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INDOOR-OUTDOOR RELATIONS FOR PM10 MASS CONCENTRATION BASED ON UNIVERSITY BUILDING

RELACJA OUTDOOR-INDOOR DLA STĘŻENIA MASOWEGO PM10 NA PRZYKŁADZIE BUDYNKU UCZELNI

Abstract: The determination of the level of pollutants and reciprocal relations "outside-inside" forms an important component in the study involving assessment and control of indoor air quality. This paper reports the results of a study with regard to the mass concentration of PM10 determined concurrently in the outdoor air surrounding a university building and inside the lecture rooms in it. The research project was undertaken in the cold season and registration included 83 independent observations with the duration of 90 minutes. The research applied a reference method involving measurements of PM10 mass concentration using gravimetric technique. The results were analyzed by application of non-parametric tests. For the purposes of classification of variables and assessment of the role of the specific variables, the analysis was based on the use of principal components. It was indicated that the mass concentration of particulate matter in the lecture rooms does not differ from the levels measured at the same time in the air surrounding the building only during the periods corresponding to periodic room ventilation. It was also found that the design and usage of the buildings, as well as the number and activity of humans determine the aerosanitary conditions in the enclosed spaces formed by the lecture rooms. It was observed that the mass concentration of particulate matter in the rooms is higher in the cold season. A statement was made that design solutions need to be implemented with the purpose of using intelligent ventilation systems.

Keywords: air contamination, aerosols, public building, PCA

Introduction

One of the most toxic pollution of the troposphere are suspended solids. This is due to their ability to absorb on the surface of many harmful substances. Worldwide epidemiological studies have shown that there is a strong correlation between the air pollutants concentration and increase the prevalence of respiratory diseases and finally mortality of people. [1, 2]. The increase in the long-term concentration of PM10

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particles of 10 microns results in a several percent increase in the incidence of respiratory diseases, especially asthma [3].

Despite the fact that monitoring of the troposphere has been conducted since the middle of the last century, the issues relating to the quality of indoor air were neglected for a long period [4]. Over the years, it was taken for granted that its quality is directly relative to the parameters of the external air penetrating the buildings. Nevertheless, around the turn of last century, it was observed that the concentration of aerosols inside the buildings is often considerably higher in comparison to the quality of external air infiltrating the area [5, 6]. Simultaneously the Blacksmith Institute report stated, that *indoor air pollution and urban air quality are listed as two of the world's worst toxic pollution problems* [7].

The recent studies indicate that the air quality indoors is relative to both the factors associated with the external environment as well as endogenic factors [8]. The studies reported in [3, 9, 10] deal with the characteristics of the factors affecting the quality of air inside buildings, which were found to include air pollution, microclimate conditions, level of air ionization, exploitation conditions of the buildings as well as their design. The factors deciding about the quality of the inside environment include the ones associated with the presence as well as animal and human activity indoors [8]. The activities inside buildings can considerably affect not only on the level of the concentration of classical aerosol particles as well as the level of bioaerosols [11–13]. Air quality is also considerably influenced by the effect resulting from the existence of ventilation and air conditioning systems [14, 15]. The concentration of aerosol particles is also dependent on the season. In the moderate climate, higher aerosol concentrations are registered during winter [16].

This paper focuses on the verification of the level of mass concentration of PM10 in the lecture rooms of a university during the cold season. It also aims to determine the relation between the particulate matter concentration and the parameters which characterize the quality of air outdoors. In the consideration of the fact that humans spend 85–90% of their time in enclosed spaces, including 40% in buildings with public access (work, study outside home) [17] as well as knowing that the level of probability of exposition to particulate matter is considerably higher during the heating (cold) season, the objective of the study seems to be justified.

The course of the study involves verification of two hypotheses;

– the value of the mass PM10 concentration inside lecture rooms does not differ from the levels determined with regard to the outdoor air in the vicinity of the building (I),

– conditions of building exploitation do not considerably affect the value of PM10 concentration (II).

