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THE CHANGES OF CARBON DIOXIDE CONCENTRATION IN A CINEMA AUDITORIUM

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Abstract: Carbon dioxide is the fourth component in terms of the concentration in the air. The high concentration of CO_2 influences people in the negative way. Heat gains, air humidity and the concentrations of the airborne pollutants are taken into consideration during ventilation system designing process. In the indoor pollution balances the amount of the air, which is needed to remove the excess of the carbon dioxide is much lower than one in the case of the excess of the heat. The measurements of CO_2 concentration, humidity and temperature in the cinema projection room are presented in the work. The results are analyzed in relation to the acceptable indoor air quality, because the cinema auditorium is assumed to be an average indoor space.

Key words: ventilation, CO_2 concentration.

1. Introduction

Carbon dioxide (CO_2) is a colourless, odourless gas. When inhaled with concentrations much higher than the usual atmospheric levels, it can produce a sour taste in the mouth. It is non-flammable compound and does not support combustion of most substances except metals such as magnesium. The CO_2 density is 1.5 times greater than that of air, therefore it accumulates just above the ground in closed spaces where processes connected with high emission of this compound are carried out. It is a compound of high stability that stays 50 to 200 years and resolves in temperature over 1 000ºC.

Carbon dioxide exists naturally in the atmosphere and it is produced by every living organism during respiration as a by-product of metabolism, cf. Targowski (2005). Carbon dioxide is generated also as a by-product of the combustion of fossil fuels or the burning of vegetable matter that is strongly related to power industry and mechanical vehicle traffic.

Atmospheric concentration of carbon dioxide constantly increases approximately by 1.5 ppm per year and has now reached the level of 385 ppm by volume. Due to the fact that it is one of the major greenhouse effect causing factors, it is continuously monitored and, concerning industry, is the subject to numerous restrictions.

As far as human health is concerned carbon dioxide is not considered to be harmful neither it is poisonous until its concentration stays close to the atmospheric one. Polish law does not regulate CO_2 amount that should be kept in the indoor air except chosen industry branches, where the highest CO_2 concentrations is limited by the ministry of labour and social policy order (2002). This concentration may reach the level where it states a threat to human life i.e. temporary concentration of 15 000 ppm (27 000 mg/m^3 – the highest acceptable temporary concentration) and constant 5 000 ppm (9 000 mg/m^3 – the highest acceptable constant concentration). The restrictions apply to mines, sugar factories, distilleries, wineries, granaries, breweries and sink basins.

In the year 1856 Max von Pettekofer, German physiologist, suggested to set the upper limited value of CO_2 concentration at the level of 1 000 ppm by volume in the indoor air in rooms meant for people. Such amount was considered to be the highest acceptable for people concentration in air. As Targowski (2005) noticed, according to the atmospheric carbon dioxide concentration in the middle of XIX century, Pettenkofer considered admissible triple increase of CO_2 content in the indoor air in relation to the fresh one.

The only sources of carbon dioxide in the rooms, where no industrial processes are carried out, are people. As it was mentioned before, CO_2 is a by-product of metabolism and it released during respiration. Therefore, the amount of CO_2 exhaled is strongly related to the amount of oxygen absorbed. Furthermore, the quantity of carbon dioxide exhaled, is strongly related to the amount

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of oxygen absorbed. What is more, the quantity of carbon dioxide exhaled, just as the heat emission, depends on type of activity performed by a person. The amounts of heat emission in relation to the kind of action are presented in tab. 1. The CO_2 emission in dependence of the physical activity is shown in tab. 2.

The carbon dioxide concentration in exhaled air is normally 4% to 5% by volume (40 000 - 50 000 ppm), whilst oxygen share decreases to approximately 16%, after Targowski et al. (2005).

