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Research of CO_2 concentration in naturally ventilated lecture room

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Abstract. Naturally ventilated buildings especially dedicated for educational purposes need to be design to achieve required level of thermal comfort and indoor air quality. It is crucial in terms of both: health and productivity of the room users. Higher requirements of indoor environment are important due to the level of students concentration, their ability to acquire new knowledge and willingness to interact with the lecturer. The article presents the results of experimental study and surveys undertaken in naturally ventilated lecture room. The data is analysed in terms of CO_2 concentration and its possible influence on users. Furthermore the outcome of the research is compared with the CO_2 concentration models available in the literature.

1 Introduction

The one of the main building task is to maintain comfortable and healthy conditions for its users. It can be accomplished on various ways depending whether the building is mechanically or naturally ventilated. The issues of indoor air quality and carbon dioxide as an indicator of ventilation efficiency in mechanically ventilated buildings are described in the literature [1-3]. However there is still huge number of existing naturally ventilated buildings were human is a main source of contaminants and where CO_2 as the sufficient indicator can be used for optimisation of indoor conditions.

As people spend most of their time indoors, IAQ has been identified as a crucial aspect of building utilization in many publication [1, 3–6]. The CO_2 concertation is described by the quantity of carbon dioxide in a million particles of air – ppm (particle per million). Other words the CO_2 concentration is an indicator of the amount of fresh air delivered to the room from the outside. The reference outdoor value is 400 ppm that is 0.04% of Earth's atmosphere [7, 8]. The human body exhales even about 2–4% [7, 9, 10] this is why in enclosed areas dedicated for human being, the concentration of carbon dioxide can be higher. The acceptable level of carbon dioxide is related to building category and is defined in European Standard 13779:2008 [11]. The standard states that the typical ranges of CO_2 concentration above the outdoor level are: for building category I: < 400 ppm, category II: 400-600, category III: 600-1000 and IV: > 1000. The literature also indicates [8], following

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Venture Industries Sp.z o.o., that the outdoor level of CO_2 for rural areas is 300 to 350 ppm, while for cities and urban areas the level increases to 400 ppm.

The CO_2 as an indicator of indoor conditions has been described in the literature. The [12] presents the numerical study of CO_2 dispersion from breathing in an auditory room. The study indicate that CO_2 concentration accumulates on a lower levels of the space and decreases with height. It also states that the level of carbon dioxide describes the effectiveness of the ventilation systems which is responsible for diluting also more harmful indoor contaminants the human is exposed to. The [5] presents the research outcome on naturally ventilated school rooms in terms of carbon dioxide level. The literature [5, 13] indicates that CO_2 concentration is an important factor influencing the performance of learning ability and concentration. Publications [4, 7, 10] point out that when the threshold defined by WHO as acceptable of 1000ppm is exceeded, room users can suffer of headaches, tiredness, lack of concentration or throat and nose ailments [1, 4].

In the paper [4] authors present the results of measurements of carbon dioxide concentrations conducted in the school buildings located in two different climates: Białystok (Poland) and Belmez/Córdoba (Spain). They developed a model for CO_2 level estimation that is further applied and validated for the lecture room located in one of the buildings at the Wroclaw University of Science and Technology (Poland). The outcome of this investigation is described in this paper.

2 Description of the building and lecture room

The measurements were conducted in a building situated in Wrocław city, Poland, located at the altitude 110–125 m above sea-level. The climate is mild climate, moderately warm with significant rainfall throughout the year. The average annual temperature is 8.4°C, and the average rainfall is 551 mm. The warmest month of the year is July with an average temperature of 17.7°C, while January has the lowest average temperature throughout the year and it amounts to -2.1°C.

The investigated lecture room is located in D-2 building (fig. 1) – one of the twin buildings that belong to the oldest part of main campus of Wroclaw University of Science and Technology in Wroclaw [14–16]. The layout of both these twin 5-floor buildings is quadrangular with internal courtyard. The buildings were designed according to the doctrine of socialist realism, and therefore are characterized by monumental, some squat proportions and monotony. However their architecture, composition and economy of measures used define them as high level construction works [16]. Both buildings are founded on two-storey rusticated base course, over which a regular rhythm of window openings is shaped. The building body is crowned with a strongly accented cornice and steep ceramic roof. Facade architecture is very modest concerning the details [15, 16]. The building D-2 was constructed in the 1955's [14–16].

