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Particulate Deposition on Indoor Surfaces - Its Role, with Ventilation, in Indoor Air Quality Prediction

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Particulate Deposition on Indoor Surfaces - its Role, with Ventilation, in Indoor Air Quality Prediction.

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Synopsis.

There is an increasing concern at the possible health effects of fine suspended particulate (aerosol) upon human health, particularly in the urban environment. Aerosol infiltrating indoors may arise from transport, power generation and natural sources. Aerosol also arises from indoor sources, through cooking processes for example, and from animal dander.

In zones within a building, within which the air is reasonably well-mixed, the levels of aerosol will depend upon the ventilation rate and the rate of deposition on indoor surfaces. For conditions of low air exchange rate, surface deposition will be the dominant removal process. It will depend upon the nature and orientation of surfaces and on the airflow conditions and is usually expressed in terms of a characteristic deposition velocity.

This paper describes a sensitive aerosol labelling technique which allows experiments to be conducted, in both occupied test houses and aerosol test chambers, aimed at measuring aerosol deposition velocities to a range of surface types. Progress is also reported in developing a CFD code capable of making use of the boundary layer parameters which result from the experimental work.

1. Introduction.

Since the human population spends significant time periods in enclosed environments, a subject of primary importance is the effect of indoor air quality on the health of building occupants. Indoor air may contain a variety of components in particulate form which arise from both indoor sources and outdoor sources. Significant aerosol hazards of outdoor origin are those arising from vehicular emissions; there is strong recent evidence that fine particles, particularly those less than 10 μm in diameter (PM_{10}) produced by diesel combustion, are linked to respiratory problems and an increase in mortality (1). Environmental tobacco smoke is a major source of genotoxicity indoors; tobacco smoke particles span a significant size range and are highly respirable. Pollens are allergenic aerosols of outdoor origin, while aerosols associated with animal dander and house-mite excreta arise when indoor surfaces are disturbed. In respect of airborne pathogenic particles, notably *legionellis,* it is ironic that one of the major transfer mechanisms into the indoor environment is through air-conditioning systems.

Airborne contaminant transport modelling has an important role in health risk assessment and is also a useful tool in the design of ventilation strategies for improving indoor air quality. However, in formulating a model which includes aerosol contaminants, there is a need to recognise that the behaviour of airborne particles is complex relative to the gaseous constituents of air. Although aerosol particles approaching molecular dimensions are subject only to diffusive forces and behave approximately as gases, the movement of larger airborne particles, notably those in the 0.1-1 μm range, has been shown to be strongly influenced by electrostatic and thermal factors while particles of super-micrometre dimensions settle readily from an airstream under gravitational influences (2).

Figure 1 shows the predicted equilibrium indoor/outdoor aerosol concentration ratio for an outdoor aerosol pollutant source, computed using a single compartment model (3). Experimental aerosol deposition rate data generated by the authors (4) has been used to make predictions at a range of air exchange rates. It can be seen that, particularly at low air exchange rates, aerosol deposition is an important modifier of indoor air quality. If aerosol deposition is neglected in indoor air quality prediction (refer to the bold line on Figure 1) the inhalation exposure of building occupants may be overestimated. An additional important consequence of ignoring the aerosol deposition process is that human exposure to particulate pollutants by routes other than inhalation will be neglected. Ingressed radioactive aerosol, the product of accidental industrial emissions, presents a risk of carcinogenisis not only through inhalation but also through ingestion and dermal penetration. In addition, it has been shown (5) that the primary route of child exposure to metal dusts from ingressed vehicular emissions is through hand-to-mouth transfer from contaminated indoor surfaces after dust deposition. Surface soiling through aerosol deposition is also of significance in a context unrelated to health; in many non-domestic environments, such as art galleries and semi-conductor fabrication plants, the economic consequences of surface degradation following particulate deposition can be severe.

