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**STUDY OF THE EFFECT OF HUMIDITY, PARTICLE
HYGROSCOPICITY AND SIZE ON THE MASS LOADING
CAPACITY OF HEPA FILTERS (U)**

by

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**STUDY OF THE EFFECT OF HUMIDITY, PARTICLE HYGROSCOPICITY AND SIZE
ON THE MASS LOADING CAPACITY OF HEPA FILTERS**

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by

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Bachelor of Technology

Indian Institute of Technology, Delhi, India, 1987.

Committee Chair : Professor Pratim Biswas

*This work is dedicated
to
my parents and my brother
whose patience, support and hope
always
be a source of inspiration.*

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ABSTRACT

The effect of humidity, particle hygroscopicity and size on the mass loading capacity of glass fiber HEPA filters has been studied. At humidities above the deliquescent point, the pressure drop across the HEPA filter increased non-linearly with the areal loading density (mass collected/filtration area) of NaCl aerosol, thus significantly reducing the mass loading capacity of the filter compared to dry hygroscopic or non-hygroscopic particle mass loadings. The specific cake resistance, K_2 , has been computed for different test conditions and used as a measure of the mass loading capacity. K_2 was found to decrease with increasing humidity for the non-hygroscopic aluminum oxide particles and the hygroscopic NaCl particles (at humidities below the deliquescent point). It is postulated that an increase in humidity leads to the formation of a more open particulate cake which lowers the pressure drop for a given mass loading. A formula for predicting K_2 for lognormally distributed aerosols (parameters obtained from impactor data) is derived. The resistance factor, R , calculated using this formula was compared to the theoretical R calculated using the Rudnick-Happel expression. For the non-hygroscopic aluminum oxide the agreement was good but for the hygroscopic sodium chloride, due to large variation in the cake porosity estimates, the agreement was poor.

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Nomenclature

A	Filtration Area (cm^2)
C	Cunningham Slip Correction Factor
d_g	Geometric Mean Particle Diameter (cm)
d_p	Particle Diameter (cm)
d_{mm}	Mass Median Diameter (cm)
K_1	Clean Filter Resistance ($\text{g cm}^{-2} \text{s}^{-1}$)
K_2	Measured Specific Cake Resistance (s^{-1})
K_{2c}	Polydisperse Specific Cake Resistance (s^{-1})
$K_{2\text{Stokes}}$	Stokes Specific Cake Resistance (s^{-1})
M	Total Mass of Particles Collected on the Filter (g)
R	Resistance Factor
R_s	Calculated Resistance Factor based on Stokes Formula
R_c	Calculated Resistance Factor including polydispersity
V	Filter Media Velocity (cm s^{-1})
ΔP	Pressure Drop Across Loaded Filter (N m^{-2})
ΔP_{filter}	Initial Pressure Drop Across Filter (N m^{-2})
ΔP_{cake}	Pressure Drop Across the Particulate Cake (N m^{-2})

Greek Symbols

ϵ	Porosity of Particle Cake
μ	Gas Viscosity ($\text{g cm}^{-1} \text{s}^{-1}$)
σ_g	Geometric Standard Deviation

CHAPTER 1

INTRODUCTION

1.1 Background

High Efficiency Particulate Air (HEPA) filters are often used as the primary particulate containment device in gas cleaning and ventilation systems. The term "high efficiency" is applied to a filter capable of removing 0.3 μm dioctyl phthalate (DOP) particles with an efficiency of at least 99.97% (Tillery, 1987). As the HEPA filter removes particles from the gas stream, the initial pressure drop across the filter increases due to the formation of a particulate cake on its surface. With continued particulate cake build-up, the flow rate through the ventilation system decreases. Eventually, due to pressure drop limitations of the exhaust fan, the gas flow through the filter approaches zero. Such situations are of serious concern in nuclear installations, especially during an accident wherein large quantities of radioactive aerosols could be generated (Hasenclever, 1971). In some postulated accident scenarios associated with water cooled nuclear reactors, a large quantity of steam could also be released along with a variety of aerosols. The interaction of water vapor with the generated aerosols may significantly affect the ability of the filtration systems to maintain sufficient flow for the entire accident sequence hence contain any aerosol formed within the reactor building.

In certain previous studies the effects of humidity on the pressure drop across filters has been studied. In one of the studies, Durham and Harrington (1971) examined the influence of relative humidity on filtration resistance and efficiency of fabric dust filters. They varied humidity in the range of 20% to 60% RH and observed a decrease in pressure drop across fabric filters when fly ash particles were used. They did not observe any decrease in the pressure drop for cement dust, pulverized limestone, or amorphous silica. In another study, Ariman and Helfrich (1977) examined how changes in relative humidity altered the pressure drop in fabric filters. The test dusts used in the study were fly ash, ground silica dust and asphalt rock dust. On increasing the humidity in the range of 20% to 80% RH, they observed a decreasing trend in the pressure drop for all the test cases.

Recently, Novick and Higgins (1989) and Novick et al. (1990) reported that the pressure drop across a HEPA filter increased non-linearly when sodium chloride (NaCl) particles from a high humidity aerosol stream were loaded onto the filters. However, they noted that at low humidities (35%) the increase in the pressure drop with mass loading remained linear for the NaCl aerosol. Smith et al. (1990) also investigated the effect of humidity on the pressure drop change across a HEPA filter being loaded with NaCl aerosol. Experiments were conducted at two average humidities of 80% (65% to 99%) and 14% (9 to 18%). Higher pressure drops were reported at higher humidities. This was qualitatively attributed to a more effective plugging of filters due to fusing of salt (NaCl) in the presence of moisture. Ricketts et al. (1990) examined the pressure drop across pre-loaded HEPA filters previously used in the ventilation system of their laboratory, under different humidity conditions. They found that the rate and extent of the pressure drop increase was significant only at humidities above 70%.

Though the above studies have indicated trends, no definite conclusions could be made about the effects of relative humidity on the alterations of pressure drop. Furthermore, the effects of relative humidity are bound to be dependent on the aerosol material properties, such as hygroscopicity and may also depend on the particle size of the aerosol. The apparent contradictions in the effects of humidity on the pressure drop as observed by Smith et al. (1990) and Durham and Harrington (1971), and Ariman and Helfrich (1977) could have been due to differences in the hygroscopicity or size of the test particles.

1.2 Objectives

The objective of this study was to determine the effects of humidity on the pressure drop-mass loading characteristics of a HEPA filter vis-a-vis particle hygroscopicity and size. Controlled laboratory experiments were conducted using two sizes (0.5 μm and 1.0 μm nominal mass median diameter) of two different particle materials : non-hygroscopic aluminum oxide and hygroscopic sodium chloride.

The development of an expression for calculating the specific cake resistance using the commonly reported mass median diameter is presented in Chapter 2. The expression is valid for lognormally distributed aerosols.

The experimental set up and methodology is discussed in Chapter 3. A modified Tapered Element Oscillating Microbalance (TEOM) was used to measure the pressure drop and mass loading on the HEPA material. Aluminum oxide and sodium chloride were used as the non-hygroscopic and hygroscopic test aerosols respectively. Desired

levels of relative humidity were attained by mixing humidified air with the aerosol stream.

The experimental results are presented in Chapter 4. The observed pressure drop versus mass loading characteristics vis-a-vis particle hygroscopicity, relative humidity and particle size are qualitatively explained. Also presented is the comparison of the theoretical resistance factor with the resistance factor obtained from the expression developed in Chapter 2.

Chapter 5 discusses the conclusions and recommendations for future work. Properties of test aerosols, derivation of the expression for specific cake resistance, humidifier calibrations, representative sampling characteristics of the sampling system, results of the TEOM performance tests, TEOM transducer calibrations, impactor Mach number calculations, conversion of MMAD to MMD, and porosity data are presented in Appendices I to VIII.

