

**AIR POLLUTION CONTROL, WASTEWATER AND SOLID WASTES MANAGEMENT**  
**BMEGEÁTBG04**

lecture handout

**AIR POLLUTION CONTROL: “Particle removal from gases”**

by

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**Contents, main topics of the lecture:**

1. Characterisation of particle-laden mixtures
2. Particle dynamics: equation of motion
3. Measurement of particle concentration
4. Gas cleaning equipment, various types of particle separators

**1. Characterisation of particle-laden mixtures. Aerosols**

**Aerosols**

Definition of aerosols:

Aerosol is a mixture of gas and particles in a quasi-stable state. In aerosols, the gas is the primary (carrier) phase, and the solid/liquid particulate matter is the secondary (dispersed) phase.

The “quasi-stable state” means that the characteristics of the mixture (e.g. particle total number density, mass concentration etc.) in a given control volume do not change significantly, i.e. they are nearly stable in time.

Changes in the characteristics of the mixture can occur due to the following:

- settling out of larger particles from the given volume of the mixture or
- diffusion and agglomeration of the small particles.

Both may cause an increase or a decrease in the total mass of the particles in the fixed volume and, hence, may cause non-negligible changes in the characteristics of the mixture.

Diameter range of aerosol particles:

Typically,  $0,01\mu\text{m} \leq d_p \leq 50\mu\text{m}$  is the diameter range of the particles in aerosols. Note that the lower & upper limiting values are not very strict limiting values due to the stochastic behaviour of the real particles in gas flow. Therefore, it is suggested to interpret the given limiting values of “ $0,01\mu\text{m}$ ” & “ $50\mu\text{m}$ ” as they indicate approximately a few times a hundredth of a micron & a few times ten microns.

**Note:**  $1\mu\text{m} = 10^{-3}\text{mm} = 10^{-6}\text{m}$

*Examples: The resolution of sensitivity of a human fingertip is about 40 microns.*

*The human hair diameter is between 40÷100 microns.*

*The average height of surface roughness of a bearing ball is approximately 0,01 micron.*

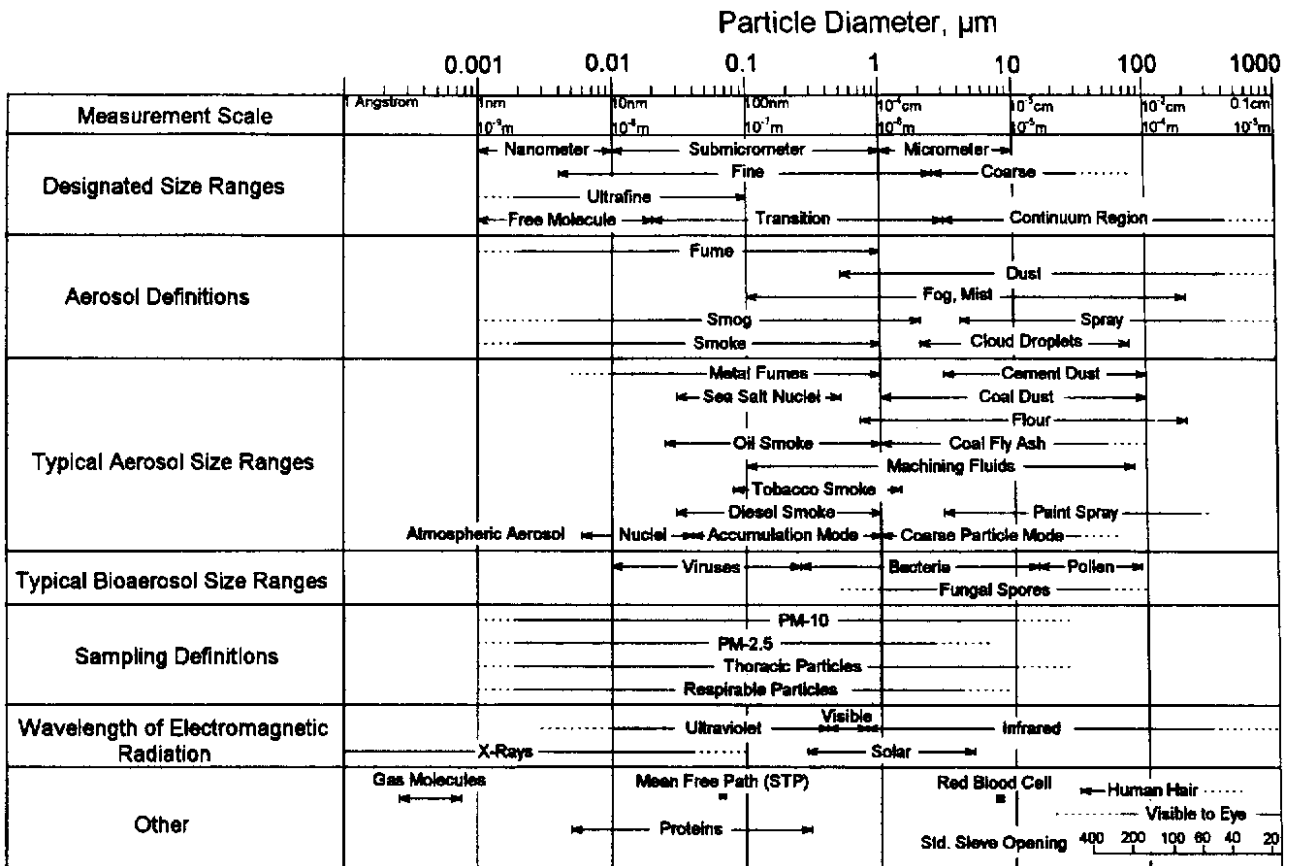
*The diameter of seeding particles for Laser Doppler Velocimetry and flow visualisation (oil smoke or spherical oil droplets from fog generator) is approx. 1÷3 microns.*

Types of aerosol particles and their characteristic parameters

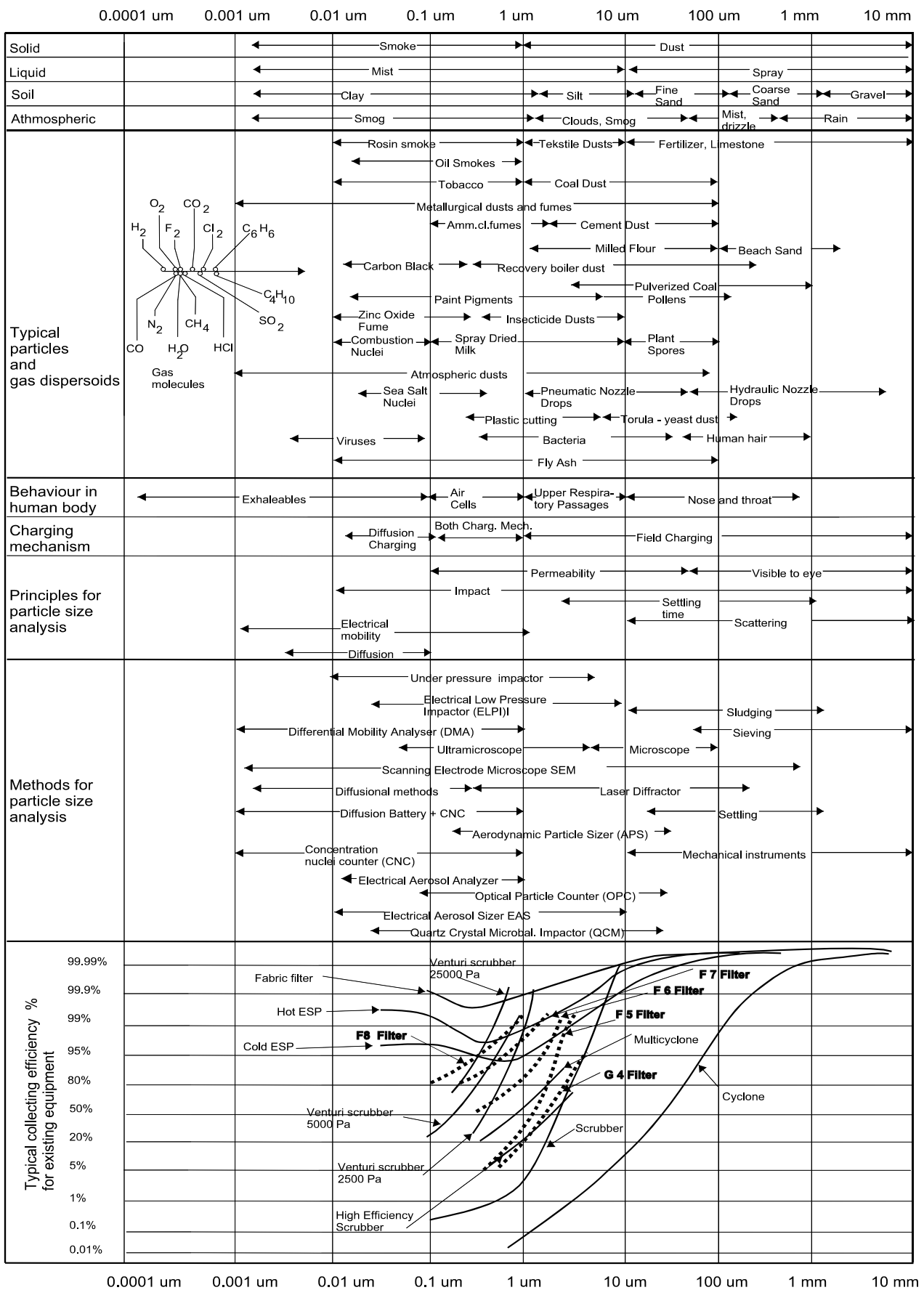
**DUST:** size range:  $d_p \geq 0,2 [\mu\text{m}]$   
 description: **solid** particles, produced by breaking or attrition, abrasion, wearing of solid substances, perceptible to the eye, the diameter is larger than the wavelength of light.

**SMOKE / FUME:**  
 size range:  $d_p \leq 1 [\mu\text{m}]$   
 description: **solid or liquid** particles or droplets, originated from condensation or chemical reaction, in most cases chain-like structures. Produced at combustion, chemical processes etc.

**MIST / FOG:** size range: -  
 description: **liquid** droplets originated from steam condensation or by atomisation or spraying. Droplets in the mist are in an equilibrium state with their saturated steam.



### Particle removal from gases (handout)



Size of particles:

NOTE: In the case of spherical particles, the diameter is denoted here by  $x$ .

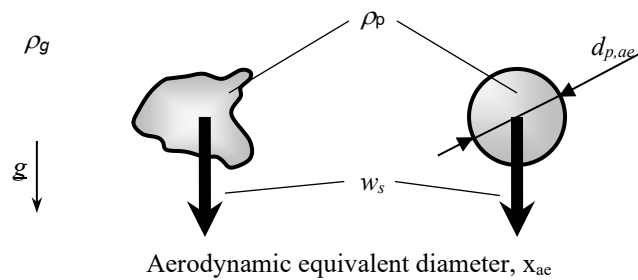
Elsewhere, and sometimes also here in the handout, the *diameter* of a *particle* is usually denoted by  $d_p$ .

How to characterise - define - the “size” of non-spherical particles? By practical reasons, it is needed to introduce the so-called equivalent diameter, the diameter of an ideal sphere made from the same material as the real particle of arbitrary shape.

Various types of the equivalent diameter can be defined based on:

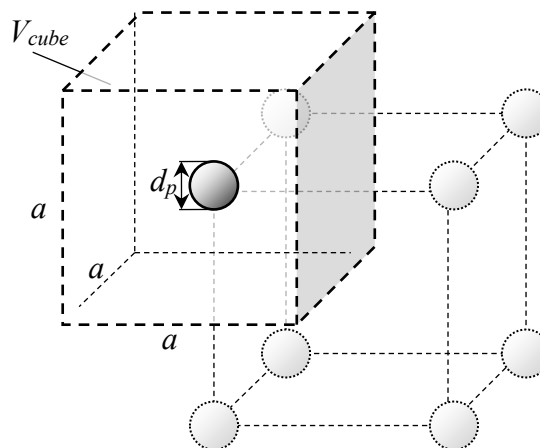
- geometrical equivalence (based on the particle surface, volume or projected area) / used e.g. in chemical reaction calculation/
- **aerodynamic equivalence (see below in more detail)**
- optical equivalence (based on refractive index) /in optical concentration measurement devices/
- electrical equivalence (based on electric conductivity, resistance) /used when concentration measurement is performed by electric resistivity measuring devices/.

In particle dynamics, most relevantly, the  $d_{p,ae}$  **aerodynamic equivalent diameter is used**. It is defined as the diameter of a spherical particle from the same material ( $\rho_p$ =same) as the real particle, settling with the same constant  $w_s$  settling velocity in the same gas ( $\rho_g$ =same) and force field.



Average relative distance ( $a/x$  or  $a/d_p$ ) between neighbouring particles in gas:

Let’s calculate the  $c_p$  [ $\text{kg}/\text{m}^3$ ] mass concentration of  $n$  particles evenly distributed in a particle-gas mixture having a volume of  $V_{g+p}$ . Let’s assume that each particle is sitting in the centre of a cube. (see Figure below).



The concentration can be calculated as follows.

$$c = \frac{\sum m_p}{V_{g+p}} \cong \frac{\sum m_p}{V_{g+p}} = \frac{\sum V_p \cdot \rho_p}{V_{g+p}} = \frac{n \cdot \frac{x^3 \cdot \pi}{6} \cdot \rho_p}{n \cdot a^3} = \frac{x^3 \cdot \pi}{6} \cdot \rho_p \cdot \frac{1}{a^3}$$

Here  $c$  [kg/m<sup>3</sup>] is the mass concentration,  $a$  [m] is the average distance between particles,  $\rho_p$  [kg/m<sup>3</sup>] is the density of particles and  $n$  is the number of particles.

For the average relative distance ( $a/d_p$ ) between neighbouring particles in gas, we get:

$$\frac{a}{x} = \sqrt[3]{\frac{\rho_p \cdot \pi}{6 \cdot c}}$$

Example:

If we consider monodisperse particle distribution where all particles have  $d_p=3\mu\text{m}$  diameter with  $\rho_p=2000\text{kg/m}^3$ , and  $c = 10 \text{ g/m}^3$  (that is relatively very high concentration of particles), the  $a/d_p = 47$ .

a) It means that aerosols are very **dilute mixtures**: the neighbouring particles are far from each other (approx.  $a=5\text{m}$  when  $x=10\text{cm}$  would be the particle diameter). Hence, the possibility of collision, momentum exchange between two particles is relatively small.

b) In  $1\text{cm}^3$  volume there are 350000 particles for  $c=10 \text{ g/m}^3$ . Even in case of small  $0,1 \text{ g/m}^3$  concentration we get 3500 particle in  $1\text{cm}^3$  volume. Notwithstanding that it is a **dilute mixture**, the number of particles is very high in a given volume, even for low concentration. That is important to know when very strict demand is defined on air quality (e.g. at surgery rooms, when dealing with toxic or infective particles is concerned)

| $c[\text{g/m}^3]$ | $\frac{a}{x}$ | $N [\text{db/cm}^3]$ |
|-------------------|---------------|----------------------|
| 10                | 47            | 350.000              |
| 1                 | 101           | 35.000               |
| 0.1               | 218           | 3.500                |

Conclusion:

- in case of usual particle concentration values, the particle-laden flows are very dilute mixtures. (the distance between neighbouring particles is very large).
- particles are present with a very high number even in particle-gas mixtures having very low concentration.

