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स्वागत!

Aerosol Sampling and Transport

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TSI, Global Product Manager
September 22, 2011

This webinar will begin at:
Greenwich Mean Time (GMT): Thursday, 16:00

UK, London	5:00pm
Germany, Berlin	6:00pm
US CDT	11:00am
US PDT	9:00am
Brazil, São Paulo	1:00pm

Global Aerosol Education

Interactive Webinar Format

1. **Connection Information**

   Visual: link information included in login e-mail

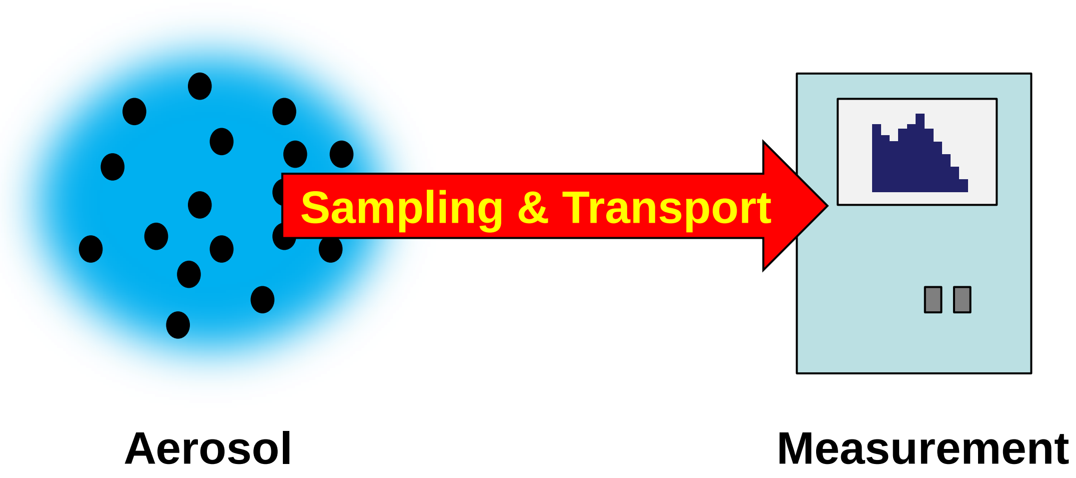
   Audio

   1. We are now able to 'live stream' the audio. If you have a computer with a speaker, you should automatically hear the audio if the speaker is properly configured for your computer.
   2. If you do not have a computer speaker available you can dial in via the telephone. Phone numbers and access codes were included with e-mail login information.
2. **Sound quality:** for large groups, the sounds quality is much better if the conference attendees have their telephones on 'mute'.
3. **Multi-media - Interactive chat:** Please send questions via chat during and after the presentation.
4. **Follow-up:** an e-mail including a Adobe pdf file of presentation will be sent to registered attendees.
5. **Recording:** this webinar is being recorded for future reference.

Overview

- Motivation
- Some physics (sorry for that!)
- Particle losses during transport
- Sample inlets and their efficiency
- Flow mixing and flow splitting
- Aerosol conditioning
- Good practice

Motivation



- If an aerosol measurement cannot be made in situ, sampling and transport can’t be avoided.
- Sampling and transport will always bias the measurement.
- **This webinar is about minimizing the bias**

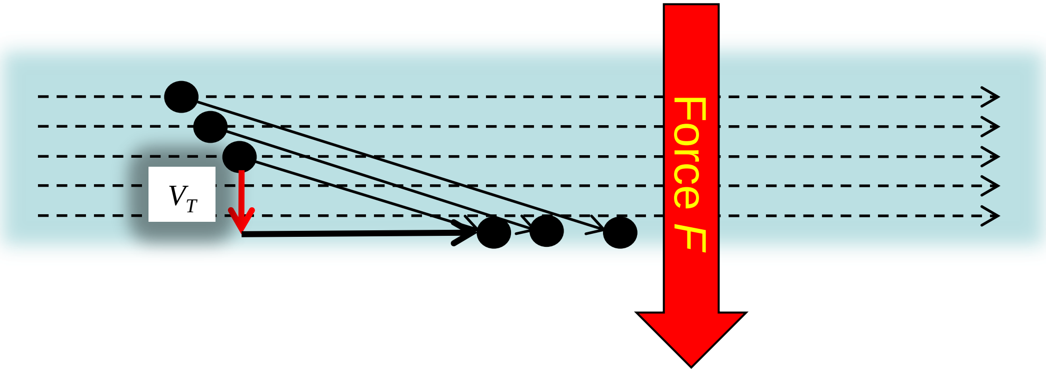
Some Basics

- Small particles which reach the wall of a tube are captured and stick to the wall due to van-der-Waals force.
  - To avoid transport losses, transport tubing must be optimized such that as few as possible particles reach the wall.
- External forces acting on the particle are required to accelerate the particles towards the wall of the transport tubing.
- Unfortunately, some of these forces are always present.

Mechanical Mobility B

- Consider straight laminar flow lines in a transport tube.
- Without the influence of external forces, particles would simply follow the straight flow lines of the gas flow.

Mechanical Mobility B



- A force F will move the particle in its direction; if F is constant, the particle will reach a terminal velocity V_T.
- V_T results from the balance between F and the drag force counteracting the particle‘s movement in the gas.
- The ratio V_T / F is called mechanical mobility B

$$B = \frac{V_T}{F}$$

Mechanical Mobility in the Stokes Region

- In the so-called Stokes region (Re_p<1), both drag force and mechanical mobility are functions of the particle diameter *d* and the gas properties

$$B = \frac{C_C(d)}{3\pi\eta d} \qquad \mathrm{Re}_p = \frac{\rho_{gas} V_P d}{\eta} < 1$$

For V_p = 10 cm/s and d = 100 µm, Re_p is 0.67 (ambient air)

- where, η is the viscosity of the gas and $C_c(d)$ is the slip correction factor (Cunningham, 1910):

