

CO₂ concentration in naturally ventilated classrooms located in different climates—Measurements and simulations

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ABSTRACT

The paper shows the results of measurements of carbon dioxide concentrations conducted in the school buildings located in two different climates: Białystok (Poland) and Belmez/Córdoba (Spain). CO₂ concentration in first 45 min met requirements of regulations, but with medium occupation of places in classrooms, then the recommended values were exceeded. We developed a model for CO₂ level estimation. This model allowed us to simulate the CO₂ concentration for full occupation of classrooms in both countries. In these cases CO₂ concentration would exceed maximum value (1000 ppm) during the first hour. Furthermore required air change rates were calculated: for actual occupation they should be in a range 2.5–5 h⁻¹ to maintain IDA2 and carbon dioxide concentration below 1000 ppm, while in case of full occupation even 6–9 h⁻¹. Finally, surveys of student satisfaction were performed in situ during the measurements of CO₂ level to obtain the dependence of student comfort perception on this concentration.

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1. Introduction

Since 2002, when the European Parliament and Council approved the directive on energy performance of buildings [1] in all the EU member countries, a process of changing buildings' envelopes and HVAC (Heating, Ventilation and Air Conditioning) systems to reduce the energy consumption has started. One of the most significant groups in the public building sector are schools where energy is used for heating, cooling, hot water production, lighting and electrical appliances [2]. The refurbishment of school buildings is assumed as an appropriate strategy to improve their indoor environment, because it is well established that often indoor environmental quality in classrooms is poor but it is also an exceptional opportunity to guarantee a significant improvement in the energy efficiency of buildings [3]. As demonstrated by Almeida and Peisoto de Freitas [3] the growing awareness of need to use sustainable strategies in school buildings is observed, as well as various international studies have been conducted to evaluate student's performance and the most significant factors that influence indoor air quality (IAQ) of classrooms. Many European countries have sponsored nationwide programs for school buildings

refurbishment, although in some cases the achieved results differed from theoretically estimated [3,4]. Importantly, some of improvements leading to reduction in the energy consumption, especially connected with replacing old windows with new, very tight ones resulted in a deterioration of the microclimate. As shown by Fanger [5] the indoor environment in a huge number of buildings is mediocre and it is a source of dissatisfaction and complaints. Carbon dioxide level is an important factor in the IAQ, because high CO₂ concentration could negatively affect the perception of people and cause health problems. Permissible concentration of carbon dioxide in the closed spaces according to World Health Organization (WHO) is 1000 ppm [6]. When the level exceeds 1000 ppm, occupants may complain about headaches, nose and throat ailments, tiredness, lack of concentration, and fatigue [7–13]. In both countries, Poland and Spain, depending on CO₂ level rooms could be assigned to four categories with similar standard values, whereas Polish standard gives also recommended ranges [14,15] like American standards [16,17]. The recommended values are shown in Table 1.

In Poland it is up to a designer which method is used to the calculations in a building.

In Spain different methods can be used for calculation of outdoor airflow [15]:

- a) For rooms with a metabolic activity of about 1.2 met, where is low pollutant production by different sources and smoking is not

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- allowed, indirect method of outdoor airflow per person is mostly used (according the value of airflow from [Table 1](#))
- b) For buildings with high metabolic activities like clubs, local sports and physical activities, etc, it is possible to use a direct method using the CO₂ concentration from [Table 4](#).
- c) For locals with high known pollutant production for instance swimming pools, restaurants, café, etc, the last method can be used. It is also possible to apply a specific dilution method described in [\[19\]](#).

According to Spanish National Regulation [\[15\]](#) most places located in schools like classrooms, offices or reading rooms are expected to meet category IDA2, whereas gyms and computer rooms are included into IDA3. Proper indoor microclimate increases the learning efficiency of children at schools [\[20\]](#) and particular attention should be paid to buildings where children spend their time [\[21\]](#). Santamouris et al. [\[22\]](#) conducted measurements in Greek schools and found that all data sets presented CO₂ concentration equal to 1000 ppm for air flows around to 8 l/p.s. However the carbon dioxide concentration often exceeds recommended limits, for instance Coley and Beisteiner [\[23\]](#) found the average value in seven tested classrooms as 1957 ppm, while the maximum concentration was higher than 4000 ppm. Turanjanin et al. [\[24\]](#) presented results of measurements conducted in Serbian schools that were also above recommended values (max about 3600 ppm). Dorizaset al. [\[25\]](#) showed that the mean value of CO₂ concentration in nine Greek schools for the non-teaching period was 1055 ppm, while during teaching activities was 1482 ppm. Hussin et al. [\[8\]](#) conducted research in ten laboratories found that in eight classrooms CO₂ level had been below 1000 ppm, while in two labs exceeded this level (max 1801 ppm). Ramalho et al. [\[26\]](#) worked on correlation between CO₂ concentration and indoor air pollutants.

The content of carbon dioxide in closed buildings is higher than in atmospheric air. It depends on a number of users and their metabolism [\[27,28\]](#). As showed by Recknagel et al. [\[29\]](#), adults with heavy-duty produce 68 g/h while during light work or rest about 35 g/h. The amount of CO₂ exhausted by children is estimated between 7.5 and 18 g/h, according to their age. Coley and Beisteiner [\[23\]](#) suggested 00541 l/s for adults and 0.00411 l/s in case of children.

