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VENTILATION CONTROL BASED ON THE CO_2 AND AEROSOL CONCENTRATION AND THE PERCEIVED AIR QUALITY MEASUREMENTS – A CASE STUDY

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Abstract: One of the concepts of the ventilation rate control in buildings with dense and unpredictable occupancies is based on the CO_2 measurements. There are many limitations regarding the validity of CO_2 measurement inputs as suitable to the ventilation rate control. Verifying research has been conducted in an air-conditioned auditorium, in the real conditions at altered ventilation air thermal parameters and variable occupancy. The CO_2 and the number concentrations of the fine and coarse aerosol particles (> 0.3 μm) and bioaerosol particles (bacteria and staphylococci) as well as the indoor air thermal parameters were measured in the individual sectors of the occupied area. The sensory assessments and instrumental determinations of the acceptability of indoor air quality (ACC) were also performed. The ventilation control strategy based, apart from the CO_2 measurements, on the continuous monitoring of the perceived air quality (PAQ) in the auditorium sectors has been suggested. The PAQ monitoring could be accomplished by aerosol concentration measurements and the ACC instrumental determinations. This strategy should ensure a desired PAQ in sectors which benefit the occupants' comfort, health and productivity as well as energy savings not only in the case of its implementation in the considered auditorium.

INTRODUCTION

A positive assessment of the indoor air quality is necessary for the occupants to feel comfortable in indoor environments. Unfortunately, despite the efforts of the designers and contractors, the number of buildings in which the indoor air quality is negatively assessed is constantly increasing [30, 32]. It concerns a wide spectrum of buildings including residential homes, offices, recreation facilities and schools [7, 17, 20, 22]. The majority of the objections are connected with the indoor air pollutants perceived by the sense of smell. Aerosol particles, both organic, nonorganic and biological, are those contaminants, which significantly affect the perceived indoor air quality (PAQ) [32, 8, 34]. Room occupants and their activities are approved to be one of the main sources of such widely apprehended indoor generated aerosols [1, 4, 12, 16, 18, 19]. Heating, ventilation and air-conditioning systems are also of significance. It is due to the fact, that the concentration level of the aerosol particles is dependent on the indoor air thermal parameters and the correlated infiltration-exfiltration processes in the building [2, 13]. Air-conditioning systems themselves could be a source of aerosols (bioaerosols) [14, 35]. Taking into account the room occupants, their presence, apart from generating aerosols, is connected with bioeffluent emissions and CO_2 concentration changes indoors. Since people produce a predictable amount of CO_2 as a result of respiration, the CO_2 level could be treated as an indirect measure of room occupancy [9, 15, 21]. The measurements of the CO_2 concentration in the indoor air are often used to monitor the performance of the ventilation systems. These measurements are also crucial to adjust the outdoor airflow rate as regards the concept of the CO_2-based demand control ventilation (DCV) [9, 21]. However, according to the literature data, the maintenance of the CO_2 set point levels does not always guarantee an acceptable indoor air quality [9, 23, 36].

The determination of the influence of the number of people, their activity and the duration of their stay on the aerosol particle and CO_2 (bioeffluents) concentrations is important when proper PAQ has to be assured in buildings with variable occupancy. It is essential as the available methods of controlling the ventilation rate do not always ensure the desired PAQ. The implementation of the CO_2-based DCV strategy which takes into account only CO_2 levels and overrides other important indoor air pollutants and relevant relations may carry such risks.

Much data on the indoor air thermal parameters, pollution levels, the indoor air quality and human sensation in relation to the occupation can be found in the literature. It comes from the studies of different indoor environments with different types of occupancy. Different methods of ventilation control are also presented. Only few of them present the idea of measuring the air parameters deciding about the PAQ in every occupied zone of the indoor environment and to control the ventilation on the basis of such measurements. However, there are no works which describe the ventilation control on the basis of a direct instrumental determination of the PAQ indoors. The present study aims to verify on the example of an auditorium the relations between the indoor air parameters and the occupancy and to indicate that in addition to the CO_2 measurements, zonal monitoring of aerosols and continuous instrumental determinations of the PAQ could be important while implementing an effective ventilation control in indoor environments with variable occupancy.

