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Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse

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Abstract

Several studies have shown the importance of particle losses in real homes due to deposition and filtration; however, none have quantitatively shown the impact of using a central forced air fan and in-duct filter on particle loss rates. In an attempt to provide such data, we measured the deposition of particles ranging from 0.3 to 10 μm in an occupied townhouse and also in an unoccupied test house. Experiments were run with three different sources (cooking with a gas stove, citronella candle, pouring kitty litter), with the central heating and air conditioning (HAC) fan on or off, and with two different types of in-duct filters (electrostatic precipitator and ordinary furnace filter). Particle size, HAC fan operation, and the electrostatic precipitator had significant effects on particle loss rates. The standard furnace filter had no effect. Surprisingly, the type of source (combustion vs. mechanical generation) and the type of furnishings (fully furnished including carpet vs. largely unfurnished including mostly bare floor) also had no measurable effect on the deposition rates of particles of comparable size. With the HAC fan off, average deposition rates varied from 0.3 h^{-1} for the smallest particle range (0.3–0.5 μm) to 5.2 h^{-1} for particles greater than 10 μm. Operation of the central HAC fan approximately doubled these rates for particles <5 μm, and increased rates by 2 h^{-1} for the larger particles. An in-duct electrostatic precipitator increased the loss rates compared to the fan-off condition by factors of 5–10 for particles <2.5 μm, and by a factor of 3 for 2.5–5.0 μm particles. In practical terms, use of the central fan alone could reduce indoor particle concentrations by 25–50%, and use of an in-duct ESP could reduce particle concentrations by 55–85% compared to fan-off conditions.

Keywords: Fine particles; Coarse particles; Deposition; Filtration; Residential indoor air quality

1. Introduction

Numerous studies have documented the contribution of indoor sources (e.g. smoking and cooking) to elevated concentrations of particles indoors (Özkaynak et al., 1996; Wallace, 1996). Indoor sources such as combustion tend to elevate ultrafine and fine particle concentrations whereas mechanically generated sources (sweeping, dusting, resuspension from clothes and carpets) tend to elevate concentrations in the coarse fraction. Following the generation of particles indoors, concentration levels may be reduced through several mechanisms including exfiltration through air exchange, filtration using portable or in-duct air cleaners, and deposition. Of these mechanisms, exfiltration losses are relatively easy to quantify for a given space, based on the air change rate, and these losses apply equally to all particle sizes. The other loss rates, however, are dependent on several factors including particle size, shape, composition, concentration, room air velocity, room surface characteristics, and volume flow of air

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through filters and duct work (Nazaroff and Cass, 1989). Coagulation is another important mechanism that affects particle concentrations in a specific size range. However, Xu et al. (1994) estimated coagulation rates for environmental tobacco smoke in a room-size chamber and determined it only affected the concentration of particles less than 0.5 μm in diameter and for concentrations greater than 8000 particles cm^{-3}, a very high concentration for typical residential environments. Thus, the more significant loss mechanisms for residential particle concentrations in need of further study are filtration and deposition. To date, there are only a few studies quantifying size-dependent particle loss rates in furnished homes due to deposition (Thatcher et al., 2002; Long et al., 2001; Vette et al., 2001; Abt et al., 2000; Fogh et al., 1997; Wallace et al., 1997; Thatcher and Layton, 1995), none of which also examine the loss due to operation of the ventilation system or use of air filtration devices.

We conducted a multi-year monitoring study in an occupied three-story townhouse to increase the existing database of particle deposition rates for indoor sources representing a wide range of particle sizes. The study included real-time monitoring of tracer gas concentrations and indoor and outdoor concentrations of particles ranging from 0.3 to 10 μm. Following the peak concentration of an indoor particle source, the decay rate was calculated allowing for the determination of deposition and filtration particle losses. The heating and air conditioning (HAC) configuration was varied between off, on with no filter, and on with either a typical furnace filter or an electrostatic precipitator (ESP) installed. The extended duration of this study allowed for determination of deposition and filtration rates for numerous indoor particle sources.

The use of a single house normalized the impact of different surface characteristics on deposition losses. Thus, the relative importance of deposition as a loss mechanism may be determined between different types of sources. Additional decay experiments were completed in a second uninhabited house with the same source, thereby allowing another comparison of decay rates.

2. Experimental methodology

The determination of decay rates for indoor particle sources is part of a larger monitoring study that has been described elsewhere (Wallace et al., 2002; Wallace and Howard-Reed, 2002). In summary, a three-story townhouse located in Reston, VA (approximately 35 km NW of Washington, DC) was equipped with several instruments to continuously monitor air change rates and indoor and outdoor particle concentrations. The end unit townhouse consists of three levels including a partial basement with recreation room, utility room, and bathroom on the bottom level; a kitchen/dining room, living room, and bathroom on the middle level; and four bedrooms and two bathrooms on the top level. The overall volume of the townhouse is approximately 400 m^3 with a floor area of approximately 50 m^2 per level. The house's primary heating system is a gas furnace and the cooling system includes central air conditioning and a temperature-actuated attic fan to vent the attic on hot days. The HAC system uses 100% recirculated air and its ductwork does not enter the attic, resulting in minimal duct leakage to the outdoors. For the source decay rates described in this paper, the HAC system was either turned off, operated with no filter, or operated with either a typical panel furnace filter or ESP. The ESP positively charges particles with ionizing wires at 6200 V. The charged particles are then removed by ground collector plates. The ESP required frequent cleaning to maintain high removal efficiencies.