CHAPTER 2

EXPRESSION FOR SPECIFIC CAKE RESISTANCE ACCOUNTING FOR POLYDISPERSITY

The total pressure drop across a filter, ΔP , is the sum of pressure drops across the filter media, ΔP_{filter} , and that across the particulate cake, ΔP_{cake} . Mathematically, it can be written as

$$\Delta P = \Delta P_{\text{filter}} + \Delta P_{\text{cake}} \quad (2.1)$$

Assuming the filter media and the particulate cake to be two rigid porous beds superimposed on each other, and flow through them to be laminar, then each component of the total pressure drop can be described by Darcy's law and written as

$$\Delta P_{\text{filter}} = K_1 V \quad (2.2)$$

$$\Delta P_{\text{cake}} = K_2 V \left(\frac{M}{A} \right) \quad (2.3)$$

where K_1 is the clean filter resistance, V is the filtration velocity, K_2 is the specific cake resistance, M is the mass deposited and A is the filtration area. K_2 is generally computed experimentally by using measured values of ΔP and ΔP_{filter} in equations (2.1), (2.2) and (2.3)

$$K_2 = \frac{(\Delta P - \Delta P_{filter})}{V \frac{M}{A}} \quad (2.4)$$

The theoretical expression for the specific cake resistance, K_2 , is derived by applying Stokes law to the particles in a cake by assuming that they are monodisperse and sparsely distributed (flow over a particle is not influenced by the presence of other particles). Assuming that there are N such particles in the cake, the pressure drop is given by

$$\Delta P_{cake} = \frac{3\pi\mu V d_p N}{A C} \quad (2.5)$$

where μ is the gas viscosity, d_p is the particle size and C is the Cunningham slip correction factor. Rewriting equation (2.5) in terms of the mass of particles collected

$$\Delta P_{cake} = \left(\frac{18\mu}{\rho_p d_p^2 C} \right) \left(\frac{V M}{A} \right) \quad (2.6)$$

where ρ_p is the particle density. Using the definition of the specific cake resistance from equation (2.4), the following theoretical expression is derived

$$K_{2,theor} = \left(\frac{18\mu}{\rho_p d_p^2 C} \right) \quad (2.7)$$

The specific cake resistance determined using equation (2.7) is the minimum value corresponding to a sparse distribution of monodisperse spherical particles.

Equation (2.7) shows that K_2 is inversely proportional to the square of particle diameter. If the particles in the cake are not monodisperse, a mean particle diameter must be used. For mass loading studies, the mass median diameter becomes the appropriate choice because it is directly indicative of the particle mass. However, it is not representative of the particle cross sectional area responsible for the drag. Rudnick (1978) suggested that for polydisperse dusts, the volume-length mean diameter should be used to calculate the resistance factor, R (explained later). Since aerosol size distributions are often represented by lognormal functions and the volume-length mean diameter is not commonly reported, an expression for calculating specific cake resistance for the lognormally distributed aerosols is developed in this paper.

Assuming that the size distribution of particles on the cake can be represented by $n(v)$, the pressure drop due to the cake can be computed by integrating equation (2.5) over all particle sizes (or particle volumes)

$$\Delta P_{cake} = \frac{3\pi\mu V}{(\pi/6)^{1/3} A} \int_0^{\infty} \frac{v^{1/3}}{C} n(v) dv \quad (2.8)$$

where, v is the particle volume ($v = \pi d_p^3/6$). Assuming C to be evaluated at the geometric mean diameter, equation (2.8) reduces to

$$\Delta P_{cake} = \frac{(162)^{1/3} (\pi)^{2/3} \mu V M_{1/3}}{A C} \quad (2.9)$$

where $M_{1/3}$ is the 1/3rd volume moment of the aerosol size distribution. For lognormally distributed aerosols the k^{th} moment, M_k , is expressed in terms of the zeroth moment, M_0 , (Biswas et al., 1989)

$$M_k = M_0 v_g^k \exp(4.5 k^2 \ln^2 \sigma_g) \quad (2.10)$$

where v_g is the geometric volume mean and σ_g is the geometric standard deviation. Using $k = 1/3$ in equation (2.10) and substituting in equation (2.9) we have

$$\Delta P_{\text{cake}} = \frac{(162)^{1/3} (\pi)^{2/3} \mu V M_0 v_g^{1/3}}{A C} \exp(0.5 \ln^2 \sigma_g) \quad (2.11)$$

Multiplying and dividing equation (2.11) by $M_1 \rho_p$ (=mass collected, M) and using equation (2.10) we have

$$\Delta P_{\text{cake}} = \frac{(162)^{1/3} (\pi)^{2/3} \mu}{\rho_p C v_g^{2/3}} \left(\frac{V M}{A} \right) \exp(-4.0 \ln^2 \sigma_g) \quad (2.12)$$

Using equation (2.4) an expression for the specific cake resistance, K_{2C} , for a polydisperse aerosol with the slip correction factor evaluated at the mean geometric size can be derived

$$K_{2C} = \frac{18\mu}{\rho_p d_g^2 C} \exp(-4.0 \ln^2 \sigma_g) \quad (2.13)$$

where d_g is the geometric mean diameter of the particle size distribution which can be calculated from mass median diameter obtained from impactor data (Hinds, 1982)

$$d_g = d_{mm} \exp(-3.5 \ln^2 \sigma_g) \quad (2.14)$$

Substituting in equation (2.13) we get

$$K_{2C} = \frac{18\mu}{\rho_p d_{mm}^2 C} \exp(3.0 \ln^2 \sigma_g) \quad (2.15)$$

In the limit $\sigma_g \rightarrow 1$ (monodisperse particles), K_{2C} in equation (2.15) approaches $K_{2Stokes}$ in equation (2.7).

In a real cake the particles are not sparsely distributed. On the contrary, they are in close proximity of each other such that the flow around a particle is influenced by the presence of its neighboring particles. This non-ideality results in pressure drops higher than those predicted by equation (2.13). To account for the differences in the experimentally measured value, K_2 (equation (2.4)) and the theoretically computed value (equation (2.13) or equation (2.7) for monodisperse aerosols) a resistance factor, R , is defined

$$R = R_C = \frac{K_2}{K_{2C}} \quad \text{or} \quad R_S = \frac{K_2}{K_{2Stokes}} \quad (2.16)$$

Rudnick (1978) proposed the following expression, based on Happel free surface model, for the determination of theoretical R

$$R = \frac{3 + 2(1-\epsilon)^{5/3}}{3 - 4.5(1-\epsilon)^{1/3} + 4.5(1-\epsilon)^{5/3} - 3(1-\epsilon)^2} \quad (2.17)$$

where ϵ is the cake porosity. This expression has limited use in determining the pressure drop as a function of mass loading as it requires the knowledge of cake porosity which is often difficult to estimate theoretically or measure experimentally due to the complexities and fragility of the cake structure.

CHAPTER 3

EXPERIMENTAL

3.1 Experimental Apparatus

A schematic representation of the experimental set-up used for measuring pressure drop variation with mass loading at different relative humidities is shown in Figure 3.1. An identical experimental set-up, except for the aerosol generation techniques, was used for the two tests materials (hygroscopic and non-hygroscopic). The schematic diagrams of the aerosol generation techniques used in the tests are shown in Figure 3.2. The materials and equipments used in the experiments are listed in Table 3.1.

3.1.1 Aluminum Oxide Aerosol Dispersion

A Wright Dust Feeder (WDF) was used for dispersing non-hygroscopic aluminum oxide powders. The WDF was operated at 5-10 psig pressure range, resulting in an aerosol flow rate of 14 lpm to 16 lpm. Only 3.0 lpm of the aerosol was required for loading the filters. The remaining aerosol flow was filtered and then exhausted to the laboratory environment (Figure 3.2).

Figure 1 Schematic of the experimental system to measure pressure drop as a function of mass loading of hygroscopic and non-hygroscopic aerosols at different humidities.

3.1.2 Sodium Chloride Aerosol Generation

The smaller (MMD=0.5 μm) NaCl particles were generated by atomizing a 1% (Weight/volume) aqueous solution of NaCl in a TSI (Thermo-Sysytems Inc.) atomizer model 3076. The atomizer was operated at 35 psig resulting in an output aerosol flowrate of approximately 3.5 lpm. The larger (MMD=1.0 μm) NaCl particles were generated by a 3-jet Collison nebulizer from a 5% (weight/volume) solution of NaCl in water. The 3-Jet Collison was operated at 20 psig. At this pressure, an output aerosol flow rate of approximately 3.0 lpm was produced. In both cases the entire output of aerosol was used for loading the filters. The high pressure air, used for atomizing, was pre-filtered and dried to a relative humidity of <1% by a air dryer (Balston, Model 75-20). Atomized liquid aerosol droplets (NaCl) were passed through three diffusion dryers, in series, to yield a solid and dry test aerosol of NaCl (Figure 3.2). A multiple drying system was found to be necessary for complete drying of the NaCl particles which show significant hysteresis in the drying and wetting cycle (Tang et al., 1977).

3.1.3 Humidification

The desired relative humidity (RH) of the test aerosol was attained by mixing it with a humidified air stream. The humidified air stream was obtained by bubbling particle free dry air through a heated water bath. The water bath temperature could be maintained within $\pm 1^\circ\text{F}$ of the set temperature, hence, stable humidity levels were achievable. Any desired changes in the RH could be made by adjusting the water bath temperature or the humidified air flow rate. Typically, the flow rate of the humidifying air stream was 0.75 lpm. This was mixed with 3.0 to 3.5 lpm aerosol stream and approximately 2.0 to 2.5 lpm

Aluminum oxide dispersion

Sodium chloride generation

Figure 3.2 : Schematic of the aerosol generation system used for generating aluminum oxide and sodium chloride aerosols

of self adjusting bypass flow (Figure 3.1). This helped in maintaining at total flow of 6.2 lpm to the sampling chamber during all stages of an experiment. Any change in the humidified air flow rate caused a corresponding change in the bypass air, thereby altering the ratio of dry air to the humidified air. By doing so fine adjustment in RH could be made which was particularly useful in offsetting the minor humidity changes due to ambient temperature variations or changes in dryer effectiveness over the duration of an experiment. With these controls, the relative humidity could be maintained within $\pm 3.0\%$ of the desired value (Appendix-III).

