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# Effects Of Room Furnishings and Air Speed on Particle Deposition Rates Indoors


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# Effects of room furnishings and air speed on particle deposition rates indoors

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**Abstract**

Particle deposition to surfaces plays an important role in determining exposures to indoor particles. However, the effects of furnishings and air speed on these rates have not been well characterized. In this study, experiments were performed in an isolated room (volume = 14.2 $m^3$) using three different indoor furnishinglevels (bare, carpeted, and fully furnished) and four different airflow conditions. Deposition loss rates were determined by generating a short burst of polydispersed particles, then measuring the size-resolved (0.5-10 μm) concentration decay rate using an aerodynamic particle sizer. Increasing the surface area from bare (35 $m^2$ nominal surface area) to fully furnished (12 $m^2$ additional surface area) increased the deposition loss rate by as much as a factor of 2.6, with the largest increase seen for the smallest particles. Increasing the mean airspeed from < 5 cm/s to 19 cm/s, by means of increasing fan speed, increased the deposition rate for all particle sizes studied by factors ranging from 1.3 to 2.4, with larger particles exhibiting greater effects than smaller particles. The significant effect of particle size and room conditions on deposition loss rates argues against using a single first-order loss-rate coefficient to represent deposition for integrated mass measurements ($PM_{2.5}$ or $PM_{10}$).

*Keywords*: Aerosol, Deposition, Indoor, Particle, Air speed, Furnishings

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## 1. Introduction

Particulate air pollution is associated with increased morbidity and mortality even at the generally low levels of pollution in United States cities (Dockery et al., 1993, Pope et al. 1995). The exact compounds and particle size ranges responsible for these health effects have not yet been determined. However, particle exposures that occur indoors probably constitute a significant fraction of the overall exposure to hazardous particles since typically people spend most of their time indoors (Jenkins et al., 1992, Robinson and Nelson, 1995). Indoor concentrations of particles of outdoor origin can be comparable to outdoor concentrations (Ott et al., 2000; Riley et al., 2001). In addition, particles generated from indoor sources, such as tobacco smoke, cooking fumes, or pet dander, may present significant health concerns. Ordinary indoor environments contain a wide variety of particles arising from both indoor and outdoor sources.

Particle deposition to surfaces can substantially reduce indoor airborne particle concentrations, resulting in reduced inhalation exposures. For this reason, understanding deposition as a removal process is important for assessing human health impacts from indoor exposure to particles. Many recent experimental studies have reported size-resolved particle deposition rates for indoor environments (Xu et al., 1994; Byrne et. al., 1995; Thatcher and Layton, 1995; Fogh et al., 1997; Vette et al., 2001; and Mosley et al., 2001; Long et al., 2001). Taken as a whole, these studies show large variability in deposition rate for any given particle size. The studies provide indications but not a full basis for understanding the effects of various environmental factors on indoor deposition rates. In this work, we investigate the effects of increasing surface area (by adding furnishings) and changing mean airspeed (by altering fan speed) on the size-resolved particle deposition rate in a room.

## 2. Method

The first-order deposition loss rate coefficient, $\beta$ ($h^{-1}$), depends on properties of the particles, such as size, shape, and density, as well as properties of the deposition environment such as surface area and orientation, surface roughness, airflow conditions, electrical charge, and surface-to-air temperature difference. For larger particles (diameter greater than a few μm), the indoor deposition rate is thought to be determined largely by the gravitational settling velocity; for smaller particles (diameter less than 0.1 μm), gravitational settling is relatively unimportant.

