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Particle Size Distribution Of Indoor Aerosol Sources

A Thesis

by

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ABSTRACT

As concern about Indoor Air Quality (IAQ) has grown in recent years, it has become necessary to determine the nature of particles produced by different indoor aerosol sources and the typical concentration that these sources tend to produce. These data are important in predicting the dose of particles to people exposed to these sources and it will also enable us to take effective mitigation procedures. Further, it will also help in designing appropriate air cleaners.

A new state of the art technique, DMPS (Differential Mobility Particle Sizer) System is used to determine the particle size distributions of a number of sources. This system employs the electrical mobility characteristics of these particles and is very effective in the 0.01-1.0 μm size range. A modified system that can measure particle sizes in the lower size range down to 3 nm was also used. Experimental results for various aerosol sources is presented in the ensuing chapters.

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Chapter 1

INTRODUCTION

Particles are a major source of concern in the modern technological world. It is not only a problem for the semi-conductor industry and pharmaceutical industry where a particle free environment is of utmost importance but particles can also pose a health problem for human beings. As concern about indoor air quality (IAQ) have grown in recent years, an understanding of indoor aerosols has become increasingly important so that their effects on public health can be assessed and control techniques can be implemented in order to reduce the effects of these aerosols.

One of the most important approaches to look into this problem of particulate contamination is to identify potential sources of indoor aerosols, to determine sizes, and typical concentrations of particles that these sources tend to produce. This information will then enable us to predict the dose, which is a function of particle diameter and total mass inhaled, to human lungs. Furthermore, this data on particle sizes will be useful in designing test methodologies for air cleaners and other mitigation devices that will be useful for the efficient removal of particles.

Aerosol sources being polydisperse in nature cannot be fully described without measuring their size spectrum. Since this size distribution potentially spans the range from a few nanometers to several hundred microns, size distribution measurements become difficult using conventional methods like screen diffusion batteries or electron microscopy. The commonly used screen diffusion battery (DB) suffers from negligible penetration of highly diffusive ultrafine particles in the 0.5-5 nm size range, even past the first DB stage as well as limited in size resolution because of the inherent limitations of particle diffusion. On the other hand, electron microscopy provides a direct method of performing

such measurements. It can be a laborious and costly procedure unless done on an automated basis. However, this method is subject to artifacts of sampling, aerosol volatilization in the vacuum of the microscope, and is limited in sensitivity for particle sizes below 0.2 μm .

Thus, it is necessary to carry out the studies using a method that allows the measurement of a continuous size distribution in the size range between 0.5-500 nm. Particle mobility related measurements are most common. These include electric mobility measurements using the Differential Mobility Analyzer (DMA) (Knutson and Whitby, 1975) or Electrical Aerosol Analyzer (EAA) (Liu *et al*, 1974). The DMA which measures a response only from those particles within a chosen size range gives a more direct and accurate measurement of mobility distribution than EAA which measures response from all particles larger than a chosen range. To obtain the particle concentration within this range, it is necessary to examine the difference in response between 2 adjacent size ranges. Thus, DMA has been used to obtain size distribution measurements in this size range. This particle size distribution measurements will also assist in the understanding of the specifics of indoor aerosol dynamics.

The purpose of this research project is to identify potential indoor particle sources that are prevalent in a typical American home, to measure particle size distribution of these aerosol sources using a TSI 3071 Electrostatic Classifier and a TSI 3068 Aerosol Electrometer or TSI 3025 Ultrafine Particle Counter as the particle detection instruments. The data will then be used to validate a mathematical model for indoor aerosol dynamics and to correlate it with activity size distribution measurements undertaken in a separate study. This work is described in detail in the ensuing chapters.

Chapter 2

DMPS SYSTEM

The Differential Mobility Particle Sizer (DMPS) measures the size distribution of submicrometer aerosols by the electrical mobility detection technique. The aerosols are classified with a TSI Model 3071 Electrostatic Classifier and their concentration measured with a TSI Model 3068 Aerosol Electrometer or TSI Model 3025 Condensation Particle Counter. The size resolution of this system is four times greater than an EAA with much broader concentration range capabilities (Keady *et al.*, 1983). The system is automated with a microcomputer that controls the individual instruments and performs data reduction. The theory and description of the individual instruments is described in the following paragraphs.

2.1 ELECTROSTATIC CLASSIFIER

The Model 3071 electrostatic classifier consists of a bipolar diffusion charger and an electrical mobility analyzer. The bipolar charger contains a 2 mCi radioactive ^{85}Kr source that produces bipolar ions and brings the aerosol to a Boltzmann equilibrium electrostatic charge level. The mobility analyzer is a differential type that removes particles in a preset electrical mobility range. Aerosol particles are first introduced into the bipolar charger where they interact with the bipolar ions, resulting in particles with a specific charge distribution. They are subsequently classified by the differential mobility analyzer and their electrostatic mobility spectrum can then be determined. The Model 3071 can be used as a main component for generating, measuring, or sampling aerosols.

2.1.1 Theory of Aerosol Neutralization

This section briefly reviews the electrical neutralization and equilibrium bipolar charging theory.

A: Electrical Neutralization

Aerosol generated by artificial means often carries a high initial electrostatic charge level which can be reduced by exposing the particles to a bipolar ion environment. In this environment, particles can discharge themselves by capturing ions of the opposite polarity. The rate of discharge depends on the product of bipolar ion concentrations N and the reaction time t , i.e., Nt .

In the continuum regime, the Nt product required to reduce the particle charge from some initial level n_i to some final level n_f is given by the following equation

$$Nt = \frac{1}{4\pi Ze} \ln\left(\frac{n_i}{n_f}\right) \quad (2.1)$$

where Z is the ion mobility and e is the elementary unit of charge (1.6×10^{-19} coulombs).

The maximum charge that the particle can carry without becoming mechanically unstable is given by the Rayleigh limit. Under bipolar charging, the equilibrium charge level that the particle will eventually attain is given by Boltzmann's law. If n_f and n_i have these two extreme values, the Nt product calculated from above equation will represent the maximum Nt that is needed for charge neutralization. For all practical purposes, a Nt value of 6×10^6 (ions-s-cm³) is sufficient for charge neutralization process.

