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Research paper

Indoor air quality in the primary school classroom in Poland – case study

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Abstract: Children spend on average 7–10 hours per weekday at school, that's why the indoor air quality in the classrooms plays a key role in the assessment of the effects of their personal exposure to the air quality. Many scientific articles indicate the substantial influence of carbon dioxide (CO_2) levels and overall air quality within educational environments on the well-being and cognitive performance of children. This article presents the case study of the classroom in the primary school in Cracow with very unfavourable indoor air quality caused by the usage pattern. In the classroom, there is a natural ventilation system, still the most common in the Polish existing buildings. The very high level of CO_2 exceeding the standard requirements connected with low ventilation efficiency effects in harmful indoor conditions. Based on the measurements conducted in the classroom during the lessons with the users in and taking into account formal requirements authors assessed the quality of indoor air. The main reason for those unfavourable conditions is an inefficient natural ventilation system. This paper is also supposed to answer the question of whether temporary opening windows can assure proper concentration of CO_2 in a standard classroom and, if not, what would be the optimal ventilation rate. In the next step, this optimal minimum required ventilation rate for the classroom was calculated. It could be used as a design assumption in the selection of a ventilation system.

Keywords: CO_2, indoor air quality, natural ventilation, school

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1. Introduction

Children spend almost 12% of their life inside classrooms, which is more than in any other building except their homes [1]. That is the reason why the ensuring of high indoor air quality (IAQ) in those particular buildings is so important. IAQ in schools is recognized as one of the most important factors affecting pupil' and students' health and learning outcomes. IAQ in classrooms is mainly assessed by CO_2 levels due to the large amount of users per square meter who exhale contaminated air. Too low oxygen concentration can cause a feeling of breathlessness and headaches, and consequently reduce concentration and the effectiveness of learning. There are many studies in the literature confirming this fact. The review of this research can be found in articles [2–7]. The authors proved that an increased concentration of carbon dioxide negatively affects the absorption of knowledge, therefore, when designing ventilation, special attention should be paid to controlling this concentration. Various groups of students and pupils were subjected to the researches. The results obtained in tests (mathematical, reading comprehension, etc.) with a controlled concentration of carbon dioxide in the range of 600–5000 ppm (depending on the test) were analyzed. All researchers agree that at concentrations above 2000–3000 ppm, the results obtained by students are significantly worse comparing with the results obtained at concentrations below 1000 ppm [2, 6]. The authors [6], on the basis of their own literature review and research, specified the effects of a specific concentration of carbon dioxide:

- 1000 ppm – maximum hygienic,
- 5000 ppm – feeling of fatigue, discomfort,
- 15,000 ppm – breathing disorders,
- 30,000 ppm – dizziness, headaches,
- 50,000 ppm – difficulty breathing, visual disturbances,
- 100,000 ppm – unconsciousness.

Taking into account the research on the correlation of scientific results with the concentration of carbon dioxide and knowing the effects of increased CO_2 concentration, it should be stated that this parameter is very important in educational buildings.

There are many factors affecting the indoor air quality (IAQ) [8], environmental, building related and occupant-related ones. Environmental factors such as climatic conditions and season; building-related factors such as airtightness, schools' location, classrooms and windows' design, type of ventilation, ventilation rate, internal temperature, draughts from windows and room volume. Occupant-related factors such as CO_2 exhalation rate, occupants' behavior, maintenance and operation of systems, operating schedule, number of occupants, activity levels, amount of time spent in the room, occupants' age and individual's thermal comfort.

Healthy IAQ is vital for the health of children as they are more sensitive towards indoor air pollutants. Hence, the effect of occupant-related factors on IAQ is remarkable in the context of primary school buildings, especially considering potential unpredictability of occupant-related factors [8].

Rumor has it that airing by opening windows from time to time (during breaks) is sufficient to ventilate a typically used class served by the natural ventilation system. However, windows cannot be opened when pupils are inside due to draft which causes discomfort and may cause some health problems.