3.1.4 Neutralization

Freshly generated aerosol particles always have associated electrostatic charge. Presence of charge on the particles can influence the pressure drop across a filter. To reduce the electrostatic charge associated with the aerosol particles to a Boltzman equilibrium level, the aerosol/water vapor mixture was passed through a neutralizer (TSI, Model 3077).

3.1.5 Aerosol Sampling

After neutralization, the humidified aerosol stream was inlet to the sampling chamber to which three identical aerosol sampling probes were attached (Figure 3.3). Each probe was made out of a 10 cm long 1/4" metal tube. The sampling end of each probe was shaped to simulate a thin walled sampling tube. Each probe was inserted through a drilled 1/4" swagelok-pipe union, screwed at the top of the sampling chamber, to sample the aerosol. This was done to prevent obstructions due to variations in the internal diameter of the sampling probe. As shown in Figure 3.3, to these probes were

connected a 47 mm filter holder, a Tapered Element Oscillating Microbalance (TEOM), and a cascade impactor (Intox Products, Model 5B). All these devices were mounted in an upside-down configuration such that they sampled aerosol against gravity. Initial experiments indicated that gravity aided sampling resulted in the formation of non-uniform cakes, especially on the 47 mm filter. These filters were observed to have a pile of particles at the center of the filter. It was found that particle agglomerates when sampled in the direction of gravity were leaving the diverging flow streamlines inside the filter holders and were getting deposited in the center of the filters in the form of a conical pile. However, by connecting the three devices in an inverted position, the tendency of pile formation was reduced considerably because the particles agglomerates were unable to gain sufficient inertia to be able to leave the flow streamlines. The sampling characteristics of the sampling system in the inverted configuration is presented in Appendix-V.

3.1.6 Data Collection

The modified TEOM used in the present study had the ability to measure mass loading and pressure drop across the filter in real time. Figure 3.4 presents the essential features of a TEOM schematically. As shown in Figure 3.4, a TEOM filter is seated at the top end of the oscillating glass element. The test aerosol is pulled into the TEOM by a vacuum pump located outside the TEOM. The particles trapped on the filter increase the mass of the oscillating system (stem and filter) thereby altering the reference oscillation frequency of the stem. The oscillating frequency of the stem is continuously monitored by a photo-sensor. Repeated shadowing of the photo-sensor by the stem results in an effective alternate current. The generated current is then amplified and compared with

Figure 3.3 : Schematic of the aerosol sampling system.

the frequency of a reference quartz crystal. The direct proportionality between the frequency and the oscillating mass pre-calibrated such that the new frequency of the stem is converted to the total mass of the filter. The concomitant increase in the pressure drop across the filter due to particle deposition is monitored by a pressure transducer (Appendix-IV). The aerosol flow through the device is controlled and held constant by a massflow controller (Tylan, Model 260C). In the present study, the flow through the TEOM was controlled by metering valve located outside the unit. The metering valve was adjusted using an electronic flow calibrator (bubble meter) such that the TEOM filter face velocity of the TEOM filter was 3.00 cm/s. The instantaneous values of the total mass of the filter (g), the pressure drop (inch water), along with the values of aerosol flow (lpm), the rate of mass collection (g s^{-1}), the mass concentration (g/cc), are all recorded and displayed on a personal computer. The stored data is accessible for later analysis and re-plotting. The confidence test results for the mass loading and pressure difference across the TEOM filter with respect to two 47 mm filter holders are presented in Appendix-IV. One of these 47 mm filter holder was used to simultaneously sample all test aerosols to verify the test end points (particles per unit filtration area and the specific cake resistance) of the TEOM filter data. The HEPA filter media was identical for both the 47 mm filter sampler and the TEOM and they sampled aerosol from two ports attached to the sampling chamber.

3.1.7 Particle Size Measurements

Studies by Biswas et al. (1987) observed that many particle size distribution measuring devices tend to be biased while sampling humid aerosols. In their paper they discuss the effect of humidity on the accuracy of Optical Particle Counter (OPC) and

Figure 3.4 : Design of a TEOM Filter and the TEOM Oscillating Element.

cascade impactor.

In an OPC the sampled gas stream is mixed with the recirculating gas causing a change in the humidity of the gas at the point of measurement. Consequently, the moisture associated with the particles establishes a new equilibrium with the new ambient conditions. In the case of hygroscopic particles this loss of moisture will eventually cause a change in the particles size. The error in particle size measurement was significant at humidity levels of 80% and beyond. It was reported that, to be able to measure particle size with reasonable accuracy at such humidity levels the instrument had to be running for 8 to 9 hours prior to measurements so that the recirculating gas could equilibrate with the inlet gas. This additional operating time period was not practical for these mass loading experiments.

Contrary to an OPC, in an impactor, repeated expansion of the inlet gas stream through the jets causes a decrease in gas temperature and pressure progressively with each stage causing water vapor to condense, especially under high humidity conditions. The study, however, reported that if the Mach Number in all the stages can be maintained below 0.005, the bias in particle size measurements due to condensed water droplets would be minimal even at relative humidities exceeding 90%. Keeping this in mind a brief study was carried out to select proper impactor.

The impactor used in the present study sampled aerosol at a flow rate of 5 lpm, and had a maximum Mach number of 0.004 (Appendix-VI). Therefore, even under high humidity conditions (>90%), the bias in the size distribution was considered negligible.

The size measurements were done at the end of each run. A sampling time of 3 to 4 minutes was found to be necessary for the sufficient loading on the impactor substrates. An analytical mass balance (Mettler, Model Gram-Attic) with a resolution of at least 10^{-4} g or 0.01 mg was used for weighing the impactor substrate mass. From these measurements the Mass Median Aerodynamic Diameter (MMAD) and the Geometric Standard Deviation (GSD) of the aerosol was computed. To be able to use the theoretical expression developed earlier (Chapter 2), the MMAD was converted to Mass Median Diameter (MMD) (Appendix-VII) and then to Geometric Mean Diameter.

3.1.8 Relative Humidity Measurement

As shown in Figure 3.3, a portion of the humidified aerosol was sampled from the top of the sampling chamber. The sampled aerosol was filtered before inletting into the hygrometer sensor to prevent the fouling of the hygrometer (General Eastern, model M2 with sensor 1111H). The metal tube transporting the sample was heated to prevent loss of water vapor due to condensation. By preventing loss of water vapor and by measuring the gas temperature inside the sampling chamber, the sampling chamber relative humidity was accurately measured by the hygrometer located outside the sampling chamber.

3.2 Design of Experiments

In the present study sodium chloride (NaCl) and aluminum oxide (Al_2O_3) were used for the hygroscopic and the non-hygroscopic mass loading tests. Sodium Chloride was used for the hygroscopic studies because its hygroscopic properties are well characterized (Appendix-II), it is easy to generate and is non-toxic. Choice of Aluminum

oxide powder (Al_2O_3) as the non-hygroscopic test aerosol was based on the fact that it is a metal oxide and somewhat similar to the oxides which result from a possible accident scenario (Cuddihy et al., 1989). For a reasonable comparison between the hygroscopic and the non-hygroscopic test results, experiments were performed over a wide range of humidities (Table 3.2).

The lowest achievable humidity, for the duration of an experiment (approximately 6 hrs), for NaCl aerosol was determined to be 35% RH. This value was obtained by aerosolizing pure water with a Collison nebulizer and recording the humidity with a strip chart recorder. From an initial humidity of about 1%, the relative humidity increased to 20% in the first 5 minutes of the experiment. Subsequent increase in the humidity was gradual took approximately 4 hours to reach a value of 30%. Since an experiment was expected to run for about 6 hours, it was safe to fix the base line humidity at 35% for NaCl aerosol. The solid NaCl aerosol deliquesces and turns liquid at a relative humidity

Table 3.1 : Equipment and Materials used in the Experiments

Equipment/Material	Manufacturer	Model
Dry Air Supply	Balston	Type 75-20
Flow Meter	Aalborg	GMP-1700
Flow Controllers	Tylan	260 C, 360 C
Collison Aerosol Generator	BGI	3076
TSI Aerosol Generator	TSI	3-Jet
Wright Dust Feeder	BGI	WDF-II
Neutralizer	TSI	3077
47mm Filter Holders	Intox Products	--
TEOM	Rupperecht & Patashnick	1100
Impactor	Intox Products	5B
Hygrometer	General Eastern	Hygro-M2
RH Sensor	General Eastern	1111H

of approximately 75%. Therefore, tests were carried out at humidity conditions both below and above the deliquescent point (Table 3.2).

