World Calibration Centre for Aerosol Physics

GAW - WCCAP recommendation for aerosol inlets and sampling tubes

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Aerosol sampling

An ideal aerosol sampling system allows an undisturbed sample flow from the environment right to the instrumentation, meanwhile removing some unwanted air ingredients, such as hydrometeors or excessive moisture.

An ideal sampling system

- excludes precipitation and fog droplets from the sampled aerosol,
- provides a representative ambient aerosol sample under as little diffusional and inertial losses,
- provides aerosol particles at a low relative humidity (< 40%),
- minimizes the evaporation of volatile particulate species.

The most common set-ups combine an outdoor aerosol inlet, smooth transport pipes, an aerosol conditioner to dry the sampling flow, and a final flow splitter to distribute the aerosol among the various instruments and samplers. Aerosol instrumentation should generally be housed in a room that provides a clean laboratory environment and temperatures between 15 and 30°C. Optimum indoor temperatures range between 20 and 25 °C.

Size cut-offs

The cut-off size of the aerosol inlet and the height above ground are usually guided by the purpose of the measurement network. The most widely used options are currently PM_{10}, $PM_{2.5}$, or PM_1, implying upper aerodynamic cut-off diameters at 10, 2.5, and 1 µm, respectively, under ambient conditions. These inlets are based on particle separation by either an impactor or a cyclone.

Observational networks, such as WMO-GAW, recommend an upper cut point of 10 µm at ambient conditions (WMO-GAW report 153). The rationale is that particles larger than 10 µm tend to be of local origin and are, thus, not representative for the regional-scale aerosol and its impact on climate effects. TSP (Total Suspended Matter) inlets, in contrast, turn out to be sensitive towards wind speed and cannot provide representative samples of larger particles. To obtain additional sizing information, aerodynamic size cuts 2.5 µm (ambient conditions) and 1 µm (dry conditions) are recommended by WMO-GAW to distinguish fine and coarse particles. The recommendations of the WMO-GAW report 153 were also adopted by EMEP and the European Infrastructure Projects EUSAAR and ACTRIS.

Whole-air inlet for extreme ambient conditions

Alternative inlet designs might be considered for measurements in an extreme climate. Sampling sites that experience frequent clouds, fog or freezing may prefer using a heated whole-air inlet to capture cloud and fog droplets within the sample. This inlet concerns sites which are located in Polar regions or on high Alpine mountains. Figure 1 illustrates the concept of such a heated whole-air inlet based on the design of the inlet of the Jungfraujoch station in Switzerland as described in Weingartner et al. (1999). Heating prevents clogging of the inlet with ice. Inside the inlet, cloud and fog droplets are evaporated, so that all aerosol particles, whether activated or not, will be included in the measurement. For such whole-air inlets it is desirable to scrutinize the relationship between the ambient wind velocity and variations in the size-cut characteristics.