Materials and methods

Measurement sites and monitoring period

Research studies on the outdoor-indoor PM10 mass concentration relations were conducted at four points around and inside OUT's Mechanical Faculty building. One point (S_{out}) was located outside, at the roof of the southern wing of Mechanical Faculty building at the height of 14 m. Three of them (points E_{in}, S_{in} and W_{in}) were located inside, in the teaching rooms, at the top floor of the eastern, southern and western wings of building (E_{in}: 50°41′00.26″N, 17°56′42.51″E; S_{in} and S_{out}: 50°40′58.79″N, 17°56′42.83″E and W_{in}: 50°41′58.50″N, 17°56′40.65″E, respectively). Buildings in the wings of the E and W form a compact blocks with a basement, while the wing S is a building on stilts. Classrooms are equipped with sealed window frames. All of classrooms are ventilated by gravity.

The measurement campaign was carried out from December 2015 to the end of March 2016.

The methodology of sampling and data analysis

Observations were carried out simultaneously in two of the four points. Each time the measurements were carried out in the selected classroom within the building (E_{in}, S_{in}, W_{in}) and outside (S_{out}). Aspirations of particulate matter were carried out with constant time of 90 minutes and always was started at noon. In spaces, dust sampler worked at the central point of the classrooms. During the indoor measurements, the number of students (S), way of conducting of classes (using chalk or without (Ch)) and the use of the premises (airing, no airing) were recorded. In addition, some parameters of internal and external air was archived. Relative humidity (RH) and temperature (T) were measured using modules embedded in dust samplers. Observations of precipitation (R) have been conducted *ad oculos*, releasing three states for measurement: 0; no precipitation, 1; immediately after rainfall, 2; >8 h after the end of rainfall. Table 1 summarizes the data on the number of observations of selected parameters of air and data on the use of classrooms. Measurements were carried out during classes for groups of students from 14 to 39 people.

Table 1

Observations data. For indoor observations data divided due to usage of the rooms

Obs. location	with airing	without airing	Total obs.	Min-Max RH_{in} [%]	Min-Max RH_{out} [%]	Min-Max T_{in} [°C]	Min-Max T_{out} [°C]	Min-Max Students (S)	Chalk use (Ch) [%]
S_{in}	7	7	14	30–57	—	18–22	—	14–27	57
E_{in}	8	6	14	28–51	—	17–22	—	19–39	54
W_{in}	6	8	14	31–62	—	19–25	—	15–28	53
S_{out}	—	—	42	—	47–93	—	(–6)–16	—	—
Σ	21	21	**42 + 42**	—	—	—	—	—	—

The procedure for estimating the PM10 mass concentration was conducted in accordance with guidelines of the European Standard [18]. Measurements of the PM10 airborne particulate matter, at both sampling points were carried out in the same periods using LVS 3D sets of dust collectors with control modules. The indicated flow rate was

3 m^3/h. Whatman glass microfiber filters, grade GF/A with a diameter of 47 mm were used as separators for particulate matter. Filters were seasoned for 24 h in constant temperature and humidity conditions, before they were used, and then weighed on a differential dosing scales. The filters were seasoned and weighed again after aspiration. The content of PM10 [μg/m^3] fraction was measured on the basis of the following formula:

$$C = (m_1 - m_0)/V \quad (1)$$

where: C – PM10 mass concentration [μg/m^3];
m_1 – mass of the filter sputtered with dust [μg],
m_0 – the mass of the clean filter [μg],
V – volume of the air which has flow through the filter [m^3].

The expanded mass concentration measurement uncertainty (U) did not exceed 3.9%.

In the first stage of the study, it was examined whether the recorded data and the calculated results of PM10 mass concentration came from normal distribution. The Shapiro-Wilk test was used [19]. The test results allowed the choice of the methods of data analysis. For all of the cases not normal distribution of data were found, so for further analysis nonparametric tests were used. Hypotheses verification were implemented using the U-Mann-Whitney test [20]. The relationships between variables were examined using Spearman correlation [21]. Significance level of 0.05 was adopted. Finally, the study used Principal Component Analysis (PCA) [22].

