

MJC

Aerosol Sampling and Transport

Tutorial Session 9

Sunday September 10, 2006

1:00 to 2:40 PM

John E. Brockmann Ph.D.

Sandia National Laboratories*

Albuquerque NM 87185

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Aerosol Sampling and Transport

- **Objective**

- Provide guidance to design and evaluate aerosol sampling and transport systems
- Discuss sampling inefficiencies and deposition mechanisms
- Provide correlations



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Aerosol Sampling and Transport

- **Outline**

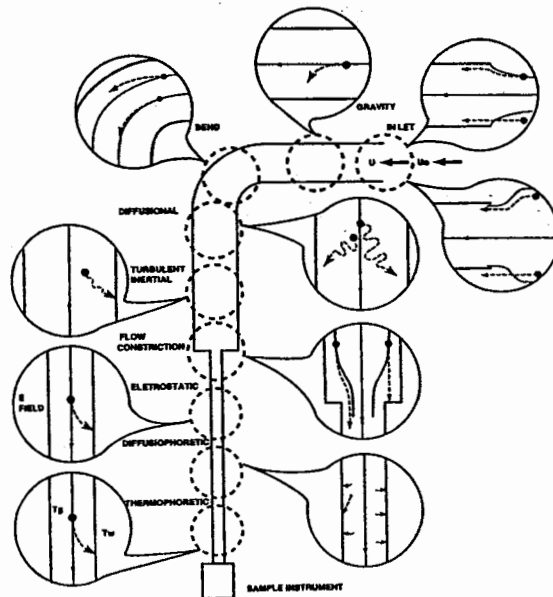
- Aerosol sampling with thin-wall nozzle isoaxially from free stream
- Aerosol sampling with thin-wall nozzle from still air
- Aerosol transport through sample lines
- Losses in bags and chambers
- Examples



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Particle Transport in Inlets and Transport Lines



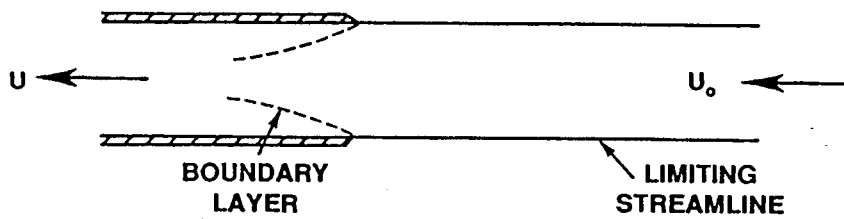
Aerosol and Flow Parameters

- Reynolds Number $Re = \rho U d / \mu$
- Stokes Number $Stk = \tau U / d$
- Settling Velocity $V_{ts} = \tau g$
- Dimensionless Settling Velocity $V^* = V_{ts} / U$
- Gravitational Deposition Parameter $Z = (L/U) / (d/V_{ts})$
- Diffusion Parameter $\xi = \pi D L / Q$

Isoaxial Isokinetic Sampling

$$U = U_0$$

(Iso-mean-velocity)

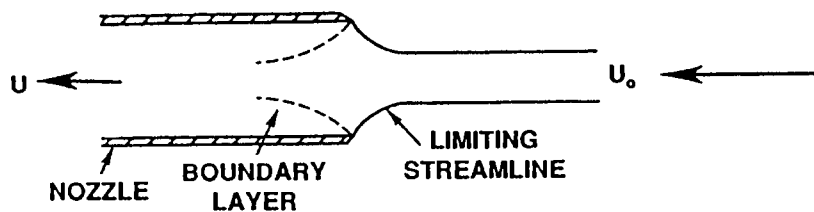


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Isoaxial Sub-Isokinetic Sampling

$$U < U_0$$

(Sub-iso-mean-velocity)

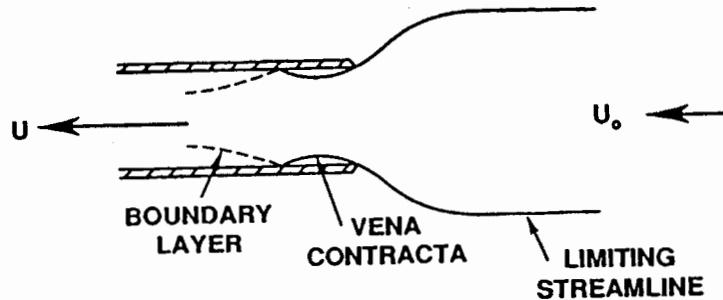


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Isoaxial Super-Isokinetic Sampling

$$U = U_0$$

(Iso-mean-velocity)



Aspiration Efficiency

- Ratio of the concentration of particles passing through the nozzle entrance to the concentration of particles in the ambient environment
- Efficiency is 1 when $U = U_0$
- Efficiency is > 1 when $U < U_0$
 - Flow diverges into nozzle
 - Larger particles cross streamlines
- Efficiency is < 1 when $U > U_0$
 - Flow converges into nozzle
 - Larger particles cross streamlines
- Free stream turbulence does not seem to effect aspiration efficiency