This paper is supposed to answer the question whether temporary opening windows can assure proper concentration of CO_2 in a standard classroom and, if not, what will be the optimal ventilation rate to obtain low CO_2 concentration.

2. Materials and methods

2.1. Internal air quality in schools

Air quality in school buildings is a very significant problem all over the world. The measurements of IAQ parameters such as temperature, humidity, pollutions and CO_2 concentrations are the subjects of analysis of large number of researchers. Godwin [9] described results of IAQ measurements in 64 elementary and middle school classrooms in Michigan (USA). In each classroom, bioaerosols, VOCs, CO_2, relative humidity, and temperature were monitored. Ventilation rates were derived from CO_2 and occupancy data. Ventilation efficiency was poor in many of the tested classrooms, CO_2 concentrations often exceeded 1000 ppm and sometimes 3000 ppm. Grimsrud [1] described results of monitoring of air quality parameters in 85 classrooms and other spaces located in eight schools in Minnesota, US. Carbon dioxide concentrations showed substandard ventilation in rooms in five of the eight schools.

Paraskevi [10] analysed the IAQ in in nine naturally ventilated primary Greek schools in Athens, during spring. The ventilation rates and pollutant levels were analysed and calculated during the teaching and non-teaching periods. The average carbon dioxide (CO_2) concentrations per school varied between 893 and 2082 ppm, while the majority of the cases were slightly above the recommended limit values. CO_2 concentrations were positively correlated to the number of students and negatively correlated to the ventilation rates.

Turanjanin [11] analysed the indoor air quality in five naturally ventilated Serbian schools during the heating season. CO_2 concentrations were measured outdoor and in three classrooms for five working days, ventilation rates were calculated using gas tracing decay method. The results showed the insufficient ventilation and the mean value of carbon dioxide concentration was mostly above 1000 ppm.

Chang [12] conducted similar measurements in five Hong Kong schools where the CO_2 level for most of the time was above 1000 ppm and the maximum level reached 5900 ppm when the classroom was occupied by pupils.

Myhrvold [2] presented the results of the Norwegian project called Indoor Environment in Schools. The aim of the project was to investigate the indoor environment in regard to the pupils' health, social environment and level of performance. Project included field measurements of 8 different schools (35 classrooms) with natural ventilation systems and 800 pupils. The CO_2 concentration at those schools at daytime ranged between 601 and 3827 ppm. The health symptoms such as headache, dizziness, tiredness, difficulties in concentration, unpleasant odour, throat irritation were analysed using questionnaires and analysing the results of computer tests analysing pupils' reaction time. The results showed strong correlation between pupils' health, pupils' performance and CO_2 concentration.

Simoni [3] described the influence of IAQ on respiratory health of schoolchildren living in Norway, Sweden, Denmark, France and Italy. Researchers proved that many disorders such as wheezing, dry cough at night and rhinitis were more prevalent in children from poorly ventilated classrooms. Schoolchildren exposed to CO_2 levels higher than 1,000 ppm showed a significantly higher risk for dry cough and rhinitis. In the analysed schools for 66% of time children were exposed to CO_2 >1,000 ppm. Authors emphasizes the poor IAQ in European classrooms; it is related to respiratory disturbances and affects nasal patency.

Gennaro [4] focused on the analysis of IAQ in schools as children have greater susceptibility to some environmental pollutants than adults, because they breathe higher volumes of air relative to their body weights, and their tissues and organs are actively growing.

Occupant window opening behaviour has a significant impact on both classroom indoor air quality and building energy use. Duton [13, 14] described results of measurements and simulations of indoor air quality conducted in two classrooms in UK including impact of window openings. The simulations were conducted in EnergyPlus program. Author tried to answer the question how to improve the prediction of building performance through improved understanding of occupant behaviour and the factors that influence behaviour. The simulation model was validated by the measurements conducted by authors. The opening of windows improves significantly the air quality, lowers the CO_2 level however due to the external low temperatures or noise outside the building cannot be assumed as the suitable solution of problems.