### Characterisation of particle assembly:

Particle size distribution curves:

Considering polydisperse particle distribution with size range of  $x_{\min} < x < x_{\max}$

Cumulative or undersize distribution related to the number of particles:  $Q_0=N/N_{\text{tot}}=f(x)$ .  $Q_1, Q_2, Q_3$ .

Subscript denotes: 0: related to the number of...

1: related to the length of... (1D – one-dimensional quantity)

2: related to the surface of...(2D – two-dimensional quantity)

3: related to the volume or mass of...(3D – three-dimensional quantity)

If  $Q_0=N/N_{\text{tot}}=f(x)$  and the overall number of particles  $N_{\text{tot}}$  are known, the number of particles in the size range between  $[x]$  and  $[x+\Delta x]$  can be calculated:

$$\Delta N = N_{\text{tot}} \cdot \frac{dQ_0}{dx} \cdot \Delta x$$

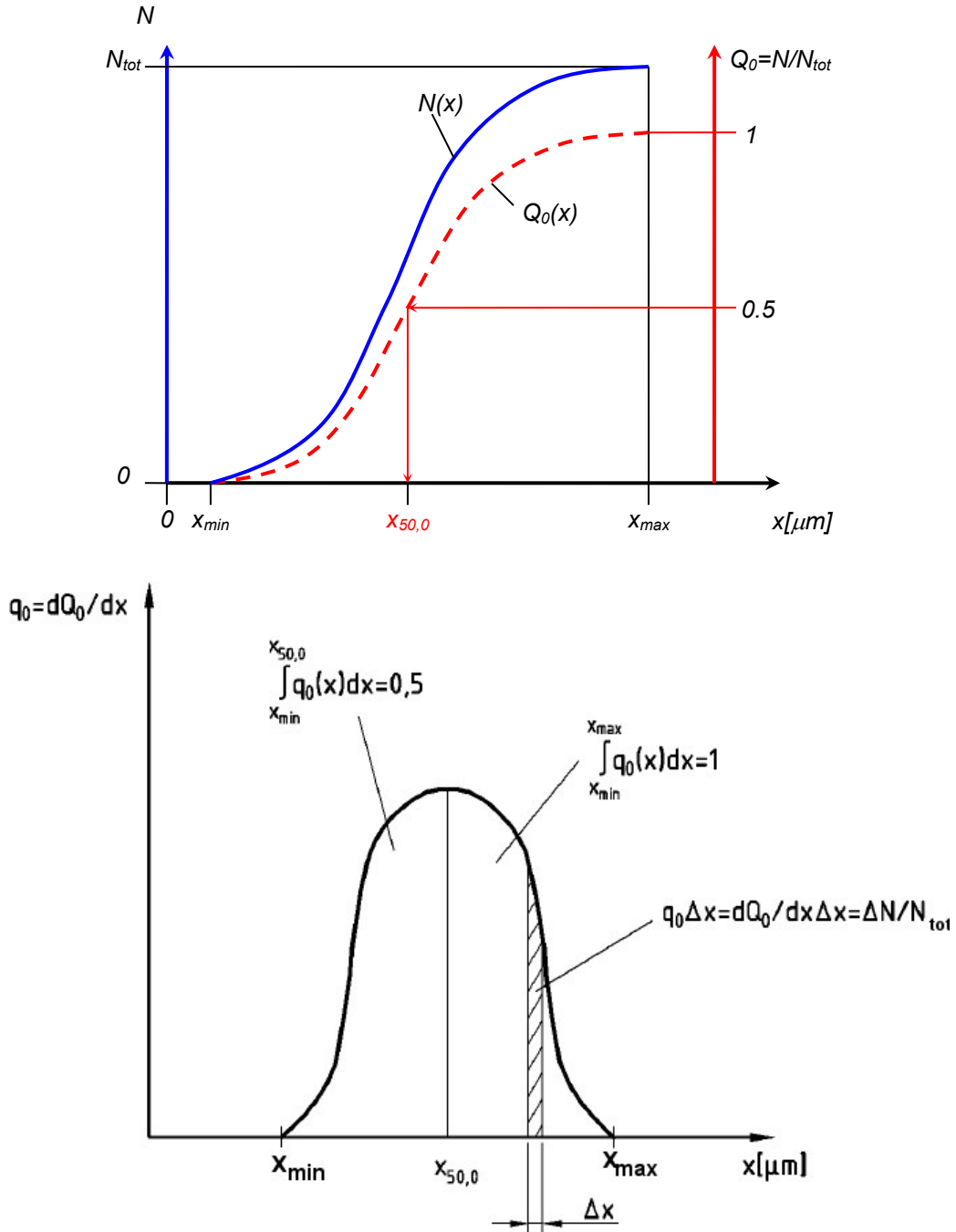
Cumulative or undersize distribution related to the number of particles:  $Q_0$ . The value of  $Q_0(x)$  for given  $x$  gives information how many percentages of  $N_{\text{tot}}$  particles have smaller diameter than  $x$ .

Taking the tangent of the  $Q_0$  curve (see Figure below) is denoted by  $q_0$  (density function):

$$q_0 = \frac{dQ_0}{dx},$$

we get for the number of particles in the range between  $[x]$  and  $[x+\Delta x]$ :

$$\Delta N = N_{tot} \cdot \frac{dQ_0}{dx} \cdot \Delta x = N_{tot} \cdot q_0 \cdot \Delta x$$

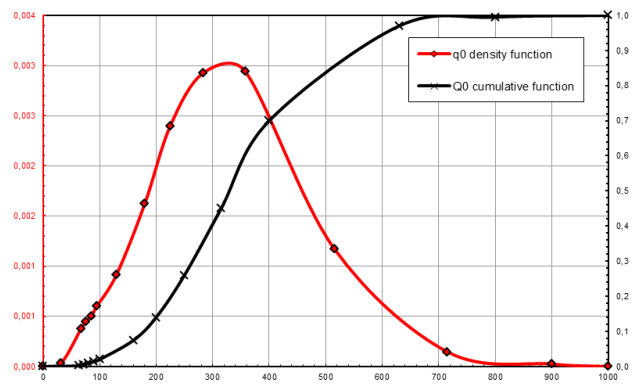
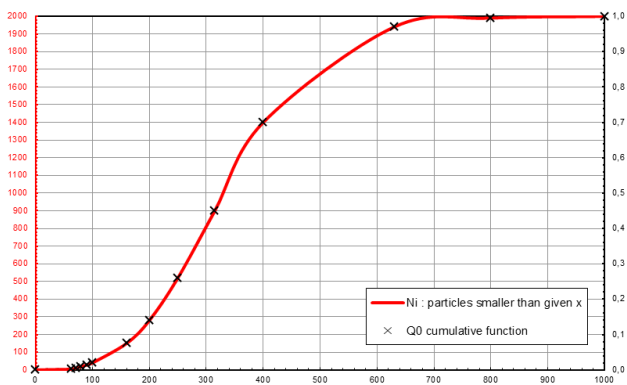


When  $q_0$  cumulative distribution related to the particle number is given (see Figure below), we can obtain the average diameter of the particle distribution ( $\bar{x}_0$ ) related to particle number:

$$\bar{x}_0 = \frac{1}{N_{tot}} \int_{x_{min}}^{x_{max}} x \cdot N_{tot} \cdot q_0 dx = \int_{x_{min}}^{x_{max}} x \cdot q_0 dx .$$

EXAMPLE for a  $N_{tot}=2000$  particle ensemble.

| $N_{tot}=2000$ particles |                         |                         |                    |                           | $Q_0=$             | $q_0=$                       | $x_{0,mean}=$                                    |                          |                          |
|--------------------------|-------------------------|-------------------------|--------------------|---------------------------|--------------------|------------------------------|--|--------------------------|--------------------------|
| $x_i$<br>$\mu m$         | $\Delta x_i$<br>$\mu m$ | $x_{i,mean}$<br>$\mu m$ | $N_i$<br>particles | $\Delta N_i$<br>particles | $N_i/N_{tot}$<br>- | $\Delta Q_0/\Delta x_i$<br>- | $\sum x_{i,mean} q_{0i} \Delta x_i$<br>$x_{1,0}$ | $x_{2,0}$                | $x_{3,0}$                |
| 0                        | 0                       |                         | 0                  |                           | 0,00               | 0                            |  |                          |                          |
|                          | 63                      | 31,5                    | 4                  | 4                         | 0,00               | 0,0000                       | 0,1  | 2,0                      | 62,5                     |
| 63                       | 8                       | 67                      | 10                 | 6                         | 0,01               | 0,0004                       | 0,2  | 13,5                     | 902,3                    |
| 71                       | 9                       | 75,5                    | 18                 | 8                         | 0,01               | 0,0004                       | 0,3  | 22,8                     | 1721,5                   |
| 80                       | 10                      | 85                      | 28                 | 10                        | 0,01               | 0,0005                       | 0,4  | 36,1                     | 3070,6                   |
| 90                       | 10                      | 95                      | 40                 | 12                        | 0,02               | 0,0006                       | 0,6  | 54,2                     | 5144,3                   |
| 100                      | 60                      | 130                     | 110                | 70                        | 0,05               | 0,0009                       | 7,2  | 929,5                    | 120835,0                 |
| 160                      | 40                      | 180                     | 130                | 20                        | 0,06               | 0,0016                       | 11,7   | 2106,0                   | 379080,0                 |
| 200                      | 50                      | 225                     | 240                | 110                       | 0,12               | 0,0024                       | 27,0   | 6075,0                   | 1366875,0                |
| 250                      | 65                      | 282,5                   | 380                | 140                       | 0,19               | 0,0029                       | 53,7   | 15163,2                  | 4283600,5                |
| 315                      | 85                      | 357,5                   | 500                | 120                       | 0,25               | 0,0029                       | 89,4   | 31951,6                  | 11422683,6               |
| 400                      | 230                     | 515                     | 540                | 40                        | 0,27               | 0,0012                       | 139,1  | 71610,8                  | 36879536,3               |
| 630                      | 170                     | 715                     | 50                 | 40                        | 0,02               | 0,0001                       | 17,9   | 12780,6                  | 9138146,9                |
| 800                      | 200                     | 900                     | 10                 | 10                        | 0,00               | 0,0000                       | 4,5  | 4050,0                   | 3645000,0                |
| 1000                     | 1000                    | 2000                    | 2000               | 1990                      | 1,00               | 0                            |  |                          |                          |
|                          |                         |                         |                    |                           |                    | 1,000                        | <b>352</b>                                       | <b>381</b>               | <b>407</b>               |
|                          |                         |                         |                    |                           |                    |                              | $x_{1,0}$<br>[ $\mu m$ ]                         | $x_{2,0}$<br>[ $\mu m$ ] | $x_{3,0}$<br>[ $\mu m$ ] |



ps.: There is a simple relation/conversion between distributions related to various quantities e.g. conversion of  $Q_0$  to  $Q_3$ :

$$Q_3(x) = \frac{\int_{x_{min}}^x x^3 \frac{\pi}{6} N_{tot} \frac{dQ_0}{dx} dx}{\int_{x_{min}}^{x_{max}} x^3 \frac{\pi}{6} N_{tot} \frac{dQ_0}{dx} dx} = \frac{\int_{x_{min}}^x x^3 q_0 dx}{\int_{x_{min}}^{x_{max}} x^3 q_0 dx}$$

## 2. Particle dynamics

### Effect of particles on the gas flow field

The Navier-Stokes equation of motion for the carrier gas flow (primary phase) is extended by the influence of the particles (secondary phase). The effect of particles on the gas flow is given by the force ( $\underline{t}$ ).

$$\frac{\partial \underline{v}}{\partial t} + \text{grad} \frac{v^2}{2} - \underline{v} \times \text{rot} \underline{v} = \underline{g} - \frac{1}{\rho_g} \text{grad} p + \nu \Delta \underline{v} + \underline{t}$$

where  $\underline{v}$ [m/s] is gas velocity vector,  $p$ [Pa] is pressure,  $\underline{g}$ [N/kg] is gravity field strength vector,  $\nu$ [m<sup>2</sup>/s] is kinematic viscosity and.

The last term on the right-hand side is  $\underline{t}$  [N/kg<sub>gas</sub>], the force acting on the gas from particles in 1 kg of gas:

$$\underline{t} = - \frac{n \underline{F}}{\rho_g}$$

$n$  [particles/m<sup>3</sup>] : particle number concentration

$\underline{F}$  [N / particle] : aerodynamic force acting on one particle

$\rho_g$  [kg/m<sup>3</sup>] : gas density

This extended form of Navier-Stokes equation is very difficult to solve in the case of aerosols since  $\underline{t}$  is to be determined for a polydispersed real-shaped particulate phase where the force for each particle is needed to determine first, and that is impossible.

Let's examine when it would be possible to neglect this term  $\underline{t}$ ?

Assuming sphericity for the particles, when taking the ratio of the total volume of the particles and the total volume of the gas in a given control volume of the aerosol, we will get the dimensionless  $\alpha$  [-] volume ratio of the phases.

Volume ratio:

$$\alpha_p = \frac{V_p}{V_g} = \frac{\frac{d_p^3 \pi}{6}}{a^3} = \frac{c_p}{\rho_p}$$

where  $c_p$  [kg/m<sup>3</sup>] is the mass concentration of the particles,  $\rho_p$  [kg/m<sup>3</sup>] is the density of the particles.

Taking the ratio of the total mass of the particles and the total mass of the gas in a given control volume of the aerosol, we get the dimensionless  $M$  [-] mass loading ratio.

