Atmospheric Aerosol Physics, Physical Measurements, and Sampling

Sampling, Drying, Losses & Impactor

São Paulo School of Advanced Science on Atmospheric Aerosols: properties, measurements, modeling, and effects on climate and health

Member of Leibniz Leibniz Association

ECAC European Center for Aerosol Calibration

WCCAP World Calibration Centre for Aerosol Physics

TROPOS Leibniz Institute for Tropospheric Research

Aerosol Sampling

Flow-Reynolds-Number

The **Flow-Reynolds-Number** depends mainly on the flow rate and the tube diameter

$$\mathrm{Re}_{\mathrm{flow}} = \frac{\rho_{\mathrm{gas}} \cdot \overline{u}_{\mathrm{flow}} \cdot D_{\mathrm{pipe}}}{\eta}$$

ρ_{gas} … gas density

u_{flow} … flow velocity

D_{pipe} … tube diameter

η … dynamic viscosity

Example

Particle diameter nm	Relaxation time s	Stopping distance m	Stokes number
10	6,95E-09	9,23E-09	2,31E-06
100	8,90E-08	1,18E-07	2,95E-05
1000	3,56E-06	4,72E-06	1,18E-03
10000	3,09E-04	4,11E-04	1,03E-01
100000	3,05E-02	4,04E-02	1,01E+01
Density: ρ_P	2000 kg/m^3		
Tube diameter: D_t	0.004 m		
Tube velocity: u_t	1.33 m/s		
	(5 l/min in ¼” tube)		

Particle Pre-Separators

Devices based on inertia are usually used as pre-separators.

- Impactors

- Cyclones

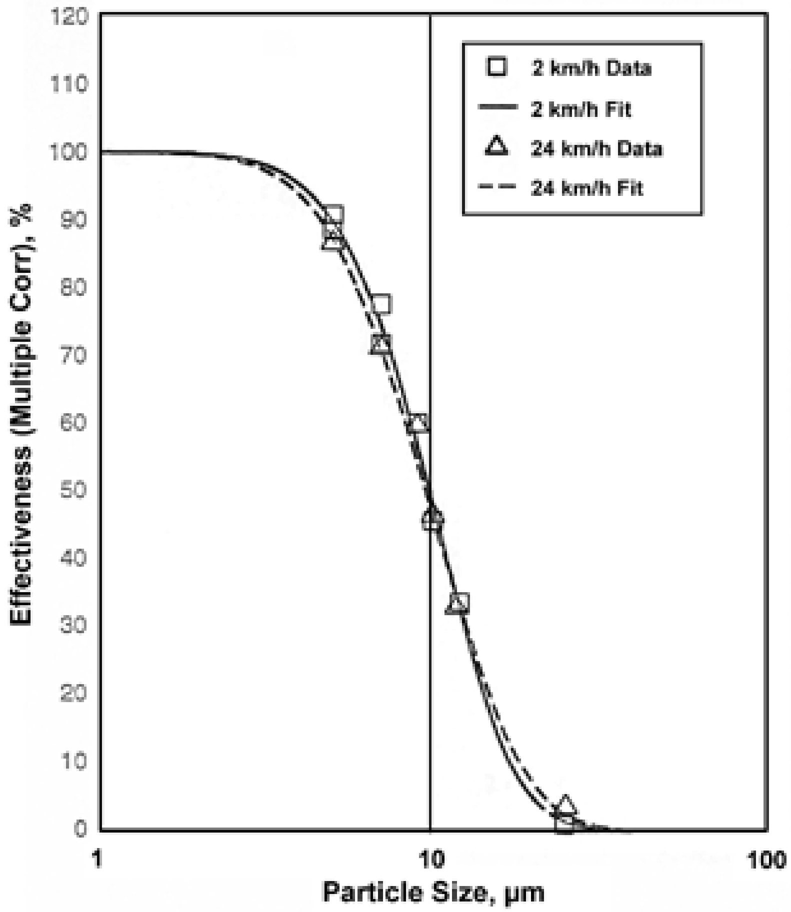
Pre-separators are used to remove particles larger (or smaller) than a certain size from the aerosol.

Impactors can be theoretically better described than all other types of pre-separators.

Cyclones and other pre-separators must be calibrated to know their behavior.

Low flow PM10 inlet:

Penetration efficiency curve



Sampling under Extreme Conditions

Special sampling requirements are needed for sites:

- in tropical and sub-tropical environments

  → high dew point temperature

- in cold environments (Arctic and Antarctica)