IAQ is affected by environmental factors temperature, humidity, air contaminants but also but human behaviour, adaptive approach to the thermal comfort and air quality Zhang [15].

Sowa [16] compared real state of environment in classrooms in Poland with accepted requirements and standards based on indoor environment measurements in 28 classrooms in Warsaw. The Polish regulations on indoor air quality drops behind similar regulations in developed countries but what is more important, generally, they are not observed. The increase of ventilation rate would have the key role. Unfortunately this action requires using of mechanical ventilation systems controlling the air change.

Sowa [17–19] described the results of simulations of indoor air quality in the school located in Zgierz after redevelopment of ventilation system from natural one to the mechanical ventilation with high-efficiency heat recovery. After the modernization the ventilation rate increased 10 times in comparison (from 3 m^3/(h pupil) to 30 m^3/(h pupil)).

2.2. Ventilation of internal space

Typical gravitational ventilation system supplies fresh and removes contaminated and humid air directly to and from the internal environment. Too low rate of air exchange can negatively affect the inside air quality and people's health while too high ventilation rate results in excess energy losses. Ventilation, that is intentional air exchange, should be considered in conjunction with infiltration, which is a natural effect of air transfer due to pressure difference between external and internal environment. In case of gravitational ventilation, where usually exhaust ducts only are organized, fresh air supply is provided by the uncontrolled infiltration rate through the cracks and leaks in building external envelope Griffithsa [20]. Airtightness of external building shell is a key factor of ventilation intensity and finally internal air quality

Griffithsa [20] described the influence of trickle ventilators on the ventilation rate on the example of classrooms. They can increase the air flow in the room and reduce the concentration of CO_2 and contaminants but usually do not reduce the concentrations to the acceptable levels.

Lis [21] was trying to answer the question if it is theoretically possible to supply enough air to meet the ventilation requirements with natural ventilation? What is the airtightness of the windows at which it would be possible? The analysis proved that without installing additional vents in the rooms, or better yet, installing mechanical ventilation with heat recovery, meeting the minimum ventilation air flow requirements is not possible.

Mijakowski, Narowski [22] compared the energy performance and indoor climate in typical school classroom with two different ventilation strategies: mechanical balanced ventilation with heat recovery and natural/hybrid ventilation. The primary energy consumption (heating energy and electricity used for ventilation) in rooms with similar ventilation rate and thermal comfort were analyzed. It was showed that providing thermal comfort is not problematic, but energy performance and indoor air quality can vary a lot between different ventilation strategies. In described cases the classroom equipped with mechanical ventilation with heat recovery, for heating and ventilation, consumed about 40% of primary energy less than the one with natural/hybrid solution. Authors proved that in a moderate climate (Europe, Poland) it is possible to meet requirements of indoor climate and keep energy consumption on reasonably level in classrooms with mechanical ventilation with heat recovery as well as in classrooms with natural/hybrid ventilation.

Mijakowski [23] compared the passive stack ventilation performance and indoor conditions before and after installation of humidity-sensitive air inlets in a kindergarten building. The analysis of indoor conditions and ventilation performance showed that although humidity-sensitive air inlets improved performance of ventilation, the effect was not sufficient to meet current Polish and European standards and recommendations.

Measurements of the increase in CO_2 concentration during the use of a building or room allow to determine the quality of indoor air. This approach has been proposed by Persily [25], Bulinska [24], Zhang [26]. The authors confirm that in rooms with natural ventilation, the level of CO_2 very quickly exceeds the legal limits, because the ventilation exchange is usually too low.

