Aerosol Sampling and Transport

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Tutorial 2

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John E. Brockmann Ph.D.

Sandia National Laboratories*

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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**

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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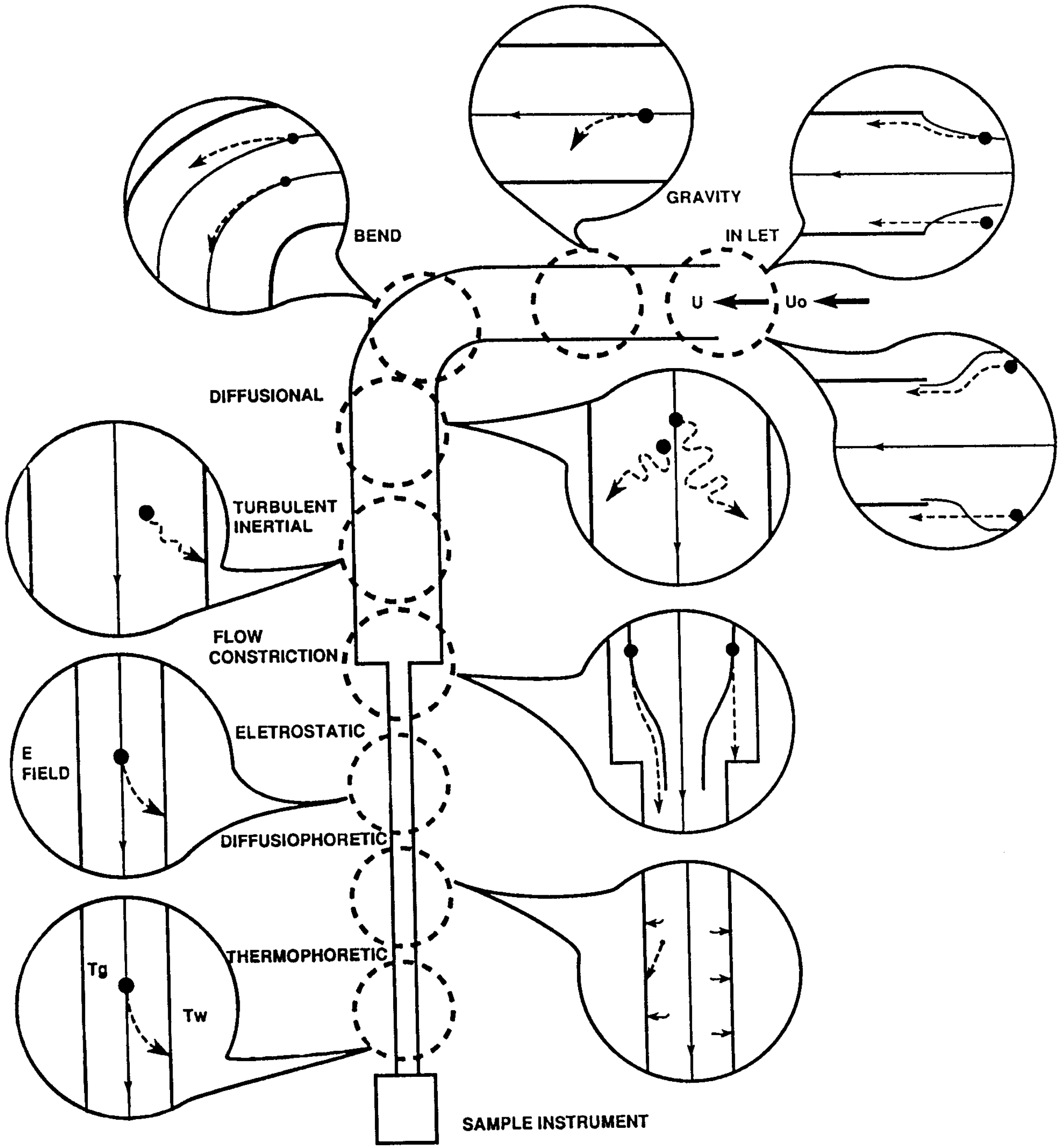
Particle Transport in Inlets and Transport Lines



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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** — $\xi = \pi DL/Q$

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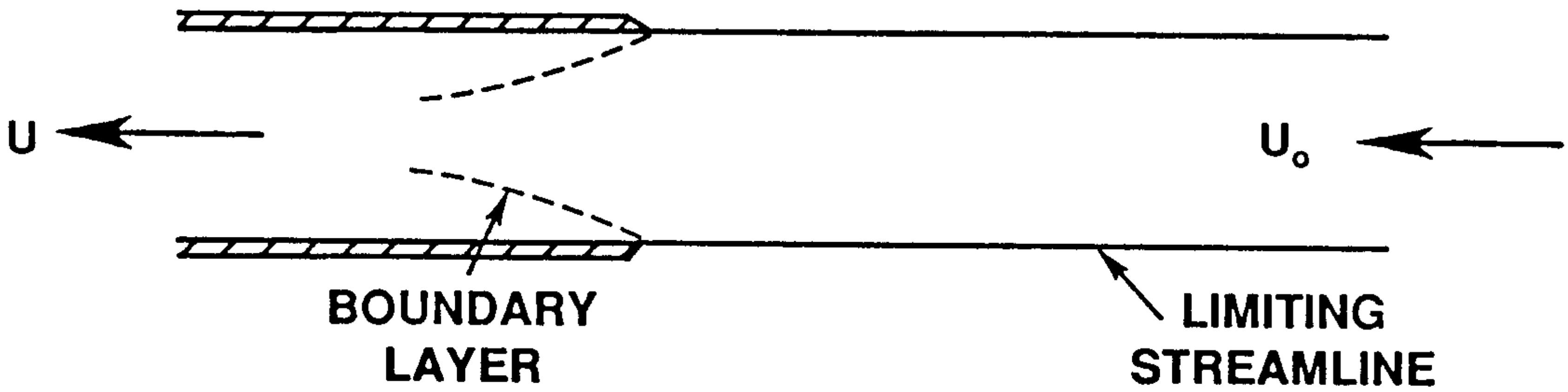
Isoaxial Isokinetic Sampling
$U = U_0$
(Iso-mean-velocity)



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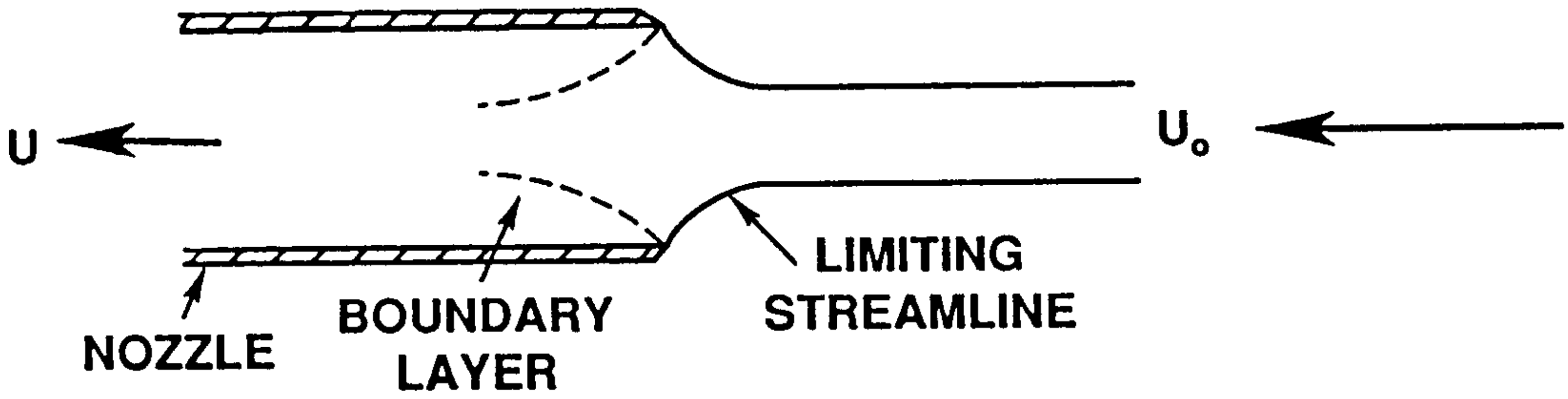
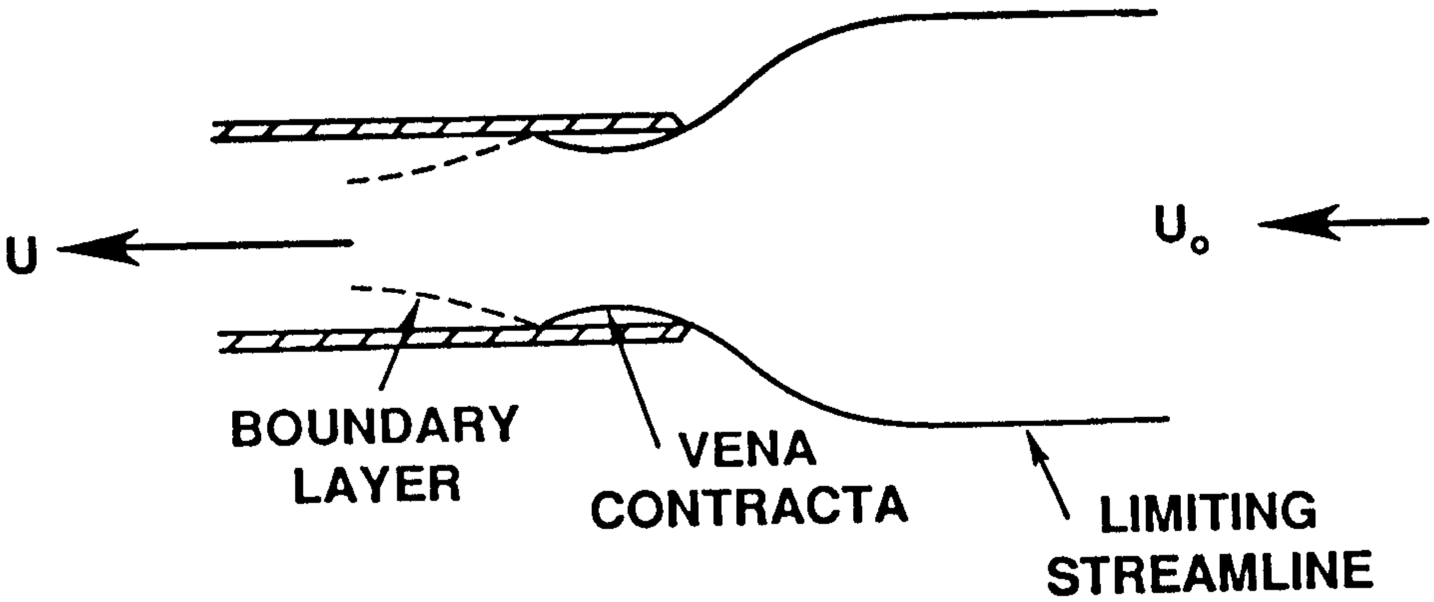
Isoaxial Sub-Isokinetic Sampling
$U < U_0$
(Sub-iso-mean-velocity)