METHODS

The experiments were carried out in a new air-conditioned auditorium at the Lublin University of Technology (LUT). The auditorium with seats for 186 people is located on the first floor of the LUT building and has a floor area of approximately 300 m^2 and a volume of approximately 1200 m^3 (average dimensions – 20x15x4 m). The auditorium has 4 double pane air tight windows (2.6 x 3 m), which overlook towards the south-west and 4 windows of the same size which overlooksthe north-east. The mounted window-blinds diminish the inflow of the solar rays into the auditorium and prevent the inside from excessive heating. All surfaces in the auditorium are finished with low-polluting materials. Apart from the occupants, the audio-visual and electronic equipment (2 projectors, speakers, a visualizer and a computer) and also the air-conditioning system constitute pollution sources which exacerbate the indoor air quality in the auditorium. The system filters are replaced every three months and were changed one week prior to the measurements. The auditorium is ventilated with a total supply of 1.6 m^3/s of conditioned air (50% recycled). The ventilation air of set thermal parameters is delivered by 12 steadily emplaced inlets. The ventilation air temperature was set from 18 to 26°C and the relative humidity from 30 to 50%. The given thermal parameters of the supplied air were maintained at the same level throughout the each whole measurement day. When the auditorium was not occupied (in the evenings and at night, i.e. between 8 p.m. and 8 a.m. the air-conditioning system was operating in the *Standby Mode* and did not deliver the ventilation air when the indoor air temperature ranged ±2°C around the set point.

The plan view of the auditorium with occupation area and marked measurement sectors is shown in Figure 1.

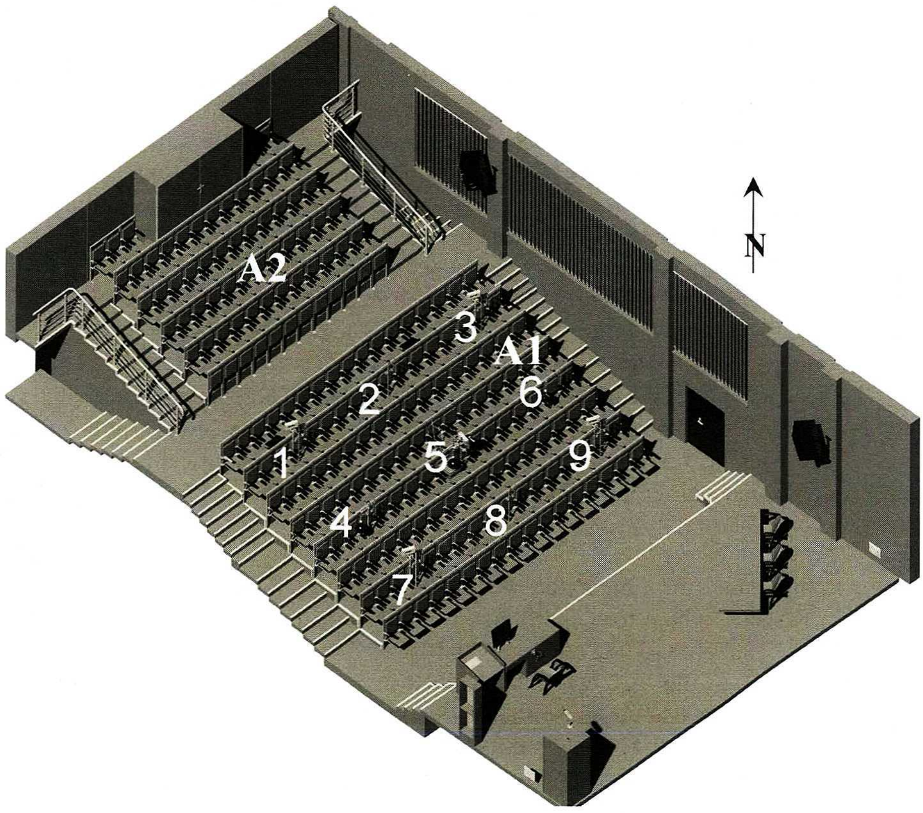

Fig. 1. Scheme of the auditorium with a non occupied area A2 and occupied area A1 with the measurement sectors: 1,2,3,4,5,6,7,8,9 – temperature, relative humidity and air velocity measurements; 1,3,5,7,9 – CO_2 measurements; 4,5,6 – radiation temperature measurements; 5 - aerosol and bioaerosol measurements.

The occupation area in the auditorium was divided into two parts: lower A1 with seats for 116 students and upper A2 with seats for 70 students. During the experiments, the students took seats only in the area A1. An approximately equal number of students (from 3 to 10 depending on the overall number of students present) was in each measurement sector. The students were not allowed to change their seats during the lecture. The auditorium occupancy usually changed every second hour according to a traditional academic system of 2-h lectures. Separate lectures were divided by 15-minute breaks during which the students moved in and out of the room. The auditorium was irregularly occupied from Monday through Friday, usually from 8 a.m. to 8 p.m. according to the schedule of the LUT courses.

