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Atmospheric pollution

ASSESSMENT OF INDOOR AIR QUALITY IN A WOODEN CHURCH FOR PREVENTIVE CONSERVATION

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Abstract. Environmental pollution and global warming effects are a particular problem for the protection of historical monuments and heritage objects. More than 1400 wooden churches have been built in Romania until 1918. They form a precious nationally and globally heritage that needs to be preserved and transmitted to future generations. A first step in this process is the indoor air quality assessment to identify the sources of pollution and potential aggressive compounds with the goal of reducing the effects on wooden structure and heritage objects. The paper presents a case study conducted in 2014 in order to assess the air quality inside a wooden church from Bucharest; the sampling campaigns were conducted inside and outside the building for simultaneously air pollutants (NO_2, SO_2, CO_2, O_3, PM2.5 and microflora) and microclimate factors (temperature, humidity) monitoring using automated methods that allow results storage, statistical treatment and interpretation. In order to identify the pollution sources and their impact on indoor air quality have been used indoor/outdoor (I/O) ratio values and the Pearson correlation which indicated that the major pollution sources are the outdoor air pollution and people attending the church services.

Keywords: indoor air, wooden church, PM2.5, I/O ratio.

AIMS AND BACKGROUND

Concerns about air quality inside museums, churches, monasteries and other spaces that are exposed or preserve heritage objects inside do not represent a new field research; since 80's Brocco and Bravery presented in their papers[1,2] the effects that air pollution can induce in historic sites and to heritage objects. Research conducted in recent years regarding the alteration degree of historic monuments has shown an intense pace of deterioration due to climate fluctuation (increasing average temperature and large variations in temperature and relative humidity) and intense pollution of the surrounding air. Special attention is given to conservation of churches because of their architectural value and spiritual heritage objects they host[3–9].

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In the case of monuments located in big cities the heavy traffic is the main source of ambient air pollution with compounds of combustion: carbon, nitrogen and sulphur oxides, dust containing heavy metals, volatile metals and a wide range of organic compounds, including aromatic polycyclic hydrocarbons[10,11]. The migration of these pollutants from outdoor to indoor air due to lack of proper ventilation may have significant effect on the exhibits. It is important in this context to control and reduce their effects to ensure long-term preservation of cultural collections[12].

In most cases the effect of chemical pollutants is amplified by unfavourable microclimate conditions (temperature and high humidity). Thus in the presence of high humidity, nitrogen and sulphur oxides forms acids that can react with the materials they are made and form at their surface sparingly soluble salts, unsightly; the depositing of particulate matter on the exhibits can have effects on their appearance, but also in the presence of moisture and other compounds may cause corrosion and affect surface by scratching in the cleaning operation[13].

The ozone present in the air reacts with organic materials, including wood, causing pigment discoloration[14,15].

Organic materials such as paper, textiles, leather, wood, especially if they contain wax, grease or oils may be ideal environments for fungal development, especially in optimum microclimate (15–20°C and 70% relative humidity).

The purpose of the paper is to present the results obtained in the first stage of a study dedicated to assessing air quality inside wooden churches, monuments of architecture and spirituality, in order to implement a preventive conservation plan.

In this first stage the microclimate parameters (temperature and humidity) and the concentration of inorganic compounds (NO_2, SO_2, CO_2, CO, O_3, PM2.5 particulate matter) were continuously monitored inside and outside the wooden church. The tests tracked: (a) the evolution of the concentration of compounds in the air inside the church in summer; (b) the interpretation of monitoring data by the Pearson correlation statistical analysis and I/O ratio; (c) use this information to identify sources of indoor air pollution. These are the first tests of this kind carried out in a wooden church in Romania.

