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# VARIATIONS IN PARTICLE CONCENTRATIONS AND INDOOR AIR PARAMETERS IN CLASSROOMS IN THE HEATING AND SUMMER SEASONS

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**Keywords:** Classroom, particle mass concentration, particle number concentration, student exposure, indoor air parameters.

**Abstract:** Simultaneous measurements of the indoor and outdoor particle mass (PM) and particle number (PN) concentrations as well as the air temperature, relative humidity (RH), and $CO_2$ concentrations have been conducted in 6 occupied (L) and unoccupied (V) classrooms in 3 secondary schools in Lublin, Poland, in the heating (H) and summer (S) seasons. The schools were located in residential areas where the majority of private houses are heated by means of coal-burning stoves. The ratios of the average particle concentrations in occupied and unoccupied classrooms (L/V) were higher during the heating season measurements. The ratios of the average particle concentrations during the measurements in the heating and summer seasons (H/S) were higher in occupied classrooms. In both seasons the average PM and PN concentrations amounted to 239 μg/m$^3$ and 7.4×10$^3$/cm$^3$ in the occupied classrooms, and to 76 μg/m$^3$ and 5.4×10$^3$/cm$^3$ in the unoccupied classrooms, respectively. The particle exposures experienced by students were higher in the monitored classrooms than outdoors and were on average about 50% higher in the heating than in the summer season. A positive correlation between mass concentrations of coarse particles and indoor air temperature, RH and $CO_2$ concentrations in both seasons was observed. The concentrations of fine particles were negatively correlated with the indoor air parameters in the heating season, and positively correlated in the summer season.

## INTRODUCTION

The quality of the indoor air significantly affects people's health and their well-being. Apart from such contaminants as volatile organic compounds also the aerosol particles present in the air have an impact on the quality of the indoor air in apartments, offices, schools and other educational premises as well as in means of transport [8, 9, 27].

School facilities are among the premises in which indoor particle concentrations can considerably exceed ambient particle concentrations [5, 10, 12]. Despite the fact that certain characteristic particle emission sources do not or seldom exist, e.g. smoking and cooking, particles generated in classrooms may be as toxic as particles in the ambient air [11]. Such particles can also pose a biological threat to students' health [7].

School-aged children spend a significant portion of their time indoors in classrooms. They are also more susceptible than adults to the harmful effects of indoor particles [3, 30]. Particles which are suspended in the classroom air are to a large extent responsible for increased allergies, respiratory infections, asthma exacerbations and deteriorating lung function parameters among students [34]. In turn, such health problems are related to reduced students' attendance and performance [18, 29].

Indoor particle concentration levels in typical classrooms are mainly dependent on the presence of the students and their physical activity [1, 10, 33]. They are also influenced by the outdoor air particle concentration changes and ventilation intensity [13]. In general, the higher the air exchange rate, the lower the indoor particle concentrations [12]. The outdoor and indoor microclimatic parameters can also be of significance [6, 26].

Despite intensive research, it is still not entirely clear how the concentrations of indoor particles in classrooms are associated with the occupation, outdoor particle emissions and with the indoor and outdoor air parameters related to a given season. The factors which influence the particle concentrations in classrooms and the relations between them can be important when student exposures and associated health risks are determined.

The present study constitutes a part of a broader study the preliminary results of which have been reported elsewhere [7, 25]. Its aim was to assess the indoor air quality in typical school classrooms in Lublin, Poland and to characterize the key factors that have an impact on this quality. The purpose of this study was to investigate the particle mass (PM) and particle number (PN) concentrations in classrooms. Special emphasis was placed on the influence of students' presence, the outdoor particle emissions from coal-burning stoves in residential houses located near the school, the season and the indoor and outdoor air thermal parameters.

## MATERIAL AND METHODS

The measurements were conducted in 6 classrooms in 3 secondary schools in Lublin, Poland. The population of the city and its close surroundings is about 590,000 inhabitants. The population density is 2407/km$^2$ [32]. Lublin is mostly surrounded by rural areas. The schools were located in different parts of the city in densely populated residential areas, where a significant number of private residential houses are heated by means of coal stoves. One of the schools was built in 1930, the other two were built in 1970. Table 1 summarizes the characteristics of the monitored classrooms and provides the measurement dates. In each school (numbers in parentheses), two classrooms were chosen for monitoring. These classrooms were used for teaching either computer science (C1) or biology (C2) and they were located on the first, second and third floor of the school buildings. The classrooms had various floor areas (from 29 to 71 m$^2$) and volumes (from 96 to 250 m$^3$). The maximum occupancy depended on the size of the classroom and ranged between 18–34 students. All the classrooms had ceramic tile floors and were equipped with standard school furniture. Traditional blackboards for chalk were used in the biology classrooms and whiteboards for color-board markers were used in the computer science classrooms. None of the monitored classrooms had air conditioning systems which is a standard for school facilities in Poland. Natural ventilation was obtained through large double-glazed PCV windows.