Nine measurement sectors were allocated within the area A1. Sensors for measuring the air thermal parameters and CO_2 concentrations were located in the middle of each sector, approximately at the height of the students' heads (1.2 m). The measurements of the indoor air thermal parameters and the CO_2 concentrations were performed using a multisensor system Almemo 5690-2M (Ahlborn, Germany).

Aerosol and bioaerosol concentrations were measured in the middle of the area A1 (in sector 5). Aerosol particle number concentrations were determined by means of a laser particle counter ROYCO 243A, equipped with iso-Diluter D50 (Pacific Scientific Instruments, USA). The samples were collected at 60-second intervals with a 15-minute delay time. The counter categorized the collected particles into four size ranges: 0.3-0.5, 0.5–5, 5–10 and >10 μm. Signal to noise ratio was 1.6:1 at maximum sensitivity (0.3 μm).

Bacteria concentrations were periodically determined before, during, and after lectures according to the Standard [27]. Air sampling was performed using settling plates [28]. Petri dishes containing a solid nutrient medium (Nutrient Agar for a total number of bacteria and Chapman Agar for staphylococci) were left open to air for 15 minutes. Microbes carried by inert particles fell onto the surface of the nutrient and after 48h of incubation at 37°C the grown colonies were counted. The results were presented as colony forming units per cubic meter of air (CFU/m^3).

The acceptability of the indoor air quality (ACC) which is considered as an indicator of the PAQ was determined on the basis of the measurements of the indoor air thermal parameters and with the application of the Weber-Fechner psychophysical low and the patent pending dependencies [5, 6]. The ACC was determined from the following formulae:

$$ACC = \mathrm{a} \ln t + b \ln RH + \mathrm{c} \tag{1}$$

where t is the indoor air temperature [°C], RH is relative humidity [-] and a, b, c are empirical constants, which for conditions in the examined auditorium were assumed as follows: a = -2.1508, b = -0.0727 and c = 7.0404.

These values of the ACC were determined in the auditorium sectors continuously (in every 10 seconds). The ACC for the whole auditorium was also continuously determined as well as the average ACC values calculated for 15-minute intervals. The ACC was also sensory assessed by the students participating in the experiments. Immediately upon entering the auditorium and at the end of the lecture, they were asked to fill out a questionnaire, which contained the vertical continuous scale for rating the air acceptability [33]. The scale was coded as follows: 1 – clearly acceptable, 0 – just acceptable/ just not acceptable, -1 – clearly not acceptable. The mean ACC of the subjects' votes in the given sector were used to describe the PAQ in that sector. The average values of the sensory assessed ACC for all sectors at the beginning and at the end of the lectures were calculated. Only these average values of the sensory assessed ACC were considered for this study. The subjects were untrained LUT students; male and female aged between 21 and 24, either smoking or non-smoking, having lectures in the auditorium according to the LUT course schedule. The assumption was that the students were to feel thermally comfortable; therefore, prior to each lecture they were informed about the experimental procedures and they were allowed to modify their clothing to feel comfortable. However, the students were not informed about the experimental conditions as regards the air quality and the air thermal conditions experienced during a given lecture. They were not examined medically and were not questioned about their health condition, e.g. chronic diseases, allergies or past medical conditions.

The experiments were conducted during several days in the springtime 2008.

RESULTS AND DISCUSSION

The first objective consisted in verifying how the aerosol, bioaerosol and CO_2 concentrations as well as the assessed and instrumentally determined PAQ change with the altered indoor air thermal parameters and variable occupancy in the examined auditorium.

The graphs in Figure 2 present the time series of the concentration of the measured aerosol size fractions, the indoor air temperature and relative humidity in the auditorium.

Finer aerosol particle (0.3–0.5 μm and 0.5–5 μm) number concentrations changed almost in accordance with the changes of the indoor air thermal parameters, namely they generally increased with the increase of the relative humidity and the decrease of the indoor air temperature. The reason could be the shift of the finer particle size distributions associated with water uptake or release when these particles are exposed to changing humidity conditions [25]. The opposite tendency was demonstrated by coarser aerosol particle (5–10 μm and >10 μm) number concentrations. In this case a certain increase of the concentrations was observed with the increase of the air temperature (decrease of the relative humidity). Such changes could be relevant to interdependence between coarser particle concentration, activity of occupants and indoor air temperature [4, 15]. The calculated correlation coefficients and levels of significance are presented in Table 1.

