Experimental measurements of CO$_2$ concentrations in sleeping rooms

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Abstract. People spend nearly one-third of their life on sleeping. Several factors can affect bedroom air quality and comfort of sleep, such as temperature, relative humidity and air quality. The most common indicator of indoor air quality is the concentration of carbon dioxide, its presence in indoor environment being strictly related to respiration and human metabolism. Since 2002, when the European Parliament and Council approved the directive on energy performance of buildings, EU member countries launched various programs for refurbishment of buildings and HVAC (Heating, Ventilation and Air Conditioning) systems, in order to reduce the energy consumption. Unfortunately, the renovation operations, such as replacing old windows with new tight ones or thermal insulation of the facades, lead to tightly sealed interior spaces. Insufficient infiltration of fresh air and limited natural ventilation result into increased pollutant concentration and deterioration of the indoor microclimate. Permissible concentration of carbon dioxide in the closed spaces according to World Health Organization is 1000 ppm. When the level exceeds this threshold, occupants may complain of headaches, drowsiness, lack of concentration and fatigue. The present study shows the measurements of carbon dioxide concentrations conducted in several sleeping rooms located in refurbished buildings, with or without mechanical ventilation system for fresh air supply, as well as suggested measures.

1. Introduction

According to present theories, sleep is necessary to conserve energy, having a restorative function of the body after a day’s efforts. An article has shown the role of the sleep in strengthening and consolidation of memory [1]. Nowadays, the average working person spends most of the time at home for sleeping and resting. Therefore, the sleep environment should be characterized by high indoor air quality.

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 in strict correlation with human respiration and metabolism. 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 odour-causing bio effluents [2].

Several experiments have shown that the same level of body odour acceptability occurs at a CO$_2$ concentration that is about 650-700 ppm above the outdoor concentration (400-450 ppm) [3]. Widely recognized ANSI/ASHRAE Standard 62-2001 [4] states: “Comfort criteria, with respect to human bio effluents (odour) are likely to be satisfied if the ventilation results in indoor CO$_2$ concentrations less than 700 ppm above the outdoor air concentration”.
Table 1. Category of a room / indoor air quality.

| Category | Air quality | Increase in CO\textsubscript{2} concentration compared to CO\textsubscript{2} concentration in the outside air [ppm] |
|----------|-------------|---------------------------------------------------------------|
| IDA 1    | High        | below 400                                                    |
| IDA 2    | Average     | 400–600                                                       |
| IDA 3    | Moderate    | 600–1000                                                      |
| IDA 4    | Low         | above 1000                                                    |

Carbon dioxide concentration is also used in European Standard EN 13779 [5] for classification of indoor air quality and the World Health Organization (WHO) [7] indicates a maximum value of CO\textsubscript{2} concentration of 1500 ppm, but recommends maintaining indoor CO\textsubscript{2} concentrations below 1000 ppm.

Nowadays due to increasing focus on indoor air quality, more and more buildings designs include mechanical ventilation systems controlled by the concentration of CO\textsubscript{2}. The assessment of air quality in closed rooms is based on measuring the concentration of carbon dioxide metabolically produced by humans. In European Standard EN 13779 [5] is stated that “the quality of air supplied to the building meant for human stay should enable achieving proper quality of internal air, taking into consideration metabolism and type of human activity as well as technological conditions”. Four types of rooms have been defined, Table 1, depending on the quality of interior air, which is determined as the increase of concentration of CO\textsubscript{2} above the level of CO\textsubscript{2} in the air outside.

This paper reports on the results of CO\textsubscript{2} concentrations measurements conducted in a sleeping room located in a refurbished building without mechanical ventilation. The authors use the results to evaluate the sleeping room environment, this being part of a more exhaustive research associated with air quality in buildings.

2. Theoretical calculation of CO\textsubscript{2} concentrations in rooms with people

Human breathing intensity depends on temporal activity and on individual features. According to ASHRAE Standard 62-2001 [4], the CO\textsubscript{2} concentration in exhaled air is generally around 4-5%, during sleep the respiratory rate being lowest.