Standards assessing how to design ventilation installations refer to air volume required per person. Sowa (2004) mentioned that these standards were defined on the basis of research work carried out by Yaglou in the thirties of the last century. According to Polish standard PN-83/B-03430, ventilation rate for indoor spaces meant for people should be: 20 m^3/h per person in a room, 30 m^3/h per person in a room where smoking is allowed, 15 m^3/h per child in a kindergarten or nursery. Since Yaglou times many things has changed, such as construction and insulation materials and technologies, but above all, the atmospheric CO_2 concentration and outdoor and indoor air quality requirements. The last-mentioned facts may explain why people staying in ventilated rooms experience a discomfort like irritation of eyes, nose and throat, drowsiness, headache and mental concentration problems.

Reaction to CO_2 excess is an individual matter for every organism and its influence on human increases as the amount of oxygen in air decreases.

During respiration in air where CO_2 content is higher than 5%, carbon dioxide partial pressure in blood increase what leads to hypercapnia with symptoms: flushed skin, full pulse, extrasystoles, muscle twitches, hand flaps, reduced neural activity, and possibly a raised blood pressure. Further increase of CO_2 concentration results in progress in symptomatology to disorientation, panic, hyperventilation, convulsions, unconsciousness, and eventually death. Effects, that CO_2 has on human organism are presented in tab. 3.

Tab. 1. Total heat emitted by human depending on type of performed activity according to Recknagel et. al (1994).

Type of activity	Metabolic heat production	
	W/m²	met
Lying still	46	0.8
Sitting still (relax)	58	1
Standing still (relax)	70	1.2
Sitting, light work (bureau, house, school, laboratory)	70	1.2
Standing, light work (drawing, shopping, light industry)	81 - 93	1.4 – 1.6
Moderate physical activity (housekeeping, machine operating)	116	2
Hard physical work	165	2.8

Tab. 2. Amount of CO_2 exhaled by an adult person (children 70-80%) according to Recknagel et. al (1994).

Type of activity	CO_2 exhaled
Lying still (relax)	10 – 12 l/h
Sitting (relax)	12 – 15 l/h
Light bureau work	19 – 24 l/h
Moderately hard work (gymnastic)	33 – 43 l/h
Dancing, tennis	55 – 70 l/h

Tab. 3. Carbon dioxide influence effects on human organism, cf. Targowski (2005).

CO_2 concentration in air	Influence effect on human
350 – 450 ppm	Fresh atmospheric air, ideal conditions
Under 600 ppm	Acceptable air quality in bureau and living indoor spaces
Under1000 ppm, 0.10%	Minimum hygienic requirement in Pettenkofer scale
10 000 ppm 1.00%	Slight respiration rate increase
15 000 ppm 1.50%	Maximum dosage tolerated for workers in specific working conditions, under medical control (breweries, submarines, spacecrafts)
2%	Deepened breath, respiration rate increase of 50%, prolonged exposure leads to headaches and intoxication sensation
3%	Respiration dysfunction, double increase of respiration rate, effect similar to light drug influence i.e. reduced hearing, headache, blood pressure and pulse increase
4% - 5%	Noticeable breath deepening, four-times respiration rate increase, after approximately 30 minutes exposure breathing difficulties may occur
5% - 10%	Carbon dioxide becomes to have an acrid, soda water-like smell, it is hard to breathe, headache, dimmed sight, tinnitus, consciousness loss after a few minutes
Over 10% to100%	Immediate, sudden consciousness loss, prolonged exposure leads to death by suffocation

2. Ventilation Rate Calculation

Calculations for ventilation rate in a cinema auditorium are made according to algorithm presented in Malicki's handbook (1980).

Heat gains from people are calculated as:

$$Q_L = \eta \cdot \varphi \cdot n \cdot q_1 \text{ [W]} \quad (1)$$

where: n - number of people in the room, q_1 - heat emission per person in W, q_1 = 74 [kcal/h] ≈ 86 [W], φ - factor of simultaneous gathering in the room, $\varphi = 1$ for cinemas and theatres, η - reducing factor with regard to age and sex of people in the room, $\eta = 0.6 \div 0.8$ – when there is no data.