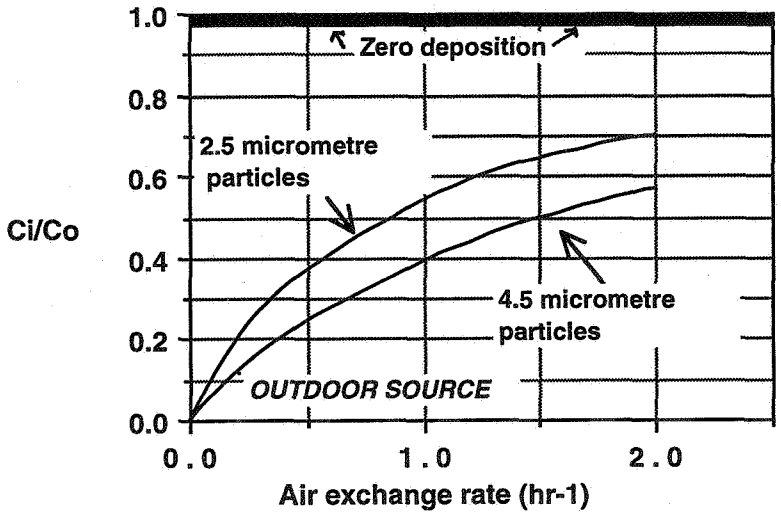

Figure 1. Calculated steady-state indoor/outdoor aerosol concentration ratio (Ci/Co), using experimentally-determined deposition rate data for 2.5 μm and 4.5 μm particles. The case for zero deposition is also shown. A building fabric filtration factor of unity is assumed.

In summary, the consideration of the aerosol deposition process when developing computational models leads to a more accurate indoor air quality predictor and increases a model's applicability to a greater range of pollutant types. The development of novel measurement techniques has allowed the authors to determine the most significant factors governing the behaviour of aerosol in both test chamber and real house environments. These data can be used to aid the development of computational codes for predicting indoor air quality. The aerosol measurement techniques, experimental results and computational developments are described in the remaining sections of this paper.

2. Experimental.

2.1 Aerosol generation and labelling.

In designing aerosol deposition experiments under conditions of building occupancy, careful consideration should be given to the type of tracer aerosol and detection technique used. A tracer aerosol deposition study should span the particle size range of real pollutant aerosol. This range is extensive; tobacco smoke particles can be as small as 0.01 μm while pollens of several tens of micrometres in diameter exist (6). Tracers which have low natural concentrations and high analytical detection sensitivities are ideal as aerosol labels since experiments can then be conducted using aerosol concentrations close to ambient levels, thus avoiding the occurrence of non-representative effects, such as thermal coagulation. Since the low aerosol levels constitute a negligible risk to a building occupant (or experimentalist), realistic simulation of a wide range of building occupancy conditions is possible. In addition, the use of a tracer with a high detection sensitivity presents the potential for surface analysis to complement aerosol concentration decay measurements.

A technique for generating, dispersing and detecting tracer labelled particles has been developed in a collaborative effort between the Energy Systems Section at Imperial College, the Danish National Laboratory at Risø and the Imperial College Centre for Analytical Research in the Environment. Porous silica particles, available in a variety of super-micrometre uniform size distributions, are agitated in a tracer salt solution so that tracer ions become bound to the particles' surfaces. Further details of the labelling procedure are presented elsewhere (7). The labelled particles are dispersed using a rotating brush aerosol generator. Sub-micrometre tracer particles are generated by atomisation and subsequent evaporation of a tracer salt.

Salts containing the rare earth elements dysprosium and indium are used as tracers in this work. Both exist naturally in a stable state but become unstable (i.e. radioactive) when bombarded with neutrons. Subsequent to a period of aerosol deposition in a test room/chamber, neutron irradiation of tracer aerosol-bearing materials (such as air filter papers or samples of domestic furnishing materials) in a nuclear reactor, followed by gamma-spectrometry, allows a quantitative determination of the aerosol mass present. Since dysprosium and indium occur naturally in low concentrations, the possibility of analytical interferences from particle-bearing media is minimised.

2.2 Aerosol deposition measurements in occupied rooms.

The tracer particles described in the previous section have been used in aerosol deposition measurements in three Danish and one British house, under furnished and unfurnished conditions. The details of the experimental procedures are described elsewhere (8); basically, a full-scale aerosol deposition experiment involves establishing a well-mixed tracer aerosol concentration in a suitable room and monitoring the aerosol concentration decay by sequential air filter sampling. If the air exchange in the room is simultaneously measured, by tracer gas monitoring, the rate constant for aerosol deposition can be calculated by subtracting the air exchange rate constant from the aerosol decay rate observed. Figure 2 shows the aerosol concentration decay and tracer gas decay curves generated in a typical experiment, plotted with the same arbitrary units to illustrate that air pollutants in particulate form behave quite differently from gaseous contaminants.