Assuming well-mixed conditions, in the absence of either indoor sources or active removal by filtration, the time dependent particle concentration inside a room can be described with this mass-balance equation:

$$\frac{\mathrm{d}\ C_{\mathrm{i,\,dp}}}{\mathrm{d}\ t} = \lambda_{\mathrm{v}} P_{\mathrm{dp}} C_{\mathrm{o,\,dp}} - \lambda_{\mathrm{v}} C_{\mathrm{i,\,dp}} - \beta_{\mathrm{dp}} C_{\mathrm{i,\,dp}} \tag{1}$$

where the subscript "dp" denotes the particle diameter of interest, $t$ is time (h), $C_i$ is the indoor particle concentration (# $m^{-3}$) at time $t$, $\lambda_v$ is the air exchange rate ($h^{-1}$), $P$ is the fraction of infiltrating particles which penetrate the room shell, $C_o$ is the outdoor concentration at time $t$ (# $m^{-3}$), and β is the particle deposition loss-rate coefficient ($h^{-1}$). The experiments in this study were carried out in a tightly sealed room, resulting in a very small air-exchange rate, $\lambda_v$. In addition, the indoor concentration was elevated artificially so that $C_i$ was much larger than $C_o$. Under these circumstances, particle infiltration can be neglected and, assuming that $\lambda_v$ and β are constant, the time dependent solution to equation 1 becomes

$$C_{\mathrm{i,\,dp}}(t) = C_{\mathrm{i,\,dp}}(0)\ \exp\left[-\left(\lambda_{\mathrm{v}} + \beta_{\mathrm{dp}}\right)t\right] \tag{2}$$

where $C_i(0)$ is the indoor concentration at $t = 0$. Based on equation 2, it is possible to determine β by fitting a line to a plot of the natural log of $C_i$ versus time and subtracting the air-exchange rate from the negative of the slope.

**3. Experimental protocol**

The overall loss rate ($\beta + \lambda_v$) for distinct particle size ranges was determined by measuring the decrease in particle concentration over time after generating a burst of particles within the experimental room. Measurements were performed in a single room, using three different of furnishing levels (bare, carpeted, and fully furnished) and four different airflow conditions.

*3.1 Experimental room*

This study was performed in a small experimental room at the Lawrence Berkeley National Laboratory. The floor area of the room measures 2.2 m $\times$ 2.7 m, and the ceiling height is 2.4 m (volume = 14.2 $m^3$). The room is well sealed, but otherwise of standard construction (wood framing with textured drywall surfaces). Four small axial fans were used to vary the airflow conditions within the room. Three levels of furnishings were used in these experiments: (1) unfurnished with a bare, electrically grounded metal floor, (2) unfurnished with a carpeted floor, and (3) fully furnished with carpeting, chairs, table, bookcase, and curtains. Figure 1 shows the location of equipment and furnishings within the room. Adding furnishings increased the total surface area by about one third, changing the surface-to-volume ratio from 2.4 $m^2/m^3$ for the bare room to 3.2 $m^2/m^3$ for the furnished room. Of the approximately 12 $m^2$ of additional surface area, 9.2 $m^2$ was vertical, 2 $m^2$ was upward facing, and the remaining 0.8 $m^2$ was downward facing. Approximately 1.2 $m^2$ of the original floor area was covered by solid bottomed furniture. These nominal surface area estimates include only projected surfaces and do not represent the additional surface area due to roughness.

In addition to being tightly sealed, the experimental room is located within a larger building to protect the envelope from the effects of wind, solar heating, and large thermal variations. Consequently, the air infiltration rate is very low and stable. The infiltration rate for the room was measured prior to initiating these experiments using sulfur hexafluoride ($SF_6$) tracer gas, EPA Method IP-4B. Tracer gas was injected into the room and samples were taken every minute for 35 hours. The average air-exchange rate over this period was $0.006 \pm 0.003$ $h^{-1}$, with the highest infiltration rate over any three-hour period being just under 0.01 $h^{-1}$. The low air-exchange rate permitted accurate determination of particle deposition rates for all particle sizes studied.