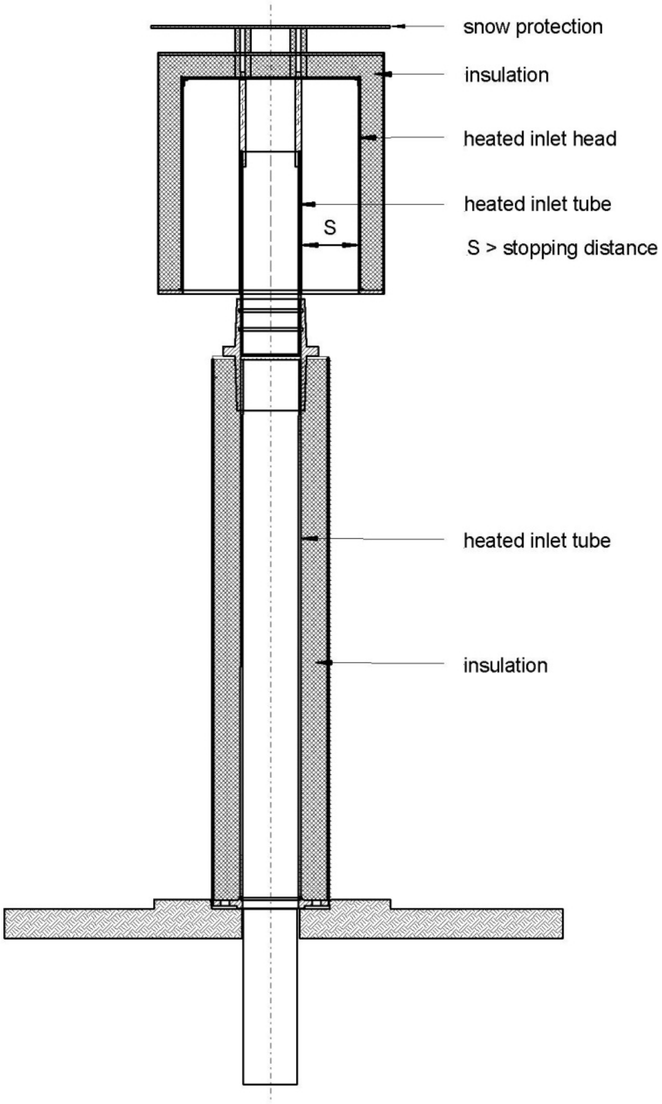

Figure 1: sketch of a whole air inlet

Tubing and flow splitters

Inside the measurements station, the aerosol flow is usually distributed among several instruments. For aerosol particles, care should be taken with the choice of the tubing and the design of flow distribution devices. Pipes conducting aerosol should be manufactured from metal, preferably stainless steel. It is vital for the sampling of particles that the pipes are made of conductive material, and electrically grounded. Otherwise, static charges may remove significant portions of the aerosol to be sampled. Short pieces of tubing might be replaced by conductive silicone tubing, which is elastic and conducting at the same time. A perfect inlet installation also avoids sources of turbulence (bends, connectors) as best as possible (turbulence enhances particle losses due to diffusion) and keeps the sampling lines as short as possible.

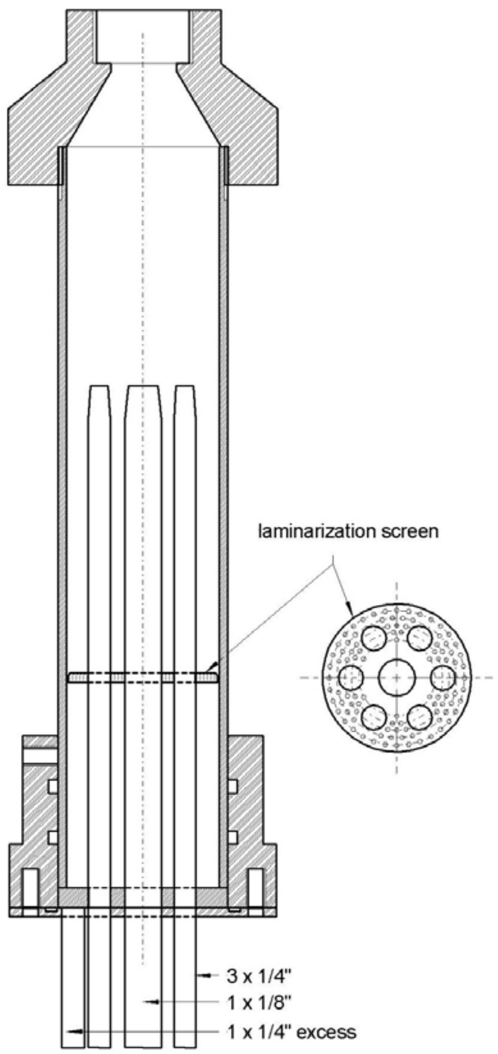

Figure 2: Example sketch for an isokinetic flow splitter

Figure 2 illustrates a custom-designed isokinetic flow splitter in which the sample flow velocity is near the flow velocity of the main flow. Another key feature of the splitter is that a sample is removed from the core of the main aerosol flow rather than from streamlines near the wall of the main pipe. This principle ensures a representative sampling especially of coarse and Nano-particles.

General aspects of particle motion

The main challenge when transporting the aerosol to collectors and aerosol measuring instrumentation is to avoid particles losses. Particle loss mechanisms are size-depending and are generally caused by particle diffusion, impaction, and sedimentation. Generally, losses due to particle diffusion are critical for ultrafine particles smaller than 0.1 µm. In contrast, particle losses due to sedimentation and impaction are related to supermicrometer particles in horizontal and sloping pipes as well as bends. The configuration of the whole sampling configuration and the regime of the main air flow are strongly dependent on the purpose of the observational network.
The regime of an air flow in a pipe, laminar vs. turbulent, is characterized by its Reynolds Number (Re). A flow in a pipe is laminar up to a Reynolds Number of approximately 2000. Above this value, the flow becomes gradually more and more turbulent. The Reynolds Number of the flow can be determined by

$$\mathrm{Re}_{\mathrm{flow}} = \frac{\rho_{\mathrm{G}} \cdot u_{\mathrm{flow}} \cdot D_{\mathrm{pipe}}}{\eta_G} \qquad \text{Eq. 1}$$

Hereby is ρ_G the gas density, u_{flow} the flow velocity, D_{pipe} the inner diameter of the pipe, and η_G the gas viscosity.

The inertia of a particle in a flow is characterized by its Stokes Number Stk.

$$Stk = \frac{\tau \cdot u_{\mathrm{flow}}}{D_{\mathrm{pipe}}}$$

with

$$\tau = \frac{\rho_{\mathrm{P}} \cdot D_{\mathrm{P}}^2 \cdot C_{\mathrm{C}}}{18\eta_{\mathrm{G}}}$$

Hereby is τ the relaxation time of the particle, u_{flow} the flow velocity, D_{pipe} the inner diameter of the pipe, ρ_P the particle density, Dp the particle diameter, C_C the Cunningham correction factor, and η_G the gas viscosity.