The required air stream:

$$V_Q = \frac{Q_L}{c_p \rho (t_w - t_n)} \text{ [m}^3\text{/s]} \quad (2)$$

where: c_p - air specific heat capacity, c_p = 1 in kJ/kgK, , ρ - air density, ρ = 1.2 in kg/m^3, t_w - removed air temperature, $t_w = t_p \Rightarrow$ 22.5ºC, t_n - incoming air temperature, $t_n = t_p - \Delta t \Rightarrow 22.5 - 5 = 17.5$ºC; $\Delta t \rightarrow 4 \div 7$ in K $\Rightarrow 4 \div 6$ in m - high room with moderate heat gains Δt = 5 K.

Humidity gain:

$$W_L = \eta \cdot \varphi \cdot n \cdot w \text{ [kg/s]} \quad (3)$$

where: w - amount of water vapour transpired per person performing physical activity in the temperature, w = 40 [g/h] ≈ 1.1 ·10^{-5} [kg/s]

The required air stream:

$$V_w = \frac{W_L}{\rho (x_w - x_n)} \text{ [m}^3\text{/s]} \quad (4)$$

where: x_w - humidity content in removed air, x_w = 6 [g/kg] = 0.006 [kg/kg]; x_n - humidity content in incoming air, x_n = 5.2 [g/kg] = 0.0052 [kg/kg]

Gas pollution:

$$G = \phi \cdot n \cdot q_i \text{ [kg/s]} \quad (5)$$

where: q_i - amount of CO_2 exhaled per person, depending on activity and age ρ = 1.5 [kg/m^3], q_i - light working or relaxing adult – 35 [g/h]

The required air stream:

$$V_n = \frac{G\Phi}{(k_d - k_n)} \text{ [m}^3\text{/s]} \quad (6)$$

where: Φ - emission unevenness factor, Φ = 1.2; k_d - an admissible concentration of gas pollution, k_d = 9 [g/m^3], k_n - CO_2 concentration in incoming air, k_n = 5 [g/m^3]

Tab. 4. Calculated air exchange rates in relation to the measured parameters.

Heat gains	Humidity gains	Gas pollution
13846.0 [W]	0.0018 [kg/s]	0.0022 [kg/s]
Ventilation rates		
12386.83 [m^3/h]	0.01 [m^3/h]	2415.00 [m^3/h]

3. Measurements

An auditorium in one of Bialystok's cinemas (Fig. 1) was chosen to perform measurements. The room is a distinctive closed space where a large number of people may gather at one time what leads to high heat gains. A European standard of 1000 ppm as the highest acceptable carbon dioxide concentration was used as a reference for measurement results analysis.

The room where research was carried out is a typical cinema room with stairs-shaped auditorium for 345 people. There are no windows in the room and air exchange is performed by mechanical system with diffusers placed in the ceiling. Multifunctional instrument Testo 435 showed in Fig. 2 was used for measurements and data collection. The device was equipped with probe to assess indoor air quality (CO_2, humidity, temperature).

There were 230 people present during 159 minute film projection. The sensor was placed in the middle of the auditorium as far from the exhaled air as possible. Such emplacement ensured reliable instrument readings. Data saved on the device allowed to analyze ventilation installation effectiveness in the means of maintaining good air quality, especially carbon dioxide content what is the object of the present article.

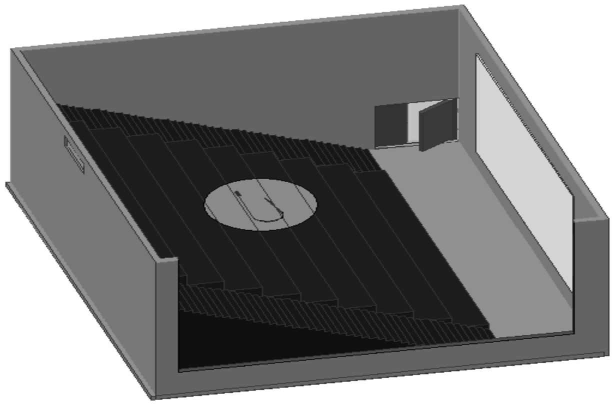

Fig. 1. Cinema auditorium; A –measurement instrument testo 435 with CO_2 probe.

