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PREVENTIVE CONSERVATION

Diagrams of equal area coverage: A new method to assess dust deposition in indoor heritage environments

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ABSTRACT

Particulate matter can cause a loss of value in indoor heritage, and for this reason it is frequently monitored. The process of deposition is well described by theoretical models that relate deposition rates with environmental variables. However, the authors find that the inputs and outputs of models are not directly relevant to preventive conservation. While heritage managers are concerned about area coverage by particulates, the existing models use deposition velocities as the main variable. The authors propose an improved graphical representation of predictions of deposition, that takes inputs that can be modified as part of preventive conservation plans (concentration and air movement) and an output that can be related to risk assessment and cleaning schedules (time to visible area coverage). By comparing the predictions with experimental data, the authors show that this approach is useful for small particles of outdoor origin, and also that further research is

INTRODUCTION

The deposition of particulate matter (PM), from fine combustion-related particles to coarse dust, is a significant concern for indoor heritage environments. PM deposition causes loss of aesthetic and sometimes material value of historical surfaces (Lloyd et al. 2007, Bartl et al. 2015, Grau-Bové et al. 2016a). Experimental protocols for monitoring particulate matter deposition have been developed (Adams 1997), and a usual approach is to monitor the amount of deposited particles on surfaces (Lloyd et al. 2007). However, even when deposition rates are monitored, it is often difficult to derive preventive conservation measures from the gathered data. Guidelines for indoor heritage environments still need to be developed, as it is unclear what the consequences are of a given concentration or level of area coverage (Grau-Bové and Strlič 2013).

The link between observed deposition and other environmental variables can be explored with mathematical models of aerosol deposition. The simplest and most well-known of these models was developed by Crump and Seinfeld (1981). This model relates certain inputs (particle properties such as diameter and density, and environmental parameters such as temperature and air turbulence) with the resulting deposition rates. Its output (Figure 1) is a classic result. It shows that the deposition rates of the smallest particles (0.01–1 μm) are relatively high and controlled by Brownian motion (and therefore by temperature). The large particles (> 10 μm), on the other hand, deposit due to gravitational settling. The deposition of both types of particles is affected by the level of turbulence: when it increases, deposition increases across all sizes, and most importantly, it tends to become independent of particle size.

In the authors' view, Figure 1 may illustrate well the dynamics of deposition, but it is not particularly well suited for heritage applications. Firstly, the output is in terms of deposition velocity, and it is unclear how this measure relates with limits of acceptable deposition. Secondly, the main independent variable of the plot is particle diameter, which is generally not monitored in the proposed low-tech monitoring strategies such as (Lloyd et al. 2011). There is scope to express predictions of particulate matter deposition in a way that lends itself to relevance for preventive conservation. The main aim of this paper is re-inventing this visualisation and verifying its usability in a heritage context.

needed to make numerical predictions relevant for cases where deposition involves coarse dust and is caused by visitor movement.

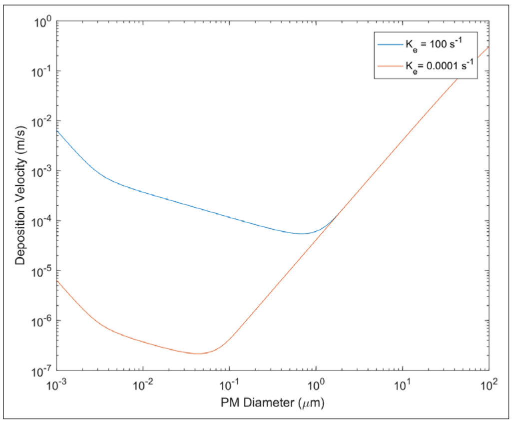

Figure 1. Relationship between particle diameter and deposition velocity calculated with the Crump and Seinfeld model (Nazaroff et al. 1994)

MATERIALS AND METHODS

Locations and measurements

The data used in this paper for the validation of the model originates in the following monitoring campaigns:

- Wellington Arch (June 2013) and Apsley House (January 2013), located in Hyde Park Corner and managed by English Heritage. Particulate pollution in these two properties at the time of monitoring was largely caused by outdoor infiltration of fine combustion soot of outdoor origin. $PM_{2.5}$ was monitored using Gradko DC1100 particle counters. Due to its proximity to the Piccadilly Road traffic underpass, the Wellington Arch experienced higher concentrations than the House. The monitoring campaign in Apsley house is described in detail elsewhere (Grau-Bové et al. 2016b).
- Hampton Court Palace, Great Hall (March 2013–March 2014), located in East Molesey (Surrey, UK) and managed by Historic Royal Palaces. It is relatively far from main roads. The contribution of outdoor pollutants is small in comparison to the coarse particles related to visitors. Deposition was monitored using glass slides by Historic Royal Palaces. Here data is used corresponding to the monthly area coverage measured on the tapestries close to the East entrance of the Great Hall.

Data about air motion and turbulence in these three locations is taken from computational fluid dynamics (CFD) simulations produced with the model developed in the Institute for Sustainable Heritage, University College London in previous research (Grau-Bové et al. 2016b).

Model

The model of deposition used here is a version of the model developed by Crump and Seinfeld (1981) as presented by Nazaroff et al. (1994). This model is convenient for its simplicity. Firstly, it is easy to solve and requires a small number of input parameters. Secondly, there is agreement in the literature that it is a good estimation of deposition rates indoors (Hussein et al. 2006). The main equations of this model are here re-stated for convenience, and a full description may be found in the literature (Nazaroff et al. 1994). The expressions for the deposition velocity towards walls (u_W) and towards the floor (u_f) are:

$$u_W = \frac{2}{\pi}\sqrt{DK_e} \quad (1)$$

$$u_f = \frac{v_g}{\exp\left(\frac{\pi}{2}\frac{v_g}{\sqrt{DK_e}}\right) - 1} \quad (2)$$

where D is the Brownian diffusion (which is a function of particle diameter and temperature), v_g is the settling velocity (which is a function of particle diameter and mass), and K_e is a parameter that describes turbulence.

DIAGRAM DEVELOPMENT

Towards an output metric

The first challenge to improve Figure 1 is to find a way to integrate it with existing guidelines relevant for preventive conservation. The first recommendations to be proposed used concentration of suspended particles. For example, 35 µg/m³of PM_{10} (particles smaller than 10 µm) (Blades 2000) or 10 µg/m³ of $PM_{2.5}$ (particles smaller than 2.5 µm) (Tétreault 2003). Other researchers have proposed to focus, instead, on the amount of particles present on surfaces (Adams 1997). Research on the human ability to detect deposition has found that between 2% and 9% coverage by soot is visible to the human eye (Bellan, Salmon and Cass 2000). Historic Royal Palaces uses a key performance indicator of dust deposition of 3% monthly area coverage (Frame 2013). Lloyd et al. (2007) demonstrated that, in historic libraries, visitors perceive surfaces as dusty beyond 3% area coverage, and as 'very dusty' above 9%.

Measurements of area coverage rather than concentration have multiple advantages. Firstly, measuring area coverage does not imply any a priori decision of the particle diameter of interest, as long as particles are visible. Secondly, it is common sense that only the particles that reach surfaces can affect their value. Therefore, if Figure 1 had the rate of area coverage as an output it would be in line with current conservation practice. The authors propose to make this output even more related to preventive conservation by combining the predicted area coverage with institutional guidelines of allowable deposition. This leads to the concept of 'time to unacceptable deposition', t_d:

$$t_d = \frac{A_{max}, Maximum\ allowable\ area\ coverage\ [\%]}{J_a, Rate\ of\ area\ coverage\ [\%/month]} \tag{3}$$

In the calculations presented in the following sections 5% is used as an arbitrary limit of maximum allowable area coverage. This can be replaced by any other guideline value. The advantage of t_d is that it can be directly related to the need for cleaning or intervention, and therefore to the costs associated with deposition.