B: Equilibrium Bipolar Charge Distribution

When particles are exposed to a gaseous medium containing bipolar ions, the particles and ions will undergo frequent collisions due to the random thermal motion of the ions. In time, an equilibrium state is attained where the particles carry a bipolar charge distribution given by Boltzmann's law. From Boltzmann's law, the ratio of particles carrying 1,2,3... n_p elementary charge units to uncharged particles (Liu and Pui, 1974) is given by

$$\frac{N_{np}}{N_0} = \exp\left(-\frac{n_p^2}{2\sigma^2}\right) \quad (2.2)$$

where

$$\sigma = \left(\frac{akT}{e^2}\right)^{1/2} \quad (2.3)$$

a is the particle radius (cm), k is Boltzmann's constant, T is the absolute temperature, and e is the elementary unit charge. The fraction of particles, f , carrying n_p elementary units of charge is then given by

$$f = \frac{\exp\left(-\frac{n_p^2}{2\sigma^2}\right)}{\sum_{n=-\infty}^{\infty} \exp\left(-\frac{n_p^2}{2\sigma^2}\right)} \quad (2.4)$$

The electrical mobility of a singly charged particle is a monotonically decreasing function of particle size. Consequently, a monodisperse aerosol can be obtained by mobility classification if the particles are singly charged. The singly charged mobility, Z_{pl} ($\text{cm}^2/\text{V.s}$), is related to the particle diameter, d_p (cm) as follows:

$$Z_{pl} = \frac{eC \times 10^7}{3\pi\mu d_p} \quad (2.5)$$

where, $e = 1.6 \times 10^{-19}$ coulombs is the elementary unit charge, $\mu = 183 \times 10^{-6}$ poise at 20°C and 1 atm, is the gas viscosity and C is the slip correction. For non-spherical particles, the above equation defines an equivalent Stokes-drag diameter. The accepted equation for calculating the slip correction (Freidlander, 1977) is

$$C = 1 + 2.492 \frac{\lambda}{d_p} + 0.84 \frac{\lambda}{d_p} e^{-0.43 \frac{d_p}{\lambda}} \quad (2.6)$$

Figure 2.1 : Cross-sectional view of the neutralizer.

where, λ (cm) is the mean free path of gas molecules. For air at 20°C and 1 atm, $\lambda = 6.53 \times 10^{-6}$ cm.

2.1.2 Description of Bipolar Charger:

The design of the bipolar charger or neutralizer is based on the above principles. Figure 2.1 is a cross-sectional view of the TSI 3077 Aerosol Neutralizer. It consists of a radioactive source placed along the inside wall of a cylindrical container. The source is in the form of a small thin wall stainless steel tube (3.2 mm diameter) containing 2 millicuries of ^{85}Kr radioactive gas. The β -radiation produced by the radioactive gas can penetrate the thin wall and ionize the gas molecules outside, producing large quantities of bipolar ions inside the metal (38 mm diameter) container where the particles collide with the ions and attain equilibrium charge level.

The equilibrium ion concentration inside the neutralizer is about 2×10^6 (ions-s-cm³). If the value of 6×10^6 (ions-s-cm³) is the maximum Nt product as described above for charge neutralization process, then the maximum flow limit through the neutralizer is calculated to be about 1.5 lpm. Since the aerosols used in our particle size distributions carry much lower particle charge than the Rayleigh limit, a maximum flowrate of about 6 lpm through the neutralizer is possible.

2.1.3 DMA Theory:

The differential mobility analyzer (DMA) has been increasingly used for particle size analysis (Keady *et al.*, 1983). Figure 2.2 is a detailed cross-sectional view of the DMA. The DMA consists of two concentric cylindrical electrodes. A high voltage supply controlled by the computer maintains the center electrode at a well defined negative potential. The outer electrode is at a ground potential. An inner core of particle-free, sheath air and an outer annular ring of aerosol flow laminarly down between the

Figure 2.2: Cross-sectional view of the DMA set up.

electrodes with no mixing of two air streams. Particles with positive charges are attracted through the particle-free sheath air toward the negatively-charged center electrode. The trajectory of such a particle is a function of the flow rate, analyzer geometry, electric field, particle diameter, and the number of charges on the particle. Only those particles with a narrow, predictable mobility range and hence particle size pass through a slit near the bottom of the center electrode. A small air flow carries the particle out of the DMA. Positively charged particles of other mobilities deposit onto the center electrode or pass out of the DMA with the excess air. Particles with negative charge deposit onto the outer electrode and they no longer play a role in the measurement.

The electrical mobility of an airborne particle is a measure of how rapidly an electrically-charged particle responds to an electric field. Electrical mobility Z_p is defined as the electrical velocity component v_e (cm/sec), of the particle per unit electric field strength, E (V/cm):

$$Z_p = v_e/E \quad (2.7)$$

where Z_p is expressed in units of $(\text{cm}^2\text{V}^{-1}\text{s}^{-1})$. The electrical mobility component, v_e is caused by the interaction of the charges on the particles with the electrical field. In the case of DMPS, v_e is the radial velocity of the particle. This velocity is an equilibrium condition between the electrical force on the particle and the fluid drag force that resists the electrical force. Since the particle quickly reaches radial velocity, v_e the two forces become equal. The two equations can be rearranged to obtain

$$Z_p = \frac{n_p e C}{3\pi \mu d_p} \quad (2.8)$$

where μ = gas viscosity (for air at 1 atm and 20°C, $\mu=183 \times 10^{-6}$ poise)

C = Cunningham slip correction factor (Equation 2.6)

n_p = number of charges on the particle.

Equation 2.8 relates mobility to particle diameter and to the number of charges carried by the particle.

The mean electrical mobility of the particles Z_p , extracted through the slit is given by (Knutson, 1972)

$$Z_p = \frac{[q_i - \frac{1}{2}(q_s + q_a)] \ln(\frac{r_2}{r_1})}{2\pi VL} \quad (2.9)$$

and the mobility band-width,

$$\Delta Z_p = \frac{(q_s + q_a) \ln(\frac{r_2}{r_1})}{2\pi VL} \quad (2.10)$$

where: q_i = total flowrate through the mobility analyser (cm^3/s)

q_s = sample aerosol outlet flowrate (cm^3/s)

q_a = aerosol inlet flowrate (cm^3/s)

r_2 = outer electrode radius (1.958 cm)

r_1 = inner electrode radius (0.937 cm)

V = voltage on center electrode (volts)

L = length of the collector rod between the aerosol entrance and the exit slit.

(44.44cm)

Combining the two expressions for Z_p results in an expression relating particle diameter to central electrode voltage, number of charges on the particle, flowrates, and geometry:

$$\frac{d_p}{C} = \frac{2n_p e V L}{3\mu [q_i - \frac{1}{2}(q_s + q_a)] \ln(\frac{r_2}{r_1})} \quad (2.11)$$

This equation allows the calculation of the diameter of particles passing the exit slit of the DMA if the number of charge units is known. Most particles exiting the DMA carry just one elementary charge, simplifying the above equation.

2.2 AEROSOL ELECTROMETER

2.2.1 Introduction

The model 3068 Aerosol Electrometer is a sensitive and precise aerosol concentration sensor for measuring the output of a Model 3071 Electrostatic Classifier. The optimum size range of this system is 0.01-0.1 micrometer. However, less precise performance is possible in the 0.005-0.01 micrometer and 0.1-0.5 micrometer ranges.

2.2.2 Principle Of Operation

The Aerosol Electrometer measures the ion concentration of the sampled air stream. This mode is normally used to accurately measure the concentration of monodisperse, singly charged particles flowing out of the Model 3071 Electrostatic Classifier. It may also be used to measure the net ion concentration of sampled air.

