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MSC

AEROSOL SAMPLING AND TRANSPORT

TUTORIAL SESSION 9

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Sandia National Laboratories
Albuquerque, NM 87185

Seventh International Aerosol Conference
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St. Paul, MN, USA

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INTRODUCTION

Frequently in aerosol measurement is necessary that an aerosol sample be conveyed to a measurement device. This is accomplished by withdrawing a sample from its environment and transporting it through sample lines to the device. A sample may also be transported to a chamber or bag for storage and subsequent measurement. An aerosol sampling system generally consists of

1. a sample inlet where the aerosol sample is extracted from its ambient environment - the inlet shape and geometry may vary but material will focus on sampling through thin-walled tubes,
2. a sample transport system consisting of the necessary plumbing to convey the aerosol sample to the measuring instrument or to a storage chamber - the components, or flow elements, of the transport system consist of such items as tubes, elbows, and constrictions, and
3. a sample storage volume (though this item is optional and its presence is determined by necessity rather than by choice) that will have an additional sample inlet and transport system to the measuring instrument - the storage volume is usually an inflatable bag that is filled with the aerosol sample over a time scale that is short compared to the time spent measuring the sample.

It is desirable that the aerosol sample be representative of the aerosol in its original environment and not affected by the sampling process. Representative sampling occurs when such characteristics as particle mass and number concentration and size distribution remain unchanged between the point at which the aerosol is sampled and the instrument performing the measurement. Particles do not always make it into the sampling inlet representatively. Particles can be lost from the sample flow by contact with the walls of the sampling system. Inertial, gravitational, and diffusional forces are among the mechanisms that can act to move particles to a wall.

Many of the mechanisms that inhibit representative sampling depend on the aerosol particle size so that a given sampling system may exhibit representative sampling over some range of particle size but not for particles larger or smaller that range. Generally speaking, larger particles are more strongly influenced by gravitational and inertial forces and are more difficult to representatively sample; smaller particles with higher diffusion coefficients are more easily lost to the walls of the sampling system by diffusion. Employing an aerosol sampling system that samples representatively for the particle size range of interest is of paramount importance.

Potential factors that can causing changes in aerosol characteristics during the sampling process or can otherwise contribute to a nonrepresentative sample are:

1. Aspiration efficiency and deposition in the sampling inlet during sample extraction,
2. Deposition during transport through a sampling line or during storage,
3. Extremes (high or low) or inhomogeneity in the ambient aerosol concentration,
4. Agglomeration of particles during transport through the sampling line,
5. Evaporation and/or condensation of aerosol material during transport through the sampling line,
6. Reentrainment of deposited aerosol material back into the sample flow, and
7. High local deposition causing flow restriction or plugging.

The following material will address only the first two items in any detail. The other items are addressed elsewhere in the literature and have been briefly reviewed by Brockmann (1993).

Aerosol Parameters

The representative extraction and transport of an aerosol sample is inhibited by loss and deposition mechanisms that are driven by gravitational, inertial, and diffusive forces. The aerodynamic equivalent diameter, D_{ae}, of a particle is appropriate when deposition is driven by gravitational or inertial forces. This is the diameter of a sphere of unit specific gravity that has the same terminal settling velocity as the particle. Correlations describing this type of deposition are often functions of the particle terminal settling velocity, V_{ts}, the particle Stokes number, Stk, and flow Reynolds number, Re.

$$V_{ts} = \tau g \tag{1}$$

$$Re = \frac{\rho U d}{\mu} \tag{2}$$

$$\tau = \frac{\rho_0 D_{ae}^2 C(D_{ae})}{18 \mu} \tag{3}$$

$$Stk = \frac{\tau U}{d} \tag{4}$$

where

τ	= particle relaxation time
ρ_0	= density of water
D_{ae}	= particle aerodynamic diameter
$C(D_{ae})$	= slip correction factor
g	= gravitational acceleration
U	= characteristic gas velocity
d	= characteristic system dimension
ρ	= gas density
μ	= gas absolute viscosity

The mobility equivalent, or diffusion equivalent, diameter, D_B, of a particle is appropriate when deposition is driven by diffusive forces. This diameter is the diameter of a sphere with the same diffusivity as the particle. Correlations describing diffusive deposition of particles are functions of the particle diffusion coefficient, D.

$$D = kTB \quad (5)$$

$$B = \frac{C(D_B)}{3\pi\mu D_B} \quad (6)$$

where

k = Boltzmann's constant
T = gas absolute temperature
B = particle dynamic mobility

The Stokes number is the ratio of the particle stopping distance (a measure of how quickly a particle can accommodate itself to a flowing gas) to the characteristic dimension of the flow geometry. The inertial behavior of particles is characterized by the Stokes number. Particles with large stopping distances have high inertia and large Stokes numbers. Representative sample extraction and transport becomes more difficult for larger particles because their higher inertia makes them less susceptible to influence by the sample flow.

Calibration

Ideally, a sampling system should be calibrated for aerosol sampling and transport efficiency fully assembled under the conditions in which it will be operating at the gas flows and over the size range of interest. Calibration of component sections at operational conditions is often adequate. Calibration at other than operational conditions may be sufficient if it demonstrates that the system or component behaves consistently with models or correlations from the literature which are then employed to predict performance at operational conditions.

In some circumstances, a user may not have the means for aerosol calibration. Use of a specified sampling protocol or use of calibration data found in the literature for some of the commercial samplers or for components in the sampling system may be adequate to assure that operation will be in a range with acceptable sampling efficiency for the user's application.

In designing or evaluating the performance of an aerosol sampling system, the sampling efficiency can be estimated when the system is made up of components that have well characterized efficiency data and models available in the literature. Uncertainty in the estimate of the actual sampling efficiency increases when estimated sampling efficiency is much different from 100 percent. There is always the danger that the sampling system contains some uncharacterized element that introduces uncertainty in the estimated performance.

SAMPLE EXTRACTION

An aerosol sample is extracted from its environment into an inlet for transport to the measuring instrument. Drawing a representative aerosol sample into an inlet is not trivial. The velocity and direction of the gas from which the sample is being drawn, the orientation of the aerosol sampling probe,

the size, geometry, and shape of the inlet, the velocity of the sample flow, and the particle size are important factors in how representative an extracted sample is. In extracting a sample, a particle must be sufficiently influenced by the sample gas flow to be drawn into the inlet. The particle must also be transported through the inlet without being deposited in the inlet. Particle inertia and gravitational settling are impediments to representative sample extraction and representative sampling is more difficult with increasing aerodynamic particle size.

The aspiration efficiency, η_{asp}, of a given particle size is defined as the ratio of the concentration of the particles of that size in the gas entering the inlet to their concentration in the ambient environment from which the sample is taken. The transmission efficiency, η_{trans}, of a given particle size is defined as the fraction of aspirated particles of that size that are transmitted through the inlet to the rest of the sampling system. The inlet efficiency, η_{inlet}, is the product of the inlet and transmission efficiencies and is the fraction of the ambient concentration that is delivered to the aerosol transport section of the sampling system by the inlet.

$$\eta_{inlet} = \eta_{asp}\ \eta_{trans} \tag{7}$$

These efficiencies are dependent upon the ambient gas velocity, U_0, the inlet geometry, size, and position, the sampling gas velocity, U, and the particle's aerodynamic diameter, D_{ae}.