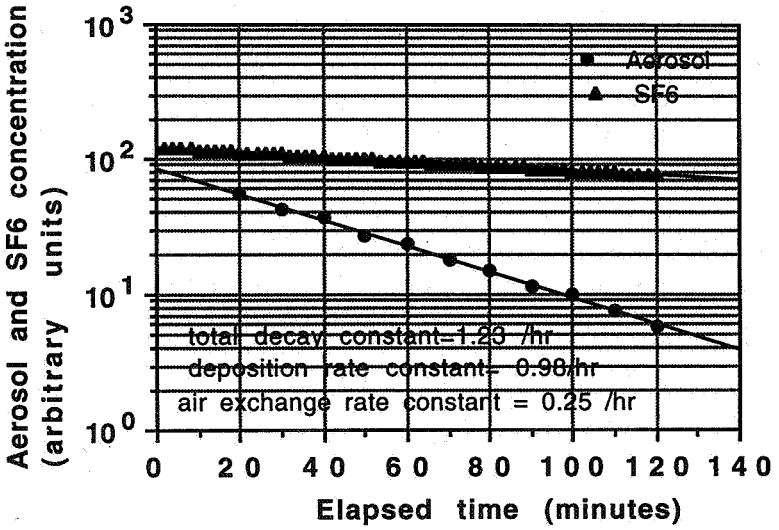

Figure 2. Aerosol and tracer gas concentration decay data, from a measurement in a single room. The decay rate constants, calculated from the data, are shown.

The average *aerosol deposition velocity*, a quantity which describes the aerosol flux to a surface for a given air concentration, to all the surfaces of a room can be determined by multiplying the aerosol decay rate constant by the volume to surface area ratio for the room. Figure 3 shows a representative selection of data; although the degree of furnishing and human occupancy was different in each test series, some general trends can be identified i.e. the average aerosol deposition velocity was seen to increase with particle size. In addition, the whole dataset indicates that, particularly for the larger aerosol particle sizes, average aerosol deposition velocities values are enhanced by the presence of furnishings.

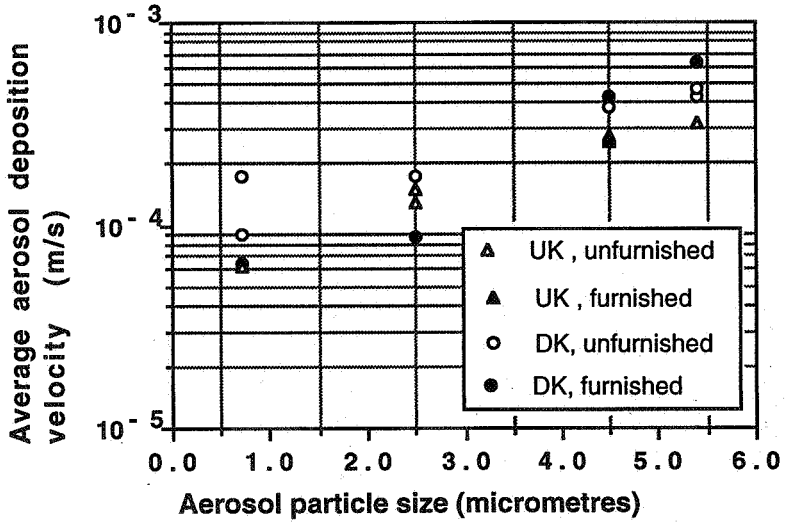

Figure 3. A representative sample of aerosol deposition data generated under furnished and unfurnished conditions in occupied houses in Denmark (DK) and the UK.

Considering the non-uniform test conditions, the results shown above are reasonably consistent, illustrating the value of sensitive detection techniques in identifying the likely

influencing factors on air pollutant behaviour in single rooms. However, for multi-zone enclosures, computational models have an important role since the accurate tracking of aerosol particles approaches the limits of even the most sensitive measurement techniques.

An understanding of the detailed physics of aerosol transport required in the formulation of a computational model cannot be inferred exclusively from data generated in real houses since too many influences on aerosol behaviour simultaneously exist. Experiments in test chambers provide data for code development and are described in the next section.

2.3 Aerosol deposition measurements in test chambers.

While contaminant mass transport in laminar flows is relatively well understood, further knowledge is required concerning the mechanisms for mass dispersion and deposition under turbulent flow conditions such as might prevail in the occupied indoor environment. The sensitive aerosol detection techniques described above have been employed to measure aerosol deposition velocities in an $8m^3$ aluminium test chamber (cubic) under turbulent conditions; the turbulence intensity generated by a small fan, suspended from the test chamber ceiling was in the range 22-43%.