Towards an input metric

In an ideal visualisation, the independent variables should be parameters that the conservation manager can measure or control. The equations of the model summarised in Section 2 give a good indication of the parameters that influence deposition. These are: temperature, pressure, the diameter and the mass of the particles, gravity, some measure of turbulence, and the concentration of particles. Of these, gravity, pressure, diameter and mass of the particles cannot be controlled. It is not possible to reduce the size of the particles, only to reduce the concentration of particles of a given size. Temperature is influential insofar as it influences Brownian diffusion, but it can be easily shown that within the temperatures of interest in heritage buildings its effect is insignificant. After this reasoning we are left, conveniently, with two inputs: air turbulence and particle concentration.

Can these be altered in a heritage environment? Not always, but often. Concentration can be reduced by eliminating indoor sources, limiting the number of visitors, or by reducing outdoor sources through filtration, the use of curtains, sealing gaps, and many other strategies (Nazaroff et al. 1994). Turbulence, or the intensity of air movement, can be altered by moving or eliminating sources of air movement.

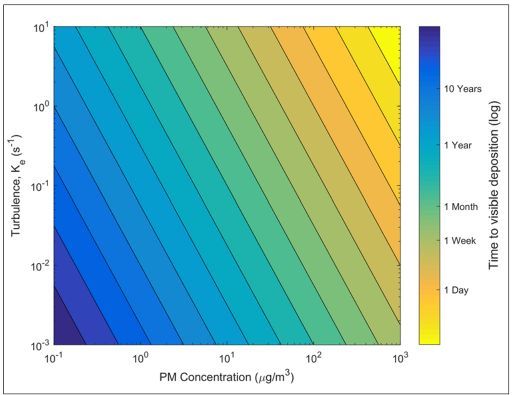

Figure 2. Base diagram of equal area coverage ($PM_{2.5}$)

Diagrams of equal area coverage

Having selected an output and two inputs, the only step left is to generate a visualisation of deposition predictions based on them. This can be seen in Figure 2. The authors call this plot 'diagram of equal area coverage', as it shows which environmental configurations will result in similar levels of deposition. It contains the same information than Figure 1, but expressed as a function of other variables. The diagram shown predicts deposition towards vertical surfaces. A limitation in comparison with Figure 1 is that a different diagram needs to be produced for each particle size.

Its usage is straightforward. The conservation manager, even without performing any measurement of deposition, can use Figure 2 to investigate the behaviour of particulate matter. Firstly, an estimation of concentration is needed. This value has been expressed in $\mu g/m^3$ because in many countries this is the metric usually provided by local authorities that routinely measure the concentration of particulate matter outdoors, mainly because it is the metric relevant for human health (WHO 2006). The plots for $PM_{2.5}$ have been produced for the same reason. It should be possible, therefore, to obtain reasonable estimations of outdoor concentration from publicly available data, in the understanding that outdoor concentration is the maximum concentration that will be achieved indoors (in absence of indoor sources). Secondly, it is necessary to estimate the intensity of air movement. Obtaining this estimation is not trivial. The next section provides a guide to the usual values of turbulence.

Interpreting turbulence

The parameter K_e is a version of the wall shear stress, which expresses how air velocity reduces from the bulk of the flow to the wall. If the flow is very turbulent, velocity will reduce sharply. In order to aid the estimation of K_e an approximate guide is provided to its value in different circumstances (Table 1). This guide is based on published values as well as the results of CFD simulations of air flow in a room.

Given that there exists a relationship between air velocity and turbulence, it could be considered whether air velocity would be a better input to the model. However, replacing K_e by air velocity in Figure 2 would be a large oversimplification, because a given air velocity can result in different

Table 1. Examples of turbulence, K_e, related to air velocity near the wall and its likely cause

Max. air velocity near the wall (m/s)	Resulting K_e in a room	Cases
1	40–60	Indoors, this velocity can only be found very close to air velocity inlets
		1.5–2 m/s is the maximum air velocity during walking (Gomes 2007)
		5 m/s is the average wind velocity in London (MET Office 2016)
0.5	15–20	0.2 m/s is classified as 'high fan speed (3070 rpm)' by Nazaroff (1994)
		0.3 m/s is the average velocity measured in air conditioned office environments (Baldwin 1998)
		0.1–0.5 m/s velocities have been calculated near walking humans (Wang 2011)
0.1	1–2	0.07 m/s is the mean velocity measured in domestic environments without forced ventilation (Matthews 1989)
0.01	0.1–0.2	Natural convection over a hot plate (Nazaroff 1994). 0.01–0.05 m/s are the usual limits of detection of hot wire anemometers

values of turbulence depending on the impediments to the flow, such as furniture, or the relative position of walls and the sources of air movement.