Fig. 2. Measuring instrument Testo 435 and probe to assess indoor air quality (CO_2, humidity, temperature).

4. Results

The results of the measurements: carbon dioxide concentration, temperature and humidity changes are presented in the Figs. 3, 4 and 5.

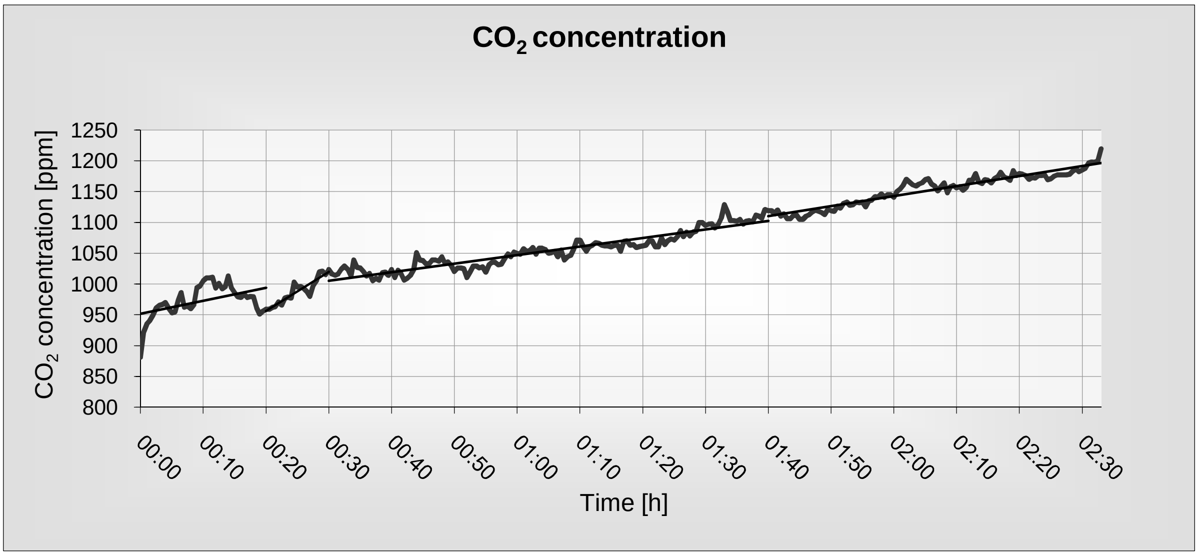

Fig. 3. Changes in carbon dioxide concentration during the projection.