2.3. Standard requirements

Polish governmental recommendations do not specify acceptable concentrations of carbon dioxide in rooms intended for permanent residence, only the permissible concentrations in the working environment are defined as follows [27]:

1. Permissible exposure limit (NDS) – the weighted mean value of concentration, the impact on an employee of 8 hours per day and the average weekly working time during his/her working activity should not result in negative changes in his/her health and health of his/her future generations;
2. Short term permissible exposure limit (NDSCh) – mean value of concentration which should not cause negative changes in the worker's health if it is present in the work environment for not more than 15 minutes and not more than 2 times during the work shift, with the a time interval not shorter than 1 hour.

3. Maximum exposure limit (NDSP) – value of concentration which due to health or life threat of the worker, cannot be exceeded in the work environment at any time.

According to this regulation NDS of carbon dioxide is 5000 ppm (9000 mg/m^3), and NDSCh cannot exceed 15 000 ppm (27 000 mg/m^3).

The permissible levels of carbon dioxide are defined in the European standards and commonly used US requirements ANSI/ASHRAE [28] and ASTM [29]. According to those requirements the upper level of carbon dioxide concentration in spaces for permanent residence of people should not exceed 1000 ppm. To keep this requirement ca. 27 m^3/h of fresh air per person should be supplied per hour [28].

According to the PN-B-03430 standard [30], which has been commonly used for years in designing the size of the ventilation flux, in public utility buildings intended for permanent and temporary stay of people, the required external air volume flow should be at least 20 m^3/h per person. However, in the case of rooms in kindergartens and nurseries where children stay, the standard allows for a reduction of the air volume flow to 15 m^3/h for each child. It should be noted that these rooms are also occupied by adults caring for children, for whom the stream should be calculated as 20 m^3/h per person.

An overview of the requirements applied in other countries can also be found in the study by Ludwiczak [5]. Detailed guidelines adapted to the age of users of educational buildings are included, among others, in the American ASHRAE 61.1 [28] guidelines. There, a detailed information on the required outside air flow can be found. The designed stream is the sum of the stream per one person staying in the room and associated with human activity and the stream associated with building materials and room equipment, calculated depending on its area. The guidelines for educational rooms are presented below:

- nursery rooms (for children up to 4 years old) – 18 m^3/h per person,
- classes (for children aged 5–8) – 18 m^3/h per person,
- classes (for children from 9 years of age) – 18 m^3/h per person,
- lecture rooms – 13.4 m^3/h per person,

Permissible levels of carbon dioxide in non-residential spaces are regulated by the standard EN 16798-1 [31]. It introduces four acceptable levels of carbon dioxide concentration depending on the selected level of indoor air quality. The Table 1 shows the permissible values of the carbon dioxide concentration according to the air quality category.

Table 1. Permissible values for carbon dioxide concentration to the air quality category, acc. to standard EN 16798-1 [31]

Category of air quality in the room	**Increment of CO_2 concentration above CO_2 level in external air, [ppm]**
High quality of air	350
Medium quality of air	500
Moderate quality of air	800
Low quality of air	1200

In every enclosed space where a human resides, the concentration of carbon dioxide increases because of depletion of the oxygen due to process of breathing. The carbon dioxide concentration in exhaled air is about 40 000 ppm [29]. However, the exact amount of CO_2 produced by human body may differ depending on its weight and level of metabolic activity [28, 29].

The European standard EN-16798-1 [31] assumes that the indicative CO_2 emission is equal to 20 l/h per person. This value will be taken as a standard in further calculations.

2.4. Tested classroom

The analysed classroom is located on the ground floor of the two-storey primary school building located on Mackiewicza Street in Cracow about two kilometres from the old city centre Fig. 1, Fig. 2. Room can be used by maximum of 31 people (30 pupils plus teacher). The room has only one external wall with three large (2.55 m width and 1.8 m height) windows at west elevation of building. In the room there is natural ventilation system with four ventilation ducts 10 cm by 10 cm located 3.0 m above floor level.

Total floor area of the classroom is equal to 51.92 m^2 and its internal volume is 166.14 m^3.