Table 1. Characteristics of the monitored classrooms and the measurement dates

| Classroom attributes | | School 1 | | School 2 | | School 3 | |
|---|---|---|---|---|---|---|---|
| | | C1(1) | C2(1) | C1(2) | C2(2) | C1(3) | C2(3) |
| Floor number | | 2 | 1 | 3 | 2 | 3 | 1 |
| Volume | [$m^3$] | 96 | 130 | 205 | 250 | 221 | 183 |
| Floor area | [$m^2$] | 29 | 46 | 57 | 69 | 71 | 59 |
| Number of seats | | 18 | 32 | 18 | 34 | 22 | 32 |
| Measurements | | | | | | | |
| Heating season (H) | L | 03.09.10 | 03.10.10 | 03.30.10 | 03.31.10 | 03.16.10 | 03.17.10 |
| | V | 03.13.10 | 03.14.10 | 04.03.10 | 04.04.10 | 03.20.10 | 03.21.10 |
| Summer season (S) | L | 06.10.10 | 06.11.10 | 05.20.10 | 05.21.10 | 06.15.10 | 06.16.10 |
| | V | 06.12.10 | 06.13.10 | 05.22.10 | 05.23.10 | 06.19.10 | 06.20.10 |

L – occupied classroom, V – unoccupied classroom

Continuous measurements of indoor and outdoor air particulate matter concentration levels, thermal parameters and $CO_2$ concentrations were performed both in the heating season (H), and then again in the summer season (S). Two-day measurements were performed in classrooms during teaching hours (L) and in unoccupied classrooms (V) and lasted for a few hours per day. The sampling devices for the indoor measurements were placed on empty desks in the middle of the classrooms at the height of 110 cm. The sampling devices for the parallel outdoor measurements were located outside the windows of the monitored classrooms. Laser photometers Dust Trak DRX model 8533 (TSI Inc., Shoreview, MN, USA) were used for continuous determination of the concentrations of particle size-segregated mass fractions $PM_1$, $PM_{2.5}$, Respirable, $PM_{10}$, and TSP (Total Suspended Particle). Fractions $PM_1$ and $PM_{2.5}$ characterize mass concentration of fine particles with an aerodynamic diameter less than or equal to 1 μm and 2.5 μm cut point, respectively. Mass concentrations of coarse particles (greater than 2.5 μm cut point) are characterized by $PM_{10}$ and TSP fractions. Because the data obtained for $PM_{2.5}$ and Respirable fraction did not differ significantly, the latter was not considered in this paper. Number concentrations of particles with the size range from 0.02 to greater than 1 μm were determined using the P-Trak model 8525 (TSI Inc., Shoreview, MN, USA) condensation particle counters. The indoor and outdoor air temperature and relative humidity (RH) were measured by Onset Hobo U12 External Data Logger sensors with the temperature measurement range from –20 to 70°C and the RH from 5 to 95%. The GMD/W20 sensors manufactured by VAISALA with a measurement range from 0 to 5000 ppm were used to measure the $CO_2$ concentration. The chosen sampling interval for all the measuring instruments was 60 s. Before the measurements, all instruments were calibrated by their producers. The distribution of the measurement results allowed to use the Spearmen correlation coefficients as indicators of the mutual relations between the indoor and outdoor PM and PN concentrations, air parameters, occupation and characteristic attributes of the classrooms.

## RESULTS AND DISCUSSION

***PM and PN concentration changes***

Different coexisting factors affecting particle concentration levels in the monitored classrooms are evident on the indoor PM and PN concentration time series. Figures 1 and 2 illustrate the exemplary PM and PN concentration changes in an occupied and empty classroom C1(1), in a determined time period, during one-day measurements performed respectively in the heating and summer seasons. The time series data for PM and PN concentrations in the outdoor air and also for the indoor and outdoor air temperature (Temp), relative humidity (RH) and $CO_2$ concentrations are also shown.

In both seasons the presence and physical activity of students in the classrooms seem to be the most important factors which change the particulate matter concentration levels and the measured indoor air parameters. The observable fluctuations are clearly connected with the changes in the classroom occupancy status. Their rough quantity evaluation for particle concentrations could be accomplished by taking into account the maximum and average PM and PN concentration levels. For example, in the heating season measurements, the maximum concentrations of the TSP fraction which periodically occur in the variably occupied classroom C1(1) were up to 14 times higher than the average level (~50 $\mu g/m^3$) in the unoccupied classroom. In the summer season measurements this proportion was lower (TSP maximum concentrations were up to 4 times higher than the average level), however, the average TSP concentration level in the empty classroom was slightly higher (~80 $\mu g/m^3$). The maximum PN concentrations during the measurements in both seasons reached the average PN concentration levels in the outdoor air.