Aspiration Efficiency

- Stokes Number

$$Stk = \frac{\tau U_0}{d}$$

$$\eta_{asp} = 1 + \left[\frac{U_0}{U} - 1 \right] \left[1 - \frac{1}{1 + k Stk} \right]$$

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

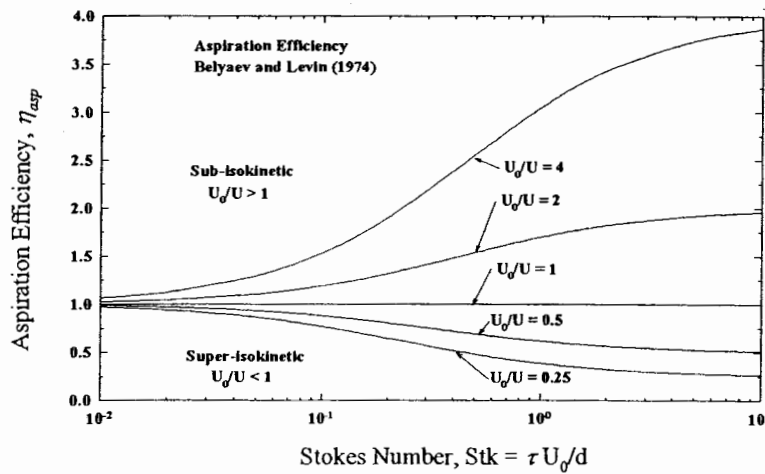
$$k = 2 + 0.617 \left[\frac{U_0}{U} \right]^{-1}$$

- Belyaev and Levin (1972, 1974)



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Aspiration Efficiency of a Thin-Walled Nozzle In Isoaxial Sampling Under Anisokinetic Conditions



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Transmission Efficiency

- Ratio of the concentration of particles transmitted through the nozzle to the concentration of particles passed through the inlet
- Inlet deposition from inertial forces
 - No losses for $U = U_0$
 - Particle trajectories toward wall when $U < U_0$
 - Vena Contracta losses when $U > U_0$
- Inlet deposition from gravitational forces
 - Include settling in transport calculations
- Inlet deposition from Saffman lift forces
 - Correlation independent of U_0
- Free stream turbulence enhances inlet lip deposition
 - Effect reduced by larger inlet diameter



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Transmission Efficiency Inertial Losses

- Sub-Isokinetic $U < U_0$ $Stk = \frac{\tau U_0}{d}$

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

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

- Liu et al. (1989)



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Transmission Efficiency

Inertial Losses

- Super-Isokinetic $U > U_0$ $Stk = \frac{\tau U_0}{d}$

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

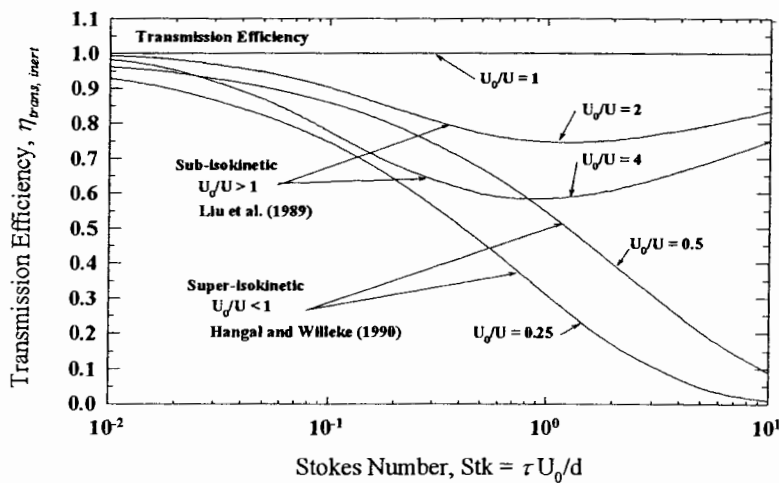
for $0.02 \leq Stk \leq 4$ and $0.25 \leq \frac{U_0}{U} < 1$

- Hangal and Willeke (1990)



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Transmission Efficiency for a Thin-Walled Nozzle In Isoaxial Sampling Under Anisokinetic Conditions



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Transmission Efficiency Saffman Lift Forces

$$Stk = \frac{\tau U}{d} \quad Re = \frac{\rho U d}{\mu} \quad Pl = 0.3246 \frac{\rho_0 D_{ae}}{\sqrt{2} \nu \frac{d}{U}}$$

$$\eta_{trans, lift} = 1 - \frac{1.769}{\left[1 + \frac{gL}{U^2}\right]^{9.19}} \frac{\left[\frac{4 \cdot Stk}{\sqrt{Pl}}\right]^{0.559}}{Re^{0.216}}$$

- Anand et al. (1993)



