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Original article

Simulation of particulate matter ingress, dispersion and deposition in a historical building

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ABSTRACT

In this work, we use a computational fluid dynamics (CFD) model to simulate the penetration, dispersion and deposition of particulate matter (mean particle size of 2.5 μm) in a historical house. We compare the simulation results with direct measurements of deposition in several rooms and with measurements of concentration in different conditions of wind direction. The computational model, based on the drift-flux approach, provides accurate predictions of the spatial distribution of deposition and the variation of the indoor/outdoor ratio, which display a good agreement with experimental measurements. Our analysis shows that while the ingress rate of particles is controlled by wind direction and pressure, the amount of particles that reaches every surface depends ultimately on the operation of the ventilation system. Concentration indoors is relatively homogeneous, however, the spatial arrangement of the rooms and the position of air inlets and outlets results in significant gradients of deposition rates, which has direct implications for cleaning and preservation. These findings illustrate the potential of CFD to produce meaningful predictions of yearly and monthly deposition in large, multi-room environments, and to offer site-specific evidence, which can inform heritage managers and enable risk assessment.

1. Research aims

This research aims to:

- investigate the applicability of computational fluid dynamics (CFD) model of particulate matter deposition to large, multi-room heritage environments;
- validate, for the first time, a CFD model of deposition using spatially resolved deposition measurements in a real historical house;
- simulate deposition under different conditions of wind and operation of the building;
- demonstrate the potential of CFD as a predictive tool that enables risk assessment and decision-making in the heritage field.

2. Introduction

This work focuses on the use of computational fluid dynamics (CFD) to assess and quantify particulate matter (PM) deposition in indoor heritage in order to understand its sinks and sources and obtain actionable evidence. Heritage is a novel field of application of deposition models, which offers very particular challenges. The simulation of PM deposition indoors has long been motivated by health concerns. The purpose of such simulations has been, consequently, to accurately predict the concentration of suspended PM, which can be related to health risks. However, in the art and heritage context, the interest is not in the concentration of PM in the air, but in the amount of particles that reach every surface.

Many heritage institutions are concerned about the loss of value caused by PM deposition. This loss of value can be aesthetic (an area coverage of 5% may be visible to visitors [1]), mainly caused by coarse dust, or can be physical, either through unintended damage during cleaning or through chemical interaction between the particles and the substrate [2], mainly caused by fine particles. In order to understand deposition in such environments, and to enable risk assessment, we must be able to estimate the deposition rates and, most importantly, the spatial distribution of deposition.

Models of PM deposition have been used in the past to study deposition in museums. Nazaroff successfully simulated the size-resolved deposition of PM on walls, floors and ceilings in museum environments [3] using the expression developed by himself and Cass [4], based on early work by Crump and Seinfield [5]. Recent

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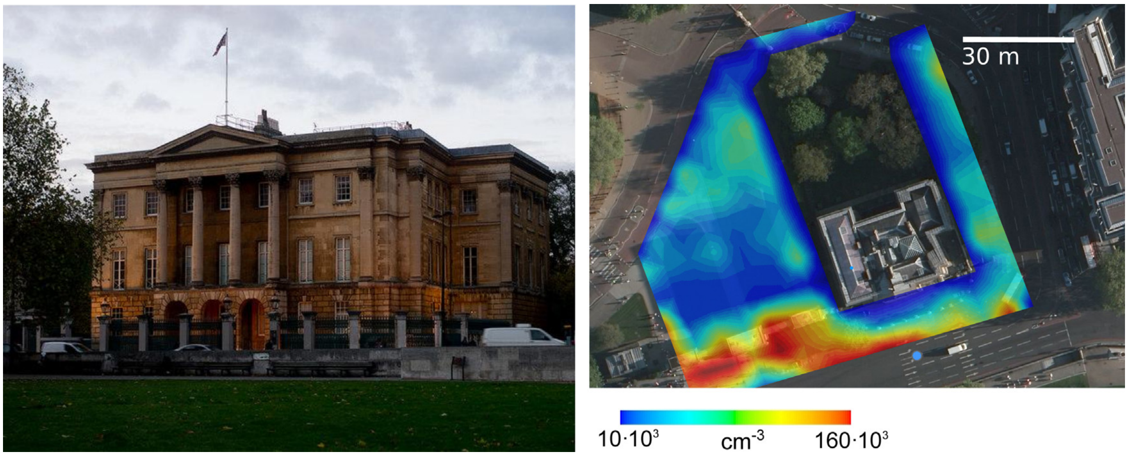

Fig. 1. View of Apsley House and a contour plot of fine PM concentration in the morning of 18 March 2013.