Table 1. Correlation coefficients between the temperature (T), relative humidity (RH), number of students (SN), CO_2 concentration (CO_2), bacteria concentration (C_B), staphylococci concentration (C_S), acceptability of the air quality (ACC) and concentration of the measured particle size fractions

	Particle size fraction [μm]				
	0.3 – 0.5	0.5 – 5	5 – 10	> 10	> 5
T	-0.196***	-0.266***	0.213***	0.209***	0.217***
RH	0.216***	0.168***	0.043	0.041	0.043
SN	0.034	-0.001	0.573***	0.565***	0.634***
CO_2	-0.045	-0.062	0.769***	0.728***	0.775***
C_B	0.240	0.222	0.611**	0.499*	0.599**
C_S	0.305	0.280	0.546**	0.461*	0.561**
ACC	0.167***	0.225***	-0.209***	-0.208***	-0.214***

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

It must be noted that the indoor air temperature in the occupied auditorium evidently increased above the set values of the input air temperature. In turn, the sole presence of the students favored coarser aerosol particles. It is confirmed by the graphs in Figure 3, which show the changes of the concentration of the measured particle fractions and the variations of the number of students present in the auditorium.

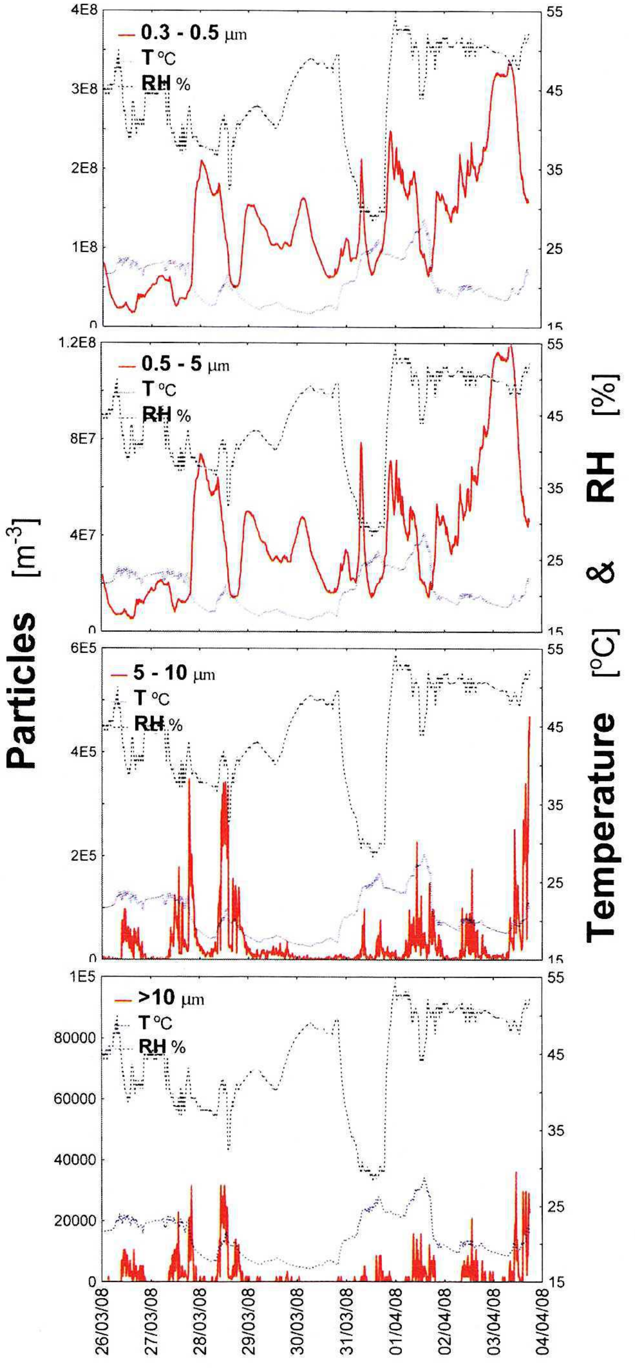

Fig. 2. Time series of aerosol particle number concentration, the indoor air temperature and relative humidity in the auditorium.

