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Particle penetration and deposition inside historical churches

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ABSTRACT

Particle sources and deposition inside two historical churches, differing in size and construction were examined. The particle concentrations indoors and outdoors were monitored for at least 10 months. The air exchange rate (AER) was determined by fitting an exponential decay curve to the recorded concentration of indoor-generated CO_2. The two-parameter mass balance equation, taking into account the particle sources and sinks in the indoor environment of churches, was used to determine the particle deposition velocities and penetration factors. Large indoor and outdoor particle concentration variability helped to separate the effects of penetration and deposition losses. For example, liturgical services regularly generated high indoor particle concentrations, owing to the burning of incense. During the particle concentration decay after the services, losses due to deposition could be reliably determined, whereas the events of high outdoor aerosol concentrations with no emission of particles indoors allowed the penetration factors to be precisely determined. The minimal AER values of 0.1 and 0.3 h^{-1} were observed in the closed brick and wooden church, respectively. Typically, area-averaged deposition velocities for particles of diameters 0.3–1 μm or above 1 μm were $1.5 \cdot 10^{-5}$ and $2.1 \cdot 10^{-5}$ m/s, respectively, and were very consistent between the two churches studied in spite of the differences in their design, size, construction materials and pattern of use. Penetration factors ranged from 0.7 to 0.86.

1. Introduction

Religious buildings from various historical periods represent a unique legacy of art and architecture. Many places of worship contain valuable interior furnishings and wall paintings, as well as liturgical and decorative objects safeguarded by the congregations, relevant advisory bodies, and local, regional or national authorities. However, development and implementation of effective preservation strategies require a thorough understanding of existing risks, especially those induced by the environment. The indoor environment in a religious building is influenced by the outdoor conditions and the properties of the building envelope which protects the indoors by preventing outdoor air from entering, buffers relative humidity (RH) fluctuations and insulates the indoor climate from outdoor temperatures. The building usage patterns: opening doors and windows, presence of visitors, heating to ensure human comfort, burning incense and candles also affect the indoor environment.

Generally, historical religious buildings are ventilated using two mechanisms: natural ventilation and infiltration – for technical, economic and conservation reasons, the mechanical ventilation in a vast majority of these buildings is rare. The air exchange rate (*AER*) depends on the gaps in building structure, tightness of windows and doors, pressure differences induced by wind and temperature, and the pattern of use. Excessive or insufficient ventilation of historical religious buildings can disturb the stability of indoor RH. Understanding of the effect of RH, both absolute levels and fluctuations, on materials and objects has become very detailed [1]. Consequently, initial attempts to formulate international standards for the microclimate in the environment of sensitive historical objects have been made [2].

It has also been recognised that the soiling of valuable surfaces and objects is caused by indoor particle pollution and depends on particle size, number concentration and chemical composition [3,4]. Particles of both outdoor and indoor origin add to the total soiling rate. However, research on particulate air pollution inside religious buildings has largely concentrated on combustion processes – burning candles and incense during liturgical services [5–7], and the implications for human respiratory health that high levels of combustion particles might have [8,9]. The studies concentrated on particle emissions associated with single church activities and the measurements were conducted over short time

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intervals, usually not exceeding a few days.

Therefore, there is a need to obtain systematic information on the long-term relationships between particles of outdoor origin and particles generated from indoor sources in historical churches. Particles of outdoor origins enter the church interiors through gaps in the building envelope or, especially during periods of warm weather, due to the prolonged opening of doors and windows. This process can be described by *AER* and particle penetration factor (P) – the fraction of outdoor particles of a specific diameter that pass through the building envelope. Inside the church, particles are in turn deposited on indoor surfaces, the process being described by deposition loss rate (k). To take account of continuous variation in both outdoor and indoor concentrations, researchers use dynamic data to determine k and P. However, it has become clear that it is difficult to determine unique, independent values of both parameters as they represent two mechanisms of particle losses both leading to the reduction of particle concentration indoors. Acknowledging this difficulty, researchers have begun to use the average values of k and P from the pairs which best correlate with the measured dynamic data [10,11]. Alternatively, experimental procedures artificially changing the indoor concentration were adopted so that k and P were determined independently. In the 'concentration rebound method' used by Thatcher et al. [12], indoor particle concentration in the investigated spaces was first elevated artificially to measure the deposition loss rate and then rapidly reduced through induced ventilation to measure the particle concentration rebound owing to the penetration from outdoors.