Table 2. Carbon dioxide emission from persons and their activity.

| Activity                        | Respiration per Person (m\textsuperscript{3}/h) | CO\textsubscript{2} Emission per Person (m\textsuperscript{3}/h) |
|---------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| Sleep                           | 0.3                                           | 0.013                                                         |
| Resting or low activity work    | 0.5                                           | 0.02                                                          |
| Normal work                     | 2 – 3                                         | 0.08 – 0.13                                                   |
| Hard work                       | 7 – 8                                         | 0.33 – 0.38                                                   |

Figure 1. Carbon dioxide concentration influencing factors.
\[ c = \left( \frac{q}{n*V} \right)^* \left[ 1 - \frac{1}{e^{nt}} \right] + (c_0 - c_i) * \left( \frac{1}{e^{nt}} \right) + c_i \]  

where:

- \( c \) = carbon dioxide concentration in the room (m\(^3\)/m\(^3\))
- \( q \) = carbon dioxide supplied to the room (m\(^3\)/h)
- \( V \) = volume of the room (m\(^3\))
- \( e \) = base of the natural logarithm
- \( n \) = number of fresh air shifts per hour (h\(^{-1}\))
- \( t \) = time in hours
- \( c_i \) = carbon dioxide concentration in the fresh air (m\(^3\)/m\(^3\))
- \( c_0 \) = carbon dioxide concentration in the room at start, t = 0 (m\(^3\)/m\(^3\)).

From equation (1), the CO\(_2\) concentration depends mainly on the number of fresh air shifts per hour \( n \) and CO\(_2\) production rate \( q \).

Figure 2 shows the variation of CO\(_2\) concentration in a sleeping room of 41.6 m\(^3\) for 8 hours sleep of two persons, at different ventilation flow rates. Initial considered values for CO\(_2\) concentration in the room and CO\(_2\) concentration in the fresh air was 450 ppm (normal carbon dioxide concentration in outdoor air).

In the absence of ventilation, the CO\(_2\) concentration increases linearly with time and the slope depends on CO\(_2\) production rate. Fresh airflows per occupant ensure a reduction of CO\(_2\) concentration in the room. Higher the airflows, faster the CO\(_2\) concentration reduction and attainment of the steady state comfort with high quality indoor air.

Fresh airflows are correlated according with the indoor concentration of CO\(_2\) as follows:
- fresh air rate of 20 m\(^3\)/h per occupant – approx. 1100 ppm level of CO\(_2\)
- fresh air rate of 30 m\(^3\)/h per occupant – approx. 900 ppm level of CO\(_2\)
- fresh air rate of 40 m\(^3\)/h per occupant – approx. 800 ppm CO\(_2\).

\[ \text{Figure 2. Theoretical CO}_2\text{ concentrations calculated for 8 hours sleep of two persons.} \]
3. Measurements – methods and results

Measurements were performed to investigate the indoor air quality in a sleeping room from a house located near Bucharest, Romania. The building has been thermally rehabilitated two years ago by adding 15cm-thick insulation on the façade and replacing the old windows with new “air tight” ones. The studied building is not equipped with a mechanical ventilation system. Furthermore, because measurements were carried out during winter season, windows and doors of the room were closed during night. In all experiments, the sleeping room has been naturally ventilated by window opening before sleep. Measuring instrument was placed as shown in figure 3.

The measurements for indoor air temperature, air humidity and CO$_2$ concentration were conducted using multifunctional measuring instrument Testo 480 equipped with an indoor air quality probe with the following characteristics:

- temperature (NTC) in the range between 0 and +50 °C with an accuracy of ±0.3 °C,
- humidity (capacitive) in the range between 0 and +100 %RH with an accuracy of ±1.8 %RH,
- ambient CO$_2$ in the range between 0 and +5000 ppm with an accuracy of ±75 ppm and the range between +5001 and +10000 ppm with an accuracy of ±150 ppm.