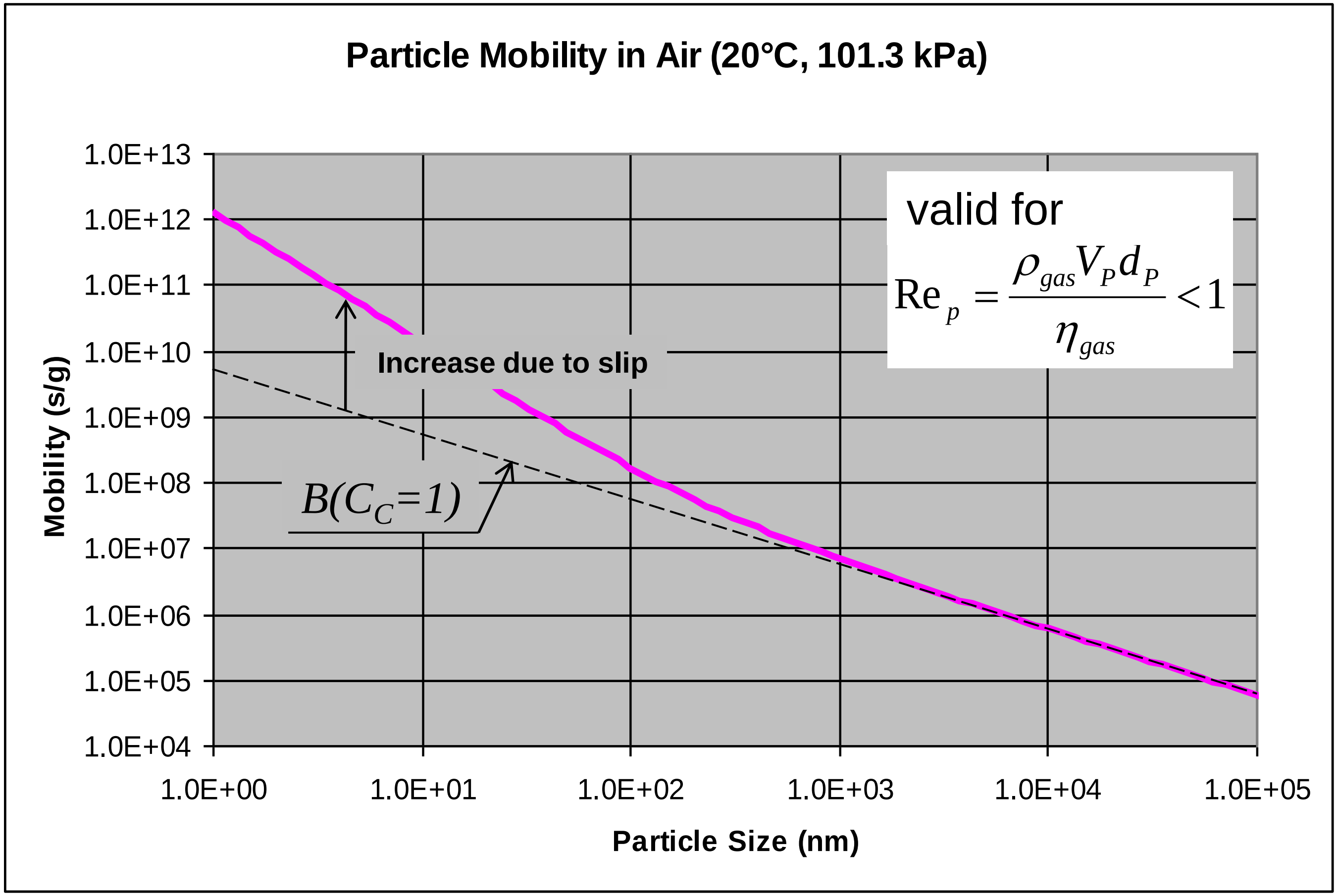
$$C_C(d) = 1 + \frac{\lambda}{d}\left[2.330 + 0.966\exp\left(-0.4985\frac{d}{\lambda}\right)\right]$$

[ISO 15900]

- λ is the mean free path of the gas molecules

  λ = 6.73·10^{-8} m for dry air at 296.15 K (23°C) and 101.3 kPa) [ISO 15900]

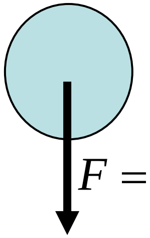
Mechanical Mobility



- Particle mobility decreases with increasing particle size
- With equal external force, small particles move faster (e.g. towards a tube wall).
- *B* does not depend on the nature of force *F*
- $V_T=BF$ can be applied to all forces which move a particle towards the tube wall

A Simple Example

Gravity as External Force (Linear Acceleration)



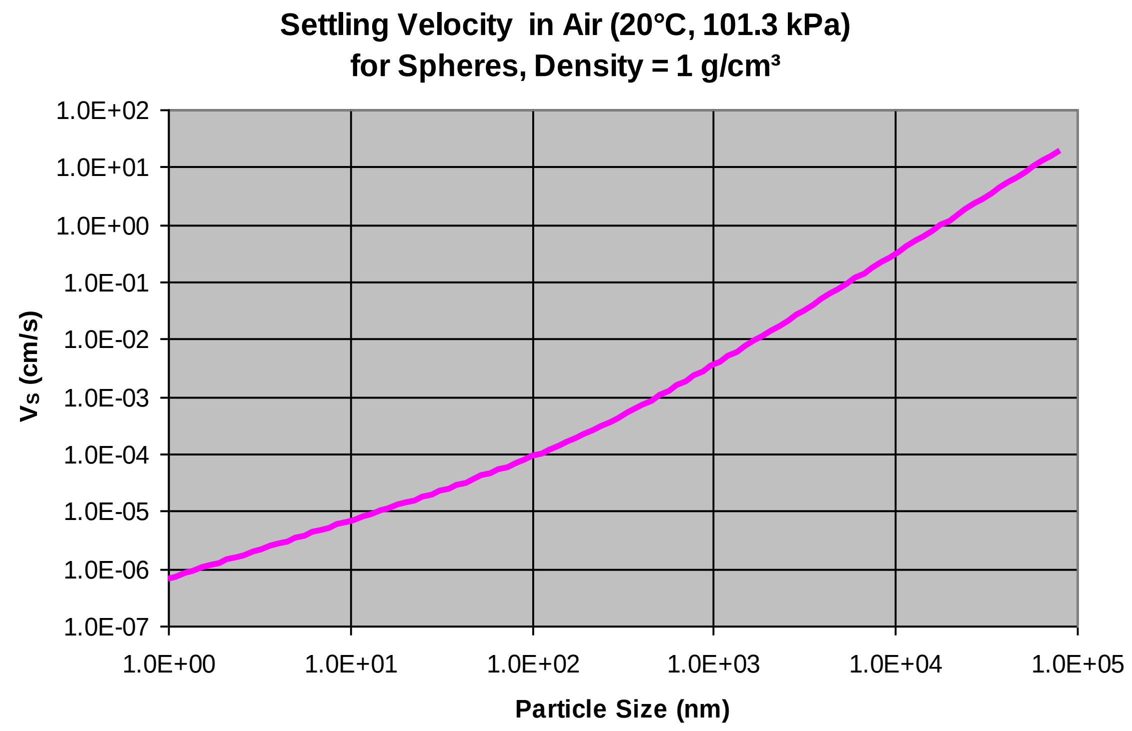
$$V_S = B \cdot F$$

$$F = mg = \frac{\pi}{6} d^3 \rho_P g$$

(for $\rho_p >> \rho_{gas}$)

Gravitational force increases with d^3

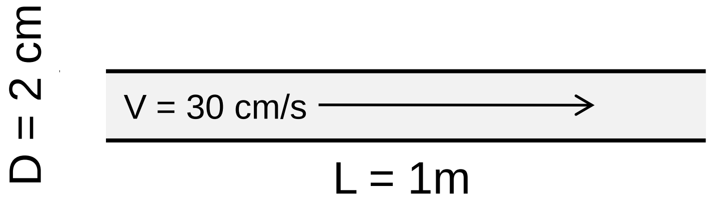
→ Gravity moves large particles much faster than small particles.