Two particle size distributions, nominally with mass median diameters (MMD) of 0.5 μm and 1 μm were tested to determine the effect of particle size. The choice of particle size was such that it represents possible particle sizes predicted by the experiments designed to simulate certain nuclear accidents (Buckle, 1991).

Temperatures and pressures were maintained at the ambient laboratory conditions. The filtration velocity was 3.00 cm/s at which most HEPA filters are tested. Table 3.2 lists the experimental conditions.

Table 3.2 : Experimental conditions for the non-hygroscopic aluminum oxide and the hygroscopic sodium chloride test aerosols.

Test Aerosol	Non-hygroscopic Aluminum oxide	Hygroscopic Sodium Chloride
Particle Size	Table 4.2	Table 4.3
Relative Humidity (RH)	1%, 35%, 80%, 90% and 100%	35%, 55%, 65%, 80% and 90%
Filtration Velocity	3.00 cm s ⁻¹	
Temperature	(25 °C)	
Pressure	(1 atm)	

3.3 Estimation of Theoretical R

To use the Rudnick-Happel expression (Chapter 2) for calculating theoretical R, values of cake porosity are required. These porosity values were calculated indirectly by first estimating the cake density

$$\text{Cake density} = \text{cake mass} / \text{cake volume} \quad (3.1)$$

To determine the cake thickness, a movable microscope, fitted with a micrometer, was focussed on the bare 47 mm filter surface and then on the center of the cake. The difference between the two readings is the local cake thickness. Ten cake thickness measurements were made at different cake locations to compute a statistically reliable average thickness. Any data point which was more than twice the standard deviation away from the average was discarded and a new average was calculate without it. Three such observations in three different data sets were discarded. Knowing the average cake thickness, the cake volume was computed using the cake diameter. The mass of the particles in the cake was determined gravimetrically. The ratio of the mass to the cake volume yielded an average cake density. The ratio of the cake density to the dry particle density is then subtracted from unity to determine the value of cake porosity.

$$e = 1 - (\rho_{\text{cake}} / \rho_p) \quad (3.2)$$

The data used for computing cake porosities are presented in Appendix-VIII for aluminum oxide and NaCl respectively.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of Humidity on Clean HEPA Filter

The glass fiber HEPA filter material used in the present study was pre-treated with a hydrophobic compound. Initial tests performed to determine the effect of humidity on the clean filter pressure drop, ΔP_{filter} , indicated that ΔP_{filter} remained constant for relative humidity changes in the range of 1% to 100%. These tests like all other tests were conducted at a constant filtration velocity of 3.00 cm s^{-1} . The values of K_f calculated from the initial pressure drop data are presented in the Table 4.1 for all the cases investigated.

Table 4.1 clearly indicates that the variation in K_f is minimal even at 100% humidity. To determine the long term effects of water vapor on K_f , the TEOM filter was subjected to particle free air at 100 % RH. The experiment was carried out for 2 hours and 19 minutes. During this time period the TEOM did not record any steady increase in mass. The change in the collected mass fluctuated in both increasing and decreasing directions and could be attributed to the minor variations in the oscillation frequency of the stem. The pressure drop also fluctuated around the initially observed value. Visual examination of the TEOM filter under a magnifying glass did not exhibit any liquid on the filter surface indicating the absence of condensed water. Subsequent overnight drying of the filter in

an oven at 105 °C also did not show any loss in mass. All these tests confirmed that K_1 remains constant even at 100 % RH, therefore, no correction was required for the calculation of K_2 from the pressure increase versus mass loading data.

Table 4.1 : Variation of Clean Filter Resistance with Humidity

Humidity (%)	ΔP_o (Pa)	Velocity (cm s ⁻¹)	K_1 (s ⁻¹)
1	245	2.96	0.33
1	300	3.01	0.40
35	260	3.00	0.35
35	317	3.07	0.41
55	220	3.01	0.29
55	272	3.03	0.36
80	260	2.96	0.35
80	225	3.00	0.30
90	260	3.05	0.34
90	260	3.02	0.34
100	252	3.00	0.34
100	260	2.98	0.35
$(K_1)_{av} = 0.347 \text{ (s}^{-1}\text{)}$ $\sigma_x = \pm 0.033$ Coefficient of variation = $\pm 9.5 \%$			

4.2 Results of Non-Hygroscopic Tests

The non-hygroscopic mass loading tests used two sizes of aluminum oxide particles to challenge the TEOM and the 47 mm HEPA filters at various humidities. The MMD's of the two powders, as specified by the manufacturer, were 1.19 μm and 0.45 μm . The MMDs calculated from the measured MMADs are given in Table 4.2. A particle density

of 3.9 g/cm^3 was used for these calculations (Appendix-VII).

At the start of the experiment the aerosol was passed through a start-up filter until a stable humidity was attained in the system (Figure 3.1). Then the start-up filter was shut off and the aerosol was directed to the TEOM and 47 mm filters. The pressure drop across the TEOM filter and the mass collected on the filter as a function of time were recorded. This data combined with the knowledge of filter area allowed the pressure drop versus areal loading density (mass loading per unit filtration area) were plotted for each test. Except for the hygroscopic tests above the deliquescent point, these plots were linear. The slope of these plots was then divided by the filter face velocity (equation 2.4) to compute the experimental value of the specific cake resistance for each test.

For the larger ($1.0 \text{ }\mu\text{m}$ nominal MMD) aluminum oxide particles, the decrease in K_2 is observed at all humidities (Table 4.2 & Figure 4.2). Qualitatively, this effect can be attributed to an increase in the particle to particle adhesive forces as the humidity is increased. The magnitude of these forces is dependent on several factors such as the nature of the particle material (here hygroscopicity), its size and shape, surface roughness and the relative humidity of the surrounding gas (Zimon, 1969). Therefore, at high humidities, the particles are expected to have higher adhesive forces effecting firmer bonding between themselves. Consequently, during cake formation, the particles tend to stick to the particles already present on the cake surface rather than rolling into and filling the interstitial spaces. This pattern of deposition is expected to form a cake comprising of chain like particle structures with relatively straight channels between them. When compared to the cake with a random network of particles, the cake formed at high humidity will offer less resistance to the flow due to the "straightness" of the channels and

consequently more mass can be loaded to attain a given pressure drop. Similar observations of reduction in the pressure drop with increase in humidity have been made by Durham and Harrington (1971) and Ariman and Helfrich (1977) for non-hygroscopic dusts.

It was seen that for the smaller (0.5 μm nominal MMD) aluminum oxide particles K_2 did not vary significantly until a RH of 90%, however, above 90% RH the decrease in K_2 was significant (Table 4.2 & Figure 4.1). This decrease in K_2 could be due increased particle to particle adhesion caused by presence of minute quantities of condensed water on the surface. However, more work, taking into account the particle morphology and all the other factors influencing the forces between the particles, needs to be done in order to describe the behavior below 90% RH.

The variation in the porosities estimated by the procedure outlined earlier (Chapter 3) was random and could not be attributed to the changes in RH. Most likely, these variations were caused by the errors associated with the cake thickness measurements. The coefficient of variation (COV) of local cake thickness varied from 5.1 to 37.3% (average COV=20.6%) for the aluminum oxide particle cakes. This caused a deviation of 1.5 to 8.4% in the porosity estimates (Table 4.2). The experimental R ($R_c = K_2/K_{2c}$ and $R_s = K_2/K_{2\text{Stokes}}$) values and the theoretical values calculated from the Rudnick-Happel expression (equation 17) using the estimated porosity values are compared in Figure 4.3 for the aluminum oxide. The R_c values (except for one point) are in reasonable agreement with the theoretically determined R values (equation 2.17) indicating that for the lognormally distributed aerosols the developed expression (equation 2.13) is accurate in determining the specific cake resistance.

Figure 4.1 : Measured pressure drop versus areal density for 0.5 μm nominal MMD aluminum oxide at different humidities.

Figure 4.2 : Measured pressure drop versus areal density for 1.0 μm nominal MMD aluminum oxide at different humidities.

Table 4.2 : Measured particles size, geometric standard deviation, specific cake resistance and resistance factors for aluminum oxide test aerosol.