  → freezing inlets

- on mountains, which are frequently in cloud

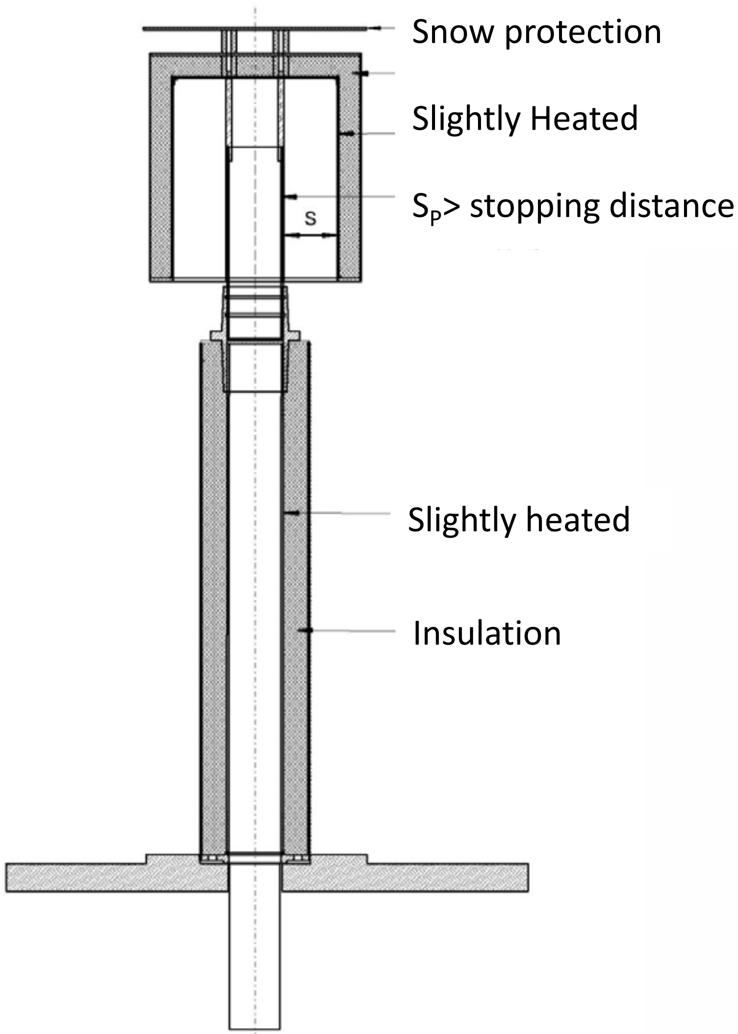
  → whole air vs interstitial inlet

Sampling under Extreme Conditions

- Heated whole air inlet for sites which are frequently in cloud or fog or/and freezing conditions.
- Cloud droplets are drawn into the inlet and evaporated.
- Cloud droplets and interstitial aerosol particles are sampled → whole air inlet

$$\tau_P = m_P \cdot B = \frac{\rho_P \cdot D_P^2 \cdot C_C}{18\eta}$$

$$s_P = u_G \cdot \tau_P$$



Isokinetic Sampling

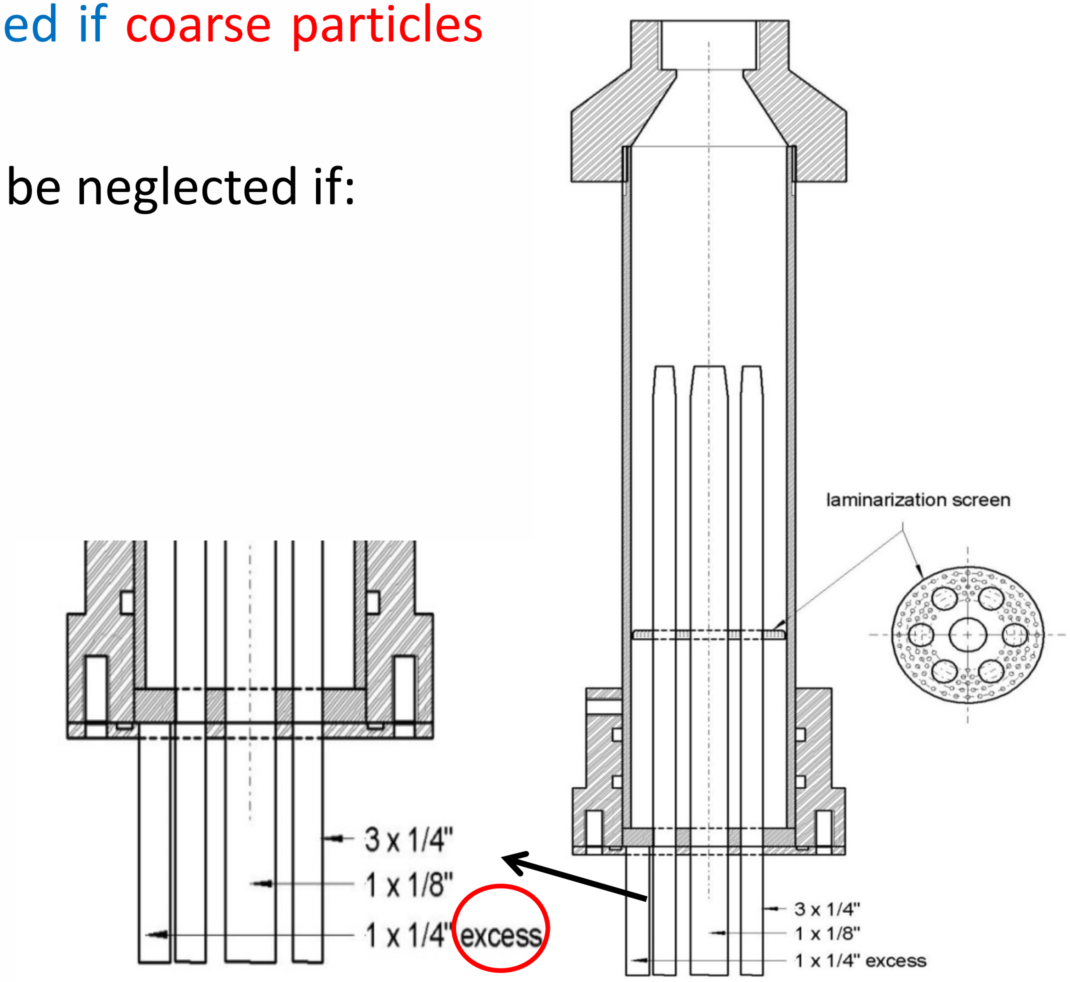
An isokinetic aerosol splitter should be used if coarse particles are sampled or characterized.