Results and discussion

The results of all concurrent aspirations did not yield statistically relevant differences with regard to the indoor and outdoor mass concentration of PM10. Although the median C_{in} (52 μg/m^3) was 18% higher than C_{out} (44 μg/m^3), the comparison of 42 pairs of results conducted by the Mann-Whitney test led to the confirmation of the hypothesis (I). The value of the test probability ($p = 0.07$) was higher from the adopted critical level. The result outlined above suggests that the value of the mass concentration of PM10 inside the lecture rooms was predominantly affected by the quality of outdoor air. A similar approach is found in [3], where it was stated that air condition is affected by the operation of gravitational ventilation. Fig. 1 presents the results of the study with the breakdown relative to the individual localities (building wings). Despite the lack of statistically valid differences between the overall values of C_{in} and C_{out}, the median of PM10 concentration inside the building was higher for all localities (S, W and E). Such a condition is normal for mechanical ventilation systems [3], which was not the case in in the analyzed building. The above can indicate that for the case of micron-sized particles, the effect of endogenic sources has a more important role deciding on the level of the mass concentration. The statistical analysis of the results confirms the theory developed by the Fanger team [9], stating that the design characteristics of the buildings have a considerable impact on the value of PM10 concentration indoors. In the south building wing supported on pillars, there are statistically relevant differences

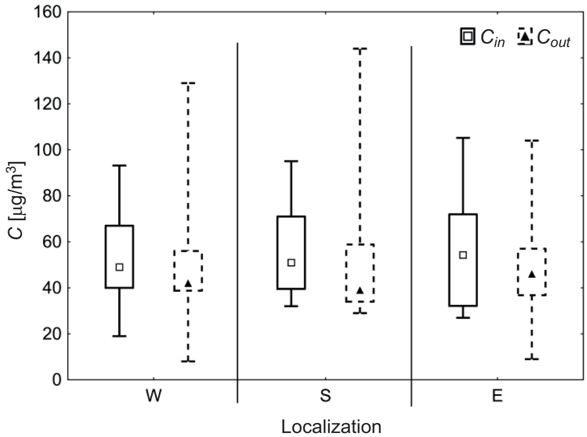

Fig. 1. PM10 concentrations inside (C_{in}) and outside (C_{out}) the building of the Mechanical Faculty with indication of lecture room locations in the examined building wings

between the in-out concentrations (p-value = 0.03), and the value of the median reaches 25%. For the case of observations performed in rooms situated in the wings of the building with a compact design and including a basement (W and E wings), the differences are statistically irrelevant (p = 0.35), with the in-out median difference of around 10%. The most probable reason for this can be associated with the thermal conditions in the distinct parts of the building, as the wings demonstrate different design solutions. In the winter, the rooms in the S wing are permanently cold. The lower internal temperature does not promote gravitational ventilation and seems to confirm the observation that the endogenic sources play a principal role in the formation of aerosanitary conditions indoors.

The comparison of the concurrent measurements of mass concentration of PM10 inside and outside the building is presented in Fig. 2. The triangles indicate the data for the case when additional air circulation is absent when windows and open. The circles

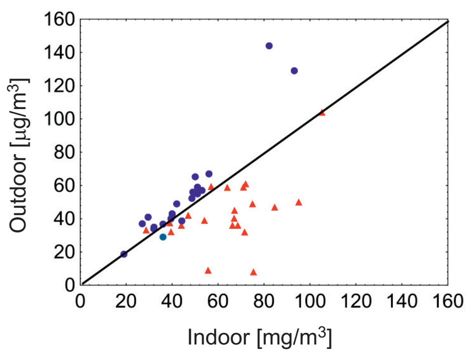

Fig. 2. Comparison of concurrently measured indoor and outdoor concentration for distinct ways of utilizing lecture rooms