EXPERIMENTAL

The wooden church is dedicated to Saints Hierarchs Gregory and Spyridon and is situated in the northern part of Bucharest, in an area with rich vegetation (Fig. 1*a*) at a distance of approx. 150 m from the main road, it was completed in 2012 and it is dedicated to the heroes of aviation. It was built in the style of Maramures, using 10-year dried oak, fireproofed and varnished by hand both inside and outside. The exterior is carved by craftsmen in traditional Romanian sculpture representing the most important saints of the Orthodox religion (Fig. 1*b*). It is not equipped with air conditioning, ventilation is provided by natural ventilation via two access doors and a window from altar. In winter it is heated only during the religious service that takes place, with two electric radiant systems positioned in the centre of the space. The church itself is a heritage monument, as well as icons painted on wood, solid wood furniture and religious objects present in this place. The church houses the relics of St. Hierarch Gregory.

a *b*

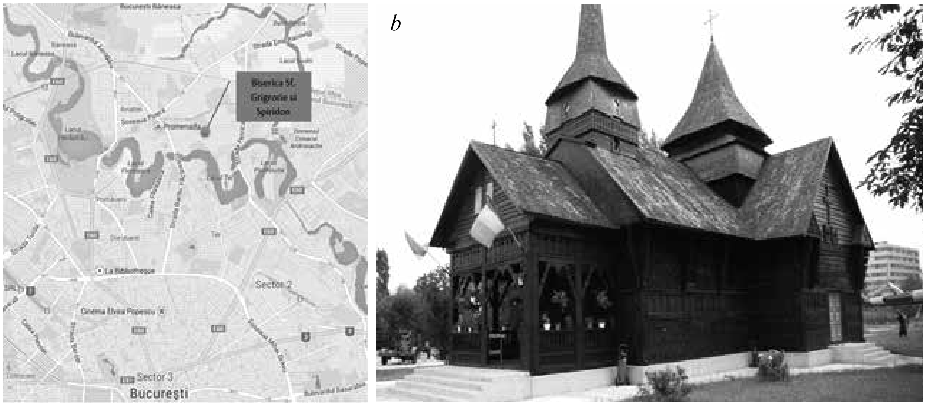

Fig. 1. Church 'St. Hierarchs Gregory and Spyridon' in Bucharest: *a* – location; *b* – side view

To assess the air quality inside the wooden church and to identify the sources of pollution specific to hot season, during the period 27.06–09.07.2014 were continuously monitored inside and outside the building the following indicators: NO_2, SO_2, CO, O_3, PM2.5, and the indicator of pollution due to the presence of people in the place of worship, the concentration of CO_2. Temperature and humidity were also recorded because they can directly affect the wooden church and can create favourable conditions for the development of molds. Horiba automatic environmental monitors were used in order to monitor the concentrations of NO_2, SO_2, CO, O_3. The analysers have been connected to a sampling device that was programmed to change sampling air source (indoor/outdoor) with a specific ratio. Analysers were calibrated periodically in order to ensure the quality of results using calibration gas cylinders according to standards: EN 14626/2012 for CO, EN 14211/2012 for NO_2, EN 14212/2012 for SO_2 and ISO 10313: 1995 for O_3. Hourly stored data were treated with AnalyseIt data treatment software. Temperature and humidity were measured outdoor with a MetaPak weather station, and indoor with a WOLF analyser, equipped also with an electrochemical cell for CO_2 determination.

Daily average PM2.5 dust concentrations were determined by gravimetric method according to EN 14907: 2005 for sampling using two Sven Leckel Ingenieurbüro GmbH samplers fitted with impactors for separating the size fractions and quartz filters (47-mm diameter). The sampling rate was 2.3 m^3/h. The quartz filters were equilibrated for 24 h in a climate-controlled chamber at 20°C and 50% humidity before and after use. The quartz filters were weighed before and after exposure, using an analytical balance AG 135 (Mettler-Toledo GmbH, Greifensee, Switzerland) with a 10-μg resolution. The mass gained by the filter was taken to be the particulate mass in the air volume that was sampled.

The microbiological contamination of indoor air is a current problem with negative effects on population health, especially in buildings with a large people flow as churches.

Aero microbiological analysis was based on sedimentation method in 4 sampling points. There were controlled total number of bacteria that growth at 37°C, coliform bacteria and Enterococci species.

