



Atmospheric standardized observations:
Methods and maintenance in in-situ
observatories

Aerosol sampling and physical properties

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IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



Background

Physical aerosol particle measurements

- Physical properties of atmospheric aerosol particles are important to understand climate- and air-quality-related aerosol effects.
- Important for atmospheric data are comparable and high quality measurements under standardized sampling conditions.

Physical and optical particle variables

- Particle number concentration and size distribution
- Particle light scattering and absorption coefficient
- Equivalent Black Carbon (eBC)
- Hygroscopicity: growth factor and mixing state
- Volatility: size distribution and mixing state

General Definitions

Definition of an aerosol

Solid and /or liquid particles suspended in a gas

Coarse Particles

Particles $>1 \mu\text{m}$ in diameter

Fine Particles

Particles $<1 \mu\text{m}$ in diameter

Accumulation mode range 100-1000 nm

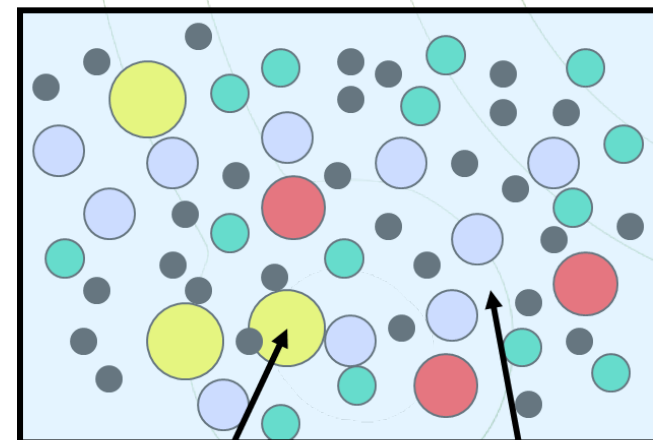
Ultrafine Particles

Particles $< 100 \text{ nm}$ in diameter

Aitken mode range 10-100 nm

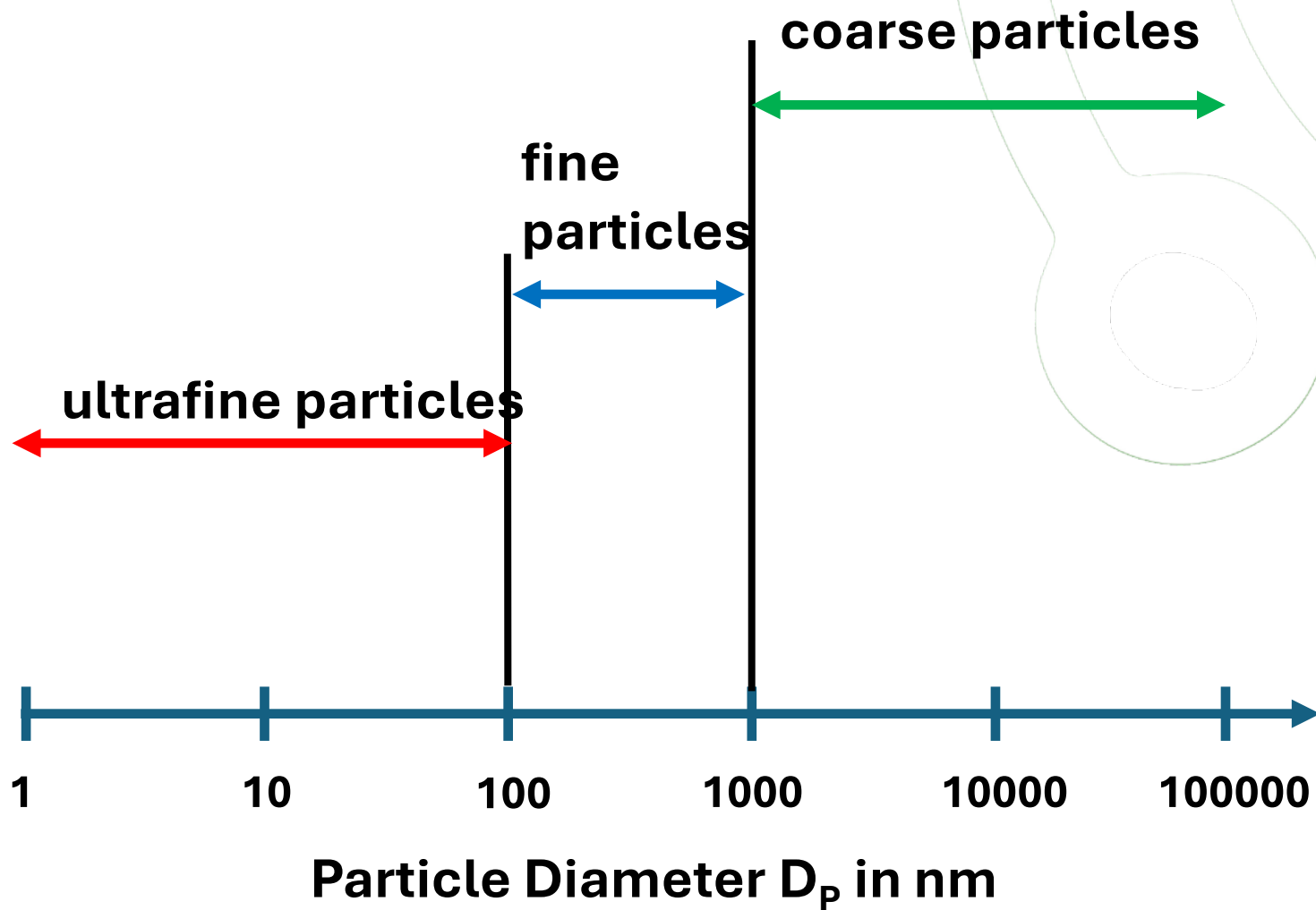
Nucleation mode range 1-10 nm

→ What is an aerosol ?



Particles + Gases = Aerosols

Particle size ranges



Particle Size

Definition

$$1 \text{ nm} < D_p < 100 \text{ }\mu\text{m}$$

$$10^{-9} \text{ m} < D_p < 10^{-4} \text{ m}$$

Micro-Range

1 nm particle

350 nm particle

2.5 μm particle

100 μm particle

Macro-Range

0.1 mm tip of a needle

3.5 cm ping-pong ball

25 cm soccer ball

10 m balloon

Particle shape

Aerosol particles are normally non-spherical.

However, particles are often assumed to be spheres for a simpler description and use (equivalent diameter).

Aerosol particles with extreme shapes should not be described as spherical particles.

Examples for non-spherical particles

- Asbestos fibers
- Chain agglomerates

Examples for “spherical particles”

- Droplets
- Fly ash particles
- Inorganic salt particles (crystals)
- Compact particles (pollen, secondary particles, ...)

Particle Concentration

- The **particle number concentration** is described by the parameter N .
- It is defined by the number of particles per volume unit, and given in $\#/cm^3$.

Other concentrations:

- Particle surface area concentration S [$\mu m^2/cm^3$]
- Particle volume concentration V [$\mu m^3/cm^3$]
- Particle mass concentration M [$\mu g/m^3$]

- The mass concentration can be calculated from the volume concentration and the particle density ρ_p .
- The particle density is given in [g/cm^3].

Example for number concentrations

Micro range

100 nm particle

Arena : 100 m x 50 m x 20 m

Particle number concentration

100 cm⁻³

10,000 cm⁻³

100,000,000 cm⁻³

Macro range

3.5 cm ping-pong ball

Ping-pong balls

1 in 4000 arenas

1 in 40 arenas

200 in 1 arena

A little bit of particle Physics: Settling Velocity

Newton's Resistance Law (negligible viscous forces) is not valid

Stokes Law: negligible inertial force compared to viscous force

$$F_D = \frac{3\pi\mu V d_p}{C_c}$$

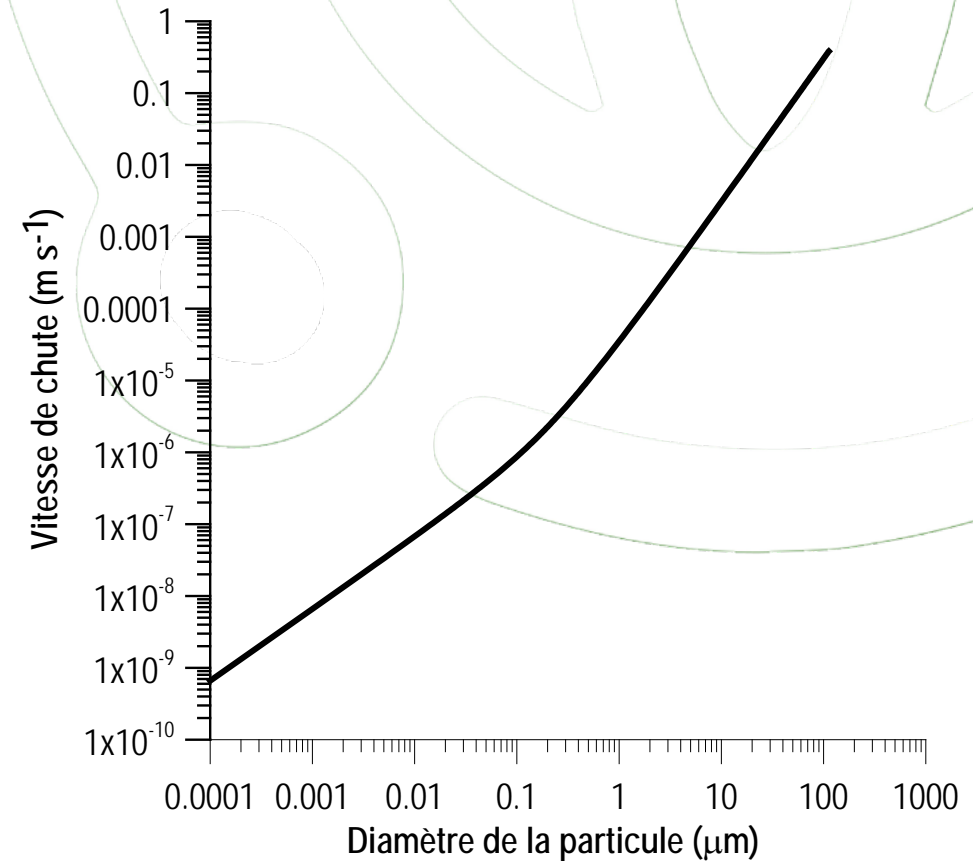
Slip correction factor
(Cunningham)

