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Importance of microclimate conditions and CO_2 control in educational buildings: a case study

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Abstract. Current efforts to minimize energy losses and maximize energy savings for heating of all houses are most often gained by insulating facades and replacing windows. However, these measures can have a significant negative impact on human health and these problems can occur in buildings with a high concentration of people, such as school buildings. The aim of this paper is to analyse the results of measurements of air temperature, relative air humidity and carbon dioxide in winter period in the classrooms of two universities, Estonian University of Life Sciences (EULS) in Tartu and Czech University of Life Sciences (CULS) in Prague. The measurements have carried out in 2017–2018 in eight classrooms of the EULS and two classrooms of the CULS. The external and internal temperature, relative humidity and concentration of carbon dioxide have measured in the classrooms during a few days in the winter period. In the lecture rooms of CULS, when the air conditioning was off, the levels of CO_2 exceeded the recommended levels about two times. The average internal temperature and CO_2 concentrations in the classrooms of EULS follows the norms and refers on good ventilation. The extremely low relative humidity in the classrooms of EULS at 17.1 ± 2.6% refers to a high risk of allostatic load and respiratory symptoms among students. It is important to pay attention on regular ventilation and relative air humidity control in the teaching rooms, especially with high number of students to prevent seasonal sickness of upper respiratory tract.

Key words: air-conditioning, health impact, lecture rooms, measurement, students.

INTRODUCTION

In the last few decades, the number of studies focusing on the effect of indoor climate conditions on human health has increased rapidly (Fisk at al., 2007; Karottki et al., 2015). In some works, the importance of microclimate for schools' environment (Karwowska, 2003; Kic, 2015) and offices (Seppänen et al., 2006; Tint et al., 2012) is shown. The relationships between the illness, indoor climate and regularity of attendance at a school or office have studied. Inappropriate microclimate may contribute to higher sickness rate and thereby increase the number of days when people do not come to the office or to school. The critical analysis of the research results by Wargocki & Wyon (2017) has demonstrated, that any economic gains achieved by energy conservation in the buildings greatly exceeded the costs, whereby the majority of people reported reduced performance 5−10% for adults and 15−30% for children.

Cross-sectional surveys in many schools in the USA have confirmed that poor ventilation and higher CO_2 levels may play a part in reducing the number of pupils managing to pass language and mathematics tests (Haverinen-Shaughnessy et al., 2011).

In a study of three German Bundeslander (Fromme et al., 2016) the indoor air of 63 day-care centres was analysed for carbon dioxide (CO_2), airborne particulate matter (PM_{10} and $PM_{2.5}$) and volatile organic compounds. The median daily CO_2 concentrations in the individual facilities ranged from 670 ppm to 3,958 ppm (median: 1,297 ppm).

In the areas where people live, air quality deteriorates with substances that enter the air through metabolism, especially by breathing. Exhaled air contains approximately 4% CO_2 and 5% water vapour. It has been revealed that indoor environmental quality significantly influences allostatic load in the body and it can be a predictor for reporting Sick Building Syndrome (SBS) with information on system-specific (neuroendocrine and metabolic) effects (Jung et al., 2014).

Human senses are not able to directly judge the concentration of CO_2, therefore the personal self-assessment of air quality is very unreliable. Humans can approximately sense the CO_2 concentration, since the central nervous system regulates the breathing rate based on blood CO_2 levels (Cummins & Keogh, 2016). The human organism ceases to perceive the concentration of odour after some time, and olfactory organs adapt to the environment in which people find themselves. Certainly everybody knows the situation when a person enters to a small room where already several people are there. When one enters the environment, one smells the stuffy air, but after a while one stops to perceive it as an inconvenience. Once their olfactory organs adapt, one stops to perceive the concentration of odours. However, at a certain concentration, the effect of elevated CO_2 levels is reflected by concentration problems as fatigue, deteriorated attention and mental work. At higher CO_2 concentrations, human fatigue is already increasing and headaches, nausea and breathing problems can occur. Table 1 summarizes the approximate effects of CO_2 on the human organism (Zikan, 2011).