*3.2 Air speed*

The air speed within the experimental room was varied by means of changing the voltage to the four small, instrument-cooling fans. The airflow conditions were characterized in terms of the average core airspeed in the room as measured on a $3 \times 3 \times 3$ grid. The measurement locations were 0.6 m, 1.2 m, and 1.8 m above the floor, and 1/4, 1/2, and 3/4 of the distance between the walls. The measurements were made using a hot-film anemometer (TSI, Velocity Probe Model 8470). Two sets of velocity measurements, each averaged over 90 seconds, were taken in both the furnished and unfurnished room for each of the 27 points in the grid. Table 1 presents the average and standard deviation of the core airspeed measurements for both the bare and furnished room. In these measurements, the standard deviation represents the variation in flow between the measurement locations. For two consecutive 90-second measurements taken at the same location, the variability was approximately 10%. The core airspeed was not significantly affected by the addition of furnishings.

For most measurements, the fans were oriented so that pairs faced each other (in Figure 1, fans 1 and 3 blew towards each other, as did fans 2 and 4). To explore the effect of fan orientation on deposition within the room, one additional set of experiments was performed with a different fan orientation. The flow pattern in this second configuration was circular (fan 1 blew towards fan 2, 2 toward 3, 3 toward 4, and 4 toward 1).

In experiments with the fans on, the average core airspeeds studied ranged between 5.4 and 19.1 cm/s, depending on the voltage applied to the fans. When the fans were off, the core airspeed was less than 2 cm/s, too low to obtain accurate measurements with the omnidirectional probes used. These airspeeds are similar to those that have been measured in typical indoor environments. Matthews et al. (1989) reported median airspeeds in 4 residences that ranged from 1.5 to 5.8 cm/s when the central, forced-air fan was off and from 5.7 to 15.5 cm/s when the fan was operating. Hanzawa et al. (1987) measured airspeeds in offices, meeting rooms, and other commercial spaces and found that the majority fell between their lower detection limit of 5 cm/s and 20 cm/s. Thorshauge (1982) also performed measurements in similar types of indoor environments and reported mean airspeeds between 5 and 40 cm/s. The individual measurement values were highly dependent on the type of ventilation and where the measurement was taken within the room.

*3.3 Particle generation and measurement*

For these experiments, particles were generated using a 3-s burst from an atomizing nozzle (Spraying Systems, Inc., Model SU13) to spray approximately 7 $cm^3$ of a mixture of 10% olive oil in isopropyl alcohol into the room, producing polydispersed oil droplets over the diameter range of interest (0.5 μm to 20 μm). This generation method introduced enough particles to provide accurate particle decay rates without yielding high enough concentrations to make coagulation effects significant. Calculations (based on the method given in Hinds, 1999) indicate that the isopropyl alcohol will evaporate from the droplets in less than 1 s, yielding stable droplets of olive oil. Three-minute averages of size-resolved particle concentrations were sampled and recorded using an Aerodynamic Particle Sizer (APS 3320, TSI Incorporated) located on the floor of the chamber as shown in Figure 1. The APS uses a time-of-flight technique to classify particles with aerodynamic diameters between 0.5-20 μm. Particles larger than 10 μm settled too quickly to provide accurate estimates of the deposition loss rate. As a result, deposition rates are only reported for particles between 0.5 and 10 μm.

For some experiments, a small amount of aqueous ammonium fluorescein solution was added to the spray mixture to allow for subsequent analysis of the total mass deposited to the floor surface and the fan blades. The fluorescent deposits were analyzed by means of extracting the particles into a buffer solution and measuring the fluorescence of the extract using a fluorometer (Turner Instruments, model TD-700). Airborne concentrations were measured over the course of each experiment using 5 sets of duplicate pairs of open face micropore filters (0.7

μm nominal) sampling at 1.5 L/min. Sample periods varied from 10 minutes early in a run to 30 minutes at the end of each run. These methods are similar to those used by Thatcher and Nazaroff (1997). Quality assurance experiments showed that the fans and deposition plates had low background fluorescence and that the extraction methods achieved good recovery rates.