$$C_c = 1 + \frac{2.52\lambda}{d_p} \quad (d_p > 0.1\mu m)$$

$$F_D = F_G = mg$$

Settling velocity

$$V_{TS} = \frac{\rho_P \cdot d^2 \cdot g \cdot C_C}{18 \cdot \eta}$$



Reynolds Number Laminar or Turbulent Flow

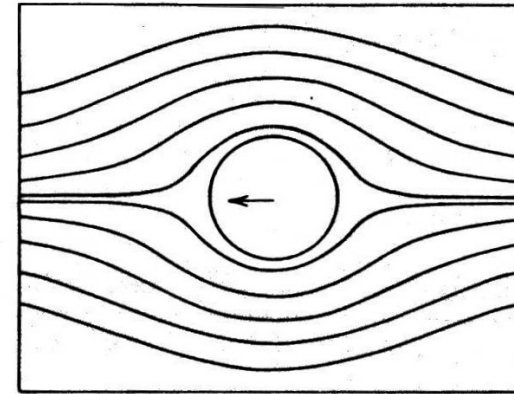
Reynolds Number:

inertial force/frictional force

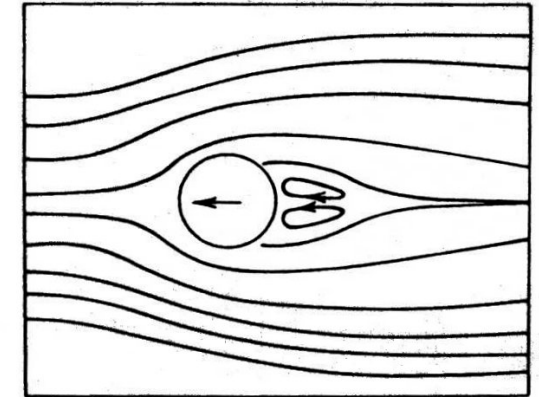
$$Re_p = \frac{\rho_g V d_p}{\mu}$$

μ = air viscosity

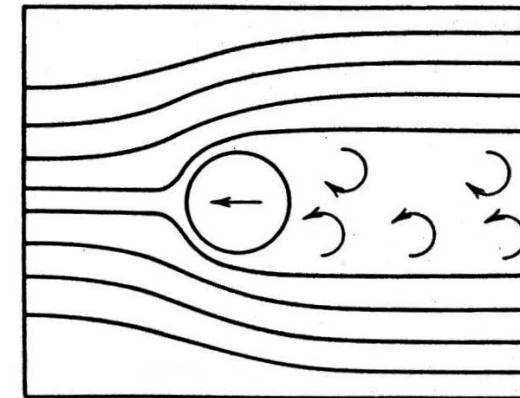
V = velocity of flow



(a)



(b)



(c)

The **Reynolds number** represents the ratio between **inertial forces** and **viscous forces** acting on a fluid.

$Re_{flow} < 2000$ Laminar > 3000 Turbulent
 $Re_p < 1$ Laminar > 250 Turbulent

Relaxation Time / Stopping Distance

Time to adjust to changing flow motion

Relaxation Time:

indication of the time required for a particle to adjust/relax its velocity to a **new** condition of force

$$\tau = mB = \frac{\rho_p d_p^2 C_C}{18\mu}$$

Stopping Distance:

indication of the distance required for a particle to adjust/relax its velocity to a **new** condition of force

$$s = v\tau$$

If the fluid is very viscous, the **relaxation time** is short → the particle stops quickly.
 If the particle is very dense or large, it has a **high** τ → it travels a longer distance before stopping.

Relaxation time/stopping distance

| d_p (μm) | 3τ (ms) | S^* (cm) |
|-------------------------|--------------|----------------------|
| 0.01 | 0.00002 | 6.8×10^{-6} |
| 0.1 | 0.00026 | 8.8×10^{-5} |
| 1 | 0.011 | 3.6×10^{-3} |
| 10 | 0.94 | 0.23 |
| 100 | 92 | 12.7 |

* $V_0=1000$ cm/s

Time for unit density particles to reach their terminal velocity

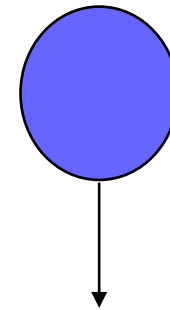
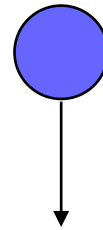
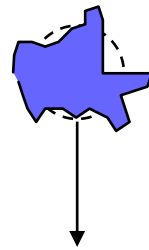
In **aerosol particle sampling**, the relationship between **relaxation time** and **stopping distance** is crucial for understanding which particles are able to follow the airstream within the sampling system (e.g., in an **impactor**, **cyclone**, or **filter**), and which are **deflected or lost**

Which Diameter ?

- The **Stokes diameter**, d_s , is the diameter of the sphere that has the same density and settling velocity as the particle.
- The **aerodynamic diameter**, d_a , is the diameter of the unit density ($\rho_0=1 \text{ g/cm}^3$) sphere that has the same settling velocity as the particle.

$$V_{TS} = \frac{\rho_p d_s^2 g C_c}{18\mu} = \frac{\rho_0 d_a^2 g C_c}{18\mu}$$

$$d_a = d_s \sqrt{\frac{\rho_p}{\rho_0}}$$



Used to calculate relaxation time and stopping distance.
Used in numerical models and particle transport simulations.

Useful in the design of filters and separation devices.

Standard metric used in sampling devices (e.g., PM10 = particles with aerodynamic diameter $\leq 10 \mu\text{m}$).

It allows classification of particles based on their ability to penetrate the respiratory tract.

It makes particles with different shapes and densities comparable.

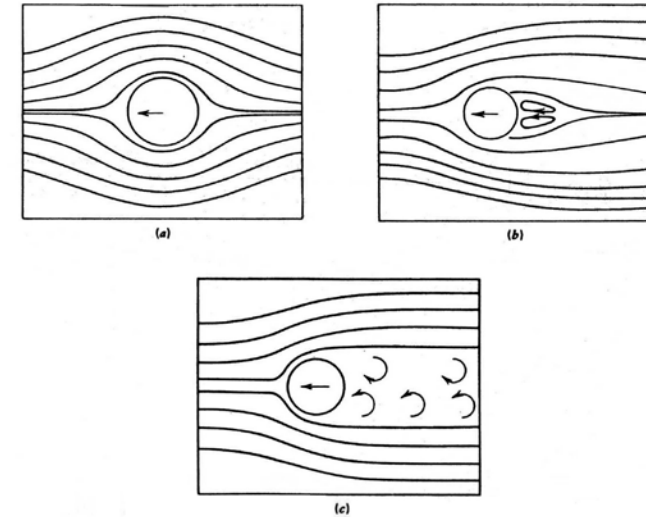
General Sampling Considerations

Flow-Reynolds-Number

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

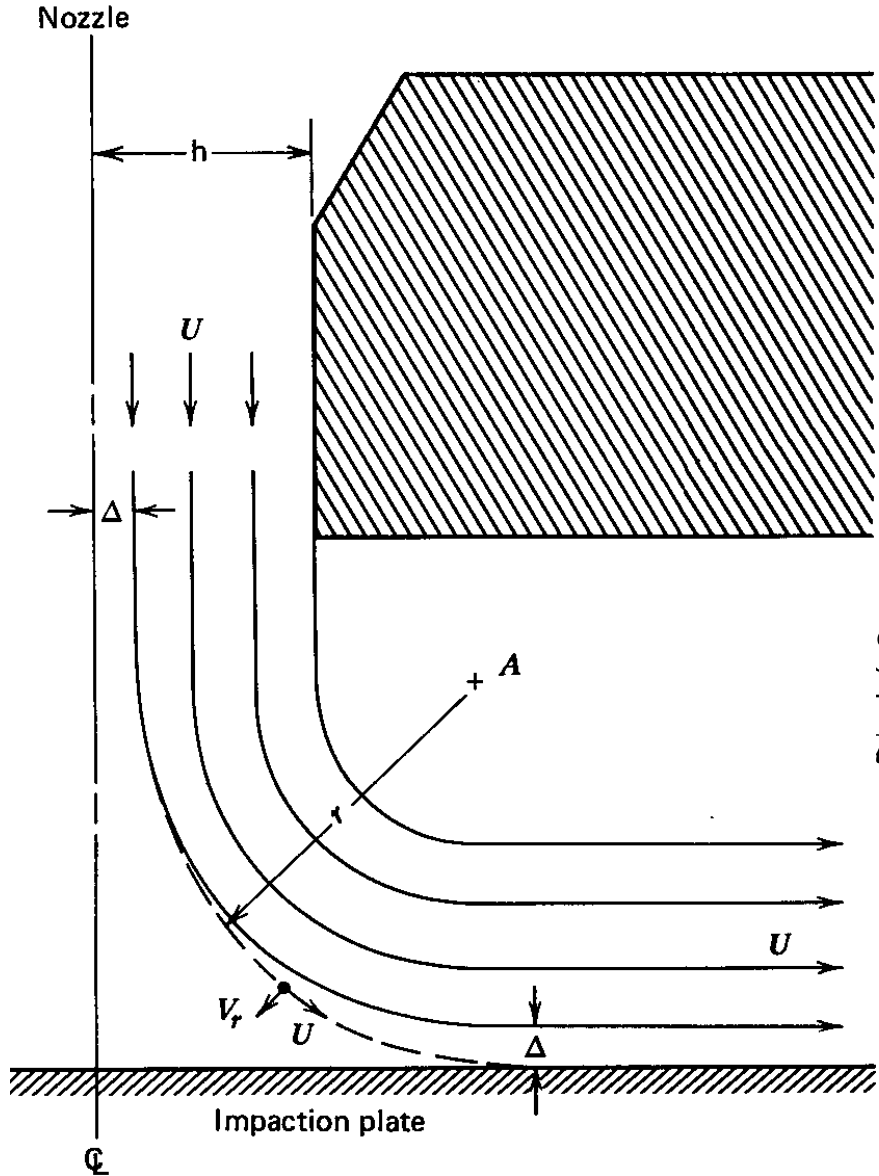
$$\text{Re}_{\text{flow}} = \frac{\rho_{\text{gas}} \cdot \bar{u}_{\text{flow}} \cdot D_{\text{pipe}}}{\eta}$$

ρ_{gas} ... gas density
 u_{flow} ... flow velocity
 D_{pipe} ... tube diameter
 η ... dynamic viscosity



- **Re < ~2000** → **Laminar flow** (smooth and orderly)
- **Re > ~4000** → **Turbulent flow** (chaotic and vortical)
- **Re between 2000 and 4000** → **Transitional regime**

