Collection of Atmospheric Aerosols

Collection of atmospheric aerosols can be divided in two general procedures:

filtration
impaction

with filtration the more common and cheaper technique.

Filtration

For particle collection by filtration the air is directed through a filter and particles are deposited at the surface or inside the filter bulk. Three different filter types can be distinguished:

Fiber filter
Fiber filter show a mat of fine fibers for the retention of particles. They are commonly made of glass, quartz or plastic fibers. The filter is placed perpendicular to the air stream and particle removal happens by collision and attachment to the filter surface.

Membrane filter
Membrane filter consist of an irregular arrangement of cellulose ester or other materials forming a structural element to remove the particles. They are generally less porous than fiber filter and particles are separated preferably at the surface. Their efficiency is higher than for fiber filters and they are cleaner. Most common materials for membranes are cellulose ester, sintered metals, PVC, PTFE and other plastics. Their drawback compared to fiber filters is the less durability to high air flows.

Capillary membrane filter
This kind of filter have extremely uniform pores and can be manufactured very clean. They are often used in combination with electron microscopy to observe the surface and particles deposited on it. Their efficiency is somewhat between the fiber and the membrane filter.

Basic Parameters for filtration

The filter efficiency describes the fraction retained on the filter when air passes through the medium. We can distinguish between two types:

particle collection efficiency: $$E = \frac{N_{in} - N_{out}}{N_{in}}$$

mass collection efficiency: $$E_m = \frac{C_{in} - C_{out}}{C_{out}}$$

with N as the number of particles and C the mass concentration of particles.
The *velocity of air at the face of the filter* U_0 is defined in the following way:

$$U_0 = \frac{Q}{A}$$

with Q as the volumetric flow through the filter and A the cross sectional area of the filter exposed to the air stream. The *velocity of the air inside the filter U* is always larger than the face velocity U_0 since the volume inside the filter is reduced by the volume of the fibers or membranes:

$$U = \frac{Q}{A(1-\alpha)}$$

α represents the volume fraction of the fibers in the filter.

α = fiber volume/total volume = 1 - porosity

The *penetration P* of the particles decreases exponentially with increasing filter thickness and can be calculated by:

$$P = e^{-\gamma t}$$

with t the total thickness of the filter and γ the fractional capture per unit thickness for a differentially thin element dt. P depends on particle size, face velocity, packing density of the fibers and fiber size.
The particle size distribution changes as the aerosol passes through the filter, with the "easy-to-collect" particles be removed first and the "hard-to-collect" ones last. Fiber filter show a minimum efficiency for particle sizes between 0.05µm and 0.5µm as none of the deposition mechanisms discussed below is very efficient in this range. The resistance caused by the filter structure to the air stream is called the pressure drop Δp. The pressure drop of a filter is directly proportional to the filter thickness by given face velocity U_0. Thus doubling the filter thickness has the same effect as running two filter after each other. The flow inside the filter is considered as laminar and therefore the pressure drop directly proportional to the flow rate. The best filter has the highest efficiency and the lowest pressure drop.
Separation of particles by filtration of air happens by five different mechanisms, with more or less efficiency.

- Interception
- Inertial Impaction

- Diffusion
- Gravitational Settling
- Electrostatic Attraction

The overall efficiency is given by the sum of efficiency for a single fiber:

$$E_\Sigma = E_G + E_D + E_I + E_R + E_{DR}$$

E_G: Efficiency by gravitational settling
E_D: Efficiency by diffusion
E_I: Efficiency by impaction
E_R: Efficiency by interception
E_{DR}: Efficiency by interaction due to interception of the diffusing particle

For small particles interception and impaction are negligible, but increase rapidly for particles larger than 0.5µm. If particles are smaller than 0.2µm diffusion is the only important deposition mechanism. For larger particles this mechanism is negligible. For all particles gravitational settling is very small compared to other deposition mechnisms. In general for small particles (<0.5µm) the collection mechanism depends on their physical diameter, whereas for particles >0.5µm the mechanism depends on their aerodynamic diameter. All filters have regions with highest efficiency and ones with smallest efficiency.

Membrane filter

For membrane filter all previously discussed separation mechanisms are the same valid. The structural elements in membrane filter behave as fibers, except that the efficiency is almost always 100% compared to the fiber filter.

Capillary Membrane Filter

Capillary membrane filter have a lower efficiency as ordinary membrane filter since impaction and interception happens primarily only at the inlet of the pores.

Collection by Impaction

Equivalent Diameter

Solid particles show very different shapes and sizes one needs to find a uniform definition to formulate a proper collection theory. In order to make any predictions the equivalent diameter was introduced referring to the diameter of a sphere with the same value of a particular physical property as the irregular shaped particle.

Aerodynamic diameter d_a

The aerodynamic diameter as a special case of the equivalent diameter is defined as the diameter of a sphere with unit density (1g/cm^3) and the same settling velocity as the observed particle.