RESULTS AND DISCUSSION

Results of the monitoring carried out during 27.06–09.07.2014 inside and outside the church for NO_2, SO_2, CO, O_3 and PM2.5 in the air and the temperature and relative humidity (RH) parameters are summarised in Table 1.

WEATHER PARAMETERS AND MICROCLIMATE FACTORS

The weather during the sampling period was characterised by temperatures between 14 and 33°C, and relative humidity (RH) between 26 and 99%, specific to the warm season when sunny days are often followed by rainy periods.

It can be seen that the wide range of temperature and humidity values from outdoor has a very small influence to the values measured in indoor microclimate; thus, if outdoor the maximum differences/period were 18.9°C and 73.5% RH, indoor the maximum differences/period for the same parameters were only 5.9°C and 11.6% RH, which indicates a good insulation of the building made of timber that does not allow easy air exchange outside/inside. This conclusion is sustained by the results of statistical Pearson correlation analysis (Table 2) which indicates a weak direct correlation between the indoor and outdoor temperature ($r = 0.3$) and a very weak indirect correlation between indoor temperature and outdoor RH ($r = -0.15$). Also it can be noticed that there is no correlation between the values obtained for the indoor humidity and outdoor temperature ($r = 0$) and the humidity from indoor and outdoor ($r = 0.01$). A very good indirect correlation ($r = -0.95$) has been found between the parameters temperature and humidity inside the church; these parameters maintained relatively constant in most of the test.

Table 1. Results of air quality monitoring inside and outside the church in 27.06–09.07.2014

Source	Indoor								Outdoor						
Indicator	CO_2 (ppm)	Temperature (°C)	RH (%)	CO (µg/m^3)	NO_2 (µg/m^3)	SO_2 (µg/m^3)	O_3 (µg/m^3)	PM2.5 (µg/m^3)	RH (%)	Temperature (°C)	CO (µg/m^3)	NO_2 (µg/m^3)	SO_2 (µg/m^3)	O_3 (µg/m^3)	PM2.5 (µg/m^3)
Number of hourly data/day	286	286	286	143	143	143	143	13*	286	286	143	143	143	143	13*
Average	462.22	23.28	56.89	0.29	14.10	5.330	65.63	9.01	63.15	22.84	0.18	13.55	5.770	76.59	18.05
Minimum	396.50	20.72	50.94	0.1565	3.32	2.888	60.69	6.70	25.76	13.80	0.1249	2.342	3.068	61.06	15.40
Maximum	1304.40	26.70	62.60	1.321	75.20	14.860	75.52	13.20	99.25	32.70	0.5139	43.94	16.060	96.06	23.40
Difference/period	907.90	5.98	11.66	1.1645	71.88	11.972	14.83	6.50	73.49	18.90	0.389	41.598	12.992	35.00	8.00
Maximum daily allowance difference		2.25	6.55						58.11	15.12					

*Dayly averages.

Table 2. Results of statistical analysis using Pearson correlation (r) for temperature and relative humidity inside and outside the church in 27.06–09.07.2014

Indoor	Temp	RH	Outdoor	Temp	RH	Indoor/outdoor	Temp	RH
Temp	1	–0.95	Temp	1	–0.41	Temp	0.3	0
Rel. hum	–0.95	1	Rel. hum	–0.41	1	Rel. hum	–0.15	0.01

A particular danger is due to the phenomena of repeated expansion/contraction that wood can cause large diurnal temperature and humidity variations[16]; analysing the maximum values of these diurnal variations for the period analysed, 2.25°C and 6.55% RH compared with the recommendations of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) of the storage conditions found that these variations are within the limits imposed by class control B, this involves moderate risk of mechanical damage for wooden constructions and low risk vulnerability for different objects and books[17]. We conclude that even if the period analysed was characterised by high temperatures and weather instability specific to the warm season, the wooden church ensures inside the values of parameters of microclimate beneficial for long-term preservation of valuables present in the interior and for the building itself.