Indoor air quality can be improved by increasing the air change rates per hour (ACH) as suggested by Wargocki et al. [\[30\]](#) but it would raise energy consumption for heating or cooling, depending on the season and building's location. Sarbu and Pacurar [\[31\]](#) noted this increasing was dependent on the energy usage and the indoor environment in high-quality school buildings. The problem of applying energy saving policy together with maintaining a proper thermal comfort and the IAQ was described in some papers for instance Gladyszewska and Krawczyk [\[7\]](#) studied offices to find the minimum ACH that provides recommended air quality. The comprehensive analysis of indoor environment quality and energy consumption in Europe was shown by Kolokotsa and Santamouris [\[32\]](#). Moreover Santamaouris described the energy policy changes in the building sector [\[33\]](#).

Table 1

The categories of indoor air [\[14,15,18\]](#).

| category | Air quality | Increase in CO ₂ concentration compared to CO ₂ concentration in the outside air [ppm] | | Required outdoor air flow [dm ³ /s per person] | |
|----------|-------------|--|--|---|--|
| | | Recommended range in Poland | Standard values in Spain and in Poland | Recommended range in Poland | Standard values in Spain and in Poland |
| IDA 1 | High | below 400 | 350 | Above 15 | 20 |
| IDA 2 | Average | 400–600 | 500 | 10–15 | 12.5 |
| IDA 3 | Moderate | 600–1000 | 800 | 6–10 | 8 |
| IDA 4 | Low | above 1000 | 1200 | Below 6 | 5 |



Fig. 1. Classroom in Białystok University of technology (Poland).

In modern buildings with mechanical ventilation the Demand Controlled Ventilation (DCV) systems that change ventilation flow depending on number of occupants and CO₂ concentration started to be more popular. The problems with maintaining a good environment and predicting CO₂ level were discussed in [\[34–36\]](#).

However there is a huge number of existing naturally ventilated buildings where there is a need to estimate optimal ACH taking into account both: energy savings and proper IAQ.

In this paper the results of CO₂ concentration measurements in eight classrooms located in two different climates, Poland and Spain, are shown. The condition of temperature and pressure can have a clear influence on the CO₂ concentration and its time evolution. An original model, where influence of these parameters was included has been developed. Moreover this model was used to estimate the CO₂ amount changes in time and experimentally verified. Based on it, we estimated CO₂ level in maximum occupancy areas and minimal air change rates required to meet standards, what is extremely important to maintain proper IAQ and set energy consumption for heating or cooling on the optimal level. Moreover, last section presents the results of student surveys about the perception of comfort performed in situ in the classroom, giving the relationship between the degree satisfaction student and CO₂ concentration.

2. The material and methods

2.1. Description of buildings and a learning schedule

The measurements were conducted in September in two schools located in Poland and Spain. The first one ([Fig. 1](#)) is the Białystok University of Technology building. The building was built in 1988 and consists of two parts: the higher one (three floors and basement) and the lower building (one floor and basement).

The second object belongs to University of Cordoba, School of Engineering Sciences of Belmez/Cordoba ([Fig. 2](#)), and was built

Table 2

The characteristic parameters of classrooms.

| Location | Class | Floor | Places for students | Students number during test | Percentage of occupation [%] | Volume [m ³] | Area per student [m ² /student] |
|------------------|-------|-------|---------------------|-----------------------------|------------------------------|--------------------------|--|
| Białystok | 1 | I | 120 | 70 | 58 | 416 | 2 |
| Białystok | 2 | II | 48 | 35 | 73 | 248 | 3.3 |
| Białystok | 3 | II | 50 | 21 | 42 | 200 | 3.3 |
| Białystok | 4 | I | 32 | 12 | 38 | 100 | 3.3 |
| Belmez (Córdoba) | 5 | II | 100 | 40 | 40 | 375 | 3.3 |
| Belmez (Córdoba) | 6 | I | 70 | 36 | 51 | 270 | 2.5 |
| Belmez (Córdoba) | 7 | I | 50 | 25 | 50 | 240 | 3.3 |
| Belmez (Córdoba) | 8 | II | 100 | 40 | 40 | 375 | 3.3 |



Fig. 2. Classroom in University of Cordoba (Spain).

1975. It consists of a main building has four floors and one-story extension.

The localization of both schools differs significantly in climatic data, although the outdoor carbon dioxide concentration is similar (Table 3). Long term data records show that the minimum monthly temperature in winter in Białystok is -4.9°C , while in Cordoba $+9.5^{\circ}\text{C}$. The maximum monthly temperature in July are respectively $+17.3$ and 26.9°C . In both universities we chose four classrooms, located in different parts of buildings. The characteristic parameters of rooms are presented in Table 2.

As shown in Table 2 in Polish classrooms the area per student was $2\text{--}3.3 \text{ m}^2$ what is higher than national recommended minimum value 1.5 m^2 per person. Spanish students have similar free space to Polish ones: $2.5\text{--}3.3 \text{ m}^2$ per student.

In Poland classes start at 8:15 a.m. Depending on a type of activities they last 45 or 90 min, and after that 15-min break takes place. Some specialist laboratories are used only few hours a day, but most in most classrooms lectures are given till 6 p.m. In Spain classes start at 9 a.m. and finish at 9 p.m. with 2 h break between 2 and 4 p.m. In most cases lessons last 90 min without breaks, however sometimes students learn 120 min with one 20-min break in the middle of doing.

Table 3

Outdoor air parameters during measurements.

| Parameter | Białystok-Poland | Belmez/Córdoba Spain |
|-------------------------------|------------------|----------------------|
| Average temperature | °C | 18 |
| Average relative humidity | % | 56 |
| Average atmospheric pressure | hPa | 1003 |
| CO ₂ concentration | ppm | 388 |
| | | 398 |

During our research all students taking part in classes filled surveys on their comfort. In Poland 74 women and 64 men participated in our tests, while in Spain 90 men and 51 women fulfilled questionnaires. They judged their comfort as "satisfied", "neutral" or "dissatisfied" at the beginning of lectures, after 30 and 60 min.