Settling Velocity in Air (20°C, 101.3 kPa) for Spheres, Density = 1 g/cm³

For particles larger than 1 µm, consider gravitational losses!

Gravitational Loss

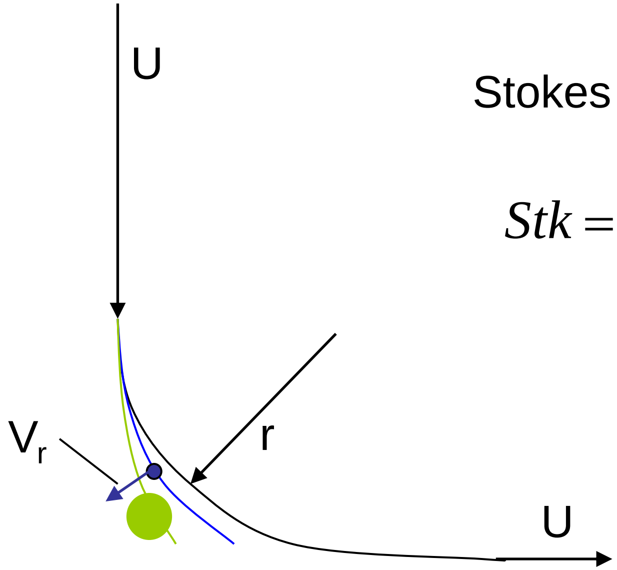


Particle Diameter	Transport Loss
100 µm	100 %
10 µm	89 %
1 µm	1.5 %
0.1 µm	0.04 %

- Calculated for air at 101.3 kPa and 20°C.
- Spherical particles with density of 1 g/cm³
- Horizontal tubing

- Large particles are lost in horizontal tubing
- Vertical tubing (downward flow) has no gravitational loss
  - But: large particles arrive earlier
- Vertical tubing (upward flow) lets only particles with settling velocity $V_T < V$ penetrate.
  - But: large particles arrive with delay.

Centrifugal Accelaration and Curvelinear Motion

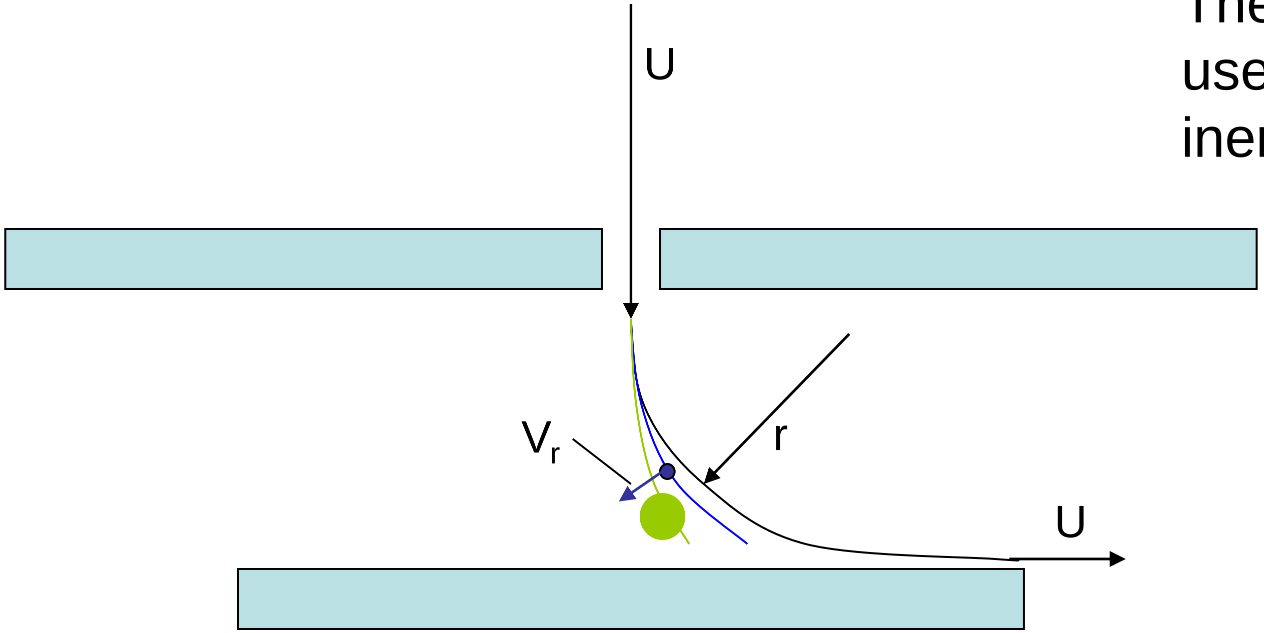


Stokes Number Stk:

$$Stk = \frac{m_p \cdot B \cdot U_{gas}}{r}$$

$$V_r = F_r \cdot B = m_p \cdot a_r \cdot B \approx \rho_p \cdot \frac{\pi d^3}{6} \cdot \frac{U_{gas}^2}{r} \cdot B = Stk \cdot U_{gas}$$

Centrifugal Accelaration and Curvelinear Motion

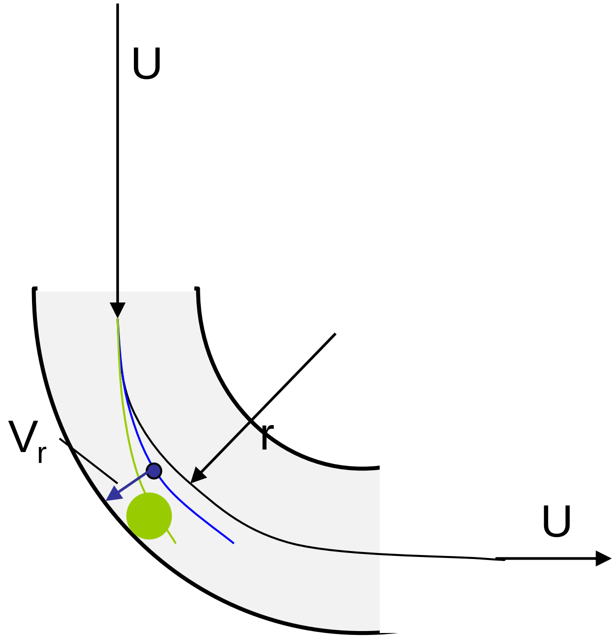


The principle is used e.g. in the inertial impactor

$$V_r = F_r \cdot B = m_p \cdot a_r \cdot B \approx \rho_p \cdot \frac{\pi d^3}{6} \cdot \frac{U_{gas}^2}{r} \cdot B = Stk \cdot U_{gas}$$

TRUST. SCIENCE. INNOVATION.