Inertial impaction



Stokes Number: the ratio of stopping distance of a particle to a characteristic dimension of the obstacle.

$$\frac{S}{l_c} = \frac{\tau U}{D_j / 2}$$

- Stk $\ll 1$**
Particle with **low inertia**: follows the flow
- Stk ~ 1**
Balance between inertia and fluid forces: probable impact
- Stk $\gg 1$**
Particle has **high inertia**: it ignores the deviation and impacts

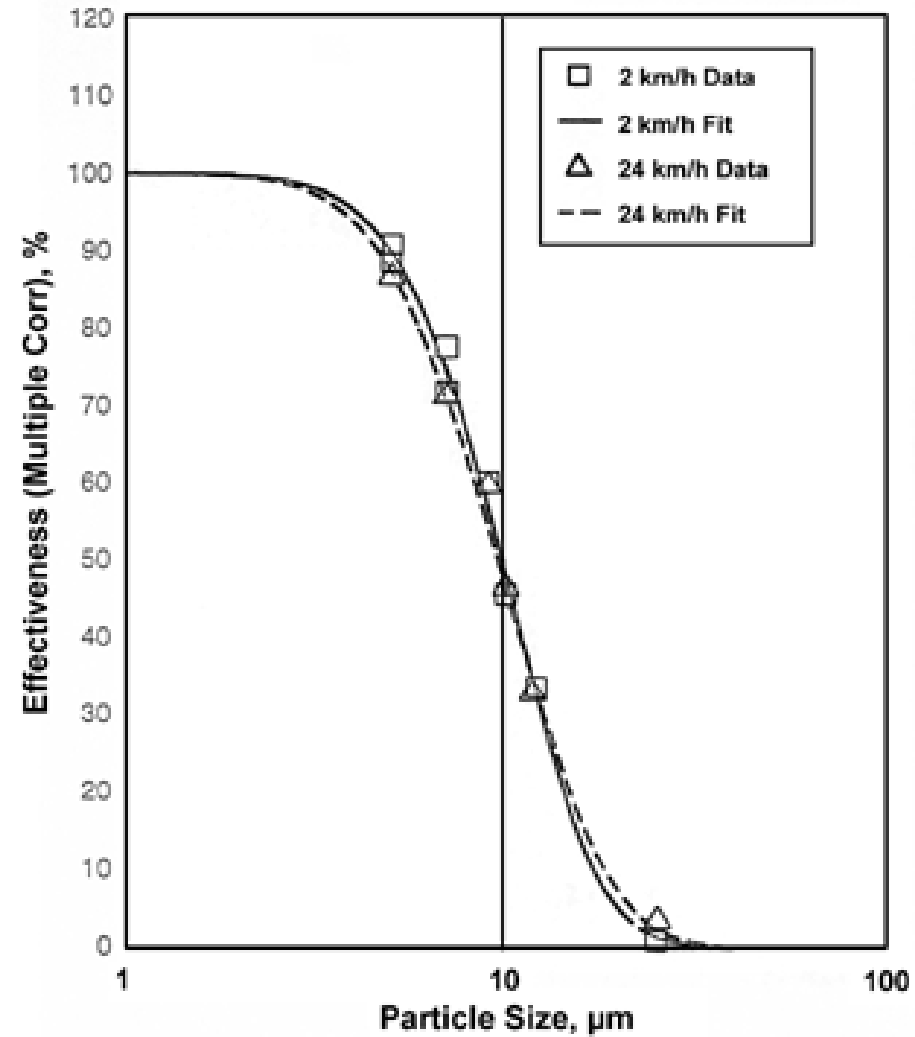
Inertial impaction – sampling cut off

- 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)

