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Dynamic of Changes in Carbon Dioxide Concentration in Bedrooms

Piotr Batog[a,*], Marek Badura[b]

[a,b]*Department of Heating and Air Conditioning, Faculty of Environmental Engineering, Wrocław University of Technology, Wybrzeże Wyspiańskiego St., 50-370 Wrocław, Poland*

Abstract

The paper presents results of preliminary studies on indoor air quality in polish sleeping rooms. Objects in typical blocks of flats with low ventilation rates were taken into consideration. Carbon dioxide concentrations were used as an indicator of indoor air quality. Theoretical calculations, results of CFD simulations and results of conducted measurements were presented. Detected high levels of CO_2 concentrations (above 3000 ppm) indicated improper ventilation and poor air quality in tested bedrooms. Airtight windows associated with modern energy-efficient construction trends were recognized as the reason of this situation. Authors of publication recommended using proper window air vents in case of buildings without mechanical ventilation. Using demand-controlled ventilation and sensory information in objects with mechanical ventilation was also suggested.

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Keywords: indoor air quality; bedrooms; ventilation; CO_2 concentration; sensors; CFD simulations.

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1. Introduction

People spend nearly one-third of their life on sleeping. Many theories were proposed to explain the function of sleep. According to some of them, sleep is necessary to conserve energy. Other theories say about the restorative function of sleep and the need of rehabilitation of the body after a day's efforts. Some studies consider also the role of sleep in the strengthening and consolidation of memory [1], [2]. Regardless of the various theories, sleep is a natural and essential part of life and is very important for normal functioning. These days the major part of time spent at home is meant for sleeping and resting. Therefore, the sleep environment should be characterized by high quality. Unfortunately, the drive for high-efficiency buildings with low heat losses is observed nowadays, which leads to indoor spaces more tightly sealed than ever. Insufficient infiltration and limited natural ventilation resulted in increase of indoor pollutant concentration. This, in turn, caused the rise in sick building syndrome (SBS) complaints, e.g. headaches, tiredness, eyes, nose or throat irritation. The problem of poor ventilation and low indoor air quality obviously also relates to bedroom environments, where windows and doors are typically closed during the night. Conditions in such spaces can influence the sleep process and further daytime health or work efficiency.

There are several factors that can affect bedroom air quality and comfort of sleep. One group of them is related to thermal comfort and includes factors like temperature, relative humidity and air speed. The other group is associated with contaminants occurring in bedroom air. Those can have a form of physical, chemical or biological agents. Great part of indoor pollutants may originate from building materials, furniture and ventilation system. However, a lot of pollution comes from occupants and is associated with their metabolic activity [3], [4].

In issues related to assessing ventilation in buildings, a common indicator of indoor air quality is the concentration of carbon dioxide. The presence of this gas in indoor environment is strictly connected with respiration and human metabolism. In this process the oxygen is consumed and CO_2 is generated at rates that depend on the level of physical

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* Corresponding author.
E-mail address: piotr.batog@pwr.wroc.pl

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activity, body size and diet. The link between indoor CO_2 concentrations and indoor air quality comes from the fact that at the same time people are generating CO_2 and producing odor-causing bioeffluents. Because both CO_2 and bioeffluent generation rates depend on physical activity, the concentration of CO_2 and the odor intensity from human bioeffluents in a space exhibit a similar relationship with the number of occupants and the outdoor air ventilation rate. Several experiments have been conducted in which people evaluated the acceptability of the indoor air in terms of body odor. These studies concluded that about 7.5 l/s of outdoor air ventilation per person will control human body odor such that roughly 80% of visitors will find the odor at an acceptable level. Furthermore, it was shown that the same level of body odor acceptability was found to occur at a CO_2 concentration that is about 650-700 ppm above the outdoor concentration (350-450 ppm) [5], [6]. Results of these studies have been a major consideration in the development of most ventilation standards and guidelines. For example, widely recognized ANSI/ASHRAE Standard 62-2001 states: "Comfort criteria, with respect to human bioeffluents (odor) are likely to be satisfied if the ventilation results in indoor CO_2 concentrations less than 700 ppm above the outdoor air concentration". Carbon dioxide concentration is also utilized in European Standard EN 13779 [8] for classification of indoor air quality and in German norm DIN 1946-2, which gives a maximum value of CO_2 concentration at the level of 1500 ppm but recommends keeping indoor CO_2 concentrations below 1000 ppm.