Isoaxial Super-Isokinetic Sampling
$U = U_0$
(Iso-mean-velocity)



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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

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Aspiration Efficiency

- Stokes Number

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

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

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

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

- Belyaev and Levin (1972, 1974)

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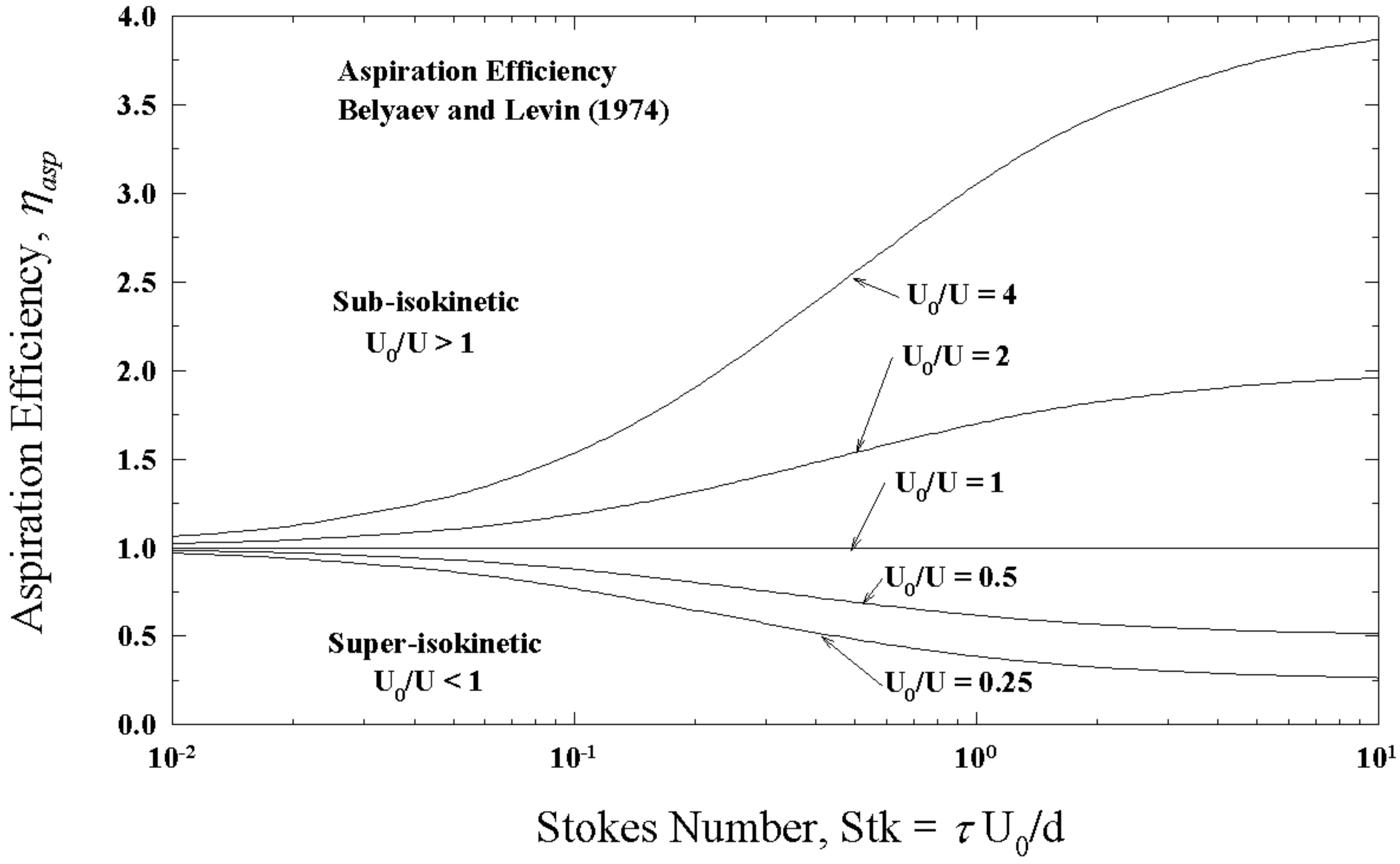
Aspiration Efficiency of a Thin-Walled Nozzle In Isoaxial Sampling Under Anisokinetic Conditions



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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 $U < U_0$

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

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

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

- Liu et al. (1989)

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Transmission Efficiency
Inertial Losses

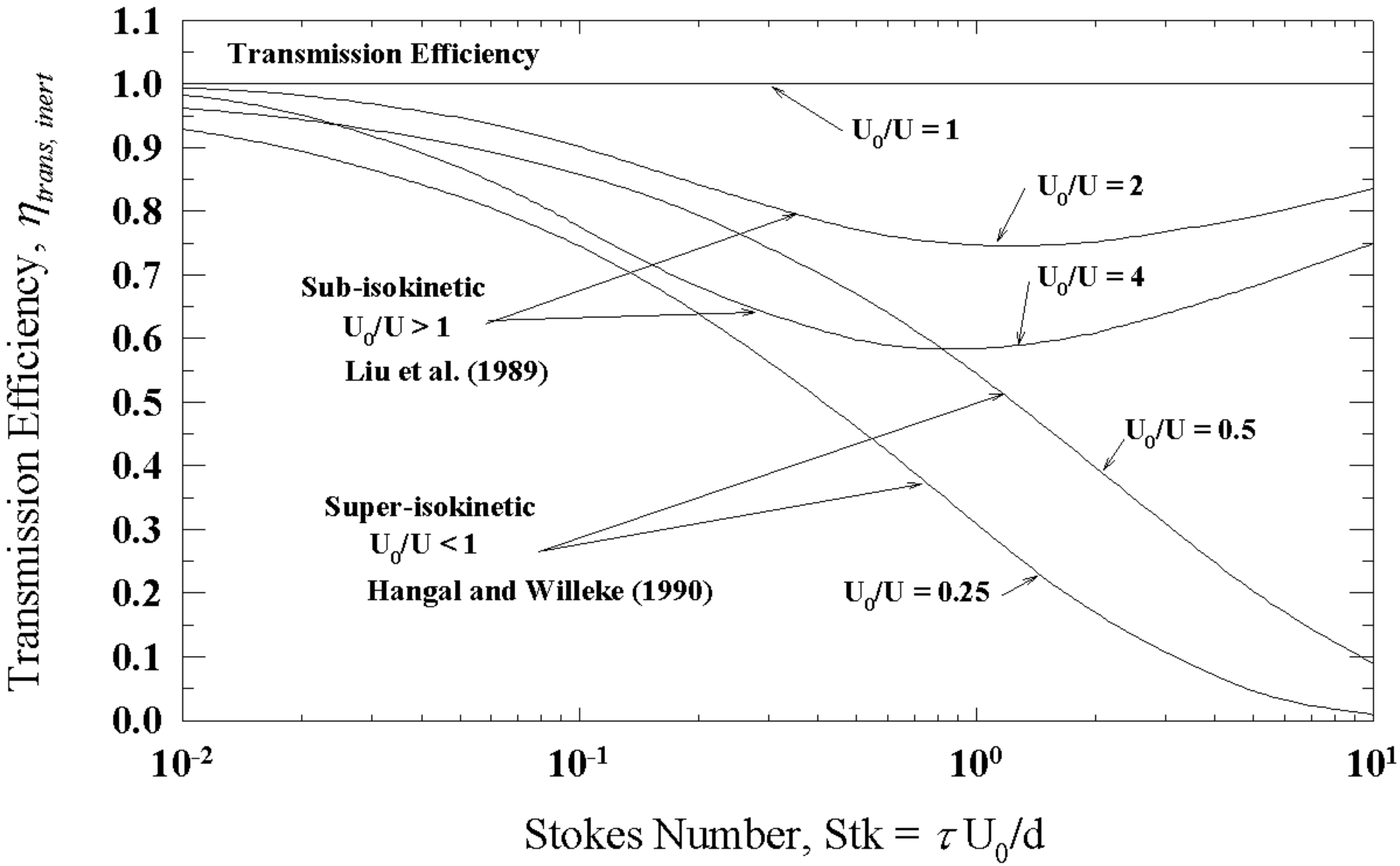
- Super-Isokinetic $U > U_0$ $\qquad Stk = \dfrac{\tau U_0}{d}$

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

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

- Hangal and Willeke (1990)

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



Transmission Efficiency
Saffman Lift Forces

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

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

- 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**

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

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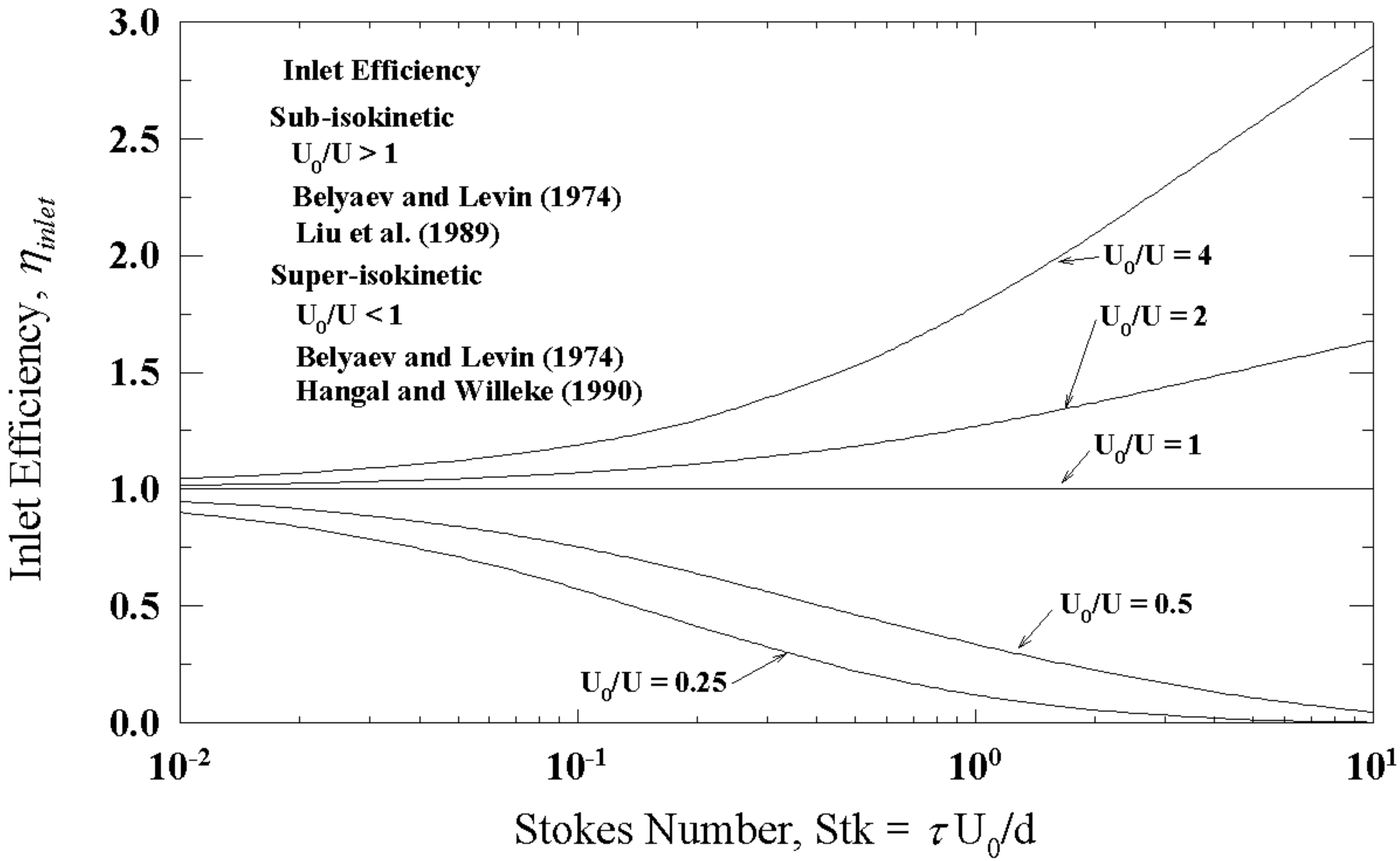
Inlet Efficiency for a Thin-Walled Nozzle In Isoaxial Sampling Under Anisokinetic Conditions