This material addresses sampling through a thin-walled nozzle. This nozzle is an idealized sampling nozzle which does not disturb ambient flow and which has no rebound of particles from the leading edge into the nozzle. Sampling with a thin-walled nozzle has received more extensive study than sampling with blunt samplers or a thick-walled nozzle has. For practical usage, a nozzle can be regarded as "thin-walled" when the ratio of its external to internal diameter is less than 1.1 (Belyaev and Levin 1972).

Sampling from still air and from a flowing gas is considered for constant sample flows. In the case of sampling from a flowing gas, the sampling nozzle is iso-axial, that is, the axis of the nozzle is aligned to the direction of the ambient gas velocity so that the gas flows into the opening of the nozzle.

Ambient free stream gas velocity variations may be beyond the control of the user because of flow adjustments or conditions in the duct from which the sample is being drawn. This situation is commonly encountered. Under these conditions, one may sample at a constant sample flow rate over the range of free stream flows and note the largest particle size for which representative sampling still occurs over this range. The measurements made with this sampling system would need to disregard particles larger than this noted size since their sampling efficiency would be effectively unknown. This is a similar approach to that used in ambient sampling but may not be optimized for large particles. One may develop an inlet along the lines of an ambient air sampler to optimize performance for larger particles over a wide range of free stream velocities. This has been done by McFarland and co-workers (McFarland et al. ,1988; Fan et al., 1992; and Chandra and McFarland, 1997) in which they present a shrouded aerosol sampling probe that representatively samples 10 μm and smaller particles from duct flow ranging from 2 to 14 meters per second.

In efficiently extracting a sample, the sampling gas velocity must be low enough so that the sampled particle can accommodate itself to the sampling gas flow within a distance comparable to the inlet diameter. This is an inertial condition. The sampling gas velocity must also be high enough so that

the sampled particle does not settle appreciably in the time that sampling occurs. This is a gravitational settling condition (Davies 1968).

In sampling from a flowing gas with a nozzle it is implicitly assumed that the flow velocities are large compared to the settling velocity of the particles being sampled, that is, that the gravitational settling condition is met. Grinshpun et al. (1990) point out that in low velocity sampling, the aspiration efficiency will depend on the ratio of settling velocity to ambient gas velocity. It is prudent to determine the ratio of particle settling velocity to ambient gas velocity for the particle size of interest to assure that the gravitational settling condition is met.

Sampling is said to be isokinetic when it is isoaxial and the mean sample flow velocity through the face of the inlet is equal to the gas flow velocity. Strictly speaking, the term isokinetic applies only to laminar flow in the ambient free stream. The more general term, iso-mean-velocity, is applicable to both laminar and turbulent flow conditions in the free stream. Convention, however, applies the term isokinetic to both flow regimes. The conventional terminology is employed here but one should be aware of the distinction. Sampling with a sampling velocity not equal to the gas velocity is anisokinetic (aniso-mean-velocity) sampling. When the sampling velocity is higher than the gas velocity, the sampling is super-isokinetic (super-iso-mean-velocity) and when the sampling velocity is lower than the gas velocity, the sampling is sub-isokinetic (sub-iso-mean-velocity).

In isokinetic sampling, gas flows directly into the nozzle without deviation. In this case, aspiration efficiency is 1 (100 percent). Transmission losses arise from gravitational settling inside the nozzle (Okazaki, Wiener, and Willeke 1987b) and from Saffman lift forces in the developing boundary layer in the nozzle (Anand, et al. 1992). Losses in the inlet can also be caused by free stream turbulence (Wiener, Okazaki, and Willeke 1988) in which the particles' lateral motion caused by the turbulence causes them to impact the inlet internal wall.

In sub-isokinetic sampling, the gas flow must diverge into the nozzle. Particles with sufficient inertia can cross the streamlines to be aspirated by the nozzle. In this case the aspiration efficiency is 1 or more for all particles; increasing from 1 to a limit of (U_0/U) for larger particles. Transmission losses arise 1.) from the gravitational settling in the nozzle (Okazaki, Wiener, and Willeke 1987b), 2.) from free stream turbulent effects (Wiener, Okazaki, and Willeke 1988), 3.) from inertial impaction on the inner wall of the nozzle by particles with velocity vectors toward the wall caused by the expanding streamlines (Liu, Zhang, and Kuehn 1989), and 4.) from Saffman lift forces in the developing boundary layer in the nozzle (Anand et al. 1992).

In super-isokinetic sampling the gas flow must converge from the ambient free stream flow into the nozzle. Particles with sufficient inertia can cross streamlines and not be aspirated by the nozzle. In this case aspiration efficiency is 1 or less for all particles; decreasing from 1 to a limit of (U_0/U) for larger particles. Transmission losses arise 1.) from the gravitational settling in the nozzle (Okazaki, Wiener, and Willeke 1987b), 2.) from free stream turbulent effects (Wiener, Okazaki, and Willeke 1988), 3.) from turbulent deposition of particles in the vena contracta formed in super-isokinetic sampling (Hangal and Willeke 1990b), and 4.) from Saffman lift forces in the developing boundary layer in the nozzle (Anand et al. 1992).

Sampling From Flowing Gas With a Thin-Walled Nozzle

The correlations for aspiration efficiency and transmission efficiency are listed below along with

their equation numbers and the conditions for which they apply.

η_{asp}	Aspiration efficiency for isoaxial sampling (8)
$\eta_{trans,\ inert}$	Transport efficiency for inertial deposition in sub-isokinetic isoaxial sampling (11), super-isokinetic isoaxial sampling (12)
$\eta_{trans,\ lift}$	Transportation efficiency for lift force deposition in isoaxial sampling (13)
$\eta_{trans,\ grav}$	Transport efficiency for gravitational settling in the inlet region of a nozzle uses the expression for settling in a tube. It is implicit that the ambient free stream gas velocity and the sample gas velocity remain constant over the period of sampling for the correlations to apply. The reader is cautioned that the following correlations apply only to conditions of constant gas velocities.

For isoaxial sampling where the ambient gas stream velocity is U_0 and the sampling velocity is U, the well known correlation of Belyaev and Levin (1972, 1974) for aspiration efficiency, η_{asp}, has proven satisfactory with an accuracy to within 10 percent. The range of applicability has been extended by other investigators (Stevens, 1986; Lipatov et al., 1986; and Rader and Marple, 1988).

$$\eta_{asp} = 1 + \left[\frac{U_0}{U} - 1\right]\left[1 - \frac{1}{1 + k\,Stk}\right] \qquad (8)$$

$$\text{for } 0.005 \le Stk \le 10 \text{ and } 0.2 \le \frac{U_0}{U} \le 5$$

where

$$Stk = \frac{\tau U_0}{d} \qquad (9)$$

$$k = 2 + 0.617\left[\frac{U_0}{U}\right]^{-1} \qquad (10)$$

U_0 = ambient gas velocity

U = sampling gas velocity

Vincent et al. (1986) have developed a correlation for aspiration efficiency at sampling angles from 0 to 90 degrees using the general form of equation (8). The isoaxial form yields a constant value of 2.1 for k that, over the range of applicability, is within 3% of Belyaev and Levin.

Particles are deposited in the nozzle inlet by gravitational settling, by inertial effects, and by lift

effects. The particle losses in the nozzle are accounted for by the transmission efficiency.

