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Modeling of the aerosol infiltration characteristics in a cultural heritage building: The Baroque Library Hall in Prague

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ABSTRACT

Three intensive campaigns in spring, summer and winter 2009 where conducted in the Baroque Library Hall in Prague, Czech Republic. The number concentration of particulate matter (PM) was measured online and simultaneously, both indoors and outdoors with an SMPS (0.014–0.7 μm) and an APS instrument (0.7–20 μm). A dynamic mass balance model was introduced taking account particle penetration from outdoors and indoor losses (deposition, ventilation). The model was used to determine deposition rate k and penetration efficiency P in 13 discrete size intervals. Model performance was evaluated using the coefficient of determination (R^2) by selecting different pairs of k and P. No unique solution found, thus, averaged values of k and P from the best correlated pairs were used to estimate infiltration factor. Good agreement between infiltration factor and I/O ratio confirmed that modeled k and P were well-estimated. The deposition rate was found to depend strongly on particle size with higher rates for ultrafine and coarse particles. Penetration efficiency, on the other hand, was not clearly related with particle size. The infiltration factor varied substantially with particle size with less effective removal for accumulation fraction (0.1–0.7 μm). Higher infiltration factor for ultrafine particles, compared to coarse particles, indicates that enrichment of the library at this size is caused by penetration from outdoors. On the other hand, human presence during visiting hours found to contribute significantly to coarse particles by increasing the indoor number concentration by a factor of 3, 3.2 and 2 during spring, summer and winter respectively.

1. Introduction

Indoor air quality in cultural heritage buildings is a common issue in modern societies. Outdoor pollution changed considerably the last 50 years [1], thus, it is crucial to assess the impact of outdoor pollution to the indoor one, as well as indoor pollutants since they threat the conservation and preservation of the collections [2].

Particulate matter can cause soiling by deposition and adsorption, material degradiation or damage by chemical reactions [3–6]. Indoor pollutants in cultural heritage buildings may originate either from indoor sources or penetrate indoors through the building envelope [4,7–9]. Common indoor sources include heating, smoking, cleaning or walking. On the other hand, penetration depends on particle dynamics [10]. Particulate matter characteristics generated indoors are strongly connected with the primary indoor sources [11,12], whereas, particles that originate from outdoors are determined by building characteristics, ventilation, transport, particle dynamics and outdoor PM characteristics [10,13–17].

Numerous studies have already focused on indoor air characterization of libraries and museums with regard to chemical pollutants, indoors sources, chemical reactions and environmental factors [2,4,6–8,18–23,24]. Moreover, the characteristics of indoor PM in museums were also studied with regard to the outdoor environment [7,9,25,26]. These studies include buildings belonging to a complex or individuals, in suburban or urban areas, with natural or mechanical ventilation and different construction materials.

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In all cases, the results underline the influence of the indoor environment by the chemical composition of indoor pollutants, particulate matter concentration and the contribution from outdoor sources along with the impact from indoor human presence. Thus, the estimation of indoor pollutants originating from outdoors along with the impact from indoor sources became a crucial issue.

Penetration of outdoor particles indoors and building characteristics were studied thoroughly. The relationship of indoor and outdoor particulate matter was examined in several environments [27–32] and the reported results strongly associated the indoor PM concentration with the outdoor one. In respect to particle dynamics and using mass balance models, the authors managed to determine deposition indoors and penetration from outdoors, although the variability of the results indicated the strong dependence on assumptions, different methodologies and building characteristics [33–41]. However, all studies provided insight to particle dynamics indoors and associated both deposition and penetration with particle size.

The present study examined the particle number characteristics in Baroque Library Hall (BLH) in Prague, Czech Republic. A former study on indoor pollutants and indoor/outdoor pollutants relationship can be found in Ref. [22]. The BLH is a naturally ventilated building, which, along with the controlled access from the visitors, provided a sampling site appropriate for determining the infiltration of outdoor originated particles and investigation of the visitor's impact on indoor PM. The contribution of the present study is that it employs infiltration characteristics with size resolved analysis in a cultural heritage building as most of the studies in the topic involve domestic environments (houses). The objective was to evaluate particulate matter characteristics indoors with respect to outdoors, to estimate penetration of outdoor particles and deposition rates indoors using a dynamic mass balance model, to determine the infiltration factor and its dependence on particle size and finally to investigate the contribution of the visitors to the indoor particle concentration.