RH (%)	d_{mm} (μm)	σ_g	K_2 (s^{-1})	$K_{2Stokes}$ (s^{-1})	R_s	K_{2C} (s^{-1})	$\epsilon \pm \text{std. dev}$	R_C
0.5 μm nominal MMD Aluminum Oxide								
1	0.54	1.73	1510000	219761	6.9	546519	0.95 $\pm$ 0.01	2.8
1	0.62	1.66	1592500	171931	9.3	410073	0.94 $\pm$ 0.01	3.9
35	0.53	1.73	1600000	227119	7.0	561753	0.92 $\pm$ 0.01	2.8
35	0.57	1.68	1737500	199719	8.7	478001	0.93 $\pm$ 0.02	3.6
80	0.65	1.64	1472500	157961	9.3	371287	0.94 $\pm$ 0.01	3.9
90	0.69	2.20	1352500	141841	9.5	532684	--	2.5
95	0.75	1.80	820000	121931	6.7	359246	0.94 $\pm$ 0.02	2.3
100	0.73	1.96	794750	128074	6.2	435201	0.90 $\pm$ 0.01	1.8
100	0.63	1.58	720000	167074	4.3	361363	--	2.0
1.0 μm nominal MMD Aluminum Oxide								
1	0.99	1.80	918250	73158	12.6	232157	0.86 $\pm$ 0.03	3.9
35	1.33	1.46	839750	42059	20.0	81997	0.86 $\pm$ 0.03	10.2
35	1.03	1.80	802500	67960	11.8	217722	0.83 $\pm$ 0.06	3.7
80	1.07	2.06	705000	63298	11.1	274509	0.87 $\pm$ 0.03	2.6
90	1.12	1.61	606500	58117	10.4	142755	0.92 $\pm$ 0.01	4.2
100	1.07	1.60	520000	63298	8.2	152200	--	3.4
100	1.30	1.60	494250	42882	11.5	107938	0.84 $\pm$ 0.02	4.6

4.3 Hygroscopic Aerosols

4.3.1 Behavior of Hygroscopic Aerosols in Humid Environments

The phase rule of physical chemistry states that the equilibrium of a system of C components and P phases possesses $C-P+2$ degrees of freedom. For a system of three phases consisting of a soluble salt, its aqueous solution and water vapor with two components - water and salt - the degrees of freedom are $2-3+2 = 1$, which means that if we specify one thermodynamic variable - temperature - the other variables must take on a prescribed value and are not free to vary. In other words at a given temperature, water vapor, solution and solid can exist only at one vapor pressure or relative humidity, which also implies a fixed composition for the liquid phase. This relative humidity therefore represents a phase transition point and is generally known as the *deliquescent point*. As reported by Tang et al., (1977) the deliquescent point for the pure NaCl particles is at 75% RH. Considering a solution drop, large enough that effects of curvature can be neglected, the concentration of soluble material in the solution determines its equilibrium relative humidity. If the RH in the environment is higher than equilibrium RH, the drop will grow, displaying hygroscopic nature, and become more dilute. If the RH is lower, the drop will evaporate thereby increasing the solution concentration. Continued evaporation of the drop will result in solute crystallization and eventually a solid particle will be obtained. In the reverse phenomenon, a solid particle takes up moisture and eventually turns into a liquid drop in humid environments. In most cases the phase transition point is not identical for the drying and wetting cycle. This effect is commonly known as hysteresis. In the case of pure NaCl the crystallization occurs at 44% RH (Tang et al., 1977).

Figure 4.3 : Comparison of experimental and theoretical resistance factor, R_c for non-hygroscopic aluminum oxide.

4.3.2 Estimation of Equilibrium Contact Time for Sodium Chloride

According to Tang et al. (1977) and Golli et al. (1974), submicron NaCl particles require approximately 2.0 sec to reach equilibrium size at a given humidity. The contact time between the aerosol and the water vapor based on the total volume of the experimental apparatus and the volumetric flow rates was estimated to be around 11.0 ± 2.0 seconds. The contact time was also estimated by an independent method in which the humidifier was cut-off from the system after the humidity in the system had stabilized (Figure 3.1). At the same time a stop watch was started to note the time elapsed until the hygrometer indicated a change. Typically, this time varied from 13.0 to 15.0 seconds. By subtracting the hygrometer response time (1.5 seconds) from this value the actual contact time of 11.5 to 13.5 seconds was obtained. It is clear from these estimates of contact time that for the given system the contact time was least five times the interval required to attain equilibrium.

4.3.3 Results of Hygroscopic Tests Below Deliquescent Point

The results of the mass loading experiments performed with a hygroscopic aerosol, NaCl are presented in Figures 4.4 to 4.10. For humidities less than the deliquescent point (<75%), a linear relationship of pressure drop to mass loading was obtained (Figures 4.4 and 4.5). As observed for the non-hygroscopic particles, the specific cake resistance, K_2 , also decreases with an increase in humidity. The decrease in K_2 , however, is greater compared to the similar size non-hygroscopic aluminum oxide particles. A possible reason for this may be the higher adhesiveness of the hygroscopic NaCl particles compared to the non-hygroscopic aluminum oxide particles at elevated humidities, thus leading to the formation of a more open cake structure. Higher particle

adhesiveness of NaCl also caused the particles to stick together to form agglomerates indicated by the observed increase in the particle size (Table 4.3). A larger effective particle size due to coagulation also contributes to the decrease in K_2 as dictated by its inverse relationship to the square of particle size (equation 2.7 or 2.13). However, it should be noted that thermodynamically it is not possible for a NaCl particle to grow below the deliquescent point (Tang et al., 1977). As explained earlier (section 4.3.1), below the deliquescent point water exists only in vapor form in the system and can not contribute towards particles growth.

Similar to the non-hygroscopic aluminum oxide case, the variation in the estimated porosities was random and could not be attributed to the changes in RH (Table 4.3). However, the errors associated with the cake thickness measurements were higher than the aluminum oxide particulate cakes. The coefficient of variation (COV) of local cake thickness varied from 9.2 to 48.2% (average COV=31.2%) leading to a variation of 2.5 to 33.3% in the porosity estimation (Table 4.3). As shown in Figure 4.6 the corresponding R_c values were much lower than the theoretical R calculated using equation (2.17).

Table 4.3 : Measured particles size, geometric standard deviation, specific cake resistance and resistance factors for sodium chloride test aerosol.

RH (%)	d_{mm} (μm)	σ_g	K_2 (s^{-1})	$K_{2Stokes}$ (s^{-1})	R_s	K_{2c} (s^{-1})	$e \pm \text{std. dev}$	R_c
0.5 μm nominal MMD NaCl								
35	0.55	1.61	1741500	383434	4.6	465842	0.80 ± 0.08	3.7
55	0.56	2.20	1097500	371405	3.0	684888	0.77 ± 0.12	1.6
65	0.63	1.97	867000	301105	2.9	536675	0.60 ± 0.20	1.6
1.0 μm nominal MMD NaCl								
35	1.21	1.95	571250	90596	6.3	203518	0.72 ± 0.08	2.8
55	1.45	1.72	434500	64354	6.8	108271	0.64 ± 0.06	4.0
67	2.12	2.20	380165	31101	12.2	113320	0.78 ± 0.02	3.4

Figure 4.4 : Measured pressure drop versus areal density for 0.5 μ m nominal MMD NaCl at different humidities.

Figure 4.5 : Measured pressure drop versus areal density for 1.0 μm nominal MMD NaCl at different humidities.

Figure 4.6 : Comparison of experimental and theoretical resistance factor, R_c for hygroscopic sodium chloride.

4.3.4 Results of Hygroscopic Tests Above Deliquescent Point

Above the deliquescent humidity the pressure drop increases linearly with mass loading in the very early stages of mass loading, approximately up to 0.0006 g.cm^{-2} . The K_2 values computed from the linear portion of the curves are equal to 370875 and 381625 (s^{-1}) at the humidities of 80% and 90% respectively for the larger NaCl droplets whereas for the smaller NaCl droplets they are equal to 515125 and 516950 (s^{-1}) respectively at the two humidities. When compared to the K_2 values for solid NaCl particles (below the deliquescent point), these values are of the same order of magnitude (Table 4.3). Furthermore, the calculated K_2 values are smaller for the larger NaCl droplets as compared to the values for the smaller NaCl droplets indicating a size effect similar to the solid particles. However, with continued loading the pressure drop increase becomes non-linear, and this is shown for measurements at 80% and 90% humidities in Figures 4.7 to 4.10 for the $0.5 \text{ }\mu\text{m}$ and $1.0 \text{ }\mu\text{m}$ MMD dry size NaCl particles respectively. Due to the overall non-linearity of pressure drop with mass loadings the specific cake resistance, a constant K_2 , is not defined. Moreover, at humidities above the deliquescent point, the aerosol is in the form of droplets, which on collection, percolate into the filter due to capillary action rather than forming a cake. Inside the filter these droplets start filling up the interstitial spaces between the filter fibers. With continued filling of the interstitial spaces, the pressure drop increases non-linearly and finally reaches a maximum when the interstitial space is completely filled. The results in Figures 4.7 to 4.10 indicate that this non-linearity or sudden increase in pressure drop is initiated at lower mass loadings for humidities closer to the deliquescent point. The size of the droplet at humidities above the deliquescent point is determined by liquid-vapor equilibrium considerations. If the initial particle size (dry) is same, the concentration of the droplet solution is lower