Mass loading ratio:

$$M = \frac{c_p}{\rho_g} = \alpha_p \frac{\rho_p}{\rho_g}$$

$$\frac{M}{\alpha_p} = \frac{\rho_p}{\rho_g}, \text{ or } \frac{\alpha_p}{M} = \frac{\rho_g}{\rho_p}$$

where:

$c_p$ : particle mass concentration

$\rho_g$ : density of gas (carrier phase)

$\rho_p$ : density of particle (material)



For example: typical values of volume ratio and mass loading ratio can be seen in tables below.

| $\alpha_p$    |        | $\rho_p [kg/m^3]$    |                      |                      |
|---------------|--------|----------------------|----------------------|----------------------|
|               |        | 800                  | 1500                 | 2500                 |
| $C_p [g/m^3]$ | 0,0001 | $1,3 \cdot 10^{-10}$ | $6,7 \cdot 10^{-11}$ | $4,0 \cdot 10^{-11}$ |
|               | 0,001  | $1,3 \cdot 10^{-9}$  | $6,7 \cdot 10^{-10}$ | $4,0 \cdot 10^{-10}$ |
|               | 0,01   | $1,3 \cdot 10^{-8}$  | $6,7 \cdot 10^{-9}$  | $4,0 \cdot 10^{-9}$  |
|               | 0,1    | $1,3 \cdot 10^{-7}$  | $6,7 \cdot 10^{-8}$  | $4,0 \cdot 10^{-8}$  |
|               | 1      | $1,3 \cdot 10^{-6}$  | $6,7 \cdot 10^{-7}$  | $4,0 \cdot 10^{-7}$  |
|               | 10     | $1,3 \cdot 10^{-5}$  | $6,7 \cdot 10^{-6}$  | $4,0 \cdot 10^{-6}$  |
|               | 100    | $1,3 \cdot 10^{-4}$  | $6,7 \cdot 10^{-5}$  | $4,0 \cdot 10^{-5}$  |

| $M$           |        | $\rho_g [kg/m^3]$   |                     |                     |
|---------------|--------|---------------------|---------------------|---------------------|
|               |        | 0,8                 | 1,0                 | 1,2                 |
| $C_p [g/m^3]$ | 0,0001 | $1,3 \cdot 10^{-7}$ | $1,0 \cdot 10^{-7}$ | $8,3 \cdot 10^{-8}$ |
|               | 0,001  | $1,3 \cdot 10^{-6}$ | $1,0 \cdot 10^{-6}$ | $8,3 \cdot 10^{-7}$ |
|               | 0,01   | $1,3 \cdot 10^{-5}$ | $1,0 \cdot 10^{-5}$ | $8,3 \cdot 10^{-6}$ |
|               | 0,1    | $1,3 \cdot 10^{-4}$ | $1,0 \cdot 10^{-4}$ | $8,3 \cdot 10^{-5}$ |
|               | 1      | $1,3 \cdot 10^{-3}$ | $1,0 \cdot 10^{-3}$ | $8,3 \cdot 10^{-4}$ |
|               | 10     | $1,3 \cdot 10^{-2}$ | $1,0 \cdot 10^{-2}$ | $8,3 \cdot 10^{-3}$ |
|               | 100    | $1,3 \cdot 10^{-1}$ | $1,0 \cdot 10^{-1}$ | $8,3 \cdot 10^{-2}$ |

The  $M$  mass loading ratio for typical concentration for dusty gases (upstream of particle separators) has a value of at least  $10^{-1}$ . Notwithstanding that the number concentration is high, the mass loading ratio is very small. The particle's forces  $\underline{f}$ , hence the effect of particle phase on the gas flow field can be neglected when

- the mass loading ratio  $M \ll 1$ , i.e.  $\frac{c}{\rho_g} \ll 1$ ,

and

- the particle acceleration is in the same order of magnitude as the carrier gas-phase acceleration  $\frac{d\underline{u}_p}{dt} \approx \frac{d\underline{v}}{dt}$ .

Therefore, in cases when  $\frac{c}{\rho_g} \frac{d\underline{u}_p}{dt} \ll \frac{d\underline{v}}{dt}$ , the effect of particle phase on the flow field can be neglected.

From other viewpoint, we can state that one single particle moving in the gas in this dilute mixture (aerosol) cannot change significantly the gas' momentum, the effect of particles can be neglected. It is worth to mention here that the particle's pathline due to the drag is always influenced by the carrier gas flow, see in next chapter: defining the aerodynamic (drag) force acting on the particles.

**Aerodynamic (drag) force acting on a single particle:**

The particle Reynolds number ( $Re_p = \frac{w \cdot x}{\nu}$ ) is small, and viscosity is dominant in a fluid flow around the particle (using the relative coordinate system fixed to the particle). See calculated results for the flow field around a sphere for various particle Reynolds-number (Source: MICHAELIDES: Particles, Bubbles, & Drops (2006) p.109.)

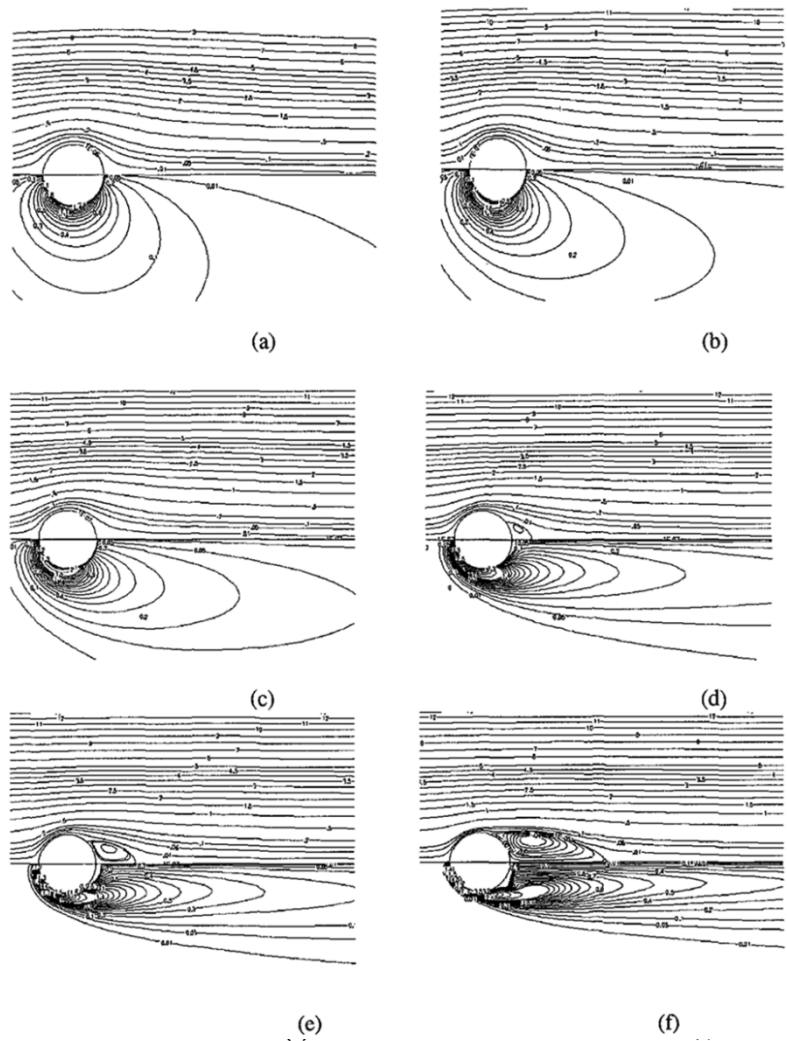


Fig. 4.1 streamlines and vorticity around a rigid sphere. The six parts correspond to  $Re=1, 5, 10, 50, 100$  and  $500$ . The top half depicts the streamlines and the bottom half the vorticity contours

Stokes assumed the following: if  $Re_p < 0.1$ , the well known Stokes relation for  $\underline{F}_d$  drag force acting on a particle (having particle diameter  $x$ ) moving with  $\underline{w}$  relative velocity in the gas ( $\mu$  is dynamic viscosity) is:

$$\underline{F}_d = \underline{F}_{Stokes} = 3 \cdot \pi \cdot \mu \cdot x \cdot \underline{w}$$

where  $\underline{v} = \underline{u} + \underline{w}$

$\underline{v}$  absolute (gas) velocity

$\underline{u}$  particle velocity

$\underline{w}$  relative velocity

The  $c_d$  drag coefficient of the particle is defined by the relative force to the dynamic pressure of the relative flow and the reference cross-section of the spherical particle:

$$c_d = \frac{|\underline{F}_d|}{\frac{\rho}{2} w^2 \cdot A_{\text{ref}}} = \frac{|\underline{F}_d|}{\frac{\rho}{2} w^2 \frac{x^2 \pi}{4}}$$

Substituting the Stokes relation for  $\underline{F}_d$  into the equation of  $c_d$ , we get a very simple elementary form for the drag coefficient of a sphere using particle Reynolds-number:

$$c_d = \frac{24}{\text{Re}_p}$$

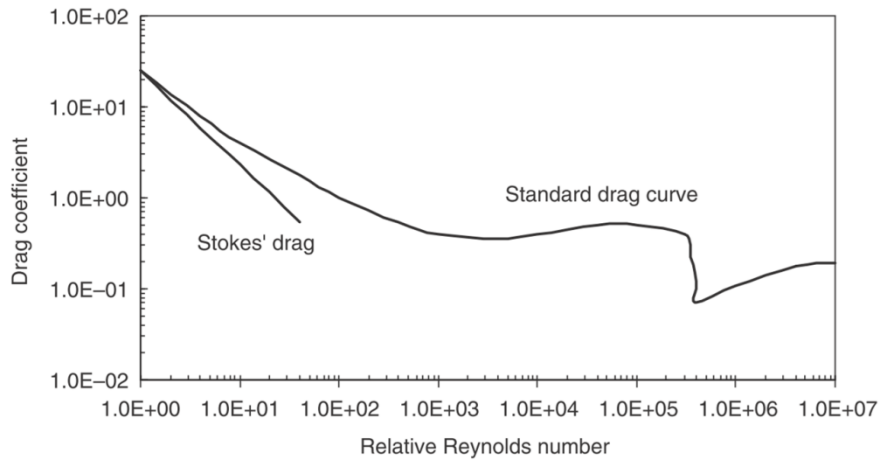
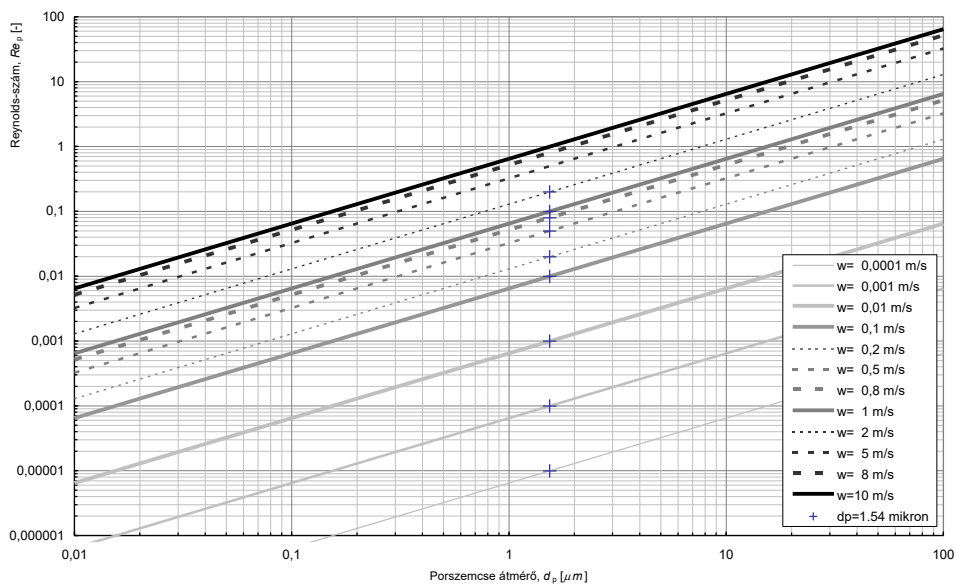


FIGURE 1.9 The standard drag coefficient curve for a solid sphere in steady flow.

Typical particle Reynolds number is plotted (see diagram below) for particles having diameter between  $0.01\mu\text{m} < d_p < 100\mu\text{m}$ , and for relative velocity  $10^{-4}\text{m/s} < w < 10\text{m/s}$ . That ensures that Stokes' drag form can be used in typical engineering applications when particles are separated from aerosols.



The Stokes' drag form can be used only in cases when  $\text{Re}_p < 0.1$  (or even for  $\text{Re}_p < 0.01$ ). Researchers in this field obtained various corrected forms for the Stokes' drag coefficient for higher particle Reynolds numbers since the real drag differs from this Stokes' drag for higher relative velocities or

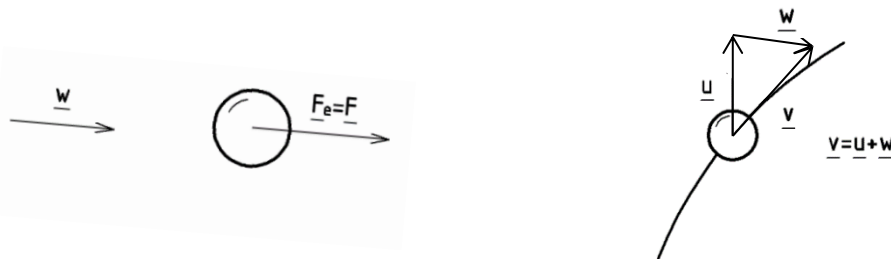
larger particles. Based on experiments and/or CFD numerical simulation studies, the following expressions can be used for drag coefficient, e.g.

a) Oseen's drag:  $c_d = \frac{24}{Re_p} \left( 1 + \frac{3}{16} Re_p \right)$  for  $Re_p < 5$ .

b) Michaelides's drag:  $c_d = \frac{24}{Re_p} \cdot (1 + 0,15 \cdot Re_p^{0,687})$  for  $0.1 < Re_p < 1000$ .

**Momentum equation for particles** moving with  $\underline{w}$  relative velocity in gas flow

The particle drag force vector ( $\underline{F}_d$ , denoted in the figure below by  $\underline{F}_e = \underline{F}$ ) is defined by the direction of the relative velocity  $\underline{w}$ . The particle's relative velocity to the gas flow is  $\underline{w} = \underline{v} - \underline{u}$ .



