The Influence of the Air Temperature on the CO₂ Emissions by Occupants Indoors

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Abstract. Data in human physiology have shown that the generation of metabolic CO₂ in the temperature interval 18-28 °C could vary only because of the temperature of the environment. Our study investigated the influence of two air temperatures (23 °C and 27 °C) on the CO₂ concentration in the classroom. Sixteen volunteers participated in the field study. It was found that the change in the room air temperature from 27 °C to 23 °C provoked a statistically proven change in the CO₂ concentration. The air relative humidity also shifts: it increased with the decrement of the room temperature.

1. Introduction
To reach category IV of EN 16789-1:2019 [1] standard on the energy performance of buildings, the air temperature in the indoor environment may vary from 18 °C to 28 °C, the whole year-round. However, the human body’s metabolic rate depends on environmental conditions and the air temperature in particular. According to [2], the minimum metabolic rate of a dressed, fasting person at rest is obtained for 30 °C. It was estimated that the human metabolic rate in 18 °C is 15% higher than in 28 °C, for the same conditions (dressed, resting person) [2]. Therefore, it can be expected that the generation of metabolic CO₂ in the temperature interval 18-28 °C would vary only because of the temperature of the environment, despite the other conditions that could influence it (activity level, drugs, health conditions and others).

The air people breathe consists of 21% oxygen (O₂) and 79% nitrogen (N₂) (neglecting the humidity) [3]. In the lungs, some of this oxygen penetrates the blood, and is then moved throughout the whole body as an energy source. The blood also contains as a waste product carbon dioxide (CO₂), transferred to the air in the lungs to be exhaled [2]. As a result, in the composition of the exhaled air, the O₂ concentration is less, and the CO₂ concentration is higher than in the inhaled air: approx. 8% O₂, 78% N₂, and 4.0% CO₂ [3]. Besides, the air inside the lungs is humidified and reaches relative humidity of 100%.

The generation of CO₂ in the human body is due to cellular respiration. The reaction involves glucose (C₆H₁₂O₆) from the ingested nutrients and oxygen, which produces energy in the form of adenosine triphosphate (ATP) [4]:

\[
\text{C}_6\text{H}_12\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}
\] (1)

The produced ATP (energy) helps the cells to perform all metabolic activities. While cellular respiration is only catabolic, the metabolism involves both catabolic and anabolic reactions.

Several studies have investigated the relationship between extreme air temperature and human metabolism. In a cold environment, for example, the metabolic rate (MR) increases to boost heat...
production [5]. Experiments were conducted in a hot environment [6, 7] and a mild-cold environment [8, 9]. Recently, the exposure to metabolic CO\textsubscript{2} has been studied in rooms with different air distributions [10] and the importance of sensor positioning has been evaluated [11].

Our study aimed to investigate the effect of the air temperature on the CO\textsubscript{2} emissions by occupants indoors. Two cases were investigated: the accumulation of CO\textsubscript{2} in a ventilated university classroom during regular lectures at two air temperatures 23 °C and 27 °C. The initial hypothesis was that the CO\textsubscript{2} concentration in the air would be different at the two temperatures.

2. Materials and methods

2.1. Participants
The study was performed in a ventilated classroom at the Technical University of Sofia (Sofia, Bulgaria) with installed heating, ventilation and air conditioning (HVAC) system (11.8 m length, 5.4 m width and 3.2 m height, with a total volume of 204 m\textsuperscript{3}) – fig1.

![Figure 1. The investigated classroom – a panoramic view](image)

The measurements were done during regular lecture classes, with 16 volunteers: 14 students (age 21-23 years) and 2 teachers (age 40 and 51). One of the teachers was lecturing, and the other was monitoring the measurements. The volunteers were provided with details about the purpose and methods of the study. They declared the absence of symptoms of COVID-19 or influenza. The measurement followed the governmental and university prescriptions (as of October 2020). In that period, the use of face masks in the classrooms was not obligatory.

2.2. Environmental conditions
Two values of the room air temperature were set, using the installed HVAC system: 23 °C and 27 °C. The HVAC system was in a recirculation mode to prevent the mixing with outside air, and both windows and the door were closed. The outdoor temperature was 14.8 °C at the beginning of the measurements and 15.6 °C at the end. The outside air relative humidity was 62 %. The central heating was switched off.

2.3. Measurements
Two CO\textsubscript{2} sensors (K-30 FR) were used, placed in the front and the back zone of the classroom at a distance of 600 mm from the floor. The sensors’ place was changed between the two stages to avoid possible errors introduced by the sensor itself.

A sensor (CM-4X) for simultaneous measurement of the O\textsubscript{2} concentration, air temperature, relative humidity and pressure was placed in the front zone of the classroom, at the same distance above the floor. The closest people were more than 2 m away from the sensors to avoid direct impact on the sensor from the breathing of a particular participant.
The change in the CO₂ concentration in the room was monitored continuously with a time step of 5s. The same frequency was used for the measurement of the O₂ concentration and environmental parameters.