Okazaki, Wiener, and Willeke (1987a and 1987b) assume that a particle that has penetrated into the boundary layer formed in the entrance region of the inlet will deposit by gravitational settling on the inside wall of the inlet. Yamano and Brockmann (1989) point out that correlations for gravitational settling in tubes are adequate to estimate the inlet losses due to gravitational settling.

Inertial losses have been examined by Liu, Zhang, and Kuehn (1989) and by Hangal and Willeke (1990b) In the case of (U_0/U) greater than 1 (sub-isokinetic sampling), some particles with velocity vectors directed toward the nozzle walls are deposited and the transmission efficiency is less than 1 (Liu, Zhang, and Kuehn 1989). Liu, Zhang, and Kuehn (1989) give an inertial transmission efficiency, $\eta_{trans,\ inert}$, for sub-isokinetic isoaxial sampling of

$$\eta_{trans,\ inert} = \frac{1 + \left[\frac{U_0}{U} - 1\right] \Big/ \left[1 + \frac{2.66}{Stk^{2/3}}\right]}{1 + \left[\frac{U_0}{U} - 1\right] \Big/ \left[1 + \frac{0.418}{Stk}\right]} \qquad (11)$$

$$\text{for } 0.01 \le Stk \le 100 \text{ and } 1 < \frac{U_0}{U} < 5$$

Hangal and Willeke (1990b) assume no inertial transmission losses for sub-isokinetic isoaxial sampling.

Hangal and Willeke (1990b) maintain that in super-isokinetic sampling a vena contracta is formed in the nozzle inlet and that turbulence in the vena contracta will deposit particles contained in it. They give an inertial transmission efficiency for super-isokinetic sampling as

$$\eta_{trans,inert} = \exp\left[- 0.61 \left[Stk \frac{U - U_0}{U_0} \right]^{0.6} \right] \qquad (12)$$

$$\text{for } 0.02 \le Stk \le 4 \text{ and } 0.25 \le \frac{U_0}{U} < 1$$

Liu, Zhang, and Kuehn (1989) assume no inertial transmission losses for super-isokinetic isoaxial sampling.

Fan, McFarland, and Anand (1993) suggest that Saffman lift forces on particles decelerating in the boundary layer of the inlet can cause them to be deposited on the walls. Anand et al. (1993) give an expression for the inlet transmission efficiency considering the losses from the Saffman forces.

$$\eta_{trans,\ lift} = 1 - \frac{1.769}{\left[1 + \frac{g\,L}{U^2}\right]^{9.19}} \frac{R_s (D_p)^{0.559}}{Re^{0.216}} \qquad (13)$$

$$Pl = 0.3246 \frac{\frac{\rho_0}{\rho} D_{ae}}{\sqrt{2\nu \frac{U}{d}}} \frac{U}{d} \quad (14)$$

$$R_S(D_p) = \frac{4\,Stk}{\sqrt{Pl}} \quad (15)$$

where

L = the length of the nozzle
ν = kinematic viscosity of the gas

The Hangal and Willeke(1990b) correlation the Anand et al. (1993) correlation are based on data and the two may be describing the same phenomena. It is not immediately clear which correlations to use. Fan et al. (1992) indicate that these two correlations are close in the range of windspeed from 5 to 10 m/sec. It is recommended that either the inertial deposition expressions or the Saffman lift expression be used to estimate inlet transmission efficiency.

Free Stream Turbulence Effects

The limited amount of research on the effects of free stream turbulence in sampling with thin-walled nozzles seems to indicate that there is little effect on the isoaxial aspiration efficiency (Rader and Marple 1988; Vincent, Emmett, and Mark 1985). Wiener, Okazaki, and Willeke (1988) note that although there does appear to be little effect on the aspiration efficiency, there is a measurable effect on the transmission efficiency that can increase or decrease deposition in the nozzle inlet. Larger nozzle inlets (on the order of a centimeter in diameter) were less susceptible to these effects. They observed that for Stokes number less than 1 and turbulence intensity less than 7.5%, the spread in sampling efficiency caused by turbulence was less than 15%. This is on the order of the uncertainty in the sampling efficiency correlations.

Summary

The inlet efficiency for sampling with a thin-walled nozzle depends on the Stokes number based on ambient gas velocity and the nozzle inlet diameter, the ratio of ambient gas velocity to sampling gas velocity, and the sampling angle. To obtain a representative sample, the sampling should be isoaxial and isokinetic (iso-mean-velocity) and the Stokes number ($\tau U_0/d$) should be kept small. The ambient free stream and sampling gas velocities should be large compared to the particle settling velocity. Larger inlet diameters (on the order of a centimeter) are less susceptible to deposition caused by free stream turbulence.

Sampling in Calm Air

Davies (1968) points out that in sampling from calm air with a small tube at an arbitrary orientation, two conditions must be met for representative sampling. The first is an inertial condition to assure that particles are drawn into the nozzle. This is expressed as

$$\mathrm{Stk} \le 0.016$$

$$\frac{V_{ts}}{U} \le 0.04 \qquad (16)$$

Where the Stokes number is based on the average inlet sampling velocity, U, and the inlet diameter, d. The second is a particle settling velocity condition to assure that the orientation of the nozzle has no influence on sampling. This is expressed in terms of the ratio of settling velocity to sampling velocity.

These two conditions constitute the Davies criterion for representative sampling through a tube in arbitrary orientation. This criterion has proven to be a sufficient condition for representative sampling.

Agarwal and Liu (1980) have established a somewhat more relaxed criterion than Davies. They have developed a theoretical prediction based on solution of the Navier-Stokes equations for the flow field around an upward facing inlet and calculation of the particle trajectories and sampling efficiencies. Their prediction is supported by the experimental results of a number of researchers. The Agarwal and Liu criterion for accurate sampling (a sampling efficiency of 90% or higher) with an upward facing nozzle is

$$\mathrm{Stk}\,\frac{V_{ts}}{U} \le 0.05$$

$$\frac{\tau V_{ts}}{d} \le 0.05 \qquad (17)$$

This criterion depends on particle relaxation time, τ, particle settling velocity, V_{ts}, and nozzle diameter, d, only; it does not depend on the sampling flow velocity. Agarwal and Liu (1980) note that the experimental data indicate a dependence on the sampling gas velocity but that at higher sampling efficiencies this dependence is reduced and the criterion is adequate. Grinshpun et al. (1990) have reviewed work on sampling from calm air. They present data for $V_s' = V_{ts}/U \ge 0.005$ and $\mathrm{Stk} \ge 2.5$ that show lower efficiencies than Agarwal and Liu (1980) would indicate. Grinshpun et al. (1990) point out that though the Agarwal and Liu (1980) analysis is qualitatively correct, it is a first order approximation. The supporting experimental data of Agarwal and Liu (1980) fall in a region in which (V_{ts}/U) is less than about 10^{-3} and Stokes number is less than about 1000. These data are outside of the Grinshpun et al. (1990) data range. This would suggest that the use of the Agarwal and Liu (1980) criterion might not apply for values of (V_{ts}/U) greater than 10^{-3} when Stokes number is larger than about 1000.