Due to Newton's 2<sup>nd</sup> law, the particle's momentum equals to the sum of the acting forces. Forces: gravity force and Stokes' drag force term. (Usually we may neglect the buoyancy force when solid/liquid particles are dispersed in gaseous fluid flow.)

$$m_p \frac{d\underline{u}}{dt} = \underline{F}_g + \underline{F}_d$$

Assuming a spherical particle with a diameter  $x$ , and substituting Stokes' drag term, we get:

$$\frac{x^3 \pi}{6} \rho_p \frac{d\underline{u}}{dt} = \frac{x^3 \pi}{6} \rho_p \underline{g} + 3\pi \mu x \underline{w}$$

**Dimensionless equation of motion of the particle:**

As a usual non-dimensionalising formulation procedure, let's multiply the equation with  $\frac{l_0}{v_0^2}$ , where

$l_0$  is a characteristic length (e.g. the particle's diameter  $l_0 = x$ , as being the most energetic eddy size in the flow around the particle), and  $v_0$  is a characteristic velocity (e.g.  $v_0$  average gas flow velocity).

$$\frac{x^3 \pi}{6} \rho_p \frac{d\underline{u}}{dt} = \frac{x^3 \pi}{6} \rho_p \underline{g} + 3\pi \mu x \underline{w} \quad \left| \cdot \frac{l_0}{v_0^2} \right.$$

Then we get the following dimensionless form of the equation of motion:

$$\frac{d \frac{\underline{u}}{v_0}}{d \frac{t}{l_0/v_0}} = \frac{\underline{g} l_0}{v_0^2} + \frac{18 \mu}{x^2 \rho_p} \frac{l_0}{v_0} \frac{\underline{w}}{v_0}$$

The dimensionless momentum equation of particles

$$\frac{d\underline{u}'}{dt'} = \frac{\underline{g} l_0}{v_0^2} + \frac{18 \mu}{x^2 \rho_p} \frac{l_0}{v_0} \underline{w}'$$

where the sign ' (dash) denotes dimensionless quantities, e.g. the dimensionless particle velocity is

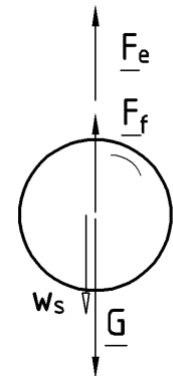
$$\text{denoted by } \underline{u}' = \frac{\underline{u}}{v_0}.$$

Before rewriting this form of dimensionless momentum equation, the settling velocity ( $w_s$ ) of the particle is needed to define. It is essential, and it can be included in the equations later.

**Settling velocity of the particle ( $w_s$ ):**

Settling of a particle, having  $\rho_p$  density in a still ambient of gas, having  $\rho_g$  density, calls for an equation of motion for the particle. The particle settles with a constant settling velocity of  $w_s$ .  $\underline{G}$  is the gravity force; drag force is  $\underline{F}_d$  - denoted in figure below again by  $\underline{F}_e$ . Here we do not neglect the  $\underline{F}_f$  buoyancy force:

$$\frac{x^3 \pi}{6} \rho_p g = \frac{x^3 \pi}{6} \rho_g g + 3\pi \mu x w_s$$



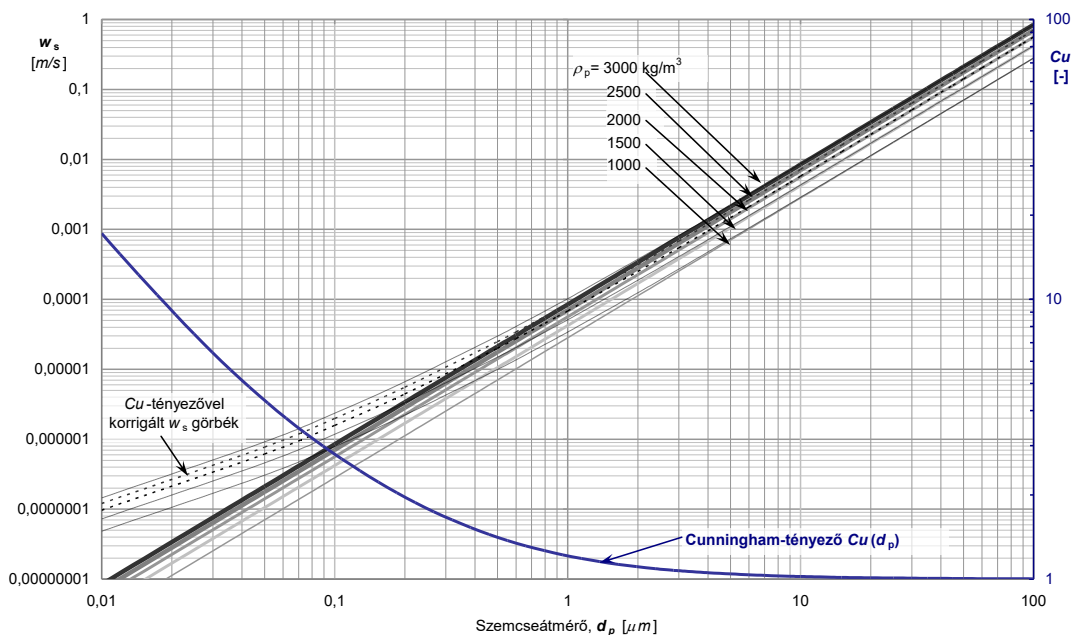
Settling velocity:  $w_s = \frac{x^2 (\rho_p - \rho) g}{18\mu}$  if  $\rho_p \gg \rho \Rightarrow w_s = \frac{x^2 \rho_p g}{18\mu}$ .

Correction of settling velocity is needed due to the diffusion effect in the submicron size range. We use the Cunningham correction factor ( $Cu$ ):

$$w_{s,corr} = Cu \cdot w_s$$

where  $Cu = 1 + \frac{2 A \lambda}{x}$  is the Cunningham correction factor (or the Cunningham coefficient),

where  $A \approx 1.4$ , and  $\lambda$  is the mean free path of molecules, at room-temperature  $\lambda = 6.5 \times 10^{-2} \mu m$ .



$w_s$  settling velocity (cont. lines) ad  $w_{s,corr}$  corrected settling velocity (dashed lines)  
**Settling velocity as a function of particle diameter and density**

Using the settling velocity now, we can rewrite the dimensionless momentum equation for particles in the following form.

Firstly, by neglecting the effect of the gravity field strength, the dimensionless equation of motion of particles will turn to another form using the  $w_s$  settling velocity:

$$\frac{du'}{dt'} = \frac{l_0}{v_0^2} g + \frac{18\mu}{x^2 \rho_p} \frac{l_0}{v_0} \underline{w}' \cong \frac{18\mu}{x^2 \rho_p} \frac{l_0}{v_0} \underline{w}' = \frac{g \cdot l_0}{w_s v_0} \underline{w}'$$

$$\frac{du'}{dt'} = \frac{g \cdot l_0}{w_s v_0} \underline{w}'$$

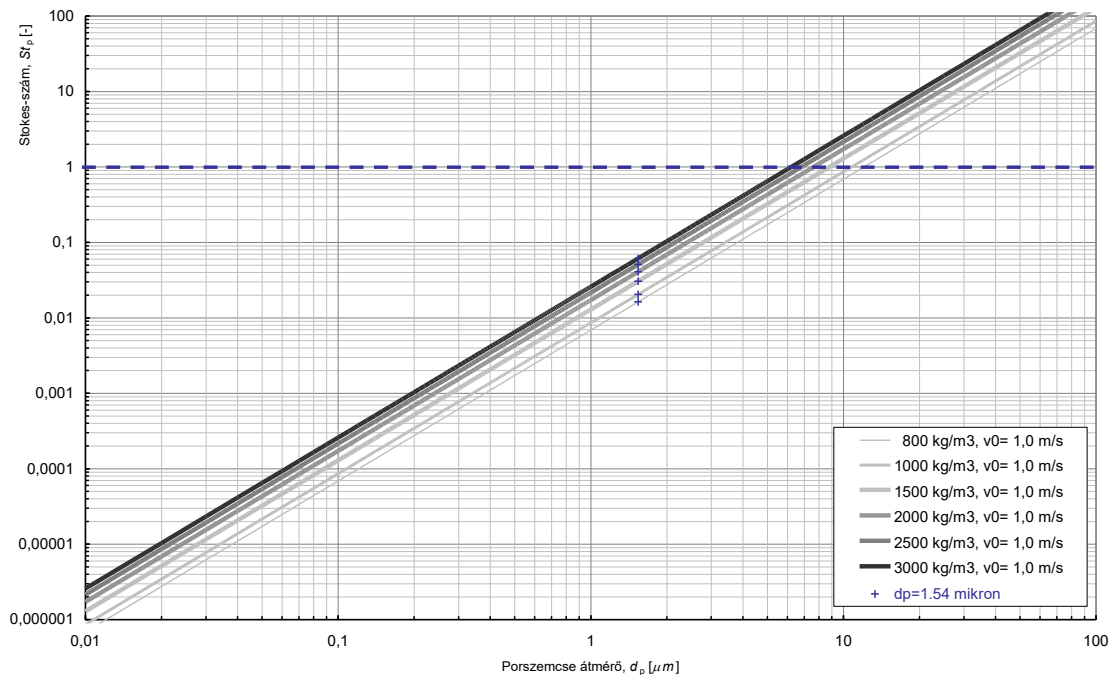
Introducing  $\Psi_p$  inertia parameter will help us to evaluate the particle motion in gas flow:

$$\Psi_p = \frac{w_s v_0}{g \cdot l_0}$$

Inertia parameter of particles  $\Psi_p$  is also called as the particle Stokes-number,  $St_p$ . The particle Stokes number is usually defined in CFD by the relative time scales of the particle and gas flow field.

$$\frac{w_s v_0}{g \cdot l_0} = \Psi_p \equiv St_p = \frac{\tau_p}{\tau_g}$$

Let's calculate the inertia parameter e.g. for solid/liquid particles ( $0.01\mu\text{m} < d_p < 100\mu\text{m}$ ) in gas having a density between  $800\text{kg/m}^3 < \rho_p < 3000\text{kg/m}^3$  while the reference velocity is  $v_0=1\text{m/s}$ .

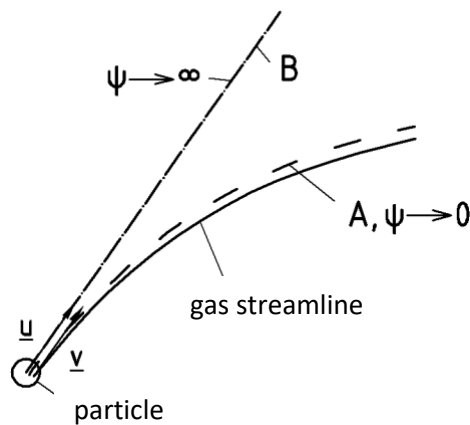


Inertia parameter ( $\Psi_p$ )/or particle Stokes number ( $St_p$ )/ vs. particle diameter

Introducing the inertia parameter into the dimensionless momentum equation for particles, we get:

$$\frac{du'}{dt'} = \frac{1}{\Psi_p} \underline{w}' = \frac{1}{\Psi_p} (\underline{v}' - \underline{u}')$$

Now we can examine how particles move in gas flow depending on their inertia parameter.

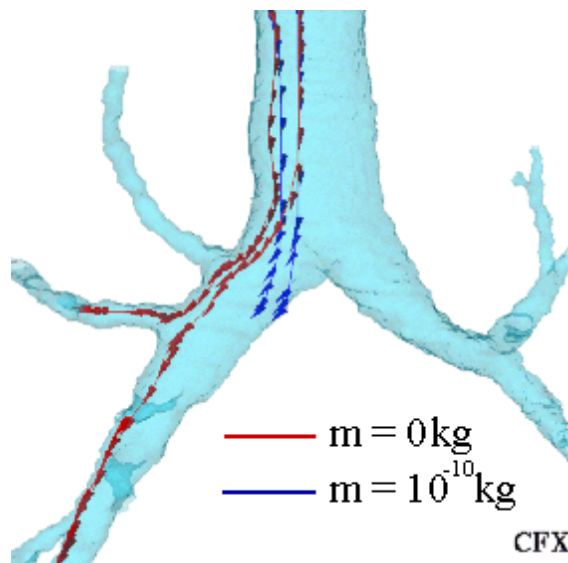


**case A)** dashed line in the upper figure: When  $\psi \rightarrow 0$ , for small ( $x$  is small) and/or light ( $\rho_p$  is small) particles, which settling velocity is small, or  $w_s \rightarrow 0$ , and if  $(\underline{v}' - \underline{u}') \neq 0 \Rightarrow \frac{d\underline{u}'}{dt'} \rightarrow \infty$ , hence particle moves along the gas streamline, particle follow the carrier gas flow.

**case B)** dash-dot line in the upper figure: When  $\psi \rightarrow \infty$ , for large and/or heavy particles, which settling velocity is large,  $\frac{1}{\psi} \rightarrow 0$ , consequently  $\frac{d\underline{u}'}{dt'} \rightarrow 0$ . hence particle move along its initial path, leaving the gas streamline.

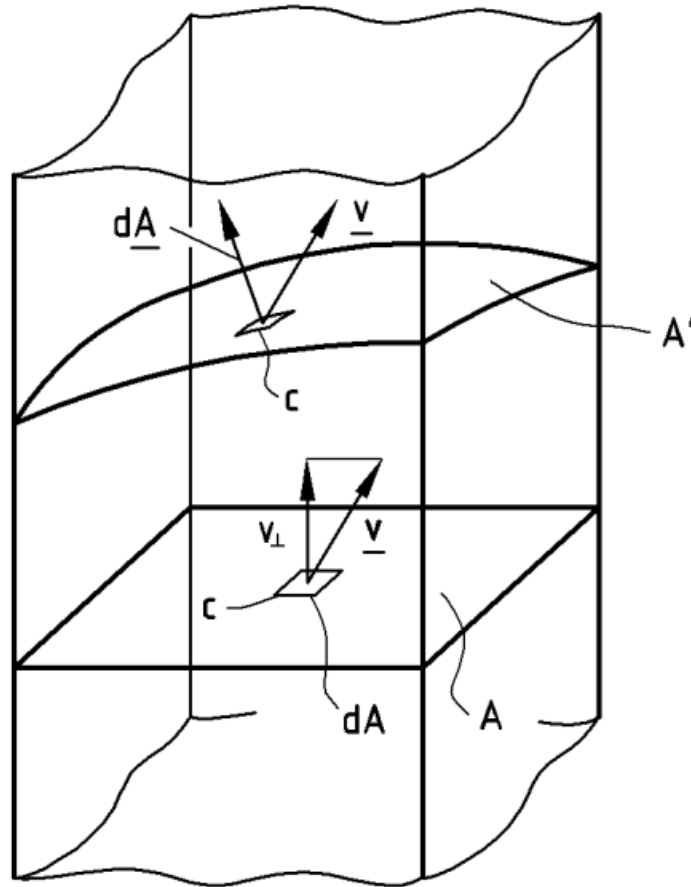
Numerical simulation (CFD) result of particle pathlines in human bronchial duct-segment are shown in figure below:

- RED LINE: „weightless” ( $m=0\text{kg}$ ,  $\Psi=0$ ) particle, this particle fully follows the inhaled air streamline, even in the high curved Y-ducts,
- BLUE LINE: a particle having a diameter of approx.  $d_p=40\mu\text{m}$  ( $m=10^{-10}\text{kg}$ ,  $\Psi \approx 250$ ) leaves the inhaled air streamline in the first Y junction.