The particle over- und under sampling can be neglected if:

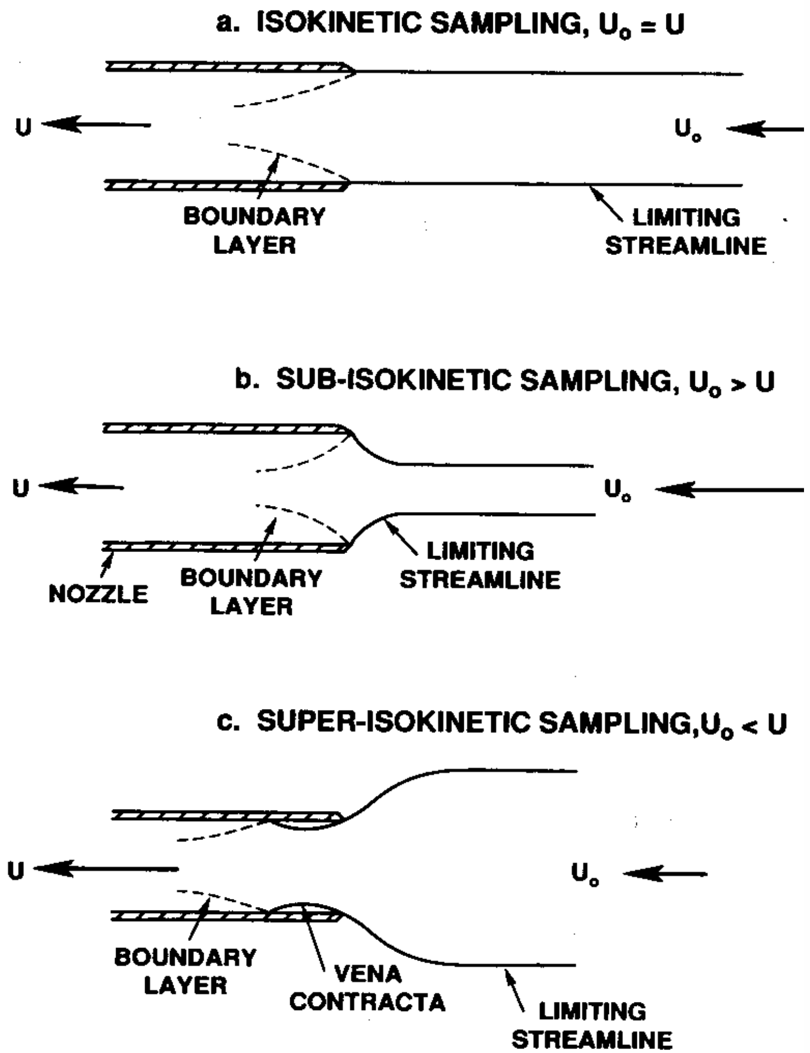
$$\mathrm{Stk} \leq 0.01$$

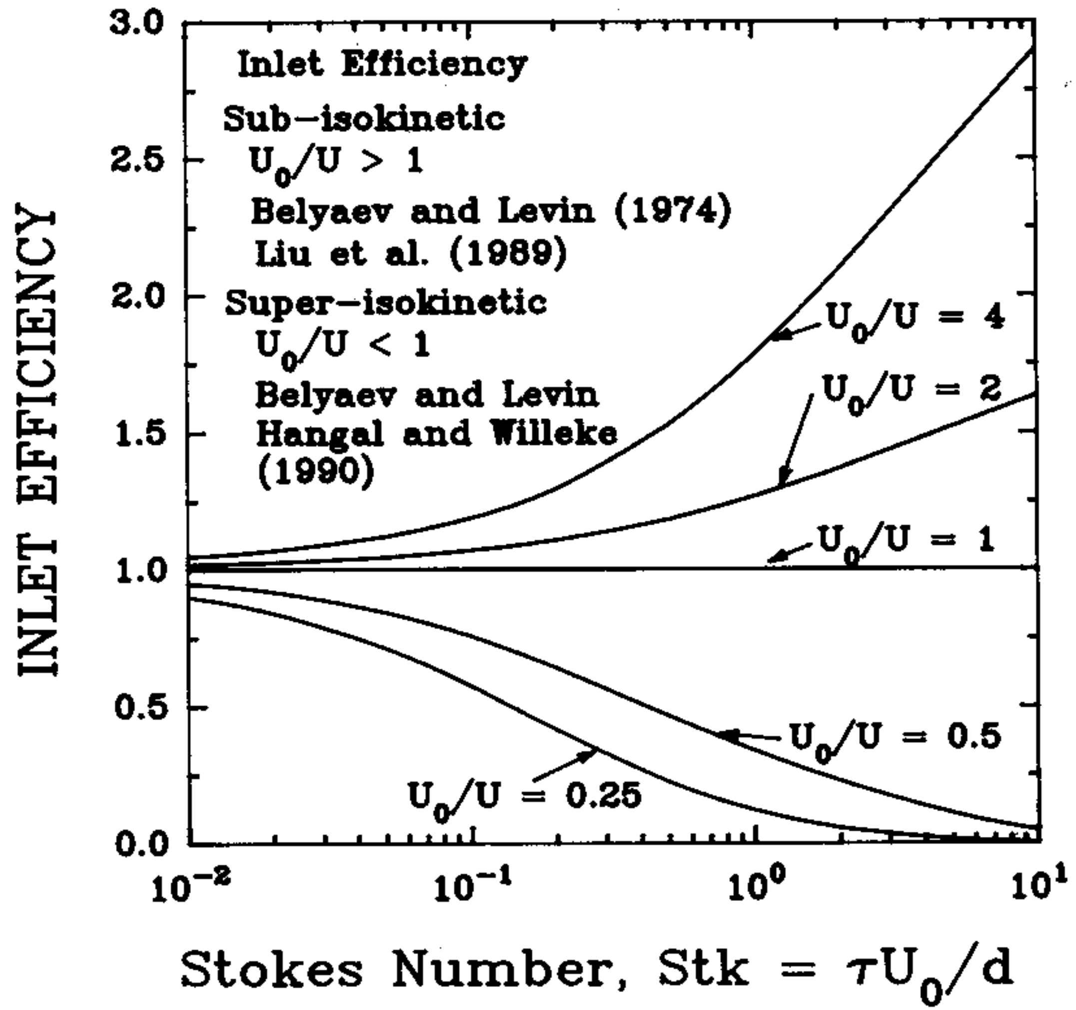
$$0.2 \leq \bar{u} / u_0 \leq 5$$

$$\mathrm{Stk} = \frac{\tau_P \cdot u_P}{D_{\mathrm{pipe}}}$$



Isoaxial Sampling ($\Theta = 0$)





Inlet Efficiency
Sub–isokinetic
U0/U > 1
Belyaev and Levin (1974)
Liu et al. (1989)
Super–isokinetic
U0/U < 1
Belyaev and Levin
Hangal and Willeke
(1990)
U0/U = 4
U0/U = 2
U0/U = 1
U0/U = 0.5
U0/U = 0.25
INLET EFFICIENCY
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10−2
10−1
100
101
Stokes Number, Stk = τU0/d

Aerosol Drying

Why Aerosol Drying

- With increasing relative humidity, aerosol particles take up water a function of size and solubility.

- This effect can be significant for measurements of particle number size distributions or light scattering coefficients.

- The RH should be <40% to be able to compare e.g. physical and optical aerosol measurements (particle growth <5% in diameter).

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- No dryer is needed, if T_{room} will be higher than 22°C (72°F) and the T_{dew} never exceeds 10°C (50°F).