The lecture room located on the highest storey and has a form of auditorium (fig. 2). The dimensions of the room plan are 21.2 x 16.9 m. The room height varies from 7.9 m to 5.5 m. A volume of the space is 2400 m^3. The room is dedicated for 300 students. The area per student is 1.19 m^2, what is lesser that national recommended minimum value 1.5 m^2 per person [4]. The room has 4 facing west windows with dimensions of 1.74 x 3.25 m. The windows are equipped in interior vertical blinds to protect the room against excessive sunlight. Additionally, the natural light is delivered into the lecture room via 20 skylights mounted in the flat roof (fig. 2). The lecture room is naturally ventilated and is served with a classic radiator-based water central heating system.

Fig. 1. View of inter-faculty laboratory-didactic building D-2 from front and from the internal courtyard side [15, 16].

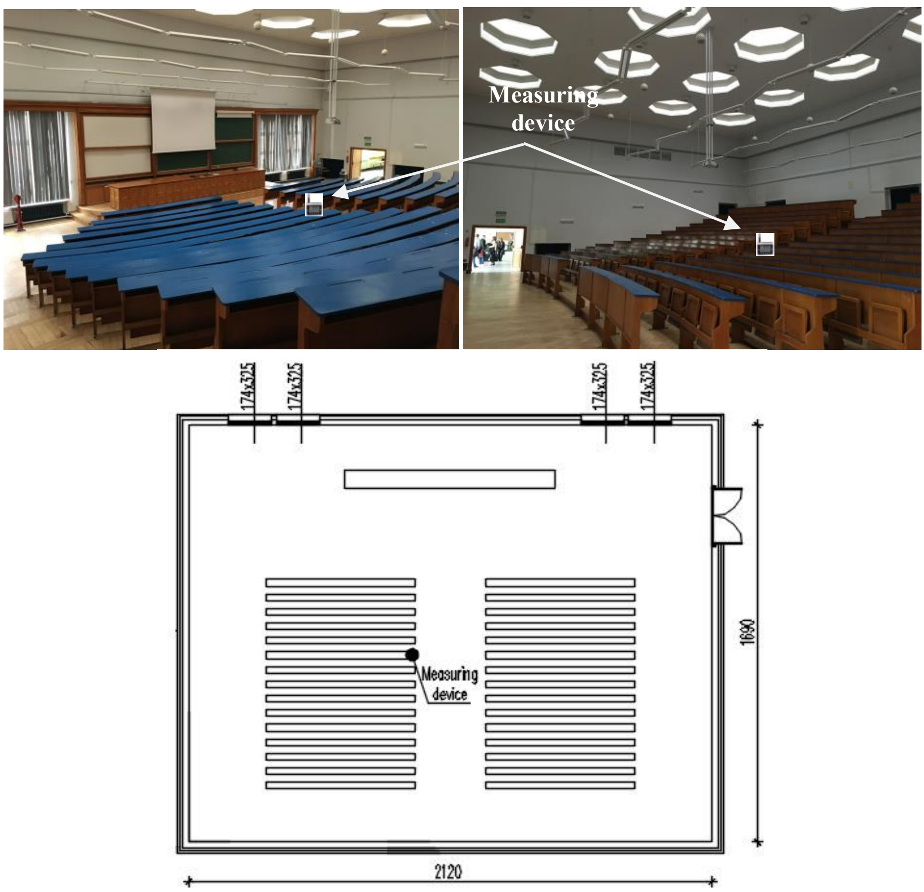

Fig. 2. Lecture room in building D-2.

3 Research methodology

The measurements of CO_2 concentration in the auditorium were conducted in 1-minute interval for 6 days in March and April 2016, during the classes for students. The length of each set of measurements lasts about 90 minutes that corresponds to the length of the lecture at the university. The equipment used for the experiment was Indoor Air Quality Data Logger Rotronic CL11. The accuracy of the data logger is ±0.3°C for the temperature range from 0°C to +50°C, <2.5% RH for the range from 10 to 90% and ±30 ppm ±5% of the measured carbon dioxide value. The measuring and recording device was placed, following [17, 18] at 1.2 m above the floor level, in the middle of the auditorium. Thus the data was collected from the central location of the room, with a special attention of being away from direct influence of room occupants. Additionally the indoor parameters and outdoor atmospheric pressure was measured by precise logger SensoData550. The accuracy of the device regarding the atmospheric pressure in the range of 500 to 1500 hPa is ± 3 hPa.