### 3. Measurement of concentration

Measurement of mean dust concentration and dust mass flow rate in a duct.



Mean dust concentration  $\bar{c}$  [ $kg/m^3$ ]

$$\bar{c} = \frac{\int_{A'} c \underline{v} \, d\underline{A}}{\int_{A'} \underline{v} \, d\underline{A}}, \quad \bar{c} = \frac{\int_A c v_{\perp} \, dA}{\int_A v_{\perp} \, dA}, \quad \bar{c} \approx \frac{\sum_{i=1}^n c_i v_{\perp i} \Delta A_i}{\sum_{i=1}^n v_{\perp i} \Delta A_i}$$

where  $v_{\perp}$  is the velocity component perpendicular to the A cross-section.

If each  $\Delta A = A/n$ , i.e. the cross-section is divided into n measuring cross-section:

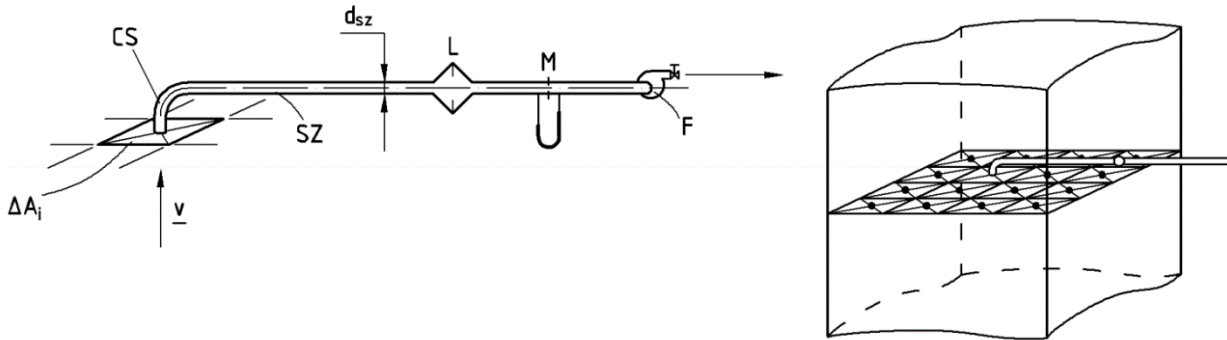
$$\bar{c} \approx \frac{\sum_{i=1}^n c_i v_{\perp i}}{\sum_{i=1}^n v_{\perp i}}$$

Mass flux  $q_m$  [ $kg/s$ ] through cross-section:  $q_m = \bar{c} \cdot q_v$  where  $q_v$  [ $m^3/s$ ] gas flow rate.

$$q_v = \sum_{i=1}^n v_{\perp i} \Delta A_i$$



Measurement of concentration by sampling.



Sampling rig and sampling in a stack

- “CS” : probe’s head (in Hungarian “leszívó csonk”)
- “SZ” : probe’s tubing (in Hungarian “szonda szár”)
- “L” : particle separator (filter) (in Hungarian “leválasztó”)
- “M” : flow rate measurement (in Hungarian “térfogatáram mérő”)
- “F” : blower with rpm regulation (in Hungarian “fúvó”)

$\bar{c}_M$  : the average concentration from the measurement:

$$\bar{c}_M = \frac{\sum_{i=1}^n \frac{d_{szi}^2 \pi}{4} v_{szi} \Delta t_i c_{szi}}{\sum_{i=1}^n \frac{d_{szi}^2 \pi}{4} v_{szi} \Delta t_i}$$

In i-th sampling point:

$v_{szi}$  sampling velocity

$c_{szi}$  concentration in the sample probe

$d_{szi}$  diameter of the probe’s head

$\Delta t_i$  sampling time period.

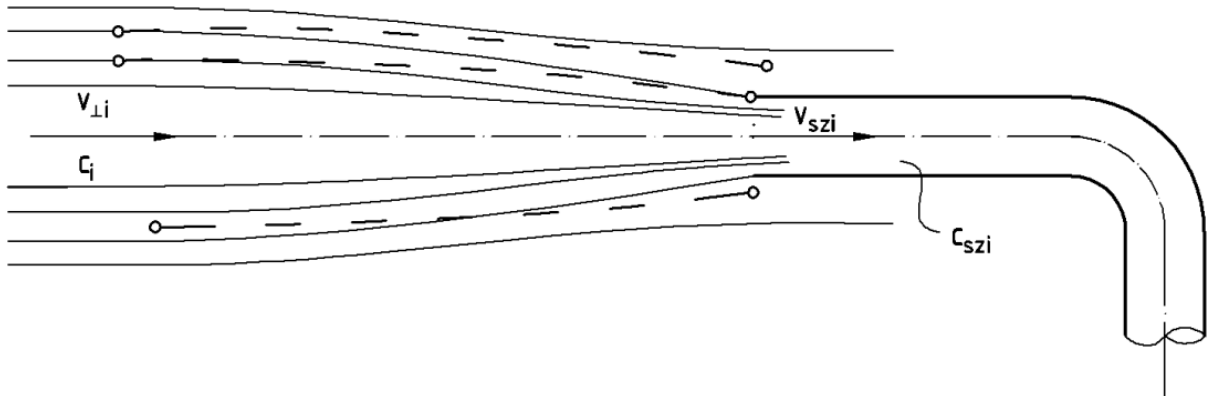
By multiplying the numerator and denominator of the fraction by  $v_{\perp i} / v_{\perp i}$ :

$$\bar{c}_M = \frac{\sum_{i=1}^n \frac{d_{szi}^2 \pi}{4} v_{szi} \Delta t_i c_{szi} \frac{v_{\perp i}}{v_{\perp i}}}{\sum_{i=1}^n \frac{d_{szi}^2 \pi}{4} v_{szi} \Delta t_i \frac{v_{\perp i}}{v_{\perp i}}}$$

If  $\boxed{d_{szi}^2 \frac{v_{szi}}{v_{\perp i}} \Delta t_i \equiv \text{const.}}$ ,

$\bar{c}_M \approx \frac{\sum_{i=1}^n c_{szi} v_{\perp i}}{\sum_{i=1}^n v_{\perp i}}$ . It is equal to  $\bar{c} \approx \frac{\sum_{i=1}^n c_i v_{\perp i}}{\sum_{i=1}^n v_{\perp i}}$  if the concentration in sampling probe is equal to that of in front of the sampling head in the gas flow.  $c_{szi} = c_i$ .

Sampling velocity



Streamlines and paths of particles if  $v_{szi} > v_{\perp i}$

The curved streamlines in front of the sampling probe cause differences in gas streamlines and paths of dust particles, so if  $v_{szi} > v_{\perp i}$  the concentration in probe is smaller than that is in front of the probe.

The requirement of the correct sampling procedure is:  $\frac{v_{szi}}{v_{\perp i}} = 1$  (iso-kinetic sampling)

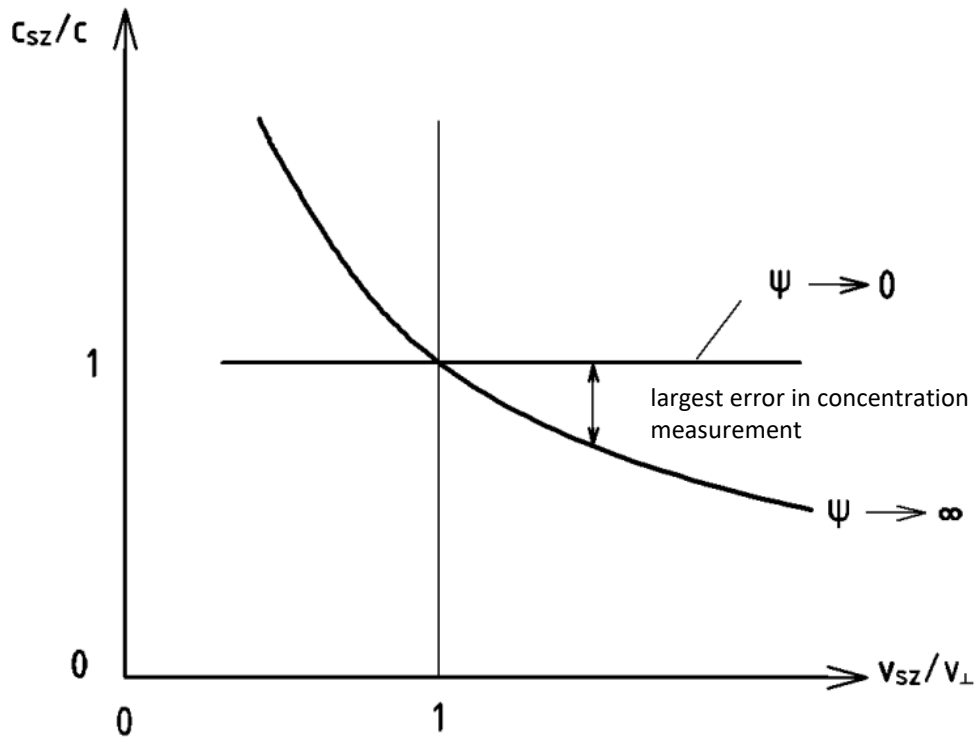
When iso-kinetic sampling is applied:  $c_{szi} = c_i$ .

In case of deviation from the iso-kinetic sampling the largest error (at  $\psi \rightarrow \infty$ ) in concentration measurement:

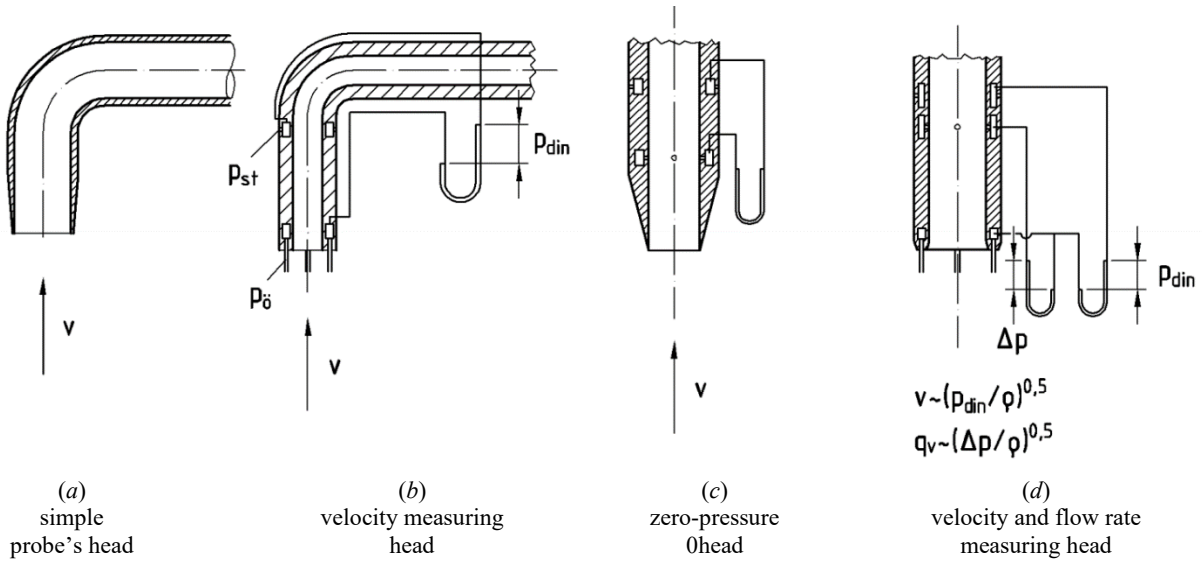
$$c_{sz} = \frac{v_{\perp} \frac{d_{sz}^2 \pi}{4} c}{v_{sz} \frac{d_{sz}^2 \pi}{4}} = \frac{v_{\perp} c}{v_{sz}} \Rightarrow \frac{c_{sz}}{c} = \frac{1}{v_{sz} / v_{\perp}}$$

Problems of sampling:

- deviation from iso-kinetic sampling (measuring local velocity and sample flow rate, pressures, temperatures),
- changing operation state of the plant,
- deposition of the dust in the probe's head of the sampling apparatus,
- cooling of sampled gas,
- condensation of the humidity in the probe's head (can be solved by heating, particle separator in the stack).



Types of sampling probes: simple, probe capable for measurement of local velocity, “zero pressure” type probe’s head, probe capable for measuring both velocity and flow rate.



**Mass balance (mass flow rate balance) of a separator**

$M_{in}$  [kg/s] mass flow rate of pollutants entering the separator (“in”)

$M_{sep}$  [kg/s] mass flow rate of pollutants separated (“sep”)

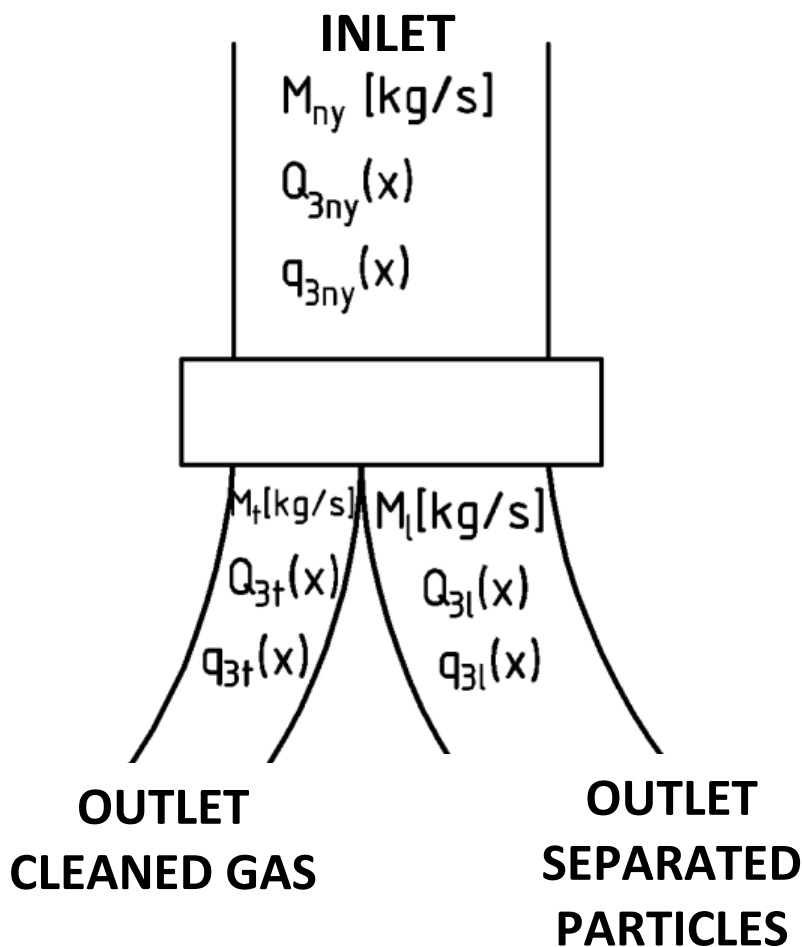
$M_{out}$  [kg/s] mass flow rate of pollutants escaping the separator (“out”)