The biggest increases of the PM and PN concentration levels were observed at the beginning of the classes and during breaks between classes. This can be explained by the increased physical activity of the students during that time which in consequence results in the intensified air movement in the classrooms. This, in turn, increases the resuspension of dust particles deposited on indoor surfaces and thus the particle concentration in the indoor air [22, 23]. Resuspension mainly affects supermicrometer particles but in the case of the considered classrooms it could be of significance for smaller (about 1 μm) particles as well. The considerable amounts of such particles originate from emissions from coal-burning stoves in the residential houses located near the schools. The main mass concentration of coal combustion particles ranges between 0.8–10 μm with predominance of 1–2 μm particles [21]. These particles enter the classrooms and are deposited on indoor surfaces and could be accumulated due to insufficient cleaning. During the students' physical activity they undergo resuspension processes and they have a major impact on the measured PM concentrations. They could also affect the measured PN concentrations due to particle detection range of the applied instruments.

During the breaks between classes, especially in the summer season, the classrooms were frequently ventilated by opening the windows and doors. This manner of ventilation caused additional intensive indoor air movement and substantial changes in the indoor particle concentrations. It is also important to note that the average outdoor particle concentration levels were higher than the corresponding indoor levels in the vacant classrooms [16, 19]. According to the number of studies, in naturally ventilated spaces, such as the monitored classrooms, the input of the outdoor particles is a very important factor which has an impact on the indoor particle concentration levels [12, 20]. Moreover,

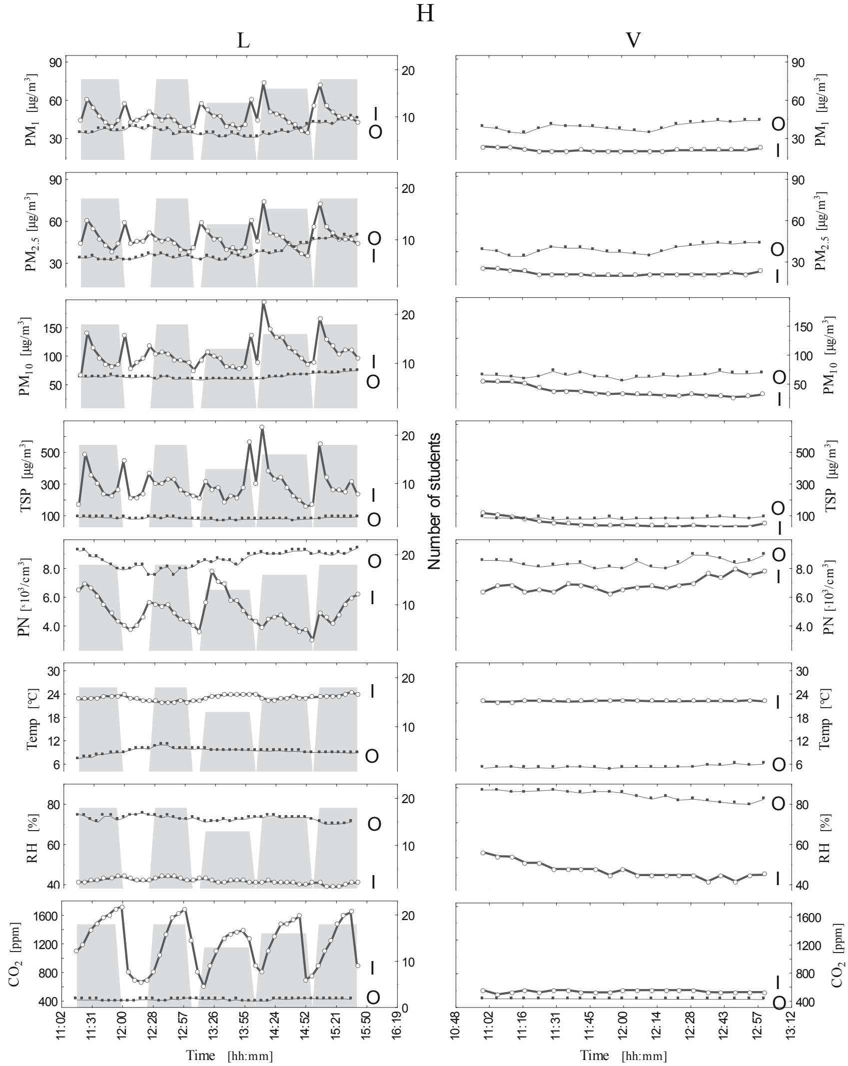


Fig. 1. Indoor (I) and outdoor (O) particle mass (PM) and particle number (PN) concentration, air temperature (Temp), relative humidity (RH) and $CO_2$ concentration time series in the occupied (L) and unoccupied (V) classroom C1(1) during one school day in the heating (H) season measurements

particles generated by other unidentified sources inside the schools, e.g. cleaning or renovation activity could also have entered the classrooms.