Sampling in Still Air

- Davies Criterion – Perfect Sampling

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

- Davies (1968)

- Agarwal and Liu Criterion – Efficiency > 90%

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

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

- Agarwal and Liu (1980)

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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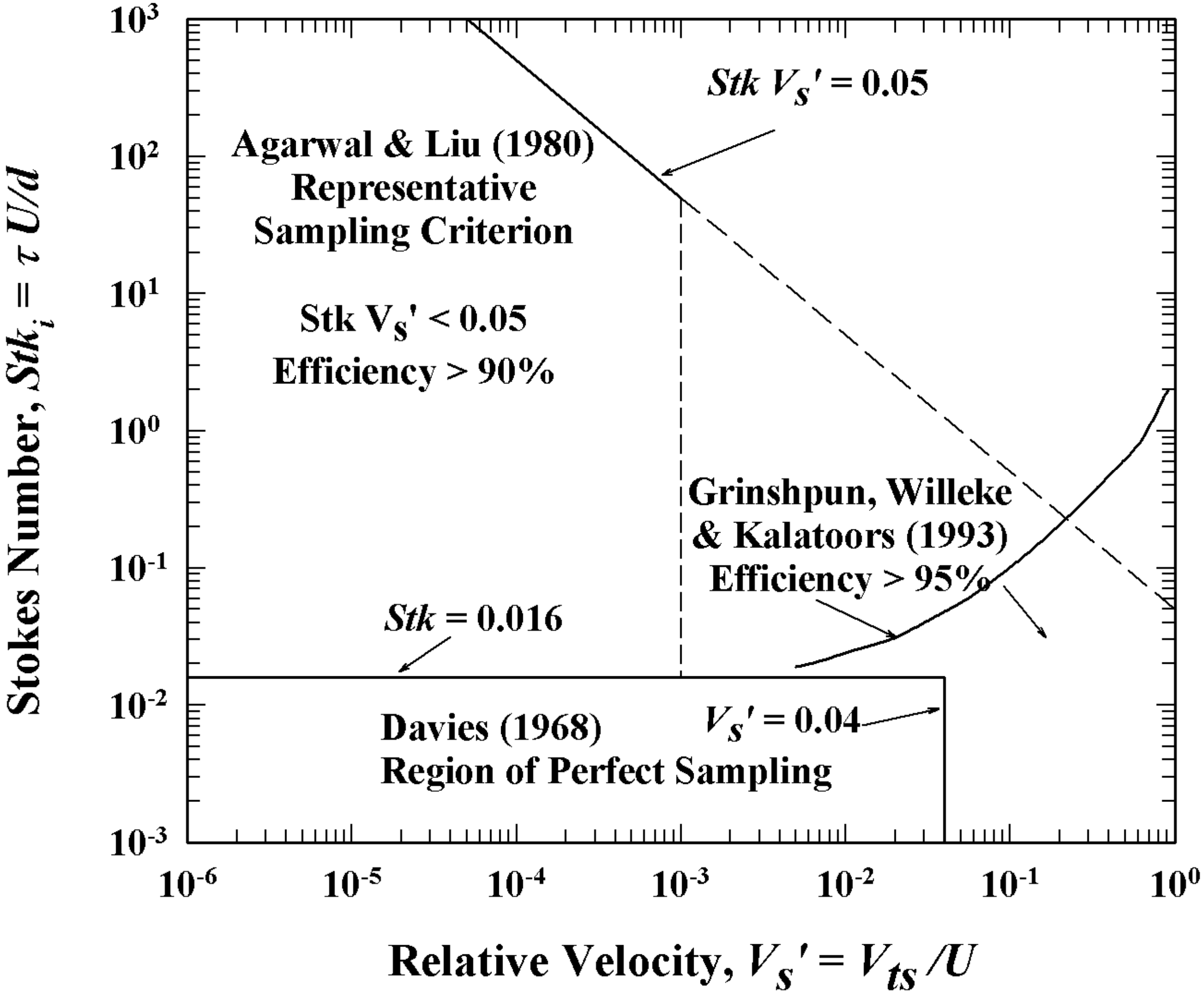
Still Air Sampling Criteria for Thin-Wall Nozzles



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 efficency over all the mechanisms and all the flow elements**

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

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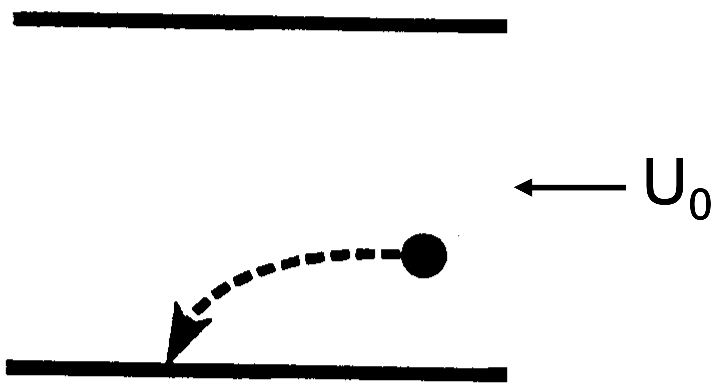
Transport Efficiency

- 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

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**

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

  - **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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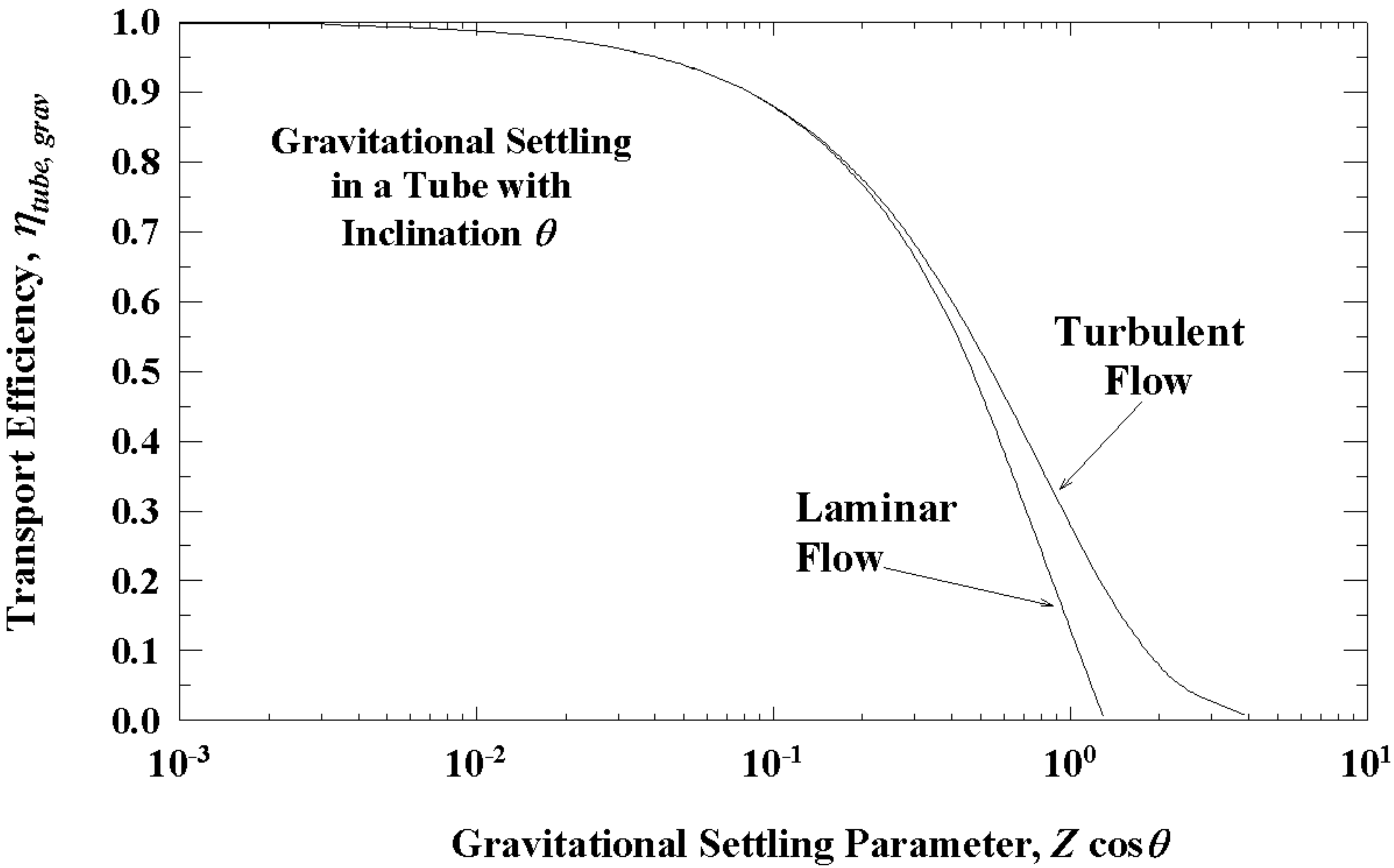
Gravitational Deposition In Tube Flow