Laminar flow sampling configuration

Generally, a laminar aerosol sampling is recommended in the ACTRIS network to minimize particle losses due to diffusion and inertia over a wide size range, especially for nucleation and coarse mode particles. Furthermore, the pressure drop from the inlet to the instruments can be kept in the range of few hPa. Minimum losses due to particle diffusion in a laminar flow can be achieved by keeping the length of the pipe as short as possible and the flow rate as high as possible. Particle losses of supermicrometer particles can be minimized by avoiding bends or horizontally orientated sampling pipes.

To design a laminar sampling configuration, the size-dependent particle penetration can be calculated (Hinds, 1892) by:

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

For µ< 0.007

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

For µ>0.007

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

Hereby, D is the particle diffusion coefficient, L_{pipe} the length of the pipe, and Q the volume flow rate. In cases that bends cannot be avoided in the sampling pipe, the size-depended particle penetration can be calculated by

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

Hereby, θ is the angle of the bend.
Size-dependent losses due to sedimentation of supermicrometer particles in horizontal or sloping pipes can be calculated by

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

with

$$\kappa = \varepsilon \cdot \sin(\theta)$$
$$\varepsilon = \frac{3}{4}Z$$
$$Z = \frac{L_{\text{pipe}}}{D_{\text{pipe}}} \cdot \frac{u_{\text{S}}}{\overline{u}_{\text{flow}}}$$

Hereby, L_{pipe} is the length of the pipe, D_{pipe} the inner diameter of the pipe, u_S the sedimentation velocity, u_{flow} the mean flow velocity, and θ the angle of the pipe against the horizontal plain.

Turbulent flow sampling configuration (NOAA inlet)

High Flow turbulent aerosol sampling configurations may be used at monitoring sites with a primary focus on particles that are responsible for radiative climate forcing. To design a turbulent sampling configuration, the size-dependent particle penetration can be calculated using the below equations. The size-dependent particle losses due to diffusion can be estimated to:

$$\delta = \frac{28.5 D_{\mathrm{pipe}} \cdot D^{1/4}}{\mathrm{Re}_{\mathrm{flow}}^{7/8} \left(\eta_{\mathrm{G}} / \rho_{\mathrm{G}}\right)^{1/4}}$$

Hereby is D the diffusion coefficient, D_{pipe} the inner diameter of the pipe, η_G the gas viscosity, ρ_G the gas density, and Re_{flow} the Reynolds number of the flow. The particle size-dependent deposition velocity u_{dep} to the wall is then given to:

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

The particle size-dependent penetration can be calculated to:

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

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

Hereby is u_{flow} the mean flow velocity and L_{pipe} the length of the pipe. The particle penetration through a bend depends on the Stokes Number and curvature of the bend. The size-depended particle penetration can be approximated by

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

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

The penetration in a horizontally oriented pipe due to sedimentation is described by

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

<u>Example of a sampling configuration with a turbulent flow:</u>

This sampling configuration with a turbulent flow is used at NOAA's long-term aerosol monitoring stations and is designed to provide up to 120 l/min of conditioned aerosol flow from a shared inlet to analyzers and sample collection devices. This design is optimized to provide quantitative

measurements on particles in the size range 0.02 - 2 µm aerodynamic diameter, with an additional goal of achieving 50% collection of particles up to 10 µm. The design can support multiple analyzers and filter samplers that need flow rates up to 30 l/min each to be operated in parallel.
The tradeoffs required to achieve these design goals include turbulent flow conditions in the sample lines, sub-isokinetic conditions at transitions to smaller diameter sample lines, and non-isoaxial conditions in which the flow is split into four separate lines. In spite of these tradeoffs, calculations of particle losses due to turbulent diffusion, impaction, and sedimentation show that the design criterion for size-dependent sampling efficiency is met in many implementations of the system as shown in Figure 5.

The design of the inlet can be briefly summarized to:

- A 20-cm diameter PVC sampling stack is supported by a triangular meteorological tower, and generally extends 10 m above adjacent structures.
- An inverted stainless steel pot is used as a rain hat.
- A 5-cm diameter heated stainless steel tube extracts 150 l/min aerosol sample flow with a Re=4500 from the center of the 1000 l/min main stack flow with Re=7500.
- The heater is controlled by a downstream relative humidity sensor to maintain the RH at no more than 40%, with a thermostat disabling the heater if the air temperature reaches 40°C.
- Air leaving the heated tube is split into four analytical sample lines (1.9 cm diameter, 30 l/min each, Re=2700) and one bypass line (30 l/min).
- The sample lines are at an angle of 3.75° from the axis of the heated sample tube.
- The 1.9-cm diameter sample lines are made of stainless steel and/or conductive silicone tubing of various lengths, depending on the particular station.

Advantages and disadvantages of this turbulent sampling configuration are following:

- High aerosol flow rate
- Short residence time in sampling system
- Fewer losses due to sedimentation in horizontal pipes
- Increased losses of ultrafine particles due to enhanced diffusion
- Increased losses of coarse particles due to enhanced impaction
- Limited ability to actively dry the aerosol flow