**4. Results and discussion**

Figure 2 shows a typical plot of size-dependent particle concentrations versus time during an experiment. The values for the first half hour represent baseline particle concentrations. After 30 minutes, a burst of particles is injected and the concentrations rise rapidly. Approximately 3 minutes after particle generation, the decay rate stabilizes for all particle sizes, indicating that the particles are well mixed within the room.

The linear portion of the plot of the log concentration versus time was used to calculate the particle loss rate. In general, the $r^2$ correlations for the slopes were very good (between 0.95 and 1). For the smallest particles the correlations were typically lower, owing to the very small slope of the decay rates, which accentuated the influence of sample-to-sample variability. To determine the deposition loss rate, losses due to exfiltration (0.006 $h^{-1}$) and APS sample flowrate (0.02 $h^{-1}$) were subtracted from the total particle loss rate. For the experiments using fluorescent tracer, the loss rate due to filter sampling (0.01 $h^{-1}$) was also subtracted.

For particles larger than about 3 μm aerodynamic diameter, the decay rate plateaus prior to the end of the experiment. At the plateau, nearly all of the particles in that size range have deposited. These plateaus occur at concentrations that are significantly above background. The cause appears to be an inherent limitation of the APS whereby a small fraction of submicron particles enter the analysis region in pairs and are misclassified as larger particles. This artifact also has been observed when a large number of small monodispersed particles are introduced into the instrument and a secondary 'false peak' of larger particles is recorded. Data were corrected for this artifact by assuming that the number of misclassified particles is constant throughout the experiment at the plateau value and subtracting this value from the measured concentration for the larger particle size ranges.

In reality, the apparent plateau is not actually constant, but decays slowly as the concentration of small particles decreases. Calculations showed that adding a correction for the probable value of the artifact at the beginning of the decay period based on the slope of the plateau decay and subtracting that portion of the particle loss rate due to loss of artifact counts could increase the calculated deposition rate for larger particles by up to about 10%. However, given the inherent uncertainty in the values for this correction, it is unclear that this would indeed increase the accuracy of the calculated values. Therefore, only a first-order correction using the particle count rate at the plateau was used.

Figure 3 shows deposition loss rates for the two different fan configurations, the "standard" opposing fan orientation where pairs of fans faced each other and a circular orientation which was used only for the runs shown in this figure. For both configurations, the rooms were unfurnished with the fans on medium speed (mean airspeed in room = 14.2 cm $s^{-1}$). The loss rates and standard deviations shown are based on three and four independent experiments for the opposing and circular fan configurations, respectively. The values show that fan orientation may only have a slight influence on deposition rates for particles with diameters at or below a micrometer, and no discernable effect is seen for larger particles.

Replicates runs showed that the experimentally determined deposition loss rates were very consistent from run to run. For the seven runs shown in Figure 3, the values from individual runs deviated from the median of the runs by an average of 7%. Therefore, only 2 replicates were performed for all other combinations of furnishing and fan speed tested. For these pairs of replicate runs, the average difference between an individual replicate and the mean of the two replicates was 10%. The variation between replicates also showed the trend in relative difference that was seen in Figure 3, i.e., the relative difference was higher for smaller particles where the deposition loss rates are small.

Table 2 summarizes the deposition loss rate coefficient measured under all experimental conditions. Figures 4 and 5 illustrate the effects of furnishing and airflow conditions, respectively.

Figure 4 shows the effect of adding furnishings for the four airflow conditions studied. Each point represents the average of the values from two separate experiments. The amount of furnishing had a larger relative effect on the deposition rate for smaller particles as compared with larger particles. For example, for particle diameters less than or equal to 1.0 µm, the ratio of deposition rate coefficients for the furnished room to the bare room was 2.1 ± 0.3 (mean ± standard deviation for all respective pairs). For supermicron particles, the corresponding result was 1.2 ± 0.3. This result is consistent with the idea that larger particles deposit mainly due to gravitational settling and are therefore not strongly affected by increases in vertical and downward facing surface area. Conversely, submicron particles would be more strongly influenced, since they deposit effectively to surfaces of all orientations. Although the nominal surface area for the fully furnished room was only 34% larger than for the bare room, it is important to remember that only the projected surface area was measured. The additional surface area due to fibers and textures was not included. Moreover, carpeting and furniture increased average roughness of surfaces, changed the flow patterns within the room (although the mechanical energy input remained the same), and may have increased electrostatic surface effects. These factors may have contributed to the enhanced deposition rates observed.