Fig. 1. East elevation of analysed school building

Fig. 2. Internal view of classroom

All the measurements were conducted using set of remote sensors iBros allowing the continuous measurements and registration of CO_2 concentration, temperature and relative humidity (Fig. 3). Recordings were taken every 30 seconds. CO_2 measurement precision was ±50 ppm, temperature ±0.4°C, relative humidity ±5%.

Fig. 3. iBros remote sensors set measuring CO_2

The simultaneous measurements of CO_2, temperature and humidity have been conducted using nine detectors. The detectors were located in different places of the tested space, which allows for the evaluation of spatial distribution of CO_2, temperature and fluctuations of the momentary concentration within the internal space. Description of sensors' locations was presented in Table 2. Before performing the test all the sensors were calibrated in accordance with the manufacturer's instruction.

Table 2. Description of the sensors' locations

Sensor number	**Sensor location**
#1	Located on the window sill or outside on the window sill
#2	Located on the window sill or outside on the window sill
#3	Attached to the entrance door frame, 2.0 m above floor.
#4	Located on the desk next to the wall, opposite the windows.
#5	Located on the desk next to the wall, opposite the windows.
#6	Located on the wardrobe, 1.8 m above floor, next to the ventilation ducts
#7	Located on the wardrobe, 1.8 m above floor,
#8	Located on the internal window sill
#9	Located on the projector 20 cm below the soffit

Measurements of internal air quality were carried out for 3 days 04.01.2019, 11.01.2019 and 01.02.2019 in the morning hours during the classes.

The detailed analysis were based on one representative day (04.01.2019) to emphasize the observed phenomena. The trends in the CO_2 and temperature distributions in all days were similar. The outdoor CO_2 concentration on the chosen day averaged 557 ppm.

Figure 4 presents variability of air temperature in the classroom on 4th of January. There are significant differences between values due to the location of sensors. Sensors #2 and #8 are located on the window sills inside the class. The temperature at both are the lowest due to the leaks of cold air from outside. During the second break at 10:40 sensor #2 was moved on the external sill. The significant drop can be noticed and the readings after that shows external temperature conditions. The drops on all sensors can be observed during breaks when the windows were opened. The highest values are recorded on the sensor located next to the ceiling on the projector. The temperature there is the highest due to the convection of warm air.

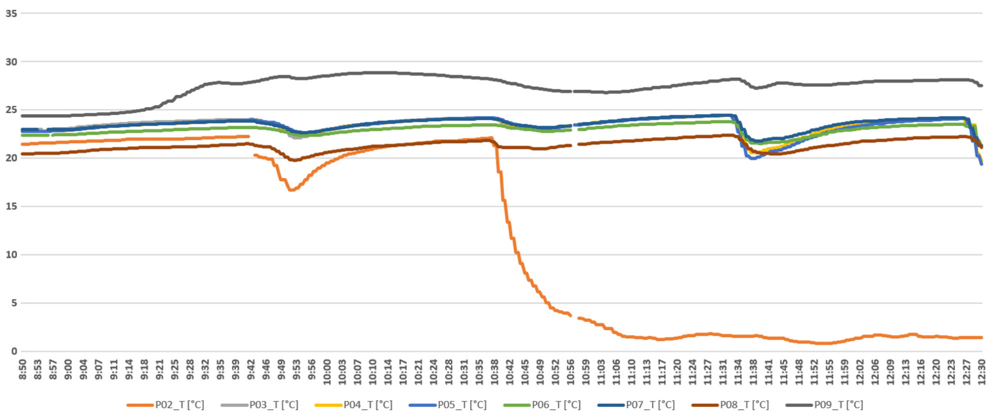

Fig. 4. Temperature distribution at all sensors on 4^{th} of January

Figure 5 shows the trend for rising and fall of CO_2 levels during school occupancy in the classroom on 4th of January. Number of users – 21 pupils plus two adults. Figures 4 and 5 present the shorter time range, two lessons with the break between lessons when the windows were opened. Fig. 6 based on data taken on 11th of January, Fig. 7 average data from 6 sensors taken on 1st of February.

