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Empirical verification of the carbon dioxide concentration model in a teaching room

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ABSTRACT

Validation of the created mathematical model was based on the measurements of carbon dioxide concentration conducted in a teaching room in two variants. The highest average deviation of the results of the carbon dioxide concentration from the simulations and measurements is 2.1% (room A) and 1.6% (room B). The deviation of the results obtained from the simulation and the results obtained during experimental tests is smaller than the total measurement error for a given test series. The study showed the versatility of the model. It gives an opportunity to apply for a description of the hygiene conditions in different types of rooms, used by different number of people under variable internal conditions (temperature, relative humidity, atmospheric pressure). The assumptions and simplifications of the model are its advantages, because make the model easy to use. Simulation of carbon dioxide concentration in closed rooms using a model can be useful to determine the time of mechanical ventilation switching on or to determine its efficiency. The model can be used in the design of air quality monitoring systems, including the CO_2 sensors that control ventilation. It can also be useful for creating the tools for counting people in a room.

Keywords: carbon dioxide concentration, indoor air quality, simulation, classroom, didactic room.

INTRODUCTION

For some time, many researchers have been addressing the values in the air in which people spend their time. Studies have considered the concentration of carbon contained in classrooms in a large measure (Norbäck et al., 2013; Oha et al., 2019; Tureková et al., 2022). The concentration of carbon contained in the enclosure affects the health of those in its presence. The type of air quality is influenced by the type of effects and air transmission, which is the effect (Azuma et al., 2018, Branco et al., 2019, Deng and Lau, 2019). Many scientific studies conducted in Polish teaching rooms (Gładyszewska-Fiedoruk and Wiater, 2025; Jerominko and Cichowicz, 2025; Szczepanik-Ścisło and Ścisło, 2023) concluded that certain internal activities do not differ from the effects reported by researchers (Sakhi et al., 2019; Sidorin, 2015; Fromme et al., 2005).

Studies on carbon dioxide distribution in closed rooms were mainly based on measurements conducted under real conditions (Norbäck et al. 2013; Kapalo et al., 2021; Wilk et al., 2025; Lu, et al., 2021). Due to the limited number of carbon dioxide sensors, measurements are usually taken at several points in the room. On the other hand, numerical simulation ensures the distribution of carbon dioxide concentration at all points in the room. In the literature (Braun and Lawrence, 2006; Johnson, et al., 2018; Mahyuddin and Awbi, 2012) one can find research based on numerical modeling of the spatial distribution of carbon dioxide in various rooms.

There is a lack of publications related to a mathematical description of the phenomenon of carbon dioxide emission and dispersion in rooms. This prompted the authors to create and verify the mathematical model. Models presented in the literature are case studies. The presented model was created for passenger cars (a special case of rooms with a small cubic capacity and a relatively large number of people) (Gładyszewska-Fiedoruk, 2011), and after modification, it is suitable for rooms occupied by a significant number of people.

MATHEMATICAL MODEL

On the basis of the developed model, it is possible to determine the amount of exhaled carbon dioxide by a person performing a specific activity (specific physical or intellectual activity) under specific internal conditions at a given time. After taking into account the room volume, the model can be used to determine the carbon dioxide concentration in the room.

The ventilation air flow optimization problem was developed based on the energy cost analysis (Simanic et al., 2019) and in the publication by Mossolly et al. (2009) using genetic algorithm optimization.

When verifying the model and using it for simulation needs, it is necessary to provide the internal conditions at which the measurements of carbon dioxide concentration in the room were performed: temperature and relative humidity of air as well as atmospheric pressure. Under simulation conditions, normative data for temperature and relative humidity were provide (parameters specified in standards (PN-83/B-03430 and PN-EN 12599:2002/AC:2013) as optimal for a given type of room) and normal pressure (pressure equal to 101325 Pa, approximately corresponds to atmospheric pressure).

The following simplifications have been introduced in the model used:

- closed room,
- humidity in the calculation room is determined and recorded at the beginning of the experiment,
- humidity, temperature and pressure at a constant level,
- no airflow from leaks,
- a constant amount of carbon dioxide inhaled by a human being at a given time, regardless of external conditions and human weight, but depending on the age and type of activity,
- the amount of carbon dioxide exhaled depends on the number of people in the room and is calculated as the sum of the components of carbon dioxide emissions, the only carbon dioxide source in a given room is generated by humans.

The calculation algorithm of the presented model can be presented in the form of a block diagram presented in Figure 1.