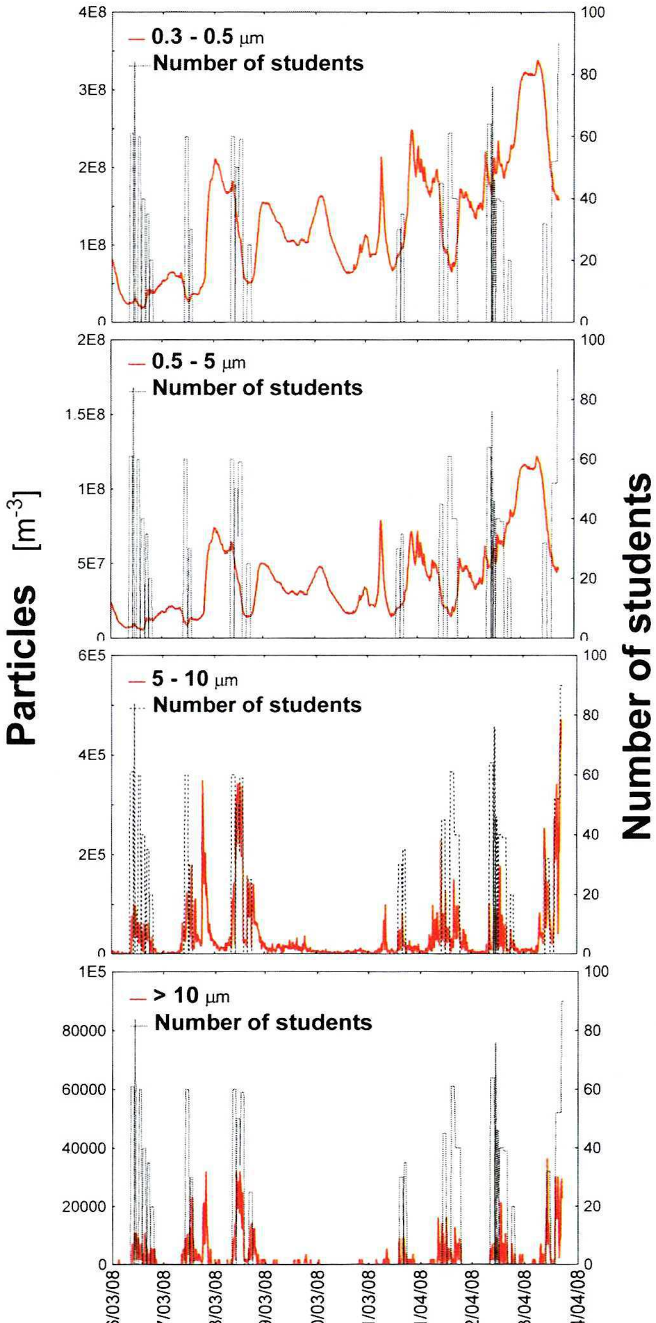

Fig. 3. The changes of the aerosol particle concentration and the number of students in the auditorium.

It can be seen that the coarser aerosol particles were mainly measured when the students were present in the auditorium. The statistically significant positive correlations were found between the number of students and concentrations of these particles (Table 1). Braniš *et al.*, Ferro *et al.* [4, 12] and other researchers reported analogous results as far as the trend is concerned. However, such high correlation was not obtained in the conducted measurements ($r \approx 0.60$). It could result from the fact that coarser particles were registered generally at the beginning of the lectures when the students were taking seats and in the end when they were leaving the auditorium. At that time, there was an increased air turbulence which resulted in the resuspension of the particles deposited on the indoor surfaces as well as in more intensive emissions from the handled materials [14, 18, 19]. During the lectures or when no lectures were conducted, either small amounts of coarser particles were registered or they were not registered at all. According to the literature data, both aerosol particles [3, 31] and interdependent indoor air thermal parameters [10, 11] influence the PAQ. The above is also verified by the obtained results in the examined auditorium. The graphs in Figure 4a,b present the changes of the PAQ which could be equivalently displayed by the changes of the instrumentally determined ACC and the concentrations of the fine (0.3–5 μm) and coarse (> 5 μm) aerosol particle fractions.

It can be clearly seen from the graphs that the changes of the ACC in the auditorium trace the variations of the fine aerosol particle concentrations. In the case of coarse aerosol particles, this relation is reversed (the ACC decreases when the coarse particle concentrations increase). Indoor air thermal parameter changes should not be disregarded because, as it has been mentioned before, they influence the aerosol concentrations and the ACC. According to the study of Fang *et al.* [10] the ACC is in inverse to the air thermodynamic properties – the ACC linearly decreases with the increase of the air enthalpy. However, taking into consideration the fact that the main cause of the coarse particles increase is the presence of the students in the auditorium, one can assume that they are responsible for the deterioration of the PAQ. The graphs in Figure 4c which present the time series of ACC and the number of present students may confirm it. The variable occupancy in the considered auditorium can, in turn, be closely tracked by the CO_2 concentration changes. This is due to the fact that the students who perform a specific activity in the auditorium exhale CO_2 at a predictable level. The observed changes of the CO_2 concentration and simultaneous changes of the PAQ shown in Figure 4d are consistent with the variations of the number of the present students. The changes of the PAQ are displayed by the according changes of both the instrumentally determined and sensory assessed ACC values [5]. These two ways of the ACC determination in the sectors of the occupied area in the examined auditorium gave similar results. The mean differences were within the error of the ACC sensory assessments which amounted to 0.15. The graphs in Figure 5a,b,c,d illustrate respectively the relationships between the CO_2, the coarse aerosol particle and the bacteria (staphylococci) mean concentrations as well as the instrumentally determined/sensory assessed ACC and the number of students present in the auditorium.