It should be noted that CO_2 is not generally considered as a health hazard at the concentrations that typically occur in nonindustrial indoor environments. Exposure limits for CO_2 established by agencies associated with safety and healthy working conditions, e.g. National Institute for Occupational Safety and Health (NIOSH) from USA, are 5000 ppm for time weighted average (average exposure on the basis of an 8-hour day and a 40-hour workweek) and 30 000 ppm for short-term exposure limit (time weighted average exposure that should not be exceeded at any time during a workday) [9]. Similar threshold values are provided by European regulations (e.g. [10]. Adverse health effects have not been observed below the level of 7000-10000 ppm during prolonged exposure to CO_2 and below 20 000-30 000 ppm by short-term exposure [5], [11], [12], [13]. Some investigations showed an association between elevated indoor CO_2 levels (1000-4000 ppm) and increases in SBS symptoms. Nevertheless, no direct link between exposure to CO_2 and SBS symptoms was found – only the correlation with other indoor pollutants that may cause adverse effects was suggested [14], [15], [16].

Taking into account the common use of CO_2 as an indoor air quality indicator, authors of the paper attempted to use it for evaluating bedrooms environments in a few typical polish blocks of flats. Studies were carried out on objects where low ventilation rates may occur. Article presents some theoretical considerations and calculations associated with CO_2 levels which may be encountered in such spaces. Special attention was given to the dynamics of CO_2 concentration change. Results of the simulations based on computational fluid dynamics (CFD) were used to illustrate the spatial distribution of CO_2 in one of the considered rooms. Results of measurements from all examined objects were also shown. Presented studies are merely a beginning of researches associated with air quality in bedrooms.

2. 1. Theoretical basis

Human breathing intensity depends on temporal activity and on the individual features. The CO_2 concentration in exhaled air is generally around 4-5%. During sleep, the respiratory rate is lowest [17], therefore human produce in this state about 0.007 g/s of CO_2 [18]. In the following theoretical consideration, this standard CO_2 production rate per capita was used. CO_2 concentrations in ventilation flow, and in the initial state before sleep (at time $t = 0$) equal to CO_2 concentration in outdoor air, on average 400 ppm, were assumed.

Presuming uniform distribution of CO_2, differential equation for change of the total mass of CO_2 inside the considered space can be formulated:

$$\frac{d\,m(t)}{dt} = \lambda + \left(c_0\rho - \frac{1}{V}m(t)\right)Q, \tag{1}$$

where:
$m(t)$ – total CO_2 mass in investigated room at time t, kg,
λ – CO_2 production rate, kg/s,
c_0 – concentration of CO_2 in ventilation flow, $c_0=0.0004$ (400 ppm),
Q – ventilation rate, m^3/s,
V – overall room volume, m^3.
Solving Equation (1), the average molar concentration of CO_2 can be easily calculated:

$$c(t) = \frac{\lambda V_m}{QM}\left(1-\exp\left(-\frac{Qt}{V}\right)\right) + c_0, \tag{2}$$

where:
$c(t)$ – the average concentration of CO_2 at time t,
V_m – air molar volume, 2.24 *10^{-2} m^3/mol,
M – CO_2 molar mass, 4.4*10^{-2} kg/mol.

It can be noticed from Equation (2) that CO_2 level in steady state depends only on ventilation rate Q and CO_2 production rate λ.

Figure 1 shows time dependency of CO_2 concentration in typical small sleeping room (V = 21 m^3) during 8-hours long sleep of one person for different ventilation flow rates. Initial concentration of CO_2 was equal to 400 ppm. As can be seen, in the absence of ventilation CO_2 level will increase linearly with time and the slope depends on CO_2 production rate. The bigger amount of fresh ventilating air causes lower CO_2 level and faster achieving of the steady state.