The infiltration rate was measured using the tracer decay method as described in ASTM Standard E741 (ASTM, 2001) with sulfur hexafluoride (SF_6) as the tracer gas and a gas chromatograph with electron capture detector (GC–ECD) detection system. The system was automated to inject SF_6 every 2–4 h into the HAC system where it was distributed to the rest of the house. The GC–ECD measured tracer gas concentrations sequentially every minute from 10 locations in the house: two locations in the lower level, the central return of the HAC system, three locations on the middle level, three locations on the top level, and the attic. The GC–ECD was calibrated biweekly to measure SF_6 concentrations between 30 and 900 $\mu g\,m^{-3}$ (5 and 150 ppb(v)) with an accuracy of approximately ±2%. We observed that with the central HAC fan operating, it normally took about 30 min following injection to achieve relatively uniform concentrations in all rooms. Therefore, hourly air change rates were calculated from 30 min past the hour to 30 min past the next hour, for all hours in which no injection took place. This allowed a calculated air change rate for about 4500 h out of 8760 h possible in the year 2000. Air change rates were estimated by linear regression of the natural logarithm of SF_6 concentration versus time. The uncertainty of the calculated air change rates was approximately ±10%.

The duct velocity in the HAC system was measured every 5 min with a hot wire anemometer that had an accuracy of approximately ±2.5%. The duct velocity was converted to a volumetric airflow rate of approximately 2000 $m^3\,h^{-1}$ (an equivalent air change rate of 5 h^{-1}) when the central fan was operating. This airflow rate was not significantly affected by the presence of the ESP.

Particle concentrations were integrated over a 1-min time period every 5 min with a Climet (Climet Instruments Model 500-I, Redwood City, CA) optical scattering instrument that counts particles in the following six size ranges (modified to include one boundary at

2.5 μm): 0.3–0.5, 0.5–1.0, 1.0–2.5, 2.5–5.0, 5.0–10, and > 10 μm. Four Climets were used in this study, including one for counting outdoor particle concentrations. Limitations of this instrument have been discussed elsewhere (Wallace and Howard-Reed, 2002). All samples were collected directly by the Climet without tubing attached to the inlet. The precision of the Climet varies according to the size range considered, with the best precision at the smallest size ranges (which have the largest number of particles). Precision varies from a few percent at these small size ranges to much higher values at the largest size ranges, which may have less than 10 particles collected over a 1 min sampling period at typical indoor concentrations. Each Climet was calibrated by the manufacturer on an annual basis. Any bias between the instruments was corrected based on side-by-side measurements.

Indoor and outdoor environmental conditions were also continuously monitored. Temperature was measured sequentially every minute in 10 indoor locations (same locations as SF_6 samples) and outdoors with thermistors (accuracy of approximately $\pm 0.4°C$). Relative humidity (RH) was measured every 5 min in four indoor locations, the attic, and outdoors using bulk polymer resistance sensors with an accuracy of $\pm 3\%$ RH. Wind speed and direction were measured with a sonic anemometer (Climatronics, Inc.) mounted 2 m above the townhouse roof. The anemometer was capable of measuring wind speeds from 0 to $50\,\mathrm{m\,s^{-1}}$ ($\pm 5\%$) with a resolution of $0.1\,\mathrm{m\,s^{-1}}$. For wind speeds above $4.5\,\mathrm{m\,s^{-1}}$, the wind direction had an accuracy of $\pm$ 5% with no stated accuracy for lower wind speeds. Since the attic fan came on automatically when attic temperatures reached a certain point, the times it turned on or off were recorded electronically and transmitted to a computer.

Finally, a detailed record of activities was kept by the two non-smoking adult occupants. Specifically, all cooked meals, cleaning events, and combustion activities were recorded as well as ventilation status (e.g. windows open or closed, central fan off, patio door open, etc.). Sources causing substantial increases in indoor particle concentrations suitable for calculating decay rates included burning a citronella candle, pouring kitty litter, frying tortillas, and other cooking events.

2.1. Deposition calculations

The following mass balance equation was used to estimate particle decay rates due to infiltration, deposition, and filtration following a source event (assuming no particle generation or coagulation during decay):

$$\frac{dC_p}{dt} = P_p a C_{\mathrm{out},p} - aC_p - k_p C_p - k_{p,\mathrm{HAC}} C_p - k_{p,\mathrm{ac}} C_p, \tag{1}$$

where, C_p is the indoor particle concentration for specific particle size p (particles $\mathrm{m^{-3}}$), P_p the penetration coefficient for specific particle size p (dimensionless), a the air change rate ($\mathrm{h^{-1}}$), $C_{\mathrm{out},p}$ the outdoor particle concentration for specific particle size p (particles $\mathrm{m^{-3}}$), k_p the deposition loss rate coefficient for specific particle size p describing losses to room surfaces ($\mathrm{h^{-1}}$), $k_{p,\mathrm{HAC}}$ the deposition loss rate coefficient for specific particle size p describing losses during HAC operation ($\mathrm{h^{-1}}$), $k_{p,\mathrm{ac}}$ the equivalent loss rate coefficient for specific particle size p describing losses by air cleaner, where $k_{p,\mathrm{ff}}$ corresponds to typical furnace filter, and $k_{p,\mathrm{ESP}}$ corresponds to electrostatic precipitator ($\mathrm{h^{-1}}$).