Table 1. Effects of CO_2 on the human organism

Concentration CO_2 (ppm)	Effect on the human organism
about 350	Outdoor environment
up to 1,000	Recommended indoor conditions
1,200–1,500	Recommended maximum level in indoor areas
1,000–2,000	Beginning of fatigue and decreased concentration
2,000–5,000	Beginning of possible headaches
5,000	Maximum safe concentration without health risks
> 5,000	Nausea and increased heart rate
> 15,000	Breathing problems
> 40,000	Possible loss of consciousness

Attention to the CO_2 concentration in classrooms and office rooms has paid in previous studies. According to Heudorf et al. (2009) the levels of CO_2 were very high in all studied schools and could be diminished by intensified ventilation (mean 1,459 to 1,051 ppm). A cross-sectional study in 21 office rooms in Taiwan (2011–2012) showed, that the concentration difference of indoor and outdoor CO_2 (dCO_2) and the ratio of indoor and outdoor CO_2 (CO_2 I/O ratio) levels were a markers of ventilation rate and associated with allostatic load score on the neuroendocrine system, and cough and musculoskeletal pain ($p < 0.05$) (Jung et al., 2014).

An Estonian study held by the Health Board (2015) on indoor air conditions in school classrooms of the renovated and non-renovated buildings showed no differences in room temperature and relative humidity. However, there was a difference in average CO_2 levels, with a higher CO_2 concentration in renovated school buildings (R = 0.204, $p < 0.01$). The effects of indoor air quality (IAQ) problems on school building occupants are often non-specific symptoms rather than well-defined diseases, based on a study by the European Commission (2014). Symptoms commonly attributed to IAQ problems include: eye, nose, throat and skin irritation, sinus congestion, coughing and sneezing, shortness of breath, headaches, and fatigue.

Reinvee et al. (2013) revealed that the Estonian Meteorological measurements (1970–2000) showed an average relative humidity below 20% at indoor temperatures of 21 °C were measured in the winter period from December to March, whereby the effect of humidifiers in EULS teaching rooms increased relative air humidity only by a maximum of 12%. Based on a study by Wolkoff (2018), low relative air humidity increases the transmission and survival of the influenza virus, increases the occurrence of dry eye disease, voice perturbation, body fluid loss, and the symptoms of asthmatics compared to normal relative air humidity. An increased air humidity with hot temperatures increases coughing in allergic rhinitis patients. Increased air humidity also lowers the threshold for smelling odours, the acceptability of the thermal climate and physical performance. Guidelines for healthy environments within European schools stress the importance to promote research and innovation to develop sustainable measures aimed at improving IAQ in the school environment to prevent negative impact on students' health (European Commission, 2014).

The aim of this paper is to analyse the results of measurements of air temperature, relative air humidity and carbon dioxide in winter period in the classrooms of two universities EULS and CULS.

MATERIALS AND METHODS

The first part of this research activity focused on measuring indoor conditions in the lecture rooms of the Faculty of Engineering at the CULS in Prague. It was carried out in the big lecture room A and small seminar room B.

The big lecture room A has a capacity of 121 student places in 11 rows of school desks. The lecture room is stepped and has the following dimensions: length 12.2 m, width from 7.7 m in the lowest point (on blackboard for the presenter) to 9.1 m at the highest (by the entrance) point, the height of the ceiling at the highest point (by the entrance) is 3.2 m and at the lowest point (on blackboard for the presenter) is 4.1 m. The volume is approximately 374 m^3. During the winter, thermal comfort in lecture room A is ensured by warm-water central heating system using classical radiators located on the walls under the windows. Ventilation is only by air conditioning (AC).

Measuring points represent the main characteristic locations on the middle axis of the lecture room, in the central part (sixth bench), which also suitably corresponds to the position between the air inlets. The instruments and sensors installed at the level 1.1 m above the floor. The registration of measured values was in one minute frequency during the whole measured period. Measurements included determination of the quality of indoor air in the lecture room during the different operating modes of AC equipment.