During the classes, when the students were already seated and their physical activity was relatively low, a decrease of the indoor particle concentrations was observed. It was especially visible for concentrations of coarse particles characterized by $PM_{10}$ and TSP fractions. These particles undergo effective gravitational sedimentation hence they were relatively quickly removed from the indoor air and deposited on indoor surfaces as dust [2, 24]. The concentrations of fine particles ($PM_1$ and $PM_{2.5}$ fractions) decreased to

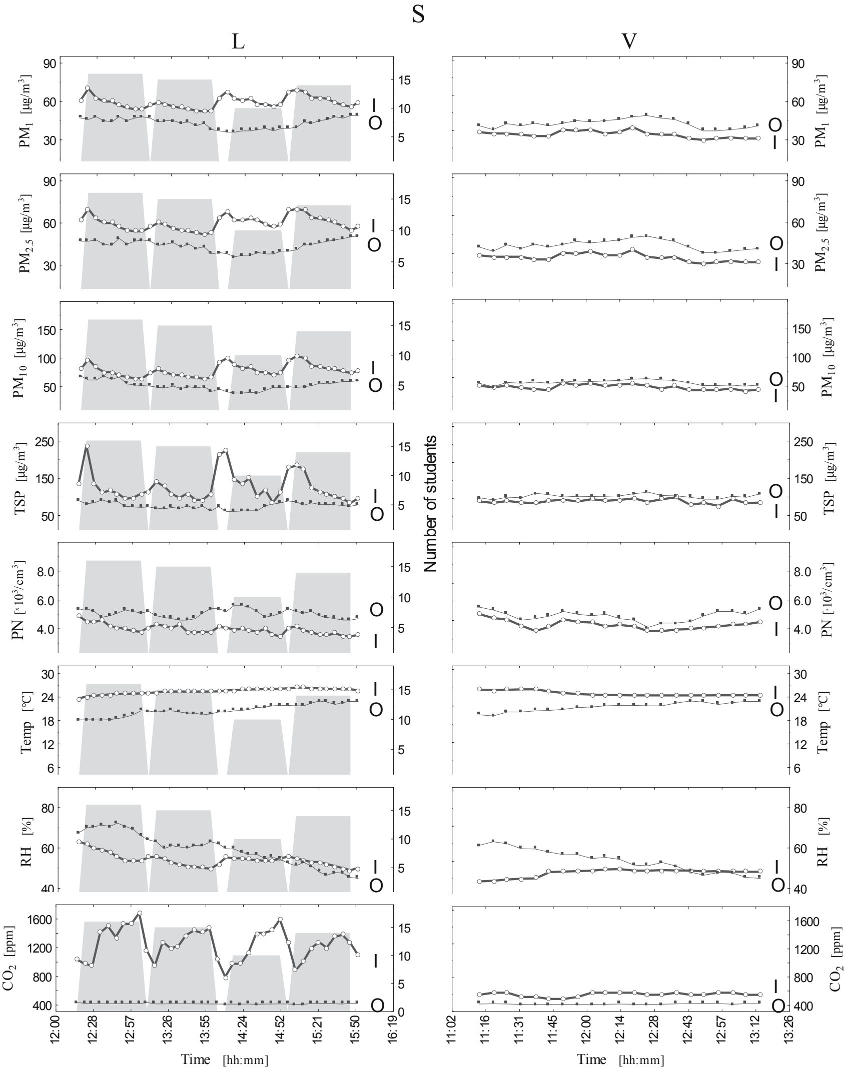


Fig. 2. Indoor (I) and outdoor (O) particle mass (PM) and particle number (PN) concentration, air temperature (Temp), relative humidity (RH) and $CO_2$ concentration time series in the occupied (L) and unoccupied (V) classroom C1(1) during one school day in the summer season (S) measurements

a lesser extent. This, in turn, results from the greater stability of these particles to remain suspended in the indoor air [14, 15].

***Occupation and season***

The presence of the students in all the monitored classrooms, regardless of the season, resulted in a significant increase in the concentrations of the measured particles. For example, for the measurements in both seasons, the average concentrations of the $PM_1$ and TSP in the occupied classrooms amounted to 61 and 239 μg/m$^3$, and in the empty classrooms to 49 and 76 μg/m$^3$, respectively. The average PN concentration in the occupied classrooms amounted to $7.4\times10^3$/cm$^3$ and to $5.4\times10^3$/cm$^3$ in the empty classrooms. Occurring cases of higher $PM_1$ and PN concentrations in the empty classrooms could be the effect of the already mentioned, instable ventilation conditions during the measurements or the coexistence of other affecting factors e.g. particle sources inside the schools or particle concentration changes in the outdoor air [4, 17, 21, 22].

It was also observed that for the measurements in both seasons the ranges of particle concentration changes were greater in occupied classrooms. For example, the ranges of the $PM_1$ and the TSP fraction concentration changes in the occupied classrooms were on average about 5 and 18 times greater than in the empty classrooms respectively. In the case of PN concentrations, such ratio amounted to about 7. The average coefficient of variation (CV) values for $PM_1$ and TSP concentrations in the occupied classrooms amounted to 19.0 and 42.5%, and in the empty classrooms to 6.4 and 9.7%, respectively. The corresponding average CV values for the PN concentrations were 20.5 and 5.2%. The maximum standard error of the evaluated CVs was 1.2%.

