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Particle Size Distributions for an Office Aerosol

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As attention has focused on indoor air quality, it has become important to obtain basic information on the effects of heating, ventilating, and air-conditioning system operating parameters on office aerosols. In addition, it is important to know the particle size distributions (PSDs) in a typical office environment in order to address mitigation strategies. Therefore, this study was undertaken to evaluate the effect of percent outdoor air supplied and occupation level on the PSDs and mass concentrations for a typical office building. The outdoor, return, and supply air streams, as well as hallway air, were sampled using measuring equipment covering particle diameters from below 0.1 to above 3.5 μm. The mass concentrations, when the building was occupied, increased by a factor of approximately 2 when return air was recycled over ventilating with maximum outdoor air. The concentrations when unoccupied were at least as low using minimum outdoor air as those when occupied using maximum outdoor air. As expected, the outdoor air was cleaner than the other streams. The next lowest concentrations were obtained for supply air, then return air, with hallway air showing the highest concentrations. The normalized number distributions were found to have a single mode consistently near 0.13 μm; the volumetric distributions show a peak at 0.3 μm. The influence of the damper setting and occupancy level shows up only in the magnitude of the peaks. The distributions found in the hall and for the air streams showed the same general shapes, but the differences in instrumentation preclude other conclusions.

INTRODUCTION

The objective of this research was to document the effect of the heating, ventilating, and air-conditioning (HVAC) system on indoor aerosols under conditions and occupancy in a small office building. The purpose of obtaining this information was to help define the requirements for control technology and to provide data for comparison to a predictive model under development (Owen et al., 1989). Measurement of the particle size distribution (PSD), rather than the respirable mass, was performed because of the need to document any possible change in distribution.

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Since indoor pollutant concentrations can exceed established ambient limits (Panekala and De Oliveira, 1975; Sterling and Kobayashi, 1977; Budiansky, 1980; Caceres et al., 1983; Leaderer et al., 1984), mitigation strategies can gain significant importance in building design and operation. Therefore, it is important to know what effect the readily available HVAC system settings have on the concentrations in a building. In addition to this result, it is important to know the actual size distribution of the particles since air cleaner effectiveness and potential health effects are directly related to particle diameter.

An HVAC system includes the ductwork and equipment necessary to heat or cool, clean, and deliver air to the appropriate

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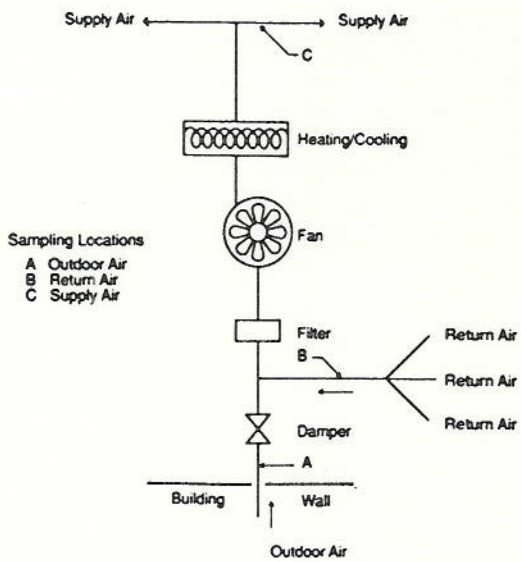


FIGURE 1. Schematic diagram of HVAC system.

locations inside a building. Figure 1 shows a fairly general schematic of an HVAC system which is also representative of the main sampling site in this study. This figure shows the return air (RA), which comes from several locations inside the building, joining with outdoor air (ODA) to form the supply air (SA), which is conditioned and sent to the room registers. This HVAC equipment allows cleaning of the SA. In this case, as in most buildings, in-duct filters are employed. In other buildings electronic air cleaners and/or carbon filters may be used. In addition to cleaning devices, the percentage of ODA can usually be varied. In this system the ODA damper setting may be varied from approximately 5% to 95% ODA, the nominally "closed" and "open" settings.

In order to examine the effect of the HVAC system on the circulating air, the three air streams in the HVAC ducts (RA, ODA, SA) were sampled as was the hall air. In order to determine the maximum effect of the damper settings on the particulate concentrations in the air, testing took place with the dampers both open and closed.