Grinshpun, Willeke, and Kalatoors (1993) give an empirical equation for the sampling efficiency of a sharp edged round inlet with the inlet axis oriented at angle φ with respect to gravity ($\varphi = 0°$ is upward facing, $\varphi = 90°$ is horizontal)

$$\eta_{asp,\,calm\,air} = \frac{V_{ts}}{U}\cdot\cos(\varphi) + \exp\left[-\frac{4Stk_i^{1+\sqrt{\frac{V_{ts}}{U}}}}{1+2Stk_i}\right] \tag{18}$$

for $0° \le \varphi \le 90°$, $10^{-3} \le V_{ts}/U \le 1$ and $10^{-3} \le Stk_i \le 100$

The first term on the right addresses the effect of gravitational settling of particles directly into the sampling nozzle. For vertical sampling, $\varphi = 0°$, it accounts for the enhancement of particles settling into the upward facing nozzle and for horizontal sampling, $\varphi = 90°$, this enhancement is gone. The second term on the right hand side of the equation addresses the other combined inertial and gravitational effects and is independent of orientation.

For vertical sampling, we can specify a criterion for greater than 95% sampling efficiency (greater than 100% in some cases) that relates the inlet size and flow

$$\frac{U^2}{g\cdot d} \le 1 \tag{19}$$

where U is the sample velocity, d is the inlet diameter, and g is the gravitational acceleration.

Summary

The Davies criterion is stringent and applies to any nozzle orientation. The Agarwal and Liu criterion is more relaxed and is supported by experimental data for $V_{ts}/U \le 10^{-3}$ and Stk $\le$ about 1000. However, this criterion is for an upward facing nozzle and its use for other nozzle orientations is not recommended. The Grinshpun et al. correlation is useful for a more exact calculation of the aspiration efficiency.

SAMPLE TRANSPORT

Transport of the aerosol sample through sample lines from the inlet may be directly to the measurement instrument or into a temporary storage volume for subsequent transport to instruments via sample lines. These sample lines may contain bends, inclines, contractions, and other flow elements; flow

may be laminar or turbulent. Deposition of particles during residence in a bag and during transport will alter the characteristics of the aerosol reaching the measurement instrument. Other phenomena that will change the characteristics of the aerosol in the sample flow are particle growth by agglomeration or condensation, particle evaporation, and reentrainment of previously deposited material into the sample flow. These other phenomena are briefly discussed later; sample transport will address aerosol deposition.

During transport through the sampling line or residence time in a storage in a chamber, particles are lost by various deposition mechanisms. The more common ones that will be discussed in this section are listed below.

1. Gravitational settling
2. Diffusional deposition
3. Turbulent inertial deposition
4. Inertial deposition at a bend
5. Inertial deposition at flow constrictions
6. Electrostatic deposition
7. Thermophoretic deposition
8. Diffusiophoretic deposition

The transport efficiency for a given particle size, through a given flow element, being acted on by a given deposition mechanism, $\eta_{\text{flow element, mechanism}}$, is defined as the fraction of those particles entering the flow element that are not lost by that deposition mechanism during the transit of that flow element. The total transport efficiency, $\eta_{\text{transport}}$, for a given particle size is the product of the transport efficiencies for each mechanism in each flow element of the sample transport system for that particle size.

$$\eta_{\text{transport}} = \prod_{\substack{\text{flow} \\ \text{elements}}} \prod_{\text{mechanisms}} \eta_{\text{flow element, mechanism}} \tag{20}$$

The sampling efficiency, η_{sample}, is the product of the inlet and total transport efficiencies.

$$\eta_{\text{sample}} = \eta_{\text{inlet}}\, \eta_{\text{transport}} \tag{21}$$

Correlations for the transport efficiencies for various mechanisms operating in various flow elements are presented below so that the reader can estimate the total transport efficiency for a sampling system. In the following review of particle deposition during transport, the sampling lines are assumed to be tubes of circular cross section.

The mechanisms and flow elements in which they occur for which correlations are given in this section are listed below along with the equation number.

$\eta_{\text{tube, grav}}$	Gravitational settling in sample lines for laminar flow (22) turbulent flow (25)
$\eta_{\text{tube, diff}}$	Diffusional deposition in sample lines for laminar flow (27 and 26 or 30) turbulent flow (29 and 26)

$\eta_{\text{tube, turb inert}}$	Turbulent inertial deposition in sample lines for turbulent flow (31)
$\eta_{\text{bend, inert}}$	Inertial deposition in sample line bends for laminar flow (36 or 37) turbulent flow (38)
$\eta_{\text{cont, inert}}$	Inertial deposition in contraction for laminar flow (39 or 40)
$\eta_{\text{tube, th}}$	Thermophoretic deposition in sample lines for turbulent flow (44 and 41)
$\eta_{\text{tube, dph}}$	Diffusiophoretic deposition in sample lines for turbulent flow(45 and 46)
$\eta_{\text{bag, grav diff}}$	Combined gravitational and diffusional deposition in a storage chamber with a well mixed volume (48 and 47)

This is by no means an exhaustive list but it covers conditions commonly encountered in aerosol transport.

Gravitational Settling in Sampling Lines

Particles settle due to gravitational force and deposit on the lower wall of nonvertical lines in a sampling system during transport. Correlations for gravitational settling and deposition under various tube orientations and flow conditions are available.

For laminar flow in a straight horizontal tube with circular cross section, Natanson (Fuchs 1964) and Thomas (1958) independently solved the problem of gravitational settling by assuming a parabolic flow distribution. Heyder and Gebhart (1977) modified this result to obtain an expression for gravitational settling from laminar flow in a circular inclined tube which is in good agreement with their experimental results. This can be used as the general correlation for the transport efficiency, $\eta_{\text{tube, grav}}$, for gravitational deposition from laminar flow in a circular tube.

$$\eta_{\text{tube, grav}} = 1 - \frac{2}{\pi}\left[2\kappa\sqrt{1-\kappa^{2/3}} - \kappa^{1/3}\sqrt{1-\kappa^{2/3}} + \arcsin(\kappa^{1/3})\right] \tag{22}$$

$$\kappa = \frac{3}{4} Z \cos(\theta) = \frac{3}{4}\frac{L}{d}\frac{V_{ts}}{U}\cos(\theta)$$

$$Z = \frac{L}{d}\frac{V_{ts}}{U} \tag{23}$$

where

$Z =$	gravitational deposition parameter
$V_{ts} =$	particle settling velocity
$U =$	average gas velocity in the tube
$L =$	length of the tube

d = inside diameter of the tube
θ = angle to horizontal of tube incline

for

$$\frac{V_{ts}\sin(\theta)}{U} << 1 \qquad (24)$$

The criterion expressed in equation (24) states that the axial component of a particle's settling velocity should be small compared to the average gas velocity in the tube. The transport efficiency for gravitational settling from laminar flow in a vertical tube is given by equation (22) as 1 (100 percent). There is no horizontal area on which particles will deposit by gravitation in a vertical tube. The criterion expressed in equation (24) must still be kept in mind to avoid situations in sampling in which the sample gas flow is not high enough to convey the particles through a vertical sampling line.

Another consideration in laminar flow in a vertical tube is the Saffman force which can drive particles toward the wall in downward flow or from the wall in upward flow (Saffman 1965 and 1968). This force arises from the lift on a spherical particle produced by the velocity gradient in the boundary layer and leads to particle motion across stream lines. Lipatov, Grinshpun, and Semenyuk (1989) and Lipatov, Semenyuk, and Grinshpun (1990) discuss this effect. It appears to be noticeable for particles on the order of 15 μm and increases with increasing magnitude of velocity gradient and particle size.