The AC equipment is modular and consists of an inlet section and an outlet section. The inlet part consists of silencers, the filter, the valve chamber, heat exchangers (heater and cooler) and the fan connected to the silencers. The direct cooler is connected to the condenser, the cooling unit that is installed on the roof of the lecture room. A steam humidifier connected to the drinking water is used for humidification. The outlet part consists of the silencer, the filter, the valve and the fan. The AC system was designed with a fresh air inflow of V_e = 4,520 m^3 h^{-1} and an air outflow of V_i = 4,083 m^3 h^{-1} (small overpressure). The ventilation rate per person is about 37 m^3 h^{-1} if the lecture room is filled to capacity. The air change rate is 12 h^{-1}. A rotary regenerative heat exchanger is installed between the inlet and outlet sections for heat recovery from the exhaust air. The regenerator is an industrial product in which the matrix (heat transfer surface) is in a disk form and air flows axially.

Filtration of fresh and exhaust air is through the pleated filters made from the Firon Special G 460 non-woven polyester fabric. This material is G 3 class filter for coarse dust according to the international classification of air filters. According to the previous information and old international standards, this material should be used for elimination of particles over 10 µm.

All parts of the AC equipment are installed on the support frame. Air supply to the lecture room is via pipes with silencers and diffuser inlets in the ceiling, spread uniformly in the ceiling of the room. The air outlet is in the front of the lecture room with two wall grilles in the corner over the blackboard. AC operation is regulated automatically according to the internal temperature, but it was controlled manually during the measurement, to suit the intended experiment.

The small seminar room B has a capacity of 30 student places in 5 rows of school desks. The seminar room has the following dimensions: length 9.2 m, width 5.8 m, height 3.3 m. The volume is approximately 176 m^3. There is a central system of surface heating by water pipeline installed in the floor and ceiling of the whole building. Ventilation is only by opening of windows, there is no active ventilation.

The thermal comfort in the rooms was continuously measured during the experiment by the sensor FHA 646–21 including the temperature sensor NTC type N with an operative range from –30 to +100 °C with an accuracy of ± 0.1 °C, and the air humidity by a capacitive sensor with an operative range from 5 to 98% with an accuracy of ± 2%. Furthermore, the concentration of CO_2 was measured by the sensor FY A600 with an operative range from 0 to 0.5% and an accuracy of ± 0.01%. All of the data was measured continuously and stored to the measuring instrument ALMEMO 2690–8 at one minute intervals (Table 2).

Table 2. Technical parameters of the measuring device, used in CULS Prague

Parameters	Air temperature, °C	Relative air humidity, %	Carbon dioxide, ppm
Measurement ranges	From -30 to 100	From 5 to 98	From 0 to 5,000
Resolution	0.01	0.01	1
Accuracy	± 0.1	± 2.0	± 100

The CO_2 measurements were conducted in both lecture rooms during the winter period with students under normal teaching conditions inside the lecture room. There were 40 students in lecture room A. The measurement period simulated real conditions, with the AC switched off for 20 minutes and then switched on for 50 minutes during the experiment. Usually, teachers switch the AC on in the beginning of lecture. However, sometimes the AC is off for a longer time. It mainly happens in the winter.

The measurements in the small seminar room B were in normal teaching conditions. The first period was the 12-minute break with windows open, then followed the class with 20 students inside and with only several small windows partly opened. More windows were opened after 60 minutes. After the next 20 minutes the class was over and a 30-minute break started with partly opened windows before another class.

The measurements in the classrooms of the Institute of Technology of EULS were carried out in the 2018 winter, where the outside temperatures during the night were from −9 °C to −14 °C and during the day −1 °C to −4 °C. The measurements were taken in a 3-hour period in the morning on 2 separate days.

The data includes the results of measurements collected from eight teaching rooms described in Table 3.

Table 3. Main characteristic parameters of tested classrooms in EULS Tartu

Lecture room	Volume (m^3)	Maximum number of students, n
A109	169	24
A112	158	15
A208	164	15
A220	158	16
A308	102	6
A312	155	14
A403	103	24
A404	156	15

All of the classrooms are equipped by the comfort AC that forwards the microclimate information and CO_2 levels of the rooms to the central system of the whole building. This AC system includes the heating, cooling, air distribution and control system. Each room has its own sensors for measurement of temperature, relative humidity of air and CO_2 concentrations. Each room also has classical radiators located on the walls under the windows, heated by the warm-water central heating system. The occupants of those rooms can control the temperature from the control panel, the central system regulates the ventilation based on CO_2 levels.