Occupation level and source strength are two of the most influential variables, in addition to the HVAC system parameters, in the indoor environment. Since the majority of the nonhuman sources in an office building (copiers, printers, cigarettes, coffee machines, etc.) are not present as sources when the building is unoccupied, aerosol measurements taken both when the building is unoccupied and occupied will cover the spectrum for both of these variables. Therefore the testing in this project was done both for standard working days and an unoccupied day.

A review of the literature gave a variety of previously determined mass concentrations. These numbers led to the prediction that a typical office building should have mass concentrations between approximately 20 and 200 $\mu g/m^3$ (Penkala and De Oliveira, 1975; Binder et al., 1976; Repace and Lowrey, 1980; Spengler et al., 1981; Quant et al., 1982).

A review of literature on indoor, indoor source, and outdoor particle size distributions led to the expectation that a submicrometer peak would be found. Johansson et al. (1983) found an area median diameter at approximately 0.2 μm for the aerosol in a residence. Cigarette smoke, the largest single contributor to indoor air particle concentrations in the office environment (Spengler et al., 1981), consists of mainstream and sidestream smoke. Mainstream smoke has a bimodal volume distribution with modes at about 0.25 and 5.0 μm (Chang et al., 1985). The volume distribution of sidestream smoke has a median diameter of 0.225 μm with 98% of the volume between 0.05 and 1.0 μm (Leaderer et al., 1984). Volume distributions of outdoor air are bimodal, including a fine particle mode near 0.5 μm and a coarse mode between 10 and 100 μm diameter (Whitby et al., 1972). Since these aerosols contribute to indoor air, it seemed reasonable that similar distributions would be found indoors. Minimally, a large portion of the particles should be submicrometer in diameter.

In addition to the sizes found in the literature, it is important to consider the potential health effects. One of the methods for determining the level of influence of the aerosol concentration on the occupants is to determine the respirable suspended particulate (RPS) concentration. This fraction of an aerosol, the portion most likely to be inhaled, is the amount below 3.5 μm in diameter. Therefore, the equipment selection included instruments to test from below 1 to above 3.5 μm.

EXPERIMENTAL PLAN

Description of Test Site

The test site, an office building containing no laboratories or other unusual installations, consists of a main floor containing 1,756 m^2 and a partial basement of 910.5 m^2. The building is of cement block construction with brick veneer, has carpeted floors, and was built in 1964. It is situated in a lightly wooded area. The ODA ducts are located within 15 m of several dumpsters and an outlet air vent. Each office contains two inlet vents near the wall away from the hall. RA vents are located in the halls. The test program was performed in one of the building's seven separate ventilation systems.

Figure 2 represents the section of the first floor where the sampling occurred. SA and RA register locations are shown, as is the hallway sampling site. Figure 1 represents the HVAC system that ventilates this section; it is accessed in the basement level mechanical equipment room. The SA, RA, and ODA streams were sampled by passing a tube into holes drilled into the side of the ducts, making it possible to sample the three air streams with one set of equipment at one location.

Test Matrix

The study covered four working days and one unoccupied Saturday. The ODA dampers were set either fully closed or fully open. Because of leakage through the dampers, the percentages of ODA in the system are estimated to be 5% and 95%, respectively. On each day except the first, the RA, SA, and ODA streams were sampled (see Table 1). The instruments used,

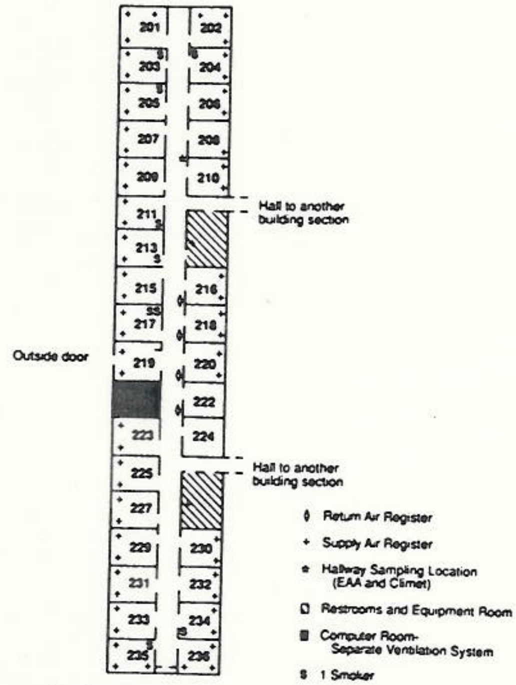


FIGURE 2. Office building section tested.