- A aerosol dryer is needed for each instrument, if the T_{dew} will be higher than 10°C (50°F) and always below the T_{room}.

- The whole inlet flow has to be dried before entering the room, if the T_{dew} will be occasionally above the T_{room}.

Aerosol Drying Methods

Aerosol diffusion dryer

A diffusion dryer works on the base of silica.

- Advantage: no dry air is needed
- Disadvantage: has to be changed frequently

Membrane dryer

A membrane dryer (e.g. Nafion) is based on the principal that water vapor is transported through a membrane surrounded by a counter flow with low humidity.

- Advantage: no frequent changes are needed
- Disadvantage: a dry air supply (or vacuum) is needed

Dilution

The aerosol is diluted with dry particle-free air.

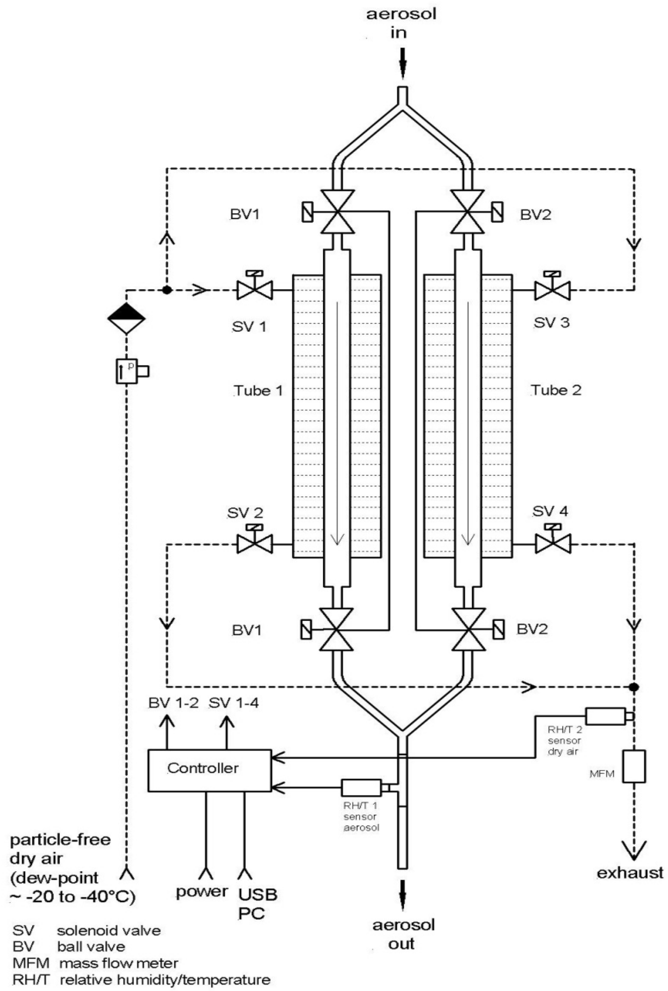
- Advantage: easy way to dry
- Disadvantage: The dilution ratio has to be exactly known. High ratios may create high uncertainties.
- Dilution is the recommended method for tropical and subtropical observatories

Heating

Heating is NOT recommended to avoid evaporation of semi-volatile particle material.