In the case of turbulent flow in a tube, gravitational settling loss is assumed to occur from a well-mixed volume through the boundary layer. Transport efficiency, $\eta_{tube,grav}$, with the modification for incline, is expressed as (Schwendiman, Stegen, and Glissmeyer 1975)

$$\eta_{tube,\,grav} = \exp\left[-\frac{4\,Z\cos(\theta)}{\pi}\right] = \exp\left[-\frac{d\,L\,V_{ts}\cos(\theta)}{Q}\right] \qquad (25)$$

where

Q = volumetric flow rate of gas through the tube.

Criterion equation (24) is also applicable in this case as in the case of laminar flow and the same caveats with respect to vertical flow apply.

Transport efficiency through a tube at incline θ with gravitational settling for both laminar and turbulent flow conditions give essentially the same results for transport efficiencies greater that 0.5. An implication of this is that for a given tube diameter and length, the higher the flow, the lower the loss from gravitational settling. For both laminar and turbulent flow, gravitational deposition depends on the parameter $Z\cos(\theta) = ((V_{ts}L)/(Ud))\cos(\theta) = (\pi d V_{ts}L/(4Q))\cos(\theta)$. Decreasing Z yields higher transport efficiency; Z can be decreased by decreasing the transport length, L, by increasing the volumetric flow, Q, by decreasing the tube diameter for a given volumetric flow, and by increasing the inclination angle of the tube, θ.

Diffusion in Sampling Lines

Small particles undergoing Brownian motion will diffuse from high particle concentration to low particle concentration. The wall of a tube acts as a sink for these diffusing particles and the concentration at the wall is taken as zero; particles will diffuse toward a wall and be deposited there. In tube flow, transport efficiency with diffusive particle loss, $\eta_{tube,diff}$, may, in general, be expressed as

$$\eta_{tube,\ diff} = \exp\left[- \frac{\pi d L v_{diff}}{Q} \right] = \exp[-\xi Sh] \tag{26}$$

where

v_{diff} = deposition velocity for particle diffusion loss to the wall
Sh = Sherwood number

The diffusive deposition velocity, v_{diff}, also called the mass transfer coefficient, can be determined from the available heat and mass transfer correlations. The Sherwood number ($Sh = v_{diff}d/D$) is a dimensionless mass transfer coefficient that contains the diffusive deposition velocity in the definition. The Sherwood number is correlated with Reynolds number ($Re = \rho Ud/\mu$) and Schmidt number ($Sc = \mu/(\rho D)$) for both laminar and turbulent tube flow. Holman (1972) gives for laminar flow

$$Sh = 3.66 + \frac{0.0668 \frac{d}{L} Re\, Sc}{1 + 0.04 \left[\frac{d}{L} Re\, Sc \right]^{2/3}} \tag{27}$$

$$= 3.66 + \frac{0.2672}{\xi + 0.10079 \xi^{1/3}}$$

$$\xi = \frac{\pi D L}{Q} \tag{28}$$

where

D = particle diffusion coefficient
L = tube length
Q = volumetric flow rate through the tube

For turbulent flow, Friedlander (1977) gives

$$Sh = 0.0118\ Re^{7/8}\ Sc^{1/3} \tag{29}$$

The diffusional deposition velocity can be determined from the appropriate correlation above and used in equation (26) to compute the transport efficiency for tube flow in which particles are being deposited by diffusion.

This expression for the laminar flow case gives very good agreement with the analytic solution by

Gormley and Kennedy (1949) for diffusional deposition from laminar tube flow. The well known formulation of Gormley and Kennedy (1949) for transport efficiency in laminar tube flow for particles undergoing diffusive deposition is

$$\eta_{tube,diff} = 1 - 2.56\xi^{2/3} + 1.2\xi + 0.177\xi^{4/3} \quad \text{for } \xi < 0.02$$

$$\eta_{tube,diff} = 0.818\exp(-3.657\,\xi) + 0.097\exp(-22.3\,\xi) + 0.032\exp(-57\,\xi) \quad \text{for } \xi > 0.02 \tag{30}$$

Calculated results from equations (27) and (26) and the Gormley and Kennedy solution in equation (30) differ by only a few percent over the range of interest.

In diffusive deposition from laminar flow, the transport efficiency is a function only of $\xi = \pi DL/Q$. There is no dependence on tube diameter. To increase transport efficiency, ξ should be kept small by keeping the transport distance, L, small or by increasing the flow rate, Q.

Examination of the ξSh term for turbulent flow in equation (26) shows that transport efficiency in turbulent flow is not strongly dependent on flow rate, Q. Decreasing the transport distance, L, or increasing the tube diameter, d, will act to increase the transport efficiency.

Turbulent Inertial Deposition in Sampling Lines

Turbulent inertial deposition occurs when the turbulence in the central region of the pipe flow propels a particle into the laminar sublayer of the turbulent boundary layer. If the particle's inertia is sufficiently high, it will fully penetrate the sublayer and be collected on the wall.

Transport efficiency, $\eta_{tube,\,turb\,inert}$, in a tube with turbulent inertial deposition of particles using the turbulent inertial deposition velocity, v_t, is expressed as

$$\eta_{tube,\,turb\,inert} = \exp\left[-\frac{\pi d L v_t}{Q}\right] \tag{31}$$

Liu and Agarwal (1974) found that the dimensionless turbulent deposition velocity, v_+, increases rapidly with increasing dimensionless particle relaxation time, τ_+, reaching a peak of 0.14 at a τ_+ value of approximately 30. Above $\tau_+ = 30$, v_+ shows only a moderate dependence on τ_+ decreasing to 0.085 at $\tau_+ = 1000$. Liu and Agarwal (1974) give the following correlation between v_+ and τ_+

$$v_+ = 6 \times 10^{-4}\,\tau_+^2 \tag{32}$$

$$\tau_+ = 0.0395\,Stk\,Re^{3/4} \tag{33}$$

$$v_+ = 5.03\,\frac{v_t}{U}\,Re^{1/8} \tag{34}$$

where

v_+ = dimensionless deposition velocity
τ_+ = dimensionless particle relaxation time
v_t = deposition velocity for turbulent inertial deposition
Stk = Stokes number formulated with the tube diameter and average gas velocity in the tube

Experimental results by Liu and Agarwal also show that v_+ may be regarded as constant for τ_+ larger than 12.9. That is

$$v_+ = 0.1 \quad \text{for } \tau_+ > 12.9 \tag{35}$$

Recent experimental work by Muyshondt (1996a) with larger diameter tubes indicate a Reynolds number dependence not reflected in dimensionless particle relaxation time. They present a fit to their data which generally gives a higher deposition than Liu and Agarwal.

Transport efficiency is increased by increasing the tube diameter, d, by decreasing the volumetric flow, Q, or by decreasing the transport length, L.