TABLE 1. Sampling Schedule

Data	Run	Sampling site[a]	Date	ODA damper setting
1	1	SA	12/11/85	"Closed"[b]
	2	RA		
	3	RA[d]		
2	4	RA	12/12/85	"Open"[c]
	5	ODA		
	6	SA		
3	7	SA	12/13/85	"Open"
	8	RA		
	9	ODA		
4	10	RA	12/14/85	"Closed"
	11	ODA	(Saturday)	
	12	SA		
5	13	ODA	12/16/85	"Closed"
	14	RA		
	15	SA		

[a]SA, supply air; RA, return air; ODA, outdoor air.
[b]"Closed" = approximately 5% ODA.
[c]"Open" = approximately 95% RA.
[d]On the first day two RA tests were performed in lieu of sampling in the closed off ODA duct.

TABLE 2. Air Sampling Equipment

Equipment	Measurement	Technique	Location
TSI, Inc. differential mobility particle sizer (DMPS)	Size distribution (0.02 to 0.5 μm)	Electrical mobility detection	Mechanical Equipment Room
Particle Measuring System Inc. laser aerosol spectrometer (LAS-X)	Size distribution (0.09 to 5.0 μm)	Aerosol spectrometry	Mechanical Equipment Room
TSI, Inc. electrical aerosol analyzer (EAA) model 3030	Size distribution (0.01 to 1 μm)	Aerosol mobility detection	Hallway
Climet Inc. optical particle counter, model CI-208	Size distribution (0.3 to 10 μm)	Light scattering	Hallway
TSI, Inc. piezobalance model 3500	Mass concentration (< 3.5 μm)	Resonance frequency shift	All

the DMPS and LAS-X, thoroughly cover particle sizes from 0.02 to 5.0 μm in diameter, yielding PSDs and concentrations (see Table 2). The EAA and Climet were used at the hall site. Measurements were taken coinciding with each equipment room run. The piezobalance was used to measure mass concentrations at all sampling sites and across the hall. Because of the differences in particle detection methods for the various pieces of equipment, somewhat different counts can result for the same aerosol sample. These potential differences must be considered when analyzing the resulting distributions.

Sampling System

The ODA, RA, and SA were sampled by passing a probe into holes drilled into the side of the ducts, allowing sampling of these three air streams with one set of equipment at one location. The 0.0127-m diameter nozzle of the probe was aligned with the flow. A pump was used to withdraw air through the tube, resulting in a short residence time (1 s) and isokinetic sampling. The samples for the instruments were drawn from a common manifold to ensure identical samples. The probe was inserted to the ducts' midpoints for the SA and ODA streams and on the centerline 61 cm into the duct for the RA stream.

Vent velocity measurements were taken in several offices and across the ducts. The velocities varied significantly over small distances, indicating that the velocity profile obtained may not be comprehensive.

Survey

To determine activity levels in the building, a survey of the building occupants was conducted. The personnel were first informed of the nature of the experiment, then asked to complete questionnaires. Office machinery was inspected onsite. On the days of the experimental runs, the area near the hall sampling station was visually inspected. The facility was tested under the condition that the productivity of the staff was not to be affected. Therefore, instead of entering each office, we looked into open offices to gauge relative activity, counted the coffee pots in use, and noted other visible signs of activity. The activity and machine usage levels did not deviate noticeably between occupied testing periods. None of the regular personnel was in the section during the unoccupied period; therefore, the only activity was that necessary to conduct the experiment.