The values of the indoor air parameters constitute the averages of their measurements in 15 minute time intervals for the whole auditorium. Only the values of the sensory assessed ACC come from the assessments performed at the beginning and at the end of the lectures. In the case of microorganisms, the data concerning their concentration levels was used only as an additional confirmation of the influence of the number of students on the PAQ in the examined auditorium. The determined bacteria (staphylococci)

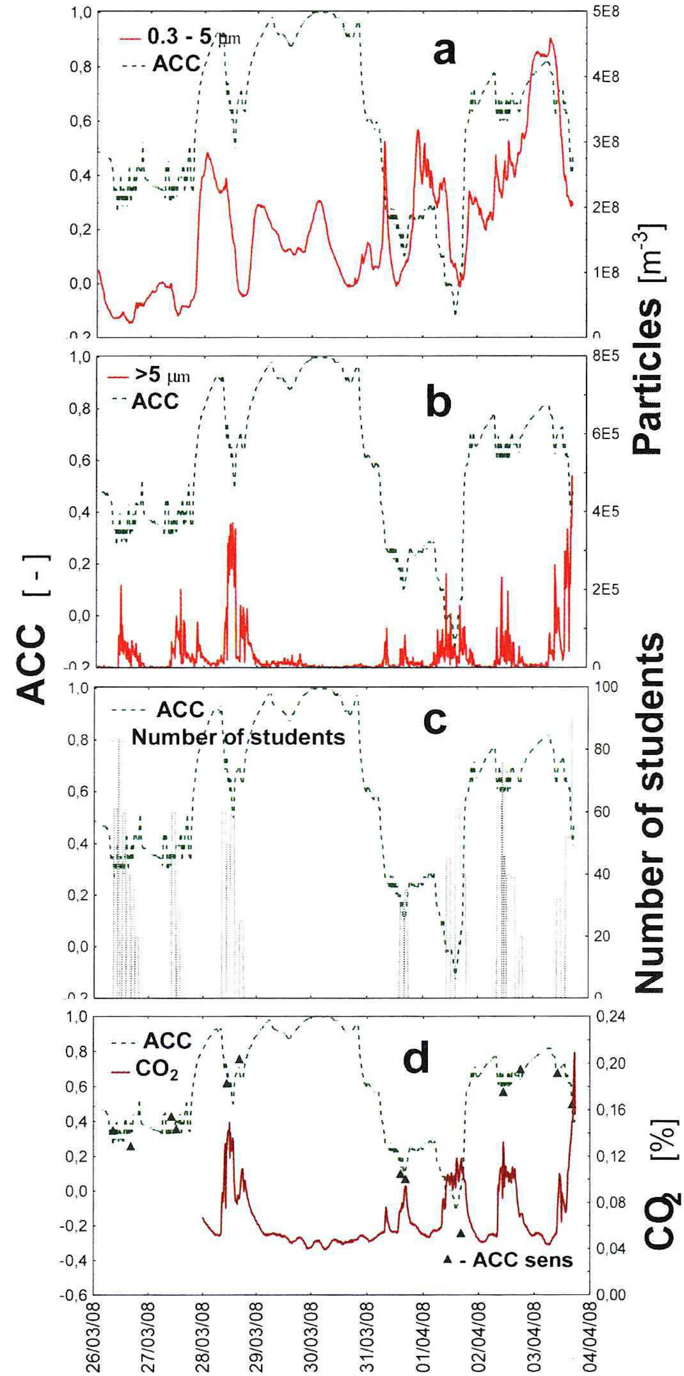

Fig. 4. The changes of the acceptability of air quality, the concentration of fine and coarse aerosol particles, the number of students and the CO_2 concentration in the auditorium.