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Inlet Efficiency

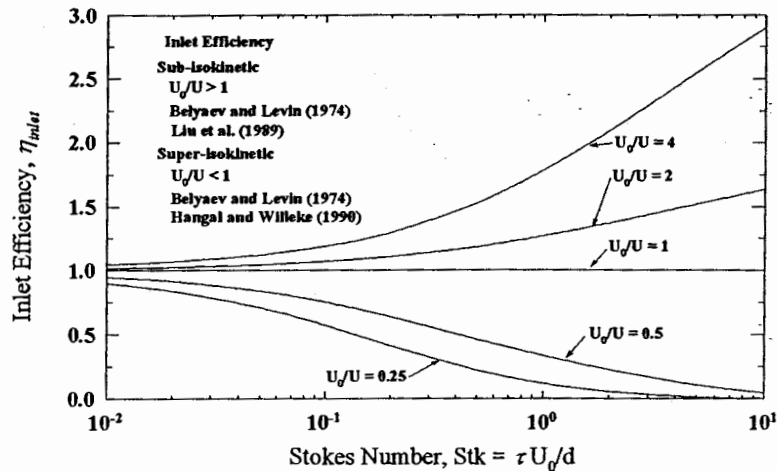
- **Ratio of the concentration of particles transmitted through the nozzle to the concentration of particles in the ambient environment, i.e., the product of the Aspiration Efficiency and the Transmission Efficiency**

$$\eta_{inlet} = \eta_{aspiration} \cdot \eta_{transmission}$$



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Inlet Efficiency for a Thin-Walled Nozzle In Isoaxial Sampling Under Anisokinetic Conditions



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Sampling in Still Air

- Davies Criterion – Perfect Sampling

$$\frac{V_{ts}}{U} \leq 0.04 \quad Stk \leq 0.016 \quad Stk = \frac{\tau U}{d}$$

- Davies (1968)

- Agarwal and Liu Criterion – Efficiency > 90%

$$Stk \cdot \frac{V_{ts}}{U} \leq 0.05 \quad Stk = \frac{\tau U}{d}$$

$$\text{for } \frac{V_{ts}}{U} \leq 0.001 \text{ and } Stk \leq 1000$$

- Agarwal and Liu (1980)



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Sampling in Still Air

- Calm air sampling expression

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

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

- Vertical Sampling Criterion – Efficiency > 95%

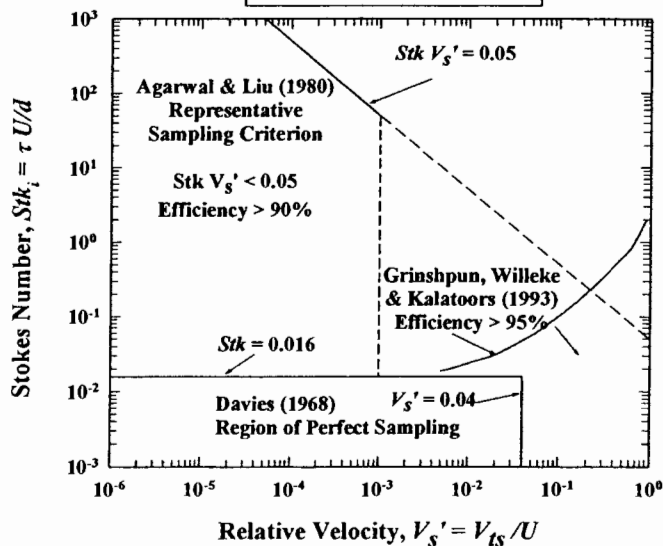
$$\frac{U^2}{g \cdot d} \leq 1$$

- Grinspun, Willeke, and Kalatoors (1993)



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Still Air Sampling Criteria for Thin-Wall Nozzles



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Transport Efficiency

- Ratio of the concentration of particles transported through the sampling line to the concentration of particles entering the sampling line
- Efficiency for a given mechanism in a given flow element is the fraction of the particles not removed by that mechanism
- Total transport efficiency is the product of the transport efficiency over all the mechanisms and all the flow elements

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



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Transport Efficiency

- Particle removal mechanisms are
 - Gravitational deposition
 - Diffusional Deposition
 - Turbulent inertial deposition (turbo-phoresis)
 - Inertial deposition in a bend
 - Inertial deposition at flow constrictions
 - Electrostatic deposition
 - Thermophoretic deposition
 - Diffusiophoretic deposition

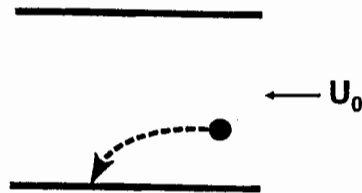


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Transport Efficiency Gravitational Deposition

- A Particle's mass causes it to settle to a wall under the influence of gravity



Transport Efficiency Gravitational Deposition

- Particles settle in sampling lines
- Settling parameter is the ratio of residence time to settling time
- Gravitational deposition can be reduced by
 - Reducing horizontal run of lines
 - Decreasing residence time

Transport Efficiency Gravitational Deposition

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

- In laminar tube flow

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

– Heyder and Gebhart (1977)