The Aerosol Electrometer consists of an electrometer current sensor that collects the particles by filtration and measures the total electrical current with an electrometer. Figure 2.3 is a schematic diagram of the electrometer current sensor. Charged aerosol enters the electrometer current sensor through a metal cover which shields the electrometer input from stray electric fields.

In the electrometer current sensor, an absolute filter removes the charged particles from the air stream. The filter is mounted on a Teflon insulator within an enclosed metal housing and connected to the input of a solid state electrometer operational amplifier. A 10^{11} ohm resistor of 1 percent accuracy is used as a feedback resistor for the amplifier. An additional 10:1 voltage divider is incorporated in the feedback path to obtain an

Fig. 2.3 Schematics of Aerosol Electrometer

overall effective feedback resistance of 10^{12} ohms. The electrometer has an output voltage range of 0 to 10 volts, corresponding to a current range of 0 to 10 picoamp. The noise current of the electrometer is approximately 1×10^{-15} amperes.

The current I , measured by the electrometer is related to the input aerosol concentration N by the equation,

$$I = N n_p e q_e \quad (2.12)$$

where, n_p = number of particle charge

$e = 1.6 \times 10^{-19}$ coulomb and

q_e = volumetric aerosol flowrate into the electrometer current sensor.

Thus, when the particle charge is known, the aerosol concentration can be calculated from the above equation.

2.3 ULTRAFINE CONDENSATION PARTICLE COUNTER

2.3.1 Introduction

The Model 3025 Ultrafine Condensation Particle Counter is a continuous flow condensation particle counter that uses a vapor sheath technique to improve the

instrument's lower particle size detection sensitivity upto 3 nm. The particles are detected and counted by a simple optical detector after a supersaturated vapor condenses onto the particles causing them to grow into larger droplets. The range of particle detection extends from less than 0.01 particle/cm³ to 9.99×10^4 particles/cm³.

The counter uses a laser-diode light source, butanol as the condensing fluid, an internal microprocessor control, an improved pump, volumetric flow control, and a front panel display of both particle concentration and instrument status. It also has the capability of full computer interfacing that enables its use as a particle detector in the DMPS system.

2.3.2 Theory

The counter acts very much like an optical particle counter. Thus, the problem involved in the development of the counter is focussed on condensation of the vapor onto the particles. This problem is discussed in the following paragraphs.

When vapor surrounding the particles reaches a certain degree of super-saturation, the vapor begins to condense onto the particles. This process is called heterogenous condensation. If supersaturation becomes high enough, condensation can take place even if no particles are present and this is called homogenous nucleation or self-nucleation, whereby molecules of the vapor form clusters due to natural motion of the gas and attractive Van der Waals forces to form nucleation sites.

The degree of supersaturation is measured as supersaturation ratio (P/P_s). This ratio is defined as the actual vapor partial-pressure divided by the saturation vapor pressure for a given temperature. For a given saturation ratio, the vapor can condense onto particles only if they are large enough. The minimum particle size capable of acting as a condensation nucleus is called the Kelvin diameter. Its value is defined as the critical

equilibrium diameter at which a pure droplet is stable, and is evaluated from the following relationship:

$$\frac{P}{P_s} = \exp \frac{4\gamma M}{\rho R T d} \quad (2.13)$$

where γ = surface tension of condensing fluid

M = molecular weight of condensing fluid

ρ = density of condensing fluid

R = universal gas constant

T = absolute temperature

d = Kelvin diameter

Thus, the higher the saturation ratio, the smaller is the Kelvin diameter. For a round liquid surface, such as the surface of a droplet, the actual saturation vapor pressure is greater. In other words, the smaller the droplet, the easier it is for the vapor molecules to escape from the liquid surface.

If the saturation ratio is controlled to a level below the critical saturation ratio, the point at which homogeneous nucleation takes place, condensation will not take place in a particle free environment. The lower size sensitivity is defined by the operating saturation ratio. For the counter, this ratio is several hundred percent, whereas in the atmosphere this ratio is only a few percent of water.

A continuous flow, diffusional, thermal-cooling CNC (Bricard *et al.*, 1976; Sinclair and Hoopes, 1975; Agarwal and Sem, 1980) first saturates the air sample with butanol vapor as the sample passes over a heated pool of liquid alcohol. The vapor-saturated airstream flows into a cold condenser tube where the air is cooled by thermal diffusion. The alcohol condenses onto particles and the droplets grow to about 10 to 12 micrometers. The

droplets are counted by single particle counting optical detector. For high concentration measurements, a classical photometric light scattering technique is used.

When growing the particles in the condenser chamber, the highest saturation ratio occurs on the centerline of the flowstream at some distance down the condensing tube (Stolzenburg, 1988). Although the saturation ratio is not uniform across the flow profile due to thermal gradients, the lower size sensitivity can still be predicted and measured. Using sheath air the UCPC confines the aerosol to the center of the tube where supersaturation is the highest. The result is a very high detection efficiency for small particles down to 3 nanometers and a fast response time. This high sensitivity makes this CPC the only instrument of its kind to measure particle size below 5 nm.

2.3.3 Design of the Instrument

The instrument consists of three major sub-systems: the sensor, the microprocessor based signal processing electronics, and the flow system.

Sensor: The sensor itself is made up of a saturator, condenser, and optical detector. The aerosol entering the instrument is split twice to form an aerosol sample flows, a sheath flow and a bypass transport flow. The sheath flow is filtered before entering the saturator section where it passes over a heated, liquid-soaked wick. The wick continually draws liquid through the inclined tube from the reservoir bottle. The liquid evaporates and saturates the sheath air stream with vapor.

The aerosol stream in the meantime, passes through a capillary tube and is injected along the centerline of a vertical condenser tube. At this point, the aerosol stream is rejoined with the vapor saturated sheath air as a laminar flow. These streams are then cooled in the condenser using a thermo-electric device. As the vapor cools, it becomes supersaturated, and begins to condense on the particle nuclei carried in the

aerosol stream to form larger droplets. The droplets pass from the condenser tube through a nozzle into the optical detector. Liquid that condenses on the walls of the tube runs down into the saturator and is absorbed into the wick for reuse.

The sensor's focussing optics consist of a laser diode, collimating lens, and cylindrical lens. This combination forms a horizontal ribbon of laser light measuring 10 micrometers by 2 millimeters above the aerosol exit nozzle. The collecting optics incorporates a pair of aspheric lenses that collect the light scattered by the droplets at 90° side-scatter angle and focus the light onto a low noise photodiode. The main beam is blocked by a light stop in the rear of the sensing chamber. A reference photodiode is mounted at the back of the light stop to monitor the intensity of the incident beam. Shifts in the light intensity are corrected for by normalizing the main photodetector voltage with the reference voltage. The surface temperature of the optics is maintained at or above the saturator temperature to avoid condensation on the lens surfaces.

The counter uses two mode of counting: single particle real time counting and single particle live time counting. At concentrations below 1000 particles/cm³, the individual electrical pulses are counted, but only when the signal processing electronics is available for counting, that is, in live time. The length of time during which a particle is actually being detected is called dead time and is not included in live time. This arrangement automatically corrects for particle coincidence.