Inertial Deposition in a Bend keep bend $\phi > 2\times\phi$

When the direction of sampling gas flow is diverted in a bend, an aerosol particle may deviate from the gas flow due to its inertia and deposit on the wall of the bend. In laminar flow, secondary recirculation flow patterns develop that push the axial flow core to the outside of the bend and are responsible for particle deposition on both the inside and outside of the bend. These recirculation flows influence particle deposition and they are in turn dependent on the flow Reynolds number and the radius of curvature of the bend. Laminar flow is more stable in a bend than through a straight tube and flow can remain laminar up to Reynolds numbers of 5000. The pertinent parameters in characterizing particle deposition from laminar flow through a bend are the curvature ratio, R_0, defined as the radius of the bend divided by the radius of the tube, the flow Reynolds number ($Re = \rho dU/\mu$), and the Stokes number formulated with the tube diameter and average gas velocity ($Stk = \tau U/d$).

The simple empirical correlation given by Crane and Evans (1977) for transport efficiency, $\eta_{bend,\,inert}$, of particles undergoing inertial deposition in a 90° bend is adequate for estimates of particle deposition from laminar flow in bends and can be extended to bends of other angles.

$$\eta_{bend,\,inert} = 1 - Stk\,\phi \tag{36}$$

where

ϕ = angle of the bend in radians

This correlation is an approximation of experimental data (Crane and Evans 1977). It assumes zero deposition only at Stokes number of zero. The numerically calculated deposition rates of particles from laminar flow in a circular bend (Cheng and Wang 1981) and the experimental work of Pui et al. (1987) indicate that for small Stokes number (Stk on the Reynolds number) no deposition occurs. If Stokes

numbers in bends in laminar flow can be kept below this limit, then no inertial deposition is expected.

Cheng and Wang (1981) present only the results of their numerical calculations for Reynolds numbers of 100 and 1000. Pui et al. (1987) found that the Cheng and Wang (1981) numerical results for Reynolds number of 1000 agreed well with their experimental data whereas the calculations for Reynolds number of 100 did not. This disagreement was attributed to differences in the assumed and actual flow fields at the lower Reynolds number. The experimental results support the use of the Cheng and Wang (1981) model for Reynolds number of 1000 and curvature ratios between 4 and 30. No correlation is given but the transport efficiency for laminar flow through a 90° bend at a Reynolds number of 1000 and a curvature ratio of 8 is 1 at Stk ~ 0.05, 0.5 at Stk ~ 0.16, and 0.1 at Stk ~ 0.32. These results may be used as a guide to estimate transport efficiency.

Data for particle deposition in a bend from laminar flow are given by Pui et al. (1987) for Reynolds number of 1000, a curvature ratio of 5.6 and 5.7, and tube internal diameter ranging from 4 mm to 8.5 mm. A fit to these data yields a correlation that may be more satisfying than the Crane and Evans (1977) relationship.

$$\eta_{\text{bend, inert}} = \left[1 + \left[\frac{\text{Stk}}{0.171}\right]^{0.452\,\frac{\text{Stk}}{0.171} + 2.242}\right]^{-\frac{2}{\pi}\phi} \tag{37}$$

Pui, et al. (1987) also found that deposition from turbulent flow in a bend can be expressed independently of Reynolds number. They present an analysis showing that particles are deposited through the boundary layer from a well mixed core at a constant rate with total deposition proportional to the angle through which the aerosol flows. This analysis is in good agreement with the data. A data based correlation for transport efficiency of particles through a bend in turbulent flow, $\eta_{\text{bend,inert}}$, is given.

$$\eta_{\text{bend, inert}} = \exp[-2.823\,\text{Stk}\,\phi] \tag{38}$$

When sampling lines must go through bends, the curvature ratio should be on the order of 4 or higher; abrupt turns should be avoided. To obtain higher transport efficiency through bends, the Stokes number should be kept small. If the flow is laminar and the Stokes number can be kept less than 0.05, losses from inertial impaction in the bend will be minimal. If the flow is turbulent, equation (38) is an adequate correlation for predicting the losses.

Inertial Deposition in Flow Constrictions in Sampling Lines

Flow constrictions in a sampling line should be avoided if at all possible; they produce losses that are difficult to characterize. Examples of constrictions are flow through a valve (although some ball valves present little more disturbance to flow than commonly used tube unions and connections), in-line orifices, abrupt changes in flow direction such as a tee or a cross or a right angle bend with a curvature ratio close to 1, and changes from a large to small tube diameter either through an abrupt contraction or through a converging tube. If a sampling system must be used that has one or more of these features, particle transport should be characterized experimentally over the range of applicable operating conditions. Similarly, sudden expansions in a flow path can produce eddies from which particle

deposition is difficult to characterize. These features should also be avoided.

Estimates for particle transport through flow constrictions can in some cases be made. For example, the transport efficiency correlations for a 90° bend from the previous section may be used to estimate the transport efficiency for flow elements such as a tee, cross, or sharp right angle bend. In this case the highest velocity in the element should be used in the calculations.

Ye and Pui (1990) have developed a correlation for inertial particle deposition from laminar flow in a tube with an abrupt contraction. The correlation is based on numerical calculation and has been compared favorably with experimental data found in the literature. The applicable geometry consists of a large (diameter d_i) and a small (diameter d_o) coaxial circular tubes with a step reduction in cross section from the large to the small tube. This type of geometry is found or approximated in common tube and pipe fittings. Ye and Pui (1990) give a correlation for the transport efficiency, $\eta_{cont, inert}$, for particles undergoing inertial deposition in an abrupt contraction. It is a function of the tube diameter ratio (d_o/d_i) and the Stokes number based on the small tube diameter and average velocity in the large tube, $Stk = \tau U_i/d_o$.

$$\eta_{cont, inert} = 1 - \left[1 - \left(\frac{d_o}{d_i}\right)^2\right]\left(1 - \exp\left(1.721 - 8.557\,x + 2.227\,x^2\right)\right)$$

$$\text{for } 0.213 \le x \le 1.95 \qquad (39)$$

$$x = \sqrt{Stk}\left(\frac{d_o}{d_i}\right)^{0.31}$$

This range of x covers the range of maximum to minimum penetration. The transport efficiency, $\eta_{cont, inert}$, is one for x smaller than this range and $(d_o/d_i)^2$ for x larger than this range.

The limit of transport efficiency at large Stokes number is the square of the diameter ratio. Transport efficiency may be kept high by keeping the Stokes number small.

The Ye and Pui (1990) correlation is applicable for deposition on the upstream side of a coaxial orifice and to a case where the contraction tapered at 60° instead of 90°. In the case of an orifice, deposition downstream is not considered. In the case of a less than abrupt contraction, some deposition could occur and the Ye and Pui (1990) correlation provide at least a bounding estimate on transmission efficiency. The reader is referred to additional work by Chen and Pui (1995) for conical contractions in laminar flow and by Muyshondt et al. (1996b) for contraction fittings in both laminar and turbulent flow if more detailed estimates are needed.

Muyshondt, McFarland, and Anand (1996) correlate their data with penetration as a function of the quantity $Stk(1-(d_o/d_i)^2)$ given as

$$\eta_{cont,\,inert} = 1 - \frac{1}{1 + \left\{ \frac{2\,Stk\left[1 - \left(\frac{d_o}{d_i}\right)^2\right]}{3.14\,\exp(-0.0185\theta)} \right\}^{-1.24}} \qquad (40)$$

where θ is the contraction angle in degrees.

This correlation fits the data well and is mathematically simpler than the correlations presented by Ye and Pui (1990) and Chen and Pui (1996).