The ratios of the average particle concentrations in the occupied and empty classrooms (L/V) in the heating and summer season measurements are presented in Table 2.

Table 2. Occupied-to-unoccupied ratios (L/V) of the average particle mass (PM) and particle number (PN) concentrations in the monitored classrooms during the heating (H) and summer season (S) measurements. N is a time-weighted average number of students present during the measurement periods which include the breaks between the classes when the students were not present in the room

| Classroom | | $PM_1$ | $PM_{2.5}$ | $PM_{10}$ | TSP | PN | N |
|---|---|---|---|---|---|---|---|
| C1(1) | H | 2.14 | 2.09 | 2.69 | 5.03 | 0.72 | 13.2 ± 6.9 (16–18) |
| | S | 1.74 | 1.76 | 1.63 | 1.52 | 0.94 | 11.6 ± 5.6 (15–16) |
| C2(1) | H | 1.90 | 1.92 | 2.65 | 4.27 | 3.20 | 9.2 ± 4.6 (10–13) |
| | S | 1.50 | 1.50 | 1.68 | 2.34 | 0.99 | 6.5 ± 7.5 (7–17) |
| C1(2) | H | 0.75 | 0.75 | 1.36 | 3.49 | 2.40 | 11.2 ± 5.9 (12–17) |
| | S | 1.24 | 1.27 | 1.96 | 3.59 | 1.60 | 11.2 ± 5.3 (12–16) |
| C2(2) | H | 1.61 | 1.64 | 2.04 | 3.30 | 2.68 | 18.4 ± 10.2 (22–29) |
| | S | 0.76 | 0.78 | 1.22 | 2.45 | 1.37 | 19.2 ± 9.7 (25–26) |
| C1(3) | H | 1.07 | 1.07 | 1.80 | 4.19 | 1.26 | 12.3 ± 6.5 (14/19) |
| | S | 0.52 | 0.53 | 1.14 | 2.49 | 0.81 | 10.7 ± 8.8 (12–24) |
| C2(3) | H | 1.78 | 1.80 | 2.39 | 3.94 | 3.32 | 13.9 ± 7.5 (16/22) |
| | S | 1.21 | 1.22 | 1.94 | 3.72 | 1.31 | 10.5 ± 10.9 (14–28) |
| Average | H | 1.56 | 1.55 | 2.16 | 4.04 | 2.26 | 13.0 ± 3.6 (15–20) |
| | S | 1.16 | 1.18 | 1.60 | 2.69 | 1.17 | 11.6 ± 3.4 (15–22) |

N – mean ± sdev. (median-maximal) number of students.

In all the monitored classrooms the L/V ratios were higher in the heating season and their biggest values were for the concentrations of coarse particles. It may indicate that more particles, especially coarse ones, were generated by students in the classrooms in that season. However, it has to be pointed out that the number of students in the monitored classrooms was, on average, slightly higher during the heating season measurements (Table 2).

In the heating season, the concentrations of the considered particles in the occupied classrooms were higher than in the summer season. It is connected with the increased outdoor particle emissions from coal combustion in that season and the increased particle deposition and resuspension in the classrooms. Table 3 presents the ratios of the average PM and PN concentrations in the heating and summer seasons (H/S) for the occupied and empty classrooms.

The values of H/S ratios in the occupied classrooms are, on average, higher for the coarse particles. For example, the average H/S ratio amounted to 1.26 for the $PM_1$ fraction and 1.43 for the TSP fraction. In case of vacant classrooms these ratios for all considered particles were smaller than 1.

The exposures experienced by students in the monitored classrooms were higher in the occupied classrooms than those estimated outside. In the heating season they were on average about 50% higher. It has to be noted that a substantial portion of the PM exposures (~50%) and the PN exposures (~30%) were attributed to particles generated inside the classrooms.

***Indoor air parameters***

The indoor air parameters in the monitored classrooms are affected by heating (in winter), by the outdoor air parameters, intensity of the ventilation as well as the presence of students

Table 3. Heating to summer season ratios (H/S) of the average particle mass (PM) and particle number (PN) concentrations for the occupied (L) and unoccupied (V) classrooms

| Classroom | | $PM_1$ | $PM_{2.5}$ | $PM_{10}$ | TSP | PN |
|---|---|---|---|---|---|---|
| C1(1) | L | 0.80 | 0.80 | 1.35 | 2.25 | 1.25 |
| | V | 0.65 | 0.68 | 0.81 | 0.68 | 1.63 |
| C2(1) | L | 1.51 | 1.53 | 1.84 | 1.89 | 1.61 |
| | V | 1.17 | 1.19 | 1.16 | 1.04 | 0.50 |
| C1(2) | L | 0.86 | 0.87 | 0.64 | 0.90 | 2.14 |
| | V | 1.44 | 1.46 | 0.92 | 0.93 | 1.44 |
| C2(2) | L | 1.69 | 1.67 | 1.32 | 0.98 | 1.63 |
| | V | 0.80 | 0.80 | 0.79 | 0.73 | 0.83 |
| C1(3) | L | 1.36 | 1.35 | 1.25 | 1.51 | 1.19 |
| | V | 0.66 | 0.67 | 0.80 | 0.89 | 0.76 |
| C2(3) | L | 1.37 | 1.37 | 1.23 | 1.05 | 0.99 |
| | V | 0.93 | 0.93 | 1.00 | 0.99 | 0.39 |
| Average | L | 1.26 | 1.27 | 1.27 | 1.43 | 1.47 |
| | V | 0.94 | 0.96 | 0.91 | 0.88 | 0.93 |