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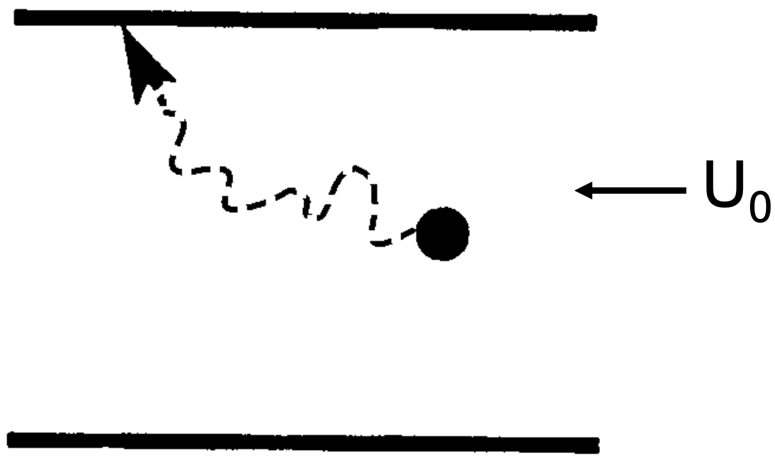
Transport Efficiency
Diffusional Deposition

- **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**

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

$$\text{for } \xi < 0.02$$

$$\eta_{\text{lam\_diff}} = 0.818\exp(-3.657\,\xi) + 0.097\exp(-22.3\,\xi) + 0.032\exp(-57\,\xi)$$

$$\text{for } \xi > 0.02$$

  - **Gormley and Kennedy (1949)**

- **In turbulent tube flow**

$$\eta_{\text{turb\_diff}} = \exp\left[-\xi^{2/3} \cdot 0.0187 \cdot \text{Re}^{13/24} \cdot \left(\frac{L}{d}\right)^{1/3}\right]$$

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

  - **Friedlander (1977)**

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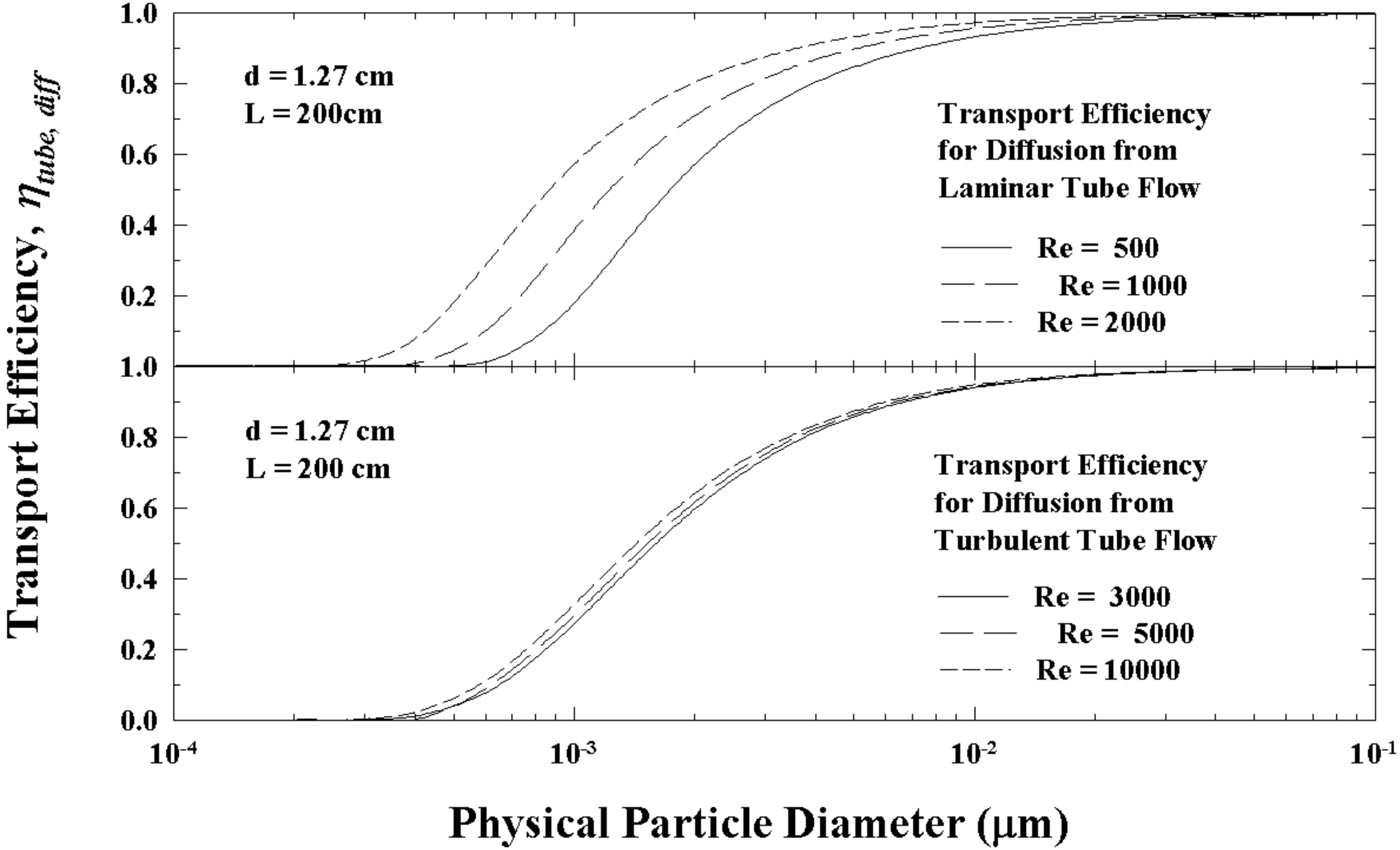
Diffusional Deposition In Tube Flow



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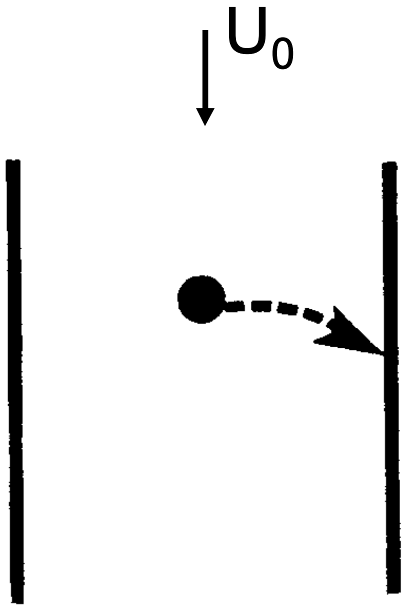
Transport Efficiency
Turbulent Inertial Deposition

- **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** $Stk = \frac{\tau U}{d}$ $\mathrm{Re} = \frac{\rho U d}{\mu}$
- **Model**

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

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

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

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

- **Liu and Agarwal (1974)**

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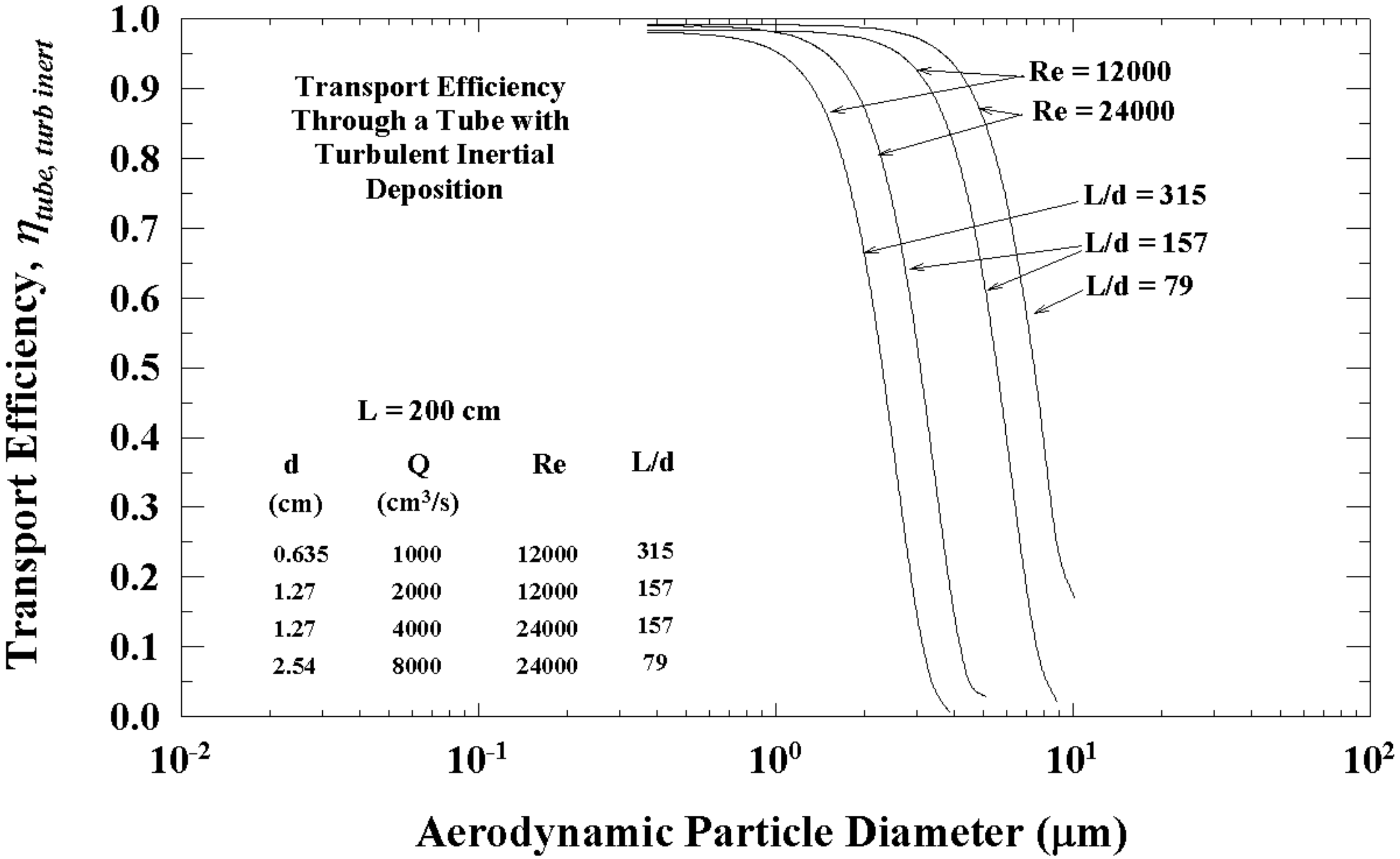
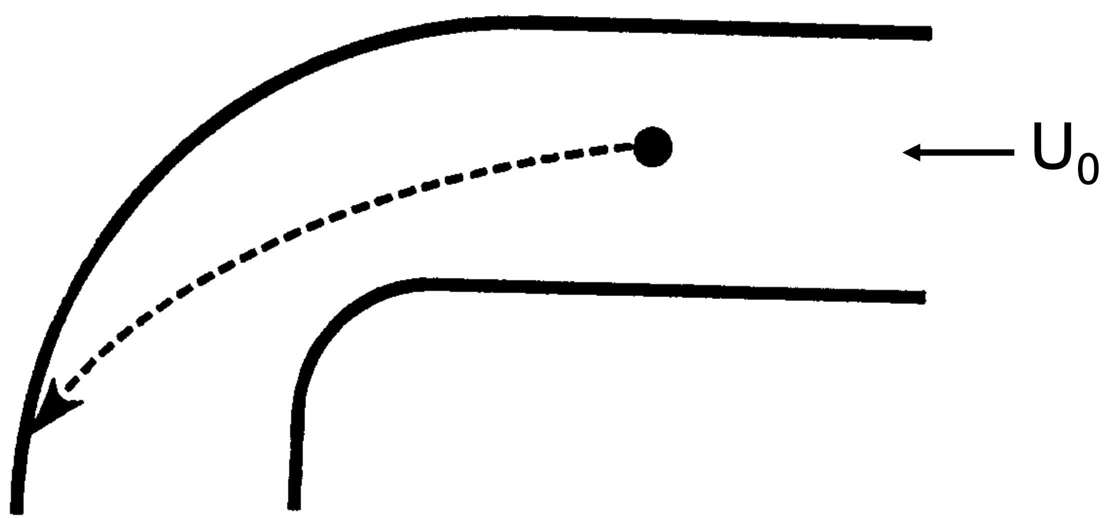
Turbulent Inertial Deposition In Tube Flow