Assuming P_p, $C_{\mathrm{out},p}$, a, k_p, $k_{p,\mathrm{HAC}}$, and $k_{p,\mathrm{ac}}$ are constant, the solution to Eq. (1) is

$$\begin{aligned} C_p = {} & \frac{P_p a C_{\mathrm{out},p}}{a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}}} \\ & \times (1 - \exp[-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t]) \\ & + C_{p,0} \exp[-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t], \end{aligned} \tag{2}$$

where, $C_{p,0}$, indoor particle concentration for specific particle size p at time = 0 (particles $\mathrm{m^{-3}}$), At steady-state conditions, the solution to Eq. (1) becomes

$$C_{p,\mathrm{SS}} = \frac{P_p a C_{\mathrm{out},p}}{a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}}}, \tag{3}$$

where, $C_{p,\mathrm{SS}}$ is the indoor particle concentration for specific particle size p at steady-state conditions (particles $\mathrm{m^{-3}}$).

Eq. (3) may be used to approximate particle concentrations during relatively stable ambient conditions with no indoor sources. This equation was used as an estimator of background particle concentrations in the townhouse. Using the background concentration and substituting Eq (3) into Eq. (2) results in

$$\begin{aligned} C_p = {} & C_{p,\mathrm{SS}}(1 - \exp[-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t]) \\ & + C_{p,0} \exp[-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t], \end{aligned}$$

$$\begin{aligned} (C_p - C_{p,\mathrm{SS}}) &= (C_{p,0} - C_{p,\mathrm{SS}}) \\ & \quad \exp[-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t], \\ \ln(C_p - C_{p,\mathrm{SS}}) &= [-(a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}})t] \\ & \quad + \ln(C_{p,0} - C_{p,\mathrm{SS}}). \end{aligned} \tag{4}$$

The negative of the slope of the best-fit line of $\ln(C_p - C_{p,\mathrm{SS}})$ versus time is the value $a + k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ac}}$. Subtracting the independently measured air change rate from the total decay results in an estimate of the loss rate due to deposition and filtration. An example plot of a decay rate for 2.5–5.0 μm particles generated by pouring kitty litter with the fan off is shown in Fig. 1.

Several criteria were established to minimize the error associated with applying Eq. (4) to calculate decay rates. First, the indoor source of interest must produce particle concentrations substantially higher than (e.g. 10 times) background levels. No other known indoor particle sources should be active and the outdoor concentration must be relatively constant during the decay calculation period. There also needed to be evidence of mixing of both the SF_6 injection and particle emissions into all rooms or floors of the house. Fig. 2 shows the concentration of 0.5–1.0 μm particles resulting from a candle burned in the basement. For this case, the fan was not on, thereby showing the maximum time it takes to reach a relatively uniform concentration in the house. All calculations of deposition rates were made after complete mixing had occurred. Fig. 2 also illustrates the order of magnitude increase in particle concentration above background and the relatively low and constant outdoor concentration. If particle concentrations were not measured on every floor, then the decay rate was not calculated until the fan had been on for at least 10 min (except for kitty litter experiments conducted in the basement, which was purposely closed off from rest of house). In addition, the R^2 for the decay of a given particle size needed to be greater than 0.9. Also the air change rates for all rooms were required to be similar (i.e. having a relative standard deviation (RSD) < 15%). Although there were hundreds of particle source events in the townhouse, only 15 cooking events, 18 candle burns, and 12 kitty litter pours met all of the criteria and are presented in this paper.

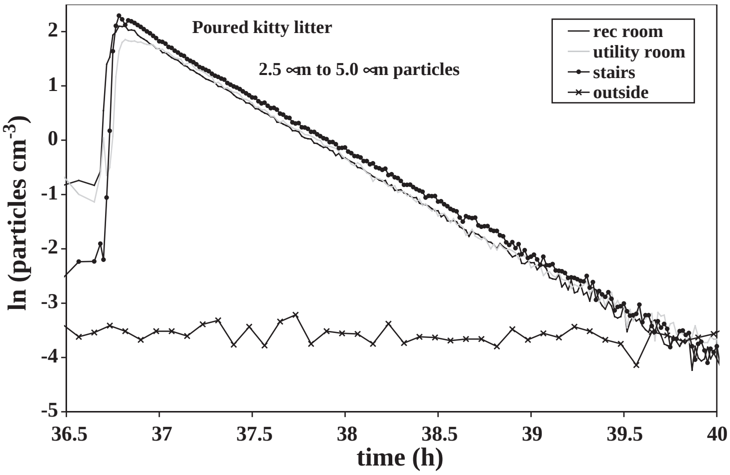

Fig. 1. Example calculation of decay rate for kitty litter event. Rec room: $a + k_p = 1.94\,\mathrm{h}^{-1}$ ($R^2 = 0.995$). Utility room: $a + k_p = 1.87\,\mathrm{h}^{-1}$ ($R^2 = 0.99$). Stairs: $a + k_p = 1.94\,\mathrm{h}^{-1}$ ($R^2 = 0.99$).