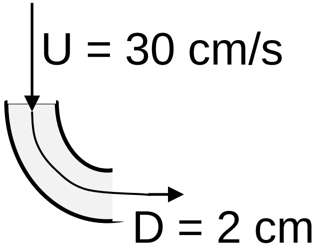
Centrifugal Accelaration and Curvelinear Motion



However, it also works when particles have to pass through bent tubing.

$$V_r = F_r \cdot B = m_p \cdot a_r \cdot B \approx \rho_p \cdot \frac{\pi d^3}{6} \cdot \frac{U_{gas}^2}{r} \cdot B = Stk \cdot U_{gas}$$

Particle Loss in Bent Tubing



Particle Diameter	Transport Loss at U = 30 cm/s	Transport Loss at U = 100 cm/s
100 µm	73 %	100 %
10 µm	0.7 %	2.5 %
1 µm	0.01 %	0.3 %
0.1 µm	0.0002 %	0.0007%

Same mechanism also applies for abrupt contractions in tubing, where the flow lines are bent.

- Calculated for air at 101.3 kPa and 20°C.
- Spherical particles with density of 1 g/cm³
- Laminar Flow

Brownian Diffusion

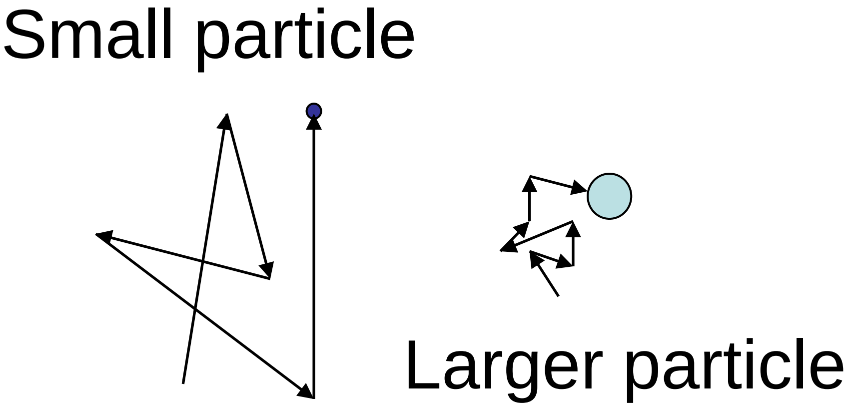
- Particle motion due to energy exchange (collisions) with surrounding gas molecules
- Diffusion coefficient, mean diffusion displacement and mean diffusion velocity increase with decreasing particle size

$$D = kTB$$

(Einstein, 1905 & Smoluchowski, 1906)

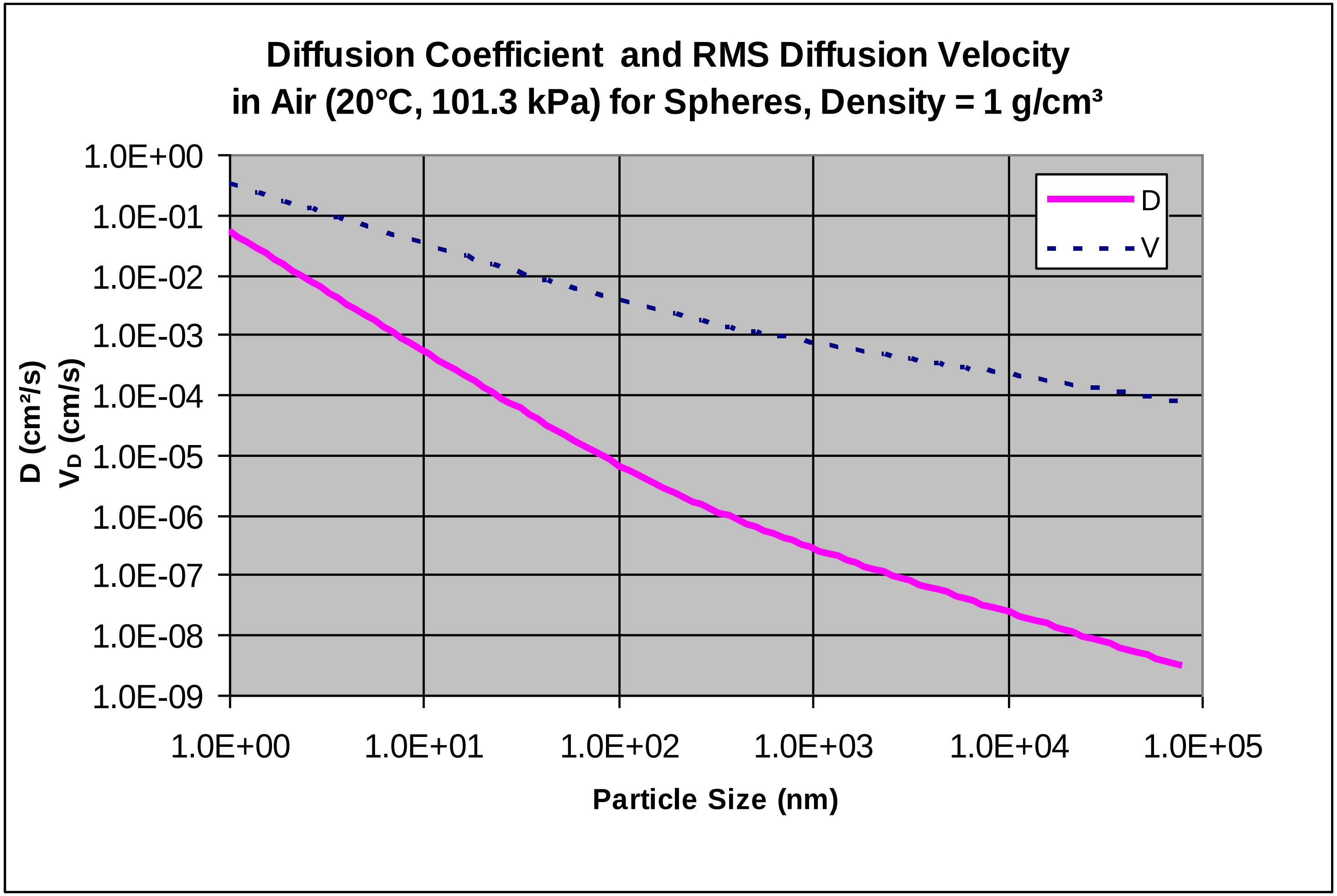
$$\bar{x} = \sqrt{2Dt}$$

$$\bar{V}_D = \frac{\bar{x}}{t} = \sqrt{\frac{2kTB}{t}}$$

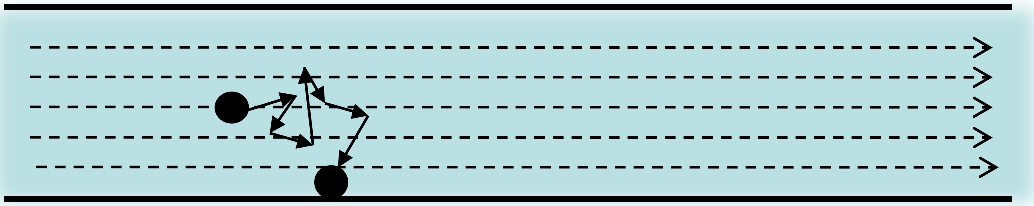


D	Diffusion coefficient
k	Boltzmann constant
$\bar{x}$	RMS diffusion displacement
$\bar{V}_D$	RMS diffusion velocity