RESULTS

In this section the predictions of the model are compared with measurements of deposition in several properties. Rather than validating or fine-tuning the simulation approach, this comparison aims to understand the limitations of the proposed diagrams. To facilitate the interpretation of the results expressed in Figure 3, the isoline that corresponds with the key performance indicator used in Historic Royal Palaces has been highlighted.

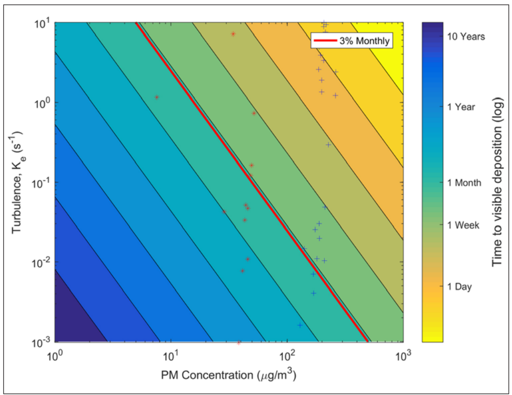

Figure 3. Diagram of equal area coverage for $PM_{2.5}$ with deposition data from Apsley House (*) and the Wellington Arch (+). The red line indicates the KPI of Historic Royal Palaces

Performance with fine particulate matter

The data of deposition collected in the Wellington Arch and Apsley House fall squarely within the limits of the plot. As mentioned in Section 2, the data obtained in these properties consist of values of concentration and turbulence obtained with CFD simulations in past research. The concentration of $PM_{2.5}$ in the two sites at the time of the experiments was markedly different, due to differences in the air-tightness of the building envelope. In the case of the Arch, the concentration of fine particles was markedly high. In Figure 3, it can be observed that both sites present a great variety of values of K_e, spanning over several orders of magnitude. If one uses the guide provided in Section 3.3, these span from natural convection to ventilation outlets. These are differences of turbulence to be expected between rooms with very different levels of ventilation. In both properties, there are areas with steady air next to areas with forced ventilation, which results in a notable diversity of turbulence levels. This in turn results in a variety of levels of deposition, which in the case of Apsley House span from times to allowable deposition of a year down to a week. This indicates the importance of air motion in the regulation of deposition on horizontal surfaces. In the case of the Wellington Arch, the air velocities are roughly similar but the concentration higher, which leads to very short times to reach 5% deposition, as short as a couple of days in some locations. This corresponds well with reports by the cleaning staff at the time of the experiment.

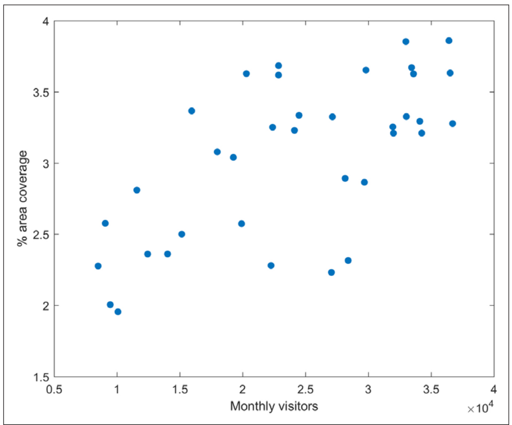

Figure 4. Correlation of deposition and visitor number in the Great Hall of Hampton Court Palace