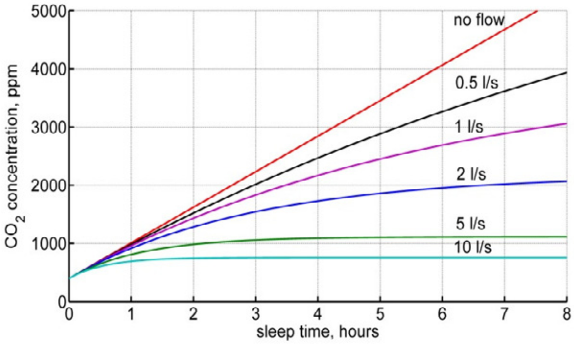

Fig. 1. Theoretical CO_2 concentrations in typical sleeping room in block of flats (V=21 m^3) during 8-hours long sleep of one person

3. CFD simulations

Dynamic of CO_2 changes using methods of computational fluid dynamics was tested. Especially, the assumption about uniform distribution of CO_2 in whole volume of small sleeping room was checked. The simulated room model corresponds to one of the real sleeping rooms where measurements were conducted. The presented model is simplified – only big and important solids and surfaces like bed, wardrobe, heater, door and window were taken into consideration. Two examples of simulation are shown below. In both cases, the carbon dioxide is emitted with constant emission rate from one source located in position of man head during sleep.

In first simulation no fresh air inlets were assumed, so the air motion inside room is caused by temperature differences on surfaces, such as warm heater, bed and cold window. In second simulation the total air flow through gaps around window and door was about 2 l/s. In Figure 2 the influence of small gaps on air velocity distribution is shown.

The distribution of carbon dioxide concentration after 8 hour sleep in case of lack of ventilation is shown in Figures 3 and 4, in horizontal cross-section in the middle of room, and in vertical cross-section on height 0.8 m, respectively. It can be easily observed that CO_2 concentration spatial gradient is considerably high only in close vicinity of the chemical emission source. The maximum deviation in CO_2 concentration (excluding source surroundings) is about 200 ppm, therefore less than 4% of average CO_2 concentration. It can be expected that in reality the CO_2 distribution should be even more uniform, because of randomized direction of exhaled air velocity (man is changing the position and orientation of head during sleep).

The spatial distribution of CO_2 in room with ventilation flow rate at level of 2 l/s is shown in Figures 5 and 6. Similarly to the previous case, it can be seen that there is no big concentration gradient excluding the region nearby gaps and chemical source. The maximum difference in CO_2 concentration in this case is about 150 ppm – it is less than 8% of average CO_2 concentration.

In reality velocity distribution depends on many disregarded factors and this result can be treated only as general demonstration. However this simulation provided important and useful information about proper placement of CO_2 sensors. Measurements points should not be located in corners, below the bed level, near doors and windows. If sensor is located in the middle of the volume of the room, its response should represent average concentration with error lower then sensor accuracy, and thereby one sensor in each monitored bedroom can be used. This fact was also confirmed by the conducted measurements.