(Figs. 1, 2). The fluctuations of the indoor air temperature, RH and $CO_2$ concentration were most distinct during the time when classes were held in the heating season. During the breaks between classes when students were not present in the classrooms and ventilation conditions were not significantly changed (windows were not opened and doors were only opened occasionally) systematic changes of the measured indoor air parameters were observed. For example, an almost exponential decrease of the $CO_2$ concentrations occurs in the classrooms. The impact of the changing ventilation conditions was more visible during the lessons and breaks in the summer season measurements when less regular fluctuations of the indoor air parameters were observed. In empty classrooms, the measured indoor air parameters were also not stable. In this case other factors, e.g. related to the previous classroom occupation or the presence of the persons setting up the measurement devices could be significant.

During the classes the indoor $CO_2$ concentrations frequently exceeded the level of 1000 ppm, which according to the ASHRAE Standards 62-1989 is the threshold concentration for satisfactory comfort. The $CO_2$ concentration did not meet the ASHRAE Standards in 56% of the teaching hours in the heating season and in 41% of the teaching hours in the summer season measurements. $CO_2$ concentration readings over 1500 ppm were found in about 25% and 7% of the teaching hours in the heating and summer season measurements, respectively.

Several strong relations between the indoor air parameters and particle concentrations were observed in the monitored classrooms. The average tendencies of these relations for the heating and summer season measurements were determined on the basis of the mean correlation coefficients. This way a positive correlation between the mass concentration of coarse particles and indoor air parameters in occupied classrooms for the measurement periods in both seasons was obtained. A negative correlation between the mass and number concentration of fine particles and the measured indoor air parameters was determined for the heating season, whereas a positive correlation was found for the summer season measurements. The exemplary relations between the $PM_1$, TSP and PN, and the indoor air temperature, RH and $CO_2$ concentration in the heating and summer seasons, which best represent the above mentioned tendencies are shown in Figure 3. All the presented correlations are statistically significant, $p < 0.01$.

***Comparison with previous research***

The simultaneous measurements of PM and PN concentrations in occupied and empty classrooms as well as outdoors in both the heating and summer seasons are seldom reported. If they were performed, they were not confronted with the indoor and outdoor air parameters. Most of the individual results presented in this paper are comparable with those in previous studies. Based on the 6-week (October–November) measurements performed in two classrooms in one primary school in Munich, Fromme *et al.* [11] reported the median $PM_{2.5}$ concentration of 37.4 μg/m$^3$ and $PM_{10}$ of 118.2 μg/m$^3$ indoors, while the corresponding results for the outdoor air were 17.0 μg/m$^3$ and 24.2 μg/m$^3$. Heudorf *et al.* [13] measured the indoor air quality in two primary school classrooms in Frankfurt/M for 3 weeks (February–March). Their findings showed that the average level of $PM_{10}$ was 69 μg/m$^3$ and that the measured concentrations were determined by the occupancy, student activity and the frequency of cleaning the classrooms. Lower PM concentrations in a lecturing room in Prague were observed by Braniš *et al.* [6] during the measurements in the fall season