The lessons starts at 8:55, children get into the classroom around 8:40–08:50. Each lesson is 45 minutes long. The first lesson ends at 9:40 and children leave for a short 10 minutes break (9:40–9:50 a.m.). According to Fig. 3, mean CO_2 concentration goes up to 2500 ppm until the first break and reduces to 1250 ppm during the first break (50% reduction) due to the opened windows. The reduction of 1250 ppm during 10 minutes break gives 125 ppm/min among studied classroom. Breaks are not long enough to decrease CO_2 levels below 1000 ppm. After the first break, children remain in the classroom until next 10 minutes break (9:50–10:35). The upper value of CO_2 concentration at the second lesson is even higher 3000 ppm as the initial value was higher. The same trend repeats during next two lessons. This trend for rising and fall of CO_2 levels in studied schools is described in many other studies [8, 16].

Figures 4, 5 show that breaks between the lessons can lower the level of CO_2 concentration however they are not long enough to exchange the air inside the classroom or to at least lower the level to less than 1000 ppm.

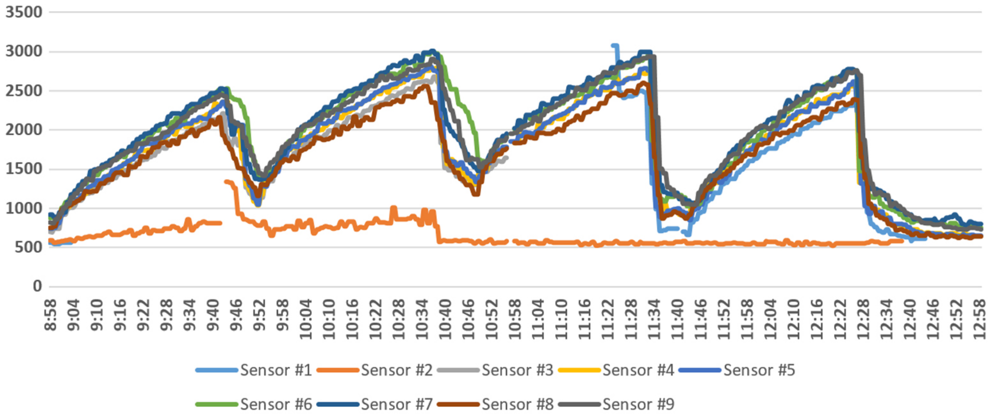

Fig. 5. CO_2 concentration in the classroom on 04^{th} January 2021

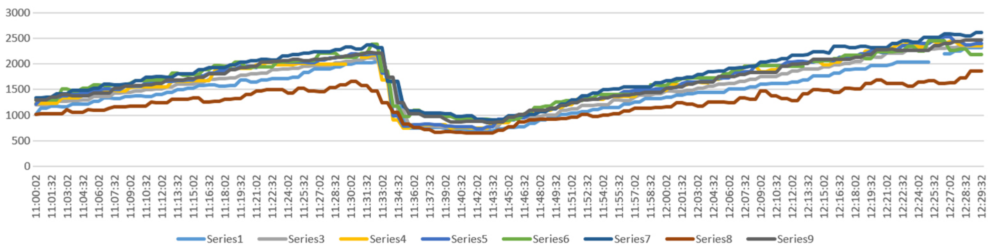

Fig. 6. CO_2 concentration in the classroom on 11^{th} of January 2021 between 11:00 am and 12:30 am; two 45 minutes lessons with the break at 11:30–11:45 – windows opened