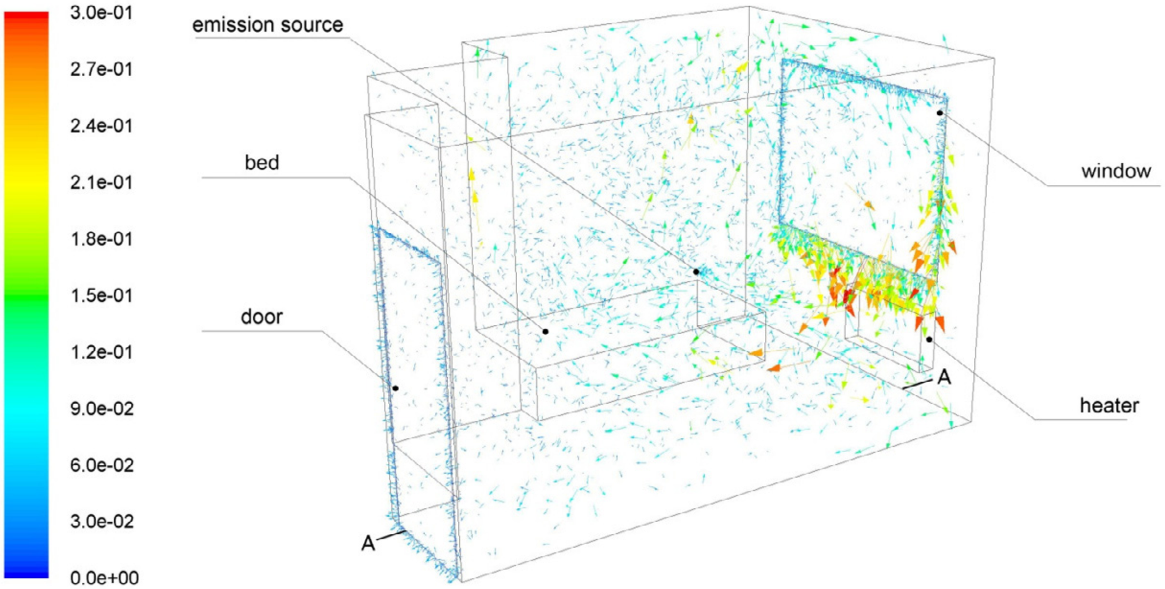

Fig. 2. The air velocity distribution in case of total flow through leaks about 2 l/s. Vectors colored by velocity magnitude, m/s

3. The measurements

A set of measurements was conducted to investigate the actual indoor air quality in small sleeping rooms, 5 objects were selected for the study. All of them were located in typical blocks of flats in the city of Wrocław, Poland. None of them was equipped with mechanical ventilation. Furthermore, windows in examined objects did not have any air vents. Due to weather conditions (measurements were carried out in the winter season) and other factors, windows and doors were closed during nights. In all experiments the bedrooms were aired by opening windows before sleep. The occupants were asked to note the time of going to sleep and waking up in the morning.

The DeltaOHM HD37B17D devices containing NDIR (Non Dispersive InfraRed) sensors were used in experiments. They offered accuracy ±50 ppm + 3% of the measurement. Other parameters of microclimate (air temperature and humidity) of room were also recorded. Data were logged at 1-minute intervals.

In first experiment the spatial distribution of carbon dioxide was tested. Three sensors in one room were used. Location of measurement points is presented in Figure 7. Figure 8 show changes of CO_2 concentration in examined bedroom measured by three independent devices. It can be noticed that meaningful difference between sensors readings occurred only in open-window periods. The measurement results agree with the theoretical considerations presented in the previous section. The increase of CO_2 concentration is the fastest in the initial phase. It can be seen that the level of 1500 ppm is exceeded after an hour, therefore, the quality of air in examined room is inadequate by the majority of sleep time.

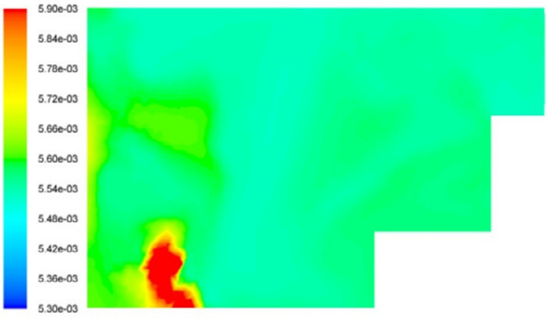

Fig. 3. Simulated CO_2 concentration after 8 hour long sleep. One person in room, $V=20.7\ m^3$, no air inlets. Horizontal cross-section at the level of 0.8 m

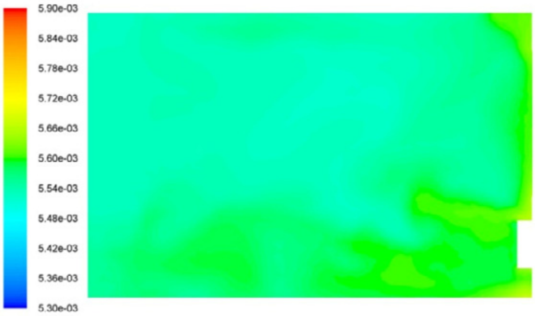

Fig. 4. Simulated CO_2 concentration after 8 hour long sleep. One person in room, V=20.7 m^3, no air inlets. Vertical A-A (see Fig. 2) cross-section