at higher humidities (droplet size larger at higher humidities). Thus, at a lower humidity, the surface tension of the droplet is higher and consequently, resistance to percolation into the filter interstitial spaces is also higher due to reduced capillary action. As a result of reduced capillary action, the interstitial spaces near the surface are filled and the non-linearity or the sudden increase in pressure drop is initiated at lower mass loadings for humidities closer to the deliquescent point for the same initial (dry) size of NaCl particles (Figures 4.7 and 4.8, 4.9 and 4.10). For different initial (dry) size NaCl particles (Figures 4.7 and 4.9, 4.8 and 4.10) the solution concentrations are same at the same humidity (dictated by equilibrium conditions) and therefore, according to the above reasoning the initiation of non-linearity should also be at the same mass loading. However, due to differences in the size of the droplets approaching the filter ($3.12\text{ }\mu\text{m}$ in Figure 4.9 compared to $1.26\text{ }\mu\text{m}$ in Figure 4.7) and the flow patterns inside the filter holder, the larger droplets tend to deposit in the central region of the filter whereas the smaller droplets distribute themselves over a larger portion of the filter. Such a deposition pattern of the large droplets delays the complete filling up of the interstitial space, consequently, the sudden increase in the pressure drop is delayed.

Figure 4.8 : Measured pressure drop versus areal density curve for NaCl droplets of 1.62 μm (initial size = 0.5 μm) at 90% RH.

Figure 4.9 : Measured pressure drop versus areal density curve for NaCl droplets of 3.12 μm (initial size = 1.0 μm) at 80% RH.

Figure 4.10: Measured pressure drop versus areal density curve for NaCl droplets of 3.77 μm (initial size = 1.0 μm) at 90% RH.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

(1) A decrease in the specific cake resistance, K_2 , with increasing humidity (from 1% to 100% RH) for the two nominal sizes (0.5 μm and 1.0 μm) of the non-hygroscopic aluminum oxide particles was observed. However, the decrease in K_2 for the 0.5 μm particles was evident only at humidities higher than 90% RH whereas for the 1.0 μm particles the decrease was observed in the entire range of the humidities studied. A similar decrease in K_2 was observed for the two sizes of the hygroscopic NaCl particles at humidities below the deliquescent point (75% RH). Unlike, aluminum oxide, the decrease was continuous for the two NaCl particle sizes. The observed decrease in K_2 suggests that humidity enhances the mass loading capacity of the tested HEPA filter material (glass fiber) for non-hygroscopic and hygroscopic materials at relative humidities below the deliquescent point. These effects are postulated to be due to alterations in the structure of the cake formed under humid conditions. The decrease in pressure drop with mass loading (or decrease of K_2) at elevated humidities is also dependent on the nature of particles (hygroscopicity) and deposition patterns which are size dependent. However, more studies need to be conducted with different non-hygroscopic and hygroscopic materials to quantitatively establish these trends and relate to physical and chemical properties of the aerosol.

(2) Above the deliquescent point the mass loading capacity of the filter is drastically reduced because of the change in the phase of the hygroscopic aerosol particles. At these humidities, the surface tension of the aerosol droplets and their penetration into the filter material are inversely related. Hence, a continuous liquid film over the filter surface is formed at a lower mass loading for humidities closer to the deliquescent point, further reducing the mass loading capacity. Hence, extreme caution must be exercised in predicting the maximum loading of hygroscopic aerosols on filters at humidities above their deliquescent point.

(3) The resistance factor, R , for the particulate cake consisting of non-hygroscopic aluminum oxide particles of either size ($0.5\ \mu\text{m}$ and $1.0\ \mu\text{m}$ MMD) and at all the humidities studied can be estimated by Rudnick-Happel expression with reasonable accuracy. The limitations in the porosity data were more apparent in the case of hygroscopic NaCl where the experimental R and the R calculated using Rudnick-Happel were far apart. To avoid the problems posed by the theoretical approach for predicting K_2 it might be worth while to develop semi-empirical equations relating R with particle size for different types of aerosols frequently subjected to filtration in industry. This eliminates the problem associated with determining an accurate cake porosity.

5.2 Recommendations for Future Work

(1) The results of this study show that the specific cake resistance decreases with increasing humidity for the $1.0\ \mu\text{m}$ MMD non-hygroscopic aluminum oxide and the two sizes (0.5 and $1.0\ \mu\text{m}$ MMD) of hygroscopic NaCl below the deliquescent point. At the same time the change in the specific cake resistance with increasing humidity for the

non-hygroscopic aluminum oxide was evident only after 90% RH. Therefore, more studies need to be conducted with different non-hygroscopic and hygroscopic materials for a complete qualitative and quantitative explanation relating to physical and chemical properties of the aerosol.

(2) The errors associated with the cake porosity estimation can only be eliminated by developing a technique capable of measuring cake porosity in-situ. Such technique will help in the development of more reliable theories pertaining to the cake resistance factor such that cake pressure drop can be predicted using the known properties of the filtered aerosol rather than depending on the simulated experiments.

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APPENDIX - I

Derivation of the Expression for Specific Cake Resistance (K_2)

The drag force (f_d) on a perfectly rigid spherical particle with a Reynolds number less than 1 is given by Stokes law

(I-1)

$$f_d = 3 \pi d \mu V$$

where μ is the gas viscosity, d is the particle size and V is the filtration velocity

To account for the slip between a small particle and the gas medium, Cunningham Slip Correction Factor, C , is often used

$$f_d = \frac{3 \pi d \mu V}{C} \quad (I-2)$$

For "n" identical particles, the total drag is

$$F_T = n f_d = n \left(\frac{3 \pi \mu V d}{C} \right) \quad (I-3)$$

Pressure drop developed due to this drag force

$$\Delta P_{cake} = \frac{F_T}{A} = \frac{1}{A} n \left(\frac{3 \pi \mu V d}{C} \right) \quad (I-4)$$

where A is the filtration area.

The specific cake resistance, K_2 , is defined as

$$K_2 = \frac{\Delta P_{cake}}{V \left(\frac{M}{A} \right)} \quad (1-5)$$

where M is the mass collected on the filter. Using $M = n \pi (d^3/6) \rho_g$ and substituting in equation (1-4) the following expression for K_2 can be arrived at

$$K_2 = \frac{18 \mu}{C \rho_g d^2} \quad (1-6)$$

This expression is valid for a monodisperse particle distribution. If the particles present on the filter are size distributed with "i" size categories containing "n" particles each, then the total drag becomes

$$F_T = \sum F_{d_i} = \sum n_i \left(\frac{3 \pi \mu V d_i}{C} \right) \quad (1-7)$$

Pressure drop developed due to this drag force

$$\Delta P = \frac{F_T}{A} = \frac{1}{A} \sum n_i \left(\frac{3 \pi \mu V d_i}{C} \right) \quad (1-8)$$

Using particle volume (v) instead of size ($d = (v 6/\pi)^{1/3}$) and integrating the above equation for all particle volumes, the following expression for pressure drop can be derived

$$\Delta P = \frac{1}{A} \int_0^{\infty} \left(\frac{3 \pi \mu V}{C} \right) \left(\frac{v}{\pi} \right)^{1/3} n(v) dv \quad (I-9)$$

Further simplifying the equation

$$\Delta P_{cake} = \frac{3 \pi \mu V}{(\pi/6)^{1/3} A} \int_0^{\infty} \frac{v^{1/3}}{C} n(v) dv \quad (I-10)$$

Assuming C to be evaluated at the geometric mean size, equation (I-10) reduces to

$$\Delta P_{cake} = \frac{3 \pi \mu V}{(\pi/6)^{1/3} A} \frac{M_{1/3}}{C} \quad (I-11)$$

where $M_{1/3}$ is the 1/3rd volume moment of the aerosol size distribution. For lognormally distributed aerosols the kth moment, M_k , is expressed in terms of the zeroth moment, M_0 (Biswas et al., 1989)

$$M_k = M_0 v_g^k \exp(4.5 k^2 \ln^2 \sigma) \quad (I-12)$$

Using $k = 1/3$ in equation (I-12) and substituting in equation (I-11) we have

$$\Delta P_{cake} = \frac{3 \pi \mu V M_0}{A (\pi/6)^{1/3} C v_g^{2/3}} \exp(0.5 \ln^2 \sigma_g) \quad (I-13)$$

where v_g is the geometric volume mean and σ_g is the geometric standard deviation.