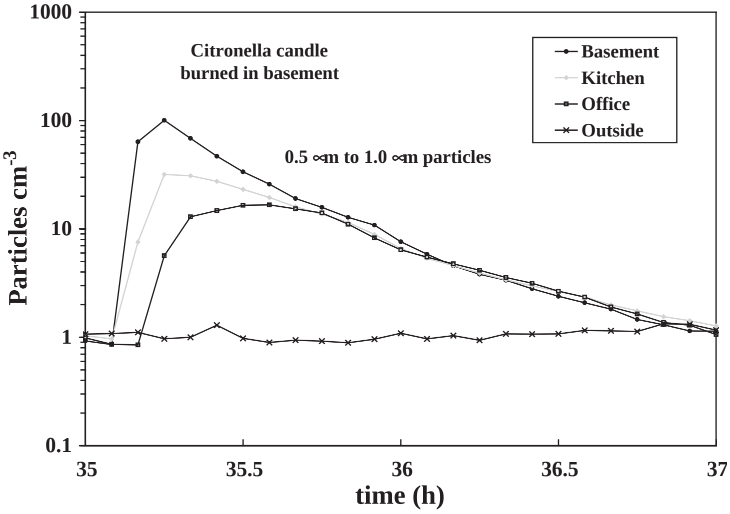

Fig. 2. Concentration of 0.5–1.0 μm particles following candle burned in basement with central fan off.

3. Results and discussion

Results from the 45 applicable tests are listed in Tables 1–3. Each table includes a single source type, within which results are organized by particle size, sampling location, and HAC fan/air cleaner status. Fig. 3 shows average deposition rates for each source type as a function of particle size for all cases when the central fan was off. As expected, deposition for each source increased with increasing size. This effect was

Table 1
Deposition rates for cooking source events

Date	No. of events	No. of locations	0.3–0.5 µm	Particle size 0.5–1.0 µm	1.0–2.5 µm
Fan off	4	9	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})
Mean			0.29	0.41	0.50
SD			0.11	0.10	0.11
Fan on	6	18	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})
Mean			0.88	0.92	1.2
SD			0.40	0.25	0.31
Fan on ESP on	5	12	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ESP}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ESP}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ESP}}$ (h^{-1})
Mean			3.7	4.8	4.4
SD			1.2	2.1	1.6

Table 2
Deposition rates for citronella candle source events

Date	No. of events	No. of locations	0.3–0.5 µm	0.5–1.0 µm	Particle size 1.0–2.5 µm	2.5–5.0 µm
Fan off	3	8	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})
Mean			0.33	0.47	0.68	1.1
SD			0.06	0.12	0.16	0.34
Fan on without furnace filter	6	18	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})
Mean			0.66	1.0	1.8	3.2
SD			0.25	0.31	0.43	0.89
Fan on with furnace filter	3	9	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ff}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ff}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ff}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ff}}$ (h^{-1})
Mean			0.81	1.4	2.0	3.0
SD			0.37	0.19	0.27	0.70
Fan on, ESP on	6	15	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ESP}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}+}k_{p,\mathrm{ESP}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}+}k_{p,\mathrm{ESP}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}} + k_{p,\mathrm{ESP}}$ (h^{-1})
Mean			2.3	3.0	3.9	4.6
SD			0.50	0.83	0.78	0.82

Table 3
Deposition rates for kitty litter source events in sealed basement

Date	No. of events	No. of locations	Particle size				
			0.5–1.0 µm	1.0–2.5 µm	2.5–5.0 µm	5.0–10 µm	> 10 µm
Fan off	10	33	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})	k_p (h^{-1})
Mean			0.41	0.88	1.5	2.7	5.2
SD			0.24	0.35	0.31	0.52	0.71
Fan on without filter	2	6	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})	$k_p + k_{p,\mathrm{HAC}}$ (h^{-1})
Mean			0.80	1.4	3.0	4.8	7.1
SD			0.26	0.33	0.50	0.54	1.7

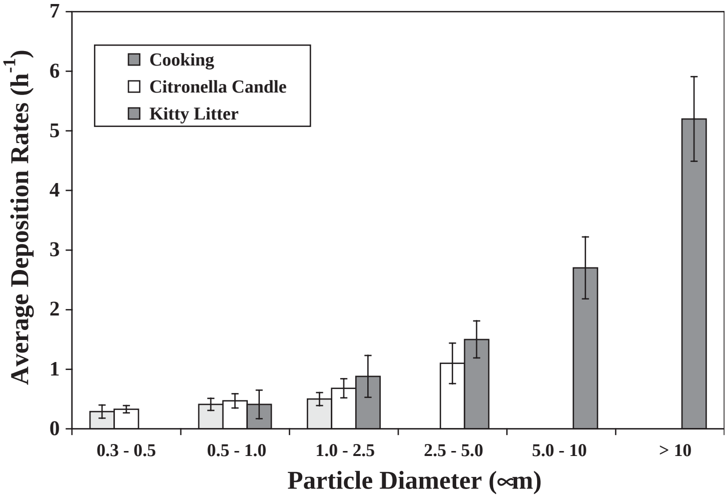

Fig. 3. Comparison of deposition rates for different particle sizes and sources with HAC fan off. Error bars are ± one standard deviation.