Brownian Diffusion



Diffusion Losses



- While any actual diffusion velocity vector is random, there will always be a net particle diffusion flux from high concentration to low concentration
  - Unfortunately, the low concentration is always at the particle sink, which is the tube wall.
- For laminar tube flow in round (circular cross section) tubing, diffusion losses for any given flow rate do not depend on the diameter of the tube.
  - Tubing length matters! The losses are proportional to the length of the tubing.

Diffusion Loss

Laminar flow (Re < 2000)

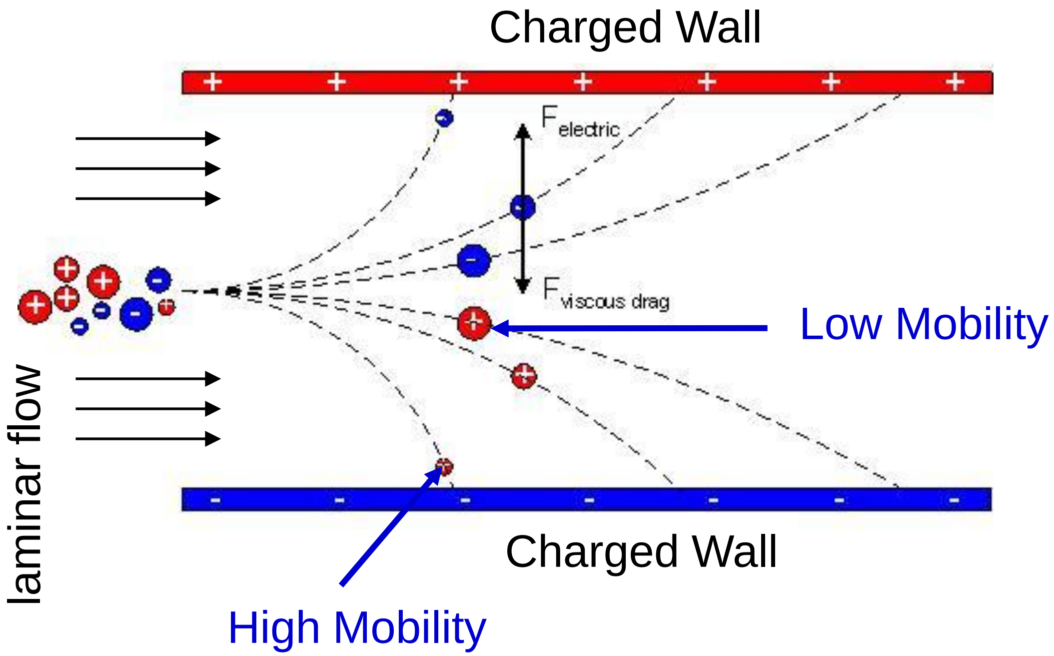
L = 1m

Particle Diameter	Transport Loss
100 µm	0 %
10 µm	0 %
1 µm	0.025 %
100 nm	0.2 %
10 nm	3.5 %
1 nm	56 %

– Calculated for air at 101.3 kPa and 20°C.
– Spherical particles with density of 1 g/cm^3

- For most practical cases, diffusion losses must be considered only for particles smaller than 100 nm.

Electrostatic Losses



Electrical mobility

$$V_T = F \cdot B = \boxed{E \cdot n_p \cdot e} \cdot B = E \cdot Z$$

Electrostatic force

E = Electric field strength
n_p = Number of charges/particle
e = Elementary unit of charge
η = Viscosity of gas
d = Particle diameter
Z = Electrical mobility

Electrostatic Losses

$$V_T = E \cdot n_p \cdot e \cdot B$$

- If E and n_p are known, V_T and electrostatic losses can be calculated (→ Electrostatic classifier).
- In real life, both values are unknowns for transport tubing and aerosol particles.
- Only the use of grounded, conductive tubing can keep electrostatic losses negligible.

Thermophoretic Losses

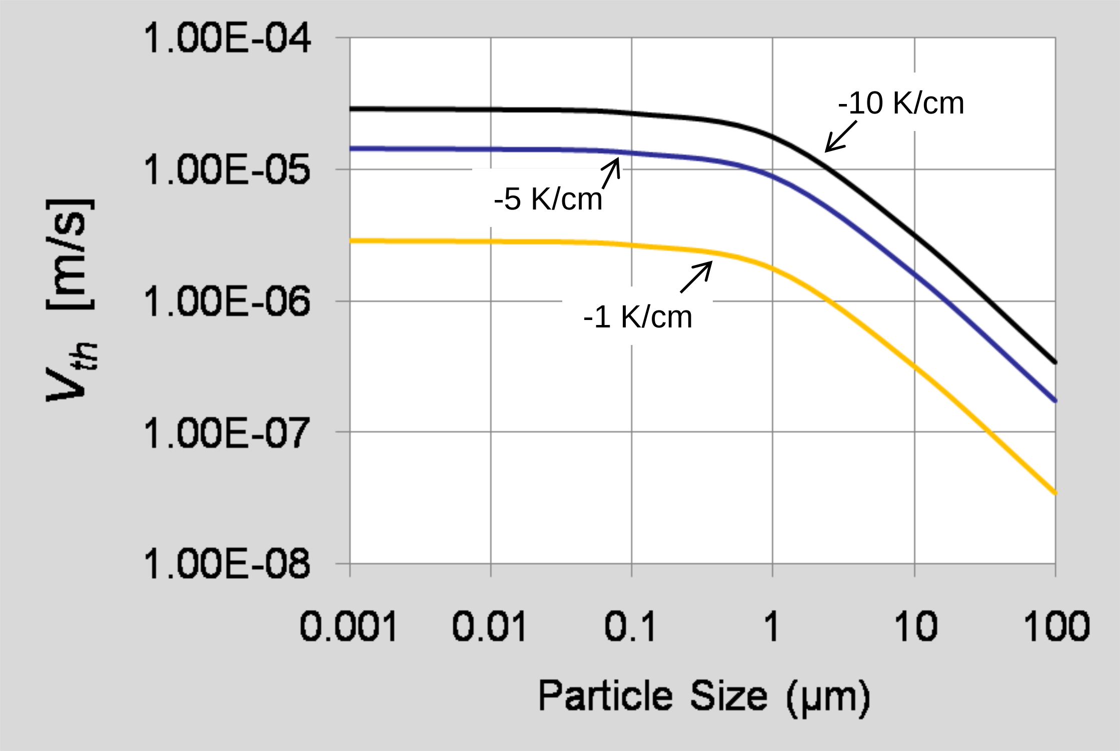
$$V_{th} = F_{th} \cdot B$$

for $d < \lambda$:

$$F_{th} = -\nabla T \frac{p\lambda d^2}{T}$$

for $d >> \lambda$:

$$F_{th} \cong -\nabla T \frac{k_{gas}}{k_p} \frac{9\pi\eta^2 d}{2\rho_g T}$$

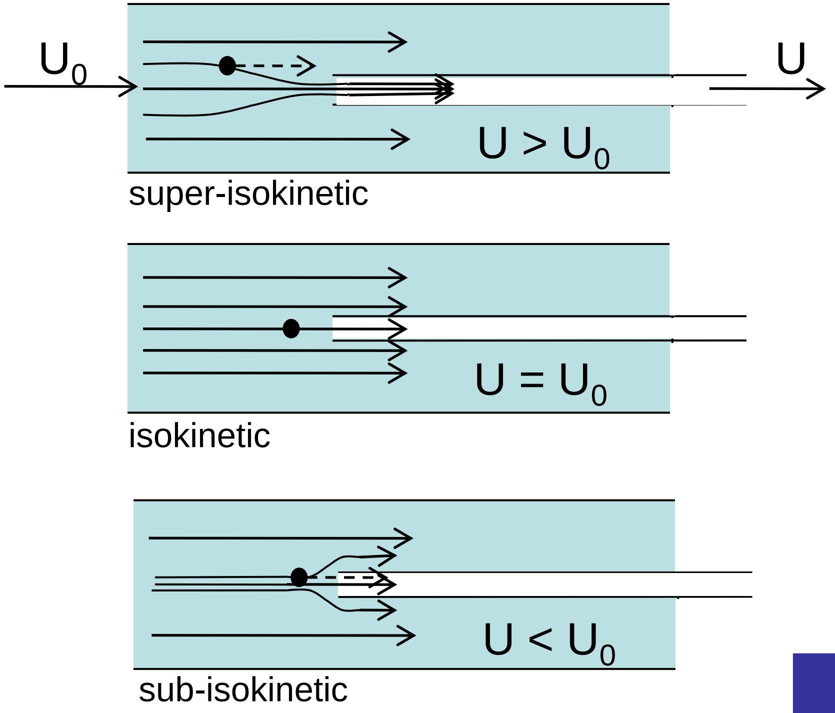


Air: p = 101.3 kPa, T = 293.15 K, NaCl particles: k_p = 6.7 W/(m K)

- When sampling at ambient temperatures, thermophoresis is negligible
- Transport of hot aerosol requires heated tubing

Talbot, L., Cheng, R. K., Schefer, R. W., and Willis, D. R., 1980, J. Fluid Mech. 101:737-758

The Inlet – Sampling from Tube Flow



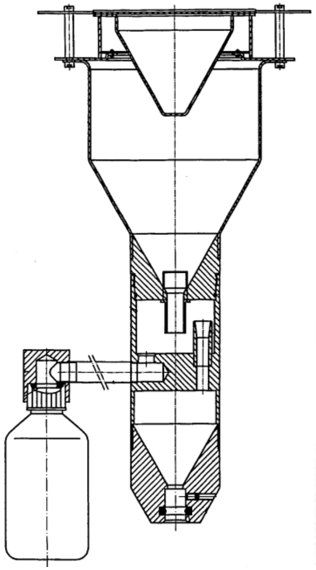
- For super-micron particles, isokinetic sampling ($U = U_0$) is important for unbiased measurements
- Below 1 µm (aerodynamic diameter!), isokinetic sampling is no longer an issue (as long as U/U_0 is kept within $0.5 < U/U_0 < 2$)

If the sample inlet is oriented off-axis, flow lines are also bent and similar losses occur!

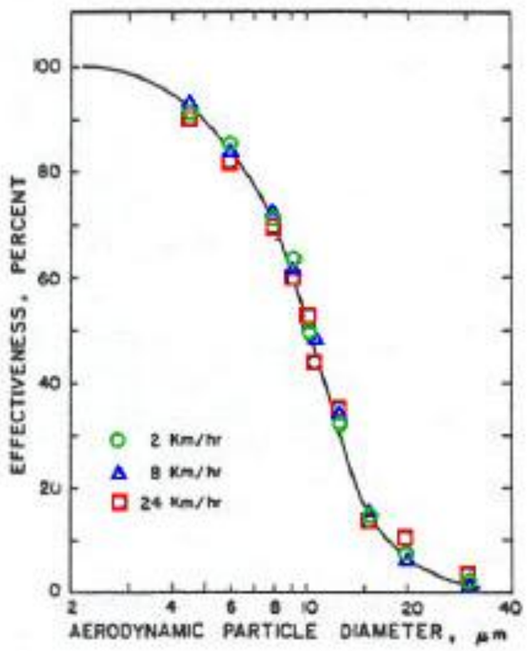
Particle Diameter	U = 60 cm/s U_0 = 30 cm/s	U = 30 cm/s U_0 = 30 cm/s	U = 15 cm/s U_0 = 30 cm/s
100 µm	63 %	100 %	190 %
10 µm	98 %	100 %	108 %
1 µm	100 %	100 %	100 %
0.1 µm	100 %	100 %	100 %

Sampling – Ambient Air

- Sampling from ambient air is not trivial at all
  - Wind speeds and wind direction are variable
  - Careful design is necessary to minimize measurement bias.
  - Often, certain cut-off or penetration characteristics are required by measurement standards (e.g. PM_{10})