Balance:  $M_{in} = M_{out} + M_{sep}$

$$1 = \frac{M_{sep}}{M_{in}} + \frac{M_{out}}{M_{in}} = E + P,$$

where  $E = M_{sep}/M_{in}$  is the overall efficiency of the separation, and  $P = M_{out}/M_{in}$  is the penetration

$$M_{in} = q_v c_{in} \qquad M_{out} = q_v c_{out} \qquad M_{sep} = q_v (c_{in} - c_{out})$$

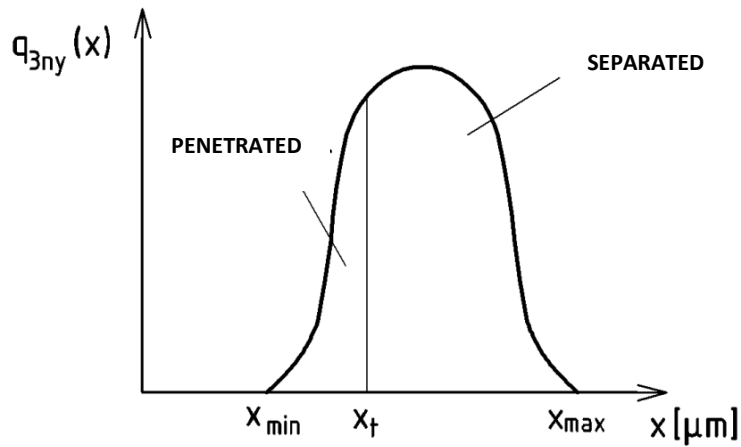


Overall efficiency expressed by  $c$  [kg/m<sup>3</sup>] pollutant concentration:

$$E = \frac{M_s}{M_{in}} = \frac{c_{in} - c_{out}}{c_{in}} = 1 - \frac{c_{out}}{c_{in}}.$$

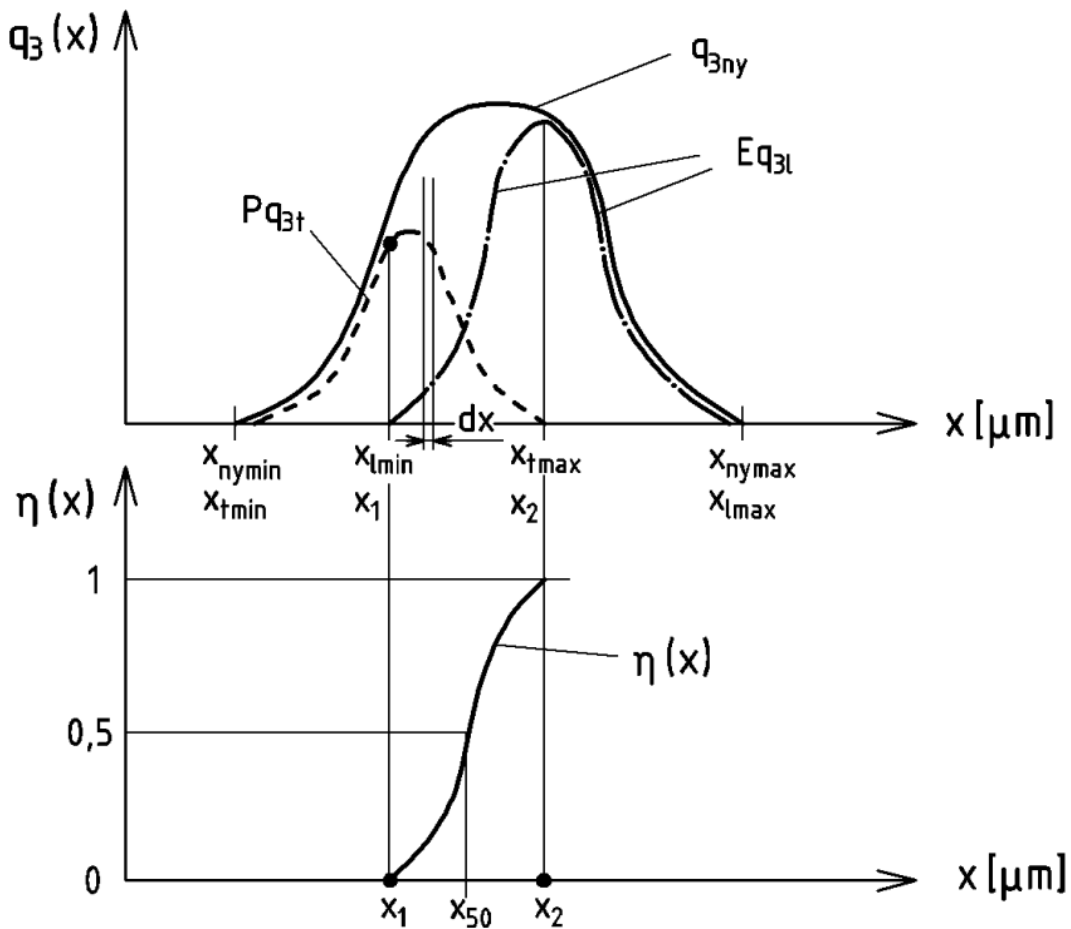
**Fractional efficiency (size dependent)  $\eta(x)$**

- a) idealistic separation means, that there is a limiting diameter ( $x_t$ ), and  
 $x < x_t$  : all particles in this size range are penetrated ( $\eta(x)=0\%$ )  
 $x_t < x$  : all particles in this size range are separated ( $\eta(x)=100\%$ )



$$E = \int_{x_t}^{x_{max}} q_3(x) dx, \quad P = \int_{x_{min}}^{x_t} q_3(x) dx, \quad E + P = 1$$

- b) In a real separation process, there is no limiting diameter but a ( $x_1 - x_2$ ) size range



- $x < x_1$  : all particles in this size range are penetrated ( $\eta(x)=0\%$ )  
 $x_1 < x < x_2$  : as diameter increases the fractional efficiency increases

$x_2 < x$  : all particles in this size range are separated ( $\eta(x)=100\%$ )

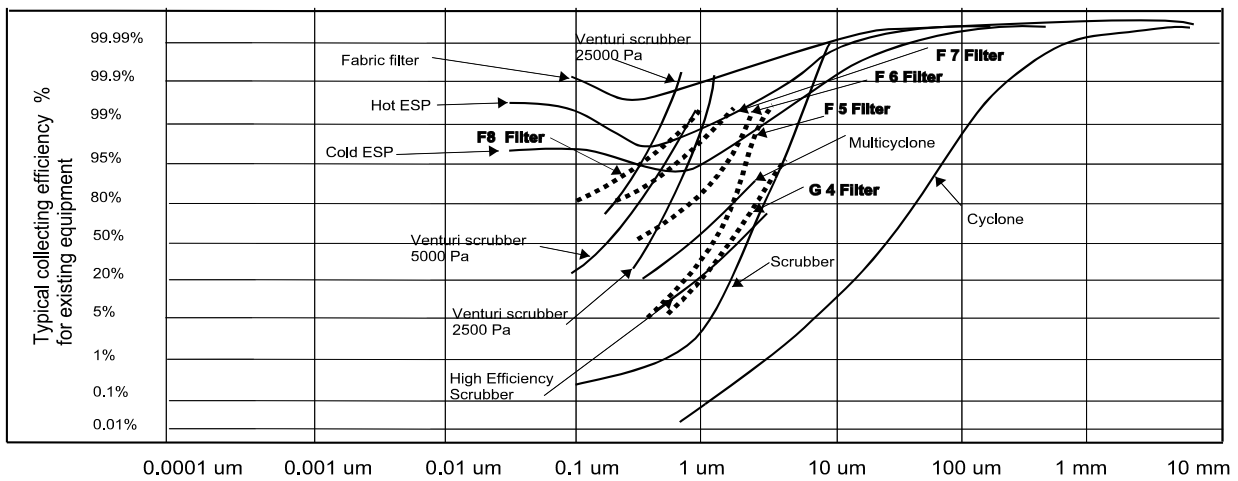
Knowing the mass flow rates (M) and  $q$  density functions in the inlet (“in”), outlet (“out”) and separated (“sep”) particle phases, we get:

$$M_{in} q_{3,in} dx = M_{out} q_{3,out} dx + M_{sep} q_{3,sep} dx$$

$$q_{3,in} = \frac{M_{out}}{M_{in}} q_{3,out} + \frac{M_{sep}}{M_{in}} q_{3,sep} = P q_{3,out} + E q_{3,sep}$$

Fractional efficiency can be calculated:

$$\eta(x) = \frac{dM_{sep}(x)}{dM_{in}(x)} = \frac{M_{sep} q_{3,sep}(x) dx}{M_{in} q_{3,in}(x) dx} = \frac{E q_{3,sep}}{q_{3,in}}$$



## **Two steps of the separation process**

### **1<sup>st</sup> step:**

**The particles should be removed from the gas streamline: they should be moved relative to the gas**

in order to establish

- a) contact with solid surfaces,
- b) contact with fluid films, of drops much larger than the particles,
- c) contact with other particles

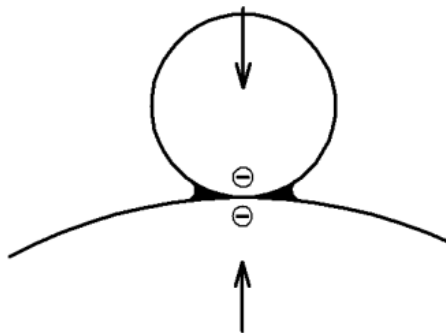
by utilising effects listed below that allow for moving the particles relative to the gas:

- inertia of the particle
- gravitational force
- diffusion caused by thermal agitation of gas molecules
- additional external (e.g. electrostatic) forces caused by the charging of particles

### **2<sup>nd</sup> step:**

**Forces should be utilised to “stick” the particles to each other, to solid surfaces and to water films. Such forces are:**

- a) Van der Waals force: is the attractive force between molecules
- b) Electrostatic attraction
- c) Surface tension, a property of the surface of a liquid that causes it to behave as an elastic sheet



**Particles “stick” due to the surface tension of the water bridge.**

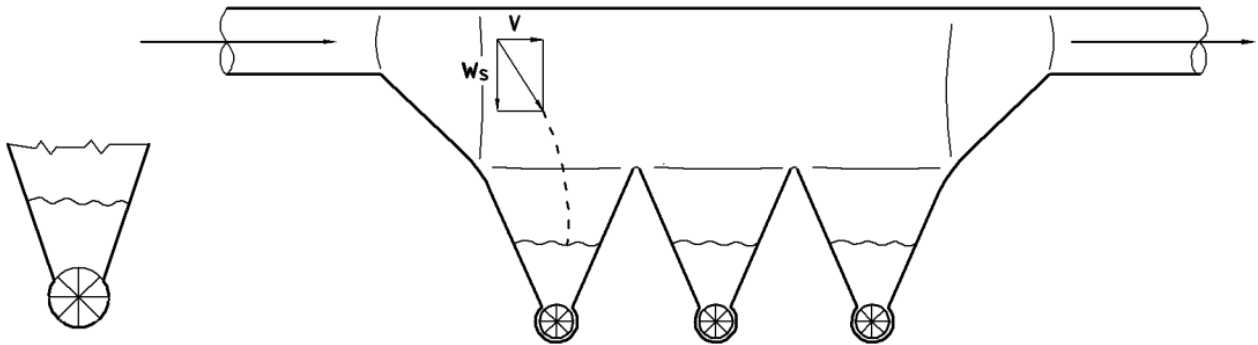
### **As a result of the above 1&2 steps:**

- The conglomeration of particles or droplets will have a higher settling velocity (and a higher inertia parameter) than a single particle. Hence, they can be separated with higher efficiency.
- Particles adhere to the filter material (to a solid surface), and they can be removed together with the filter.
- Particles are collected by large water droplets and that can be collected in an easier way, or particles are collected by using water films on the solid surfaces.

## 4. Gas cleaning equipment, various types of separators

### *Settling chambers*

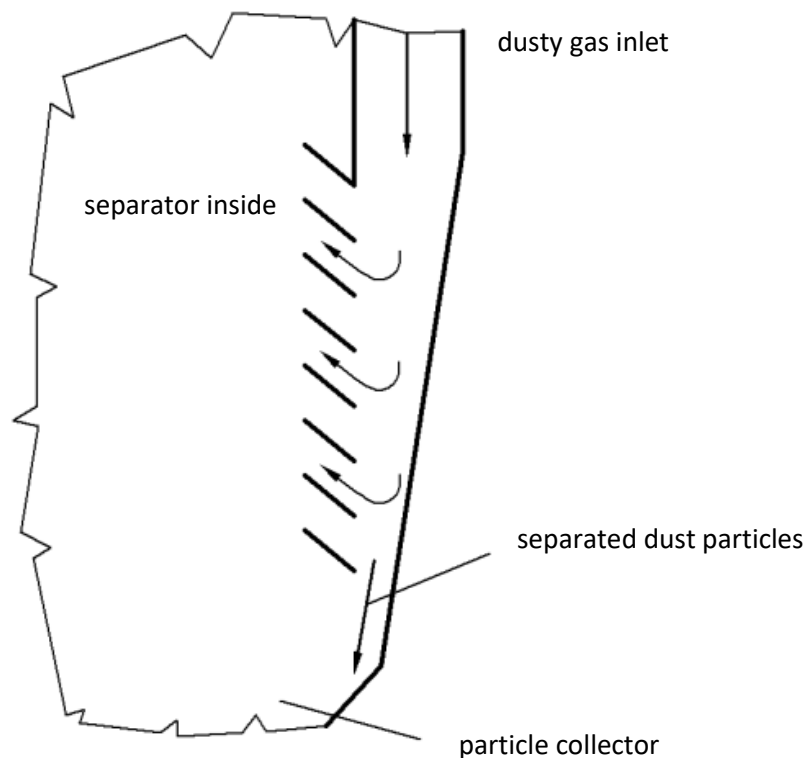
The particles are moved relative to the gas by gravitational force and Van der Waals force is utilised to “stick” the particles to each other in the hopper.



In general, the pressure in the separators is lower than the ambient, so at the removal of dust the air flow of air the hopper is not allowed. The separated dust is removed from the hopper by a charging screw or rotating cells charger.