METHODOLOGY

In order to verify the model, carbon dioxide concentration measurements were performed in

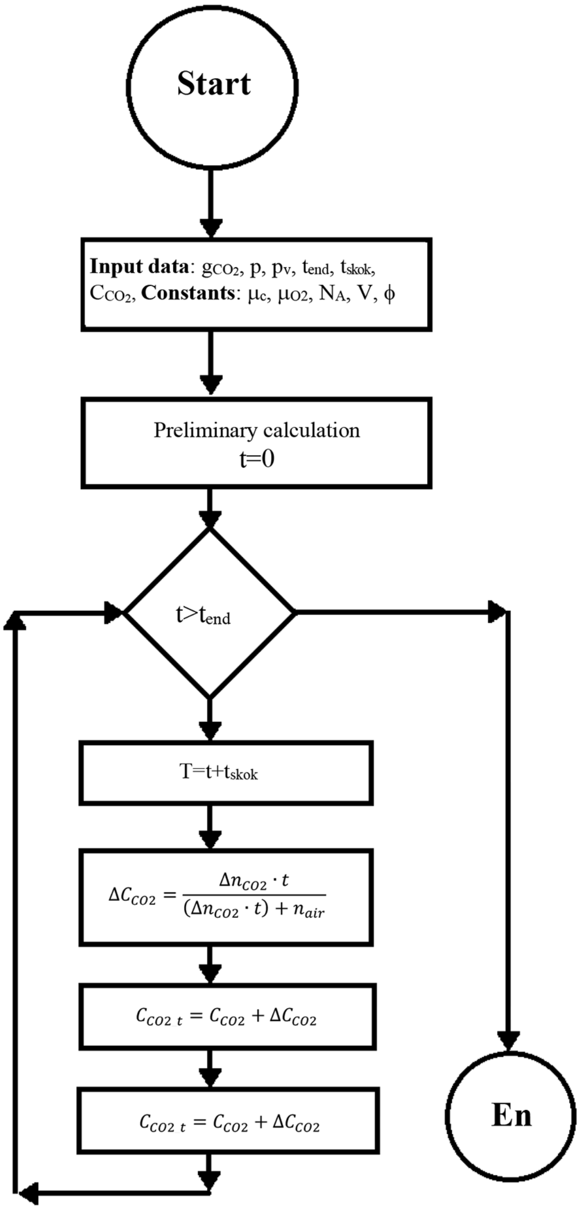

Figure 1. Block diagram of the calculation model

two teaching rooms during the heating season. Experimental studies were carried out in rooms differing in existing ventilation systems. Teaching rooms A and B (Figure 2) were of similar dimensions – about 52 m^2 (about 156 m^3). These are typical lecture and training rooms.

The room A was naturally ventilated through gravitational exhaust ventilation. Room B was equipped with mechanical. Mechanical ventilation was operated periodically, depending on the needs. The room was ventilated during the break only through the corridor door; mechanical ventilation was not turned off during the experiment.

The filling of the rooms during the measurements in the first test cycle ranged from 60% to 85% of the maximum number of students. In each of the measurement series included in the presented averages (five measurement series were made on the average), there were the same number of students.

Experimental research was conducted during lectures in the second research cycle, with a different number of students (lectures in room A – 45 people – 75%, lectures in room B – 55 people – 90% of the room filling).

The measurements of carbon dioxide concentration were conducted at the height of the student's head sitting at the bench (about 1.1 m from the floor surface level). The results of the experiment are presented in Figure 3. Measurements of carbon dioxide concentration were carried out using a Testo IAQ probe connected to a Testo 435 recorder, for which the error is ± 3% of the measured value for the range 0–5000 ppm, humidity for which the error is ± 1 %RH of the measured value for the range +10 to +98% RH and temperature for which the error is ±0.3 °C of the measured value for the range 0 to +50 °C (Teleszewski, Gajewski, 2020). Measurements were performed in the carbon dioxide concentration range of 440 ppm to 1800 ppm.

The deviation of the results obtained from the simulation and the results obtained during experimental studies was calculated from the relationship to the relative error Dn :

$$\Delta n = \frac{|n_{EXP} - n_{MOD}|}{|n_{EXP}|} \cdot 100\% \quad (1)$$

where: n_{EXP} is the concentration of carbon dioxide obtained during experimental tests, whereas n_{MOD} represents the concentration of carbon dioxide obtained from simulation tests (Teleszewski, Gajewski, 2025).

RESULTS AND ANALYSIS

In the teaching room, the initial carbon dioxide concentration was not much higher than the carbon dioxide concentration in the external air (Table 1). This means that the teaching room was well aired before the measurements.

The maximum deviation between the results obtained from the model and the results obtained during the tests was 13.8% (room A) and 18.8% (room B). The largest deviation of the carbon dioxide concentration measurements from the simulation (always at the beginning and end of the tests) indicated a very similar course of the lectures in all measurement series. The air quality disturbances at the beginning of the experiment are caused by varying student activity levels at

Room A Room B

Figure 2. The analyzed rooms

Table 1. Initial parameters of indoor

Parameter	Unit	Room	
		A	B
Temperature	°C	22.6	17.7
Humidity	% RH	57.7	45.8
Carbon dioxide concentration	ppm	439	520
Area	m^2	52	52
Max the number of students	number	60	60
Current number of students	%	75	90

the beginning of the class. One group of students enters the room, takes their seats, and is ready to participate in the class, while the other group enters enthusiastically and needs more time to begin the class. The air quality disturbances at the end of the experiment are caused by a different factor. At higher carbon dioxide concentrations, the air quality pattern changes. Human carbon dioxide production is slower, and therefore carbon dioxide concentration does not follow a straight line. This phenomenon is observed in publications (Teleszewski and Gładyszewska-Fiedoruk, 2019; Gładyszewska-Fiedoruk and Wiater, 2025).