- In turbulent tube flow

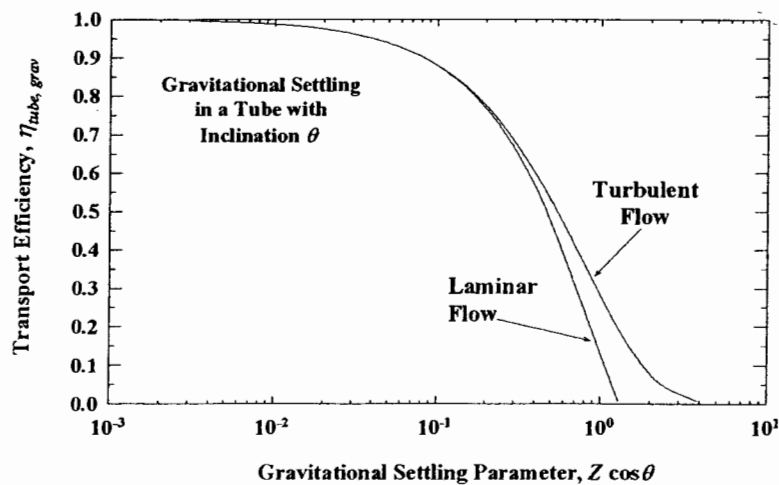
$$\eta_{\text{turb_grav}} = \exp \left[-\frac{16 \kappa}{3 \cdot \pi} \right]$$

– Schwendiman et al. (1975)



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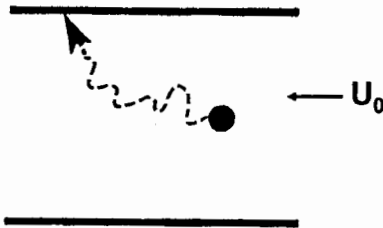
Gravitational Deposition In Tube Flow



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Transport Efficiency Diffusional Deposition

- **Brownian diffusion of a particle causes it to contact a wall**



Transport Efficiency Diffusional Deposition

- **Brownian diffusion causes particles to move from high to low concentration**
- **Diffusion parameter is the ratio of diffusion distance to system size**
- **In laminar flow, diffusional deposition can be reduced by**
 - Increasing the flow rate
 - Decreasing the line length
- **In turbulent flow, diffusional deposition can be reduced by**
 - Increasing the tube diameter
 - Decreasing the line length

Transport Efficiency Diffusional Deposition

- Diffusion parameter

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

- In laminar tube flow

$$\eta_{\text{lam_diff}} = 1 - 2.56 \xi^{2/3} + 1.2 \xi + 0.177 \xi^{4/3}$$

for $\xi < 0.02$

$$\eta_{\text{lam_diff}} = 0.818 \exp(-3.657 \xi) + 0.097 \exp(-223 \xi) + 0.032 \exp(-57 \xi)$$

for $\xi > 0.02$

– Gormley and Kennedy (1949)

- In turbulent tube flow

$$\eta_{\text{turb_diff}} = \exp \left[-\xi^{3/2} \cdot 0.0187 \cdot \text{Re}^{1/4} \cdot \left(\frac{L}{d} \right)^{1/2} \right]$$

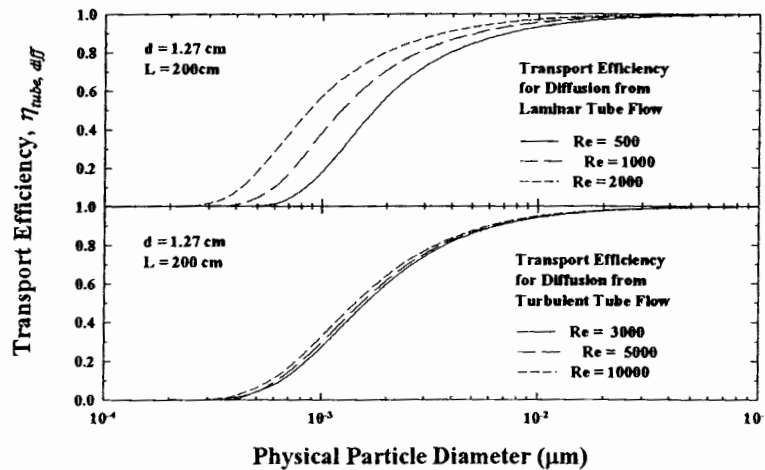
$$\text{Re} = \frac{\rho U d}{\mu}$$

– Friedlander (1977)



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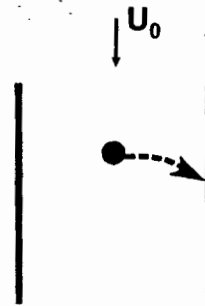
Diffusional Deposition In Tube Flow



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Transport Efficiency Turbulent Inertial Deposition

- Turbulence in the gas stream imparts a velocity to a particle sufficient for the particle to penetrate to a wall



Transport Efficiency Turbulent Inertial Deposition

- Turbulence in the central region of a tube transports particles through the laminar sub-layer to the wall
- Turbulent inertial deposition can be reduced by
 - Increasing the tube diameter
 - Decreasing the line length
 - Decreasing the volumetric flow