Microprocessor: The counter incorporates an Intel 80188 microprocessor to control all its functions. An analog to digital convertor is connected to the microprocessor and measures photodetector voltages, temperatures, and flowrates. Counters within the microprocessor keep track of the particle pulses detected by the photodetector. The display, pushbuttons, and RS-232 communications are also controlled by the

microprocessor.

Flow System: The counter has two flow options: High flow (1.5 lpm) and Low flow (0.3 lpm). The flow through the sensor is always 0.3 lpm independent of the inlet flow. In the high flow mode used with the DMPS system, the sample is brought to the counter faster minimizing the response time and diffusional particle losses. In the high flow mode, the three way valve is opened to the bypass flow, and the flow to the makeup air is shut off. The schematics of the flow system is shown in Figure 2.4. The flow splits so that 0.3 lpm flows through the sensor and 1.2 lpm flows through the bypass.

In the low flow mode, the three way valve is open to the flow of makeup air, the bypass is shut off, and the two way valve is open. Thus only 0.3 lpm is drawn into the inlet and carried directly into the sensor.

As seen in Figure 2.4, a low pressure differential HEPA filter is used in the sheath flow to filter the sheath air. A variable orifice is used to control the bypass flow. Also on the bypass flow, a filter is used upstream of the three way valve to act as a restrictor to allow flow through the inlet. An internal filter collects all counted particles in the condensor flow. Downstream of this filter, an orifice controls the balance between the bypass and condensor flows for a given pump speed. Flow upstream is protected by a damping filter. A final filter protects the environments from pump exhaust contamination.

2.4: Operating Parameters and Data Reduction of DMPS System:

The objective of data reduction process is the determination of the size distribution of the aerosol particles entering the DMPS (Keady *et al.*, 1983). The raw data measured by the DMPS is the concentration exiting from the DMA at each of a series of

Figure 2.4: Cross-sectional View of the CPC Flow System.

Figure 2.5: Transfer Function of DMA

mobility (voltage) steps. If every particle exiting the mobility analyzer carries a single charge, the measured concentration must be divided by the fraction of singly and positively charged particles predicted by the Boltzmann's equation, and divide by the transfer function. The transfer function is the probability that a particle of mobility Z_p , which enters the DMA will exit through the slit (Knutson and Whitby, 1975) and (Hoppel, 1978). Figure 2.5 shows the transfer function of the commercial Electrostatic Classifier for the standard operating conditions with q_p equal to q_s . The number of particle exiting the slit is essentially one half of the total number of particles within the mobility band ΔZ_p .

However, Boltzmann's equation predicts that a significant fraction of particles larger than $0.06 \mu\text{m}$ carry more than one charge. Thus, one must use a more complex data reduction scheme for multiply charged particles. The data reduction scheme most commonly used requires that there be no particles larger than the upper size limit of the

DMPS passing through the exit slit of the mobility analyzer. If this condition is true, then one can assume that all particles are singly charged and any doubly charged particle if any would be removed by the impactor before entering the DMA. Therefore, one can calculate the concentration within that size range which entered the DMPS, including the singly charged particle in the largest channel and multiply charged particle in the highest mobility channels.

Once the concentration of the largest size channel is known, the concentration within subsequently smaller size channels can be precisely calculated because one knows the concentration contribution of all larger particles that may be multiply charged is known. The computer proceeds in this way through successively smaller size channels, subtracting out the concentration of the multiply charged particles. The program corrects for six electric charges per particle.

In order to measure the entire mobility range, the voltage to the center electrode of the Electrostatic Classifier is stepped so that the adjoining channels are a mobility factor of 1.22 apart, the aerosol inlet and sample outlet flows are equal ($q_s = q_a$), and the sheath air flow is ten times the aerosol flow. By varying the flowrate through the EC, a total of 39 mobility channels may be chosen covering a particle diameter range from 0.01 to 1.0 μm . At any given flow setting, the range of measurable mobility channels is some fraction of the total, limited by the geometry of the EC. The use of lower flowrates allows measurement of larger particle diameters. The time required for one measurement covering the widest range is approximately 18 minutes, depending inversely on the aerosol concentration. An option in the software allows stepping through every second or fourth channel decreasing the sampling time greatly at the cost of resolution of the system. This procedure introduces measurement errors as one has to interpolate the concentration

values of the skipped channels from those measured.

Impactor Theory:

As mentioned in the above paragraph significant errors in size distribution can occur if larger particles are allowed into the DMPS system. Impactors are thus used which remove particles by directing the aerosol at an impaction plate. Nearly all particles larger than a certain size (cut size) are impacted onto the plate while particles smaller than this size will not be collected. A light coating of grease on the impaction surface avoids the particles from bouncing off. The cut size is a function of the impactor flowrate. The following equation (Reischl, 1983) is used to calculate the cut diameter.

$$St = \frac{4\rho_p Q C d_p^2}{9\pi\mu W^3} \quad (2.14)$$

where:

St = Stokes number

ρ_p = particle density, grams/cm³

Q = volumetric flowrate, cm³/s

C = Cunningham slip correction

λ = mean free path of gas (for air at 1 atm, $\lambda = 0.653 \times 10^{-5}$ cm)

D_p = particle diameter, cm.

μ = fluid viscosity (for air at 1 atm and 20°C, $\mu = 183 \times 10^{-6}$ poise)

W = impactor nozzle diameter (0.0457 cm or 0.0508 cm)

The impactor for DMPS is designed so that 50% cut size occurs when the $St = 0.49$.

Table 1 below lists some flowrates, the theoretical pressure drop, and the 50% cut size diameter for the DMPS impactors (0.0457 cm and 0.0508 cm diameter)

Table 2.1: 50% cut size and ΔP as a function of flowrates for the two impactors.

Aerosol Flowrate	0.0457 cm nozzle diameter		0.0508 cm nozzle diameter		DMPS Measuring Range
(LPM)	ΔP (cm of H ₂ O)	50% cut size	ΔP (cm of H ₂ O)	50 % cut size	(μm)
0.25	3.94	0.748	2.56	0.892	1.056-.018
0.3	5.66	0.677	3.71	0.8080	.886-0.017
0.4	10.1	0.576	6.58	0.6900	.631-0.014
0.5	15.8	0.508	10.3	0.6090	.535-0.012
0.6	22.7	0.457	14.8	0.55	.457-0.011
0.7	30.9	0.418	20.1	0.5030	.391-0.011
1.0	61.2	0.338	40.0	0.4090	0.337-0.01

The pressure drop across the impactor is directly related to flow rate squared.

$$\Delta P = \frac{1}{2} \rho_f \frac{Q^2}{A^2} \quad (2.15)$$

where:

ΔP = pressure drop, dynes/cm²

ρ_f = density of fluid (for air at 1 atm and 20°C, $\rho_f = 0.0012$ grams/cm³)

A = areas of the impactor nozzles.