2.4. Protocol
The measurements were performed in two stages: Stage 1 with 27 °C and Stage 2 with 23 °C. The participants were asked to sit evenly distributed in the classroom. The lectures duration was 45 min. The required room air temperature was reached in advance. The measurements started immediately after the room door was closed. Some seconds at the beginning of the recordings were omitted to equalize the recordings from all sensors. The measurements resulted in 2000 s (33.3 min) of records. During the measurements, the participants performed light sedentary work (listening and taking notes). Stage 2 took place after a 30 min break, needed to decrease the room air temperature. All windows were open during the break. After reaching 23 °C, the participants entered the room, taking the same seats as in Stage 1. They were asked not to change their clothes.

2.5. Statistical analysis
The statistical analysis was performed with Excel Data Analysis ToolPack. Student test (t-test) was applied to assess the existence of a difference between the average values in each group (paired two samples for means). The significance level α was set to 0.05.

3. Results and discussions

3.1. CO₂ concentration
Figure 2 presents the results for the CO₂ concentration for 23 °C (fig2a) and 27 °C (fig2b), summarizing the data from the front and back sensors.

![a/ Figure 2. CO₂ concentration measured by the front and back sensors: a/ Air temperature 23 °C; b/ Air temperature 27 °C](image_url)
In the two stages, the CO$_2$ concentration in the back zone was higher. The statistical analysis showed a proven difference between the mean values of the data from the front and back sensor for 23 °C (fig2a): $t_{stat}=76.53$, $t_{crit}=1.96$, $\alpha = 0.05$. The same was valid for 27 °C (fig2b): $t_{stat}=45.81$, $t_{crit}=1.96$, $\alpha = 0.05$. The Pearson correlation (0.997 for 23 °C and 0.991 for 27 °C) showed a linear dependence between the two data sets.

A reason for the difference in the CO$_2$ concentration in the front and back zone of the classroom could be the configuration of the workplaces: more occupants were in the back zone. The mixing effect in the room could also differ in the distinct zones of the enclosure.

The most important comparison is between the CO$_2$ concentration in the room during the two stages of the experiment. Figure 3 shows the results from the front sensor at 23 °C and 27 °C (fig3a) and the back sensor at 23 °C and 27 °C (fig3b).

![Front sensor CO$_2$ concentration](image)

![Back sensor CO$_2$ concentration](image)

**Figure 3.** CO$_2$ concentration measured in Stage 1 (23 °C) and Stage 2 (27 °C): a/ front sensor data; b/ back sensor data

Though the results look quite similar, especially in the back zone of the room, the statistical analysis showed a proven difference between the CO$_2$ concentration in Stage 1 and Stage 2. In both cases the statistical value (absolute value) of the t-test is higher than the critical value, e.g., for the front sensor ($t_{stat}=64.61$, $t_{crit}=1.96$, $\alpha = 0.05$) and for the back sensor ($t_{stat}=12.27$, $t_{crit}=1.96$, $\alpha = 0.05$).

3.2. O$_2$ concentration

Figure 4 shows the results for the O$_2$ concentration for 23 °C and 27 °C. The average value of the O$_2$ concentration in Stage 2 (23 °C) was 203922 ppm, while in Stage 1 (27 °C) it was 201631 ppm. The difference between the two data sets was statistically proven ($t_{stat}=211.79$, $t_{crit}=1.96$, $\alpha = 0.05$).

3.3. Environmental parameters

The air pressure in the room was constant during the measurements: 947 hPa. The temperature fluctuations are presented in fig5. The average value of the air temperature in Stage 1 was 27.4 °C with
a standard deviation (SD) of 0.23 °C. The average air temperature in Stage 2 was 23.7 °C with SD = 0.1 °C. It can be considered that the HVAC system had successfully overcome the continuous air warming due to the heat fluxes from the room occupants.

The air relative humidity (RH) change is summarized in Fig6 for the two stages. The average value of RH in Stage 1 was 43.7%, with SD = 1.8%. In Stage 2, the average RH was 53%, with SD = 1.4%. The lower RH in Stage 1 could be related to partial drying of the water vapour in the exhaled air in the higher ambient temperature.

Figure 4. O2 concentration in the classroom

Figure 5. Air temperature in the classroom

Figure 6. Relative humidity of the air in the classroom

4. Conclusions
The change in the room air temperature from 27 °C to 23 °C provoked a statistically proven change in the CO2 concentration under the recirculation mode of the HVAC system. The decrement was 6.6% in the front zone for the classroom and 1.5% in the back zone.

The air relative humidity also shifted: it increased with the decrement of the room temperature. Our future investigation will check the results from the performed field study in a climate chamber with prolonged measurements of human participants at the same air temperature (23 °C and 27 °C).

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**Acknowledgments**
The study and its publication are supported by Bulgarian Science Fund of the Ministry of Education and Science ДН17/12/12.12.2017.