Performance with coarse particulate matter

Deposition of fine particulate matter of outdoor origin is, however, only part of the problem. Let us consider the case of Hampton Court Palace, where the origin of particulates is linked to visitor numbers and visitor activities instead than outdoor sources. This observation is a result of the Tudor tapestries environmental protection project, described in a paper to be presented in the ICOM-CC conference. The size of the particles was also found to be much larger than the previous cases (an average of approximately 60 µm). Figure 4 shows the relationship between area coverage and visitor numbers in the Great Hall of Hampton Court between March 2013 and March 2014. The measurements correspond to three monitoring locations on the north-east corner, the Great Hall, which is the space between two entrance doors and one of the locations where the key performance indicator (KPI, 3% monthly) is exceeded. The monitoring data is available every two weeks, but in order to produce Figure 4 the

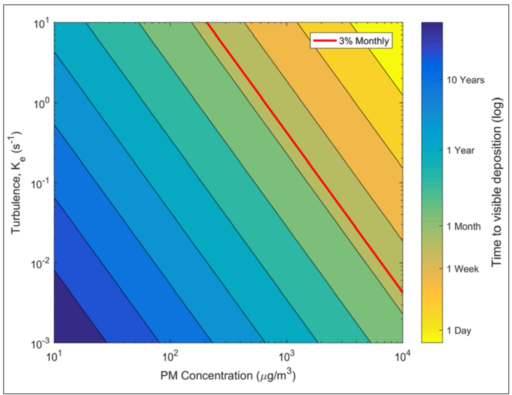

Figure 5. Diagram of equal area coverage for coarse particles (with a diameter of 60 µm).

data points have been combined to obtain values of monthly deposition that could be correlated with the monthly visitor numbers.

Figure 5 is a diagram of equal area coverage for very large particles. The reader will note that most of the experimental points of area coverage shown in Figure 4 fall above or very close to the KPI. As such, they should appear in the top right area of the diagram of equal area coverage (Figure 5). However, if these experimental points were added to Figure 5, the values of deposition would not coincide well with the 'y' and 'x' axis. According to Figure 5, the observed deposition could only be caused by concentrations of dust of 500 µg/m³ (which would be extremely high) and a turbulence parameter above 0.1 s^{-1}, which would correspond to high fan speed (Table 1). However, none of these two parameters corresponds with what can be measured in the Great Hall, as there are no fans or other sources of forced ventilation, and the concentration of suspended particles is very low. The diagram of equal area coverage predicts a rate of deposition that is much lower than the measurements.

The reason for this mismatch is that it may not be accurate to speak of 'concentration' in a case clearly dominated by coarse dust carried by visitors. It has been demonstrated that very coarse particles and clothing fibres are deposited a few meters close to the source or less (Lloyd et al. 2007), and do not distribute homogenously in the space (Yoon 2001). There is a similar problem with the level of turbulence. The air movement that controls deposition in Hampton Court Palace is not caused by any type of forced ventilation. Instead, the main cause of air motion could be the movement of visitors themselves.

We are faced now with a double question. What is the value of K_e, the turbulence parameter, that can be associated with visitor movement close to the tapestries? And secondly, how can the amount of dust related to the presence of visitors at different distances from the tapestries be quantified? These are matters for future research.

CONCLUSION

This paper has presented an improved method of displaying predictions of deposition rates that may be more relevant to preventive conservation than the common expressions of deposition models. If the inputs are available (concentration and a measure of air motion) it is possible to estimate the time before unacceptable deposition is reached. If these parameters are not available, the diagram can still be used to understand the non-linear relationships between the involved variables. The diagram highlights the importance of air motion, which can increase the deposition rates for any given concentration. Turbulence is not easy to estimate, and here only a very approximate guide is provided. Future research should explore the role of near-wall turbulence in the regulation of deposition indoors.

This paper has also shown that the diagrams of equal area coverage are only meaningful in the case of fine particles that are well distributed in the environment, where a concentration can be defined in the rooms of interest. In practice, deposition in indoor environments located far from polluted urban areas is due to large particles brought in by visitors. Further research is needed in order to identify reliable correlations between visitor numbers, distance to surfaces, and the observed deposition which can be usefully implemented in preventive conservation management.

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