The effect of airflow conditions can be seen in Figure 5. The lowest level of air motion occurs when the fans within the room are turned off. Since the experimental room is built on a raised floor and located within a larger, thermally controlled space, there is very little convective driving force and the core velocity is small in the absence of mechanical mixing. The lowest setting of the axial fan system was chosen to be the smallest applied voltage that would consistently start the fan blades spinning. Deposition rates without fans and at the lowest fan speed were generally comparable; however, further increases in the mean airspeed enhanced deposition substantially for all particle sizes studied. For particles with diameters less than 1.0

μm, changing the airflow conditions from fan off to the highest fan speed increased the deposition loss rate coefficient by an average factor of 1.5 (standard deviation = 0.2). The corresponding result for coarse particles was larger: 2.0 ± 0.2. Increases in deposition rates with increased indoor airspeed have also been reported by Xu et al. (1994) and by Mosley et al. (2001).

To confirm that the observed increase in deposition loss rate was due to increased deposition onto room surfaces rather than deposition onto the fan blades at higher speeds, experiments were performed using particles containing a fluorescent tracer. Four runs were performed: two on low speed and two on high speed. During each run, filter samples were taken to determine the change in airborne concentration over time and small metal plates were placed on the floor to collect deposited particles. After each run, the fluorescent particles were extracted from the fan blades, filters, and metal surfaces by soaking and/or wiping with a buffered water solution. Results of the fluorescent extraction showed that at the highest fan speed an average of 13% of the particle loss rate could be attributed to deposition onto the fan blades. At the lowest fan speed an average of 9% of the deposition occurred at the fan blades. The difference between these values is neither significant nor sufficient to explain the deposition enhancement observed. Therefore, it appears that the increased deposition loss rate is due to increased deposition rates to room surfaces because of more effective mass transfer at higher airspeeds. This agrees with the findings reported by Byrne et al. (1995), who found that only 1 to 2 % of the total mass loss in their chamber study could be attributed to deposition on the mixing fan blades. In our experiments, the floor samples showed that a larger portion of the deposition occurs at the floor for the lower fan speed than for the higher speed. This suggests that the enhanced deposition associated with increased air motion occurs preferentially on vertical and downward facing surfaces, although additional research is required to confirm this inference.

Overall, for any given particle size, the ratio of the maximum to minimum loss-rate coefficient varied between 2.3 and 3.2 (median = 2.8) over the range of conditions studied. This is a relatively small effect compared to the influence of particle size: for given furnishing and airspeed the ratio of maximum to minimum loss-rate coefficient across particle sizes was typically 50.

**5. Synthesis**

To put the results of the current study in a broader context, Figure 6 presents a summary from several recent studies of particle deposition loss-rate coefficients indoors. Four criteria were applied in selecting these experimental studies: (a) measurements must have been made in a full-sized room or building, (b) the effect of particle size must have been explicitly considered; (c) the experiments must consider loss to all interior surfaces; and (d) the study must have been reported in a peer-reviewed journal. Predictions from a recent modeling study are also presented. The two traces are intended to approximately span expected conditions for ordinary indoor environments: surface-to-volume ratio (S/V = 2-4 $m^2\ m^{-3}$), turbulence intensity ($u^*$ = 0.3-3 cm $s^{-1}$), and specific gravity of the particles (sg = 1.0-2.5).

Figure 6 reveals several important points. First, particle size is seen to be an important factor influencing deposition rates. For example, the central tendency of the experimental data shows an increase in deposition rate from ~ 0.1 $h^{-1}$ for 0.2 µm particles to ~ 1 $h^{-1}$ for 2.5 µm particles. This large dependence on size calls into question the utility of using a single loss-rate coefficient for a mass-integral measure such as $PM_{2.5}$.