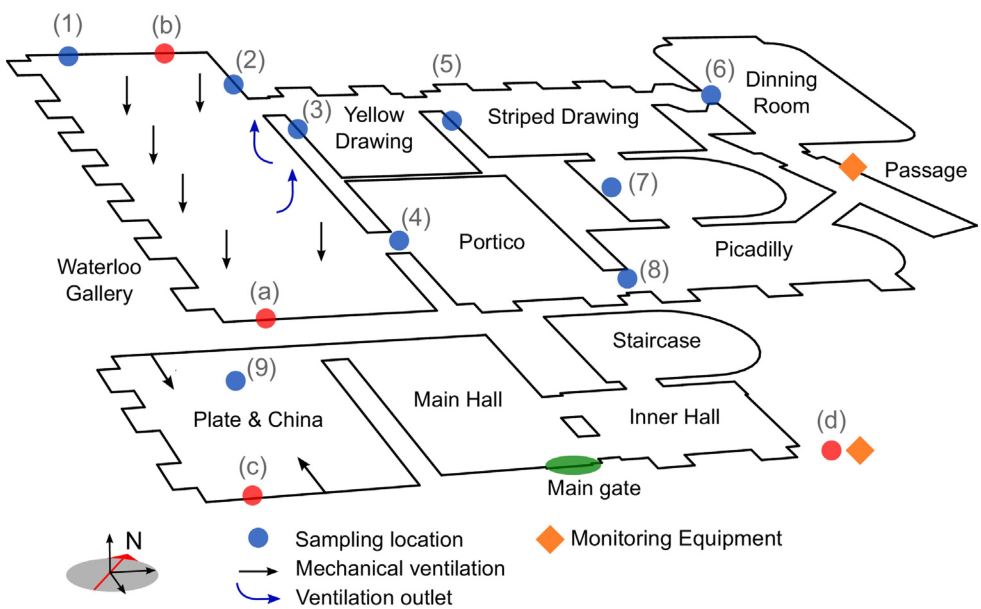

Fig. 2. Floor plan of Apsley House with sampling and PM monitoring locations. The numeric labels indicate the location of glass slides, while the letters indicate the location of SEM stubs for particle counting.

times have seen an emergence of various and more advanced CFD models of deposition, which consider particles either individually (Lagrangian approach) or as a continuous phase (Eulerian approach). Eulerian CFD models of PM deposition are generally referred to as drift-flux models, i.e. models that describe the mixture motion rather than the motion of the individual phases [6].

CFD models of indoor deposition are almost invariably validated against measurements of decay rates of PM concentration [7–13]. Few authors have compared CFD predictions of deposition with spatially resolved direct measurements of deposition. The geometries used in CFD studies of indoor deposition are generally of the scale of a single room or two adjacent rooms [10,14–16]. They tend to be simple and symmetrical, frequently allowing the use of structured meshes.

In order to demonstrate that CFD can be used to assess deposition in complex indoor heritage environments, we need two improvements over the present state of CFD deposition modelling. Firstly, the ability of the drift-flux model to describe the spatial variation of deposition must be validated experimentally. Secondly, the model has to be applied in larger, multi-room geometries with complex sources of air motion and particulate matter. In this work, we explore these possibilities by simulating a real historical house – Apsley House (London) – and by comparing the simulations with a rich ensemble of experimental data.

3. Study site

Apsley House is a 18th-century historic house located in Hyde Park Corner, London. Its position is next to a busy roundabout, with a flow of approximately 50,000 motor vehicles per day [17]. The ground and first floors of the House are open to the public during most of the year. Visitors access the House through the main hall (which faces the South West, the predominant wind direction). Visitors can access three rooms of the ground floor and all the spaces of the first floor, which contains seven interconnected rooms. The PM concentration in the surrounding environment is dominated by traffic. This is clearly seen by the high concentration of fine particles near the roads. Fig. 1 shows an image of Apsley House and its surroundings, as well as a contour plot of suspended ultrafine PM (d_p = 0.02–1 μm). This data was obtained with a condensation particle counter (TSI P-Trak) on 18th March 2013, taking measurements every 3 μm following a square reference grid of approximately 200