Automated Aerosol Diffusion Dryer

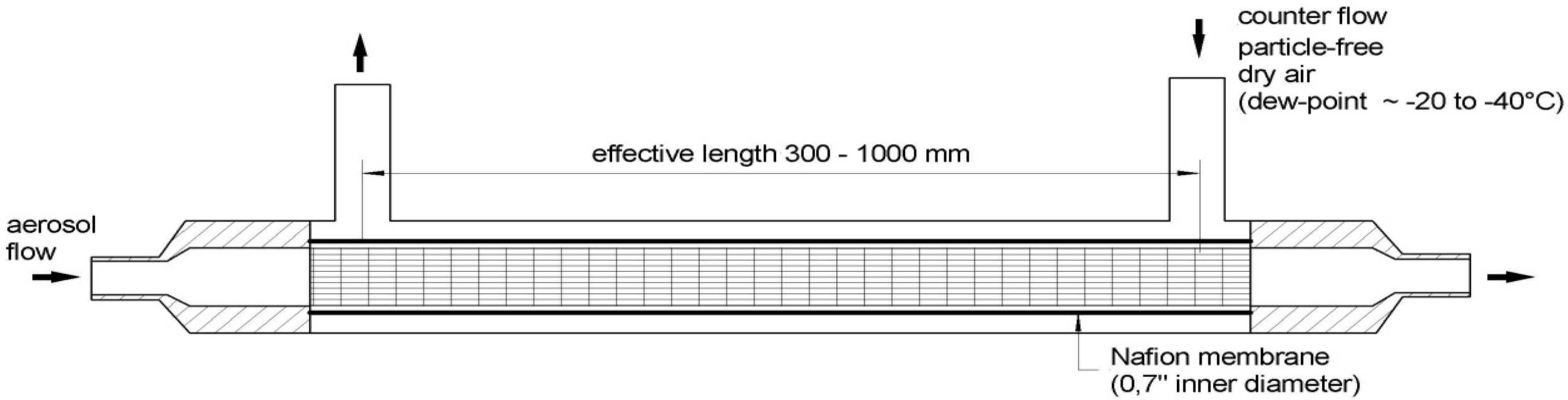
- Automatic aerosol diffusion dryer based on silica.
- Advantage: silica has to not be changed
- Disadvantage: dry air is needed



Tuch, T. M. et al. (2009). Design and performance of an automatic regenerating adsorption aerosol dryer for continuous operation at monitoring sites. AMT **2**, 417-422.

Aerosol Membrane Dryer

- A membrane dryer (e.g. Nafion) is based on the principal that water vapor is transported through a membrane, which is surrounded by a counter flow with low relative humidity.
- Advantage: no frequent changes are needed
- Disadvantage: a dry air supply is needed (or high vacuum)
- Below: a custom-designed Nafion dryer



Aerosol Particle Losses

Aerosol Particle Losses

Particle losses in pipes and instruments can occur due to:

- Sedimentation in horizontal or sloping pipes (coarse particles)
- Inertia in bends (coarse particles)
- Diffusion to the wall (ultrafine particles)
- Electrostatic forces (charged particles, mainly ultrafine)

Losses: Ultrafine Particles < 100 nm

- Pipes should be kept as short as possible.
- Only conductive tubing (e.g. stainless steel) should be used.
- The pipe should be designed for a laminar flow
  - Constant aerosol flow: Change in tube diameter → no change in diffusional losses
  - Constant tube diameter: Adjust aerosol flow to Re=2000, if possible
- Turbulent flows should be avoided, because of higher diffusional particle losses.

Losses: Coarse Particles > 1 µm

- Pipes should be vertically orientated.
- In cases when horizontal or sloping pipes cannot be avoided, the air flow should be high.
- Bends should be avoided.
- Highly turbulent flows cause increased inertial losses.
- An isokinetic sampling should be considered.

Losses due to impaction in bends

Laminar flow ($Re_{flow} < 2000$)

The particle size-dependent penetration through a bend depends on the Stokes Number and curvature of the bend. The penetration can be described by

$$P = 1 - Stk \cdot \frac{\theta^\circ}{180^\circ}\pi$$

θ in° ...angle of the curvature

Turbulent flow ($Re_{flow} > 4000$)

The size-dependent particle penetration can be described by following approximation:

$$P = \exp\left(-2.823 \cdot Stk \frac{\theta^\circ}{180^\circ}\pi\right)$$

Losses due to sedimentation in horizontal or sloping pipes

The particle size-dependent penetrations for laminar and turbulent flows can be described by approximation formulas.