Physically, M_1 is the total volume of the particles collected on the filter and hence $\rho_p \times M_1$ represents the total mass collected (M) on the filter. Multiplying and dividing the above equation by $\rho_p \times M_1$ gives

$$\Delta P_{cake} = \frac{3\pi\mu V M}{A \rho_p (\pi/6)^{1/3} C} \frac{v_g^{1/3} \exp(0.5 \ln^2 \sigma_g)}{\exp(4.5 \ln^2 \sigma_g)} \quad (I-14)$$

where M_1 is the first aerosol moment and is defined by equation (I-12).

After further simplification equation (I-14) reduces to

$$\Delta P_{cake} = \frac{3\pi\mu V M}{A \rho_p (\pi/6)^{1/3} C} \frac{\exp(-3 \ln^2 \sigma_g)}{v_g^{2/3}} \quad (I-15)$$

Using $d_g = (v_g 6/\pi)^{1/3}$ and the definition of specific cake resistance (equation (I-5)), for a polydisperse aerosol with the slip correction factor evaluated at the geometric mean diameter(d_g), the specific cake resistance, K_{2C} , is given by

$$K_{2C} = \frac{18\mu}{\rho_p d_g^2 C} \exp(-4 \ln^2 \sigma_g) \quad (I-16)$$

where d_g is the geometric mean diameter of the particle size distribution which can be calculated from mass median diameter obtained from impactor data (Hinds, 1982)

$$d_g = d_{mm} \exp(-3.5 \ln^2 \sigma_g) \quad (I-17)$$

Substituting in equation (I-16) we get

$$K_{2C} = \frac{18\mu}{\rho_p d_{mm}^2 C} \exp(3.0 \ln^2 \sigma_g) \quad (I-18)$$

In the limit $\sigma_g \rightarrow 1$ (monodisperse particles), K_{2C} in equation (I-15) approaches $K_{2Stokes}$ in equation (I-6).

APPENDIX-II

Properties of Test Aerosol Materials

Table II-1 : Properties of Hygroscopic Sodium Chloride

Deliquescent Point ¹	75% RH
Crystallization Point ¹	44% RH
Density ²	2.164 (g cm ⁻³)
Source	Fisher Chemicals

Table II-2 : Properties of Non-hygroscopic Aluminum Oxide

Density ²	3.9 (g cm ⁻³)
Morphology ³	Irregular
Source	Fujimi Corporation

¹ Tang et al., 1977

² CRC Handbook of Chemistry and Physics (1976)

³ Fujimi Corporation, Elmhurst, Illinois

APPENDIX - III

Humidifier Calibrations

To calibrate the humidifier (Figure III-1), a water bath was heated to various temperatures and the resulting RH was measured in the sampling chamber. The flow through the bath was set at 0.75 lpm and the flow through the experimental apparatus was set equal to the total actual flow rate of 6.2 lpm. With the bath temperature constant, the RH was recorded as a function of time. The data used for the humidifier calibrations is presented in Table III-1.

Table III-1 : Humidifier Calibration Data (Raw)

Bath Temperature (°F)	Average RH (%)	Average Gas Temperature (°F)
Experiment # 1		
79.0	25.5	74.7
102.0	43.2	72.5
110.5	49.6	72.7
120.5	61.2	72.9
130.0	73.9	73.3
148.0	99.3	73.4
Experiment # 2		
80.0	26.1	68.8
104.0	42.8	69.6
109.5	45.3	70.2
121.0	58.8	70.8
131.0	72.6	70.8
138.0	95.6	68.7
146.0	98.8	69.3
148.0	99.3	73.4

Average RH values from experiment # 2 were extrapolated to the values corresponding to the gas temperature of experiment # 1. These values are presented in Table III-2.

Table III-1 : Humidifier Calibration Data (Corrected)

Bath Temperature (°F)	Extrapolated Avg. RH (%) of # 2	Gas Temperature (°F)
80.0	22.0	74.7
104.0	40.0	73.0
109.5	43.0	72.0
121.0	56.0	73.0
131.0	69.0	73.5
138.0	84.0	73.0
146.0	89.0	73.5

The extrapolated RH values from experiment # 2 and the RH values of experiment # 1 were then plotted as a function of water bath temperature (Figure III-1). An exponential curve fitted the data with a regression coefficient, $R = 0.99$. Reproducibility was found to be $\pm 3\%$ full scale (100% RH) with respect to the fitted curve. The maximum deviation of the humidity measurements about the average for a given temperature was $\pm 3.1\%$.

Figure III-1 : Calibration curve for the humidifier at a total flow rate of 6.2 lpm with 0.75 lpm water bath flow rate. Error bars are set 3 % of full scale.

APPENDIX - IV

TEOM Characteristics

IV.1 Performance of TEOM

The TEOM has been tested for its accuracy and repeatability by various researchers. Whitby et al. (1985) studied the diesel particulate loading between a TEOM and 47mm filtration techniques. They reported that the TEOM typically collected 23 % less mass than the 47 mm filter at a given temperature. Differences in mass determinations were attributed to differences in volatile species retained by the filters. The difference in retention of volatile species by the TEOM filter was attributed to the higher ΔP across the TEOM filter. Otherwise, they found the TEOM instrument capable of measuring the mass collected on the TEOM filter with accuracy and precision essentially on par with gravimetric techniques. Since volatile species were not involved in the present study and the filters and pressure drop were identical, the use of TEOM was justified.

In an another study, Williams and Vinson (1986) compared the TEOM dust monitor with a personal dust sampler. They reported excellent agreement between the TEOM and the personal sampler. Further, they observed that the TEOM performance is affected only if it is used such that the stem oscillations parallel to gravity. In these orientations, the stem oscillations are affected by gravity causing variations in the data. In the present study the TEOM was used upside-down such that stem oscillations were transverse to the gravity as the case would be in the normal position. Therefore, use of the TEOM in an inverted position will not affect the instrument performance. However, to further ascertain the characteristics of the TEOM for the given system and conditions, tests were

conducted in which samples were collected to compare the performance of the TEOM, in an inverted position, with two 47 mm filters. The face velocities in the two 47 mm filter holders were calculated to be 2.6% apart. Therefore, their agreement in measuring the specific cake resistance was expected to be at least 2.6% apart. The experimental deviation in the 47 mm data was found to be 3.14%. After correcting for the variation in the flow rates, the 47 mm specific cake resistance data agreed to within 1.5%. The TEOM measured specific cake resistance was found to deviate 0.7% from the average of the 47 mm data. This adequately demonstrates the viability of a TEOM as the primary filter testing device if identical filter media and media velocities are used, and as long as care is taken to sample representatively and to maintain uniform mass loading across the filter surface. The parameter used in the evaluation is specific cake resistance. The results of this test are tabulated in Table IV-1.

TABLE IV-1 : TEOM Performance Data

	47 mm Filter # 1	TEOM Filter	47 mm Filter # 2
Filtration Area (cm ²)	13.2208	1.2517	12.7329
Mass Deposited (ΔM), (g)	0.1488	0.0151	0.1605
ΔP_{cake} (Pa)	1525.0	1675.0	1762.5
Filtration Velocity, (cm s ⁻¹)	3.0905	3.115	3.1318
$K_2^* = \Delta P / (V \Delta M / A)$, (s ⁻¹)	43840.4	43975.4	44642.9

DATA ANALYSIS

Assumption :47 mm data is representative

$$\begin{aligned} \text{Average } (K_2)_{47 \text{ mm}} &= 44241.7 \text{ s}^{-1} \\ \text{Deviation in 47 mm filters} &= 1.5\% \\ \text{TEOM Deviation} &= 0.7\% \end{aligned}$$

IV.2 TEOM Pressure Transducer Calibrations

The TEOM pressure transducer was calibrated against a water manometer. A series of vacuum levels were applied simultaneously to the combination of water manometer and the pressure transducer. The generated transducer voltage was recorded as a function of applied pressure. At least five voltage readings were taken at a given pressure. The applied pressure was then plotted as a function of voltage. A fifth order polynomial was fitted to the data and the coefficients were incorporated in the TEOM software. This exercise was done a number of times to maintain the accuracy of the pressure transducer throughout the duration of experimentation. Table IV-2 presents a sample set of calibration data and the fitted equation.