![Figure 3. Arrangement of measuring instrument.](image)

![Figure 4. CO$_2$ concentration increase during sleep; measurements from 3 nights, M - male; F – female.](image)
Table 3. Basic statistics of conducted measurements.

| Experiment | No. of occupants | Gender | Initial CO$_2$ level [t = 0 h] | Final CO$_2$ level [t = 8 h] |
|------------|------------------|--------|-------------------------------|-------------------------------|
| 1          | 2                | M, F   | 807                           | 5468                          |
| 2          | 2                | M, F   | 808                           | 5638                          |
| 3          | 1                | M      | 810                           | 4173                          |

Figure 4 depicts the measured carbon dioxide concentration along three nights in a sleeping room with a volume of 41.6 m$^3$. The level exceeded 1500 ppm after just one hour and therefore, the quality of air in the analysed room was inadequate for the majority of sleep time.

Measured data show that the increase of CO$_2$ concentration during sleep was very high in all three nights, the final recorded value being up to 7 times higher than initial value and up to 12 times higher than normal carbon dioxide concentration in outdoor air (450 ppm), table 3.

In order to get a better picture on dynamic changes of the environment in the analysed room, during second night of experiment, measurements were performed for an extended period of 12 hours.

To analyse the influence of natural ventilation on the CO$_2$ concentration, for the first 2 hours of experiment, before going to sleep, the occupants were asked to rest on bed and at every 60 minutes to open the window for 10 minutes. During measurements, outdoor temperature was 1.5 °C with very small variation ±0.2 °C. After the normal sleep period of 8 hours, the occupants were asked to remain on bed without performing any activity for additional 2 hours, to observe the CO$_2$ level evolution over a longer period of time, situation that can occur during weekends or holidays.

During the first 60 minutes, the CO$_2$ concentration increases from the initial value of approximately 800 ppm to 1500 ppm, similar to the other two nights of experiments, figure 5. The natural ventilation of the room by opening the window for 10 minutes helps reducing the CO$_2$ concentration to an acceptable value of about 750 ppm, but it generates energy losses, as the temperature decreases on average by 3.3 °C (figure 6) and the relative humidity by approximately 15% (figure 7).

During the normal sleep period of 8 hours, the increase of CO$_2$ level was similar to the results from 1$^{st}$ night of experiment (2 occupants M, F), the maximum value exceeding 5000 ppm, while for temperature and relative humidity recorded steady values for almost entire sleep period, on average of 24.3 °C and 53%, respectively.

Another interesting observation at the end of the experiment, is that the time needed to reduce the very high CO$_2$ concentration recorded after sleep period (>5500 ppm) using natural ventilation by window opening, is at least 30 minutes to reach 750 ppm and 40 minutes for 600 ppm, respectively.

Figure 5. CO$_2$ concentration evolution during 2$^{nd}$ night of experiment.
Figure 6. Temperature evolution during 2\textsuperscript{nd} night of experiment.

Figure 7. Relative humidity evolution during 2\textsuperscript{nd} night of experiment.

Figure 8 shows the good correlation between the theoretical values, calculated with equation 1, and measured values for CO\textsubscript{2} concentration increase in a sleeping room, without mechanical ventilation.

Figure 8. Comparison between calculated values and measured values of CO\textsubscript{2} concentration.
4. Conclusions
Conducted experiments show very poor air quality in sleeping rooms without mechanical ventilation, in all three nights recorded CO₂ concentrations significantly exceeded the recommended standards. It is supposed that poor air quality can affect the sleep process and further deteriorate daytime health, as well as and work efficiency. Natural ventilation is not a recommended solution due to energy loses, as the room temperature decreases on average with 3.3 °C during the 10-minutes window opening, for an outdoor temperature of about 1.5 °C.

Considering the growing trend of “zero energy” buildings and the results of this study, the indoor air quality must be taken into consideration also for residential buildings. In order to be able to provide proper quality air with reduced energy consumption, for residential applications authors recommend the use of sensor-controlled mechanical ventilation systems.

This paper reports on an investigation limited to the pollution concentration inside specific rooms on residential buildings. However, this initial experiment shows a very poor quality of the indoor air in the rooms without mechanical ventilation. The authors plan for extended further experiments.

5. References

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