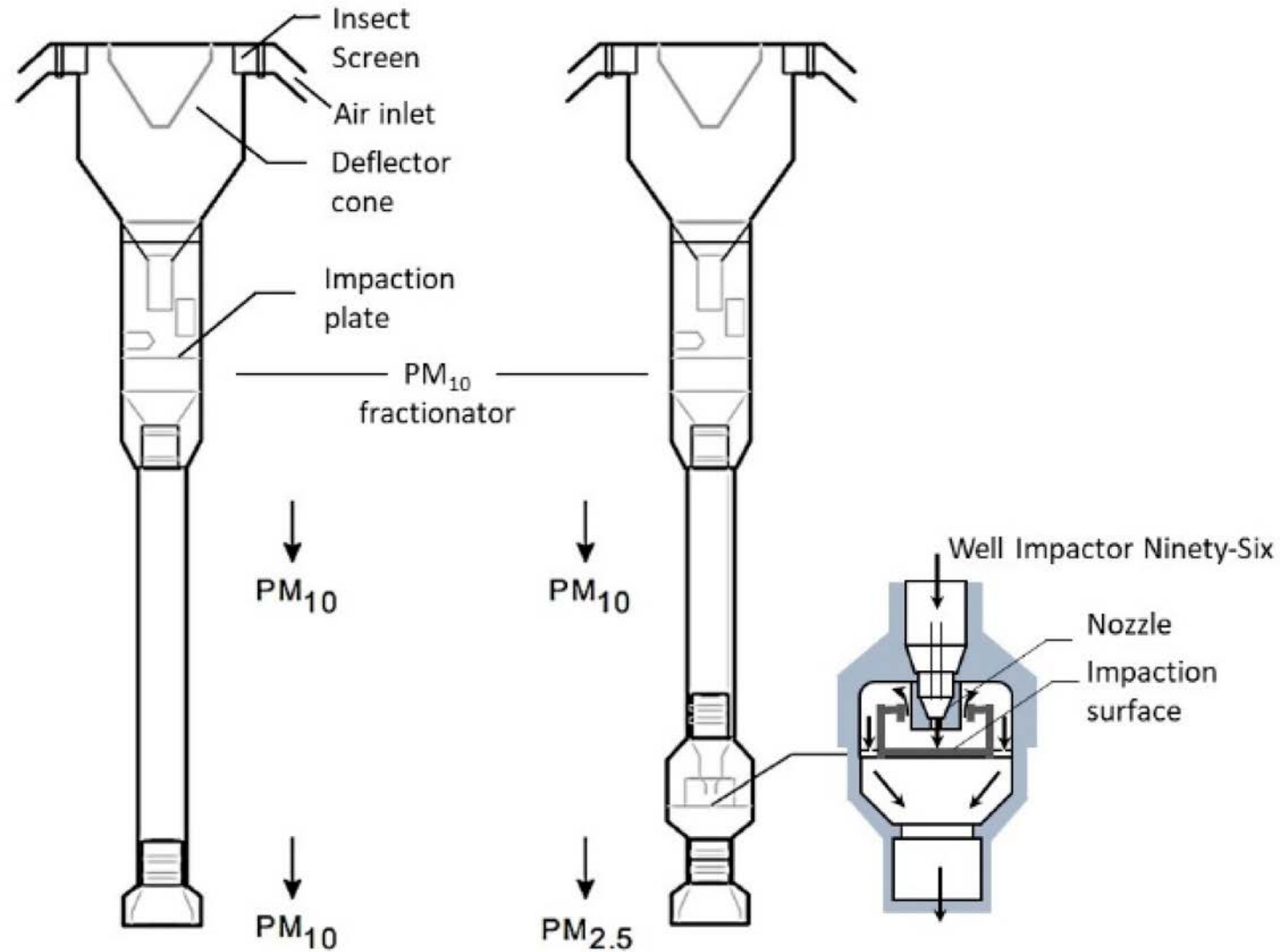
Low flow PM10 inlet

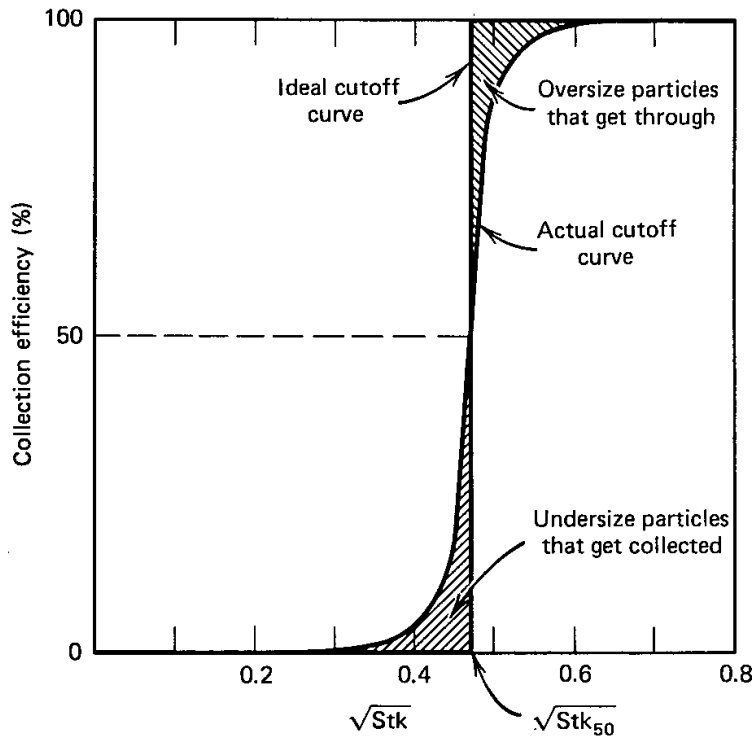


Penetration efficiency curve



Low flow PM10 inlet





$$d_{50} \sqrt{C_c} = \sqrt{\frac{9 \mu D_j Stk_{50}}{\rho_p U}}$$

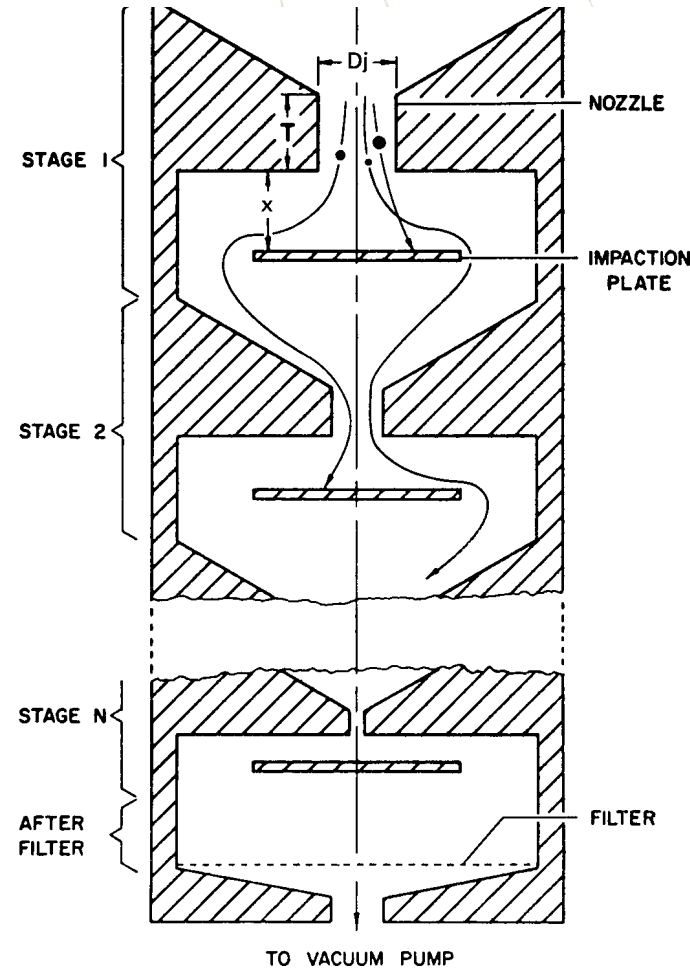


Table 5.4 Stokes Number for 50 Percent Collection Efficiency for Impactors^a

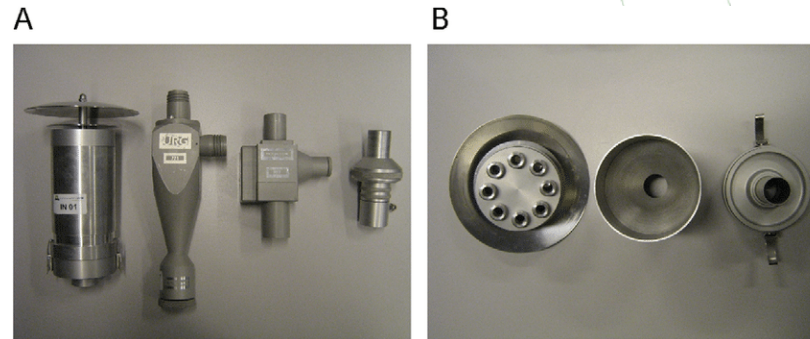
| Impactor Type | Stk_{50} | $\sqrt{Stk_{50}}$ |
|--------------------|------------|-------------------|
| Circular nozzle | 0.24 | 0.49 |
| Rectangular nozzle | 0.59 | 0.77 |

^a $500 < Re < 3000$ and $x/D_j > 1.5$.

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.

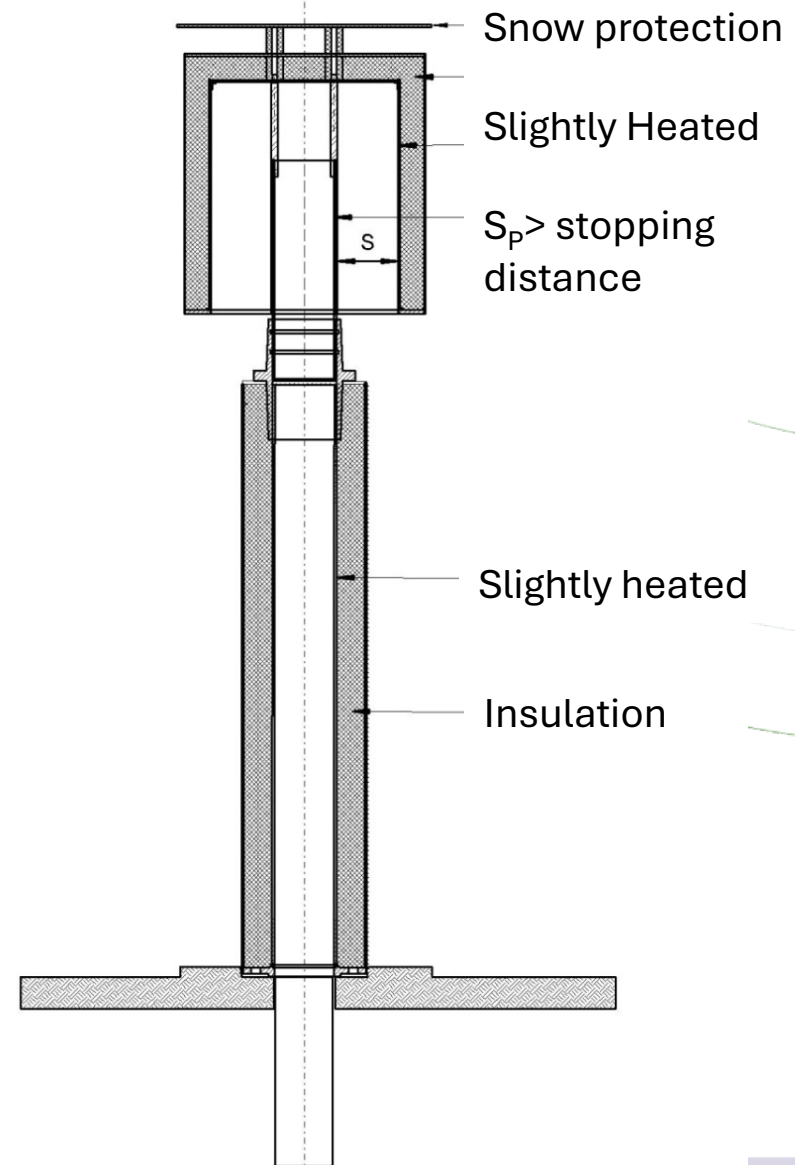
Sampling under Extreme Conditions

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



Isokinetic Sampling

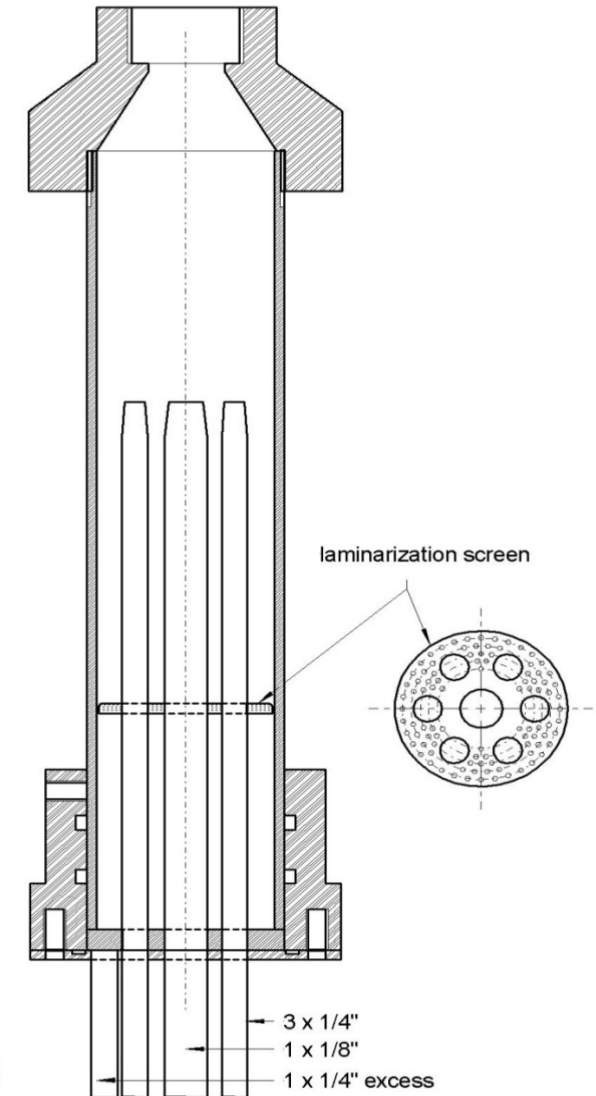
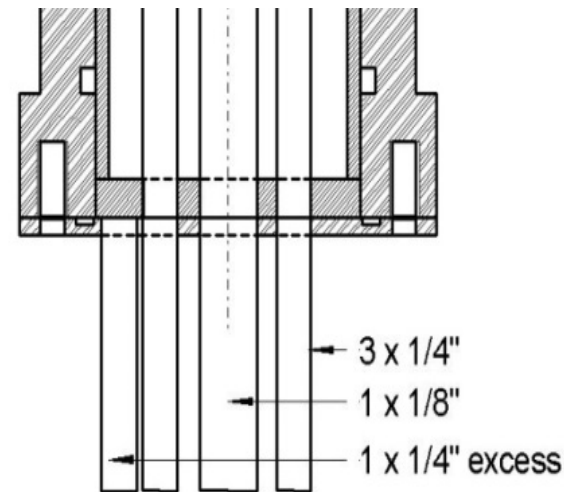
An isokinetic aerosol splitter should be used if **coarse particles** are sampled or characterized.

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

$$\text{Stk} \leq 0.01$$

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

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



Aerosol Drying

Why we need 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).

Aerosol Drying

- **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
only low flows

Dilution

The aerosol is diluted with dry particle-free air.

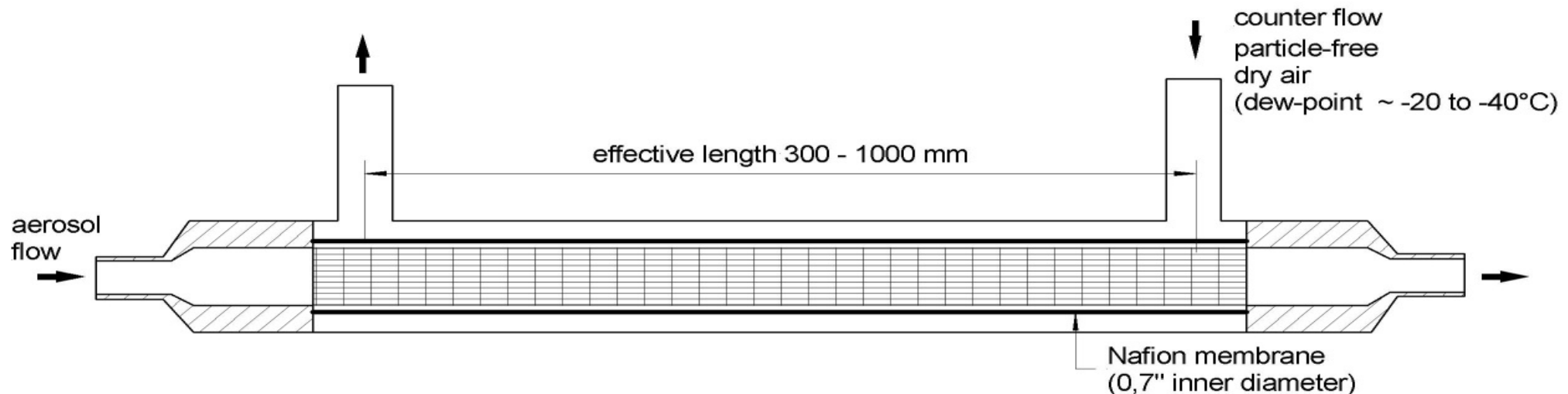
- **Advantage:** easy way to dry
- **Disadvantage:** The dilution ratio has to be exactly known. High ratios may create high uncertainties.
- Dilution is the recommended method for **tropical and subtropical** observatories

Heating

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

Aerosol Membrane Dryers

- 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

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 (<100nm)

- 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 $> 1 \mu\text{m}$

- 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.