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 inertial 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**

Crane and Evans (1977)

$$\eta_{\text{lam\_bend}} = 1 - Stk\,\varphi$$

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

Fit to Pui et al. (1987) data

- **In turbulent tube flow**

$$\eta_{\text{turb\_bend}} = \exp\left[-\ 2.823\, Stk\, \varphi \right]$$

Pui et al. (1987)

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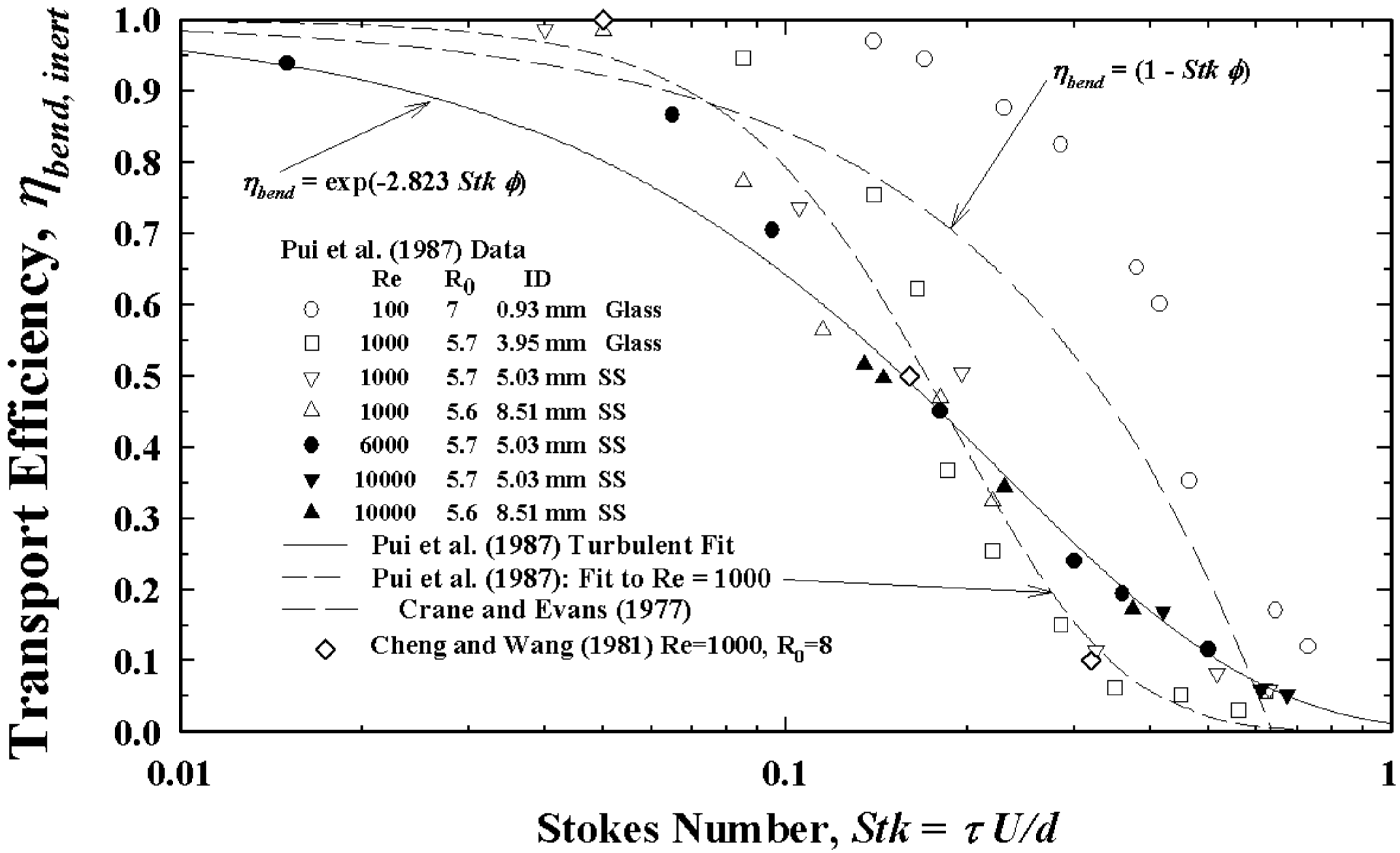
Inertial Deposition In A Bend
Data for 90 Degree Bend



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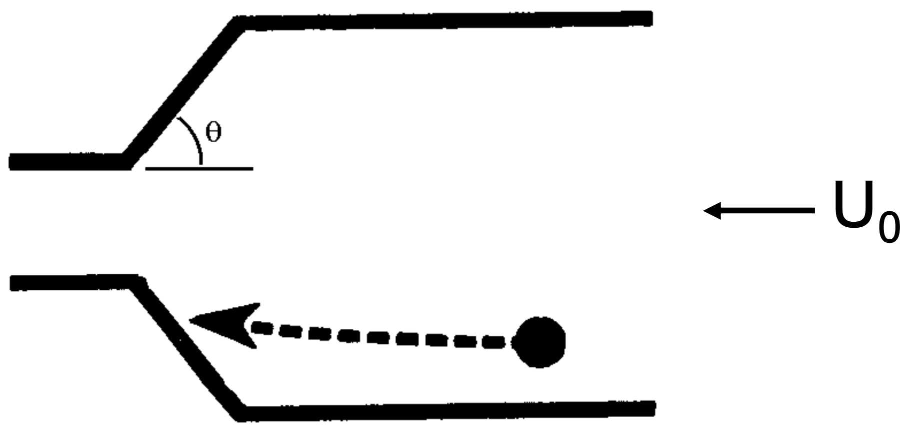
Transport Efficiency
Inertial Deposition in Flow Constrictions

- **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 inertial 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 Muyshondt et al. (1996) to make estimates

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Transport Efficiency
Inertial Deposition in Flow Constrictions

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

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

Muyshondt, McFarland. and Anand (1996)

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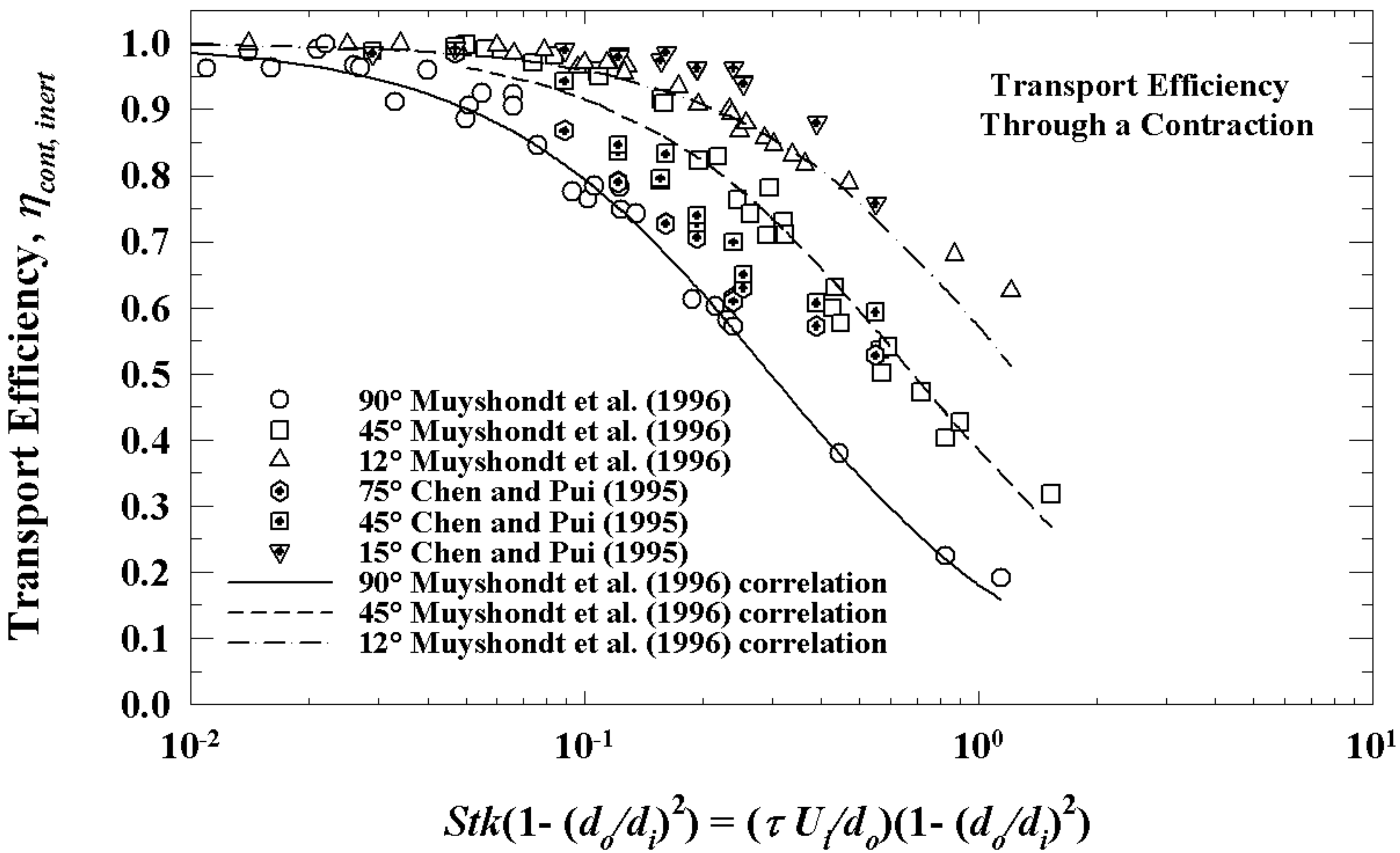
Inertial Deposition in a Flow Contraction in Tube Flow