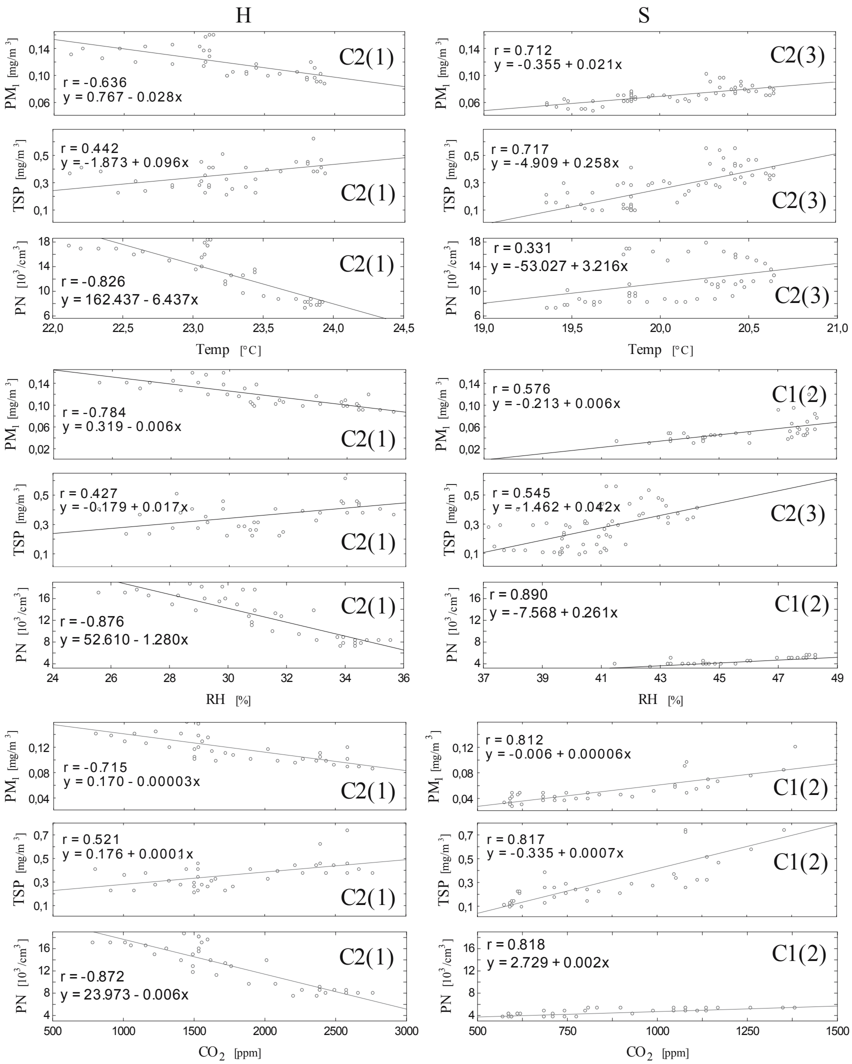


Fig. 3. The relation between the particle mass (PM1 and TSP), particle number (PN) concentrations and indoor air temperature (Temp), relative humidity (RH) and CO2 concentration in the occupied classrooms in the heating (H) and summer (S)seasons

(October–November). The average indoor $PM_{2.5}$ concentration amounted to 21.9 μg/m$^3$ and 42,3 μg/m$^3$ for $PM_{10}$. However, as they pointed out the PM concentrations were measured by the gravimetrical method whose readings are lower than from photometers (e.g. TSI Dust Trak). Relatively smaller concentrations of $PM_{10}$ were also found in 40 classrooms in Korea [28]. The average level was 46.7 μg/m$^3$ in the summer and 39.1 μg/m$^3$ in the winter. Fromme *et al.* [10] reported the median daily values of PM concentrations measured in 58 classrooms in Munich and a neighboring district in the winter between 2.7 and 80.8 μg/m$^3$ (average: 23 μg/m$^3$) for $PM_{2.5}$ and between 16.3 and 313 μg/m$^3$ (average

105 μg/m$^3$) for $PM_{10}$. In the summer the concentrations of $PM_{2.5}$ ranged between 4.6 and 34.8 μg/m$^3$ (average 13.5 μg/m$^3$) and the concentrations of $PM_{10}$ between 18.3 and 178 μg/m$^3$ (average 71.7 μg/m$^3$). Zwoździak *et al.* [34] measured the indoor and outdoor particle concentrations in a secondary school in Wroclaw in the winter/spring and summer/autumn seasons. The average $PM_{10}$ particle concentration was 115.2 μg/m$^3$ indoors and 53.8 μg/m$^3$ outdoors. The concentrations of $PM_1$ and $PM_{2.5}$ were slightly higher inside the school than outdoors and their average values amounted to 23.2 μg/m$^3$ and 46.4 μg/m$^3$, respectively. It has been also indicated that there is a significant correlation between the $PM_{2.5}$ concentration and students' lung function parameters.

When it comes to the PN concentrations, Guo *et al.* [12] reported the results of a 2 week measurement period in September in a village primary school classroom in Australia. The average PN concentration (particles 0.014–0.800 μm) amounted to 2.11×10$^3$/cm$^3$ indoors and 2.93×10$^3$/cm$^3$ outdoors. Fromme *et al.* [10] found that the median PN concentrations (particles 0.010–0.487 μm) measured in 36 classrooms in Munich in the summer, ranged between 2.62 and 12.14×10$^3$/cm$^3$ (average: 6.5×10$^3$/cm$^3$). Weichenthal *et al.* [31] performed measurements in Canada in 37 classrooms. Their study showed the average indoor PN level (particles 0.020–0.100 μm) of 5.0×10$^3$/cm$^3$, and the average outdoor level of 9.0×10$^3$/cm$^3$. Mullen *et al.* [23] measured the PN concentration of particles 0.006–0.100 μm in 6 classrooms in northern California in the summer and winter. In the presence of the students the mean indoor levels ranged between 5.2–16.5×10$^3$/cm$^3$ (average: 10.8×10$^3$/cm$^3$). The corresponding outdoor concentrations were 9.0–26.0×10$^3$/cm$^3$ (average: 18.1×10$^3$/cm$^3$).