Filter Testing

The filters in use in the test building are rated on ASHRAE Test Standard 52-76 at 25% to 30% efficiency. An identical filter was obtained and tested for particle size- and face velocity-dependent efficiencies. This testing, performed with a LAS-X, used challenge aerosol consisting of monodisperse polystyrene latex particles 0.6, 0.9, and 2.0 μm in diameter. A section of a new filter mat was removed and tested. The results led to the conclusion that the average efficiency for the particle range tested is 15% to 20%. New filters were installed at the test site and the week before the testing so that laboratory and onsite conditions were comparable.

TABLE 3. Mass Concentrations (μg/m³) for the Air Streams (Calculated from LAS-X Data Assuming 1 g/cm³ Density)

Day	Damper setting	Air type[a] ODA	SA	RA	Hallway[b]
1	Closed	—	38.6	55	75
2	Open	8.2	10.8	0.2[c]	39
3	Open	4.3	10.0	17.7[c]	30
4	Closed (unoccupied)	4.2[c]	5.0	6.1	19
5	Closed	0.9[c]	32.3	43.7	82

[a]SA, supply air; RA, return air; ODA, outdoor air.
[b]Piezobalance data.
[c]These values were taken in closed ducts.

RESULTS

The personnel survey showed a fairly even distribution of people and office machines; however, the smokers were not evenly placed as shown in Figure 3. Figure 3 also shows the mass concentrations found in the halls and offices. Each curve shows the concentrations found on a particular day. This graph shows that, when the building is occupied, mass concentrations increased by a factor of approximately 2 when all RA is used compared to all ODA. However, occupancy is shown to be as influential as the percentage of makeup air. The concentrations when unoccupied were at least as low using 0% ODA as when the building was occupied using 100% ODA. A comparison of smoker location to mass concentration shows that, in general, the higher mass concentrations were found near the higher smoker concentrations. Note that, except for one data point, all of the occupied concentrations were found in the 20–200 μg/m³ range expected from the literature.

FIGURE 3. Smoker distribution and daily mass concentration profiles in the hallway.

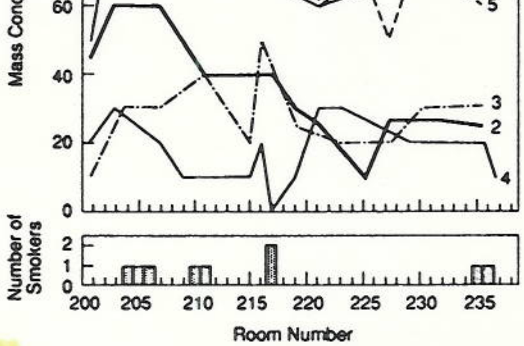


Table 3 shows mass concentrations determined for the various air streams. Because the piezobalance data for the RA, SA, and ODA reflected values for only a few minutes each day, the LAS-X data for each stream were used to calculate these mass concentrations. Hallway concentrations from the piezobalance (daily averages) are included for comparison. The LAS-X counts particles from 0.09 to 5.0 μm; on the other hand, the piezobalance has a cutpoint of 3.5 μm. Therefore, the mass concentrations shown should reflect similar but not identical measurements. In each case, the ODA is cleaner than the other streams. The next lowest concentrations were obtained for SA, then RA, with the hallway showing the highest concentrations. This is as expected (the ODA result would not be expected in all regions).

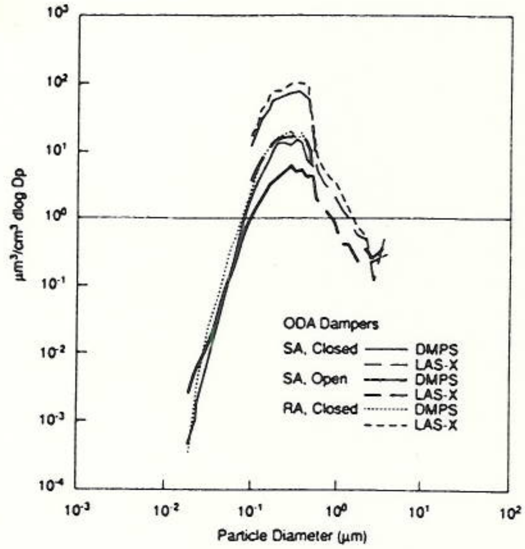


FIGURE 4. Volume distributions.