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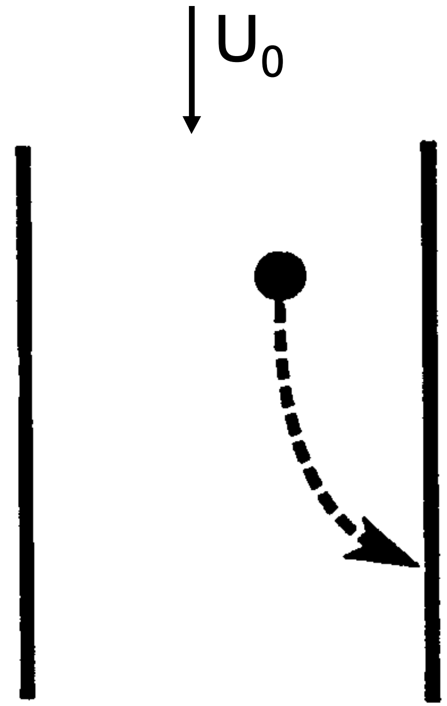
Transport Efficiency Electrostatic Deposition

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

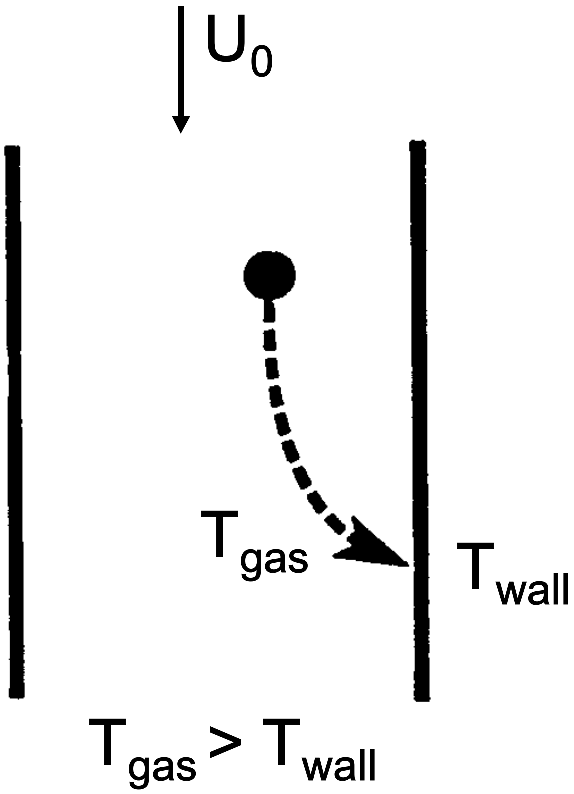


Transport Efficiency Electrostatic Deposition

- **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^{TM} is acceptable**
  - **Avoid Teflon^{TM} and Polyflow^{TM} tubing**

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**



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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**
- **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**

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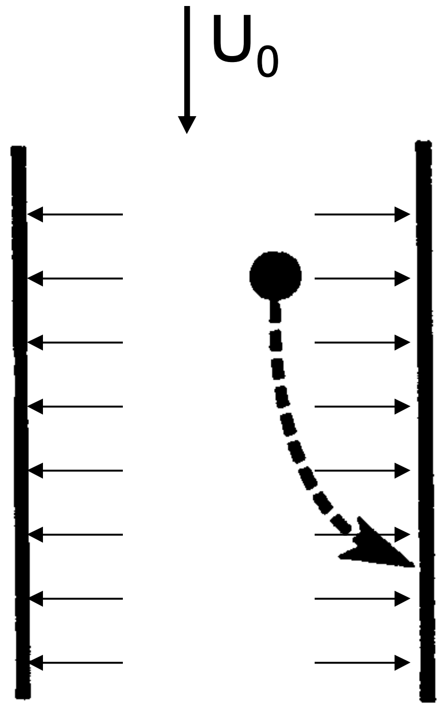
Transport Efficiency Diffusiophoretic Deposition

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



Transport Efficiency Diffusiophoretic Deposition

- **Particles are transported by diffusing gas**
  - **In the direction of the heavier gas in equimolal diffusion**
  - **In the direction of the diffusion gas in a simgle 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 conensed**

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

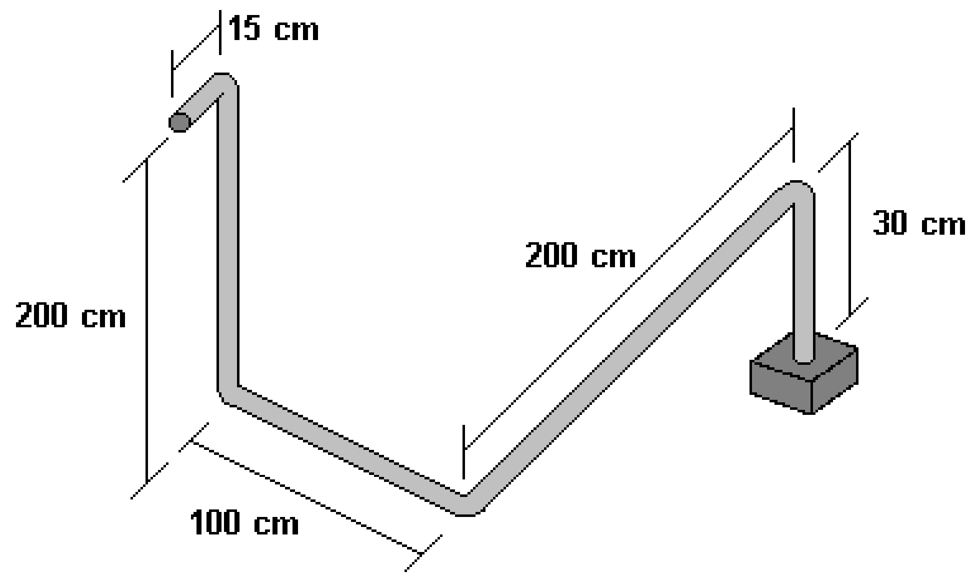
- **Sampling efficiency is the fraction of particles in the ambient environment that make it to the indtrument for measurement**
- **Sampling efficiency is the product of Inlet efficiency and Transport efficiency**