Second, for any given particle size, the experimental loss-rate data exhibit a large degree of variability. On the whole, this variability is considerably larger than the factor of 3 found in the current study. For example, for 0.2 µm particles, experimental data vary by a factor of approximately 100, from ~ 0.01 $h^{-1}$ to ~1 $h^{-1}$. With respect to assessing human exposure, removal by deposition always competes with removal by air-exchange, which seldom occurs at a rate less than 0.1 $h^{-1}$. Thus, one might argue that understanding the causes of deposition rate variability at levels below 0.1 $h^{-1}$ are of academic interest only. However, even restricting attention to loss rates above 0.1 $h^{-1}$, the data exhibit substantial variability across all particle sizes. The causes of this variability are not yet understood. The current study suggests that differences in airspeed and furnishings can contribute, but are probably insufficient to explain the whole range.

A third striking feature is model-measurement discrepancy. Overall, the model and the measurements predict similar trends. However, especially for particles smaller than about 0.5 µm, the central tendency of the model estimates is about an order of magnitude below that of the experimental results. In future work, there are opportunities for improvement on both fronts. The model is based on key assumptions that may not apply in field settings, such as smooth surfaces and particle transport only by advection, Brownian and turbulent diffusion, plus gravitational settling. The experiments that reveal the highest deposition rates were conducted in field settings with limited control over experimental conditions (Abt et al., 2000; Long et al., 2001; Vette et al., 2001). It is difficult even in the best of conditions to isolate deposition from the many competing factors that can influence airborne particle concentrations.

To summarize, recent studies on particle deposition to indoor surfaces make it clear that the deposition rate varies broadly across conditions. Particle size is undoubtedly important. However, other factors can also influence the deposition rate significantly, including the quantity (and presumably nature of) interior furnishings and the intensity of indoor air motion. Overall, the rate of deposition is sufficiently large to be an important factor influencing indoor particle concentrations. The present study has advanced our understanding of how the deposition rate of particles in the diameter range 0.5-10 µm is influenced by the amount of furnishing in a room and by the indoor airspeed. Efforts to apply similar experimental methods to study the deposition of small particles (diameter < 0.5 µm) should be fruitful. Continuing efforts to reconcile model-measurement predictions are also needed.

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**Figure captions**

**Figure 1**. Configuration of experimental room, including location of furniture during fully furnished conditions. For all experiments the fans were located symmetrically in the room, 61 cm from each of the two closest walls and 1.4 m from the floor. The ceiling height was 2.4 m.

**Figure 2**. Typical particle concentration profiles over the course of an experiment for selected particle size ranges. Pulsed particle injection occurred at 0.5 h.

**Figure 3**. Particle deposition loss-rate coefficients as a function of particle size for two different fan configurations, forming circular and opposing flow patterns, in a bare room with a mean core airspeed of 14.2 cm $s^{-1}$. Error bars represent the standard deviation.

**Figure 4**. Particle deposition loss-rate coefficients as a function of particle size at each mean core airspeed. Curves represent the three furnishing levels: bare, carpeted, and fully furnished.

**Figure 5**. Particle deposition loss-rate coefficients as a function of particle size at each furnishing level. Curves represent the four airflow conditions: without fans, 5.4, 14.2 and 19.1 cm/s (mean core airspeed).

**Figure 6**. Summary of particle deposition loss-rate coefficients from the current and recently published studies. Data for the current study reflect the maximum and minimum loss-rate coefficient at each particle size. The modeling results apply to approximately the upper bound of expected indoor conditions for surface-to-volume ratio (S/V = 2-4 $m^2$ $m^{-3}$, with 25% upward facing and 50% vertical surface), friction velocity (u* = 0.3-3 cm $s^{-1}$), and particle density (specific gravity, sg = 1.0-2.5).