2. Experimental and methodology

2.1. Sampling site

The Baroque Library Hall of the National Library is part of Clementinum Historical Complex and is located in the Vltava River valley, right in the historical center of Prague. The intensity of car traffic in this area is approximately 24,200 cars per day [42]. Clementinum, built on an area of 2 ha, is the second largest and the most historic complex of buildings in Prague. The Hall, situated in the center of the Clementinum on the second floor, holds approximately 20.000 theological books dating from the 16th century until recent times and stored in original wooden shelves.

Fig. 1 presents the internal scheme of the library. It is 39 m long and 9.4 m wide with an arched ceiling in the lowest point at 8.3 m and in the highest point 9.5 m high. There are 8 double glass windows covered by curtains along the western and eastern side and 4 entrance doors, 2 on the north side and 2 on the south side. The doors on the north side lead from the hallway, which serves as a storage room and as entrance used by librarians and restorers. The doors on the south side lead from foyer of the Hall and serve as an entrance and exit for the visitors. The library is naturally ventilated with all windows closed, while, the doors open only for visiting purposes. The visitors enter the Hall in groups of maximum 25 people with the guide and run only along the south site of the Hall. Sightseeing tours took place every day from 10 am and started every half-hour during weekend and every hour during the rest of week. A detailed description of the library can be found in Ref. [43].

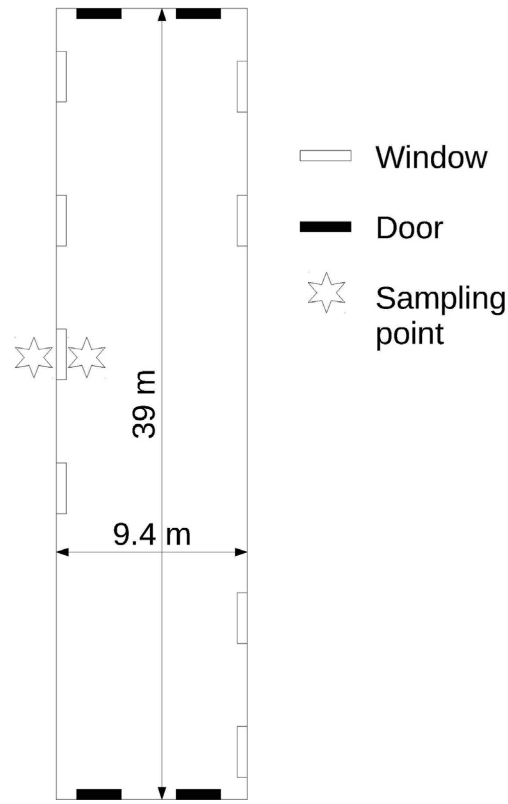

Fig. 1. Scheme of the library and position of the instruments.

Any other activities (e.g. cleaning) in the indoor environment were very limited.

2.2. Measurement campaigns/instrumentation

The campaign was conducted during spring (10th – 17th March), summer (14th – 21st July) and winter (22nd November - 2nd December) 2009. Indoor and outdoor particle number concentrations were measured by a Scanning Mobility Particle Sizer (SMPS, model 3934C, TSI, U.S.A.) consisted of a Differential Mobility Analyzer (DMA, model 3081), a Condensation Particle Counter (CPS, model 3775) and an Aerodynamic Particle Sizer (APS, model 3320, TSI, U.S.A.). Both instruments sampled from both inside and outside BLH simultaneously using its own sampling train provided with an electrically actuated three-way ball valve connected to a common programmable controller that used a CPC voltage (controlling the high voltage on the central rod of the DMA) as a signal for switching. The SMPS sampled with a flow rate at 0.3 l/min, measuring particle number concentration in the size range of 0.014–0.7 μm in 110 channels. The APS was operated with 5 l/min flow rate and measured particles in the effective size range 0.7–20 μm in 51 channels. The SMPS used 3 min upward scan, followed by one minute downward scan with one minute delay necessary to separate samples and wash sampling train after valve switching. Eventually two five-minute sampling cycles for indoor sampling followed by two five-minute cycles for outdoor sampling. The experimental set up of the instruments is shown in Fig. 2. Data from both instruments were collected using Aerosol Instrument Manager software (AIM v.1.0, TSI, U.S.A.), where particle losses inside sampling trains were incorporated. In addition temperature, relative humidity and CO_2 concentration were measured by Indoor Air Quality Monitor PS32 (Sensotron, Poland).