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

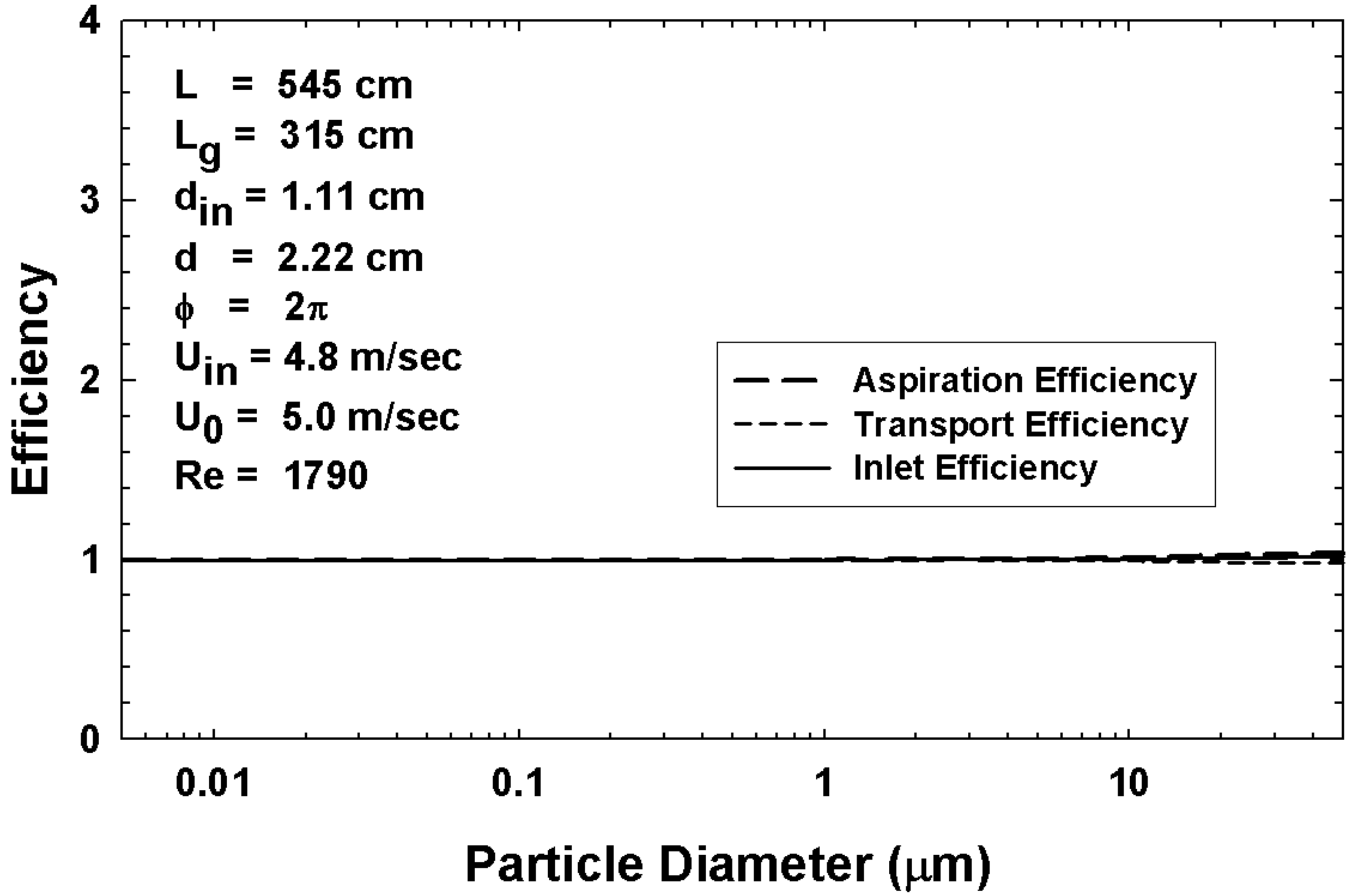
Sampling Efficiency Example 1

- 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



Inlet Efficiency



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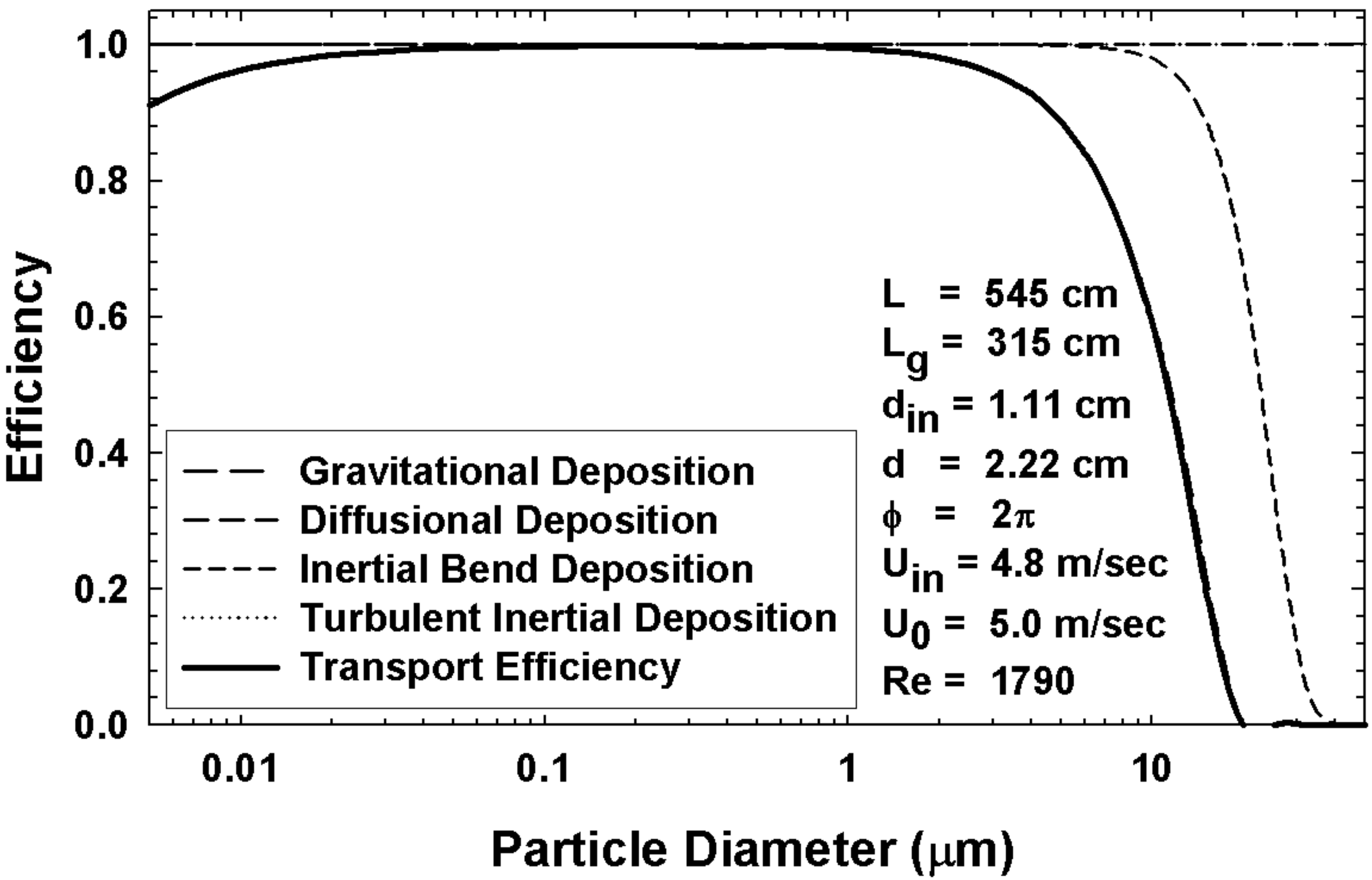
Transport Efficiency



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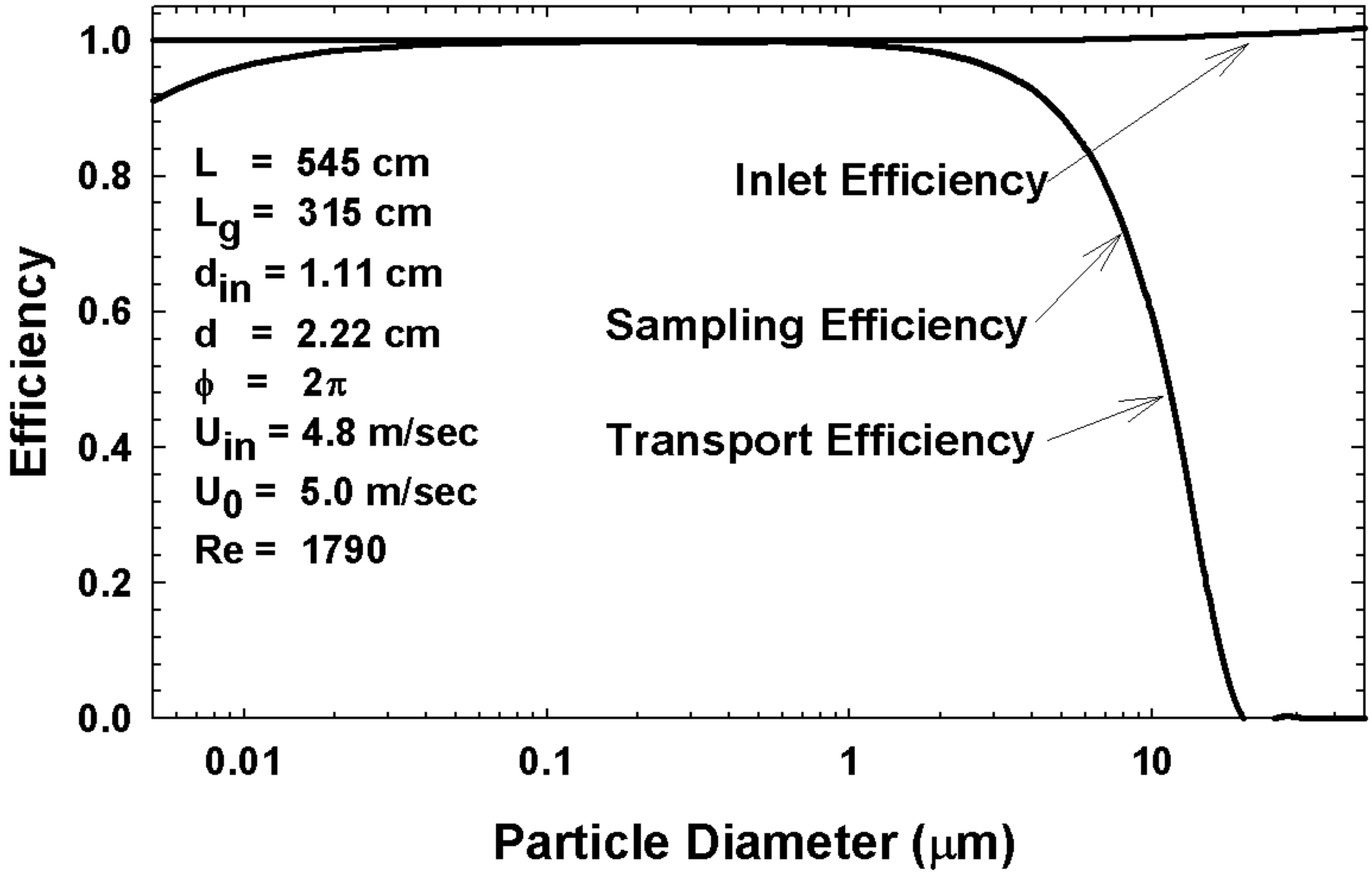
Inlet, Transport, and Sampling Efficiency



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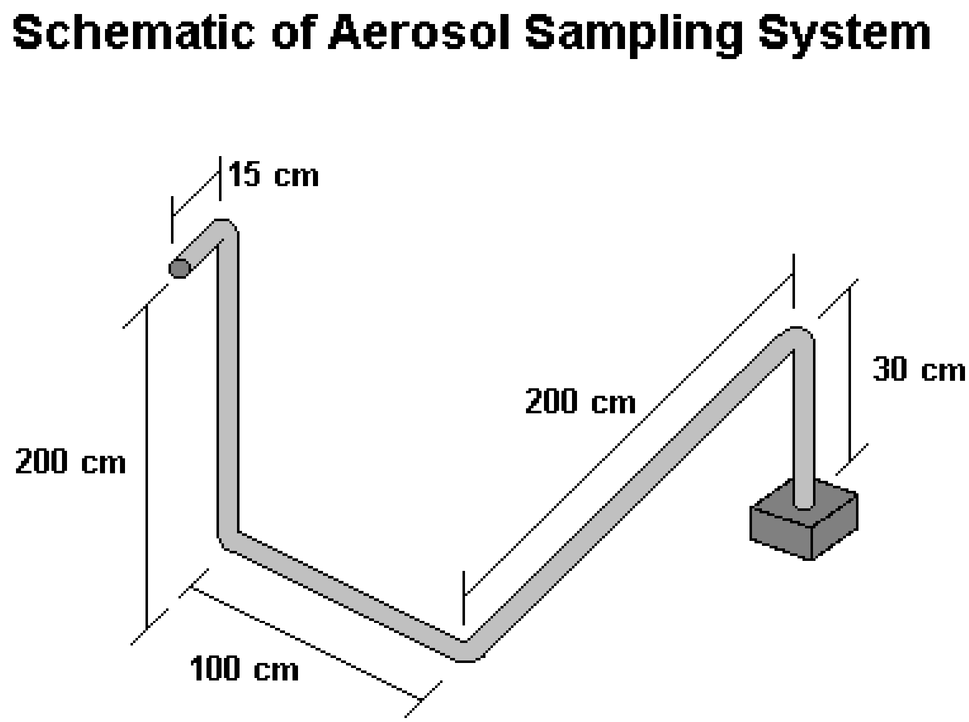
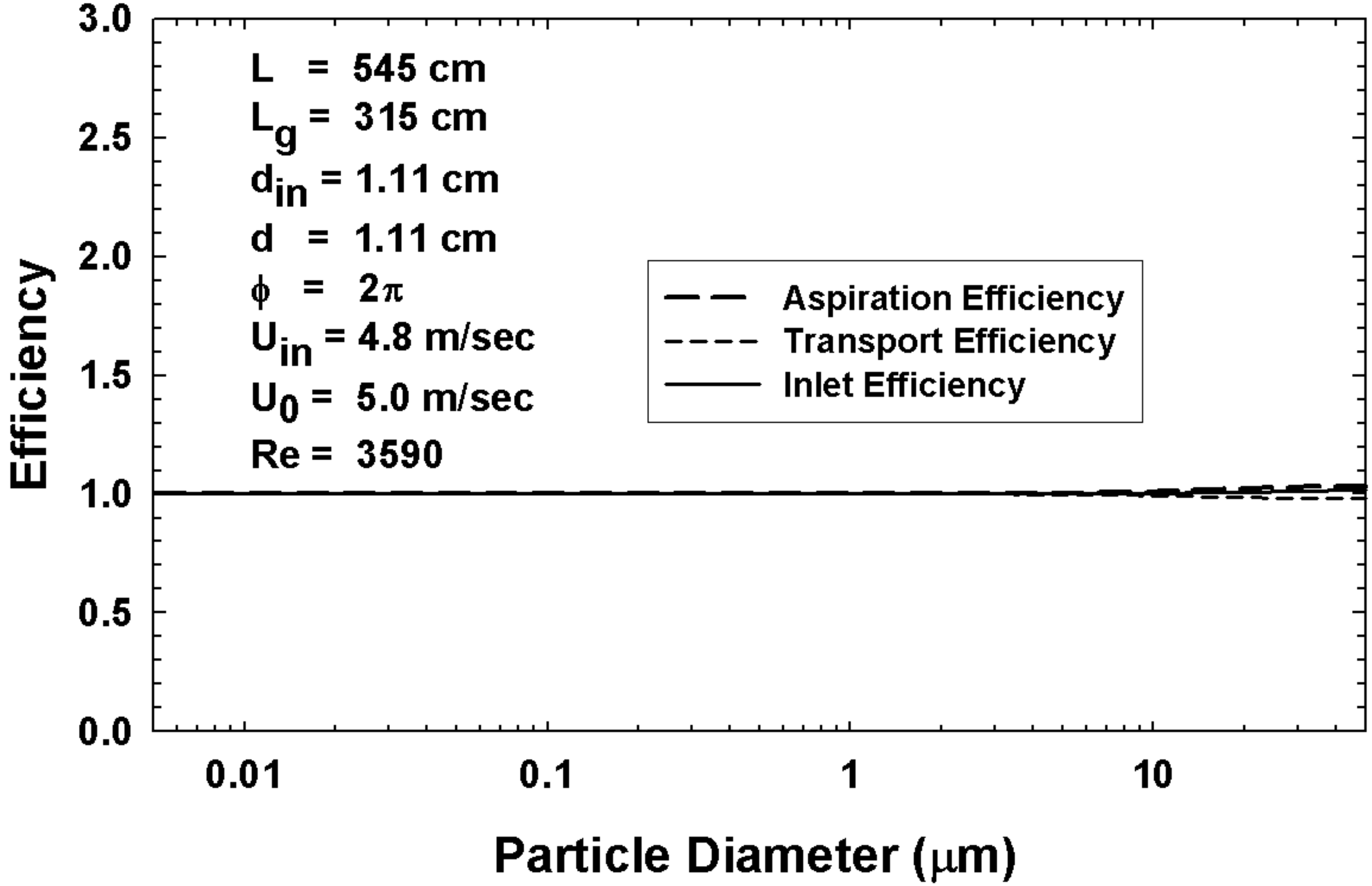
Sampling Efficiency Example 2