The measured data was applied to a model describing the carbon dioxide concentration presented by Krawczyk at all. in [4]. The CO_2 concentration is described by the following equation:

$$C_{CO2in}=[T_{in}/(P_{in}(1+ACH\cdot t)]\cdot\{C_{CO2in(t=0)}(P_{in(t=0)}/T_{in(t=0)})+$$
$$+[g\cdot N\cdot R/(\mu_{CO2}\cdot V)+C_{CO2out}\cdot P_{out}\cdot ACH/T_{out}]\cdot t\} \quad (1)$$

where:
- C_{CO2} is carbon dioxide concentration [ppm],
- $T_{in/out}$ is a temperature of indoor/outdoor air [K],
- $P_{in/out}$ is an air pressure of indoor/outdoor [Pa],
- ACH is the air change rate [1/h],
- t is a time measured from the beginning of the experiment [h],
- g is a CO_2 gain from a person [g/h·os],
- N is a number of people in the room [-],
- R is a gas ideal constant [J/mol·K],
- μ_{CO2} is a molar mass of carbon dioxide an air [g/mol],
- V is a volume of the space [m^3].

When the calculations were completed, the next step of the research was to compare the outcome with the measured data. This comparison allowed to validate the applicability of the model to the rooms type of auditorium.

4 Results of measurements and calculations of CO_2 concentration

As presented in the literature [19], in naturally ventilated buildings indoor air quality is in very close correlation with the quality of outdoor air and indoor contaminants. In the auditory room main pollution comes from occupants. For the investigated domain, the main parameters of outdoor air and the number of people occupied the room are presented in Table 1. The results of measurements and calculations of carbon dioxide concentration based on equation (1) are presented on Fig. 3. As mentioned before, the CO_2 level was calculated in 1-minute interval. Each time the former result was taken as the initial value for the next time range. The increment and variability of CO_2 concentration for all tested days are presented on Fig. 4. The percentage of occupation, the temperature of indoor air and the relative humidity at the initial stage, respectively *T0* and *RH0*, and after 90 minutes from the beginning of the experiment, respectively *T90* and *RH90,* are presented in Table 2. This table also presents the comparison between measured and calculated (following equation (1)) carbon dioxide concentration for the room. The variable of CO_2 concentration with the index *0* indicates the initial value (start point) of the measurements, while the variable with the index *90* indicates the final value – measured after 90 minutes from the beginning of the experiment.

As arises from presented in Fig. 3 variations of CO_2 concentration, and the literature mentioned before, in the lecture room the incensement of CO_2 level depends on the number of room occupants.

Table 1. Outdoor air parameters during measurements and number of people occupied a lecture room.

	17.03	**18.03**	**31.03**	**1.04**	**7.04**	**8.04**
Average outdoor air temperature [°C]	6	8	10	3	14	10
Average outdoor air atmospheric pressure [hPa]	1030	1016	1013	1016	1010	1012
Wind speed [km/h] and wind direction	7.4 W	31.5 WSW	9.3 WSW	7.4 NNW	13 SSW	6 ENE
Number of people in the room	77	42	113	59	55	44

The proposed by [4] model accurately reflects the increase in concentration of carbon dioxide in the auditory room. The most convergent values were obtained when the room has not been airing during the lecture, namely for three days: 17th, 18th and 31st of March.

The highest room air temperature increment within 90 minutes of lecture was measured on 31st of March and reached 1.56 K. That was also a day when the room was the most occupied. The high increment of indoor temperature of 1.34 K was recorded also on 7th of April when the external temperature was the highest from the investigated period and reached +14°C. For this day also the variations of CO_2 contaminations are the highest. This could be caused by the short-term airings of the room and quite strong wind pressure blowing from the South and South – West, and thus form the widow side of the auditorium. The noise caused by the impact of blinds on the windows and walls due to the strong wind caused the necessity of closing windows and allowed only a brief airing.