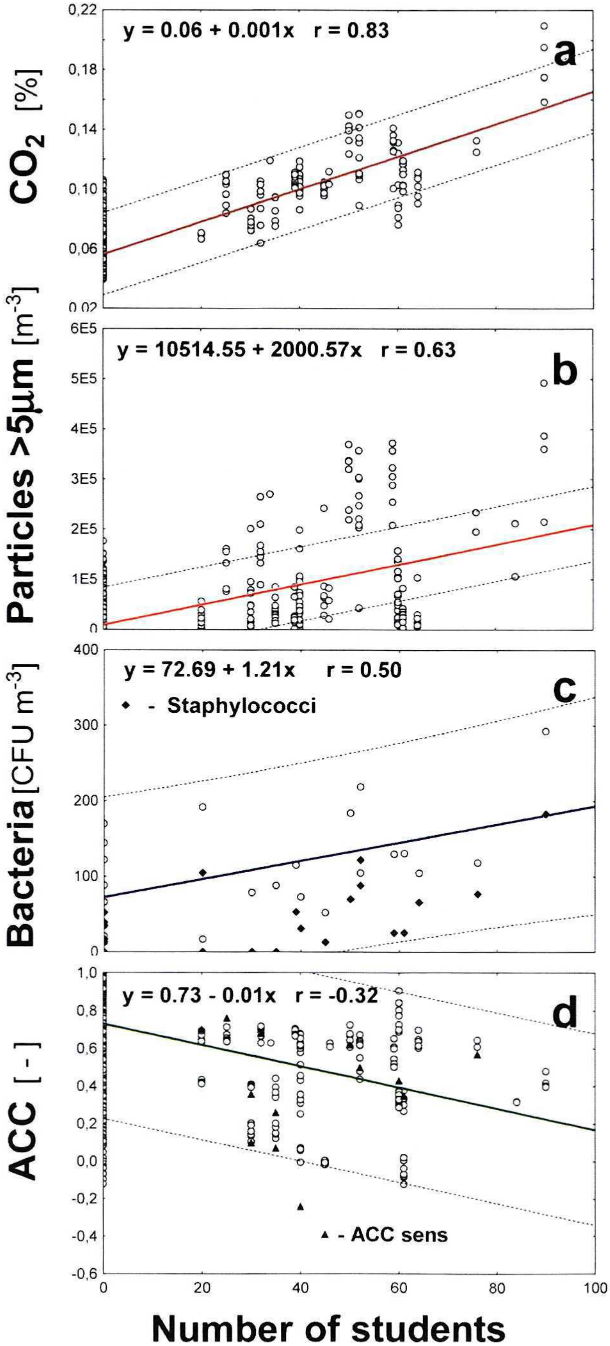

Fig. 5. The dependence of the CO_2, the coarse aerosol particle, the bacteria concentrations and the acceptability of air quality on the number of students in the auditorium.

concentrations were not significantly different from the data presented in the literature [3, 34]. Linear regressions are calculated for the individual relations presented in Figure 5 and the 95% prediction intervals are marked. It follows from the results that despite of the operation of the air-conditioning system and altered indoor thermal conditions in the auditorium, the increase of the number of students results in the increase of the CO_2, the coarse aerosol particle and the determined microorganism concentrations and at the same time in the deterioration of the PAQ. The correlation coefficients and levels of significance are presented in Table 2.

Table 2. Correlation coefficients between the CO_2 concentration (CO_2), bacteria concentration (C_B), staphylococci concentration (C_S), air acceptability (ACC) and the temperature (T), relative humidity (RH), number of students (SN)

	T	RH	SN
CO_2	0.380***	0.060	0.832***
C_B	-0.047	0.355	0.502*
C_S	-0.276	0.511*	0.557**
ACC	-0.983***	-0.096	-0.319***

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

The best association was obtained between the CO_2 concentration and the number of students. In this case the correlation coefficient $r = 0.832$; the significance level $p < 0.001$. The statistically significant relations between the coarse aerosol particle and the microorganism concentrations as well as the ACC and the number of students occur despite the substantial scattering of the experimental points around the best-fit lines. It can be assumed that all the presented relations could be more accurate if, which is planned in future studies, results from more experiments with a larger range of number of students present in the auditorium (to its maximum capacity of 186 students) were considered in determining those relations and the altered indoor conditions where taken into account.

The next aim of the paper was to present a suggestion of improving the control of the existing auditorium ventilation system and the indication of the further direction of the research. The performed measurements showed a dependency between the number of students present in the auditorium and the parameters determining the PAQ. Pursuant to the literature data [9, 36] and the performed measurements, the CO_2 level may be treated as an indirect measure of the occupancy. Therefore, the CO_2 monitoring seems to be a rational basis for controlling the ventilation in the auditorium. However, various performed research demonstrated that CO_2-based demand control ventilation strategy (DCV) may save energy but it does not always ensure the desired PAQ [9, 21, 36]. Energy savings come from controlling the ventilation on the basis of the actual occupancy indicated by the indoor CO_2 level. The PAQ is, in turn, affected by the type of pollution sources in indoor spaces. Under certain conditions, CO_2-based DCV strategy may be applied in rooms in which people are the main contaminant source. If the contaminants associated with the building are dominant, this DCV strategy may lead to an unsatisfactory PAQ. Moreover, it may be effective only in steady state conditions [9, 36]. In the case of the examined auditorium, there are constant variations of the number and activities of the students.