General Sampling Consideration

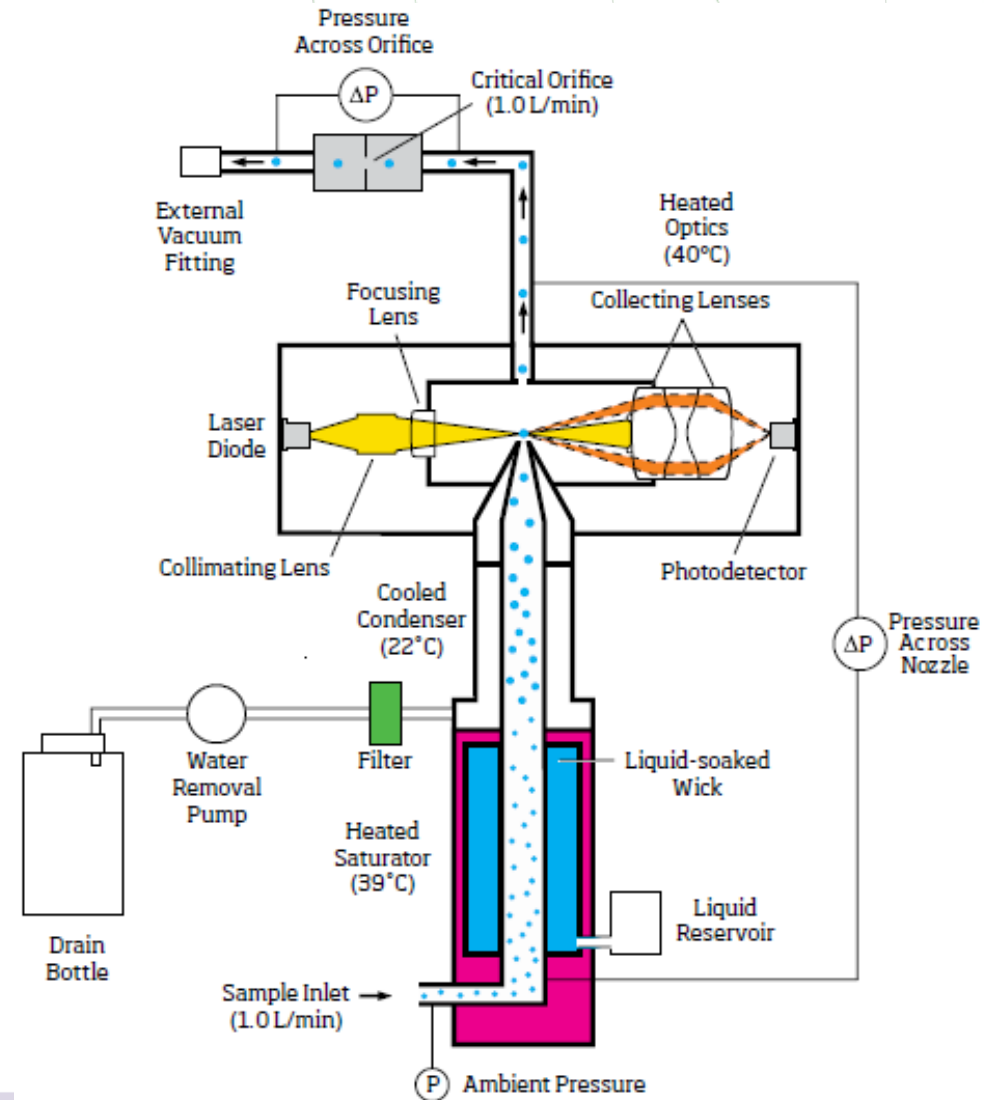
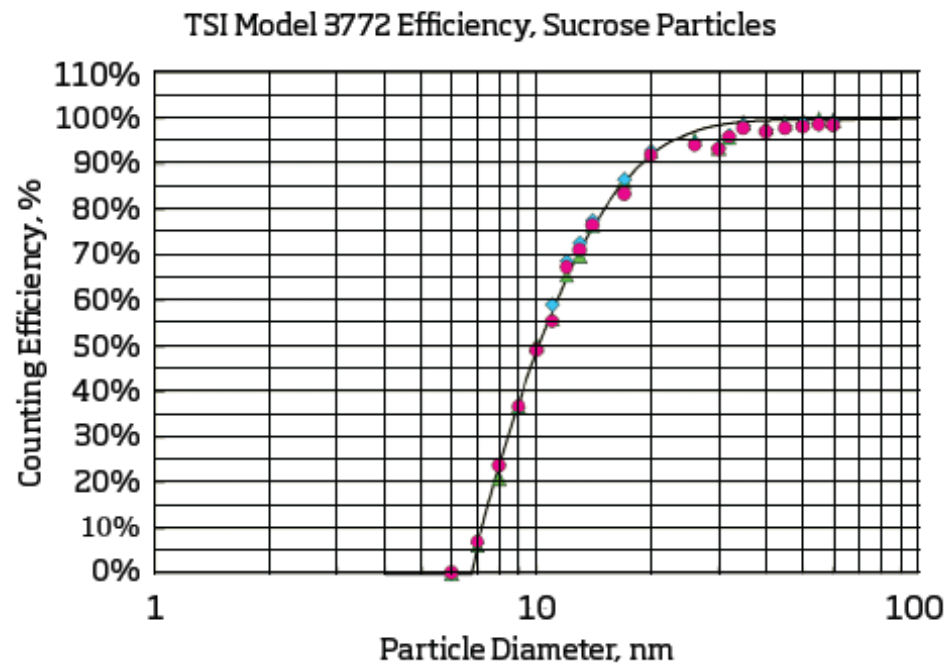
These Recommendations are based on the WMO-GAW & ACTRIS:

- 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.
- **PM₁₀** inlets should be used, while **TSP inlets are NOT recommended anymore**.
- The recommendation is to measure at a **relative humidity below 40%**.

Number concentration and size distributions

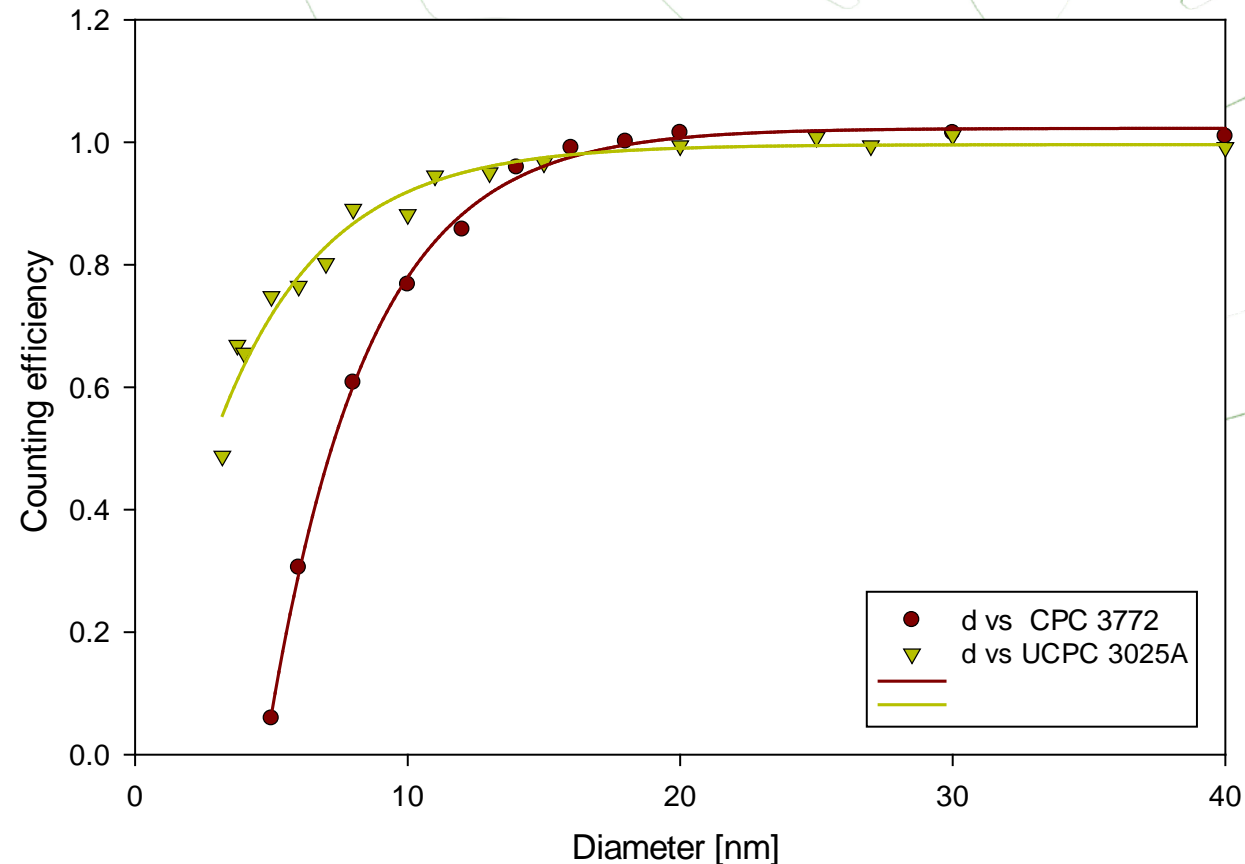
- A Condensation Particle Counter (CPC) and is used to measure the particle number concentration down to few nanometer in particle size.
- The lower detection efficiency is much lower compared to an optical particle size spectrometer.
- The aerosol flow is saturated with a vapor of a working fluid.
- The particle subsequent enlarged to droplets by condensation of a condensable gas. The particles reach a size at which they can be optically detected.
- The number concentration is measured for all particle larger than the lower detection diameter.