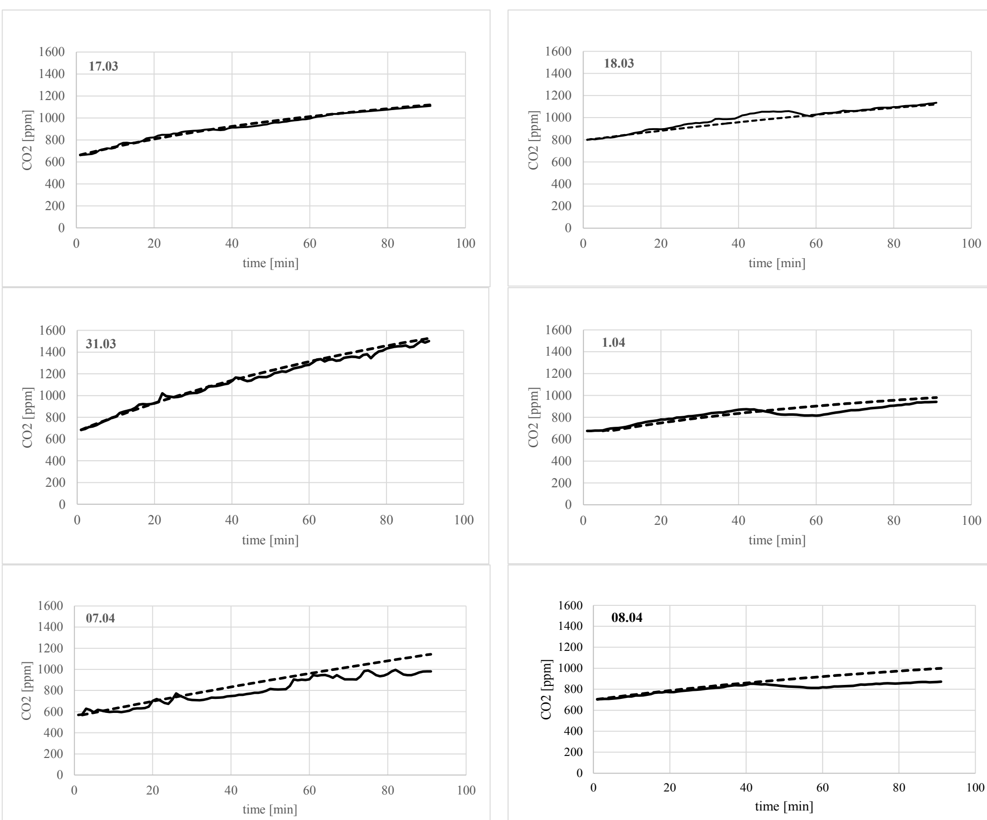

Fig. 3. Measured concentration of CO_2 (constant line) and estimated concentration of CO_2 (dashed line) in lecture room for the investigated 6 days.

The increase in the temperature of indoor air in the room is dependent on both – number of occupants due to heat gains form the human body and also on the intensity of solar radiation. The skylights are not equipped in any solar protection system, therefore during the days when the insolation is high, heat gains from the solar radiation increases the interior temperature.

During two days, namely 1st and 8th of April the low speed of the wind and its direction allowed the longer airing. The windows has been opened after 40 minutes from the beginning of the lecture. It was observed that during the first 15–17 minutes the CO_2 level was decreasing of about 49 and 34 ppm respectively, but after that time the contamination started to increase again.

The variability of the relative humidity also was observed. The highest levels of this parameter were measured on 31st of March, during the day with the highest occupancy. At this date also the CO_2 concentration and the level of indoor temperature was the highest. During the investigated period the initial concentration of CO_2 (*T0*) in the auditorium was measured at the range between 568 and 800 ppm. In days when the widows were closed, after 90 minutes the CO_2 concentration has increased from 335 to 817 ppm up to the maximum recorded value of 1502 ppm on 31st of March. This value is recognized by WHO as maximum permissible for indoors [4].

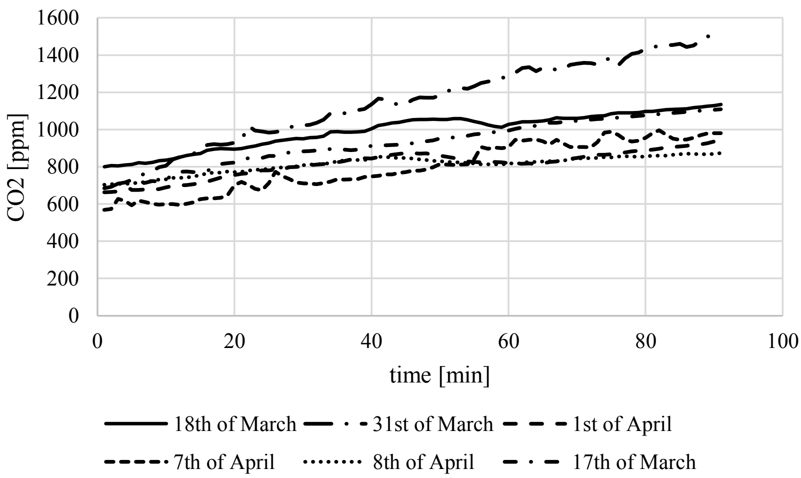

Fig. 4. Calculated concentration of CO_2 in lecture room for 6 investigated days.