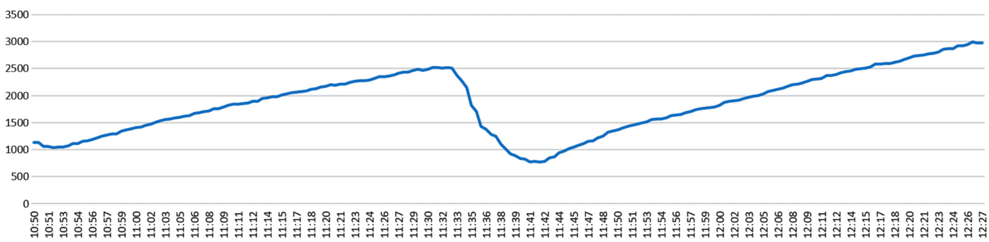

Fig. 7. CO_2 average concentration from 6 sensors – 1^{st} of February 2021

The windows are closed during teaching period due to low exterior temperatures or outdoor noise. This is typical usage scheme in the classrooms in Poland but also in different countries and was described in [8, 16].

The levels of CO_2 at different sensors differ and the values are affected by the location of sensors and usage pattern of the classroom. In general, the higher momentary concentration values are observed at the sensors located closer to the users' heads, i.e. CO_2 emission sources.

Sensor #8 was located on the internal window sill, next to the window. Due to its uptightness the values are the lowest. The highest values can be observed of the sensor located below the soffit (sensor #9) and at the one located on the back of the classroom, on the wardrobe next to the ventilation ducts (sensor #6 and #7) (Fig. 5). Regarding sensor #9, below the soffit it can be explained by the convection of warm air which moves the CO_2 particles to the top of room. Also the temperatures during the analyzed period on this specific sensor are much higher (Fig. 4).

The higher values of CO_2 next to the ventilation duct (sensors #6 and #7) indicate the direction of air flow in the classroom, the CO_2 particles move to the exhaust ventilation duct.

Based on the collected data the quality of internal air was classified. The external concentration of CO_2 during entire measurement time was assumed at the level of 400 ppm. The levels of internal concentration of carbon dioxide in the analyzed period of time were described in Table 3. Percentage share of concentration levels was based on the averaged values from seven sensors. The comfort value of 1000 ppm [29] concentration is exceeded for **98%** of occupation time. Per the classification of standard [30] that was presented in Table 1, the indoor air quality in the classroom for **73.5%** of analyzed time can be qualified as low (the worst defined in this standard category), which is very unsatisfactory result. Graphic interpretation of table is shown in (Fig. 8).

Table 3. Total concentration of CO_2 in the classroom on 4th of January between 9:00 and 12:30

	<1000 ppm	**>1000 ppm**	**>1600 ppm**	**>2000ppm**
Percentage of readings	1.9%	24.6%	22.5%	51.0%

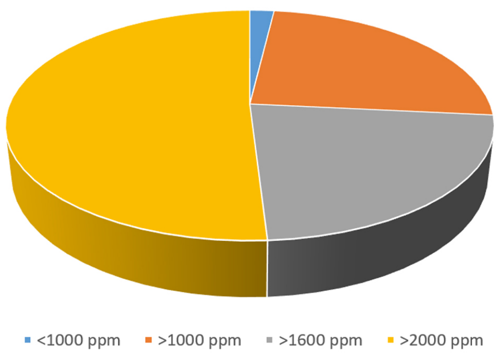

Fig. 8. Percentage of readings with different levels of concentration

The high concentration of CO_2 found in the above tests results from the insufficient ventilation efficiency. In the next steps, attempts were made to determine the intensity of ventilation in the classroom.

2.5. Improvement of ventilation in the tested classroom

One of the ways to improve the dilution process of CO_2 is to use the mechanical ventilation system. There are several types of the systems but to solve the entire problem the first step should be to determine the required airflow. The outside air flow [m^3/s] should be determined using the equation:

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v} \tag{2.1}$$

where: G_h – flow of contaminating gas [mg/s], ε_v – ventilation efficiency, $C_{h,i}$– allowable concentration of the pollutants in the air [mg/m^3], $C_{h,o}$ – concentration of the pollutants in the supply air [mg/m^3].