Consistent with the experimental design, the differences between the rooms are small, as evidenced by the mean model deviations, which are very similar in both rooms. However, it can be noted that in room B, equipped with mechanical ventilation, the agreement between the model results and the measurements was slightly better. This may be due to more stable air exchange conditions and a more predictable ventilation airflow compared to natural ventilation.

The deviation of the results obtained from the simulation and the results obtained during experimental studies was calculated from the relationship (1). It was assumed that if the deviation is smaller than the error of experimental research, the model error is within the allowable error (Galas et al., 2019).

During the research cycle, the measurement series made during the lectures can be considered as fully verifying the created model. Although the model calculations and measurement results differ as much as possible: in the case of room A by 5.2%, and in the case of room B by 6.1%; nevertheless, the average deviation of the results is only 2.1% in the case of room A and 1.6% in the case of room B (Figure 3). Using the Pearson correlation coefficient test, it should be emphasized that in the case of both teaching rooms under consideration it is above 0.99 for the given analyzed measurement range.

The results of the verification should be considered very good, considering the conditions of the experiment, where in the room A there was an exchange of air through the leaking window and door joinery. In turn, mechanical ventilation ducts were installed in room B, through which air flowed freely from the room in which the experiment was conducted, to other teaching rooms and vice versa.

It should also be noted that both the results of measurements in very similar teaching rooms as well as the results of model calculations are lines parallel to each other. The displacement of the lines in Figure 3 results from the number of students participating in the classes during

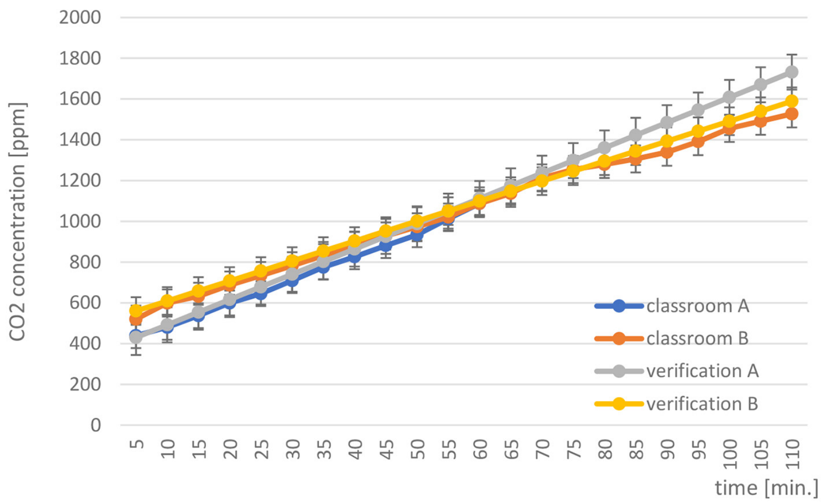

Figure 3. Results of verification of the mathematical model based on the results of measurements of carbon dioxide concentration in teaching rooms A and B

measurements of indoor air quality. The external conditions of the experiment did not disturb the nature of the changes in carbon dioxide concentration in the room.

The greater the number of people in a small area, the more accurate the results of model verification. This relationship was best observed during the experiment and simulations carried out in the same teaching room with different numbers of students.

In the literature (Vamsi Bankapalli et al., 2025; Arya et al., 2025), researchers attempt to describe the phenomenon of carbon dioxide emissions and concentration as precisely as possible in small spaces and with large occupancies. Many of the models presented in the literature describe this phenomenon very precisely (Azoulay Kochavi, et al., 2025; Dai et al., 2024). The presented model is of an engineering nature. The presented model can be used to develop the sensors that will regulate ventilation systems or simply monitor the indoor environment. This model can also be used to simulate other air pollutants, which will be the subject of future publications.

CONCLUSIONS

With the help of the described mathematical model, it is possible to determine the concentration of carbon dioxide exhaled by people, carbon dioxide at a specific physical activity and under certain internal conditions (temperature, relative humidity and atmospheric pressure).

During the verification, results of the experiments were obtained, which met two conditions:
1. Verification of the created model was carried out in the rooms where there was no air exchange phenomenon.
2. The experiment was carried out continuously at a specified time (no instantaneous measurement results).

The results of simulation calculations using the model can contribute to determining the required ventilation efficiency, i.e., the required size of the ventilated air stream, to ensure the indoor air quality.

In all model verifications presented in the study, the maximum average deviation was in the range of 1.6% ÷ 2.1%.

Simulation of carbon dioxide concentration in closed rooms using a model can be useful to determine the time of mechanical ventilation switching on or to determine its efficiency. The model can be used in the design of air quality monitoring systems, including the CO_2 sensors that control ventilation. It can also be useful for creating the tools for counting people in a room.

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