Electrostatic Deposition in Sampling Lines

Deposition of charged particles by electrostatic forces can occur in sampling lines during transport. Even in an aerosol that is on the average neutral, some particles are charged. This charging occurs from diffusion of ions to the particles. Ions are constantly produced in our environment by cosmic rays. For a given ion concentration, there is an equilibrium charge distribution over the aerosol particles. Particles may also be charged by the mechanism that produces them. Static charge in the sampling line or an externally imposed electrical field in the line can produce particle deposition. Because it is not always possible to know the distribution of charge on aerosol particles or the electrical fields in a sampling line that is subject to static charge, electrostatic deposition of particles in sampling lines is most difficult to characterize.

Electrostatic deposition is avoidable. Metal or electrically conductive lines set up to avoid electrical fields by having no electrically isolated sections will obviate the problem of electrostatic deposition. If metal lines can not be used, Tygon™ is an acceptable substitute (Liu et al. 1985). Materials to be avoided for aerosol transport are Teflon™ and Polyflo™ (Liu et al. 1985).

Thermophoretic Deposition in Sampling Lines

A temperature gradient in a gas will cause a suspended particle to move down the gradient from higher toward lower temperatures. This particle transport by a temperature gradient is called thermophoresis. The thermophoretic velocity, v_{th}, of a particle is the velocity that it achieves as a result of the thermophoretic force. The thermophoretic velocity is dependent on the temperature gradient. It is independent of particle size for particles much larger than the gas molecule mean free path (continuum regime particle), and for particles much smaller than the gas molecule mean free path (free molecule regime). The transport efficiency in turbulent tube flow with thermophoretic deposition, $\eta_{tube,\,th}$, is expressed below.

$$\eta_{tube,\,th} = \exp\left[- \frac{\pi\, d\, L\, v_{th}}{Q} \right] \qquad (41)$$

In laminar tube flow, the flow and temperature gradient conditions become more involved and no expression for transport efficiency for laminar flow is given.

The magnitude of the thermophoretic velocity for particles in the continuum regime is expressed as (Friedlander, 1977)

$$v_{th} = \frac{2\left(\frac{k_g}{k_p}\right) k_g \nabla T}{5P\left[1 + 2\frac{k_g}{k_p}\right]} \tag{42}$$

For particles in the free molecule regime the magnitude of the thermophoretic velocity is expressed as (Friedlander, 1977)

$$v_{th} = \frac{3\nu \nabla T}{4\left(1 + \pi\frac{0.9}{8}\right) T} \tag{43}$$

where

v_{th} = thermophoretic velocity
k_g = thermal conductivity of the gas
k_p = thermal conductivity of the particle
∇T = temperature gradient in the gas
P = pressure
T = gas temperature

Talbot et al. (1980) offer an expression for the magnitude of the thermophoretic velocity that covers particle sizes from the free molecule to the continuum regime and goes to the above limits.

$$v_{th} = \frac{2 C_s \nu\left[\frac{k_g}{k_p} + C_t Kn\right] C(Kn)}{(1+3 C_m Kn)\left[1+2\frac{k_g}{k_p} + 2 C_t Kn\right]} \frac{\nabla T}{T} \tag{44}$$

where

C_s = 1.13
C_t = 2.63
C_m = 1.14
Kn = particle Knudsen number defined as twice the gas molecular mean free path, λ, divided by the particle diameter, D_p.

C(Kn)= slip correction factor

Estimation of thermophoretic deposition in sample lines is not a straightforward process. Determination of the temperature gradients can be difficult. Because of the relatively low heat capacity of gases, the gas rapidly comes to the tube wall temperature causing a changing temperature gradient. The particle material thermal conductivity is not always known and in the case of an agglomerate particle, the particle thermal conductivity is not necessarily the same as the particle material thermal conductivity because of the included voids.

Thermophoretic deposition in sampling lines can be avoided by heating the lines to the gas temperature or cooling the gas to the line temperature by dilution.

Diffusiophoretic Deposition in Sampling Lines

A particle in a non-uniform gas mixture will be acted on by the diffusion of the gas molecules caused by the concentration gradients. The force which the particle experiences is called the diffusiophoretic force. This force arises from the unequal momentum transfer to the particle from the heavier molecules on the higher concentration side of the particle. The direction of this force is in the direction of diffusion of the heavier gas molecule. This force causes the particle to move with a velocity called the diffusiophoretic velocity, V_{dph}. This phenomenon should not be confused with Brownian diffusion of the particle. Diffusiophoresis is caused by a concentration gradient in the gas molecules. Near a condensing or an evaporating surface, an additional effect influences the force acting on the particle. Near the surface, the condensing or evaporating vapor has associated with it a concentration gradient that drives the vapor's diffusion through the gas effecting condensation or evaporation. In order to maintain a constant gas pressure, the gas must also have a concentration gradient equal to and in the opposite direction of the vapor's gradient. The concentration gradient in the gas produces diffusion of the gas toward the surface in the case of vapor evaporation and away from the surface in the case of vapor condensation. Because the surface is not a source or a sink for the gas, an aerodynamic flow called the Stefan flow is set up to transfer the gas away from an evaporating surface and toward a condensing surface to counteract the diffusive transfer of gas. The Stefan flow exerts a force on the particle in the direction of the flow that is in addition to the diffusiophoretic force acting in the direction of the diffusion of the heavier molecule (Fuchs 1964; Hinds 1982). Waldmann and Schmitt (1966) and Goldsmith and May (1966) give an expression for the diffusiophoretic velocity on a particle acted on by diffusiophoretic forces and Stefan flow.

$$v_{dph} = \frac{-\sqrt{m_1}}{\gamma_1\sqrt{m_1} + \gamma_2\sqrt{m_2}} \frac{D}{\gamma_2} \nabla\gamma_1 \qquad (45)$$

where

m_1 = the mass of a molecule of the diffusing species
m_2 = the mass of a molecule of the stagnant species
γ_1 = the mole fraction of the diffusing species
γ_2 = the mole fraction of the stagnant species
$\nabla\gamma_1$ = the gradient of the mole fraction of the diffusing species

In the case of water vapor and air, the velocity of a particle is away from an evaporating surface and toward a condensing surface. For diffusiophoresis arising from condensation in turbulent pipe flow the transport efficiency, $\eta_{tube,\,dph}$, of particles can be estimated with

$$\eta_{tube,\,dph} = \exp\left[-\frac{\pi d L v_{dph}}{Q}\right] \tag{46}$$

Whitmore and Meisen (1987) produced data for diffusiophoretic deposition in turbulent flow for ammonia condensing from a number of gases. The results indicated that the particle transport efficiency was comparable to the mole fraction of the noncondensing gas. Thus if 10 percent of the gas transporting particles condensed about 10 percent of the particles would be deposited. These results of Whitmore and Meisen (1978) permit a rough estimate of the transport efficiency for particles undergoing diffusiophoretic deposition based on the noncondensable mole fraction of the gas.

Conditions under which diffusiophoretic deposition would occur should be avoided in the transport of aerosol samples. This can be accomplished by avoiding condensation in sampling lines by heating or dilution.

