Ingress of fine particulate matter in indoor heritage environments
Some experimental and computational approaches

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Soiled heritage: the Waterloo Gallery in Apsley House and a statue in UCL, London.
Properties of PM

Particulate matter has distinct properties:

- It has a certain size distribution
- Decay rates are a function of this size distribution
The focus is on fine particulate matter \((PM_{1})\). Generally, in indoor heritage:

- Particles are very diluted (no particle to particle interaction)
- Stokes numbers are \(< 1\) (particles do not affect airflow)
- Velocities are low and the flow is generally turbulent
Model Development

Structure of the Model

- Geometry
- Ventilation flow rates
- Crack infiltration
- Wall temperatures
- Outdoors concentration

Particulate Matter Deposition Rates

Cleaning
Soiling
Damage
Eulerian 'Drift Flux' Model

\[
\frac{\partial C_i}{\partial t} + \nabla \cdot \left[ (u + v_{s,i} + v_{th})C_i \right] = \nabla \cdot \left[ (D_i + \varepsilon_p)\nabla C_i \right] + S_{C_i} \quad (1)
\]

Lagrangian Model

\[
\frac{\delta V_{pi}}{\delta t} = \frac{V_{fi} - V_{pi}}{\tau} + F_{Gi} + F_{Si} + F_{Therm,i} + F_{Ei} \quad (2)
\]

Indoor emission source models

\[
V \frac{\delta C}{\delta t} = \text{INDOOR SOURCE} + \text{INGRESS} - \text{VENTILATION} \quad (3)
\]
Case Study 1: Wellcome Collection
$PM_{2.5}$ concentration in Euston Road in $\mu g/m^3$ taken from http://www.londonair.org.uk.
Case Study 1: Wellcome Collection

inlet velocity $\sim 1m/s$

$dp = 0.02 \sim 1\mu m$

$\rho_p = 1000 - 5000 kg/m^3$

turbulence model: RNG $k - \epsilon$
Case Study 1: Wellcome Collection
Case Study 1: Wellcome Collection

![Simulation vs Experimental Graph](chart.png)
Deposition rates are directly proportional to the aerosol concentration. In the model, this is reflected by the fact that,

$$J = u_d C_i$$

(4)

and that

$$u_d = f(\epsilon_p, D, \nu, \tau_w)$$

(5)

This assumption is valid between two extremes: concentration has to be high enough to consider the particle field as a continuum, and it has to be small enough to prevent coagulation. This upper limit can be considered to be in the vicinity of \( \sim 5 \times 10^5 \) particles/cm\(^3\), but depends on turbulence and particle size.
Case Study 2: The Wellington Arch
Case Study 2: The Wellington Arch

THE WELLINGTON ARCH (rebuilt 1883)

- Underpass ventilation shaft
- Exhibition/hospitality room
- Viewing platform
- Exhibition/hospitality room

PORTICO
RESEARCHING ENGLISH HERITAGE SITES

0 5 1 0 m
1961
2000
20 1 1–12
1910–12
1825–33
Exhibition/hospitality room
Viewing platform
Viewing platform

1825–33
1910–12
1961
2000
2011–12

0 5 10 m
Case Study 2: The Wellington Arch

3D Doppler anemometer, P-Trak particle counter, CO monitor, RH and T monitor and glass slides to collect deposited particles. Experiment carried out during 4 days.
Case Study 2: The Wellington Arch
Case Study 2: The Wellington Arch

Contours of User Scalar 0 (Time=4.0000e+01)

FLUENT 6.3 (3d, dp, pbns, rngke, unsteady)
Case Study 2: The Wellington Arch

Contours of User Scalar 0 (Time=6.0000e+01)

FLUENT 6.3 (3d, dp, pbns, rngke, unsteady)

Aug 24, 2013
Case Study 2: The Wellington Arch
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Contours of User Scalar 0 (Time=1.5000e+03)

FLUENT 6.3 (3d, dp, pbns, rngke, unsteady)  Aug 24, 2013
Case Study 2: The Wellington Arch
Case Study 2: The Wellington Arch
$d_p$ in $m\mu$ and deposition rates in $\text{number}/(cm^3\text{day})$. 
Case Study 3: Apsley House
Case Study 3: Apsley House
Case Study 3: Apsley House

Large crack (L = 8 cm, H = 2 mm), such as a poorly sealed window frame.

Very small crack (L = 1 cm, H = 0.25 mm), such as a crack in the glass or the glass fitting.
Case Study 3: Apsley House

Contours of particle concentration (max = 150,000 particles/cm³) and Infra Red images (temperatures between 12 and 21 °C)
Case Study 3: Apsley House

Measured velocity between rooms using ultrasonic 3D ultrasonic anemometers.
Simulated airflow between rooms.
Next step: simulation in larger geometries validated with deposited particle counts with SEM.
Concluding remarks

- The model can predict I/O ratios with accuracy using very simple meshes.
- Its applicability is limited in closed rooms with a single inlet.
- This can be addressed with a proper subdivision of the simulated geometry.
- Leakage can be estimated using a combination of experimental and computational tools.
Thanks for your attention.

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We solve the model proposed by Lai and Nazaroff [K. Lai 2000];

- Particles are treated as an eulerian scalar

\[
\frac{\partial C_i}{\partial t} + \nabla \cdot [(u + v_{s,i} + v_{th}) C_i] = \nabla \cdot [(D_i + \varepsilon_p) \nabla C_i] + S_{C_i}
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\]

- Deposition is introduced as a boundary condition in the walls

\[
J(x) = -\left(\varepsilon_p + D\right)\frac{\partial C}{\partial y} = u_{s}C(x) + u_{th}C(x)
\]

- The deposition velocity is calculated as

\[
v_{d} = \frac{i v_{s,i} - \exp(-iv_{s,i}I)}{I}
\]

where \(I\) is a function of the Schmidt number (\(Sc = \nu/D\)).
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- Deposition is introduced as a boundary condition in the walls

\[
J = -(\varepsilon_p + D) \frac{\partial C}{\partial y} \pm u_s C + u_{th} C
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\[
J = - (\varepsilon_p + D) \frac{\partial C}{\partial y} \pm u_s C + u_{th} C
\]

which is defined as \( J_{(y=0)} = \nu_d C_\infty \). The deposition velocity is calculated as

\[
\nu_d = \frac{i v_s}{1 - \exp \left( -i \frac{v_s l}{u^*} \right)}
\]

where \( l \) is a function of the Schmidt number (\( Sc = \nu / D \)).
\[ y^+ = \frac{yu^*}{\nu} \quad (6) \]

\[ u^* = \frac{\sqrt{\tau_w}}{\rho} \quad (7) \]

wall_shear_force = F_STORAGE_R_N3V(face,facesuperthread)

wall_shear_stress = wall_shear_force / NV_MAG(A);