denote the data gained indoors and outdoors during periods of the regular ventilation of the lecture rooms. The scatter chart uniformly indicates that for the case of poor gravitational ventilation (closed windows, lack of air diffusers), the mass concentration of PM10 is considerably higher indoors. The graphical interpretation is supported by the analysis of the results. For the case of the observation taken during the classes without possibility of keeping constant air circulation, the mass concentration of PM10 is around 34% higher indoors than outdoors, which is confirmed by the result of the Mann-Whitney test (p-value = 0.001). For the case when air circulation is boosted by the use of additional ventilation, there are no significant differences between the values of in and out concentrations (p-value = 0.33). These results indicate that the mass concentration of PM10 could depends not only on the quality of the indoor air, but also on the condition of the microclimate, the way in which the room is utilized and the number and activity of the users. For these reasons, hypothesis (II) can be rejected.

Table 2 contains the results of the Spearman correlation between the PM10 concentration inside the building and the remaining registered data.

Table 2

Spearman correlation. Results with bold fonts are statistically significant with $p < 0.05$

Variable	C_{out}	T_{out}	T_{in}	Rain	RH_{in}	RH_{out}	No. of Students	Chalk use	Room local.
Cumulative results									
C_{in}	**0.59**	**–0.55**	0.07	–0.27	**–0.65**	–0.05	**0.84**	0.28	–0.03
Results with airing									
C_{in}	**0.90**	**–0.65**	–0.06	**–0.55**	**–0.51**	**–0.47**	**0.57**	0.00	0.20
Results without airing									
C_{in}	**0.44**	–0.38	0.28	–0.35	**–0.74**	0.04	**0.88**	**0.42**	–0.29

The results of the correlation indicate that PM10 concentration inside the building (in the lecture rooms) is significantly dependent on the outside concentration only during the period when the room are ventilated. The important impact of endogenic factors on the indoor air quality is supported by the correlations between the concentration of PM10 and relative humidity and number of students inside the rooms. The results indicate that the increase in the number of humans in the rooms leads to the increase of PM10 concentration. The process of resuspension of surface p from clothes, skin and hair is considered to be the principal source of enriching indoor air with particulate matter. Similar results and statistically relevant positive correlations between the number of students and particulate matter concentration was presented by Polednik [3], in which study the presence of humans was demonstrated by the considerable increase of the concentration of coarse particles (5–10 μm and >10 μm). The present results area also in conformity with the studies reported in [23, 24].

As mentioned above, the statistically relevant correlations between C_{in} and RH_{in} were also identified for the observations taken for existence and absence of ventilation.

The mass concentration of PM10 increases along with the increase of the relative humidity (dry air promotes the release of particles from the surface). In addition, similar results were found in [3]; yet, in this case the results related to the quantitative concentrations of PM10.

The results, which is surprising, do not confirm the data from the literature regarding the impact of the temperature on the particulate matter concentration in the lecture rooms. The matrix indicates the complete lack of a correlation between the location of the lecture rooms and indoor mass concentration of PM10. Concurrently, it is noteworthy that the use of chalk for writing leads to a significant improvement of the air in the aspect of its particulate matter context; however, this is only the case when there is a lack of additional ventilation in the rooms. The results gained in this way could be affected by the location of the particle aspirator.

For the subsequent verification of the obtained data Principal Component Analysis (PCA) was used. PCA is a technique used to emphasize variation and bring out strong patterns in a dataset. It's often used to make data easy to explore and visualize. A detailed description of the procedures for implementing the PCA is shown at work [22]. In the first step eigenvectors of the correlation matrix were determined (Table 3).