Considerable variations of the activities occurring at the beginning and at the end of the classes (the students entering and leaving the auditorium) result in noticeable changes in the PAQ. Those PAQ changes are not reflected in the changes of the CO_2 content and would not be taken into consideration in the discussed conventional DCV strategy. Similarly, the changes of the PAQ in sectors differentiated in terms of the number and activity of the students and also in terms of the local thermal loads would be considered only to a small extent or would not be considered at all. In consequence, an identical amount of air with the same physicochemical parameters would be supplied to all ventilated sectors in the auditorium. It would result in an over-ventilation in some sectors and an under ventilation in others [24, 37]. The differences in PAQ which arise in those sectors may be leveled with the use of the DCV strategy for multi-zone ventilation [9, 29]. This strategy could supply the varied amount of air of appropriate parameters according to the zonal needs. However, for such ventilation control strategy to be effective in the considered auditorium, it would have to ensure thermal comfort and PAQ in the individual sectors while maintaining ventilation requirements [26] and minimizing energy consumption. Considering PAQ, this strategy would have to be based not only on the CO_2 monitoring but also on the results of the indoor air other significant parameter measurements and relations which influence the PAQ in the sectors. The local variations in the number and activities of students could be taken into account by aerosol concentration measurements and continuous instrumental determinations of the ACC in the auditorium sectors. If such ventilation control strategy was accomplished it should ensure the comfort, health and productivity of the students. It should also bring financial benefits related to a more economical energy use as a result of improving the air-conditioning system overall performance through, e.g. the elimination of the over-ventilation and optimizing the thermal parameters of the supplied air to the sectors. Further, more detailed studies are necessary in order to implement this ventilation control strategy to the examined auditorium and to other rooms of similar type and purpose.

CONCLUSIONS

The coarse aerosol, bioaerosol particle and the CO_2 concentrations and also the PAQ in the air-conditioned auditorium with the altered indoor air thermal parameters are significantly dependant on the presence and activities of the students. The effective ventilation control strategy should take into consideration, apart from the CO_2 level, other significant parameters of the indoor air and relations which influence the PAQ in the occupied area. In order to take into account the local variations in the number and activities of students, continuous monitoring of the PAQ in the individual sectors has been suggested. The PAQ continuous monitoring could be accomplished by aerosol concentration measurements and the ACC instrumental determinations. The practical implementation of the ventilation control strategy based on continuous instrumental determinations of the PAQ in the sectors should improve the occupants' comfort, health and productivity. It should also bring financial benefits connected with a more economical energy use.

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STEROWANIE WENTYLACJĄ OPARTE NA POMIARACH CO_2, KONCENTRACJI AEROZOLI I WYCZUWALNEJ JAKOŚCI POWIETRZA – STUDIUM PRZYPADKU

Z koncepcją sterowania wentylacją w pomieszczeniach ze zmienną liczbą użytkowników, opartą na monitorowaniu CO_2, związanych jest szereg ograniczeń. Weryfikacyjne badania zostały przeprowadzone w rzeczywistych warunkach klimatyzowanej auli, przy zmienianych parametrach termicznych powietrza wentylacyjnego i zmiennej liczbie obecnych studentów. W strefie przebywania ludzi mierzone było stężenie CO_2 i ilościowe koncentracje drobnych i grubych cząstek aerozolowych (> 0,3 μm) oraz bioaerozolowych (bakterii i gronkowców), a w poszczególnych sektorach tej strefy mierzone były w sposób ciągły parametry termiczne powietrza wewnętrznego. Na podstawie instrumentalnych pomiarów oraz sensorycznych ocen określana była również akceptowalność jakości powietrza (ACC). Zasugerowana została strategia sterowania wentylacją, która oprócz pomiarów CO_2 wykorzystuje ciągły monitoring wyczuwalnej jakości powietrza (PAQ) w sektorach auli. Monitoring PAQ mógłby być realizowany na podstawie pomiarów koncentracji aerozoli i instrumentalnie określanej ACC. Strategia ta zapewni pożądaną PAQ w każdym sektorze, co powinno korzystnie wpłynąć na komfort, zdrowie i produktywność użytkowników, a poprzez usprawnienie działania systemu klimatyzacji strategia ta powinna przyczynić się do oszczędności energii nie tylko w przypadku zastosowania w rozpatrywanej auli.