Average aerosol deposition velocities were measured for particles in the size range 0.7-5.4μm; the results were found to be in good agreement with theory and are discussed elsewhere (9). Since the use of neutron activatable tracers facilitates surface sampling, additional information can be obtained by the analysis of filter papers, attached in regular arrays to each interior chamber surface for the duration of the aerosol concentration decay period. The relative contributions to the deposition process of gravitational settling (i.e. deposition to the floor) and eddy and Brownian diffusion (deposition to the floor, walls and ceiling) can thus be identified.

Figure 4 shows the relative vertical (one wall) and horizontal (floor) particle fluxes measured for four particle size distributions. It can be seen that, as a proportion of the average aerosol deposition velocity to all the surfaces, wall deposition decreases as particle size increases, in opposition to floor deposition. The figure also indicates that, for the smallest particle size tested, total deposition to the four walls becoming comparable to floor deposition; this has implications for the design of decontamination strategies for internal building surfaces.

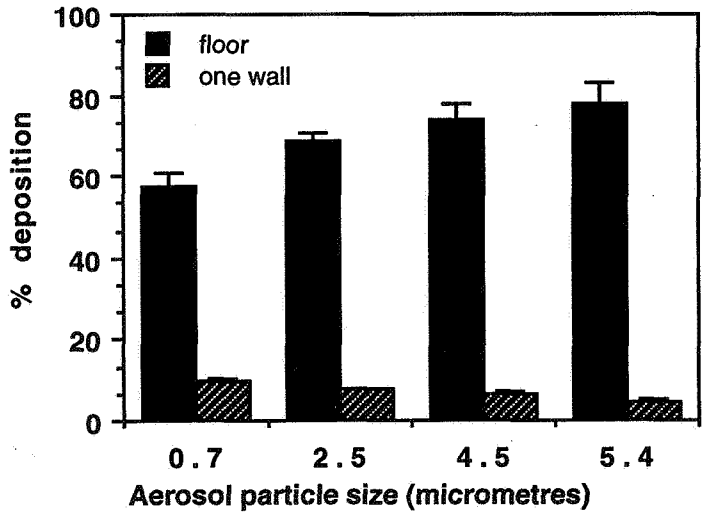

Figure 4. Measured relative aerosol particle mass fluxes to the floor and one wall of a test chamber.

The furnishings and wall and floor coverings which exist in the real indoor environment span a wide range of roughness characteristics. Having determined the average aerosol deposition velocity in the test chamber and the relative flux to each surface, the effect of surface roughness on aerosol deposition can be observed by covering one of the internal chamber surfaces with a rough material and combining the deposition velocity data for this case with the original chamber data. The aerosol deposition velocities to three rough vertical surfaces: wallpaper, short-pile carpet, and astroturf were determined by this method. Figure 5 shows the effect on vertical aerosol deposition velocity of attaching these rough surfaces to the chamber walls, for 4.5 μm particles; the roughness of the surfaces were quantified by friction velocity measurements using the method described in (10). As might be expected, greater deposition velocities were measured for the rough wallpaper, carpet and astroturf surfaces than for the visibly smoother aluminium surface. Although more data are clearly necessary to obtain a more reliable relationship between the variables, particularly in the intermediate friction velocity range, Figure 5 indicates that the particle deposition velocity to a vertical surface varies in a linear fashion with the friction velocity of that surface; it is likely that an increase in surface roughness will increase the rate of turbulent diffusion, and subsequent inertial impaction, to that surface but a limiting roughness will exist above which no further increase will increase the vertical particle deposition velocity, due to gravitational attraction of the particles to the floor.

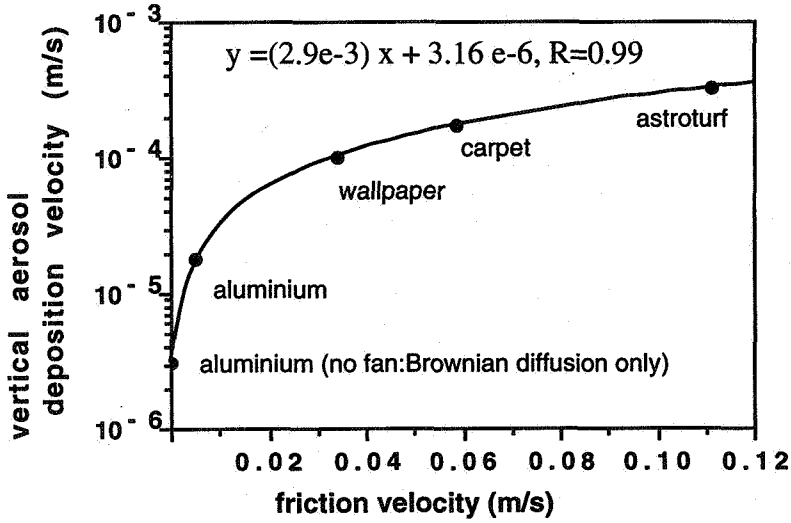

Figure 5. Measured aerosol deposition velocities (for 4.5 μm particles) to a vertical wall of a test chamber covered with materials of varying roughness.