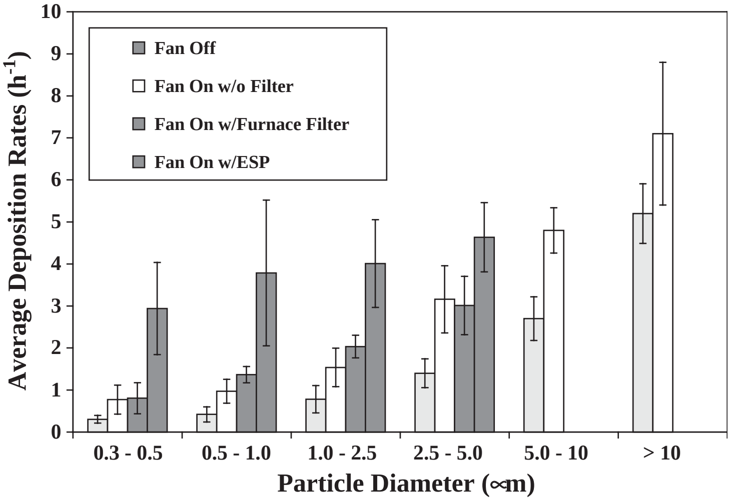

Fig. 4. Comparison of particle deposition rates for different HAC configurations. Error bars are ± one standard deviation.

most dramatic once the particle size was greater than 2.5 μm.

In addition, Fig. 3 also illustrates the lack of influence of source type on deposition rates for a given particle size. The types of particles generated by the sources included cooking oil droplets, combustion particles, and coarse particles. As such, these particles represent different shapes and composition. Although the particle characteristics between the sources are dissimilar, this difference did not appear to significantly impact deposition rates for a given particle size range. For example, the average (SD based on number of measurements) deposition rates for 0.5–1.0 μm particles were 0.41 h^{-1} ($\pm 0.10\,h^{-1}$) for cooking, 0.41 h^{-1} ($\pm 0.24\,h^{-1}$) for kitty litter, and 0.47 h^{-1} ($\pm 0.12\,h^{-1}$) for the citronella candle (furnace fan off). In fact, for each size range, decay rates for the three sources (cooking, citronella candle, kitty litter) were not significantly different whether the fan was off, on, or on with a filter present. Comparable loss rates for different sources were also determined for cases with the furnace fan on, both with and without a filter present. This finding further emphasized the importance of particle size on deposition rates and allowed us to combine size-specific results from all sources in considering the effect of the central fan and the various air filtration devices.

With the HAC fan off, deposition of particles is confined to room surfaces. As expected, this test

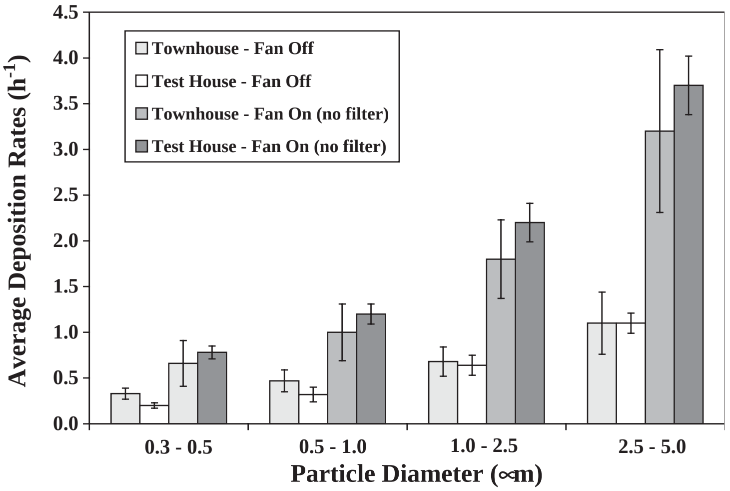

Fig. 5. Comparison of average deposition rates for particles from a citronella candle in two locations. Error bars are ± one standard deviation.

Table 4
Effect of HAC fan and in-duct filters on particle deposition rates (h^{-1})

Particle size range (μm)																		
	0.3–0.5			0.5–1			1–2.5			2.5–5			5–10			> 10		
Ventilation/filtration setting	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N
HAC fan off (k_p) (h^{-1})	0.30	0.09	15	0.42	0.18	34	0.78	0.37	48	1.4	0.34	40	2.7	0.52	33	5.2	0.71	33
HAC fan on (h^{-1})	0.77	0.34	36	0.97	0.28	39	1.5	0.46	40	3.2	0.80	22	4.8	0.54	6	7.1	1.7	6
Air cleaner (ESP) on (h^{-1})	2.9	1.1	27	3.8	1.7	27	4.0	1.0	21	4.6	0.82	14	—	—	—	—	—	—
$k_{p,\mathrm{HAC}}$ (h^{-1})	0.47	0.36	*	0.55	0.33	*	0.72	0.56	*	1.8	0.87	*	2.1	0.75	*	1.9	1.8	*
$k_{p,\mathrm{ac}}$ (h^{-1})	2.1	1.2	*	2.8	1.7	*	2.5	1.1	*	1.4	1.1	*	—	—	—	—	—	—