### *Pre-separator louvres*

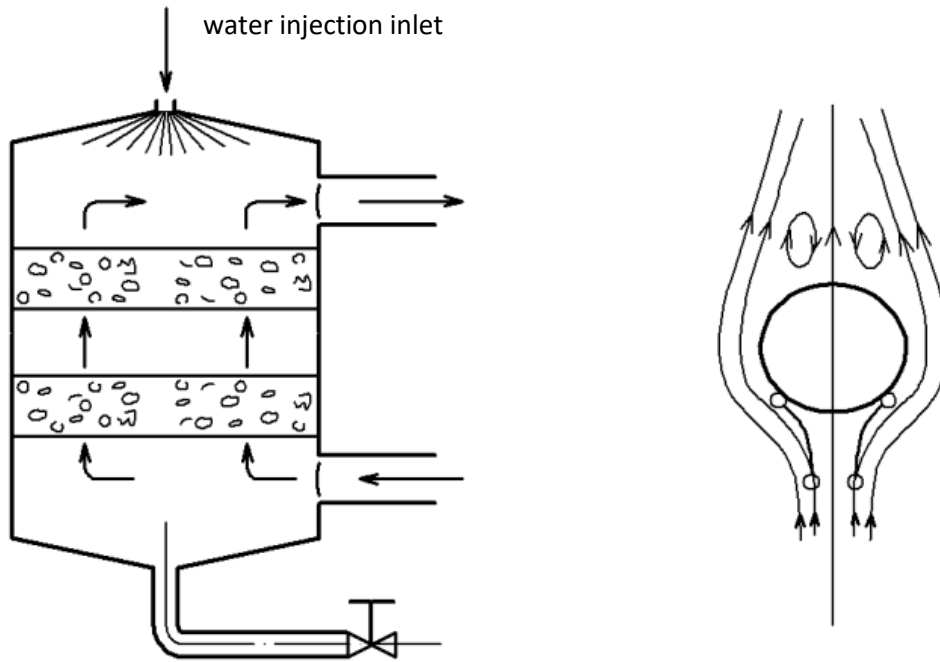
In pre-separator louvres the particles are moved relative to the gas by their inertia as well as gravitational force, and Van der Waals force is utilised to “stick” the particles to each other in the hopper.





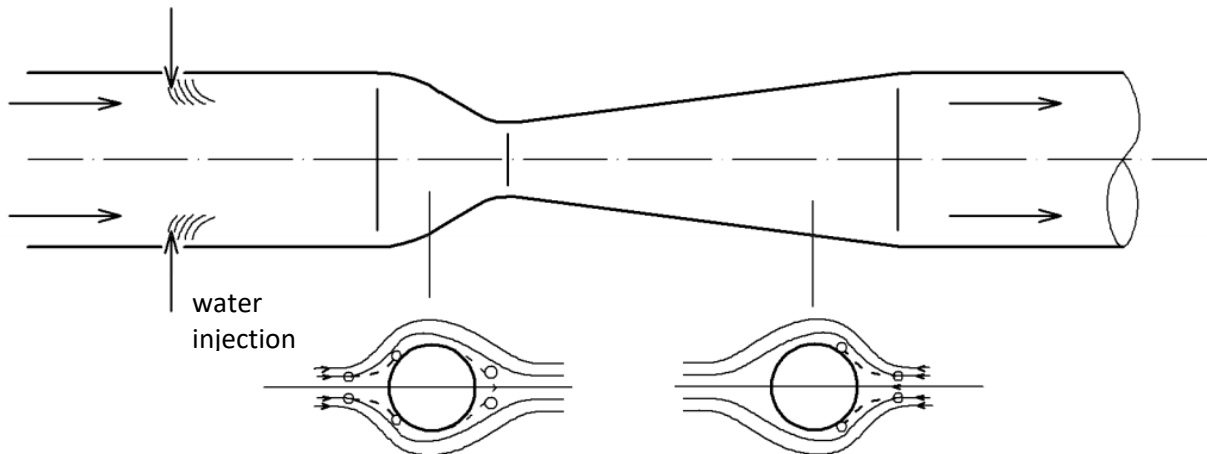
*Scrubbers (washing towers)*

The particles are moved relative to the gas and reach the relatively large water droplets mainly by their inertia as well as diffusion. The surface tension is utilised to “stick” the particles to the droplets.



*Venturi scrubber*

The particles are moved relative to the gas and reach the relatively large water droplets mainly by their inertia as well as diffusion. The surface tension is utilised to “stick” the particles to the droplets. The large droplets are separated by a cyclone separator.



### Cyclones

The particles are moved relative to the gas by their inertia to the wall and move down in a spiral path to the hopper by gravitational force and Van der Waals force is utilised to “stick” the particles to each other in the hopper.

Simple considerations result in the estimation of the limit particle diameter ( $x_{limit}$ ). The diameter of the smallest particle separated by a cyclone. Equilibrium of the forces acting on a particle moving along a circular orbit of radius  $r_1$  with tangential velocity  $v_{1t}$ . In order to maintain this motion, a centripetal force is needed on the particle:

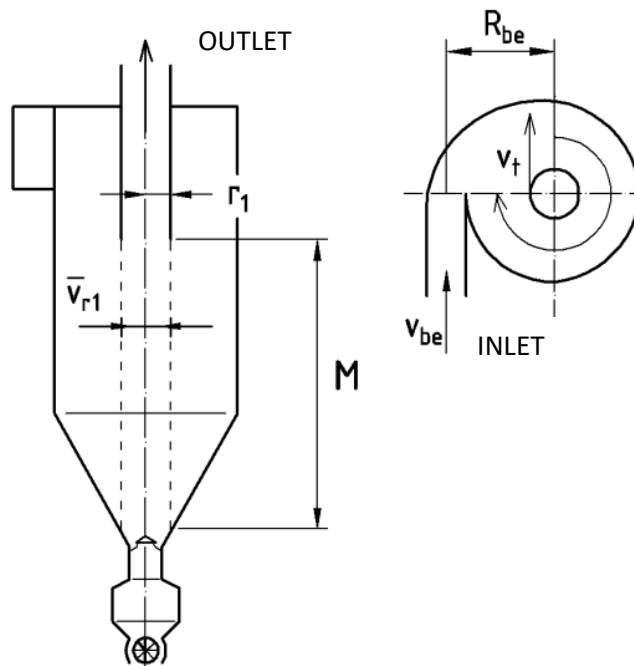
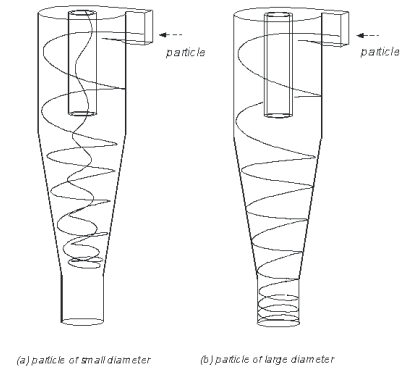
$$F_c = \frac{x_{limit}^3 \pi}{6} \rho_p \frac{v_{1t}^2}{r_1}$$

Here the radial velocity of gas is

$$v_{1r} : \frac{x_{limit}^3 \pi}{6} \rho_p \frac{v_{1t}^2}{r_1} = 3\pi \mu x_{limit} v_{1r}$$

where

$$\bar{v}_{1r} \cong \frac{q_v}{2r_1 \pi M}$$



Tangential velocity can be calculated by assuming a potential vortex in the cyclone:

$$v_{1t} = \frac{R_{in} v_{in}}{r_1}, \text{ where } R_{in} \text{ is the radius of air tangential introduction of polluted gas into the cyclone,}$$

with inlet velocity  $v_{in}$ . By expressing  $v_{1r}$  and substituting it we get:

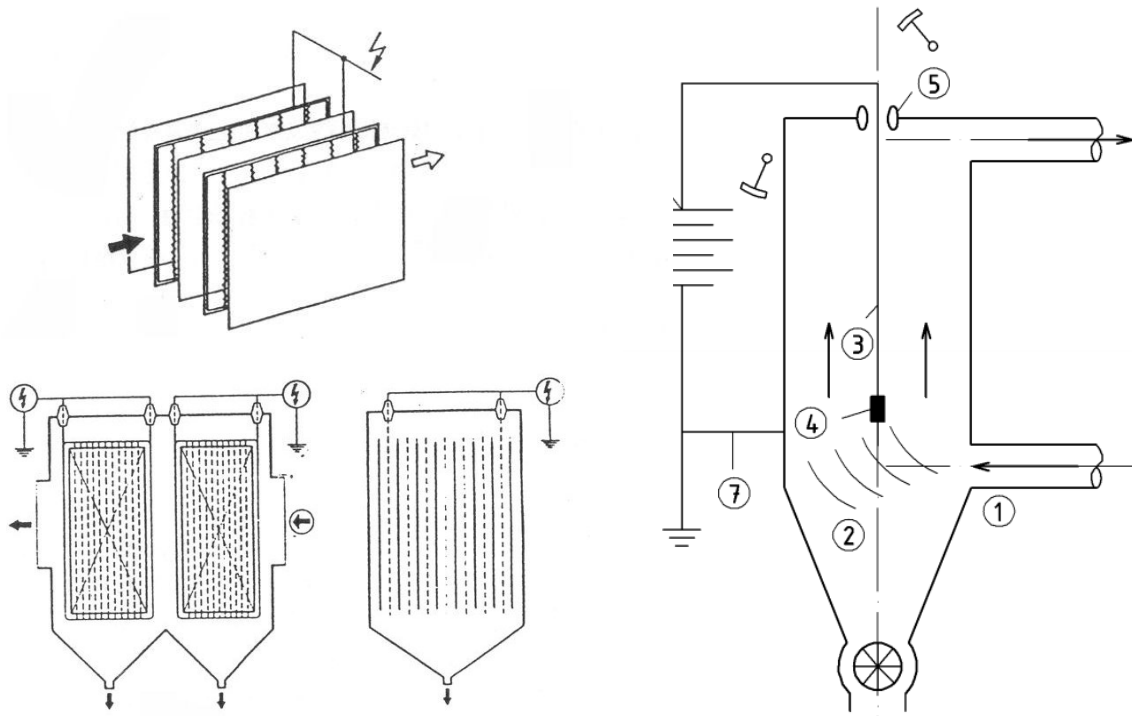
$$\frac{v_{in}^2 R_{in}^2}{r_1 r_1^2} \frac{x_{limit}^2}{18 \mu} \rho_p = v_{1r} = \frac{q_v}{2r_1 \pi M}$$

The expression for limit particle diameter ( $x_{limit}$ ) is:

$$x_{limit} = \sqrt{\frac{9}{\pi} \frac{r_1}{R_{in} v_{in}} \sqrt{\frac{\mu q_v}{\rho_p M}}}$$

*Electrostatic precipitators (ESP)*

Venturi scrubbers, electrostatic precipitators and fibrous filters meet the most rigorous environmental protection requirements.



1. Inflow of dusty gas
2. Turning vanes, perforated plates for providing uniform flow
3. High voltage electrode
4. Weight spanning the electrode
5. Insulator
6. High voltage direct current
7. Grounding, collecting electrode

At 10-30 kV voltage corona discharge – electrons are moving in the direction of collecting electrode and they ionise gas molecules, producing further electrons (electron avalanche). Electron-affine gas molecules ( $O_2$ ,  $SO_2$ ) capture electrons: molecules of negative charge move in the electrostatic field of force. They load on particles – so particles will be charged and move towards collecting electrodes.

The charged particles are moved relative to the gas by the electrostatic field of force to the collecting electrode and Van der Waals and electrostatic forces are utilised to “stick” the particles to each other. The particles are removed from the collecting electrodes to the hopper by keeping periodically the collecting electrodes hitting by hammers. The uniformity of flow and low turbulence is crucial.

Problems: unstable operation in case of particles of small electric conductivity (high electric resistance), leakage, considerable reduction of efficiency, difficulties of cleaning of collecting electrodes, in case of the electric breakdown voltage of corona the particles can escape the separator easily.

**Filters (did not presented, hence it is just for your information)**

Filters: porous sheets (woven fabrics or flieves) of elementary fibres (filter mats).

Example: mass of 1 m<sup>2</sup> filter:  $m_f = 0.4 \text{ kg/m}^2$ , thickness:  $s=0.004 \text{ m}$ , diameter and density of fibres  $d_f = 20\mu\text{m}$  and  $\rho_f = 1000 \text{ kg/m}^3$ .

Solidity:  $\alpha = \frac{V_f}{V} = 1 - \varepsilon$

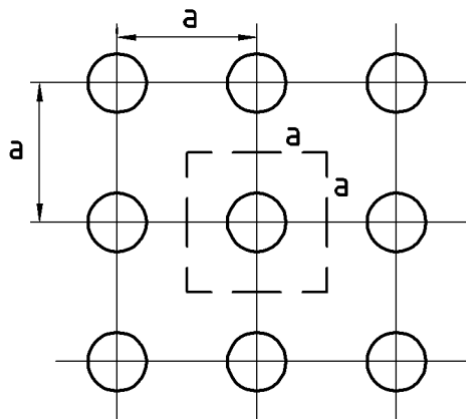
$V_f$  and  $V[\text{m}^3]$  volume of fibres and filter,  $\varepsilon$  porosity.  $\alpha = \frac{m_f}{\rho_f s} = 0.1$ . Usual values:  $\alpha = 0,01 \div 0,3$

Length of the fibres in 1m<sup>2</sup> filter sheet:  $L_{f1m^2} = \frac{V_f}{d^2 \pi / 4} = 1.27 \cdot 10^6 \text{ m/m}^2$ ,

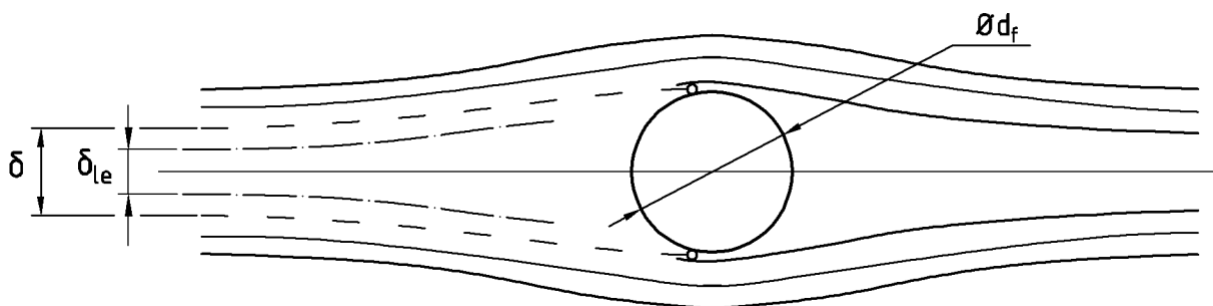
Surface area:  $A_{f1m^2} = L_{f1m^2} d \pi = 80 \text{ m}^2 / \text{m}^2$ . Average distance between fibres

$$\alpha = \frac{d_f^2 \pi}{4a^2} \rightarrow \frac{a}{d_f} = \sqrt{\frac{\pi}{4\alpha}} = 2.8.$$

If  $d_f = 20\mu\text{m}$ ,  $a = 60 \mu\text{m}$ , in  $s = 4 \text{ mm}$  70 rows of fibres.