The impactor is used as a flowmeter to aid in the setting of the DMPS flows, using the calibration data provided along with the impactors.

2.5 DMPS INTERFACE BOX

The DMPS interface box is a general purpose computer interface. It is controlled by the host computer or terminal through a RS-232 interface. The DMPS interface is

used in our case with the DMPS/Electrometer system. The DMPS interface box provides three basic measurements: analog to digital conversion (A/D), digital to analog conversion (D/A) and also a pulse counting function. Each of these functions is controlled by the instructions given on the computer's RS-232 interface.

There are four BNC type connectors at the back of the DMPS interface box which can be connected to an Aerosol Electrometer or a CPC. The four connectors are described as under:-

Mantissa: Analog input for A/D function. This accepts input voltages between 19.999 and -19.999 volts.

Exponent: Analog input for A/D function. This input accepts input voltages between 0 and 7 volts. The value output is simply the nearest whole voltage. This is mainly used with a CNC.

Analyzer Voltage - analog output: This output provides voltages between 0 and 11 volts at 10 milliamperes or less. This output is connected to the Electrostatic Classifier analyzer input. in the DMPS/Electrometer system.

Count: This takes a digital input requiring 5-volt positive going pulses. This input counts pulses to a maximum rate of 50,000 per second.

2.6 IBM AT-Compatible Microcomputer

A portable IBM AT-compatible microcomputer, Micro-Express (Road Runner) was used to run the software to control the instruments constituting the DMPS system.

2.7 SETUP AND OPERATION OF DMPS SYSTEM

This section describes the setting up of the DMPS system with the two particle

detecting instruments i.e TSI 3068 Aerosol Electrometer and TSI 3025 Condensation Particle Counter. It is then followed by the operation of these systems.

2.7.1 DMPS-ELECTROMETER SYSTEM

2.7.1.1 DMPS/ELE System Setup

The DMPS/E is used in the underpressure mode as the aerosol sources measured in our experiments are drawn into the instruments by a vacuum source. The plumbing associated with this system is shown in Figure 2.6. As seen in the figure, the monodisperse aerosol outlet on the electrostatic classifier is connected to the electrometer inlet using a stainless steel tube. Plastic tubing is avoided here because it tends to develop static charges that can lead to increase in particle losses.

Figure 2.6: DMPS/E System Set-up in the Underpressure Mode

2.7.1.2 Setting Of Flows

One critical aspect of the DMPS operation is the control of the flows so that the flow ratio between sheath air and aerosol is 10:1. The sheath and excess air must be equal and also the polydisperse and the monodisperse aerosol flows must be equal. The flow through the aerosol electrometer is a variable. If the system has perfectly laminar flow and is leak tight, there will be no current measured by the electrometer at zero voltage on the center rod. The external filter on the sheath air inlet helps remove all particles from the sheath air.

2.7.2 DMPS-CONDENSATION PARTICLE COUNTER SYSTEM

2.7.2.1 DMPS/CPC System Set Up

DMPS/CPC system is also used in the underpressure mode because the various aerosol sources under study are drawn into the electrostatic classifier by a vacuum source. The plumbing associated with this system is shown in Figure 2.7

2.7.2.2. Setting Of Flows

For this system also, it is necessary to choose flowrates for the EC such that the ratio of sheath air to the aerosol is 10:1. Further the flowrate of excess air must be equal to the flowrate of the sheath air and that the flows of the polydisperse aerosol inlet and that of the monodisperse aerosol outlet must also be equal.

Figure 2.7: DMPS/CPC System Set-up in the Underpressure Mode.

Chapter 3

RESULTS AND DISCUSSION

In this chapter the particle size distribution data for various indoor aerosol sources will be presented and discussed. The measurements were carried out in a small clean room of dimensions (2.37m×2.3m×2.3m) or volume 12.53 m³ located in one of our laboratories. The instrumental setup described in Chapter 2 was assembled. A description of the particle size distribution of the aerosols generated from various sources like cigarette smoldering, candle burning, burning of an incense, burning of a hot plate, pilot flame of a gas burner and from frying a bacon is presented in the following sections of this chapter.

3.1 Aerosol Generated from Cigarette Smoldering:

To obtain the particle size distribution data, the DMPS system was operated in the under-pressure mode with a flow of 6 lpm of sheath and excess air and 0.6 lpm of monodisperse outlet and polydisperse inlet. For this flow, a 0.0457 cm diameter nozzle impactor is used. This system corresponds to 0.017 - 0.457 μm measuring range for the DMPS system. The TSI 3068 Aerosol Electrometer is used as the particle detector. The instrument flows were adjusted with taking into account the pressure drop across the impactor.

Before the cigarette was lit inside this experimental room, the background was measured. The room was closed and the ventilation in the room was turned off. The system was run with absence of any person or active aerosol sources in the room. The size distribution were measured using either the electrometer or the CNC. This system automatically steps the voltage to the classifier corresponding to 39 mobility channels covering the entire DMPS measuring size range, receives the concentration data from the

electrometer or the CNC, performs the data inversion, and displays the resulting distribution in a tabular and/or graphical form. The resulting distribution was stored in the buffer, a option in the program that allows to subtract this saved distribution in the buffer to be subtracted channel by channel in the sample runs for different sources.

Case 1: After this initial run for background was saved in the buffer, a cigarette (Marlboro) was lit in the same room and 6 sample runs were taken consecutively inside that room without opening the room during the duration. Normally the cigarette took about 8-9 minutes to burn. Each sample took 12 minutes and 48 seconds to span the entire size range. After 3 minutes and 40 seconds, the next sample was started allowing time to print the results of the first run. This process was repeated until all 6 samples were measured.

Figure 3.1 shows the behavior of the distribution (log-normal) of the sidestream smoke produced by this cigarette. The total concentration of the particles produced was more than 7,500,000 particles/cm³ with a peak around 124 nm and the particle size ranging from 34 nm to 221 nm. i.e in the transition regime when the cigarette was burning for the first 8 minutes of the first sample.

The total concentration of the particles dropped to 3,000,000 cm⁻³ after 29 minutes because no new particles are generated. This decrease in particle concentration was in part due to ventilation of this aerosol from the room, as well as deposition onto available surfaces within the room. The distribution shifted to larger particle sizes. The lower size fraction observed in the previous sample disappeared due to coagulation and deposition. After 46 minutes, the total concentration was around 1,500,000 cm⁻³ with coagulation of lower size range particles to larger particles so that the lower size range particles was around 81 nm.

A: 13 min later (ACTIVE SOURCE)

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

F: 95 min later.

Figure 3.1: Particle Size Distribution Of Aerosol Generated On Burning a Cigarette

After 62 minutes, the total concentration was around $680,000 \text{ cm}^{-3}$ with the smallest size at 93 nm. After 79 minutes, the total concentration decreased to $250,000 \text{ cm}^{-3}$. There was a residual peak in the lower range around 140 nm. After 95 minutes, the concentration was around $93,000 \text{ cm}^{-3}$ with decreasing concentrations of the lower size particle.