The relative concentrations in the ODA and the three indoor air streams reaffirm the need for concern over indoor air, especially since the RA showed approximately eight times the mass concentration as the ODA. The SA, as the combined RA and ODA streams, should be between these two values especially after filtering. The hallway aerosol shows the effects of fresh particles that have not yet deposited from the air, causing it to be higher in concentration than the RA stream.

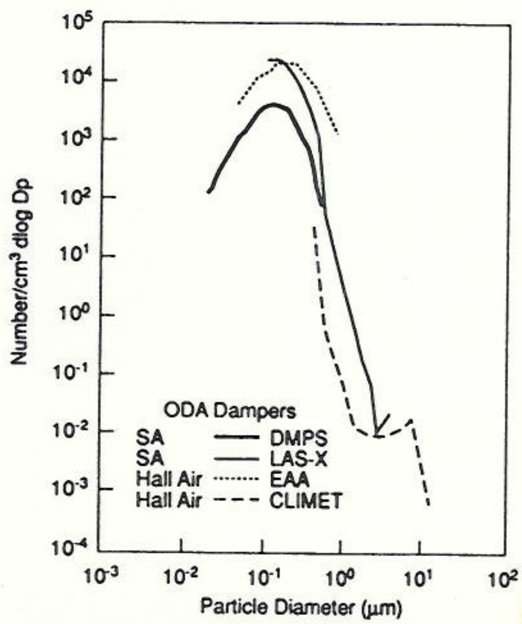
Normalized number and volume distributions were calculated from the data obtained. Figures 4 and 5 are plots of the normalized volume and number distributions for SA as determined by the DMPS and LAS-X for run 1 when the ODA dampers were closed. The results for all of the runs turned out to be quite similar; therefore, these plots are typical of the distributions found in this study. The number distributions had a single mode consistently near 0.13 μm particle diameter, and the volumetric distributions show a peak at 0.3 μm. For all of the distributions, the peaks occurred at the same particle diameters.

Figure 4 also shows an SA volume distribution for a case when the dampers were open. The influences of the ventilation setting (open or closed dampers) and occupancy show up only in the magnitude of the peaks. A comparison of these curves to those known for ODA shows that the peaks occur in the same ranges, indicating that similar mechanisms are at work in both environments. The RA, closed curves in Figure 4, show the volume distribution for the RA on the same day that the data for the SA, closed curves were obtained. A comparison of the RA and SA shows a small decrease, consistent with the filter test results. A curve typical of those obtained in the hall with the EAA and Climet is shown in Figure 5. This plot results from data taken at the same time as the data for the SA, closed curve in Figure 4. The distributions found in the hall and in the ducts showed the same general shapes, but the differences in instrumentation preclude other conclusions.

CONCLUSIONS

This study measured PSDs under varying conditions of occupancy and source strength. Mass concentrations of respirable particles

FIGURE 5. Number distributions.



and the PSDs were measured. Mass concentrations in the various air streams were compared with each other and with literature values. The effects of ODA and occupancy on the indoor mass concentrations were examined. The distributions were examined for peak positions and relative heights and were compared to distributions previously found for ODA and for tobacco smoke.

The major source of particulate pollution was along the hall as shown by the fact that the hall air was determined to have the highest particulate concentrations of any location tested. Increasing occupancy was shown to increase mass concentration levels since the mass concentrations when the building was unoccupied were as low or lower using minimum ODA than were those when the building was occupied using maximum ODA.

In this study, the mass concentrations for RA were approximately 8 times those for ODA, which indicates the effect of dilution with ODA. This effect was proven when decreasing the level of ODA entering the ventilation system yielded higher concentrations in the building. This is due to the recirculation of the pollutants generated indoors.

The number and volume distribution peaks for ODA, SA, RA, and hallway air were in the same particle diameter range under both damper settings and occupancy levels, which indicates that similar mechanisms formed each stream. The mass concentrations increased from ODA to hallway air, with SA slightly cleaner than RA. This SA to RA relationship is consistent with the efficiencies determined for the building filters (15% to 20%) and shows the relative importance of filtering in indoor air quality control.

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