The $CO_2$ concentrations in the monitored classrooms are also largely consistent with those in other published studies. Fromme *et al.* [10] reported the $CO_2$ median levels in 85 classrooms in 64 schools in Munich and a neighboring district which ranged between 589 and 4172 ppm (average: 1759 ppm) in the winter, and between 480 and 1875 ppm (average: 890 ppm) in the summer. The corresponding outdoor $CO_2$ concentrations varied from 386 to 472 ppm in the winter, and from 341 to 485 ppm in the summer. In the studies carried out by Heudorf *et al.* [13], the mean $CO_2$ levels in classrooms in 2 schools in Frankfurt/M were from 1051 to 1459 ppm.

The relationships between the particle concentration and the indoor air temperature, RH and $CO_2$ concentration in the monitored classrooms are also, to a large extent, consistent with those in the previous studies. Braniš *et al.* [6] demonstrated a high positive correlation between the $PM_1$ concentration and the RH of indoor and ambient air (the respective correlation coefficients amounted to 0.605 and 0.789). Fromme *et al.* [10] indicated a significant $PM_{2.5}$ concentration decrease by 6.4 μg/m$^3$ in the winter and an increase by 1.7 μg/m$^3$ in the summer per each 10% RH increase. Polednik and Dudzinska [27] demonstrated that coarse aerosol and bioaerosol particle and the $CO_2$ concentrations in an air-conditioned auditorium could be an indicator of the perceived air quality due to correlative and mutual relations with the indoor air parameters.

The estimated student exposures to particles in the monitored classrooms are also comparable with the student exposures reported in previous studies. The daily-integrated exposure to ultra fine particles by students in 6 elementary school classrooms in northern California estimated by Mullen *et al.* [23] was 52×10$^3$/cm$^3$ h/day. In turn, the exposure experienced by these students in their homes was approximately 6 times higher and amounted to 320×10$^3$/cm$^3$ h/day.

The measurements in the monitored classrooms were carried out in real field conditions with varied student activity, classroom ventilation, and outdoor air parameters. Most probably this was the reason why the significant correlations between the particle concentration and the number of students present or classroom location in school buildings, classroom volume, floor area, furnishing materials and blackboard or whiteboard usage in the classrooms reported in some previous studies were hard to find.

## CONCLUSIONS

The results of the measurements performed in classrooms in selected schools in Lublin are consistent with the results reported in previous research in terms of the obtained trends. The PM and PN concentrations mainly depend on the presence of students and are manifold higher in occupied than in unoccupied classrooms. The significant differences in the levels of PM and PN concentrations are observed in the measurements performed during the heating and the summer seasons. This is considerably influenced by coal combustion in the residential houses located in the vicinity of the schools. Such particle emissions substantially contribute to students' exposure and may cause adverse health effects. The mass concentrations of coarse particles in the occupied classrooms were positively correlated with the indoor air temperature, RH and $CO_2$ concentration. The mass and number concentration of fine particles were negatively correlated with indoor air parameters in the heating season, and positively correlated in the summer season.

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## ZMIANY KONCENTRACJI CZĄSTEK I PARAMETRÓW POWIETRZA WEWNĘTRZNEGO W KLASACH W SEZONIE GRZEWCZYM I LETNIM

Pomiary masowych (PM) i ilościowych (PN) koncentracji cząstek, jak również temperatury, wilgotności względnej (RH) i stężenia $CO_2$ przeprowadzono w 3 gimnazjalnych szkołach w Lublinie w sezonie grzewczym (H) i letnim (S). Szkoły były zlokalizowane w dzielnicach, w których większość prywatnych domów ogrzewana jest piecami węglowymi. W każdej ze szkół wybrano 2 klasy, w których wykonano pomiary przy obecności (L) i nieobecności (V) uczniów. Równoległe pomiary przeprowadzono dla powietrza zewnętrznego. Stosunki średnich koncentracji cząstek w klasach z uczniami i bez uczniów (L/V) były większe w sezonie grzewczym. Stosunki średnich koncentracji cząstek podczas pomiarów w sezonie grzewczym i letnim (H/S) były większe w klasach z uczniami. W obydwu sezonach średnie koncentracje PM i PN w klasach z uczniami wynosiły odpowiednio 239 $\mu g/m^3$ i $7{,}4\times10^3/cm^3$, a w klasach bez uczniów 76 $\mu g/m^3$ i $5{,}4\times10^3/cm^3$. Ekspozycje uczniów w klasach były wyższe niż na zewnątrz i były średnio o ok. 50% większe w sezonie grzewczym. W obydwu sezonach zaobserwowano dodatnią korelację pomiędzy masową koncentracją grubych cząstek a temperaturą, RH i stężeniem $CO_2$ w powietrzu wewnętrznym. Koncentracje drobnych cząstek były ujemnie skorelowane z parametrami powietrza wewnętrznego w sezonie grzewczym i dodatnio w sezonie letnim.