To determine the reproducibility of the process, the experiment was repeated in the same manner as described above. Figure 3.2 shows the particle size distributions for another 6 samples. For the first sample the total concentration is more than $6,000,000 \text{ cm}^{-3}$ and with a peak around 124 nm and ranging from 45 to 221 nm. The distribution shifted to larger sizes with 52 nm on the lower end and a concentration of about $2,920,000 \text{ cm}^{-3}$. Similarly after 46, 62, 79 and 95 minutes the particle concentration was about $1,400,000 \text{ cm}^{-3}$, $640,000 \text{ cm}^{-3}$, $325,000 \text{ cm}^{-3}$, $34,000 \text{ cm}^{-3}$ with lower end being at 81, 81, 93 and 93 nm respectively. The two runs show a close similarity of the two distributions, clearly demonstrating the reproducibility achieved by this DMPS system.

Case 2: For this case two cigarettes were used. The same procedure for background was followed as discussed above for Case 1. Sampling was started immediately after lighting the two cigarettes in the same room for 6 sample runs.

Figure 3.3 shows the particle size distributions for the 6 samples. For the first sample, the total particle concentration was approximately $16,840,000 \text{ cm}^{-3}$. This concentration was in agreement with the level that was expected when burning two cigarettes continuously for the first eight minutes of the first sample. A peak around 124 nm and range spanning from 29 nm on the lower side to 255 nm on the upper end was observed. After 29 minutes the distribution shifted to larger sizes, from about 52 nm on

A: 13 Min Later (Active Source)

B: 29 min later.

C: 46 min later.

D: 62 min later.

E: 79 Min later

F: 95 min later

Figure 3.2: Particle Size Distribution Of Aerosol Generated On Burning Cigarette. (#2)

A: 13 min later (ACTIVE SOURCE)

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

F: 95 min later.

Figure 3.3: Particle Size Distribution Of Aerosol Generated On Burning Two Cigarettes. (#1)

the lower end with a decrease in concentration to about 5,880,000 particles/cm³. Exhaustion of the sidestream smoke results in the decrease of particle concentration along with some deposition on available surfaces due to thermophoresis and also due to the process of coagulation of the smaller size range particles with larger particles to form a larger particle or coagulation of two smaller particles of the same size to form a bigger particle results in the disappearance of the smaller size peaks in the subsequent runs. Similarly the total number concentration fell to 2,760,000 particles/cm³, 1,606,000 particles/cm³, 890,000 particles/cm³ and 270,000 particles/cm³ after 46, 62, 79 and 95 minutes from the start of cigarette smoldering.

Another run of 6 samples with two cigarettes smoldering in the same room gave nearly the same particle size distribution data as shown in Figure 3.4. As seen in the figure, the particle concentration for the first sample when the two cigarettes were smoldering for the first 8 minutes produced a maximum concentration around 1.662×10^7 cm⁻³ with a peak around 107 nm and size range spanning from 34 nm to 294 nm. As described the particle concentration falls to 6,314,000 cm⁻³, 3,219,000 cm⁻³, 1,889,000 cm⁻³, 1,100,000 cm⁻³, 700,000 cm⁻³ after 29, 46, 62, 79, 95 minutes following the end of cigarette smoldering period. The lower size range particles shifted to 52nm, 70nm, 93nm, 93nm, and later it reached a steady state around 107 nm.

3.2 Aerosol Generated From Candle Burning:

Candle smoke is another major intermittent source of particle generation in a typical American home. To measure the particle size distribution of this aerosol, the instrumental flow rates were set at 3 lpm of sheath and excess air and 0.3 lpm of monodisperse outlet and polydisperse inlet. At this flow, an impactor with a nozzle

A: 13 min later (ACTIVE SOURCE)

B: 29 min later.

C: 46 min later.

D: 62 min later.

E: 79 min later.

F: 95 min later.

Figure 3.4: Particle Size Distribution Of Aerosol Generated On Burning Two Cigarettes. (#2)

diameter of 0.0508 cm is used. The flows were then set accordingly taking into account the pressure drop across the impactor.

Figure 3.5 shows the particle size distribution data for 5 samples obtained from a single run with the candle burning continuously in the same room and the background saved and stored in the buffer to be subtracted from the each subsequent runs in the same manner as discussed above in Section 3.1.

The candle produced larger size particles. It tended to have a sooty flame. For the first sample, the figure showed that the particle concentration was about 1.465×10^6 cm³ after twelve minutes of burning with a distribution spanning from 143 nm to 340 nm. After 29 minutes of burning, the particle concentration increased to about 5.062×10^6 particles/cc with the lower size particle formed initially coagulating to larger size particles of about 191 nm on the lower end of the distribution. After 46, 62 and 79 minutes of burning from the start the particle concentration averages around 6×10^6 cm⁻³ as it reaches a steady state.

Figure 3.6 showed the particle size distribution of another run in which 6 samples were taken. At the beginning during a 12 minute period as the candle had just started burning, the particle concentration was about 1.482×10^6 cm⁻³ ranging in size from 165 nm to 453 nm with a peak at 255 nm. Again as in the first run, the lower mode particles coagulated to form larger particles. The particle concentration increased to about 4.85×10^6 cm⁻³ with formation of a small mode on the upper end. For the 46 and 62 minute samples, the total particle concentration averaged around 8.2×10^6 cm⁻³. The small increase in the total concentration was not clearly understood and was different from the previous run. Finally the particle concentration decreased to 1.55×10^7 and 6.17×10^6 cm⁻³ after 79 and 95 minutes due to some ex-filtration and wall deposition.

A: 13 min later

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

Figure 3.5: Particle Size Distribution Of Aerosol Generated From Burning a Candle Continuously.(#1)

A: 13 min later

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

F: 95 min later.

Figure 3.6 : Particle Size Distribution Of Aerosol Generated On Burning a Candle Continuously.(#2)

3.3 Aerosol Generated By Burning Incense:

The instruments were adjusted to a flowrate of 6 lpm for the sheath air and excess air respectively whereas the monodisperse outlet and the polydisperse inlet was adjusted to a flowrate of 0.6 lpm. The flows were adjusted taking into account the pressure drop across the 0.0457 cm diameter impactor. Particles were detected by the TSI 3068 Aerosol Electrometer. The measurements were carried out in the same manner as discussed in section 3.1 for the cigarette aerosol. An incense stick with a burning time of about 20 minutes was lit in the sampling room without any ventilation. Before the sampling was begun, a background distribution was measured and stored in the buffer to be subtracted subsequently for the sample runs.