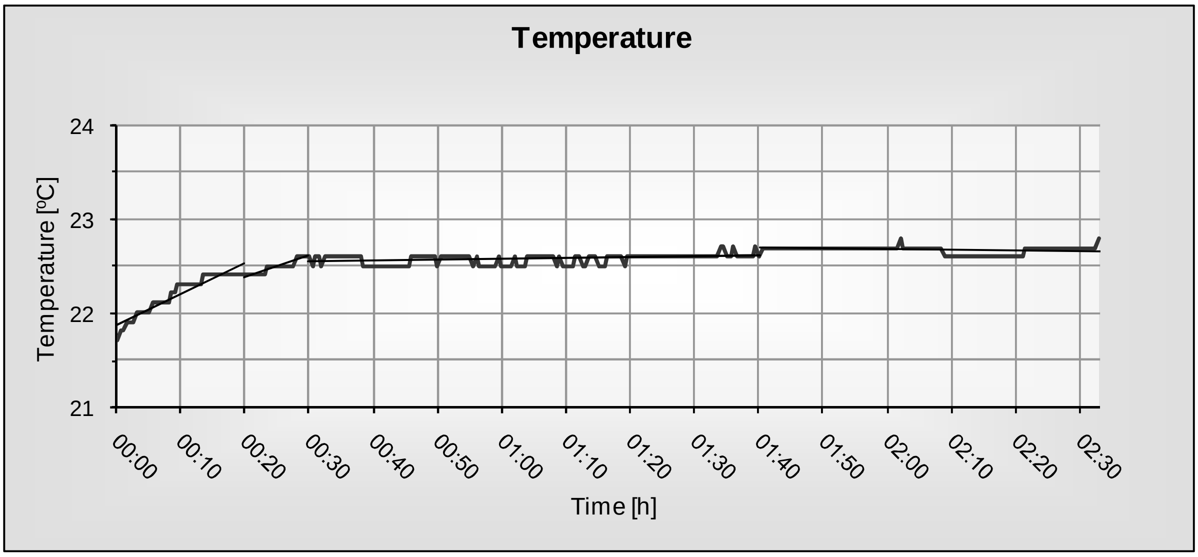

Fig. 4. Changes in air temperature during the projection.

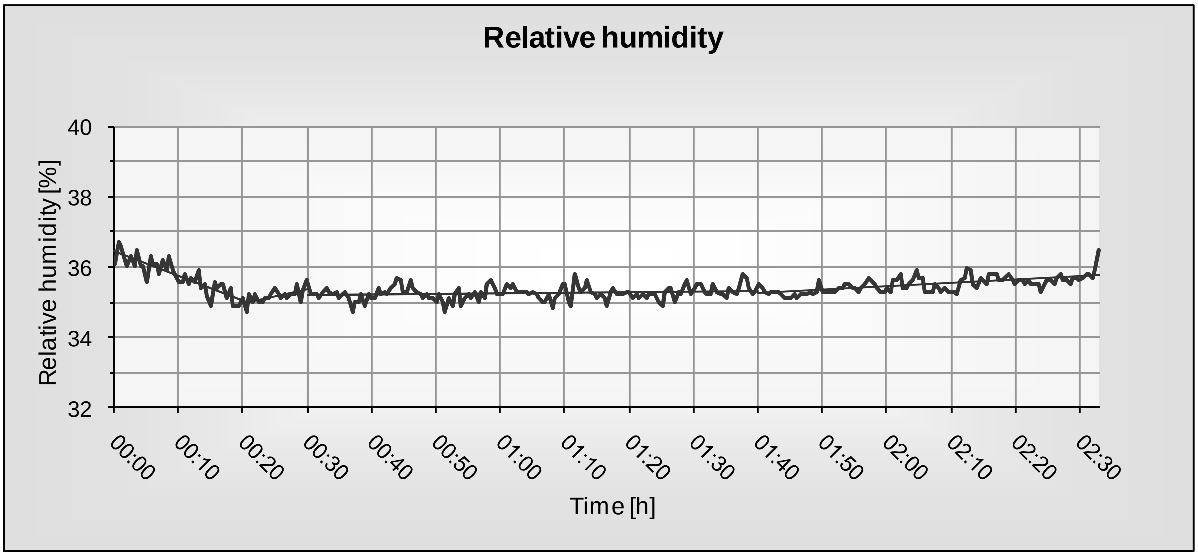

Fig. 5. Changes in relative humidity during projection.

5. Discussion of the results

Considering the fact that the temperature is a parameter regulated by the ventilation system and relative humidity by air conditioning, it can be stated that the installation in the investigated room works properly. Big effectiveness of installation performance is well reflected in Figs. 4 and 5 as both temperature and relative humidity values stay in the range defined in PN-83/B-03430. In the investigated case it is obvious that the regulated parameter is temperature as it is the only one which is stable for longer time periods as seen in Fig. 4. The relative humidity and carbon dioxide concentrations vary most of the time. Confirmation of this theory one can find analysing change tendencies represented by trend lines in the Figs. 4 and 5.

The whole measurement can be divided in four phases. In the initial one (0 – 20 min) a temperature increase is observed along relative humidity decline. It shows that the heating was turned on, as it is known when air is heated with constant humidity, the relative humidity decreases. In this particular case the humidity content was rising due to audience respiration, despite the fact that the relative humidity value was descending as the temperature increased.