The measurements were taken from 5 points in each room. The rooms were divided into 4 quadrants and the centre of each quadrant was taken as a measurement point. Also, the centre of each room was also taken as a measurement point. Measurements were taken from two heights: 0.1 m and 1.1 m. Each point was measured 3 times for 1 minute, the averages of those results are used in calculations. CO_2 measurements were recorded 3 times for 1 minute from the control panel, which receives data from two wall sensors, which were placed on opposite walls in the rooms.

The measurements of air temperature and relative air humidity in the EULS teaching rooms were taken by the COMET S3120 (Table 4).

Table 4. Technical parameters of the measuring device, used in EULS Tartu

Parameters	Air temperature, °C	Relative air humidity, %
Measurement ranges	From -30 °C to +70 °C	0 to 100 %RH
Resolution	0.1 °C	0.1%
Accuracy	± 0.4 °C	±2.5% from 5 °C to 95% at 23 °C

Measurement accuracy (error) of the equipment for air temperature is ± 0.4 °C and for relative air humidity is ± 2.5% relative humidity from 5% to 95% at 23 °C. These figures are based on the data available from the manufacturer.

RESULTS AND DISCUSSION

The results of the microclimate measurements in lecture rooms A and B during winter are summarized and presented in the Table 5 and Figs 1–2. Table 5 presents the results in both lecture rooms during different measurement times and different ventilation conditions.

Table 5. Average external temperature t_e, internal temperature t_i, relative humidity RH_i and concentration of carbon dioxide (CO_2) in the rooms during the measured periods

Measured quantity	Unit	Lecture room A		Seminar room B		
		AC off	AC on	Break	Seminar	Break
t_e	°C ± SD	1.6 ± 0.6	3.4 ± 0.3	4.4 ± 0.2	4.4 ± 0.2	5.5 ± 0.3
t_i	°C ± SD	22.7 ± 0.1	22.7 ± 0.1	22.9 ± 0.1	25.0 ± 1.0	21.5 ± 0.2
RH_i	% ± SD	38.9 ± 0.4	30.2 ± 2.3	29.6 ± 0.8	36.4 ± 2.1	31.3 ± 1.3
CO_2	ppm ± SD	2,075 ± 98	862 ± 427	495 ± 15	1,573 ± 500	616 ± 108

AC – air conditioning; SD – standard deviation.

The highest CO_2 levels were measured during the classes with higher student attendance and when the AC was switched off. In comparison, CO_2 levels were the lowest during break periods and when the AC was switched on. It is clear from Table 5 that in lecture room A the recommended indoor CO_2 level of 1,000 ppm was exceeded. When the AC was off, the levels of CO_2 exceeded the recommended levels about two times. Based on the CO_2 concentration on Fig. 1 it is obvious that the initial CO_2 level was very high (approximately 1,840 ppm). Due to the metabolism by breathing in the lecture room, it increased further to 2,260 ppm. The students and the lecturer did not perceive the worsening of the IAQ due to the slow gradual increase.

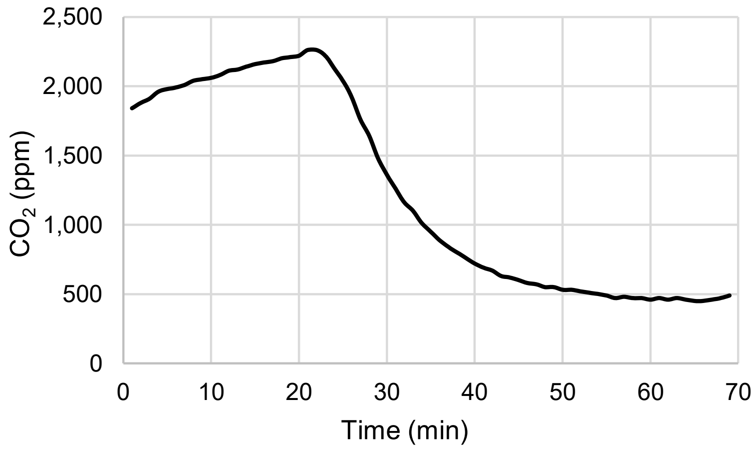

Figure 1. The course of CO_2 concentration during the measurement in the lecture room A.