CPC (TSI 3750 – 3772)



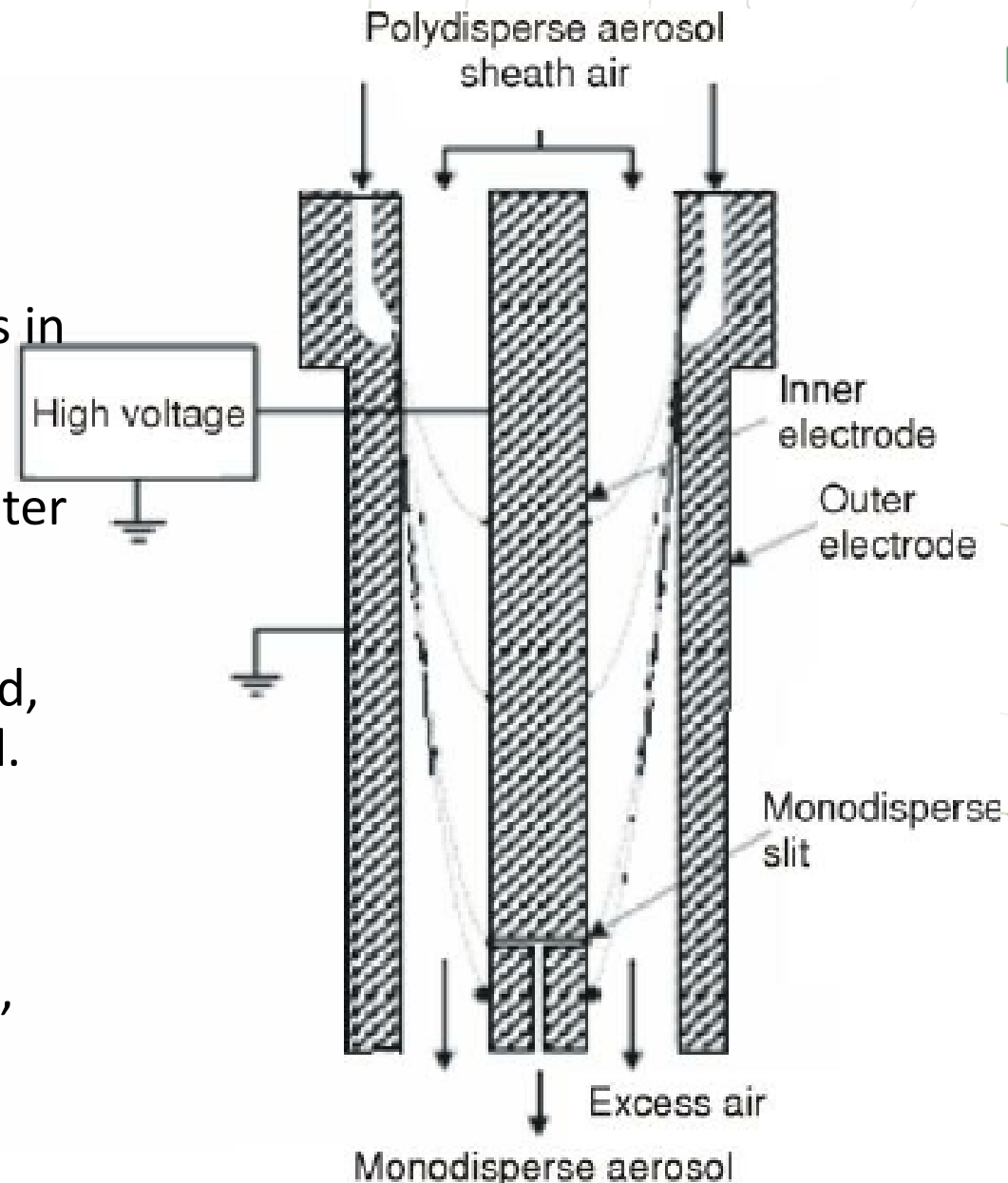
Particle Number Concentration

- There is **no direct standard** for a particle number concentration!
- The **reference** concentration is determined from an independent **aerosol electrometer** measurement
- **Following calibration chain is applied:**
 - Calibration of an aerosol electrometer
 - Calibration of reference condensation particle counter
 - Calibration of individual instruments



Particles size distribution, Differential Mobility Analyser

- transport of electrically charged particles in an electric field.
- The electrostatic force can be much greater than e.g. the gravitational force.
- Aerosol particles can be either uncharged, multiply, positively or negatively charged.
- The transport of aerosol particles in an electric field is widely used, mainly in electric particle filters, aerosol collectors, and instrumentation to measure size distributions.

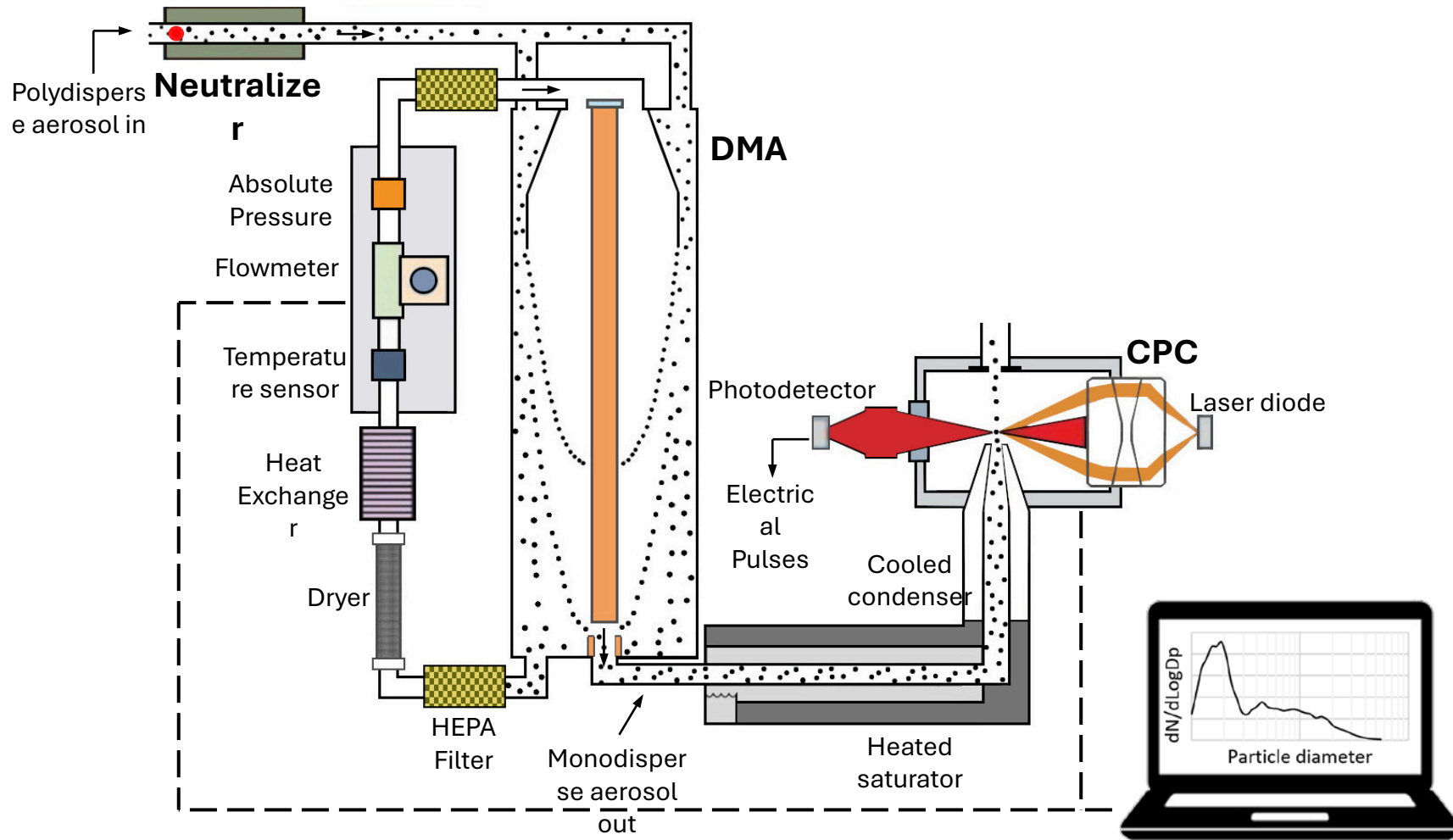


Bipolar Diffusion charging

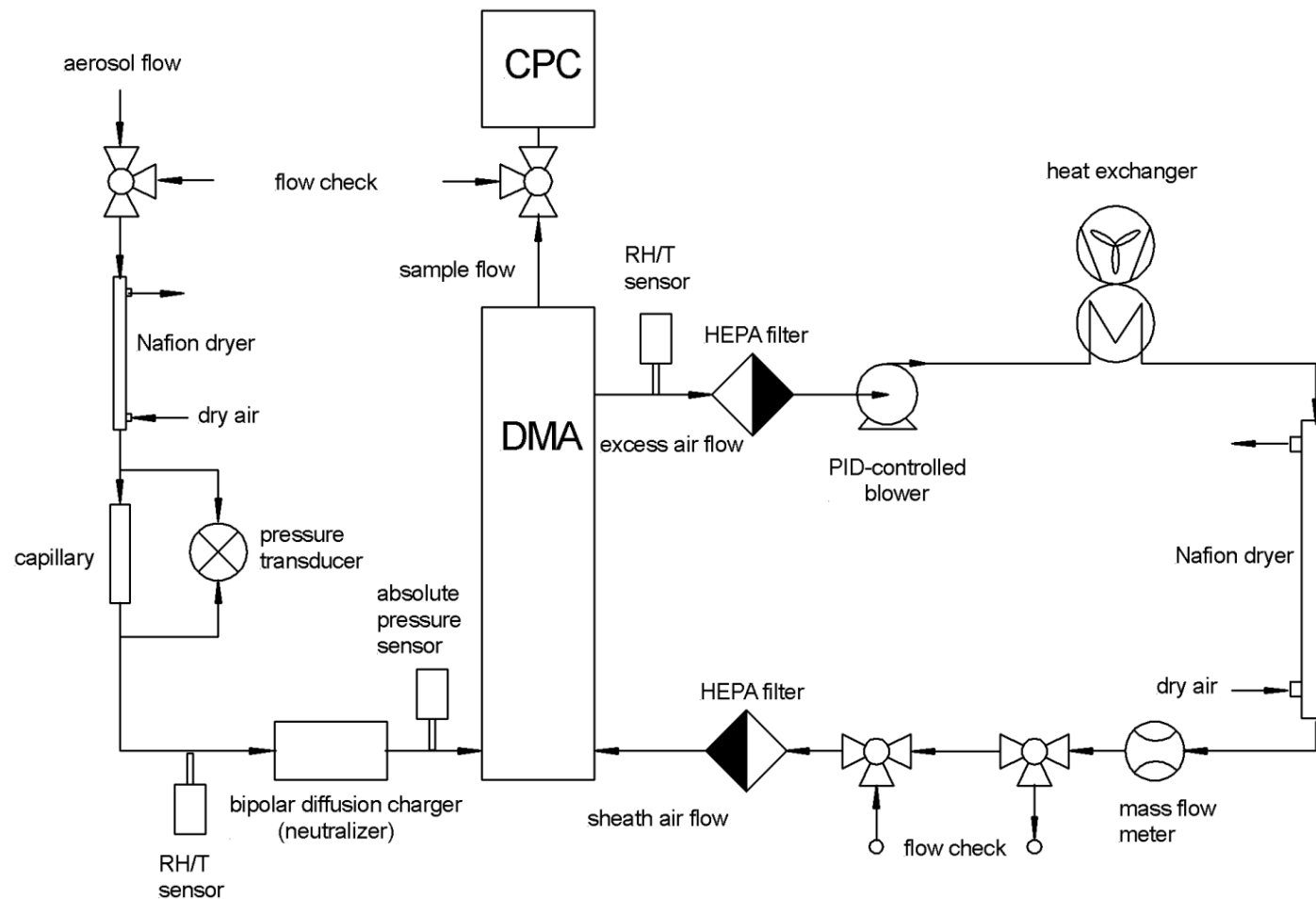
- Particles are charged by positive and negative gas ions.
- The ions are produced and transported to the particles in a neutralizer or bipolar diffusion charger.
- The ions are produced due to ionization of gas molecules by radioactive alpha or beta radiation or **X-ray**
- **Kr⁸⁵**, **Am²⁴¹**, **Ni⁶³**, **Po²¹⁰**