2.2. Research methodology

The measurements including indoor and outdoor air temperature, pressure and CO₂ concentration were conducted using multifunctional measuring instruments for air quality tests Testo 435-4 (Fig. 3), with the following characteristics:

- temperature in the range between 0 and $+50^{\circ}\text{C}$ with precision $\pm 0.3^{\circ}\text{C}$;
- carbon dioxide concentration in the range between +0 and $+5000 \text{ ppm}$ with precision $\pm 50 \text{ ppm}$ ($\pm 2\%$); between 5000 ppm and 10000 ppm with precision $\pm 100 \text{ ppm}$ ($\pm 3\%$);
- atmospheric pressure in the range between +600 and $+1150 \text{ hPa}$ with precision $\pm 5 \text{ hPa}$.

According to [8] we measured indoor climate parameters 1.2 m above the floor each time. Air stream velocity was measured using a Testo-4 fan anemometer with a measurement precision of $\pm 0.2 \text{ m/s}$. Dimension measurements were taken with a Bosch DLE 70 laser rangefinder with the precision of $\pm 0.0001 \text{ m}$. Period of measurement was chosen to ensure comparable outdoor air quality for both locations. All tests were conducted with natural ventilation of classrooms according to the assumption of this research.

2.3. Model for CO₂ concentration

To calculate the volume of carbon dioxide from human respiration, formula presented in [37,38] can be used:

$$V_{\text{CO}_2} = 0.83 \frac{0.00276 A_p M}{0.23r + 0.77} [\text{dm}^3/\text{s}] \quad (1)$$

Where: M is a metabolic rate in met, r is the ratio (0.83–1.0), A_p is a nude body surface calculated by:

$$A_p = 0.202 m^{0.425} h^{0.725} [\text{dm}^2] \quad (2)$$

Table 4

Model Errors E[ppm].

| Town/Country | Classroom | Model | Model 5 Error [ppm] | Model CISBE |
|------------------|-----------|-------|---------------------|-------------|
| Białystok-Poland | 1 | 175 | 120 | 78 |
| Białystok-Poland | 2 | 95 | 112 | 115 |
| Białystok-Poland | 3 | 117 | 203 | 192 |
| Białystok-Poland | 4 | 64 | 83 | 94 |
| Córdoba –Spain | 5 | 60 | 96 | 77 |
| Córdoba –Spain | 6 | 106 | 159 | 163 |
| Córdoba –Spain | 7 | 59 | 72 | 73 |
| Córdoba –Spain | 8 | 92 | 148 | 93 |
| Average | | 96 | 124 | 111 |



Fig. 3. Testo-435-4 during measurements of outdoor air in Spain.

where: m is mass of human body in kg and h is height of human body in m.

Results of measurements are usually compared with the simulation data using variety of methods described in literature as given in CIBSE AM 10 and presented in papers [39–43] for a well-mixed space, where the concentration of CO₂ is often estimated from:

$$C_{CO_2}(t) = C_{ex} + \frac{G}{Q} + \left(C_0 - C_{ex} - \frac{G}{Q} \right) e^{-\frac{Q}{V}t} \quad (3)$$

where G is CO₂ generation rate in cm³/s, C_{ex} is carbon dioxide concentration in outdoor air in ppm, C_0 is carbon dioxide concentration in indoor air in time 0 in ppm,

Q is the volume flow rate into a space in m³ s⁻¹, V is the volume of indoor air in m³ and t is time in s.

The system will eventually attain steady state CO₂ concentration (the exponential term is neglected) and an inverse proportional relationship between this steady state CO₂ concentration and the ventilation rate can be found:

$$C_{CO_2}(t) = \frac{G(t)}{Q(t)} + C_{ext}(t) \quad (4)$$

This is the simplified model presented by Quang et al. [44] for the operation of a building ventilation system, that can be also written in ppm:

$$C_{CO_2}(t) = \frac{N(t)G(t)}{1.8Q(t)} + C_{ext}(t) [ppm] \quad (5)$$

where: $G(t)$ is CO₂ release by an individual occupant at time t , 0.00521/s for an average adult at a normal activity in the office during sitting and writing or reading, Q is the volume flow rate into a space in m³/s, $N(t)$ is a number of occupants inside the building at time, $C_{ext}(t)$ is concentration of outdoor CO₂ in this time.

A new model for determination the dependence of CO₂ concentration on temperature and pressure in classrooms was elaborated. This model is based on the mass balance:

$$m_{CO_2in} = m_{CO_2in(t=0)} + m_{CO_2gen} + m_{CO_2sup} - m_{CO_2exh} \quad (6)$$

where m_{CO_2in} is a mass of carbon dioxide inside a classroom, $m_{CO_2in(t=0)}$ is a mass of carbon dioxide inside a classroom in initial moment ($t=0$), m_{CO_2gen} is a mass of carbon dioxide generated by people in a classroom, m_{CO_2sup} is a mass of carbon dioxide supplied into a classroom from outside, m_{CO_2exh} is a mass of carbon dioxide exhausted from a classroom.

Our assumption was that the flow of air supplied to the room and exhausted from it are equal. We also assumed that carbon dioxide concentration in supplied air is equal to CO₂ concentration in outdoor air.

The inside CO₂ mass in the initial, $t=0$, and in the instant t can be calculated by:

$$m_{CO_2in} = \xi_{CO_2}^{in} \rho_{air}^{in} V \quad (7)$$

with V is the volume of the space room and ρ_{air}^{in} and $\xi_{CO_2}^{in}$ are the air mass density and the mass fraction of CO₂ in air ($\xi_{CO_2} = \frac{m_{CO_2}}{m_{air}}$), inside room, respectively.