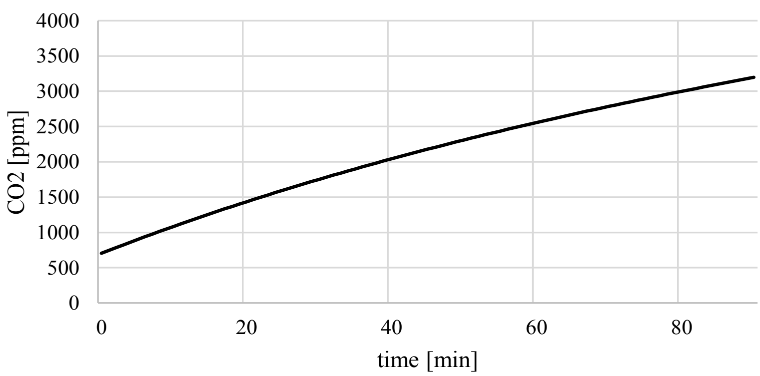

Fig. 5. Calculated concentration of CO_2 in lecture room for fully occupied room.

The presented in [4] and applied in this investigation the formula (1) allows (following the authors [4]) to calculate the CO_2 concentartion levels in lecture rooms with any number of occupants. Therefore the additional calculations for carbon dioxide contamination for fully occupied auditorium were undertaken. The results are presented on Fig. 5. As one can notice, after 90 minutes from the begining of the experiment, the CO_2 level increases about 2492 ppm and reaches 3196 ppm. The acceptable level for rooms is 1400 ppm (1000 ppm above the external contamination [4, 9, 11]), or defined by WHO is 1500 ppm. In this case the acceptable treshold was exceeded after 20–22 minutes from the beginning of the experiment.

The CO_2 level in the room is connected with the occupant's satisfaction of the indoor environment. Therefore the questionnaire survey has been conducted among room users. The outcome showed that in general students were satisfied with the indoor environment and did not suffer strong discomfort conditions like headaches, dizziness, eye, nose or throat irritation, dry or itching skin, difficulty in concentration. However some percentage of respondents experienced sleepiness and general fatigue that may have also different background than CO_2 level. The analysis of the questionnaire survey is not a subject of this article and will be raised and described in another publication.

Table 2. Temperature, relative humidity and concentration of CO_2 in the lecture room.

Date	**17.03**		**18.03**		**31.03**		**1.04**		**7.04**		**8.04**	
Percentage of occupation [%]	26%		14%		38%		20%		18%		15%	
T0 [°C]	20.94		21.56		22.22		21.83		21.83		22.33	
T90 [°C]	22		22.33		23.78		22.44		23.17		23.06	
Air temperature increment [K]	1.06		0.77		1.56		0.61		1.34		0.73	
RH0 [%]	30		29.9		37.3		35.5		38.8		34.9	
RH90 [%]	33.2		32.4		41.5		37.6		40.5		36.8	
Relative humidity increment [%]	3.2		2.5		4.2		2.1		1.7		1.9	
CO_2 0 [ppm]	663	663*	800	800*	685	685*	676	676*	568	568*	704	704*
CO_2 90 [ppm]	1110	1119*	1135	1119*	1502	1528*	941	989*	996	1149*	873	999*
CO_2 increment [ppm]	447	456	335	319	817	843	265	313	428	581	169	295

* the value calculated from the equation (1)

5 Conclusion

The paper presented the results of measurements and calculations of carbon dioxide level in an auditorium. The investigation was conducted during the 6 lecture days in one of the lecture rooms at Wroclaw University of Science and Technology, Poland. The measured data was used to validate the model derived for school rooms by [4]. It showed good agreement and thus proved its applicability also for auditorium room types.

The values of CO_2 concertation were also compared with permissible levels of CO_2 and some conclusions from the questionnaire survey, related to personal discomfort were mentioned. The assessment showed that during the lecture time, the concentration was mostly on proper level and no strong complains arisen from the room users. However the calculations based on the theoretical model indicated that under full occupation the indoor environment would fail to serve healthy conditions. Therefore is important to sensitize the lecturer and students that natural ventilated rooms need to be aired as often as possible, as the indoor conditions strongly influences the comfort and productivity of room users.

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