- 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 m/s free stream velocity
- U_0/U = 1.04 : near isokinetic



Inlet Efficiency



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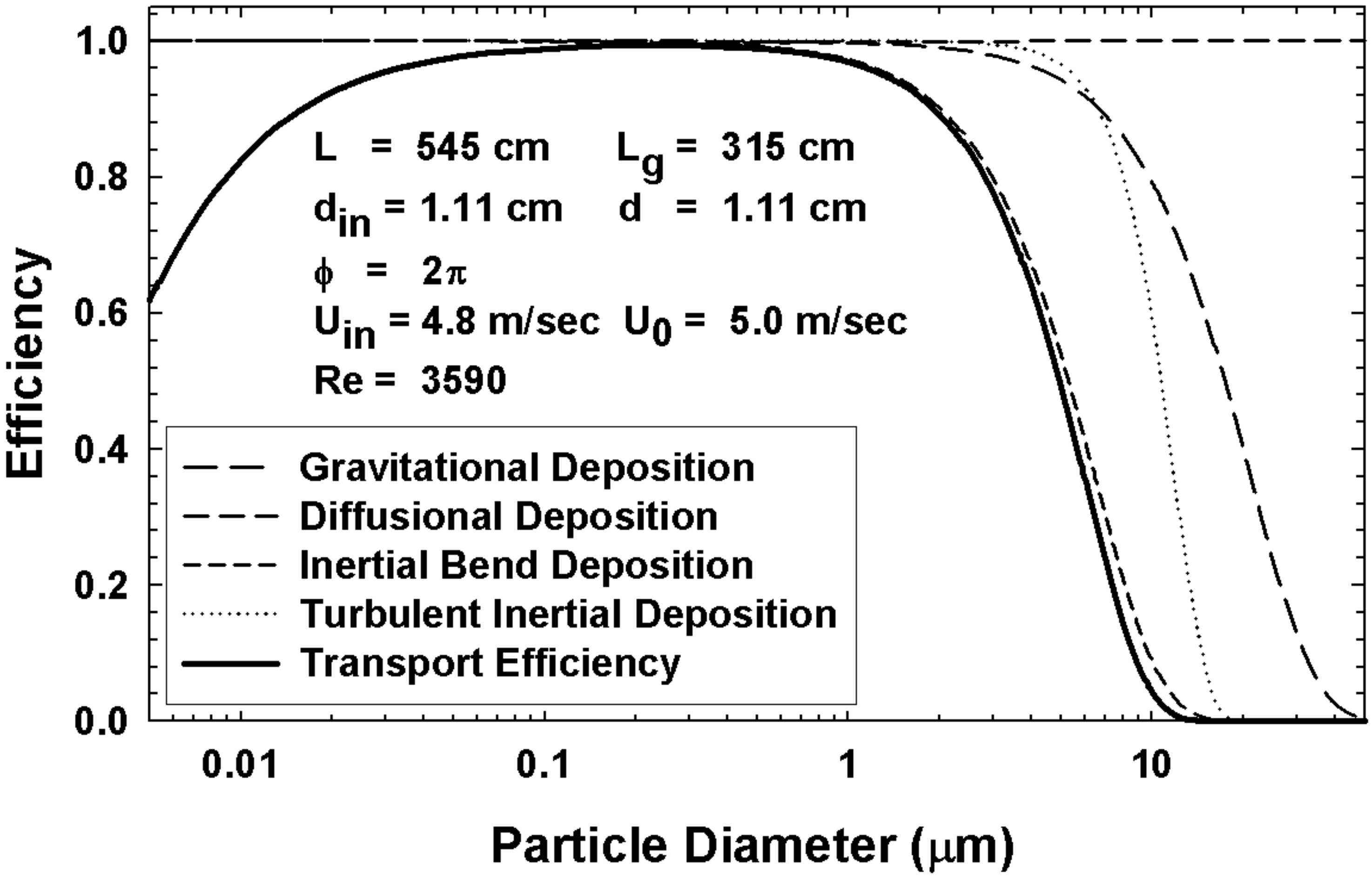
Transport Efficiency



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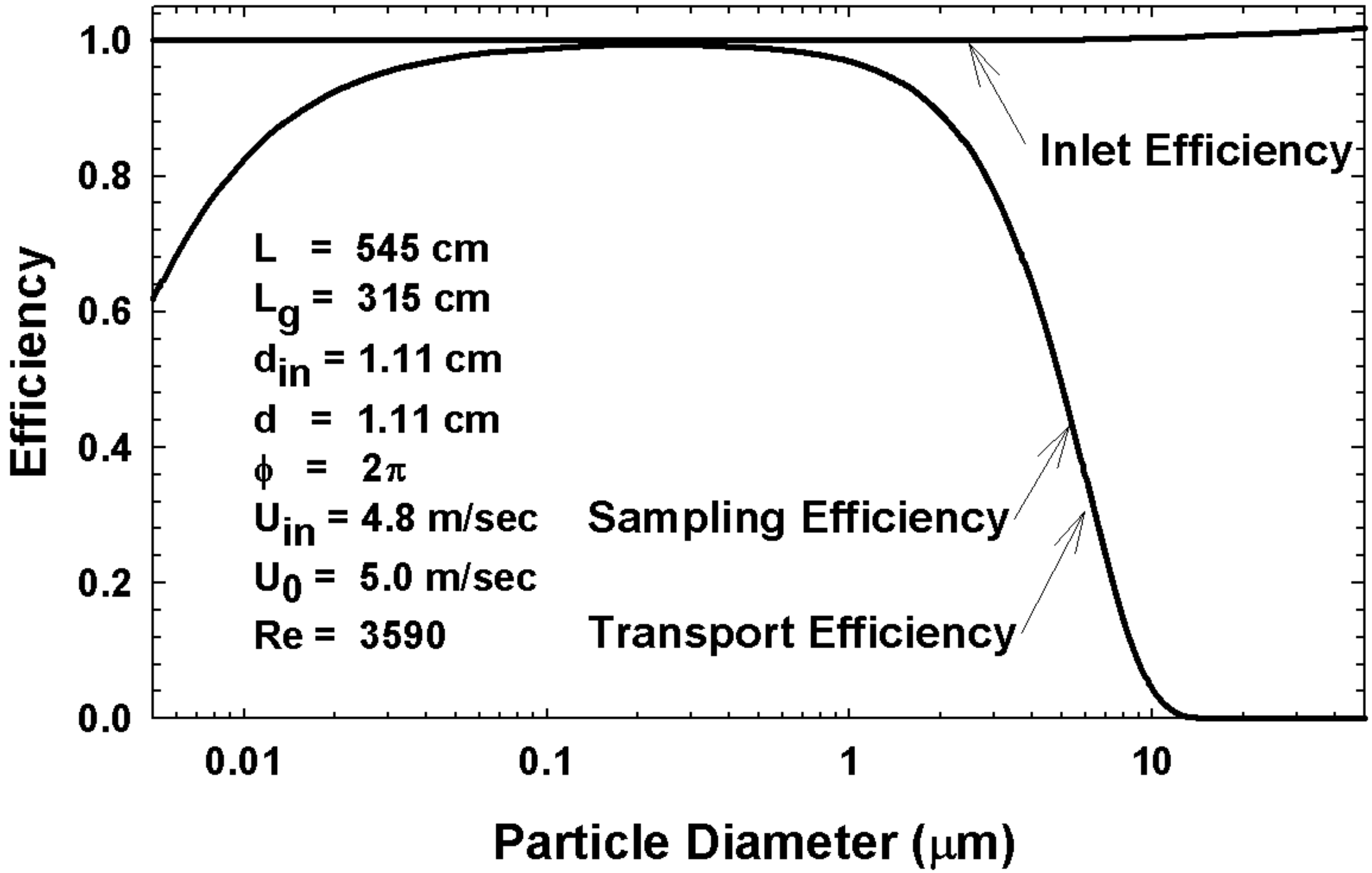
Inlet, Transport, and Sampling Efficiency



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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 diamters 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 veloctities
- Avoid conditions where electrostatic, diffusiophoretic, or thermophoretic deposition could occur
- Small particles are lost by diffusion
- Large particles are lost by inertial and gravitaional forces
- Sampling lines should be kept short with few bends
- Stokes numbers should be kept as low as possible