differences in the values of temperature which is uncomfortable from the users point of view. People sitting in different parts of the room are affected by significantly different temperatures.

Figure 7 presents changes of relative humidity for the sensors. Again significant changes between values can be observed, for the sensor located next to the window values are much higher due to much lower temperature.

5.2. Measurements of empty room.

The tests carried out on 19.09.2017 were continued when the employees left the measuring zone. Similar tests were carried in the next four days.

Figures 8-9 present concentration decay diagrams during four days after leaving the space by users. In some days users stayed longer but the data used for calculation of air flow were always taken when



the room was empty. First three days are shown on one diagram, the Friday data are listed on the separate one as the measurement step was different.

Figures 8 thru 9. Concentration decay diagrams during four days of measurements.

The specific airflow rates were calculated separately for each day using two point decay method. As the decay period time is not strictly determined in the standard [10] different periods were analysed: one, three, six and eight hours from initial concentration levels. In order to calculate the air exchange rate, equation concerning 2 point decay was used.

$$\bar{N} = \frac{1}{t_2 - t_1} \log_e \frac{c(t_1)}{c(t_2)}$$

where:

\bar{N} - time-mean specific airflow rate (1/h)

t – time (t₁: measurement start point, t₂: measurement end point) (h);

Table 2 presents initial and final values of carbon dioxide concentration at specific time ranges.

Table 2. Specific airflow rate calculations for each day

	Concentration of CO ₂ , ppm			
	Tuesday, 19.09.2017	Wednesday, 20.09.2017	Thursday, 21.09.2017	Friday, 22.09.2017
Initial concentration of CO ₂	834	1014	1273	1038
1 hour decay period	753	913	1166	940
3 hours decay period	646	768	986	776
6 hours decay period	512	607	768	599
8 hours decay period	490	535	652	536

The specific values of air flows were calculated and presented in table 3.

Table 3. Table represents concentration of CO₂ in particular time intervals

	SPECIFIC AIRFLOW RATE CALCULATION [1/h]			
	Tuesday, 19.09.2017	Wednesday, 20.09.2017	Thursday, 21.09.2017	Friday, 22.09.2017
1 hour decay period	0.102	0.105	0.088	0.099
3 hours decay period	0.085	0.092	0.085	0.097
6 hours decay period	0.081	0.086	0.084	0.092
8 hours decay period	0.066	0.080	0.084	0.083
mean value	0.078	0.086	0.084	0.090
inside;outside temp	21;12	21;12	21;10.5	20.5;11
ΔT [K]	9.0	9.0	10.5	9.5

The mean values of specific airflow rate do not differ more than 5% between each others. The external temperature conditions were similar in the analysed periods of time. The average temperatures in the analysed days were calculated based on [12].

For further considerations of the ventilation efficiency of the office room, the average airflow rate value $n=0.085$ [1/h] was assumed. This value allows for calculation of total ventilation air change per hours. The volume of analysed office room is $V=58\text{m}^3$ which gives less than 5 [m³/h] air change rate.

$$V * n = 0,085 \frac{1}{h} * 58\text{m}^3 = 4,92 \frac{\text{m}^3}{h}$$

Assuming 4 people working in the office room the stream of the air per one person is 1,23 m³/hour per person.

As it can be noticed the obtained result does not meet the requirement of minimum 20m³/h per person described in the standard [13].

6. Conclusions

Metabolically generated carbon dioxide used as a tracer gas can be a source of useful information about the quality of internal air within the space. The decay of this tracer gas allows for calculation and evaluation of ventilation system efficiency. The measurements are time consuming but did not require

very complicated equipment and the results can be a source of information about specific ventilation systems.

The conducted measurements and calculations in the office room prove that the efficiency of ventilation system is not sufficient and the air quality is poor. The basis of the gravitational ventilation is a temperature difference between the internal and external environment. Measurements were conducted in September when temperature difference was only about 10K. The efficiency of ventilation system could be higher during the winter months. The similar tests will be conducted in winter conditions to compare the results.

Low efficiency of ventilation causes high concentration of carbon dioxide in the office which can affect the employees in the room, reducing their productivity and affecting their well-being. In the tested room, the gas concentration often exceeded the recommended values, especially when the windows were closed.

The standards determine the maximum level of CO₂ concentration which in this particular room was exceeded during the working time. Comparing the results with the standards it appears that the air is low quality.

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