CHEMICAL AND BIOLOGICAL POLLUTANTS

It is well known that in big cities traffic is a very important source of environmental air pollution with NO_2, SO_2, CO, CO_2, O_3 and PM2.5. The results obtained for the pollutants NO_2, SO_2, CO, CO_2, O_3 and PM2.5 measured indoor and outdoor the wooden church in period 27.06–09.07.2014 are presented in Table 1.

The average concentrations of NO_2, SO_2, CO, CO_2, O_3 and PM2.5 obtained from outdoor air monitoring outside the building are under the limits imposed by Directive 2008/50/CE for a cleaner air in Europe. Regarding the air quality inside the church we can conclude that the values obtained are unproblematic from the point of view of conservation regarding the heritage objects and wooden structure of the church; according with the recommendations of ASHRAE (Ref. 17), these values are in the domain named ‘general collections’ (Table 3).

Table 3. Current recommended target levels for key gaseous pollutants[15]

Pollutants	Suggested pollutant limits for collections				Action limits			
	sensitive materials		general collections		high		extremely high	
	ppb	µg/m³	ppb	µg/m³	ppb	µg/m³	ppb	µg/m³
NO_2	<0.05–2.6	<0.1–5.3	2–10	4–20	26–104	110–210	>260	>530
SO_2	<0.04–0.4	<0.1–1	0.4–2	1–5.7	8–15	23–43	15–57	43–160
O_3	0.05	0.1	0.5–5	1–10	25–60	50–130	75–250	160–530
PM2.5	–	<0.1	–	1–10	–	10–50	–	50–150

After a preliminary analysis of monitoring result corroborated with the values of I/O ratio (see further Table 4), calculated for the average values of the period, we can see that for CO and NO_2 the I/O ratio is higher than 1(I/O_{CO} =1.61; I/O_{NO_2}

= 1.04) suggesting the existence of some other sources of CO and NO_2 inside the church that are overlapping to the pollution from outdoor air.

Table 4. I/O ratio values for NO_2, SO_2, CO, O_3 and PM2.5

I/O	CO	NO_2	SO_2	O_3	PM2.5
I/O min	1.25	1.40	0.94	0.99	0.31
I/O mean	1.61	1.04	0.92	0.87	0.51
I/O max	2.60	1.70	0.93	0.79	0.79

The I/O ratios reaches the highest values for CO and NO_2 during the period when ceremonials take place inside the church which indicates that most probably the main sources are burning candles and the parishioners taking part.

The existence of a common sources for these indoor air pollutants is also sustained by the results of Pearson correlation statistical analysis (Table 5) applied to the compounds measured in indoor air showing direct very good correlation between CO, NO_2 and PM2.5 (r_{CO/NO_2} = 0.90; $r_{CO/PM2.5}$= 0.81), good between CO and CO_2 (r_{CO/CO_2}= 0.69) and reasonable between CO and SO_2 (r_{CO/SO_2} = 0.40). This theory is also sustained by the graphical representation of hourly averages for NO_2, SO_2, CO, CO_2 evolution in time for Sunday 06/07/2014, samples taken inside and outside the church (Fig. 2).

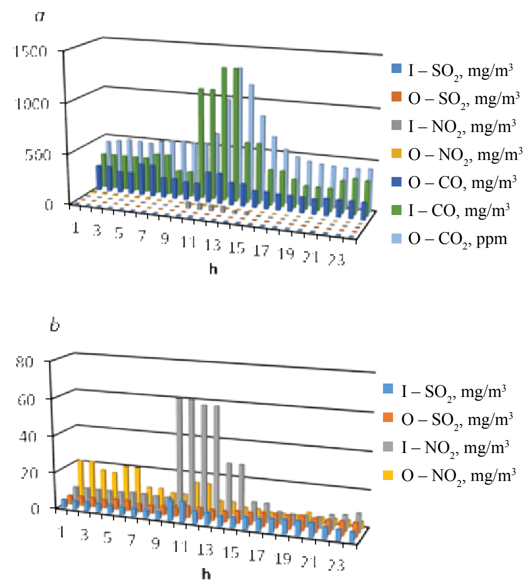

Fig. 2. Evolution in time of NO_2, SO_2, CO, CO_2, hourly averages, concentration indoor and outdoor (*a*) only NO_2, SO_2 concentration (*b*), on Sunday 06/07/2014