Laminar flow ($Re_{flow} < 2000$):

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

with

$$\kappa = \varepsilon \cdot \sin(\theta)$$

$$\varepsilon = \frac{3}{4} Z$$

$$Z = \frac{L_{\text{pipe}}}{D_{\text{pipe}}} \cdot \frac{u_S}{\overline{u}}$$

L_{pipe}	… length of the pipe
D_{pipe}	… inner diameter of the pipe
u_s	… sedimentation velocity
u	… mean flow velocity
θ	… angle of the pipe against the horizontal plain

Turbulent flow ($Re_{flow} > 4000$):

$$P = \exp\left(-4Z \cdot \cos\left(\frac{\theta°}{180°}\pi\right)\right)$$

Losses du to diffusion in cylindrical pipes

Approximation formulas are used to describe the losses due to diffusion in pipes.

Laminar flow (Re_{flow} < 2000):

The particle size-dependent penetration can be calculated to:

for µ < 0,007

$$P = 1 - 5{,}5\mu^{2/3} + 3{,}77\,\mu$$

for µ > 0,007

$$P = 0.819 \cdot \exp(-11.5\mu) + 0.0975 \cdot \exp(-70.1\mu) + 0.0325 \cdot \exp(-179\mu)$$

with:

$$\mu = \frac{D \cdot L_{\text{pipe}}}{Q}$$

D … Diffusion coefficient

L_{pipe} … length of the pipe

Q … volume flow rate

Turbulent flow ($Re_{flow} > 4000$)

The boundary layer δ of the flow close to the wall can be determined.

$$\delta = \frac{28.5 D_{pipe} \cdot D^{1/4}}{Re_{flow}^{7/8} \left(\eta_G / \rho_G\right)^{1/4}}$$

D ... Diffusion coefficient

D_{pipe} ... inner diameter of the pipe

η_G ... gas viscosity

ρ_G ... gas density

Re_{flow}... Reynolds number flow

The particle size-dependent deposition velocity u_{dep} to the wall is then given to:

$$u_{dep} = \frac{D}{\delta}$$

The particle size-dependent penetration can be calculated to:

$$P = \exp\left(\frac{-4 \cdot u_{dep} \cdot L_{pipe}}{D_{pipe} \cdot \overline{u}_{flow}}\right)$$

u_{flow} ... mean flow velocity

L_{pipe} ... length of the pipe

General Recommendations

General Sampling Consideration

These Recommendations are based on the WMO-GAW & ACTRIS:

- Sample air should be brought into the laboratory through a vertical stack.
- The aerosol inlet should be well above ground level (5-10 m) for regional sampling sites in level terrain.
- The aerosol inlet must provide a high inlet sampling efficiency for the required particle size range.
- PM_{10} inlets should be used, while TSP inlets are NOT recommended anymore.
- The recommendation is to measure at a relative humidity below 40%.

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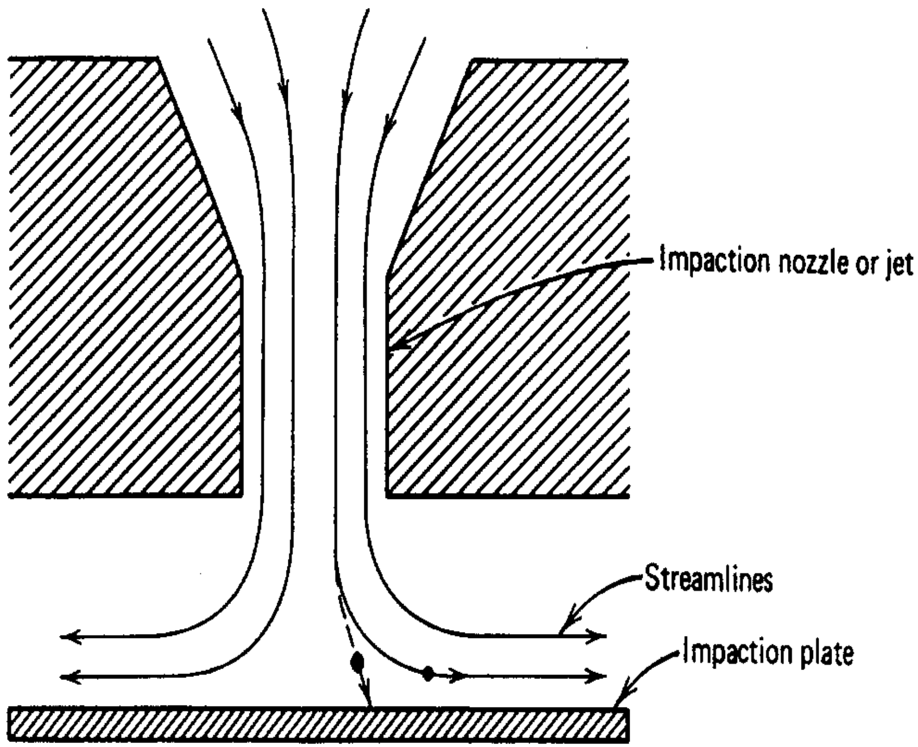
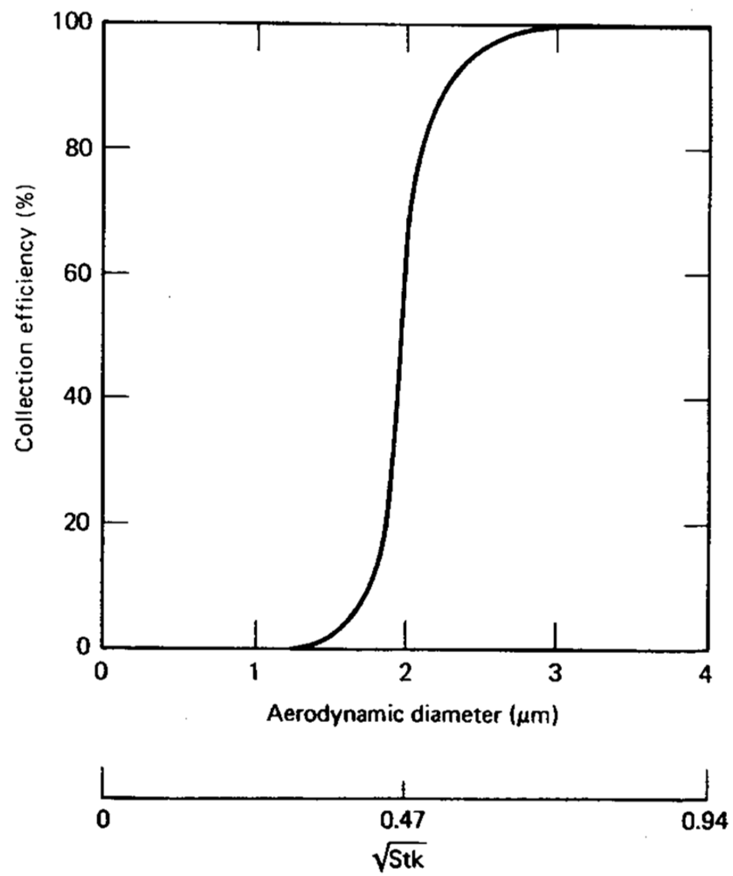
Impactor