Reynolds Number Re

The Reynolds number is one of the most important parameters when dealing with fluids. It is a dimensionless number characterizing the flow of a fluid and determining whether a flow is laminar or turbulent. Re is proportional to the ratio of inertial forces to the frictional forces acting on the fluid. For a free moving fluid a flow is laminar with Re<1 and turbulent with Re>1.

Relaxation time t

The relaxation time defines the time a particle needs to adjust –relax- its velocity to a new condition of forces. The relaxation time depends only on mass and mobility of the particles, but is affected by temperature and pressure of the gas. It will increase with particle size, meaning that a large particle will need a longer time to adjust itself to the new situation as a small particle.

Particle acceleration

When a particle is brought into an air stream it will take some time to get accelerated to its final and constant –terminal- velocity. In most of the cases this time is negligible to the time the particle moves in its terminal velocity. For particles with aerosodynamic diameter of <10μm for instance the acceleration time when released into the atmosphere and finally adjusted to the terminal velocity is only 1ms.

Stopping distance

The stopping distance tells us how long a particle will travel on its original path after all external forces are shut off. The stopping distance is in this case only determined by the friction a particle experiences in air. In case of particle collection by impactor devices, the stopping distance represents the time a particle still travels on its original path after the air stream is turned abruptly for 90° around an object.

Curvilinear motion & Stokes number

Follows a particle instead of a straight or oscillating path a curved path, it is called to have a curvilinear motion. For the flow around and obstacle/object small particles are able to follow the curved stream lines almost perfectly due to their very small inertia, whereas large particle with high inertia are too slow to adjust quickly enough to the new path and continue on their original ones. For particles in the medium size range the flow field (direction and velocity of the flow) around the object must be defined and the actual particle trajectory in the flow field in order to do any predictions or calculations of the particle path.

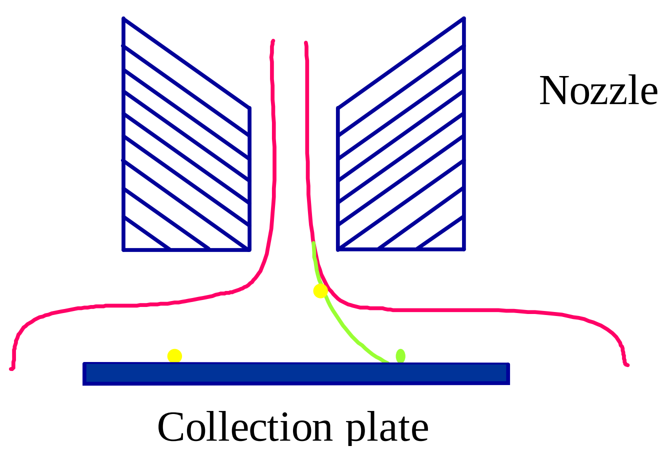
Stokes number Stk

The Stokes number is defined as the ratio of stopping distance of a particle to a characteristic dimension of the obstacle. When working with impactors the characteristic dimension would be the nozzle radius Dj/2 (see below). For Stokes numbers approaching zero the particles follow the streamlines perfectly and for the Stokes number becoming large the particles resist the change in direction.

Inertial Impaction

Inertial impaction is a special case of curvilinear motion and used for the collection of particles from air or other gases. The particles are measured by mass and not by volume or surface. The devices used for inertial impaction are called impactors. They can have different shapes and sizes, but employ all the same principle. Impaction provides besides the mass distribution of particles also the possibility to receive information about chemical composition of particles by subsequent analysis.

Principle:



An aerosol is passed through a nozzle or jet and the output stream is directed against a flat plate, here impaction plate. This flat plate forces the air stream to have an abrupt 90° bend in the streamlines. Particles with sufficient inertia are unable to follow the abrupt change and deposit on the plate. Particles with low inertia follow the stream and are not impacted. Thus the aerosol is divided into two size categories:

particles larger than a certain aerodynamic size are impacted and removed
particles smaller are passing through

Impactor theory tries to explain the shape of a collection efficiency curve versus particle size. The parameter governing the collection efficiency is the Stokes number Stk. In this case the Stokes number is defined as the ratio of particle stopping distance τ at average nozzle exit velocity U to nozzle radius Dj/2:

$$Stk = \frac{tU}{D_j/2}$$

In the graph we use the square root of Stk versus collection efficiency as the square root of Stk is directly proportional to the particle size.
Most of the impactors are well designed and can be assumed as ideal. Their efficiency curves are characterized by Stk_{50} (50% collection efficiency) meaning that the mass of particles below cut-off size collected equals the mass of particles getting through larger than the cut-off.

In most cases *cascade impactors* are used, which are arrangements of impactors in series. The single impactors are called stages and are arranged in such way that the largest particles are seperated first and the smallest last. With descending particle size the nozzle diameter and distance between nozzle and impaction plate becomes smaller, gradually decreasing the particle size collected.