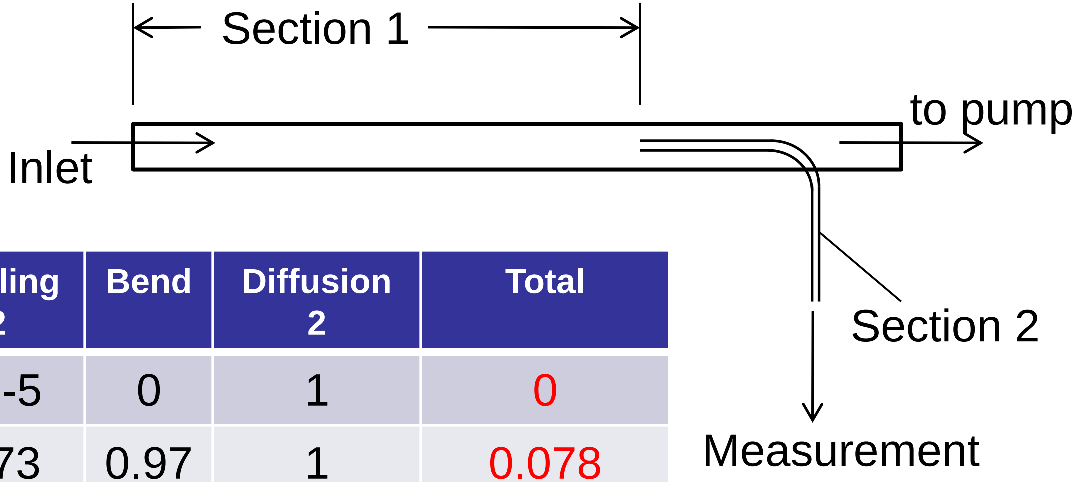
US-EPA PM_{10} Inlet



A Complete Sampling System - 1

Section 1: L = 1 m, D = 2 cm, U = 0.3 m/s

Section 2: L = 0.5 m, D = 0.5 cm, U = 0.3 m/s



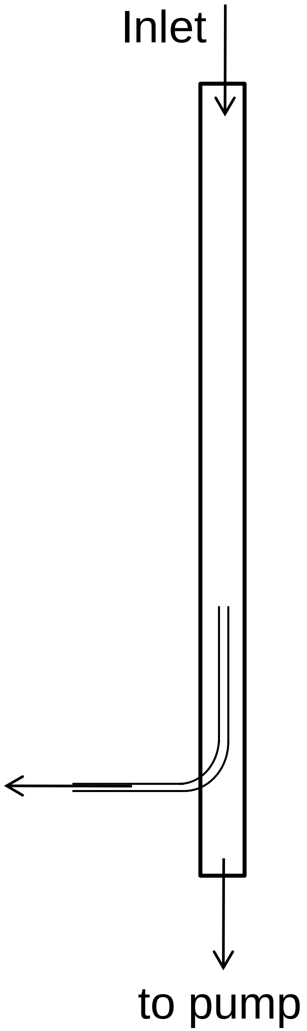
	Inlet	Settling 1	Diffusion 1	Settling 2	Bend	Diffusion 2	Total
100 µm	~1	0	1	5e-5	0	1	0
10 µm	1	0.11	1	0.73	0.97	1	0.078
1 µm	1	0.985	1	0.99	1	1	0.975
100 nm	1	1	0.998	1	1	0.992	0.99
10 nm	1	1	0.96	1	1	0.94	0.90
1 nm	1	1	0.43	1	1	0.27	0.12

Penetration through different sections of an aerosol sampling system

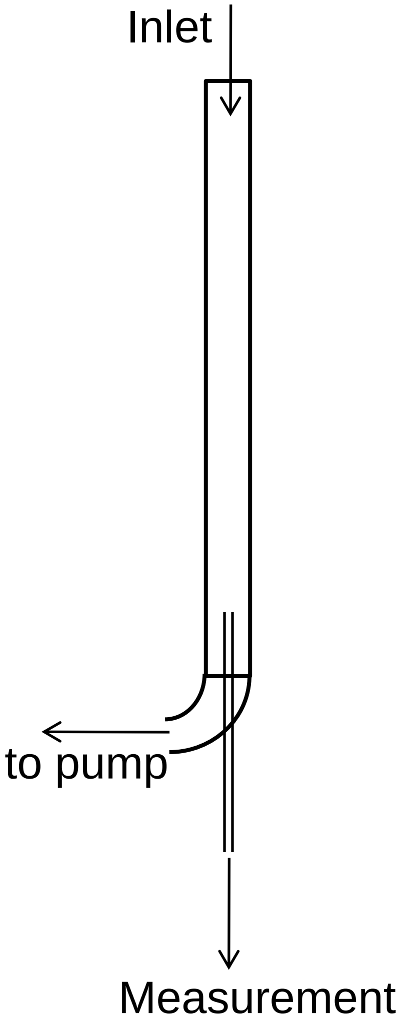
A Complete Sampling System - 2

	Inlet	Settling 1	Diffusion 1	Settling 2	Bend	Diffusion 2	Total
100 µm	1	1	1	5e-5	0	1	0
10 µm	1	1	1	0.73	0.97	1	0.71
1 µm	1	1	1	0.99	1	1	0.99
100 nm	1	1	0.998	1	1	0.992	0.99
10 nm	1	1	0.96	1	1	0.94	0.90
1 nm	1	1	0.43	1	1	0.27	0.12

Penetration through different sections of an aerosol sampling system



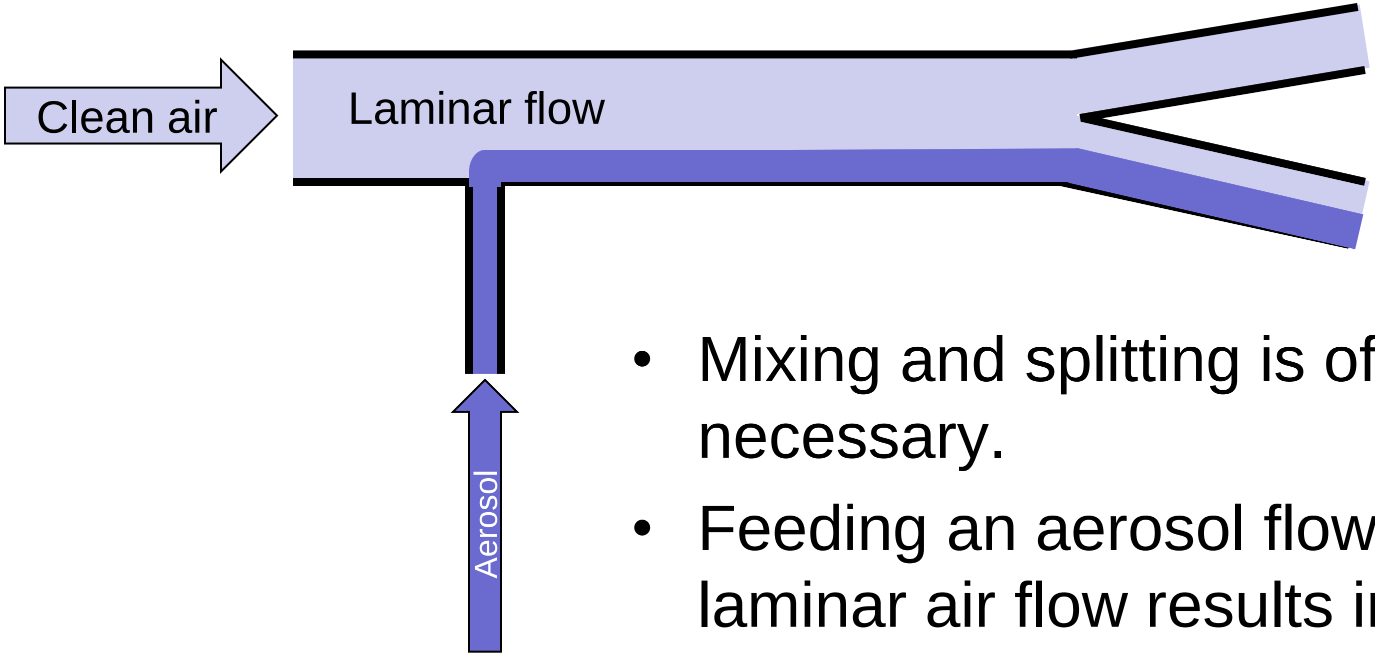
A Complete Sampling System - 3



	Inlet	Settling 1	Diffusion 1	Settling 2	Bend	Diffusion 2	Total
100 µm	1	1	1	1	1	1	1
10 µm	1	1	1	1	1	1	1
1 µm	1	1	1	1	1	1	1
100 nm	1	1	0.998	1	1	0.992	0.99
10 nm	1	1	0.96	1	1	0.94	0.90
1 nm	1	1	0.43	1	1	0.27	0.12