Operation Principle

- Impactors utilize the mechanism of inertial impaction to deposit particles onto impaction surfaces.
- Impactors are designed as a nozzle – impaction - plate configuration.
- The aerosol flow through the nozzle is accelerated.
- The impaction plate causes a strong bending of the gas stream lines.
- Small particles can follow the gas stream lines and are not deposited due to their small inertia and short relaxation time.
- Larger particles may not follow the stream lines and are deposited on the impaction plate due to their higher inertia.
- A single stage impactor separates aerosol particles into two size fractions (aerodynamic particle diameter)



Cross-sectional view of an impactor.



Typical impactor efficiency curve.

Hinds: Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles

Mathematical Description

The important parameter for the description of impactors is the Stokes-Number:

$$\mathrm{Stk}_{\mathrm{p}} = \frac{\tau_{\mathrm{P}} u}{D_{\mathrm{j}}} = \frac{\rho_{\mathrm{P}} \cdot D_{\mathrm{P}}^2 \cdot u \cdot C_{\mathrm{C}}}{9 \cdot \eta \cdot D_{\mathrm{j}}}$$

τ_P … particle relaxation time
u … gas velocity
D_j … nozzle diameter

The Stokes-Number is defined as the ratio of particle stopping distance to the nozzle diameter.

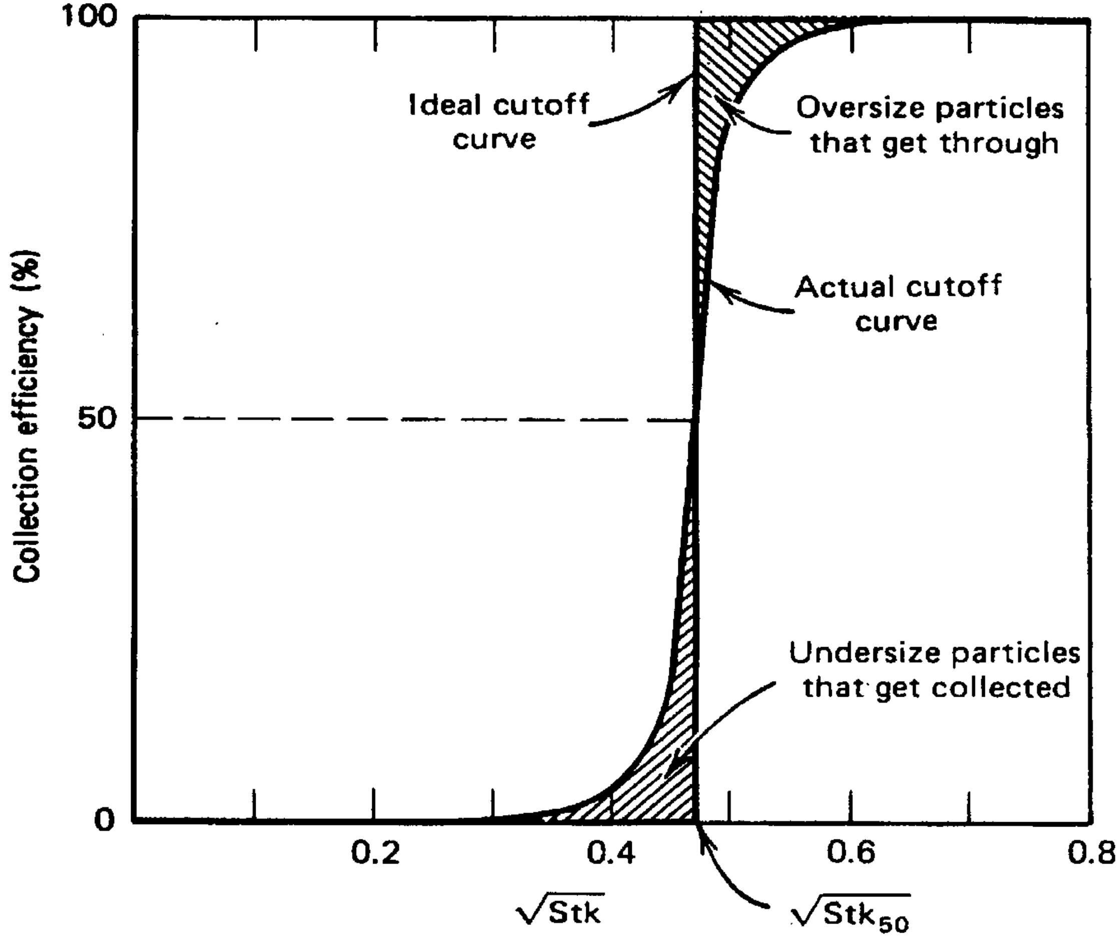
In first approximation, the “cut-off„ diameter d_{50} of an impactor can be determined by:

$$D_{P50}\sqrt{C_C} = \left(\frac{9 \cdot \eta \cdot D_j}{\rho_P \cdot u}\right)^{1/2} \cdot \sqrt{\mathrm{Stk}_{50}}$$

with 500 < Re < 3000 and $x / D_j > 1.5$ (x = distance nozzle to plate)

Impactor type	Stk_{50}	$\sqrt{\mathrm{Stk}_{50}}$
rectangular nozzle	0,59	0,77
round nozzle	0,24	0,49

- The idealized transfer function of an impactor, i.e. the deposition efficiency as function of particle size, can be described by means of a step-function at particle size D_{P50}.
- Real impactors exhibit a deposition characteristic, i.e. their transfer function deviates from the idealized transfer function.
- Impactor transfer functions are often plotted as function of $\sqrt{Stk_{50}}$.
- A theoretical calculation of real impactor transfer functions, i.e. deposition efficiencies, is possible using numerical methods.



Actual and ideal impactor cutoff curves.

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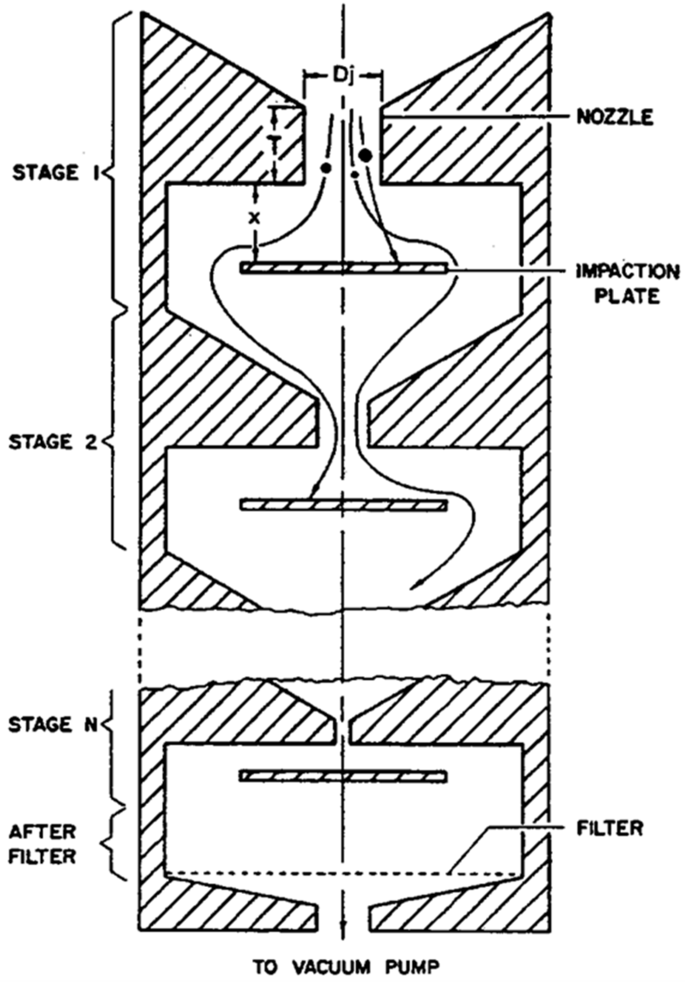
Particle Mass Size Distributions

- Multiple impactor stages are operated in series to determine of the particle mass size distribution.
- This instrument is called a cascade or multi-stage impactor .
- In a cascade impactor, the cut-off-diameter is decreased from stage to stage.
- This is achieved by decreasing the nozzle diameters and/or the number of nozzles.
- For complete deposition of the small particles, a backup filter is utilized down-stream of the last impactor stage.
- Each stage is equipped with an exchangeable impaction plate.
- The particle mass deposited in each stage is determined gravimetrically or chemically.
- In case of an ELPI, the mass concentration at each stage can be converted to a number concentration, leading to a particle number size distribution.

Cascade impactor



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