Case 1: Figure 3.7 shows the size distribution data for the aerosol generated by burning an incense stick. In this run, five samples were taken. Incense produces larger particle aerosol as can be seen from the distribution data for the first sample 12 minutes after the lighting of the incense stick. The particle concentration was around $1,675,000 \text{ cm}^{-3}$ and the size spanned the range from 52 nm on the lower end to 221 nm the upper end with a peak around 140 nm. After 29 minutes from the start, the particle concentration has increased to about $3,500,000 \text{ cm}^{-3}$. This increase in particle concentration was because of longer burning time of an incense, i.e 20 minutes. As can be seen from the figure, the smaller particle mode has decreased in concentration due to coagulation and deposition and the formation of a mode on the upper size range. After 46 minutes, from the start of the source new particles cannot be generated because the incense had burned out. The particles concentration then decreased to about $921,000 \text{ cm}^{-3}$ with the distribution showing particles only from 93 nm to 225 nm particles. The particle

A: 13 min later (ACTIVE SOURCE)

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

Figure 3.7: Particle Size Distribution Of Aerosol Generated From Burning Incense. (#1)

concentration decreased to $445,000 \text{ cm}^{-3}$ after 62 minutes. The distribution reached a steady state after 79 minutes with concentration around $150,000 \text{ cm}^{-3}$ and size range from 93 to 165 nm.

Case 2: Again the same procedure was used to examine the burning of incense in the same room. The background was measured and the distribution saved in the buffer to be subtracted from the subsequent sample runs. Figure 3.8 shows the observed size distributions following the evolution of the incense aerosol. Twelve minutes from the start of burning of the incense the size distribution shows the formation of particles from 39 nm to 221 nm with a total particle concentration of around approximately $1,500,000 \text{ cm}^{-3}$. After 29 minutes from the start of the combustion the particle concentration increases to approximately $3,000,000 \text{ cm}^{-3}$ because the incense was still burning for 20 minutes and thus more particles were being formed. This distribution shows the generation of a peak at 255 nm and the distribution looks quite similar as the previous one except the particles have coagulated on the upper region. The distribution has moved to the right. The distribution data at 45 minutes from the start showed a decrease in particle concentration to about $932,000 \text{ cm}^{-3}$ with the lower modes coagulating to the higher modes. The lower size begins at about 70 nm. Similarly after 63 and 79 minutes from start the particle concentration decreased because of ex-filtration and also there may be some deposition onto available surfaces. The concentrations were about $325,480 \text{ cm}^{-3}$ and $85,419 \text{ cm}^{-3}$ respectively.

3.4 Aerosol Generated From A Gas Burner:

In order to measure the size distribution of the aerosol generated from the flame of a gas burner, the software was modified so as to measure particles formed below 10 μm . The software was modified in such a manner so as to have 12 mobility channels and 8

A: 13 min later (ACTIVE SOURCE)

B: 29 min later

C: 46 min later

D: 62 min later

E: 79 min later

Figure 3.8: Particle Size Distribution Of Aerosol Generated From Burning Incense.(#2)

midpoint diameter channels, below 10 nm down to 2.94 nm. Further, in order to get a reasonable size distribution below 10 nm the charging probability which follows Fuch's relation below 10 nm size was taken into account. The DMPS-DATA file was modified accordingly (see Appendix) by taking the values calculated by (Winklmayr, 1988) for different charge fractions down to 3 nm and then normalising it for our charging source i.e ^{85}Kr gas.

The measurements were made in a same manner described in the previous examples and again a background distribution was stored in the buffer memory. The flowrates were 24 lpm sheath and excess air and 2.4 lpm monodisperse outlet and polydisperse inlet so as to measure ultrafine particles corresponding to a DMPS measuring range of 6.0 to 221 nm at that flowrate.

Case 1: In order to measure particles down to 3 nm, a TSI 3025 Condensation Particle Counter was used to determine the particle concentration. In order to get true concentration the detection efficiency for the instrument was taken into account in the DMPS software using the values from Stolzenburg's thesis. Four samples were taken in a single run during the continuous burning of gas in the room. As can be observed from the first graph, the flame is clearly a continuous source of ultrafine particles i.e particles in the free molecular regime. A bimodal distribution was found with the first peak around 10.7 nm and the second around 70 nm. The total particle concentration was about $23,250 \text{ cm}^{-3}$ which decreased in the second sample to about 5185 cm^{-3} . The distribution clearly shows the decrease in the particle concentration in the larger mode while still generating particles in the lower ultrafine mode. In the third sample, the second mode can be seen to virtually disappear with an increase in the lower mode from the generation of fresh ultrafine particles with a peak drifting to right at 7.0 nm. In the last sample, the upper

A: 24 min later (ACTIVE SOURCE)

B: 28 min later

C: 56 min later

D: 102 min later

Figure 3.9: Particle Size Distribution of Aerosol Generated From Gas Burner Burning Continuously. (#1)

mode has almost disappeared and the lower mode drifted to the right with the peak around 8.0 nm. The particle concentration increasing to 20,500 cm^{-3} .

Case 2: In this run, four samples were also taken and the distributions are shown in Figure 3.10. The gas flame in this example was slightly smaller than the previous case and it shows the formation of two modes again as in the last case with the peak around 12.4 nm for the lower mode with particle concentration of approximately 45,000 particles. The second graph shows moving of the distribution to the right with a peak at 29.6 nm and particle concentration of about 4000 cm^{-3} . Finally in the last two distribution, the upper mode disappeared as in the previous run and the peak at about 6.0 and 7.0 nm and particle concentration at 1820 cm^{-3} and 3500 cm^{-3} particles respectively.

3.5 Aerosol Generated From The Burning Of A Hot Plate

For this case the flow rate ratio was also 24:2.4 and the same procedure as for the gas flame was followed. The TSI 3025 Condensation Particle Counter was the particle detecting instrument.

Case 1: A hot plate was continuously operated in the high temperature mode in the room for four sample runs. Initially, there are very few particles generated with concentration about 1166 cm^{-3} and with a peak around 9.3 nm and a very low concentration of particles in the upper mode. In the second graph, the particle concentration has increased to about 207,500 cm^{-3} with an anomalous peak around 34 nm which disappeared in the third run with the particle concentration dropping to 143,300 cm^{-3} . This particle concentration again decreased to 110,700 cm^{-3} in the last sample with generation of particles over the entire range.

Case 2: In this case, a second run of four samples was made with the hot plate operating continuously in the high mode inside the clean room. The same procedure for

A: Till 24 minutes (ACTIVE SOURCE) B: 28 min later

C: Till 80 minutes

D: 108 min later

Figure 3.10: Particle Size Distribution Of Aerosol Generated From Gas Burner Burning Continuously. (#2)

A: Till 24 minutes (ACTIVE SOURCE) B: 28 min later

C: Till 80 minutes

D: 108 min later

Figure 3.11: Particle Size Distribution Of Aerosol Generated From Burning a Hot Plate Continuously. (#1)

A: Till 24 minutes (ACTIVE SOURCE) B: 28 min later

C: Till 80 minutes

D: 108 min later

Figure 3.12: Particle Size Distribution Of Aerosol Generated From Burning A Hot Plate Continuously. (#2)

background was followed as mentioned in all the previous experiments. In the first sample, 850 particles cm^{-3} are generated with a peak around 9.3 nm. However, in the second sample, particles are seen to be formed over the entire measuring range with particle concentration about 91,500 cm^{-3} with a peak at around 124 nm. In the third sample one can observe the appearance of a mode along with anomalous peak around 143 nm. The particle concentration is approximately 26,790 cm^{-3} . The last sample shows the decrease in concentration of particles to approximately 5000 cm^{-3} and the decrease of the mode with a peak around 143 nm.