Transport Efficiency Turbulent Inertial Deposition

• Parameters $Stk = \frac{\tau U}{d}$ $Re = \frac{\rho U d}{\mu}$

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

$v_+ = 6 \cdot 10^{-4} \tau_+^2$ for $\tau_+ < 12.9$

$v_+ = 0.1$ for $\tau_+ > 12.9$

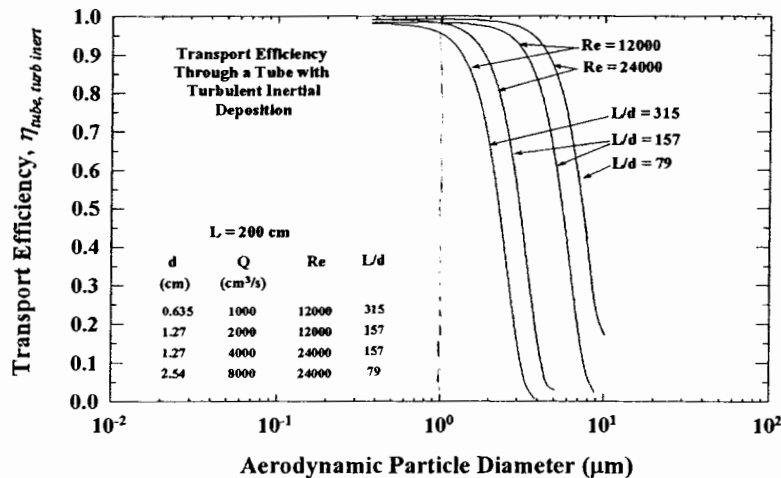
$v_+ = 5.03 \frac{v_t}{U} Re^{1/8}$ $\tau_+ = 0.0395 Stk Re^{3/4}$

- Liu and Agarwal (1974)



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Turbulent Inertial Deposition In Tube Flow



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Sub-micron particles -- this ISN'T a problem!



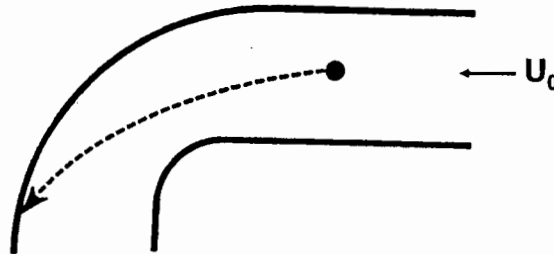
but

Re ↑

Transmission ↑

Transport Efficiency Inertial Deposition in Bends

- A particle's inertia causes it to cross stream lines to impact on a wall



Transport Efficiency Inertial Deposition in Bends

- A particle with sufficient inertia will not make the turn
- There appears to be a Reynolds number dependence in laminar flow
- In laminar flow, there are minimal losses for $Stk < 0.05$
- In turbulent flow deposition is independent of Reynolds number
- Inertial deposition in bends can be avoided by
 - Keeping the bend radius larger than twice the tube diameter
 - Keeping the Stokes number low
 - Minimize the number of bends in sampling lines

Transport Efficiency Inertial Deposition in Bends

- Parameters $Stk = \frac{\tau U}{d}$, bend angle ϕ

- In laminar tube flow

$$\eta_{lam_bend} = 1 - Stk \phi$$

Crane and Evans (1977)

$$\eta_{lam_bend} = \left[1 + \left[\frac{Stk}{0.171} \right]^{0.452} \frac{Stk}{0.171} + 2.242 \right]^{-\frac{2}{\pi} \phi}$$

Fit to Pui et al. (1987) data

- In turbulent tube flow

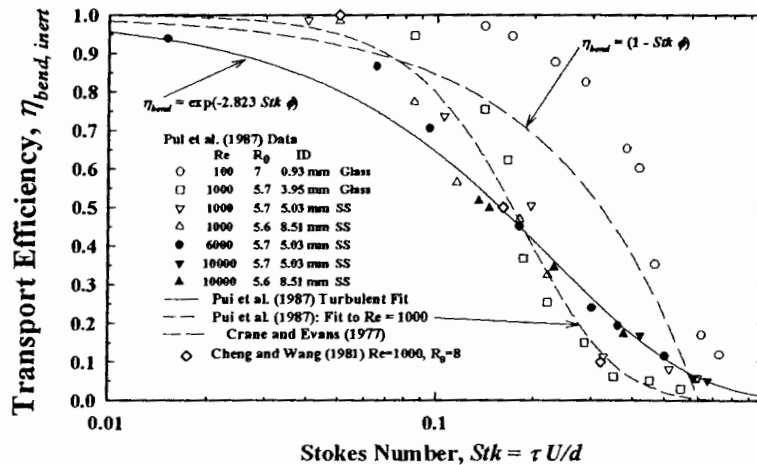
$$\eta_{turb_bend} = \exp[-2.823 Stk \phi]$$

Pui et al. (1987)



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Inertial Deposition In A Bend Data for 90 Degree Bend

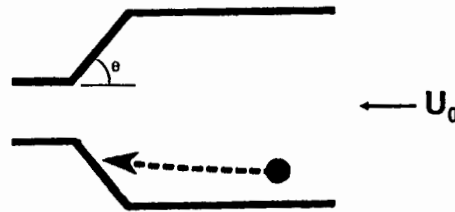


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Transport Efficiency

Inertial Deposition in Flow Constrictions

- A particle's inertia causes it to cross stream lines to impact on the face of the constriction



Transport Efficiency

Inertial Deposition in Flow Constrictions

- A particle with sufficient inertia will cross stream lines and impact on the contraction face
- Avoid flow restrictions where possible
- Keep Stokes number small
- Use Ye and Pui (1990) or Muyschondt et al. (1996) to make estimates