3. Computational.

A model is under development at Imperial College which simulates the movement of aerosol particles in a turbulent airstream. The model has three key components: the gas-turbulence interaction in the main-stream, the particle-turbulence interaction in the main-stream and the particle-surface interaction in the boundary layer close to a wall.

A two equation K-E model (11) is used to model the gas-phase turbulence. A finite difference / finite volume technique is employed to solve the gas-phase governing equations on a staggered grid arrangement. Further details of the gas-phase modelling are available elsewhere (12).

A model has been developed to account for the frequently-overlooked mechanism of turbulent transport of particles to the boundary layer close to a surface by the turbulent

diffusion of particles in the main stream; a large number of researchers have studied, both experimentally as well as analytically, the physical mechanism underlying particle deposition, but in the viscous sub-layer only, and as a process isolated from the main turbulent flow field. In the present approach, the computationally-economical "Prediction of Evolving Probabilities" (PEP) model (13) is used to simulate the particle-turbulence interaction; it is assumed that the joint gas-particle velocity distribution is Gaussian. An equation which correctly embodies particle momentum conservation is derived for the evolution of the probability of particle velocity and by implication, its position. The probability density function is discretised within the range of physically probable velocities. A Lagrangian formulation is used to calculate the particulate phase by tracking the particles from a finite number of starting locations.

The motion of a particle within the turbulent external region is dominated by turbulent dispersion until the particle reaches the edge of the boundary layer, whereas within the boundary layer, the deposition becomes the controlling parameter until the particle is either deposited or rebounds. In the boundary-layer, a 'free-flight 'model (described in (14)) is used to account for particle inertia ; the possibility of particle rebounce from a surface is treated by considering that all particles approaching the surface with a velocity less than a critical value (15) should stick to that surface.

Figure 6 shows the two-dimensional simulation of the gas-turbulence interaction in the test chamber which was described in section 2.3 of this paper. The direction of the airflow, as dictated by the presence of the fan in the test chamber, indicates that the preferential surface for particle deposition is likely to be the floor of the enclosure; as was seen in Figure 4, this was found, by experiment, to be the case.

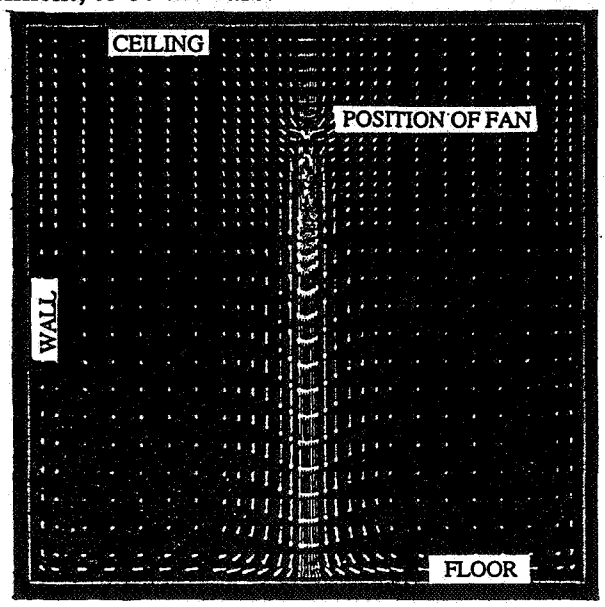

Figure 6. CFD simulation (axisymmetric) of the airflow generated by use of a fan in the aerosol test chamber described in section 2.3

4. Conclusion

It has been shown that the application of sensitive tracer detection techniques to aerosol deposition measurement facilitates studies of the effect of internal building surface character on indoor aerosol deposition, which complements aerosol concentration decay rate measurement. The data presented indicate that the orientation and roughness of indoor surfaces may significantly influence aerosol deposition velocity; these effects are relevant for environmental control considerations. These data can be used to aid in the development of computational models for indoor air quality prediction.

Acknowledgement

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