Scanning Mobility Particle Sizer (SMPS)



MPSS – Recommended Setup in GAW and ACTRIS



Wiedensohler et al., 2012, Atmos. Meas. Tech., 5, 657–685.

Regular check of MPSS

- Aerosol, CPC and sheath flow measured once per month with an independent flow standard such as an electrical bubble flow
- Leak testing, zero check (once per month)
- Humidity and temperature sensors for the aerosol and sheath air flow have to be checked prior to their deployment and afterwards at least once per year
- High Voltage check and calibration (once per month)
- The sizing accuracy of mobility particle size spectrometers have to be verified using 200 nm PSL spheres (every three months)
- Cleaning

Neutral cluster and Air Ion Spectrometer (NAIS)



Neutral cluster and Air Ion Spectrometer (NAIS)

Measurement range:

Ions

(naturally charged particles)

Particles

(charged and uncharged)

Sample flowrate

Time resolution

3 to 0.0013 $\text{cm}^2/\text{V}/\text{s}$

0.8 to 40 nm

2.5 to 40 nm

from 2.0 nm if high concentrations

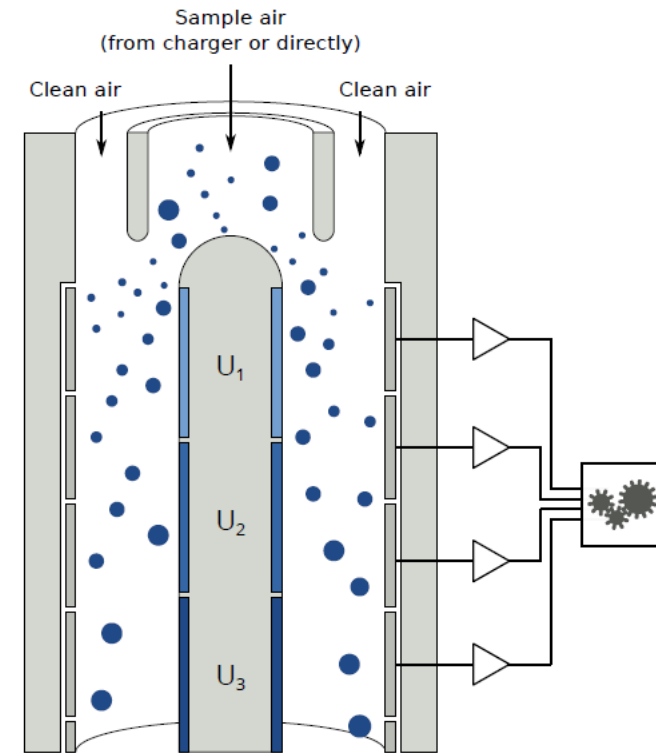
54 l/min

1 second

1 - 5 minute averages typically used
during long-term monitoring

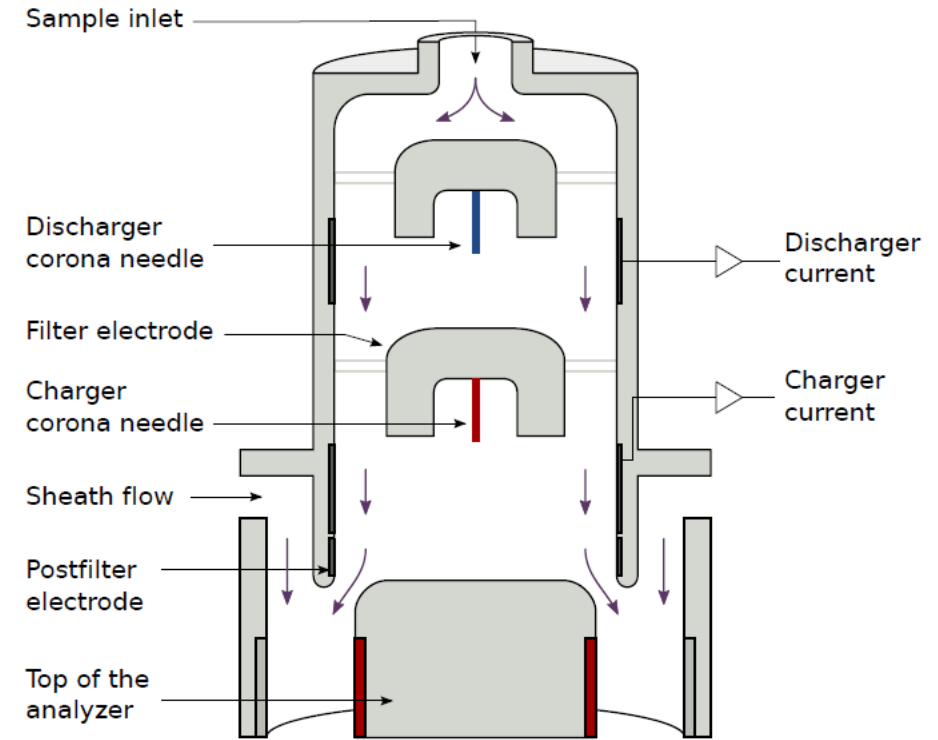
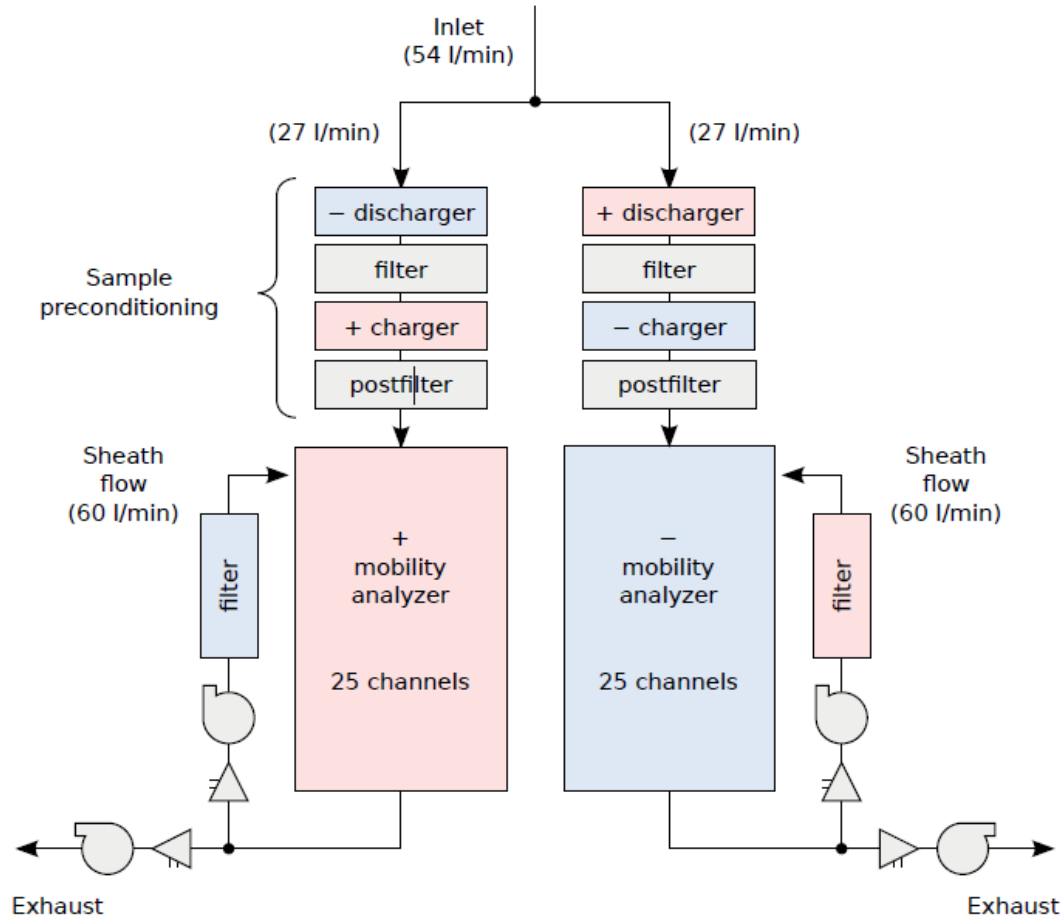
Parallel Electrical Aerosol Spectrometry

1. Particles are electrically charged*
2. Charged particles are classified by electrical mobility.
3. Electric current from each collecting section is measured.
4. Size distribution is found.