Carbon dioxide generation G in a time t from people can be estimated by:

$$G = gNt \quad (8)$$

where g is CO₂ gains from a person and N is number of people occupied a room in this instant t .

The supplied and exhaust carbon dioxide concentration to room is given by:

$$m_{CO_2sup} = \xi_{CO_2}^{out} \rho_{air}^{out} ACHVt \quad (9)$$

$$m_{CO_2exh} = \xi_{CO_2}^{in} \rho_{air}^{in} ACHVt \quad (10)$$

where ACH is the air change rate and ρ_{air}^{out} and $\xi_{CO_2}^{out}$ are the air mass density and the mass fraction of CO₂ in air outside room, respectively.

According to Eqs. (7), (9) and (10), the mass balance (6) can be written:

$$\begin{aligned} \xi_{CO_2}^{in} \rho_{air}^{in} V &= \xi_{CO_2(t=0)}^{in} \rho_{air(t=0)}^{in} V + gNt + \xi_{CO_2}^{out} \rho_{air}^{out} ACHVt \\ &\quad - \xi_{CO_2}^{in} \rho_{air}^{in} ACHVt \end{aligned} \quad (11)$$

Considering the mass fraction depends on CO₂ concentration,

$$\xi_{CO_2} = \frac{C_{CO_2} \mu_{CO_2}}{\mu_{Air}} \quad (12)$$

with μ_{CO_2} and μ_{Air} the molar mass of carbon dioxide and air, respectively, and the air mass density in gas ideal approximation,

$$\rho_{air} = \frac{\mu_{air} n_{air}}{V} = \mu_{air} \frac{P}{RT} \quad (13)$$

(n_{air} is moles number of air and R is the Gas Ideal Constant), Eq. (11) can be written:

$$\begin{aligned} C_{CO_2in} \frac{P_{in}}{T_{in}} &= C_{CO_2in(t=0)} \frac{P_{in(t=0)}}{T_{in(t=0)}} + gNt \frac{R}{\mu_{CO_2} V} + C_{CO_2out} \frac{P_{out}}{T_{out}} ACHt \\ &\quad - C_{CO_2in} \frac{P_{in}}{T_{in}} ACHVt \end{aligned} \quad (14)$$

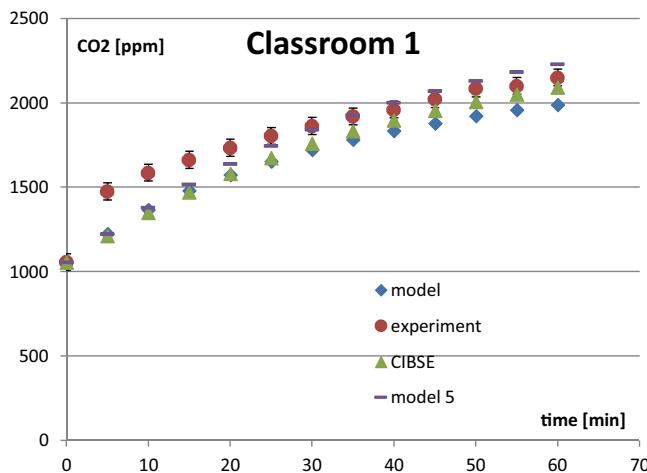


Fig. 4. Concentration of CO₂ in classroom 1 in Białystok (Poland).

Finally, the carbon dioxide concentration indoor can be obtained from the above equation:

$$C_{CO_2in} = \frac{T_{in}}{P_{in}(1+ACHt)} \left[C_{CO_2in(t=0)} \frac{P_{in(t=0)}}{T_{in(t=0)}} + \left(gN \frac{R}{\mu_{CO_2} V} + C_{CO_2out} \frac{P_{out}}{T_{out}} ACH \right) t \right] \quad (15)$$

Based on obtained equation two variants of calculation were conducted. In the first option (marked as "model") initial values "0" in formula (10) were taken as values in time 0 – when the experiment started. In second variant (called "model 5") every 5 min the carbon dioxide level was estimated and the result was taken as the initial value for the next time range.

3. Results of measurements and the model verification

Model for CO₂ concentration was verified based on measurements results.

In Table 3 main data of outdoor air are shown. As presented in [24], indoor air quality is in very high correlation with outdoor air quality and sources of pollutants, so measurements were conducted in places with similar outdoor quality.

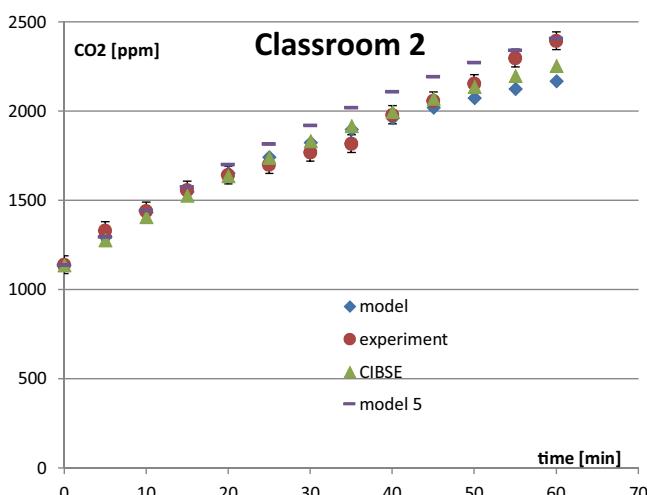


Fig. 5. Concentration of CO₂ in classroom 2 in Białystok (Poland).