Deposition in Chambers and Bags

Situations arise in aerosol sampling in which a sampled aerosol is temporarily stored. This can happen when a sample must be taken at a rate faster than the instrument can accommodate. For example, an aircraft sampling from a plume will often have only a few seconds of time in the plume to acquire a sample but the instrument can not make a measurement in that short a time period. The sample is drawn into a sample chamber or bag during the short transit period and the measurement is made on the stored sample over a longer period of time. Another sampling application in which a chamber or bag is used is the study of aerosol size distribution evolution from gas to particle conversion and coagulation. In all of these applications, the deposition of particles during their residence time in the chamber can have a definite effect on the measurement. When the time to take an aerosol measurement or series of measurements is comparable to the time for the aerosol distribution in the chamber to change appreciably from deposition, then the deposition must be accounted for.

Two deposition mechanisms are usually considered. They are gravitational settling and diffusion. Crump and Seinfeld (1981) and Crump, Flagan, and Seinfeld (1983) have developed a model for gravitational and diffusive deposition inside stirred vessels. Other, less characterizable deposition mechanisms should be avoided. Diffusiophoresis and thermophoresis can be avoided by the sampling technique, i.e., avoid temperature gradients at the chamber wall and avoid condensing conditions. Electrostatic deposition can be avoided by selection of an electrically conductive chamber material, such as aluminized mylar, or one that can be demonstrated not to be susceptible to electrostatic deposition. Teflon™ should not be used for the reasons outlined in the section on electrostatic deposition. McMurry and Rader (1985) and McMurry and Grosjean (1985) have reported experimental data in which the enhanced loss of charged particles inside of Teflon™ film chambers has been observed.

A model for simultaneous gravitational and diffusional losses (Crump and Seinfeld 1981) has been developed for a well-mixed vessel of arbitrary shape. For a spherical vessel they give an expression for the wall loss coefficient, β, where the remaining fraction of particles of a given size after time, t, is

$$\eta_{\text{bag, grav diff}} = \exp\left[-\int_0^t \beta \, dt\right] \tag{47}$$

and

$$\beta = \frac{12 k_e D}{\pi^2 R V_{ts}} \int_0^{\frac{\pi V_{ts}}{2\sqrt{k_e D}}} \frac{x}{e^x - 1} dx + \frac{3 V_{ts}}{4 R} \tag{48}$$

where

R = vessel radius
k_e = coefficient of eddy diffusion

The first term in equation (48) describes the losses from diffusion and includes the effect of declining eddy diffusivity (mixing level) approaching the wall. The second term in equation (48) is the contribution from gravitational settling. It is equal to the settling velocity times the ratio of the deposition area of the chamber to the volume of the chamber. The deposition area for gravitational settling is the projected area on the horizontal plane. This definition is applicable for stirred settling from any vessel shape.

The coefficient of eddy diffusion characterizes the level of mixing in the chamber. Higher values indicate a higher eddy diffusivity and consequently a higher loss by diffusion. A chamber with a constant throughput of gas will have a constant mixing level driven by the kinetic energy of the incoming gas but a chamber that is initially filled then closed off will have a mixing level that decays with time. Equation (47) contains the integral of β with respect to time because the coefficient of eddy diffusion, k_e, can change with time. This parameter is the only quantity not known in equation (48); it must be determined experimentally or estimated. Benes and Holub (1996) describe a means to estimate the eddy diffusion coefficient based on dimensional analysis. Nomura et al. (1997) employ the Benes and Holub (1996) expression with a gravitational term to extend the Crump and Seinfeld model.

Gravitational deposition depends only on the size of the chamber and can be reduced by using a larger chamber. The higher values of k_e produce higher diffusion loss. A larger bag will result in a lower diffusion loss.

In filling a bag with flexible sides, particles on the bag walls can be resuspended in the gas volume as a result of the mechanical forces on the wall during filling. Generally, larger particles are more easily resuspended. Resuspension of particles from the bag should be considered in selection of the bag and the decision to reuse bags. In some applications, the use of single-use bags may be prudent.

OTHER SAMPLING ISSUES

There can be times when the sampled aerosol concentration (either mass or number) is too high for the sampling instrument. Under these situations, the sample must be diluted with clean gas to bring the concentration within the measurement range of the instrument. Uncertainty in the dilution and sample flows will produce uncertainty in the calculated concentration that must be addressed. High number concentrations may drive the aerosol to undergo rapid coagulation which alters the distribution; the

number concentration decreases and the mean particle size increases. Dilution of the sample will arrest the coagulation process so that a representative sample can be measured.

Plugging of inlets and sample transport lines can occur when the lines are used for long periods of time or when the aerosol being sampled contains particle that are susceptible to deposition, especially local deposition such as an inlet, a bend, or a contraction. These particles need not be of interest; they could be large particles that just happen to be with in the particles of interest.

The sampled aerosol may be in a condensing or evaporating environment. Condensation or evaporation of material on or from aerosol particles will change the size of the particles and the total suspended mass of aerosol material. To obtain a representative sample from an environment in which material (such as water vapor) is condensing on the particles, the sample may have to be conditioned by dilution or heating. Obtaining a representative sample from an environment in which particle material is evaporating from the particle is more difficult and can be addressed by minimizing the time between sampling and measurement to keep evaporation to a minimum.

In sampling from the ambient atmosphere, from a room, from or a duct one must be concerned with the homogeneity of the aerosol throughout the volume of gas. A representative sample requires sampling at a sufficient number of points to give an accurate picture of the aerosol throughout the volume of interest (Fissan and Schwientek 1987). In the case of duct sampling, the American National Standards Institute (ANSI) standard N13.1 (ANSI 1969) provides accepted and agreed upon sampling locations to obtain a representative sample. This standard is currently under revision and new one is expected to be adopted soon. In room sampling, flow and convection in the room can cause considerable inhomogeneity in the aerosol. This is especially significant in situations of very low concentration such as in clean rooms where long sampling times are required for meaningful particle counting statistics to be obtained (Fissan and Schwientek 1987). Sampler placement in this situation may be made on the basis of flow modeling or by the use of tracer smokes or fogs.

SUMMARY

Correlations describing aspiration efficiency, transmission efficiencies, and transport efficiencies will be given in following sections. These correlations can be used to evaluate the performance of an existing sampling system or to aid in the design of a sampling system. Because these correlations are based on assumptions and experiments that are not always the same as the reader's application, they may not be applicable for calculated efficiencies much different from one. Because the efficiencies are particle size dependent, the range of particle sizes over which sampling is representative (sampling efficiency close to 1) can be estimated with a fair degree of confidence using these correlations. In designing a sampling system, the parameters such as flow, line size, orientation, and length can be adjusted using the correlations to estimate the efficiency for the particle size range of interest to achieve representative sampling. Of course, the sampling system should be experimentally evaluated whenever possible. At the end of the presentation for each type of efficiency correlation is a short qualitative discussion on how the efficiency changes with the dependent parameters. Sampling situations to avoid and how to avoid them are also discussed.

While some of the phenomena discussed have been extensively investigated and characterized, others have not. It is the purpose of this material to provide the reader with some background information in aerosol sampling and transport so that sampling systems may be accurately evaluated and appropriately designed and so that sampling pitfalls may be avoided. For additional information on aerosol sampling, the reader is referred to the review paper on sampling of aerosols by N. A. Fuchs (1975), to the more recent reviews on aerosol sampling and transport by H. Fissan and G. Schwientek (1987) and by Brockmann (1993) and to the recent book by J. H Vincent (1989) on Aerosol Sampling.

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