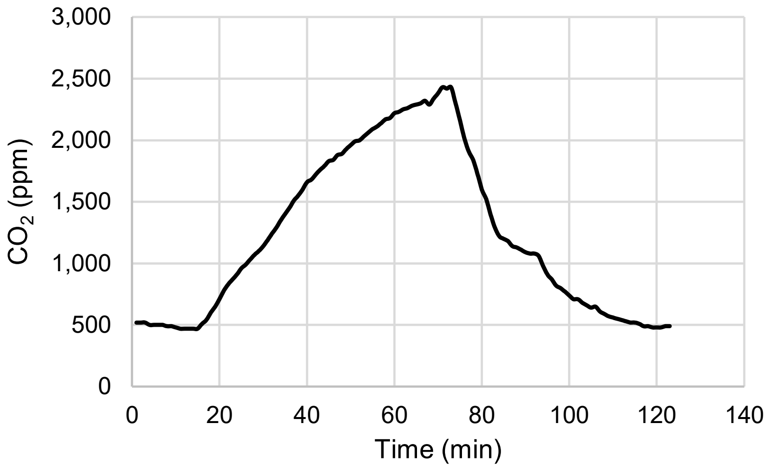

Figure 2. The course of CO_2 concentration during the measurement in the seminar room B.

When the AC was switched on, CO_2 concentration started to decrease immediately, and it slowly stabilized around 450 to 500 ppm. Significant fluctuations of CO_2 concentrations resulted in a high standard deviation value.

However, relative air humidity was on a suitable level throughout the whole measurement period. At the beginning it was at approximately 39%. When AC was switched on, it dropped to about 30% because the outside air supplied to the lecture room had a lower absolute humidity. After it was warmed, the relative humidity decreased considerably due to a higher humidity capacity of warmer air.

The air temperature was close to the desired temperature of +22 °C. At this value of +22 °C, heating and air conditioning should keep the internal temperature stable. Variations in the air temperature for the whole period were relatively small (see standard deviation value). From the thermal comfort point of view, neither the students nor the lecturer in the lecture room felt uncomfortable. Therefore, under normal conditions, the AC usually remains switched off.

According to the results in Table 3, it is clear the concentration of CO_2 was relatively low (approximately 500 ppm) inside seminar room B during the break before the lesson. Due to the large number of people (20 students and the lecturer), the CO_2 concentration rapidly increased to 2,430 ppm. Relative humidity gradually increased from about 30% to 36%. Also, the air temperature gradually increased from 23 °C to 25 °C. By that time, the indoor environment was unpleasant for many people, therefore the windows were fully opened.

By intensive ventilation through the opened windows the CO_2 concentration was gradually reduced from 2,430 ppm to 480 ppm. At the same time, the relative humidity decreased from 36% to 31% and the temperature dropped from +25 °C to +21.5 °C. If the classes last for a longer time, a similar cycle of varying ventilation intensity can be observed; windows are closed again because students sitting near the windows suffer from drafts and cold temperatures. Then the CO_2 concentration starts to rapidly rise again.

The results of microclimatic parameters and carbon dioxide (CO_2) measured in the rooms in the Institute of Technology, EULS are presented in Table 6.

Table 6. Average external (t_e, °C) and internal air temperature (t_i, °C) with the standard deviation, relative air humidity (RH_i, %) with the standard deviation and concentration of CO_2 (ppm) in the EULS teaching rooms during the winter period 2018

Lecture room	t_e, °C	t_i, °C	±SD	RH_i, %	±SD	CO_2, ppm
A109	-4	24.9	0.3	17.7	0.4	300
A112	-3	24.3	0.1	17.4	1.1	492
A208	-3	24.3	0.3	19.8	0.1	481
A220	-2	23.8	0.1	20.8	0.8	426
A308	-2	24.5	0.1	16.7	0.4	652
A312	-2	23.1	0.0	17.1	0.2	560
A403	-1	22.6	0.1	15.9	0.3	782
A404	-1	24.9	0.1	11.9	0.1	203
Mean ± SD	-2.3 ± 2.1	24.1 ± 0.9		17.1 ± 2.6		487 ± 185

t_e – external temperature; t_i – internal temperature; RH_i – relative humidity; SD – standard deviation.