In the second phase placed between 20th and 30th minute, simultaneous increase of temperature and in relative humidity values is observed. It proves that the temperature had reached the set value and the heating installation was turned off. The temperature and relative humidity increment is connected with heat and water vapour emitted by people in the room. In next phase (30min – 1h 40 min) temperature is kept on constant level, and so is relative humidity. It is possible that water vapour gains from audience were condensed during cooling process. In the last phase lasting from 1h 40min to the end the temperature was constant, but the value was higher than before, which resulted in worse cooling effect on cooler. Such situation could have led to decrease in condensation effects.

When carbon dioxide content, which is not regulated by Polish law, is taken into consideration, a linear increase is observed starting from 20th minute, as it is shown by thickened black line in the Fig. 3. The moment the data collection started, the CO_2 concentration was 881 ppm by volume and it increased during first 14 minutes. Then it decreased within the next 6 minutes. After these fluctuations the concentration of CO_2 constantly increased for the rest of the time. In the 10th minute it was the first time when CO_2 content had exceeded the hygienic minimum of 1000 ppm. The lowest observed value of 951 ppm carbon dioxide concentration occurred in the 19th minute and after this point it continuously grows by approximately 0.8 ppm/min. The second permanent exceed was recorded in the 28th minute. At the end of the projection the CO_2 concentration was 1219 ppm. Tendencies in carbon dioxide content changes may be explained as follows.

In the first phase (0 – 20 min) the CO_2 amount increased due to audience respiration. Then it decreased because of convection of the compound with warm air above the sensor. After the heat was turned off, what took place in second phase (20-30 min) carbon dioxide concentration rose along with temperature and relative humidity. From the moment that the cooling system was turned on and temperature stabilised, the CO_2 content increased linearly what showed, that there was no effort made to regulate this parameter.

The cause of incongruence between stable temperature and humidity and increasing CO_2 concentration may be perceived in the manner that the installation is working. Supposedly, because of the economics the installation works with heat recovery, i.e. the part of the return air is recirculated. Such conclusion may be made after comparing values of air stream required depending on parameter. Tab. 4 shows such comparison. As one can see the amount of air required to remove heat exceed is few times bigger than the one for gas pollution. If only outdoor air was entering the room the CO_2 exhaled by people would be completely removed. It is confirmed by the fact that temperature is constant nearly all the time whilst relative humidity and CO_2 concentration change rapidly. Constant average humidity value may be a result of air cooling (cooler is an element of every mechanical system) as temperature reduction below the dew point results in water vapour condensation. After heating in the second degree heater the final required temperature is reached while humidity is reduced. In such a case the humidity would not be kept on one level, because a humidifying process would be necessary.

The foregoing reasoning leads to a conclusion that in the control indoor air quality in the investigated room is provided by a cooling mechanical system with air recirculation.

The installation performance described above provides air quality that complies with currently standing law. In the investigated case recorded CO_2 concentration exceeding 1000 ppm does not threaten human life in reference to the influence on human organism from tab. 3. Additionally, considering the fact that people usually do not stay in cinema rooms for a long time, slight excess over the upper limiting value set neither danger to human life nor its work effectiveness.

6. Conclusions

If a large number of people gather at the same short period of time in a closed space such as e.g. a cinema room, carbon dioxide concentration exceeds then the upper limited value that happens respected in most European countries.

Air conditioning installation that is effective regarding basic thermal comfort parameters i.e. temperature and humidity does not meet the expectations for CO_2 exceed removal.

The CO_2 concentration that exceeds the value recommended by WHO in many workplaces where employees stay 8h or longer and their physical and psychological condition affects effectiveness of their work does influence their efficiency and therefore company economy. If ventilation system parameters base only on temperature, and if there is no natural ventilation, an increase of CO_2 content may occur which might lead to drowsiness and concentration problems.

A conclusion may be drawn here, that in the ventilation designing process the exchange of the air, what is connected with replacement with outside air and the dilution of carbon dioxide and airborne pollutants in closed rooms, should be emphasised because its importance is underestimated.

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