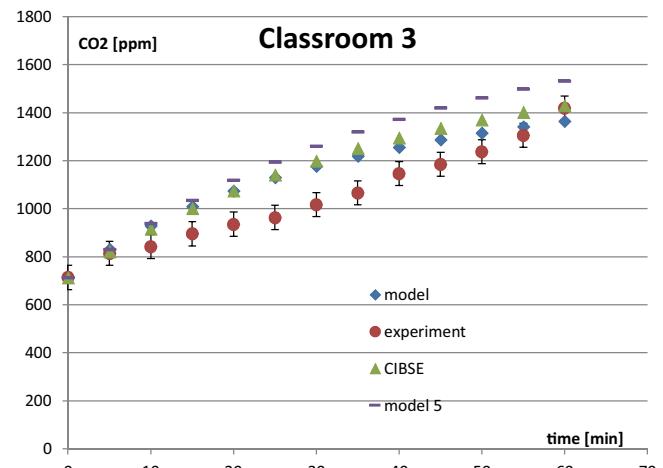


Fig. 6. Concentration of CO₂ in classroom 3 in Białystok (Poland).

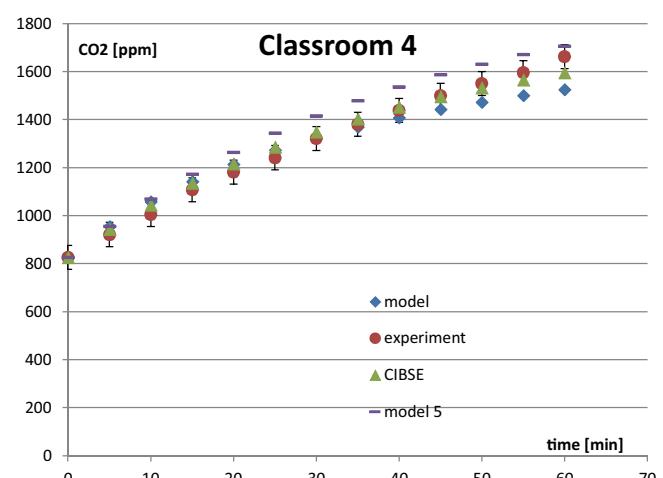


Fig. 7. Concentration of CO₂ in classroom 4 in Białystok (Poland).

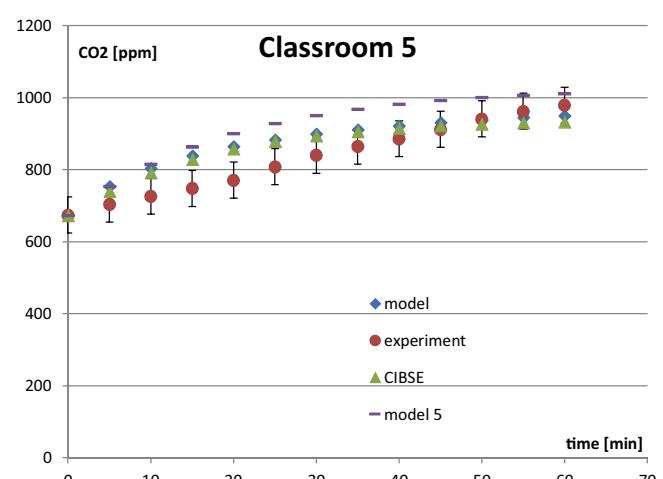


Fig. 8. Concentration of CO₂ in classroom 5 in Belmez (Spain).

Results of measurements and simulations for our model (in its two variants) were presented in Figs. 4–11. In these figures, there are also presented the results of calculation according to classical CIBSE model (Eq. (3)) in order to compare with Authors' model.

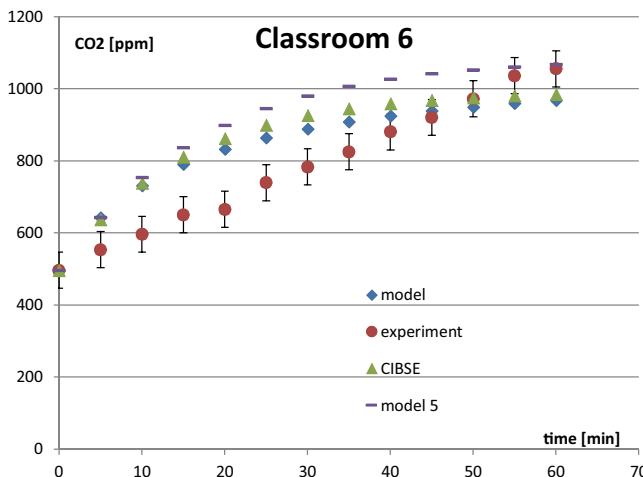


Fig. 9. Concentration of CO₂ in classroom 6 in Belmez (Spain).

Estimated Standard Model Errors are presented in Table 4, that provides the verification of three models: two versions of the proposed original model and the model CISBE described in literature (Eq.(3)). The average error for classrooms in Poland was the lowest in case of a new model (113 ppm) while for model 5 and model CISBE estimated values amounted respectively 130 and 120 ppm. In case of Spanish rooms the lowest error was found for a new model (79 ppm), while for other two values were 119 and 102 ppm. The average model error calculated for all classrooms was 96 ppm in a case of the new model, 124 ppm in model 5 and 111 ppm in model CISBE. It shows similar fitting for proposed model 5 and described in literature model CISBE while new model has lower error and could be successfully used for simulations of carbon dioxide concentration in rooms.

Reported high concentration of CO₂ in classrooms in Poland was caused by a low fresh air flow (ACH in Poland was between 1 and 1.5 h⁻¹, while in Spain in range 3 and 4 h⁻¹), long duration of classes (more than 60 min without break) and high amount of students in classes.