Transport Efficiency Inertial Deposition in Flow Constrictions

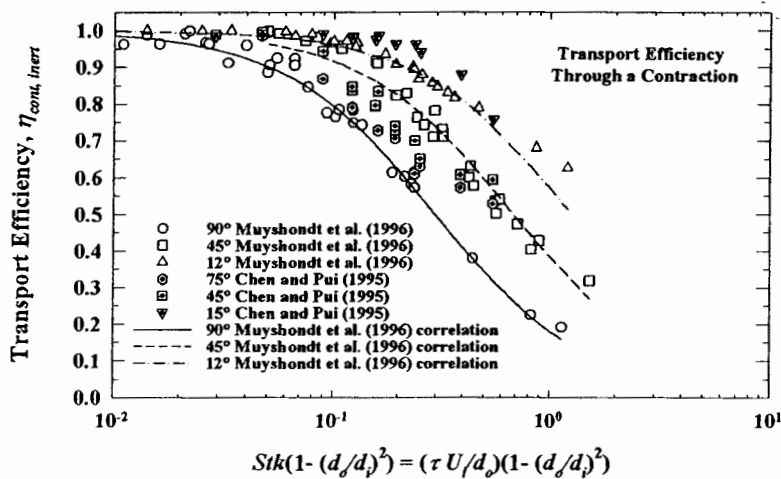
- Parameters $Stk = \frac{\tau U_i}{d_o}$, contraction angle θ

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

Muyschondt, McFarland, and Anand (1996)

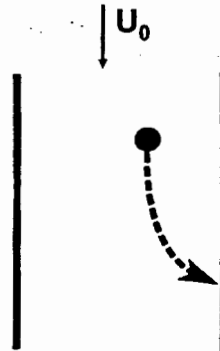


Inertial Deposition in a Flow Contraction in Tube Flow



Transport Efficiency Electrostatic Deposition

- An electric field and/or electric charge on a particle result in a force on the particle that moves it to a wall



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Transport Efficiency Electrostatic Deposition

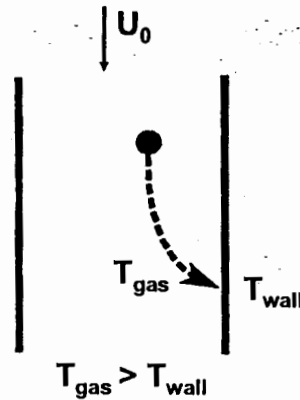
- An electric field and/or electric charge on a particle result in a force on the particle that moves it to a wall
- Not a readily characterized loss mechanism
- Electrostatic deposition can be avoided by
 - Use of conductive grounded transport lines
 - Metal lines are preferable
 - Tygon™ is acceptable
 - Avoid Teflon™ and Polyflow™ tubing



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Transport Efficiency Thermophoretic Deposition

- An temperature gradient from a hot gas to a cool wall produces a force on a particle that moves it down the gradient to the wall

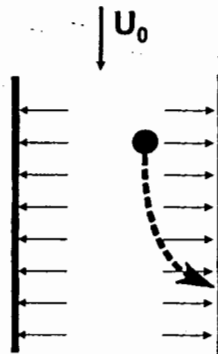


Transport Efficiency Thermophoretic Deposition

- An temperature gradient from a hot gas to a cool wall produces a force on a particle that moves it down the gradient to the wall
- Not easily characterized
 - Changes in temperature gradient
 - Requires more detailed calculation
- Thermophoretic deposition can be avoided by elimination of thermal gradients
 - Cool hot gas by dilution
 - Heat sampling probes initially in contact with hot sample gas

Transport Efficiency Diffusiophoretic Deposition

- Condensing vapor produces a net force on a particle driving it in the same direction as the vapor transport



Transport Efficiency Diffusiophoretic Deposition

- Particles are transported by diffusing gas
 - In the direction of the heavier gas in equimolar diffusion
 - In the direction of the diffusion gas in a single component diffusion, e.g., condensation, evaporation
- Diffusiophoretic deposition can be avoided by elimination of condensation in the sampling system
- An estimate of the fraction of particle removal by condensation is the mole fraction of the total gas that is condensed

Transport Efficiency Deposition in Chambers and Bags

- Samples may need to be taken into a sampling chamber and measured from there
- Model may require calibration to be useful
 - Coefficient of eddy diffusion is unknown
 - Collapsing bag during sampling will change dimensions
- Resuspension of particles from walls may be a consideration



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Transport Efficiency Deposition in Chambers and Bags

- Loss from gravitational settling and Brownian diffusion
- Penetration

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

- Loss coefficient

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

- Crump and Seinfeld (1981)