Table 3

Eigenvalues of the correlation matrix. Bold values indicate a realization of mixed Kaiser criterion and Cattell test

No of value	Eigenvalues	% of the total variance	Cumulated [%]
1	**3.46**	38.4	38.4
2	**1.44**	16.0	54.4
3	**1.19**	13.2	67.6
4	**1.04**	10.6	79.2
5	**0.91**	10.1	**89.3**
6	0.45	5.0	**94.3**
7	0.30	3.3	**97.6**
8	0.16	1.7	**99.4**
9	0.06	0.6	**100.0**

The results of the experiment reflect the relevance of the principal components in the explanation of the relevance of the input factors (per cent in the variability in the database). The Keiser criterion was used as the principal test of the selection of the relevance parameters, which meant that the factors investigated had an eigenvalue of >1 [25]. The selection of the factors was also supported by the Cattell scree test [26, 27] (Fig. 3). The graphical interpretation indicates that in the analyzed case, five of the principal components had a decisive role. Cumulative percentage of variation explained by five components reach almost 90%. Although factor no. 5 has the eigenvalue of <1, its impact on the justified variability of the primary data is relevant.

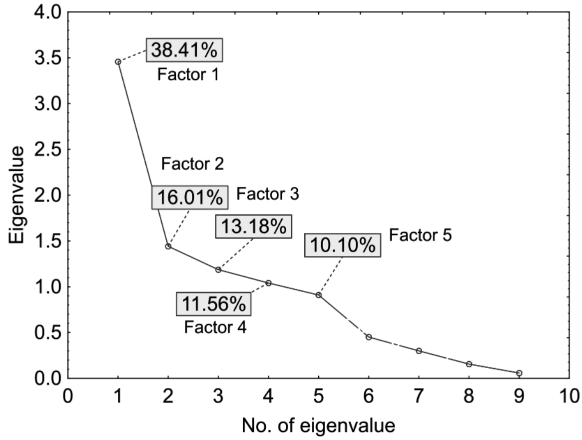

Fig. 3. Scree plot and percent of explained variability in the data

The relations between the primary and experimental principal components are presented in a graphical form in Fig. 4. Each of the variables is represented by a vector. The sense and length of the vector decides on the degree in which the particular

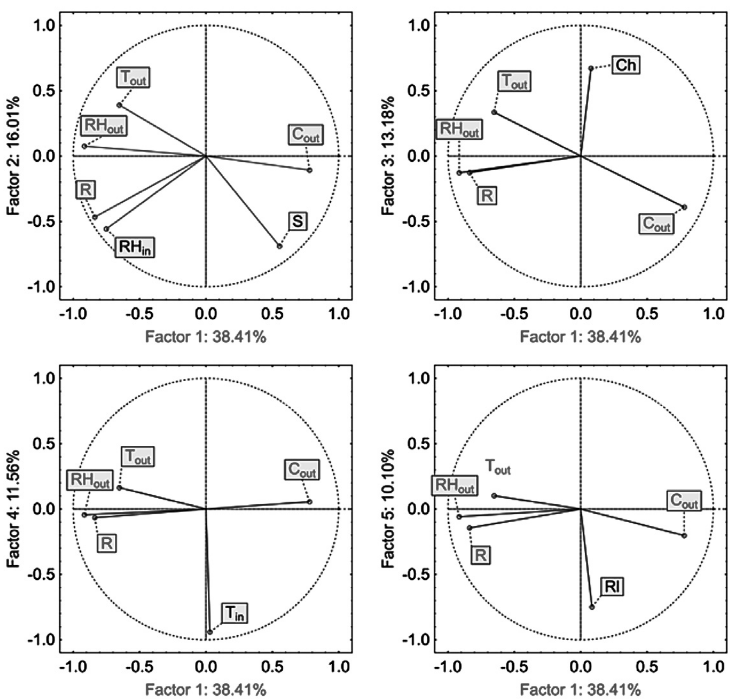

Fig. 4. Projection of variables on the factors surface on the base of eigenvector values. PCA analysis for all sites excluding C_{out}, T_{out}, T_{in}, rain (R), RH_{in}, RH_{out}, No of students (S), chalk use (Ch), classroom location (Rl)

variables have an impact on the values of the principal components. In the analyzed example, nearly all of the input variables are located in the vicinity of the circle. This means that the larger part of information contained in these variables is carried by the principal components. The fact of adjacent location of two variables indicates a strongly positive correlation. The variables located on the opposite sides are negatively correlated.