Table IV-2 : TEOM Pressure Transducer Calibrations Data

Manometer Reading (wg)	Pressure Transducer Voltage (volts)					
	1	2	3	4	5	Average
0.0	0.003	0.003	0.003	0.003	0.003	0.0030
1.0	0.122	0.122	0.123	0.123	0.123	0.1226
2.0	0.288	0.288	0.294	0.295	0.291	0.2912
3.0	0.477	0.475	0.475	0.474	0.479	0.4760
4.0	0.684	0.687	0.685	0.689	0.687	0.6864
5.0	0.890	0.890	0.887	0.887	0.893	0.8894
6.0	1.133	1.142	1.145	1.139	1.146	1.1410
7.0	1.343	1.344	1.346	1.353	1.347	1.3466
8.0	1.562	1.561	1.571	1.561	1.571	1.5652
9.0	1.755	1.764	1.761	1.761	1.759	1.7600
10.0	1.973	1.963	1.972	1.976	1.967	1.902

Equation of the curve fit is :

$$\Delta P = 2.1254 * 10^{-3} + 8.2965 * v - 5.6428 * v^2 + 3.7364 * v^3 -$$

$$1.0936 * v^4 + 0.11675 * v^5 ; R = 1.0$$

where v is the pressure transducer voltage

APPENDIX - V

Representative Sampling Characteristics of the Sampling System

Tests carried out to evaluate the viability of the TEOM as a primary filter testing device were also designed to test the sampling characteristics of the system. Two 47 mm filter holders were used as the references and were placed on the either side of the TEOM. All three sampled aerosol from a sampling system. In some of the sampling system configurations tested for representative sampling characteristics, particle sampling was assisted by gravity. In these tests the three filters were found to be as much as 13% apart. The parameter used for comparisons was specific cake resistance. The major cause of the disagreement was found to be the non-uniform distribution of particles over the filter surface. Aided by gravity particle agglomerates gained inertia and were not able to follow the diverging streamlines inside the filters holders and were preferentially deposited on the center of the filters. To avoid such deposition pattern, the sampling chamber and the filters were mounted in an inverted configuration (Figure 4) such that the sampling was done against the gravity. By doing so, the particle agglomerates prevented from gaining high inertia and therefore, were more uniformly distributed on the filters as demonstrated by a good agreement (within 0.7%) in the specific cake resistance for the three filters (Table IV-1). Thus, representative sampling was made possible irrespective of the differences in the flow rates through the TEOM and the 47 mm filter holders. Typically, the flow through the TEOM (0.2 lpm) was one order of magnitude lower than the flow through the 47 mm filters (2.3 lpm). The flow through the impactor (5.0 lpm) used for particle size distribution measurements was approximately twice that

through the 47 mm filter. Since the three sampling ports had demonstrated representative sampling characteristics over a the flow range of an order of magnitude, it was reasonable to expect that the impactor sample would also be representative.

APPENDIX - VI

Impactor Mach Number Calculations

The six stage cascade impactor (Intox Products, Model 5B) used for particle size distribution measurements in the study was designed for a flow rate of 5 lpm. Studies by Biswas et al. (1987) observed that most particle size distribution measuring devices tend to be biased while sampling humid aerosols. In an impactor, repeated expansion of the inlet gas stream through the jets causes a decrease in gas temperature and pressure progressively with each stage causing water vapor to condense under high humidity conditions. Specifically, the study reported that if the Mach Number in all the stages can be maintained below 0.005, the bias in particle size measurements due to condensed water droplets would be minimal even at relative humidities exceeding 90%. The Mach Number is highest for the last or the stage having maximum number of jets. For the given impactor, the sixth stage had 40 jets each with a diameter of 0.152 cm. Below are the Mach Number calculations for this stage:

(1) Impactor Flow Rate (Q) = 5.0 lpm

(2) Number of Jets (N) = 40

(3) Diameter of a Jet (D) = 0.0152 cm

(4) Velocity of gas in the jet ($V = 1000Q/(\pi D^2/4)$) = 1377.8 cm s⁻¹

(5) Velocity of Sound @ NTP (V_s) = 343500 cm s⁻¹

(6) Mach Number for the sixth stage (V/V_s) = 0.004

Since the Mach Number is less than 0.005, the bias in the particle size measurements can be considered negligible (Biswas et al., 1987).

APPENDIX - VII

Calculation of MMD from MMAD Data

The *Aerodynamic Particle Diameter* is the diameter of a unit density ($\rho_p = 1$) sphere that has the same settling velocity as the particle. The particle size distribution obtained from a cascade impactor is based on mass median aerodynamic diameter (MMAD) from which mass median diameter (MMD) can be determined by equating the settling velocity expressions with and without the particle density.

$$V_s = \frac{\rho_p \text{MMD}^2 g}{18 \mu} = \frac{\text{MMAD}^2 g}{18 \mu} \quad (\text{VI-1})$$

Equation VI-1 reduces to

$$\text{MMD} = \frac{\text{MMAD}}{\sqrt{\rho_p}} \quad (\text{VI-2})$$

Equation VI-2 was used to convert the observed MMAD's to MMD's used in the analysis.

These values for different tests are presented in Table VII-1.

**Table VII-1 :Calculated MMD's for the Hygroscopic and
Non-Hygroscopic Tests**

RH (%)	MMAD (μm)	MMD (μm)
0.5 μm nominal MMD Aluminum Oxide ($\rho = 3.9 \text{ g cm}^{-3}$)		
1	1.07	0.54
1	1.22	0.62
35	1.05	0.53
35	1.13	0.57
80	1.28	0.65
90	1.36	0.69
95	1.48	0.75
100	1.44	0.73
100	1.24	0.63
1.0 μm nominal MMD Aluminum Oxide ($\rho = 3.9 \text{ g cm}^{-3}$)		
1	1.96	0.99
35	2.62	1.33
35	2.03	1.03
80	2.11	1.07
90	2.21	1.12
100	2.11	1.07
100	2.57	1.30
0.5 μm nominal MMD NaCl ($\rho = 2.164 \text{ g cm}^{-3}$)		
35	0.81	0.55
55	0.82	0.56
65	0.93	0.63
1.0 μm nominal MMD NaCl ($\rho = 2.164 \text{ g cm}^{-3}$)		
35	1.78	1.21
55	2.13	1.45
67	3.12	2.12

APPENDIX VIII

Data used for Cake Porosity Estimation

The data shown in Table VIII has been used to estimate the cake porosities in accordance with the method described in chapter 3 (section 3.3).

Table VIII : Cake Thickness (t_{cake}) and the Porosity Data for the 47 mm Filters

RH (%)	$t_{\text{cake}} \pm \sigma_x$ (cm)	ΔM (g)	V_{cake} (cm ³)	ρ_{cake} (g cm ⁻³)	ϵ
0.5 μm nominal MMD Aluminum Oxide					
1	0.0196 $\pm$ 0.0047	0.0432	0.2496	0.1731	0.95
1	0.0159 $\pm$ 0.0039	0.0443	0.2025	0.2188	0.94
35	0.0122 $\pm$ 0.0024	0.0479	0.1553	0.3084	0.92
35	0.0112 $\pm$ 0.0039	0.0404	0.1426	0.2833	0.93
90	0.0179 $\pm$ 0.0035	0.0511	0.3158	0.1840	0.94
95	0.0295 $\pm$ 0.0061	0.0889	0.3762	0.2363	0.94
100	0.0260 $\pm$ 0.0028	0.1234	0.3311	0.3727	0.90
Average Cake Porosity (ϵ_{AV}) = 0.93					
1.0 μm nominal MMD Aluminum Oxide					
1	0.0131 $\pm$ 0.0020	0.0908	0.1668	0.5444	0.86
35	0.0138 $\pm$ 0.0026	0.0919	0.1757	0.5230	0.86
35	0.0102 $\pm$ 0.0038	0.0772	0.1299	0.5943	0.83
80	0.0183 $\pm$ 0.0047	0.1166	0.2330	0.5004	0.87
90	0.0367 $\pm$ 0.0021	0.1489	0.4673	0.3186	0.92
100	0.0181 $\pm$ 0.0020	0.1412	0.2305	0.6126	0.84
Average Cake Porosity (ϵ_{AV}) = 0.87					
0.5 μm nominal MMD NaCl					
35	0.0095 $\pm$ 0.0037	0.0435	0.1210	0.3595	0.80
55	0.0140 $\pm$ 0.0067	0.0696	0.1783	0.3904	0.77
65	0.0112 $\pm$ 0.0054	0.0925	0.1426	0.6487	0.60
Average Cake Porosity (ϵ_{AV}) = 0.73					
1.0 μm nominal MMD NaCl					
35	0.0161 $\pm$ 0.0044	0.1148	0.2050	0.5600	0.72
55	0.0183 $\pm$ 0.0029	0.1764	0.2330	0.7570	0.64
67	0.0303 $\pm$ 0.0028	0.1850	0.3856	0.4795	0.78
Average Cake Porosity (ϵ_{AV}) = 0.71					

It is clear from Table VIII that the changes in the cake porosity are random and can not be ascribed to the changes in the RH. These changes could be because of the errors associated with the thickness measurements. However it is clearly seen that for a particle material, the porosity varied inversely as a function of particle size. For the non-hygroscopic aluminum oxide, the average porosities of the 0.5 μm MMD and the 1.0 μm MMD particulate cakes were 0.94 and 0.87 respectively, whereas for the two sizes of the hygroscopic NaCl the average porosities were 0.73 and 0.71 respectively. Carr et al. (1969) and Rudnick (1978) also observed a similar inverse relationship between the porosity and particle size.

END

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