At the beginning of lessons most classrooms had a good air quality and could be classified as IDA1 (3,4,5,6,7,8) except rooms 1,2 in Poland (IDA3). It could be a result of not enough time to ventilate rooms properly after few morning lectures, but in fact this situation usually takes place and tests were conducted in the real conditions of schools' work. After 60 min of measurements,

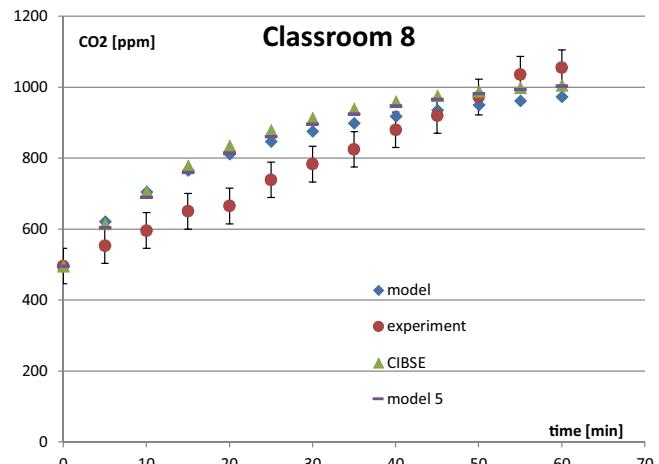


Fig. 11. Concentration of CO₂ in classroom 8 in Belmez (Spain).

classrooms in Spain met requirements of category IDA1,2 whereas in Poland IDA3,4.

Because classrooms were only partly occupied during measurements the CO₂ level was also simulated using verified model for full occupation of places. In such a case in all classrooms in both countries CO₂ concentration would exceed 1000 ppm, mostly after 35–45 min of learning activities.

Moreover we used the model to estimate CO₂ level after 45, 60 and 90 min in all classrooms with the assumption that classrooms are well-ventilated before lectures and at the beginning of classes indoor CO₂ concentration is similar to outdoor (400 ppm). Results of simulations are presented in Table 5.

The results of the simulation using the new model, with the initial assumption that when classes started CO₂ level was about 400 ppm (similar to outside air level of carbon dioxide) and classrooms are partly occupied, showed that in three classrooms in Spain CO₂ concentration would be lower than 1000 ppm during 90 min, while in one room it would exceed this recommended value after 45 min. In Poland during first 45 min the concentration of carbon dioxide would be higher than 1000 ppm, although it would meet IDA2 requirements by first 35 min. In case of full occupation of places (as classrooms were designed) in all rooms in Poland and Spain CO₂ concentration would exceed 1000 ppm after first 30 min.

Moreover, using the model we estimated ACH required to maintain the level 1000 ppm during 45 min of lectures and keep a concentration adequate for IDA 2.

In classrooms with actual occupation the ACH should be in range between 2.5 and 4.5 h⁻¹. In case of full occupation, predicted by engineers-designers, significantly higher ACH is required (6–9 h⁻¹).

4. Results of surveys about student satisfaction

Results of surveys conducted during classes are presented in Table 6. This paper is limited to the answers about the general wellbeing of students in context of CO₂ level.

At the beginning of classes higher percentage of students satisfied with indoor climate were found in Poland (60–50%) than in Spain (25–50%), although initial carbon dioxide concentration in Polish classrooms was higher than in Spanish ones (Figs. 4–11). In all cases the percentage of students who were dissatisfied because of indoor conditions was increasing during classes. The decreasing in number of students satisfied with microclimate was significantly higher in Poland where concentration of carbon dioxide exceeded 1000 ppm in all classrooms.

The results show that changes in carbon dioxide concentration could influence student satisfaction with indoor microclimate,

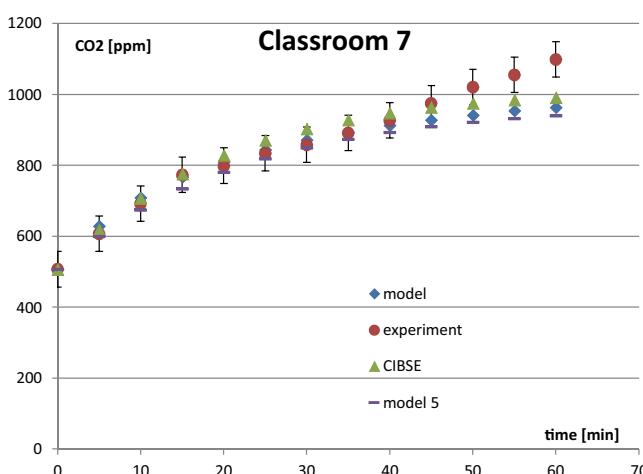


Fig. 10. Concentration of CO₂ in classroom 7 in Belmez (Spain).

Table 5

Simulation of CO₂ concentration (full occupation, CO₂ level at the beginning 400 ppm, actual ACH).

| Classroom | CO ₂ concentration [ppm] for actual occupation after | | | CO ₂ concentration [ppm] for full occupation after | | |
|-----------|---|--------|--------|---|--------|--------|
| | 45 min | 60 min | 90 min | 45 min | 60 min | 90 min |
| 1 | 1569 | 1726 | 1929 | 2404 | 2673 | 3022 |
| 2 | 1596 | 1798 | 2077 | 2040 | 2317 | 2699 |
| 3 | 1288 | 1365 | 1464 | 2303 | 2516 | 2792 |
| 4 | 1139 | 1238 | 1366 | 2154 | 2389 | 2694 |
| 5 | 907 | 950 | 999 | 1665 | 1770 | 1895 |
| 6 | 914 | 949 | 988 | 1399 | 1466 | 1542 |
| 7 | 1044 | 1115 | 1208 | 1686 | 1829 | 2013 |
| 8 | 906 | 950 | 999 | 1664 | 1773 | 1897 |

Table 6

Percentage of students satisfied with conditions, neutral and dissatisfied because of indoor comfort during classes.