*Deposition rate based on difference of mean values above. Standard deviation is the square root of the sum of the squares of the associated standard deviations.

condition consistently resulted in the lowest deposition rate. Once the HAC fan was turned on, even without a filter present, particle deposition rates increased (see Fig. 4). For example, for 1.0–2.5 μm particles, the average deposition rate doubled when the fan was turned on. Possible reasons for this increase include the additional surface area of the HAC ducts and other system components (e.g. heat exchanger, fan blades, etc.), as well as the increase in room air velocity and turbulent kinetic energy with the fan system on. As noted earlier, approximately 5 house volumes of air pass through the ducts each hour. Although an HAC system was not used, an increase in particle deposition due to use of room mixing fans has been reported by other researchers (Xu et al., 1994; Mosley et al., 2001; Thatcher et al., 2002). We also investigated the possibility that increased air change rate alone might lead to increased particle deposition rates because of increased air velocity and turbulent energy. However, no increase in deposition rate with increasing air change rates was noted for any of the six particle sizes studied under the fan-off condition. Interestingly, the addition of a standard furnace filter had no observable effect on deposition rates for particles less than 5 μm, whereas the use of an electronic air cleaner had a significant impact on particle removal rates. It should be noted that the furnace filter and ESP were only used during events that generated smaller particles (i.e. cooking and candle burning). Thus, measurable decay rates were not available for particles greater than 5 μm.

To investigate the potential impact of room surface area and types of furnishings, similar deposition tests were completed in a second house. For these tests, the same citronella candle was burned in a single room unfurnished test house in Gaithersburg, MD. As shown in Fig. 5, in cases with the HAC fan on and off, there was no significant difference in particle deposition rate between the two locations. The ratio of floor surface area to volume for the two houses was very similar with a value of approximately $0.38\,\mathrm{m}^{-1}$ per floor for the townhouse and $0.44\,\mathrm{m}^{-1}$ for the test house. However, if wall surfaces and room furnishings were to also be included, the townhouse surface area to volume ratio would be far greater than that of the unfurnished test house, indicating a lack of importance of increased surface material for a given space on most particle deposition rates. Thatcher et al. (2002) investigated the effect of room furnishings on particle deposition and found a more significant impact on particles $\leqslant 1.0\,\mu\mathrm{m}$, which is also indicated in Fig. 5. As the authors point out, this result follows deposition theory where loss of larger particles is dominated by gravitational settling, thereby being less affected by room furnishings. The ratio of volumetric flow through the HAC system to room volume was slightly higher for the test house with a value of $7.2\,\mathrm{h}^{-1}$, whereas the townhouse was $5\,\mathrm{h}^{-1}$. This difference in flow rate through the duct system was apparently not enough to cause a noticeable difference in deposition rates.

The effect of having the central fan on and using an in-duct filter is summarized in Table 4. Using the central fan increased the deposition rate by between 0.5 and $2\,\mathrm{h}^{-1}$. Adding the in-duct electrostatic precipitator increased the loss rate by an additional 1.4–$2.8\,\mathrm{h}^{-1}$.

3.1. Other studies

Over 20 previous studies have determined deposition rates for particles $> 0.3\,\mu\mathrm{m}$ in diameter. Lai (2002) has compiled data regarding 15 of these studies, 12 of which were completed in an experimental chamber. The remaining tests were conducted either in controlled test houses (Offermann et al., 1985; Xu et al., 1994; Thatcher et al., 2002; Emmerich and Nabinger, 2001) or in occupied or unoccupied houses (Thatcher and Layton, 1995; Wallace et al., 1997; Fogh et al., 1997; Abt et al., 2000; Long et al., 2001; Vette et al., 2001). A summary of these 10 studies is provided in Table 5.

Findings from all of these house studies are compared with our findings in Fig. 6. All studies agree in finding increased deposition rates for larger particles. There is also agreement that increased surface area (furnishings) and increased air speeds are associated with higher deposition rates, although the effect of both these parameters is not large compared with the effect of particle size.

However, comparing the controlled test house studies to the occupied house studies, it is possible to see that the range of deposition rates is larger in the controlled studies. In particular, at the smallest particle sizes of 0.3–$0.7\,\mu\mathrm{m}$, the deposition rates measured in the controlled studies may be an order of magnitude smaller than those in the occupied house studies. At these particle sizes, the controlled studies agree better with

Table 5
Characteristics of previous studies of deposition rates for particles $> 0.3\,\mu\mathrm{m}$