The Principal Component Analysis has successfully extracted five principal components which illustrate the sources of PM10 inside considered classrooms. For the examined case, the first component is responsible for explaining 38% of information regarding the concentrations used as part of the input variables.

One can note that the principal component No.1 explains only the specific variables responsible for external parameters. It is quite clear that the concentration of PM10 outdoor is relative to the relative humidity and occurrence of precipitation. The graphical interpretation confirms this as well. The remaining principal components account for the variables which describe the external parameters; however, all of them can be considered as individual components. On the other hand, these external components account for over 50% of information regarding the mass concentration indoor. The results confirm that the value of the mass concentration of PM10 is to a large extent dependent not only on the sources of endogenic emissions, but also on the way in which the lecture rooms are utilized.

Conclusions

The conducted study confirms that several factors are responsible for the quality of indoor air. The particulate matter in the air penetrating the building is one of the sources, which is considerably dependent on way in which the rooms are utilized as well as on the efficiency of the ventilation installation. The principal internal factors include the number of people indoors and the type of their activity as well as the type of microclimate in the lecture rooms (parameters of indoor air). Hypothesis (I) was proved to be true only for the case of adequate ventilation and during the periods when adequate air circulation is maintained in the rooms. Hypothesis (II) has to be rejected as false, in particular in the conditions of limited ventilation and air infiltration. Despite the fact that PCA is a useful method in reducing the dimensionality and classification of the variables, however, the result indicates that the comprehensive description of the issue seems to be difficult. The results of the study are relevant for a particular building; however, on the other hand, they fit well in the general conclusions recognized by other authors. The higher values of PM10 mass concentration inside the lecture rooms indicate the need to use adequate ventilation in the public buildings. In this respect, the use of an intelligent system based on multi-sectoral strategy described in [3] seems to offer a feasible solution. The results indicate the need for further research in the area of the mutual relation of the sources and factors affecting the quality of indoor air.

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RELACJA OUTDOOR-INDOOR DLA STĘŻENIA MASOWEGO PM10 NA PRZYKŁADZIE BUDYNKU UCZELNI

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Abstrakt: Określenie udziału źródeł zanieczyszczeń oraz wzajemnej relacji „outside-inside" jest istotnym problemem w szacowaniu i kontroli jakości powietrza wewnętrznego. Artykuł przedstawia wyniki badań nad stężeniem masowym PM10 określonym jednocześnie w okalającym budynek powietrzu zewnętrznym oraz w salach dydaktycznych uczelni wyższej. Projekt badawczy przeprowadzono w sezonie chłodnym, rejestrując 84 niezależne, 90-minutowe obserwacje. W badaniach wykorzystano, opartą na grawimetrii, referencyjną metodę pomiaru stężenia masowego PM10. Rezultaty badań przeanalizowano przy użyciu testów nieparametrycznych. W badaniach, celem klasyfikacji zmiennych i oszacowania odpowiedzialności poszczególnych czynników, posłużono się analizą składowych głównych. Wykazano, że wartości stężenia masowego pyłu zmierzonego w salach dydaktycznych nie różnią się od poziomów określonych jednocześnie w okalającym budynek powietrzu zewnętrznym wyłącznie podczas okresowego wietrzenia pomieszczeń. Stwierdzono, że konstrukcja oraz sposób użytkowania budynku a także liczba i aktywność osób w znaczący sposób determinują warunki aerosanitarne w pomieszczeniach zamkniętych. Wykazano, że w sezonie chłodnym stężenie masowe pyłu zawieszonego jest wyższe w pomieszczeniach. Złożono postulat przyjęcia rozwiązań polegających na implementacji inteligentnych systemów wentylacyjnych.

Słowa kluczowe: zanieczyszczenia powietrza, aerozole, budynki użyteczności publicznej, PCA