| Location | Class | Time from the beginning of class [min] | Satisfied [%] | Neutral [%] | Dissatisfied [%] |
|----------------|-------|--|---------------|-------------|------------------|
| Białystok | 1 | 0 | 80 | 11 | 9 |
| | | 30 | 80 | 9 | 11 |
| | | 60 | 41 | 19 | 40 |
| Białystok | 2 | 0 | 60 | 0 | 40 |
| | | 30 | 52 | 3 | 45 |
| | | 60 | 40 | 15 | 45 |
| Białystok | 3 | 0 | 70 | 5 | 25 |
| | | 30 | 70 | 5 | 25 |
| | | 60 | 61 | 9 | 30 |
| Białystok | 4 | 0 | 75 | 2 | 23 |
| | | 30 | 73 | 2 | 25 |
| | | 60 | 70 | 2 | 28 |
| Cordoba/Belmez | 5 | 0 | 46 | 40 | 14 |
| | | 30 | 40 | 40 | 20 |
| | | 60 | 36 | 40 | 24 |
| Cordoba/Belmez | 6 | 0 | 25 | 33 | 42 |
| | | 30 | 24 | 33 | 43 |
| | | 60 | 22 | 21 | 57 |
| Cordoba/Belmez | 7 | 0 | 50 | 30 | 20 |
| | | 30 | 44 | 34 | 22 |
| | | 60 | 44 | 30 | 26 |
| Cordoba/Belmez | 8 | 0 | 50 | 50 | 0 |
| | | 30 | 46 | 50 | 4 |
| | | 60 | 40 | 40 | 20 |

however the answers of participants of our research in the beginning of classes show that there is necessary to take into account other parameters. We intend to conduct a comprehensive analysis of various factors of microclimate like indoor temperature and humidity, air flow, smell, noise, lighting, free space etc. that could affect human feelings and show the results in a subsequent paper dedicated to human comfort vs. different indoor parameters.

5. Conclusion

The main outcomes of the research and analyses can be summarized as follows:

- In Spain ACH were higher and carbon dioxide concentration was below recommended value during 45 min of teaching activities (IDA1,2).
- In Poland ACH were too low and after lessons indoor air met requirements of category IDA3,4.
- The proposed model was verified using experimental data and compared with CISBE one. Its error is lower and the model can be successfully used for simulations of carbon dioxide concentration in rooms.

- In case of a full-occupation of places in all tested classrooms in Poland and Spain, a level of CO₂ was found too high (during first hour the level 1000 ppm would be exceeded),
- To maintain IDA2 category in classrooms with actual occupation the ACH should be in range between 2.5 and 4.5 h⁻¹, while in case of full occupation (predicted by architects) it must be significantly higher: 6–9 h⁻¹.
- The percentage of students satisfied with indoor microclimate decreased during classes more significantly in Poland, where CO₂ concentration increased above the recommended maximum level 1000 ppm.