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Sampling Efficiency

- Sampling efficiency is the fraction of particles in the ambient environment that make it to the instrument for measurement
- Sampling efficiency is the product of Inlet efficiency and Transport efficiency

$$\eta_{\text{sampling}} = \eta_{\text{inlet}} \cdot \eta_{\text{transport}}$$

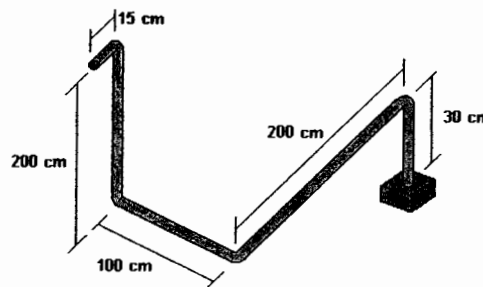


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Sampling Efficiency Example 1

- 1.11 cm diameter inlet
- 2.22 cm diameter tubing
- 545 cm total length
- 315 cm horizontal run
- 4 right angle bends
- 28 LPM sample flow
- $Re = 1790$
- $U_0 = 5.0$ m/s free stream velocity
- $U_0/U = 1.04$: near isokinetic

Schematic of Aerosol Sampling System tubing

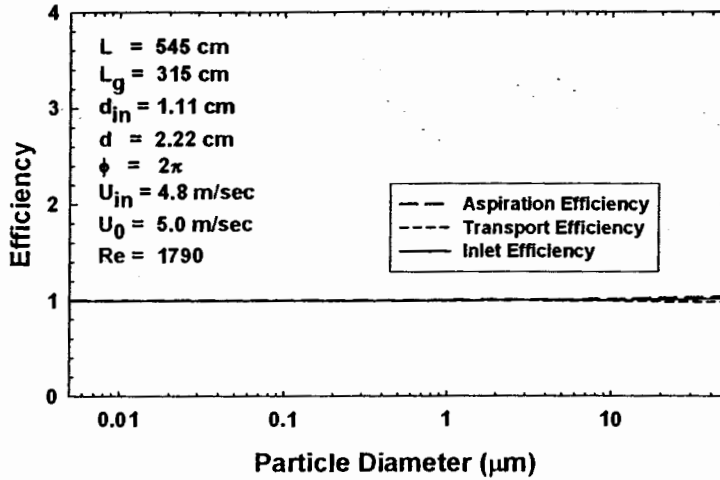


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inlet sample velocity

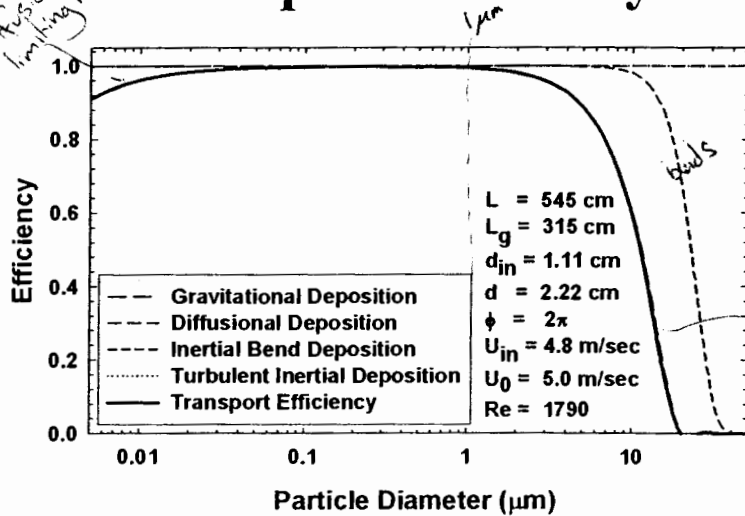
that length of the tube that is horizontal

Inlet Efficiency



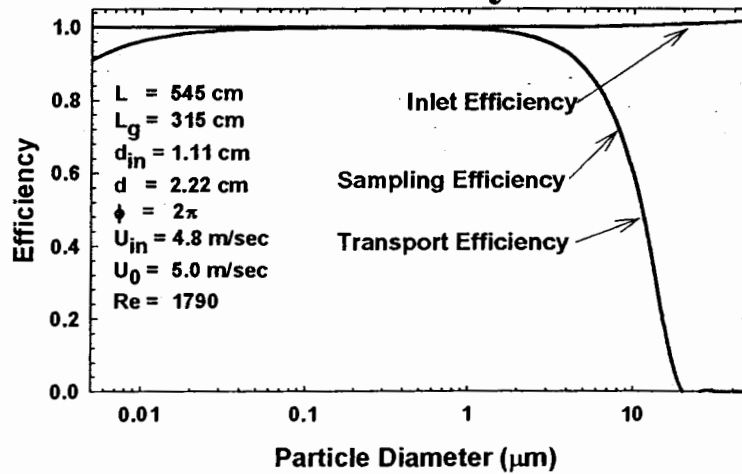
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Transport Efficiency



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Inlet, Transport, and Sampling Efficiency

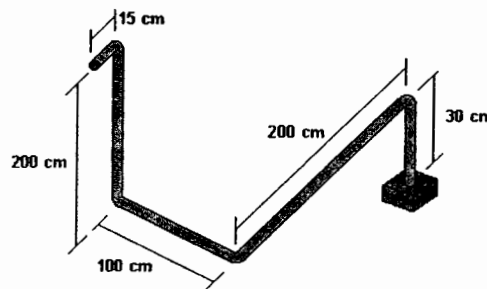


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Sampling Efficiency Example 2