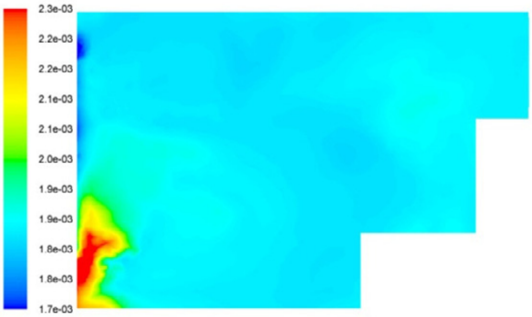

Fig. 5. Simulated CO_2 concentration after 8 hour long sleep. One person in room, V=20.7 m^3, ventilation flow rate 2 l/s.
Horizontal cross-section at the level of 0.8 m

Fig. 6. Simulated CO_2 concentration after 8 hour long sleep. One person in room, V=20.7 m^3, ventilation flow rate 2 l/s. Vertical A-A (Fig. 2) cross-section

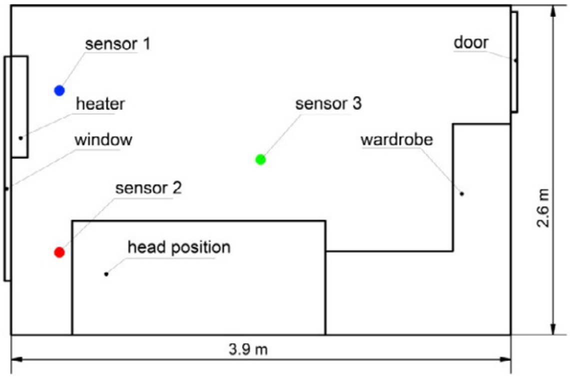

Fig. 7. Sensor arrangement in examined bedroom

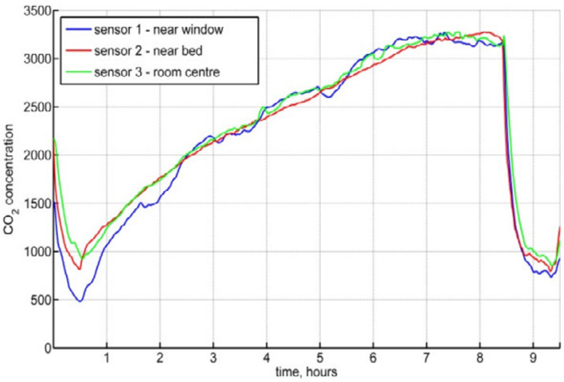

Fig. 8. Comparison of responses of three sensors in examined bedroom

Another interesting thing that can be observed is the high efficiency of ventilation by initial and final window tilting.

The measured carbon dioxide concentration during several nights in two bedrooms (one and two inhabitants respectively) is shown in Figures 9 and 10. The CO_2 level growth during night is up to 3000 ppm (7 times more than in outdoor air). It can be observed that maximum value of CO_2 concentration may differ significantly between consecutive nights. It is probably caused mainly by weather condition affecting the natural air flow through minor gaps around window, especially wind speed and its direction.

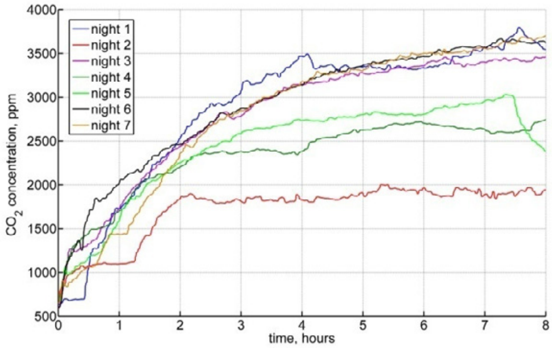

Fig. 9. Growth dynamics of CO_2 level during sleep. Two persons in room, V=23.6 m^3, measurements from 7 nights