The mean values measured in all rooms presented in Table 6 show, that the AC is functioning well based on the temperature and the concentration of CO_2.

The average indoor temperature measured from 1.1 m height, $t_i = 24.1 \pm 0.8$ °C didn't differ from the results measured from 0.1 m height, $t_i = 24.1 \pm 0.8$ °C. The results follows the values required by the Act of Health Protection Requirements for Schools (2013) (AHPRS), which dictates the different required microclimate levels for the lecture rooms and other teaching spaces.

The average relative humidity in the classrooms of EULS at height of 1.1 m 17.2 ± 2.6% and at height 0.1 m 16.7 ± 2.2% is extremely low. The value required by AHPRS is between 40 to 60% and between 25 to 60% during winter. The measurements were taken during winter, when the absolute humidity of external air is extremely low, but we can clearly see that the relative air humidity does not follow the values required by the AHPRS.

The indoor humidity production by evaporation and respiration is also very low, as there is usually a small number of students in classrooms and there are no other water vapour sources. The increase of relative humidity could be achieved only by the air humidification, which is rather complicated and expensive.

The low relative humidity in teaching rooms during winter has a negative health impact on people with chronic respiratory diseases, allergies and asthmatic symptoms. Sore eyes and voice problems are some of the more common symptoms among teachers (Simberg et al., 2009).

The Madureira et al. (2015) study in 20 public primary schools in Portugal showed that indoor air pollutants, some even at low exposure levels, are related to the development of respiratory symptoms among schoolchildren. High levels of volatile organic compounds (VOC), acetaldehyde, $PM_{2.5}$ and PM_{10} in the air were associated with higher odds of wheezing in children.

The values obtained from the CO_2 sensors are very important but based on the large standard deviation in the results, we can assume that the sensor need to be calibrated regularly. There are two sensors installed in each room. The data presented in Table 6 is the average value of the sensors monitoring the CO_2 concentration in the room. They were usually placed where the majority of students are sitting and the pollution by CO_2 is the highest. The mean CO_2 concentration of 487 ± 185 ppm in all rooms is excellent, it is lower than the required limit of 1,000 ppm. The lowest value in the room A404 is probably caused by faulty calibration, which should be provided regularly according to the manufacturers' instructions. The highest value in the room A403 could have been caused by a high number of students in the small room and by some AC control, as the mean temperature of +22.6 °C is the lowest value from all measured rooms. The automatic control of AC controls the rate of ventilation with the aim to reduce the heat losses by the ventilation system.

In Estonia, there are certain requirements for the microclimate, as required by the AHPRS. These dictate that the air temperature in classrooms must be at least 19 °C and the upper limit for CO_2 concentration doesn't exceed 1,000 ppm. Nevertheless, in the classrooms in the Institute of Technology, EULS the mean CO_2 value (782 ppm) and the air temperature values followed the AHPRS.

CONCLUSIONS

The results of main indoor parameters measurements presented in this paper show that during the winter period the CO_2 concentrations exceed the recommended maximum values inside the lecture rooms of the CULS in Prague. The temperature inside the lecture rooms and classrooms is only slightly increased (an increase of about 1K), but the concentration of CO_2 grew rapidly. The smaller the volume of the classroom and the greater the number of students in it is, the faster the indoor environment worsens. The reaction of the people inside the rooms is disproportionately slow. The natural or forced ventilation controlled by people (usually teacher) is therefore not sufficient. Impaired quality of the indoor environment therefore reduces the concentration of students and increases the transmission risk of infectious diseases.

The measurements in the lecture rooms in the Institute of Technology, EULS, confirmed the positive influence of CO_2 control together with temperature control. The measurement and regulation of these parameters allowed for the optimal indoor conditions for classes. The low relative humidity in winter period is still an ineluctable problem. The improvement could only be achieved by vapour humidification. Low relative humidity in classrooms during the winter may reduce learning efficiency when the eyes tend to dry and tire more easily and the lecturers' voice is under a higher strain. It could be a serious problem for the students in larger classes, since the low relative humidity allows the flu and other respiratory diseases to survive longer and spread more easily.

It is important to regularly monitor the air humidity, air temperature and CO_2 levels in the lecture rooms of both observed universities (EULS and CULS) and to regulate the AC system and humidifiers accordingly.

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