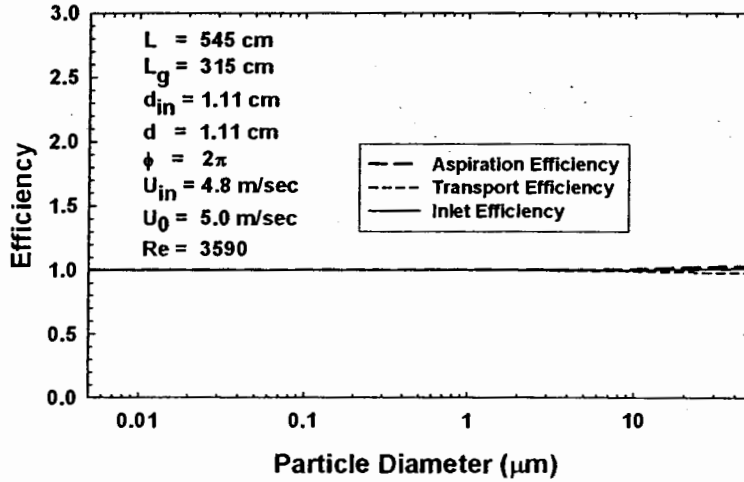
- 1.11 cm diameter inlet
- 1.11 cm diameter tubing
- 545 cm total length
- 315 cm horizontal run
- 4 right angle bends
- 28 LPM sample flow
- $Re = 3590$
- $U_0 = 5.0 \text{ m/s}$ free stream velocity
- $U_0/U = 1.04$: near isokinetic

Schematic of Aerosol Sampling System



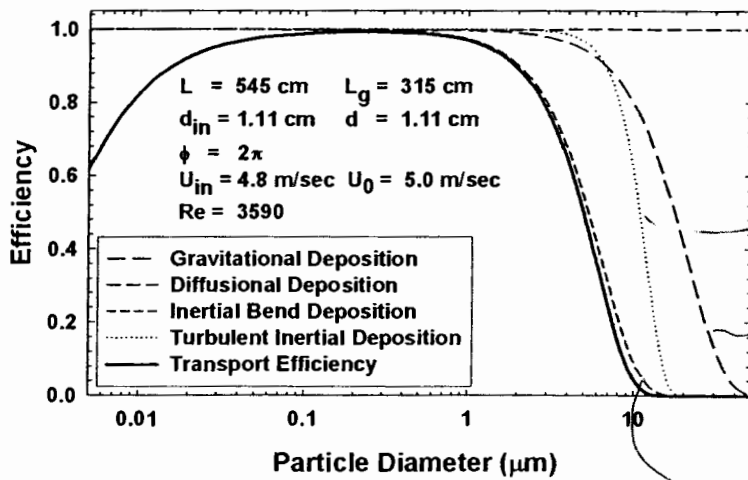
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Inlet Efficiency



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Transport Efficiency



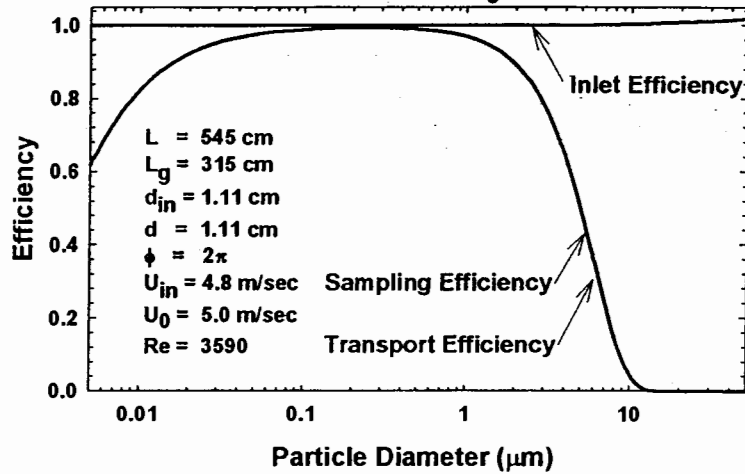
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high Re, turbulence is a problem

gravity less a problem in higher Re (less residence time)

inertial bend now a problem

Inlet, Transport, and Sampling Efficiency



Conclusions

- Use these correlations to design a Sampling and Transport system that will get at least half, preferably more than 90%, of the particles of interest to the measurement device
- Where the transport efficiency begins to fall rapidly, the uncertainty in calculated transport efficiency is high
- Correlations are just that, correlations of data taken in a system that is not necessarily the same as the one being used
- Sampling and Transport systems should be calibrated where possible

Conclusions

- **Isokinetic sampling should be used when possible**
 - New inlet designs may improve sampling velocity range
 - Inlet diameters should be on the order of a cm or larger to reduce free stream turbulence effects
- **Gas velocities should be large compared to particle settling velocities**
- **Avoid conditions where electrostatic, diffusiophoretic, or thermophoretic deposition could occur**
- **Small particles are lost by diffusion**
- **Large particles are lost by inertial and gravitational forces**
- **Sampling lines should be kept short with few bends**
- **Stokes numbers should be kept as low as possible**