This is the first of a series of papers on the particle emission, penetration and deposition in historical churches. The paper reports on the continuous monitoring, in two historical churches, of indoor and outdoor concentrations of particle number (PN) in two size modes termed fine (between 0.3 and 1 μm) and coarse (above 1 μm). The selected fine particle mode largely coincides with the size range 0.1–1 μm, referred to as the accumulation mode [13]. This size range is of particular interest to the cultural heritage field for two reasons. Firstly, the accumulation mode particles penetrate gaps in the structure of a historical building very efficiently [10,14] whereas ultrafine and coarse particles have lower penetration efficiency as they tend to deposit on the internal surfaces of gaps in the building envelope due to Brownian motion and gravitational losses, respectively. Secondly, the accumulation mode particles contribute predominantly to the soiling of surfaces in all orientations – in particular vertical walls and ceilings, frequently painted in churches – as the particles are small enough to diffuse in the space of a church and collide with the surfaces but at the same time large enough to be significant mass carriers (see Fig. 1 in Ref. [13]). In contrast, the coarse mode particles tend to deposit quickly due to the gravitational settling on the horizontal surface, mainly floors [15,16].

The monitoring of the particle concentrations was accompanied by measurements of the concentration of indoor-generated CO_2, allowing the times of the liturgical services and the air exchange rate to be determined. The paper describes a methodology of using this long-term dynamic data for determining the particle deposition loss rate on indoor surfaces that takes into account variations in the air exchange rate and outdoor particle penetration.

2. Materials and methods

2.1. Description of churches

The measurements were performed in two historical churches in Poland. To explore the effect of church building features on the penetration and deposition processes, the selected churches differed in design, size and construction materials. Information on the churches investigated was collected in Table 1. Surface areas shown in the table estimate exposed surfaces in all orientations as deposition surfaces. They comprise the areas of architectural surfaces – walls, floors and ceiling as well as the surface areas of the interior furnishings – altarpieces, the organ choir and furniture.

The church in Tarnow is a Gothic basilica with three naves – the main nave being 18 m high (Fig. 1a). Underfloor heating system installed in the nave consists of hot water pipes. Due to the thermal inertia, the system is operated continuously throughout the cold period of the year, heating the floor to a stationary level of 22 °C. The wooden church in Krakow is a log construction on a cruciform plan – the main nave and side spaces being 8.5 m and 6.5 m high, respectively (Fig. 1b). The existing heating system consists of radiant electric heaters at a height of about 3 m above the floor level, further heaters are located in the pews. The heating is switched at the beginning of the service and switched off immediately after.

In the climate of Poland, prolonged cold weather conditions prevail from November to April (variation of 24 h average temperatures between −5 and 20 °C at the church in Tarnow in the monitoring period). In the cold period, doors and windows are kept generally closed in churches and the heating systems are operated. In turn, predominantly warm weather is characteristic of a period from May to October (variation of 24 h average temperatures between 13 and 28 °C at the church in Tarnow in the monitoring period). In the warm period, heating systems are switched off and windows and doors may stay open for prolonged time. The variations of indoor temperatures measured during the monitoring period in the two churches are listed in Table 1.

2.2. Monitoring methods

Particle number concentrations in two size modes 0.3–1 and >1 μm were simultaneously measured indoors and outdoors using battery-operated laser particle counters (DC1700, Dylos Corp., USA). The measuring system consisted of one sensor used for monitoring outside at a distance of approximately 30 m from each church building and between 2 and 4 sensors used indoors to assess spatial variability of the PN concentration. The location of the sensors in the churches is marked on their layouts (Fig. 1). Additionally, a carbon dioxide sensor (GMP222, Vaisala Inc., Finland) combined with a HOBO Micro Station Data Logger (H21-002, Onset Computer Corp., USA) measured the concentration of CO_2 indoors to determine the times of the liturgical services and the air exchange rate. PN and CO_2 concentrations were recorded every 5 min. The measurements were conducted in Tarnow from November 2012 to September 2013 and in Krakow from March 2012 to November 2013.

To verify the performance of the Dylos particle counters, a DustTrak™ DRX Aerosol Monitor (8533, TSI Inc., USA) was used as a reference in each monitoring campaign to estimate particle mass concentration [17]. The PM and PN concentrations were measured with the DRX and Dylos particle counters, respectively, in the church in Tarnow over a sampling period of two weeks. DRX could be operated only during the nights due to a high level of acoustic noise emitted. The calibration of the DustTrak™ DRX represented equivalent concentrations of ultrafine ISO 12103–1, A1 Arizona Road Dust. The linear regression between the total mass concentration and PN concentration in the size range above 0.3 μm measured by the DRX and Dylos, respectively, is shown in Fig. 2. It can be seen that the readings of the DRX and Dylos follow each other closely, reflecting temporal concentrations patterns.

2.3. Calculation methods

2.3.1. Air exchange rate (AER)

The air exchange rate was determined by fitting an exponential