Reference	Site type	Occupied/unoccupied	# sites	Aerosol[a]	Source	Fan	Exhaust fan[b]	Duct filter[b]	Particle monitor[c]
Offermann et al. (1985)	Test House	Unoccupied	1	Poly	Cigarette	Off	N/A	N/A	OPC
Xu et al. (1994)	Test House	Unoccupied	1	Poly	Cigarette	On/off (3 speeds)	N/A	N/A	LAS-X
Thatcher et al. (2002)	Test House	Unoccupied	1	Poly	Generator	Off/On	N/A	On/Off	OPC
Emmerich and Nabinger (2001)	Test House	Unoccupied	1	Mono and Poly	Generator, Various	On/off	N/A	On/Off	OPC
Thatcher and Layton (1995)	House	Occupied	1	Poly	Various	Off	No	No	OPC
Wallace et al. (1997)	House	Occupied	1	Poly	Cooking oil, candle, kitty litter	On/off	On/off	No	OPC
Fogh et al. (1997)	House	Occupied	4	Mono (5 sizes)	Generator	Off	No	No	APS
Abt et al. (2000)	House	Occupied	3	Poly	Various	Mixed	No	No	APS
Long et al. (2001)	House	Occupied	9	Poly	Various	Mixed	No	No	APS
Vette et al.(2001)	House	Occupied	1	Poly	Various	Off	No	No	APS
This study (2003)	House	Occupied	1	Poly	Cooking oil, candle, kitty litter	On/off	On/off	On/off	OPC

[a] Mono = monodisperse; Poly = polydisperse.

[b] N/A = not applicable.

[c] APS = aerodynamic particle sizer; OPC = optical particle counter; LAS-X = laser aerosol spectrometer.

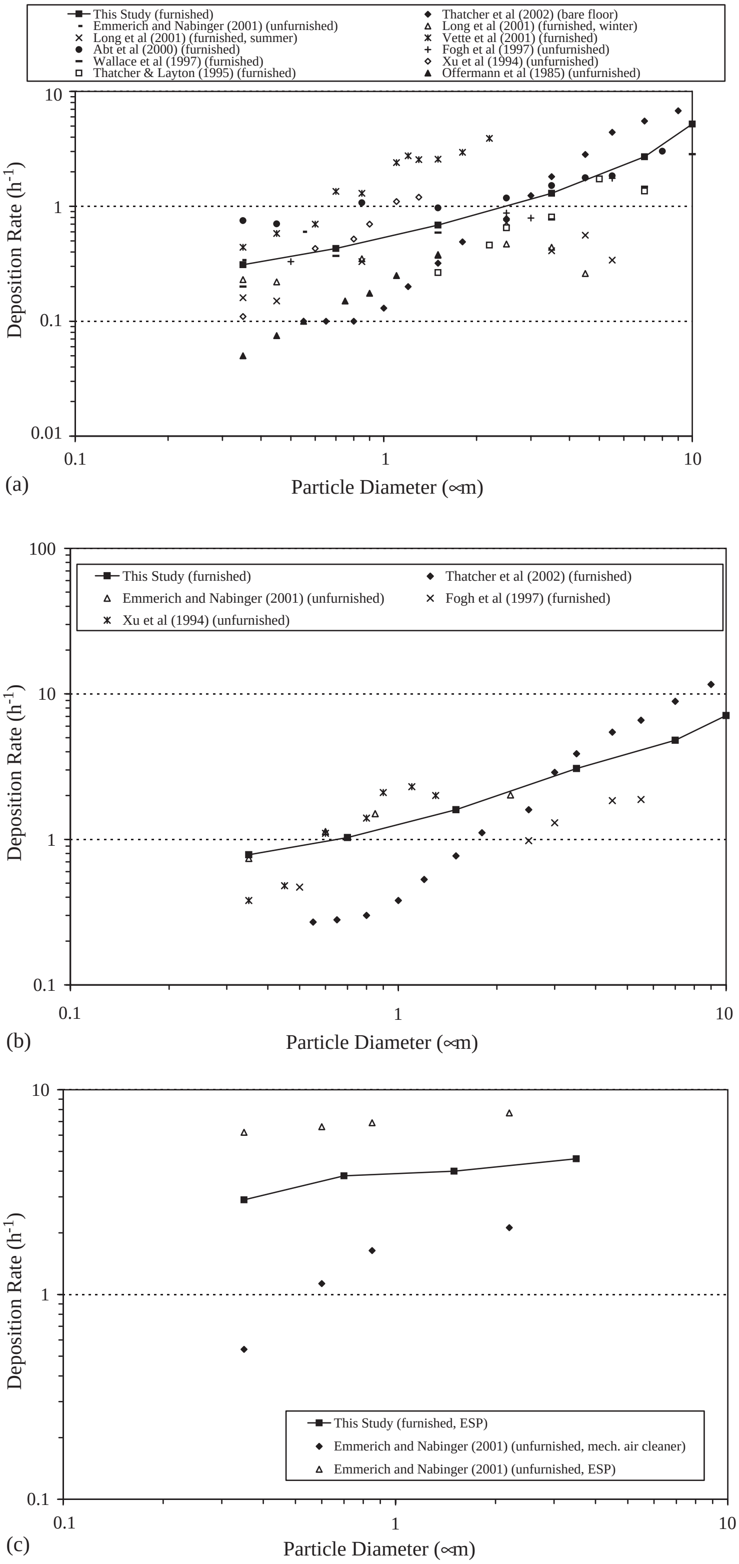

Fig. 6. Measured deposition rates in previous studies and this study for the following cases: (a) fan off; (b) fan on; and (c) fan on with air cleaner.

predicted values than the occupied house studies. For larger particles, both types of studies agree reasonably well with theoretical predictions (Lai and Nazaroff, 2000). The reason for this divergence for smaller particles is not clear.