The flow of contaminating gas was derived from the measurements and estimated as: 179.4 mg/s.

The flow seems to be large but first – it has been calculated from the average values measured in-situ, second they take into consideration the entire classroom filled with 25 kids and two adults (teacher and researcher).Ventilation efficiency depends mostly on the airflow pattern created by supply and exhaust air terminal devices as well as temperature difference between room air and supply air. For the sack of the simplicity the efficiency is set to 1.

Keeping allowable concentration at 1000 ppm (1830 mg/m^3) and outside 400 ppm (723 mg/m^3), the maximum airflow calculated from the above Equation (2.1) is: 584 m^3/h. Assuming optimal placement of supply and exhaust air terminal the required airflow to dilute CO_2 to the level of 1000 ppm the system will create the change rate at the value of 3.5 1/h.

Now it is the time to discuss the possible solutions of mechanical ventilation. One can choose from exhaust-only, supply-only, balanced and balanced with the heat recovery together with CO_2 level control system. The choice will determine the investment and operational cost of the system.

3. Conclusions

Analysis of indoor air quality in schools is very important as children spend on average 7-10 per weekday at school. The example described in this article shows very unfavorable conditions in the analyzed classroom. Due to the large number of users in the classroom the level of metabolically generated CO_2 increases rapidly. The low efficiency of natural ventilation system leads to the exceedance of standards and reaches the levels which could be harmful for users.

The opening of windows during the breaks between the lessons can lower the level of CO_2 concentration however they are not long enough to exchange the air inside the classroom or to at least lower the level to less than 1000 ppm. During the lessons windows must be closed due to low exterior temperatures or outdoor noise. This is typical usage scheme in the classrooms in Poland.

In such conditions the usage of mechanical ventilation would be necessary. Based on the data from measurements authors calculated the min air change rate at the level of 3.5 changes per hour. This result could be reached using different mechanical ventilation systems, such as exhaust-only, supply-only, balanced or balanced with the heat recovery together with CO_2 level control system. The choice will determine the investment and operational cost of the system. The deeper analyses of possible solutions will be the subject of the next analyses and simulations planned by the authors.

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Jakość powietrza wewnętrznego w sali lekcyjnej szkoły podstawowej w Polsce – studium przypadku

Słowa kluczowe: CO_2, jakość powietrza, szkoła, wentylacja naturalna

Streszczenie:

Dzieci spędzają w szkole średnio 7–10 godzin dziennie, dlatego jakość powietrza w klasach odgrywa kluczową rolę w ocenie ewentualnych skutków ich narażenia na złą jakość powietrza. Wiele artykułów naukowych wskazuje na istotny wpływ poziomu dwutlenku węgla i ogólnej jakości powietrza w środowiskach edukacyjnych na samopoczucie i zdolności poznawcze dzieci. W artykule przedstawiono studium przypadku, analizę sali lekcyjnej szkoły podstawowej w Krakowie, w której panowała bardzo niekorzystna jakość powietrza wewnętrznego spowodowana sposobem użytkowania. W klasie zastosowano system wentylacji naturalnej, wciąż najczęściej spotykany w istniejących polskich budynkach.

Na podstawie pomiarów przeprowadzonych w sali lekcyjnej podczas zajęć z użytkownikami oraz biorąc pod uwagę wymogi formalne, autorzy ocenili jakość powietrza w pomieszczeniu. Główną przyczyną tych niesprzyjających warunków jest nieefektywny system wentylacji naturalnej. Artykuł ma także odpowiedzieć na pytanie, czy tymczasowe otwieranie okien może zapewnić odpowiednie stężenie CO_2 w typowej sali, a jeśli nie, jaki byłby optymalny strumień wentylacji dla zapewnienia wymaganiej przepisami jakości powietrza. Obliczony strumień może zostać wykorzystany jako założenie projektowe przy doborze systemu wentylacyjnego.

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