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References

- [1] The European Parliament and Council approved the directive on energy performance of buildings (2002/91/EC).
- [2] N. Gaitani, C. Lehmann, M. Santamouris, G. Mihalakakou, P. Patargas, Using principal components and clusters analysis in the heating evolution of school building sector, *Appl. Energy* 87 (2010) 2079–2086.
- [3] R.M.S.F. Almeida, V. Peixoto de Freitas, Indoor environmental quality of classrooms in Southern European climate, *Energy Build.* 81 (2014) 127–140.
- [4] D.A. Krawczyk, Theoretical and real effect of school's thermal modernization – a case study, *Energy Build.* 81 (2014) 30–37.
- [5] P.O. Fanger, Human requirements in future air-conditioned environments, *Int. J. Refrig.* 24 (2001) 148–153.
- [6] WHO, Air Quality Guidelines for Europe, second ed., WHO Regional Office for Europe Copenhagen, 2000 (European Series, No. 91).
- [7] K. Gladyszewska-Fiedoruk, D.A. Krawczyk, The possibilities of energy consumption reduction and a maintenance of indoor air quality in doctor's offices located in north-eastern Poland, *Energy Build.* 85 (2014) 235–245.
- [8] M. Hussin, M.R. Ismail, M.S. Ahmad, Air-conditioned university laboratories: comparing CO₂ measurement for centralized and split-unit systems, *J. King Saud Univ. Eng. Sci.* (2014), <http://dx.doi.org/10.1016/j.jksues2014.08.005>.
- [9] P.A. Siskos, K.E. Bouba, A.P. Stroubou, Determination of selected pollutants and measurement of physical parameters for the evaluation of indoor air quality in school buildings in athens, *Greece Indoor Built Environ.* 5 (2001) 185–192.
- [10] H. Carlsson, U. Nilsson, C. Stman, Video display units: an emission source of the contact allergenic flame retardant triphenyl phosphite in the indoor environment, *Environ. Sci. Technol.* 34 (2000) 3885–3889.
- [11] M. Makowski, M. Ohlmeyer, Comparison of a small and a large environmental test chamber for measuring VOC emissions from OSB made of Scots pine (*Pinussylvestris L.*), *HolzRoh-Werkst* 64 (6) (2006) 469–472.
- [12] R. Prill, Why measure carbon dioxide inside buildings? Washington state university extension energy program, *WSUEEP* 07-003 (2000) 1–3.
- [13] O.A. Seppanen, W.J. Fisk, Summary of human responses to ventilation, *Indoor Air* 14 (2004) 102–118.
- [14] PN-EN 13779:2008 Ventilation of residential buildings. Requirements for the properties of ventilation and air conditioning.
- [15] Ministerio de Industria, Energia y Turismo, Reglamento de instalaciones termiticas en los edificios, *Boletín Oficial del Estado* 207 (2007) 35931–35984.
- [16] ASHRAE Thermal environmental conditions for human occupancy ASHRAE Standard 55, Atlanta (2004).
- [17] ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality, American Society of Heating and Refrigerating and Air-Conditioning Engineers Inc., Atlanta, 2007.
- [18] ASHRE handbook fundamentals, Atlanta, American Society of Heating and Refrigerating and Air-Conditioning Engineers Inc., 2009.
- [19] UNE-EN 13779, Ventilation for Non-residential Buildings E Performance Requirements for Ventilation and Room-conditioning Systems, AENOR, Madrid, Espana, 2008.
- [20] P.O. Fanger, What is IAQ? *Indoor Air* 16 (2006) 328–334.
- [21] A. Mainka, E. Bragozewska, B. Kozielska, J.S. Pastuszka, E. Zajusz-Zubek, Indoor air quality in urban nursery schools in Gliwice, Poland. Analysis of the case study, *Atmos. Polut. Res.* 6 (2016) 1098–1104.
- [22] M. Santamouris, A. Synnefa, M. Asssimakopoulos, I. Livada, K. Pavlou, M. Papaglastra, D. Gaitani, V. Assimakopoulos, Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation, *Energy Build.* 40 (2008) 1833–1843.
- [23] D.A. Coley, A. Beisteiner, Carbon dioxide levels and ventilation rates in schools, *Int. J. Vent.* 1 (2002) 13–21.
- [24] V. Turjanianin, B. Vučević, M. Jovanović, N. Mirkov, I. Lazović, Indoor CO₂ measurements in Serbian schools and ventilation rate calculation, *Energy* 77 (2014) 290–296.
- [25] P.V. Dorizas, M.N. Assimakopoulou, C. Helmis, M. Santamouris, An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring, *Sci. Total Environ.* 502 (2015) 557–570.
- [26] O. Ramalho, G. Wyart, C. Mandin, P. Blonseau, P.A. Cabanes, N. Leclerc, J.U. Mullot, G. Boulanger, M. Redaelli, Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values, *Build. Environ.* 53 (2015) 115–124.
- [27] Z. Bakó-Biró, D.J. Clements-Croome, N. Kochhar, N.H. Awbia, M.J. Williams, Ventilation rates in schools and pupils' performance, *Build. Environ.* 48 (2012) 215–223.
- [28] I. Škrjanc, B. Šubic, Control of indoor CO₂ concentration based on a process model, *Autom. Constr.* 42 (2014) 122–126.
- [29] H. Recknagel, E. Sprenger, W. Homann, E.R. Schramek, Taschenbuch für Heizung und Klimatechnik 07/08, OMNI SCALA, München, 2008.
- [30] P. Wargoński, Z. Bakó-Biró, G. Clausen, O. Fanger, Air quality in a simulated office environment as a result of pollution sources and increasing ventilation, *Energy Build.* 34 (2002) 775–783.
- [31] I. Sarbu, S. Pacurar, Experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms, *Build. Environ.* 93 (2015) 141–154.
- [32] D. Kolokotsa, M. Santamouris, Review of the indoor environmental quality and energy consumption studies for low income households in Europe, *Sci. Total Environ.* 536 (2015) 316–330.
- [33] M. Santamouris, Innovating to zero the energy sector in Europe: minimising the energy consumption, eradication of the energy poverty and mitigating the local climate changes, *Sol. Energy* 128 (2016) 61–94.
- [34] J. Yang, M. Santamouris, S.E. Lee, Review of occupancy sensing systems and occupancy modeling methodologies for application in institutional buildings, *Energy Build.* 121 (2016) 344–349.
- [35] J. Yang, M. Santamouris, S.E. Lee, Deb Ch Energy performance model development and occupancy number identification of institutional buildings, *Energy Build.* 123 (2016) 192–204.
- [36] A. Pantazarak, S.E. Lee, M. Santamouris, Predicting the CO₂ levels in buildings using deterministic and identified models, *Energy Build.* (2016) (accepted manuscript).
- [37] M. Luo, X. Zhou, Y. Zhua, J. Sundella, Revisiting an overlooked parameter in thermal comfort studies, the metabolic rate, *Energy Build.* 118 (2016) 152–159.
- [38] I. Sarbu, C. Sebarchievici, Review Aspects of indoor environmental quality assessment in buildings, *Energy Build.* 60 (2013) 410–419.
- [39] R.M.S.F. Almeida, V. Peixoto de Freitas, Indoor environmental quality of classrooms in Southern European climate, *Energy Build.* 81 (2014) 127–140.
- [40] T. Lu, A. Knuutila, M. Viljanen, X. Lu, A novel methodology for estimating space air change rates and occupant CO₂ generation rates from measurements in mechanically-ventilated buildings, *Build. Environ.* 45 (2010) 1161–1172.
- [41] M. Griffiths, M. Eftekhari, Control of CO₂ in naturally ventilated classroom, *Energy Build.* 40 (2008) 556–560.
- [42] M.K. Kim, L. Baldini, H. Leibundgut, J.A. Wurzbacher, N. Piatkowski, A novel ventilation strategy with CO₂ capture device and energy saving in buildings, *Energy Build.* 87 (2015) 134–141.
- [43] M.O. Ng, M. Qu, P. Zheng, Z. Li, Y. Hang, CO₂-based demand controlled ventilation under new ASHRAE Standard 62.1-2010: a case study for a gymnasium of an elementary school at West Lafayette, Indiana *Energy Build.* 43 (2011) 3216–3225.
- [44] T.N. Quang, C. He, L.D. Knibbs, R. de Deard, L. Morawska, Co-optimisation of indoor environmental quality and energy consumption within urban office buildings, *Energy Build.* 85 (2014) 225–234.