This study is the first to provide quantitative estimates of the decay rates associated with HAC systems with and without an air cleaner in an occupied house. Fig. 7 shows that the unfiltered HAC case increased the deposition rate over the fan-off condition for all particle sizes, and that the ESP case increased the decay rate still further for all particle sizes. These results indicate that for homes with central air, increasing the time that the duct fan is on will reduce the residence time of particles in the home, and installing a high-efficiency in-duct filter will reduce the particle levels even more. For example, use of the HAC fan can reduce particle levels by 23–50%, and use of an in-duct ESP can reduce the levels by 57–85% (Table 6). This is comparable to the finding by Fugler and Bowser (2002) that an in-duct ESP reduced particle levels in five homes by 30–70%, depending on resident activity level. However, a standard furnace filter had no effect on decay rates for particles less than 5 μm beyond the HAC system effect. Riley et al. (2002) estimated the effect of a continuously operating central HAC with standard furnace filter on concentrations of particles originating outdoors using a residential building model scenario. Their model results also showed a reduction in the indoor particle number concentration such that the ratio of indoor to outdoor particles for cases with the fan off were approximately 0.5 and for cases with the fan on were less than 0.3.

Additional implications of these results include the comparison of control strategies to reduce particle concentrations indoors. For example, use of the HAC fan and air cleaner will reduce particle concentrations of indoor and outdoor origin both, whereas tightening the house's envelope only reduces the influx of outdoor particles and actually increases the residence time of indoor-generated particles.

4. Conclusion

This study has presented some of the first measurements of fine and coarse particle decay rates associated with a central forced-air fan and in-duct air cleaners under realistic conditions in an occupied home. The effect of each of these actions is generally larger than the deposition rate under fan-off conditions. Since all homes with central forced air heating and air conditioning will employ the central fan on an intermittent basis, and some use the fan constantly to increase air circulation, the effect in these homes will be to reduce concentrations of indoor air particles up to twice as fast as in homes not using a central fan. The standard furnace filter was ineffective at removing particles, while the ESP was able to greatly increase the decay rate of particles.

We also found that the source of the particles appeared to have little if any influence on deposition rates, even though the particles varied from cooking oil droplets to combustion particles to coarse particles. Only the size of the particles and not their composition affected deposition rates within the uncertainty of these tests; but size alone determined about an order of magnitude difference in deposition rates (from < 0.5 to $> 10\,h^{-1}$).

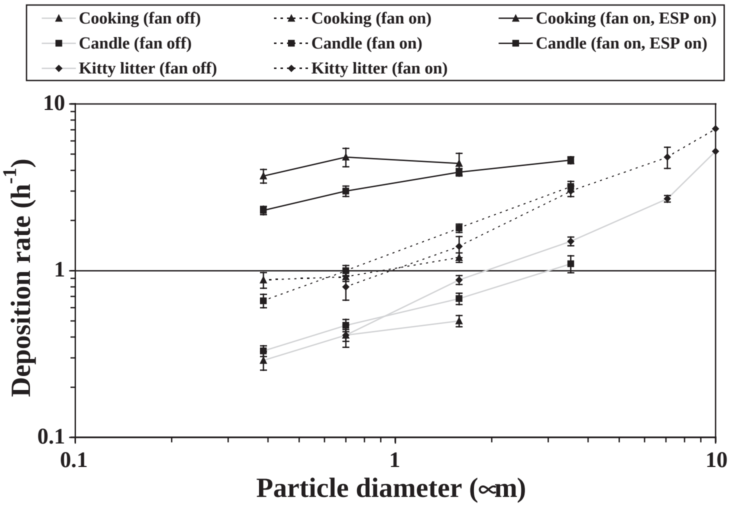

Fig. 7. Decay rates in this study by source type and fan-filter combination. The type of source (cooking, candle, pouring kitty litter) has little effect on deposition rate.

Table 6
Effect of HAC fan and in-duct filters on the fraction of outdoor particles penetrating indoors

Infiltration factors: Tight House ($a = 0.2\,h^{-1}$, $p = 1$)						
Ventilation/filtration setting	Particle size range (μm)					
	0.3–0.5	0.5–1	1–2.5	2.5–5	5–10	>10
HAC Fan off	0.40	0.32	0.20	0.13	0.07	0.04
HAC Fan on	0.21	0.17	0.12	0.06	0.04	0.03
Air cleaner on	0.06	0.05	0.05	0.04	—	—
% Reduction (Fan)	48	47	42	53	42	26
% Reduction (Air cleaner)	84	85	77	67	—	—
Infiltration factors: Drafty House ($a = 1\,h^{-1}$, $p = 1$)						
Ventilation/filtration setting	Particle size range (μm)					
HAC Fan off	0.77	0.70	0.56	0.42	0.27	0.16
HAC Fan on	0.56	0.51	0.40	0.24	0.17	0.12
Air cleaner on	0.26	0.21	0.20	0.18	—	—
% Reduction (Fan)	27	28	29	43	36	23
% Reduction (Air cleaner)	67	70	64	57	—	—

5. Disclaimer

This study was partially funded by an EPA Internal Grant to one of the authors (LAW). It has been reviewed and cleared for publication. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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