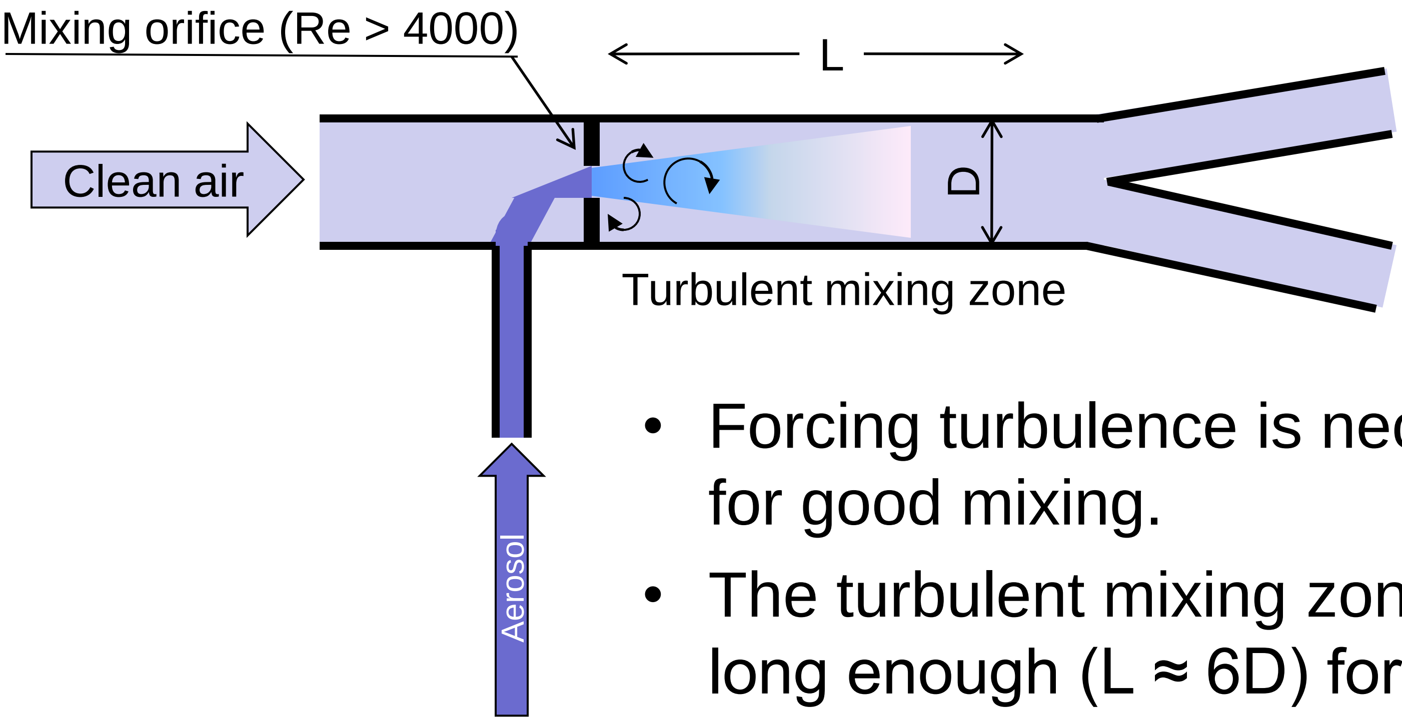
Penetration through different sections of an aerosol sampling system

Flow Mixing and Splitting



- Mixing and splitting is often necessary.
- Feeding an aerosol flow into a laminar air flow results in poor mixing
- Under such conditions, flow splitting is often asymmetric.

Flow Mixing and Splitting



- Forcing turbulence is necessary for good mixing.
- The turbulent mixing zone must be long enough (L ≈ 6D) for good mixing before flows are split
- Orifices and baffle plates make good mixers; however, they also increase particle losses.

Aerosol Conditioning

- To avoid measurement artifacts due to sampling and transport, conditioning of the aerosol may become necessary:
  - Dilution to avoid coagulation
  - Mixing (dilution) with dry gas to avoid vapor condensation on particles
  - Heated sampling probe and transport tubing to avoid vapor condensation

Good Practice (Summary)

- **Always keep transport tubing as short as possible**
- **Always use grounded, electrically conductive tubing with smooth inner surface**
- Re ≈ 1500 is a good choice for tubing diameter at fixed flow rate
- Avoid unnecessary horizontal tubing if particles are larger than 1 µm
- Avoid unnecessary bends in tubing if particles are larger than 1 µm
- Avoid abrupt changes in tubing diameter if particles are larger than 1 µm
- Hot aerosol requires heated transport tubing
- Sampling from high concentrations may require dilution to avoid coagulation
- Ensure you have well mixed aerosol before splitting flows

My Final Tips

- To read and learn more:

  Paul A. Baron, Klaus Willeke:

  Aerosol Measurement: Principles, Techniques, and Applications, 2nd Edition, Wiley, November 2005
- Many of the examples shown in this presentation were calculated with Paul Baron's Excel spreadsheet "AeroCalc".
- A free copy of this spreadsheet can be downloaded from our website: http://www.tsi.com/uploadedFiles/Product_Information/Literature/Software/Particle_Instruments_Released_Software_Versions.pdf

Thank You For Your Attention

Webinar Schedule

Global
Aerosol Education

Oct 27th	Sizing Copper and Silver Nanoparticle Colloids Using ES+SMPS by Dr. Sherrie Elzey (NIST)
Nov. 10th	Assessment of Potential Occupational Exposure to Nanoparticles by Drew Thompson (University of Minnesota)
Dec. 1st	Nanotechnology Workplace Emission Assessments by Kathleen Erickson
Jan. 12th (2012)	Chemical and morphological characterization of aerosol particles at Mt. Krvavec, Slovenia during the Ehjafjallajökull Icelandic volcanic eruption by Dr. Michael Beeston

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