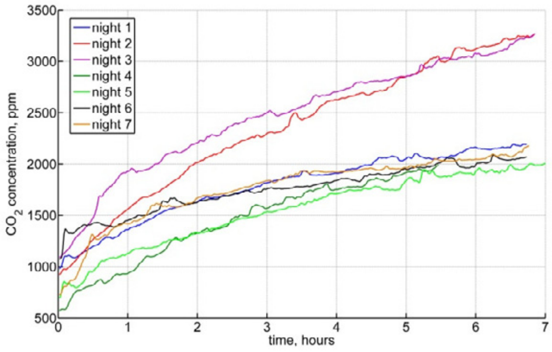

Fig. 10. Growth dynamics of CO_2 level during sleep. One person in room, V=20.7 m^3, measurements from 7 nights

Basic statistics of all conducted measurements were collected in Table 1. Authors focused on parameters related to dynamic of changes in CO_2 concentrations during particular nights ($\overline{\Delta c}$ – mean of CO_2 concentration changes) and parameters referring to indoor air quality standards and guidelines (c_{MAX} – maximum CO_2 concentrations recorded in investigated bedrooms). Parameter $\overline{t}_{1500}$ was proposed – it represented mean time of residence in environment containing more than 1500 ppm CO_2 (threshold value of bad indoor air quality).

Average increase of carbon dioxide concentration during sleep was very high in all cases (up to 2750 ppm). The final value was higher two to six times than initial.

Excluding one case (object 4), the time of residence in bad air quality environment, was longer than 75% of overall sleep time. In particularly extreme case (object 2) only 40 minutes (on average) of sleep took place in acceptable quality air.

In two objects (1 and 2) large spread of the maximum concentration was recorded. Probably these rooms were especially vulnerable to weather conditions influencing the natural air flow.

Table 1. Basic statistics of measurements conducted in bedrooms (V – volume of considered object, $\overline{\Delta c}$ – mean of CO_2 concentration changes from particular nights, c_{MAX} – maximum CO_2 concentration recorded in considered object, $\sigma_{c_{max}}$ – standard deviation from maximum CO_2 concentrations recorded on particular nights, $\overline{t}_{1500}$ – mean time of residence in environment containing more than 1500 ppm CO_2)

Object	V, m^3	No. of occupants	Sex	$\overline{\Delta c}$, ppm	c_{MAX}, ppm	$\sigma_{c_{max}}$, ppm	$\overline{t}_{1500}$, h
1	20,7	1	M	1508	3277	554	5,1
2	25,6	2	M, F	2755	3874	628	7,2
3	41,1	2	M, F	1935	2730	104	6,4
4	25,6	1	M	719	1583	200	0,1
5	52,3	2	F, F	535	1894	44	5,8

4. Conclusions

Conducted research show evidently very bad air quality in typical small sleeping rooms. In most of tested cases, observed CO_2 levels significantly exceeded recommended hygienic standards. Few times maximum recorded CO_2 levels (above 3800 ppm) were higher than 75% of exposure limit for 8 hours [9], [10]. Such high concentrations were not reported in literature [19], [20]. It is supposed that bad air quality can affect the sleep process and further deteriorate daytime health or work efficiency. The impact of bad air quality for human sleep efficiency should, however, be precisely investigated in the future. It must be remembered that indoor CO_2 concentrations do not provide a comprehensive indication of indoor air quality. This index tells nothing about other pollutants present in the sleeping rooms air, especially about those emitted by occupant-independent sources. Broader research including contamination of bedrooms by volatile organic compounds is planned by authors.

The risk of very bad air quality should not be neglected and should be taken into consideration in designing new buildings with reduced natural air infiltration and also in modernization of old buildings. Applying proper air vents in case of airtight windows is strongly recommended. In some cases the simplest solution for improving air quality, especially in mild climate or in suitable weather conditions, is windows tilting or at least airing the bedroom before sleep.

Moreover, in discussed study, significant changes of CO_2 concentrations and, consequently, indoor air quality between nights were observed. This is a strong prerequisite for applying demand-controlled ventilation using sensory information rather than systems based on designed air exchange rates. It seems to be the only proper way to provide both good air quality and good energy efficiency of a building.

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