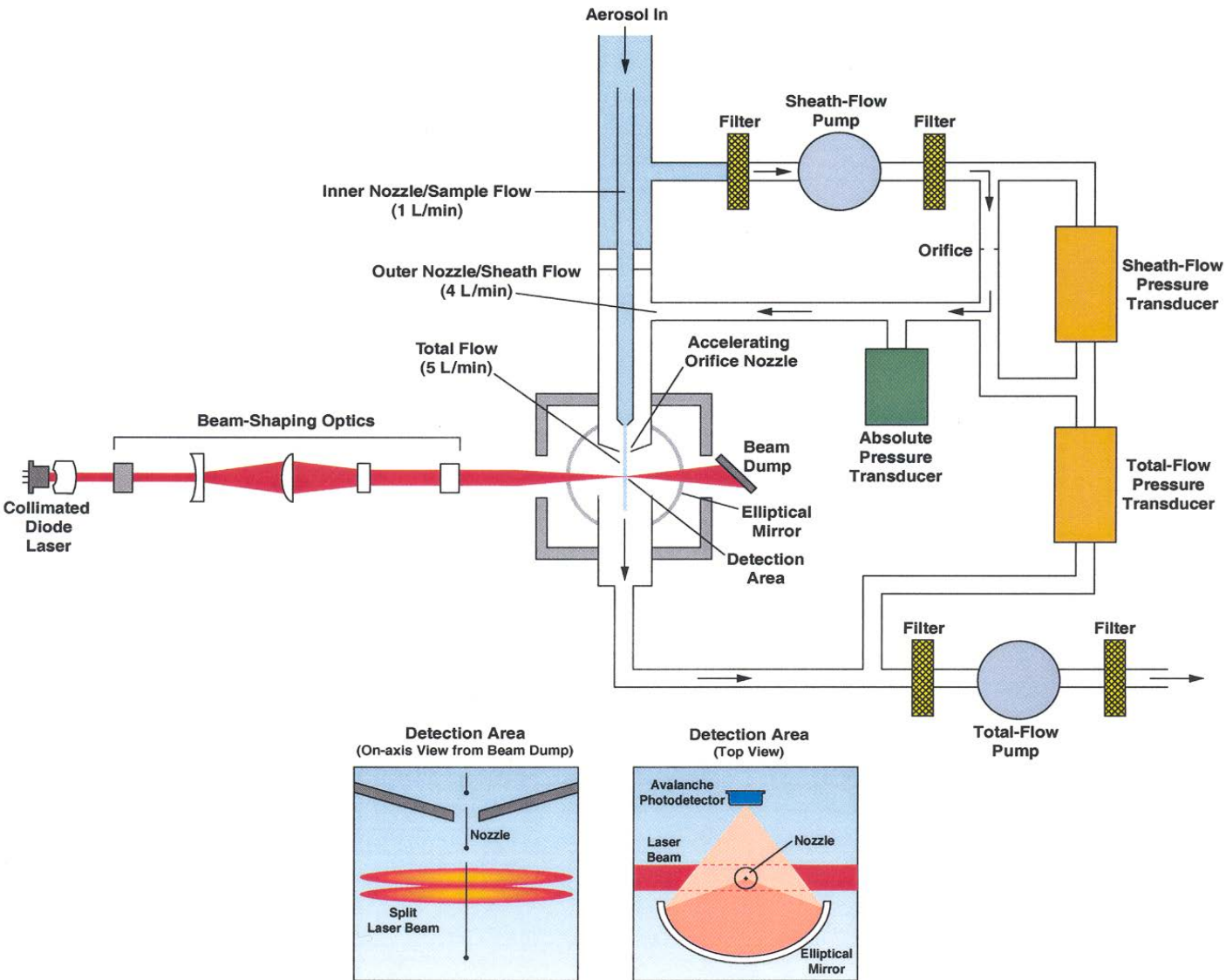
Principal schematic of the NAIS

Sample preconditioning - the charger-filter unit

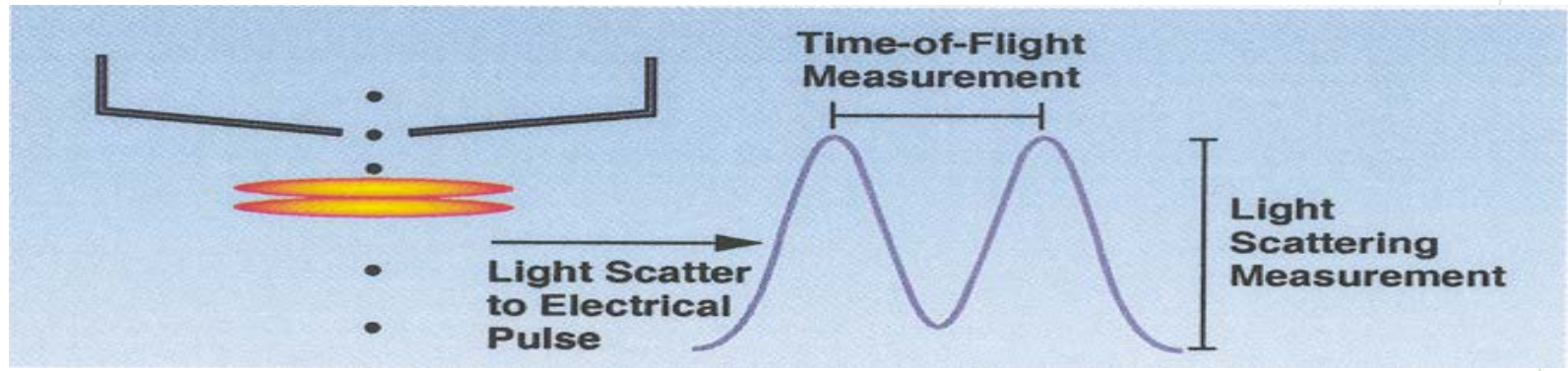


Aerodynamic Particle Number Size Distribution between 0.5 and 20 μm

- The aerodynamic particle diameter is defined as the „diameter of a spherical particle with the density of One with the same sedimentation velocity of the measured particle“.
- Aerodynamic Particle Size Spectrometer can measure the aerodynamic particle diameter.
- Aerodynamic Particle Size Spectrometer determines the aerodynamic particle number size distribution.
- In comparison, a cascade impactor measures the aerodynamic particle mass size distribution with a limited size resolution.



- The acceleration nozzle consists of an inner and outer nozzle.
- The inner nozzle focuses the aerosol flow. The aerosol flow is then surrounded by the sheath air flow.
- The entire flow is then accelerated through the outer nozzle.
- The total flow rate of 5 l/min consists of 1 l/min aerosol flow and 4 l/min particle-free sheath air.



- The laser anemometer measures the time-of-flight between two laser beams.
- The laser beams are positioned directly behind the outer nozzle.
- Particles passing the laser beams emit two light pulses.
- The time difference between the two pulse maxima is the time-of-flight.
- The time-of-flight is a measure for the aerodynamic particle diameter.

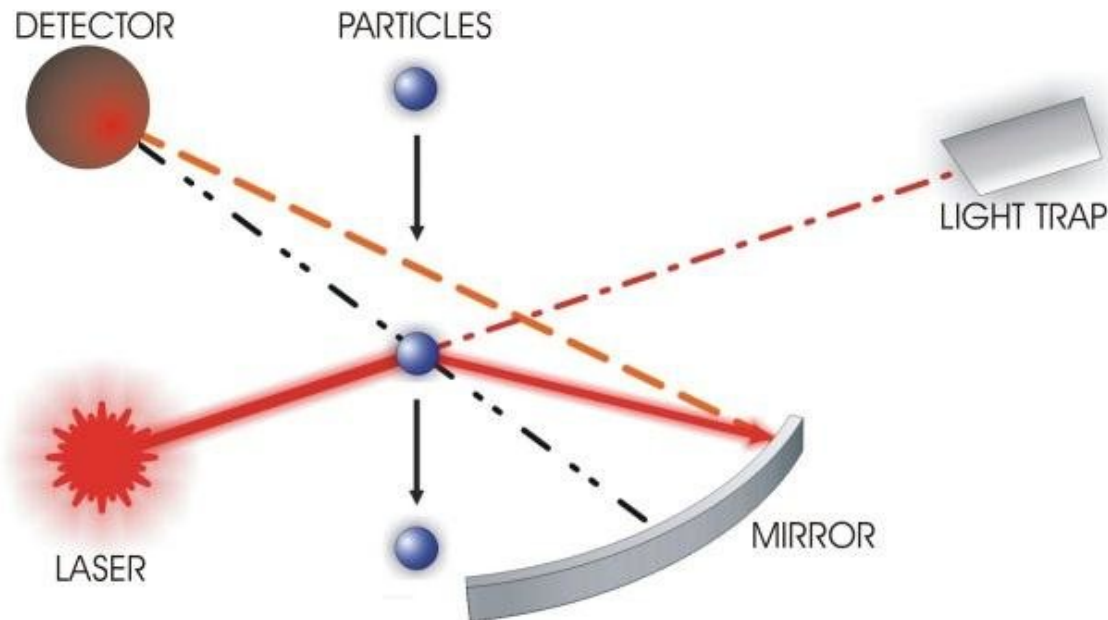
Optical measurement of coarse size distribution

Counts and size distribution of aerosol particles

The OPC counts how many particles fall into each **size bin** (e.g., 0.3–0.5 μm , 0.5–1 μm , etc.) and provides a **size distribution** over time.

Typically 0.2/0.3 to 20 μm
8-15 bins
Time resolution 1 minute





A **pump or airflow system** pulls air (with particles) through a narrow **laser-illuminated chamber** or flow cell.

- **Particles pass through a laser beam**

As each **particle crosses** the focused **laser light**, it **scatters light** in different directions.

- **Scattered light is detected**

A **photodetector** (typically 90°) measures the **intensity of the scattered light** from each individual particle (The intensity of scattered light from a 20µm particle is approximately 10 orders of magnitude larger than that from a 50nm particle)

- **Signal is converted to particle size**

The amount of scattered light is related to the **particle's size** (using Mie or Rayleigh scattering theory), so the instrument **estimates the size** of each particle.

Airborne OPCs do not account for many aerosol particle properties, such as density, shape, [refractive index](#), and absorption. As a consequence, aerosol particle counters often report light-scattering equivalent diameters and not a true physical diameter.

Coarse particle size distribution recommendation

- regular cleaning of the nozzles
- regular flow checks (total and aerosol flow) once per month with a flow standard such as an electrical bubble flow
- Flow check
- Leak testing, zero check (every three months)
- The sizing accuracy have check with one or two sizes of Latex spheres (1000 and 3000 nm (every three months). The latex sizing must be within 15% of the certified diameter (10% on average)



THANKS!

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(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 "Education and Research" - Component 2: "From research to business" - Investment
3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