Table 5. Results of statistical analysis using Pearson correlation (*r*) for gaseous chemical pollutants inside and outside the church in 27.06–09.07.2014

Indoor	CO_2	CO	NO_2	SO_2	O_3	Out-door	CO	NO_2	SO_2	O_3	I/O	CO_2	CO	NO_2	SO_2	O_3
CO	0.69	1.00	0.90	0.40	–0.04	CO	1.00	0.49	–0.13	–0.25	CO	0.28	0.43	0.36	–0.01	–0.17
NO_2	0.65	0.90	1.00	0.38	–0.12	NO_2	0.49	1.00	–0.14	–0.58	NO_2	0.00	0 .09	0.18	–0.20	–0.43
SO_2	0.10	0.40	0.38	1.00	0.44	SO_2	–0.13	–0.14	1.00	0.49	SO_2	–0.1	–0.02	–0.17	0.48	0.36
O_3	–0.01	–0.04	–0.12	0.44	1.00	O_3	–0.25	–0.58	0.49	1.00	O_3	–0.06	–0.01	–0.12	0.40	0.73
CO_2	1.00	0.69	0.65	0.10	–0.01											

It can be seen that the maximum hourly average concentration corresponds to the hour which holds religious services. The Pearson correlation coefficients indicate a better correlation between pollutant concentrations on Sunday than the rest of the week (Table 6): $r_{CO/CO_2} = 0.71$, $r_{CO/NO_2} = 0.98$, $r_{CO/SO_2} = 0.50$.

Table 6. Results corresponding to Pearson correlation using statistical analysis (*r*) for indoor chemical pollutants, Sunday 07.06.2014

Indoor	CO_2	CO	NO_2	SO_2	O_3
CO_2	1.00	0.71	0.68	0.08	0.22
CO	0.71	1.00	0.98	0.50	–0.04
NO_2	0.68	0.98	1.00	0.61	0.00
SO_2	0.08	0.50	0.61	1.00	0.40
O_3	0.22	–0.04	0.00	0.40	1.00

Regarding the concentration of O_3, as results shown, the most important source is the outdoor air, the I/O ratio was proper no matter what activities are taking place in the church; it can also be observed a good direct correlation with SO_2 (r = 0.49 outdoor and r = 0.44 indoor) and indirect with NO_2 (r = –0.58 outdoor and r = – 0.12 indoor), proving once again his implication in air chemistry and the influence of light.

The analysis did not emphasise the presence of potentially pathogenic bacteria inside the church. Therefore, the investigated enclosure meets the requirements of microbiological indoor air quality.

CONCLUSIONS

The main results of tests made in the wooden church 'Holy Hierarchs Gregory and Spyridon' from Bucharest in order to evaluate the indoor and outdoor air quality indicate the presence in indoor air of some concentrations of NO_2, SO_2, CO, CO_2, O_3 and PM2.5 that are situated most of the time under the values from outdoor air for SO_2, O_3 and PM2.5 or just a little bit over these values for NO_2 and CO; according with ASHRAE (Ref. 17) recommendations regarding the prevention of degradation and conservation of heritage objects. These values do not impose special measures for preventive conservation.

Also the values of microclimate parameters fit in an interval that involves low risk for objects and books. There are some exceptions during the days when the church holds religious ceremonies; in these periods the concentrations of NO_2, SO_2, CO, CO_2 and PM2.5 can reach values that, maintained for longer time, could affect the wood inside the church, icons, pictures and heritage objects.

These periods represent not more than 7–10% of time, and after the religious ceremonials the church is very well ventilated using the doors and windows. The main source of indoor air pollution is the outdoor air, amplified during the ceremonials by the burning candles and the presence of parishioners. The level of these emissions and their evolution in time in warm season does not represent a major danger for the wood that represent the main construction material of the church and for the heritage objects founded inside.

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