3.6 Aerosol Generated From Frying Bacon:

Frying of meat is also a potential source of aerosol generation in a typical American home. In order to get a better idea of the particle size distribution, two strips of Mello Crisp bacon were fried in the room on a pan kept on the hot plate in high mode for 8 minutes. In this case also the background was measured and stored in the buffer as for all the previous cases.

The behavior of the aerosol is shown in Figure 3.13. In the first sample taken 13 minutes after the start of frying, particles were observed over the entire DMPS measuring size range i.e 0.011 to 0.457 μm . There appeared to be single mode with a peak around 193 nm size with total particle concentration of $1.708 \times 10^7 \text{ cm}^{-3}$. The aerosolization is a bubble bursting process that generates small droplets of fat from the two strips along with some particles that had settled on the frying pan. There may also be particles from the heating coil of the hot plate. After 29 minutes the total particle concentration dropped to $1.526 \times 10^7 \text{ cm}^{-3}$ because of wall deposition, ex-filtration and some gravitational settling of larger size particles in the measuring range with a peak at 191 nm. The concentration after 46 minutes again decreased to $7.473 \times 10^6 \text{ cm}^{-3}$ with a peak at 221 nm and the mode

A: 13 min later (ACTIVE SOURCE)

B: 29 min later.

C: 46 min later.

D: 62 min later.

E: 79 min later.

Figure 3.13 Particle Size Distribution Of Aerosol Generated On Frying Bacon.

moving to the larger sizes with the appearance of a small mode on the lower end of the size range. The concentration after 62 and 79 minutes is 5.487×10^6 and $3.927 \times 10^6 \text{ cm}^{-3}$ respectively, and the peak at 221 and 255 nm, respectively. The appearance of a larger peak on the lower size end and the behavior of the aerosol is not clearly understood.

Chapter 4

CONCLUSIONS

The particle size distribution data of various aerosol sources suggests the following information about the size of particles these sources tend to produce as described below in

Table 4.1:

Particle Sources	Size Range	Maximum Concentration
Cigarette Aerosol	29 - 294 nm	7,500,000 particle/cm ³
Candle Aerosol	143 - 806 nm	6,000,000 particle/cm ³
Incense Aerosol	39 - 255 nm	3,500,000 particle/cm ³
Gas Burner	6 - 221 nm	45,000 particle/cm ³
Hot Plate	6 - 221 nm	143,000 particle/cm ³
Bacon frying	11 - 457 nm	1.708×10 ⁷ particle/cm ³

This information of particle sizes of the above indoor aerosol sources along with the typical concentration these sources tends to produce, gives us an insight into the dose of particles to people that can be given in indoor surroundings. Further, this data could be useful in designing efficient air cleaners or aid in the development of efficient mitigation procedures so as to have a particle free indoor environment.

These data give a better understanding of indoor aerosol dynamics. They can be used to test mathematical models for aerosol dynamics. Such models are of great importance in the estimation of population exposure to particles and design of controls that permit improvement of indoor air quality.

Further work is needed to account for the particle losses of the ultrafine particles from Brownian diffusion inside the Electrostatic Classifier. Diffusional losses occurs inside the neutralizer, the electrode assembly of the DMA and also inside the entrance and exit slit of the aerosols to the classifier (Adachi *et al*, 1990). One other problem with the

present detection systems are their particle detecting efficiency.

One of the most important problem encountered in this DMPS system is its sampling time. This system takes approximately 13 minutes to scan the whole measuring range with the electrometer and somewhere between 25 and 30 minutes with a condensation particle counter to measure ultrafine particles. This interval is quite long compared to the time in which conditions may change. During this interval, the aerosol changes its behavior a lot from the time of its generation. The newly developed Scanning Electrical Mobility Spectrometer (SEMS) (Wang and Flagan, 1989) reduces the sampling time drastically without sacrificing the size resolution of the system. Thus, the SEMS approach can give a better understanding of time varying aerosol sources or systems. In the SEMS method, the electric field is exponentially ramped rather than changing the electric field in discrete steps as in DMA to select particles in a given mobility range. The particles are classified in a time varying electric field, and there is a one to one correspondence between the time a particle entering the classifier and the time it leaves through the exit slit. Modification of this system will then allow us to measure particles rapidly below 10 nm giving us a true picture of the concentration of the aerosol sources.

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APPENDIX

Charge fraction (Winklmayr, 1988) for ultrafine particles for Am-241 source are given in Table A.1.1

Particle Diameter (nm)	Charge Fraction (I=1)	Charge Fraction (I=2)
3.21	0.01163	0.0000E+00
3.82	0.01463	0.0000E+00
4.55	0.01822	0.0000E+00
5.42	0.02244	0.0000E+00
6.45	0.02730	0.0000E+00
7.68	0.03277	0.0000E+00
9.16	0.03881	0.0000E+00
10.91	0.04534	0.1825E-04

Regression analysis of this above data as a linear model with particle diameter (nm) as the X- coordinate and singly charge fraction as the Y-coordinate gives the following results in the Table A.1.2:

Parameter	Estimate	Std. Error	T Value	Prob.Level
Intercept	-1.87E-3	6.50E-4	-2.87	0.0284
Slope	4.42E-3	9.45E-5	46.74	0.0000

Correlation Coefficient = 0.998629

From the estimates of slope and intercept, the charge fraction corresponding to the 12 mobility channels that are a factor 1.22 apart, corresponding to a particular size is determined by putting these values in the straight line equation to give us the values for the charge fraction for the Am-241. The calculated values for the mobility channels for the Am-241 source were divided with the corresponding values of the first four mobility charge

fraction for the TSI Kr-85 source above 10 nm and by averaging the normalised values gave a factor of 1.313 which was multiplied to the values calculated for Winklmayr's charge fraction. Table A.1.3 below shows both the calculated and the normalised single charge fraction values for the new lower mobility size channels.

Diameter Channel (nm)	Calculated Winklmayr's Charge Fraction	Normalised Charge Fraction	CPC Detection Efficiency
2.94	0.0111013	0.0145760	0.625
3.25	0.0124953	0.0164063	0.745
3.6	0.0140391	0.0184333	0.795
3.99	0.0157489	0.0206783	0.82
4.42	0.0176425	0.0231646	0.83
4.89	0.0197396	0.0259182	0.855
5.42	0.0220650	0.0289713	0.87
6.00	0.0246345	0.0323452	0.88
6.65	0.0274832	0.0360856	0.89
7.36	0.0306383	0.0402281	0.91
8.15	0.0341325	0.0448159	0.925
9.03	0.0380023	0.0498969	0.935

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