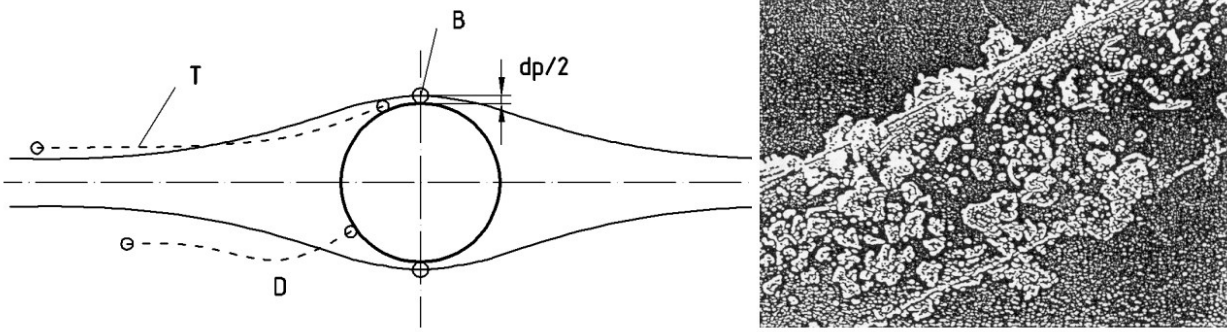


The separated particles are of diameter of several microns, so the particles are not filtered in a conventional way. The collection of particles occurs in another way:  $\Delta p$  pressure difference across the filter induces the flow of dusty gas across the filter mat:  $v_f [\text{m/s}]$  filtration velocity. In the flow past fibres viscosity is dominant.



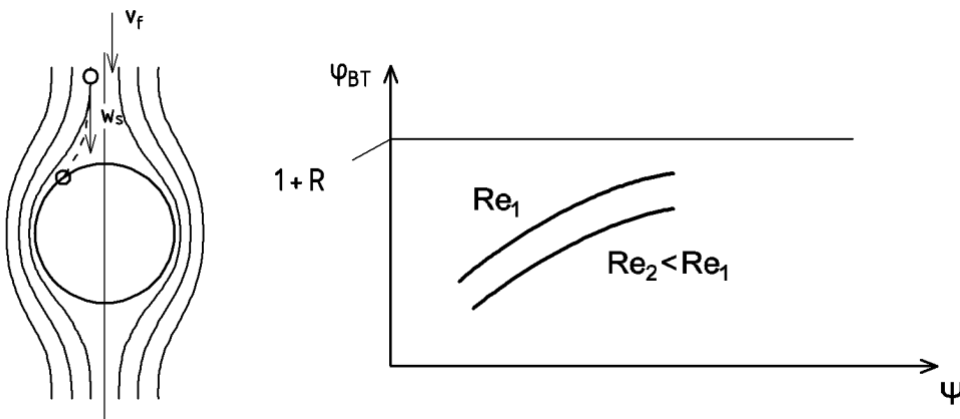
There are several mechanisms moving the particles relative to the gas towards the fibres and causes collision of particles on the fibre:

- curved streamlines: inertia of particles
- weight
- diffusion
- electrostatic forces
- blocking



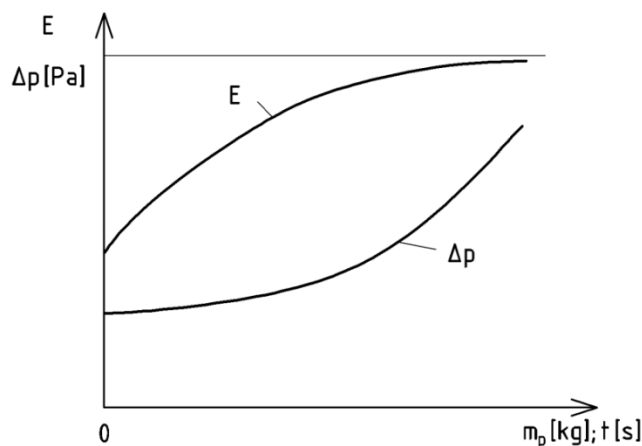
T inertia, B blocking, D diffusion

Collision efficiency of single fibre:  $\varphi = \frac{\delta}{d_f}$ , where  $\delta$  is the thickness of the layer of particles colliding the fibre. Part of the particles is collected by fibres and other part rebounds. Van der Waals and electrostatic forces as well as surface tension are utilised to “stick” the particles to the fibres and to each other.



Collision efficiency as a function of  $\psi$  inertia parameter:  $\Psi = \frac{v_f w_s}{g d_f} = \frac{v_f \rho_p x^2}{18 \mu d_f}$

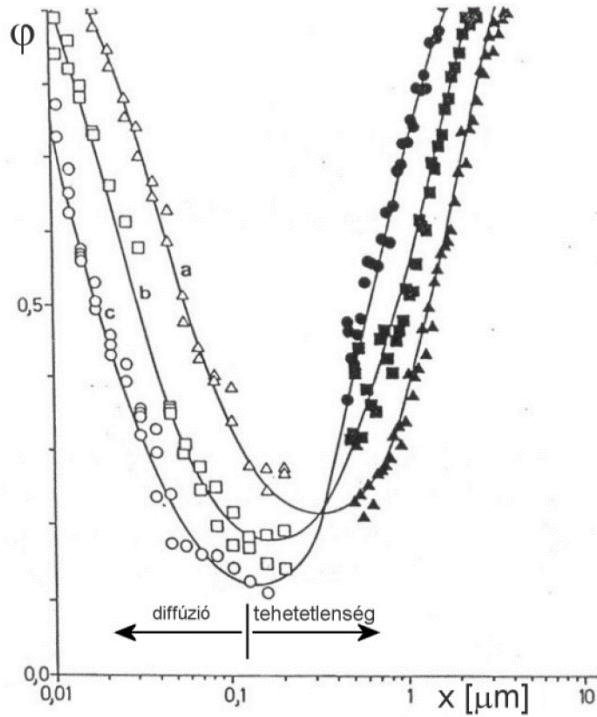
Collected particles increase the collecting surface and the solidity (layer of particle and dendrites), so both the efficiency and the pressure drop increase in time. The deposited particles can be removed from the *deep bed filters* so they should be replaced if the pressure drop exceeds a given value. So they can be used only for small concentration (e.g. aftercleaners or at ventilation of clean rooms).



Change of pressure drop and filtration efficiency in time (separated dust mass)

The most particles are deposited in the layer of the filter mat close to its raw gas side. If the solidity of filter is higher, a layer of particles (dust cake) develops on the surface of the filter that separates

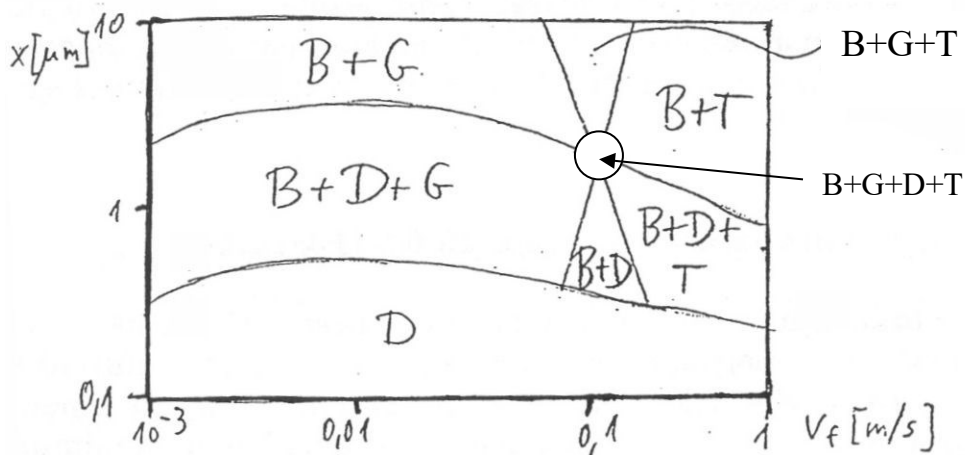
the particles. This dust cake can be removed by shaking, deforming the filter: regeneration of filters. Polluted gases of much higher concentration than at deep bed filters can be cleaned by this type of filters: *surface filters*.



Collision efficiency as a function of particle diameter and filtration velocity

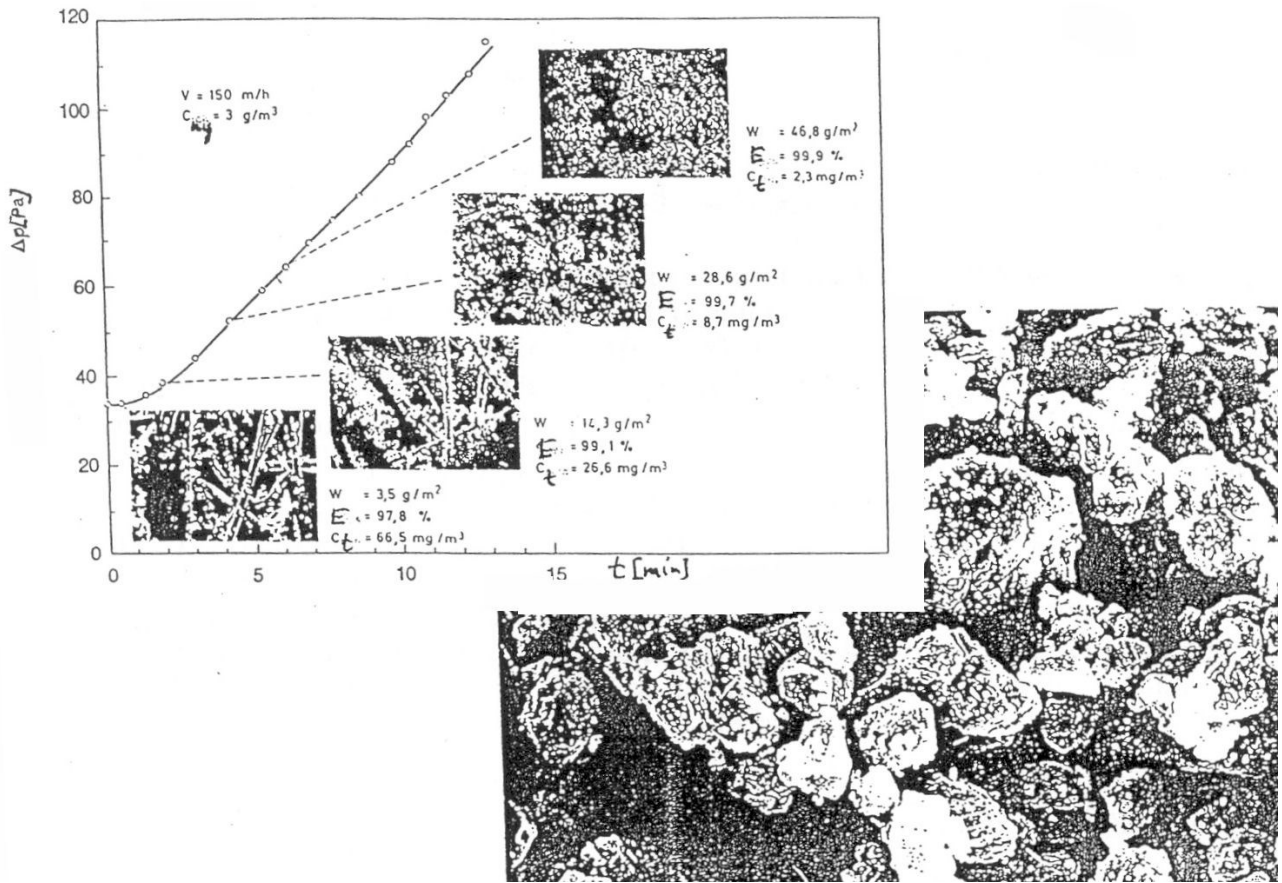
$$v_c > v_b > v_a$$

The domain of dominant effects influencing the collision efficiency

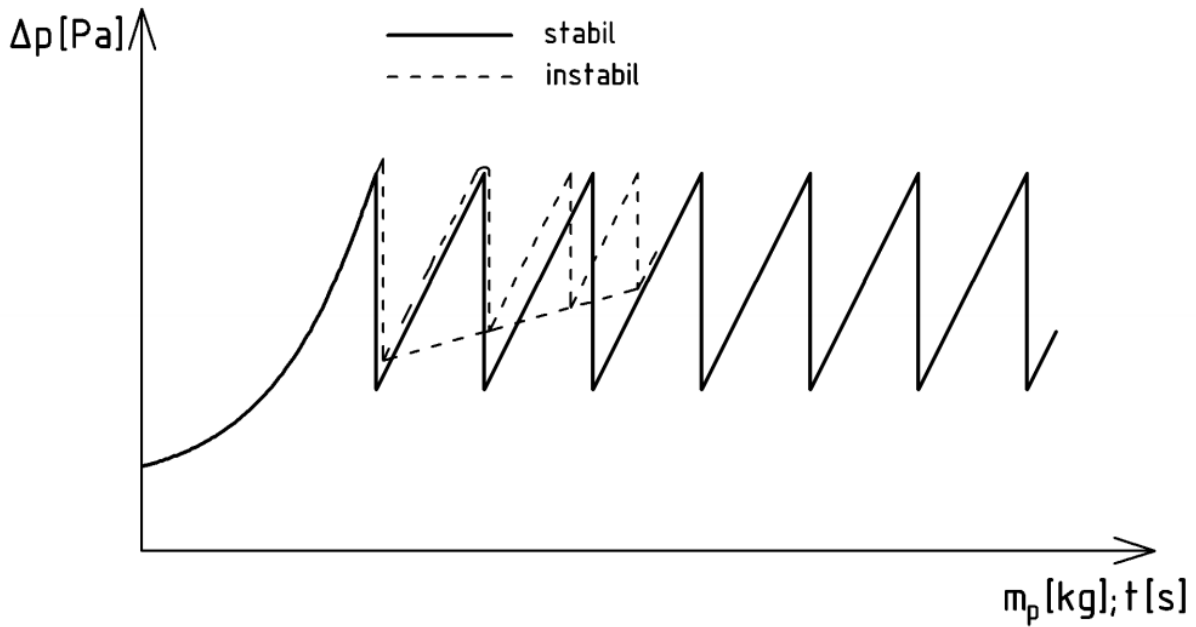


Where: T inertia, G weight, D diffusion, B blocking

*Surface filters*



Stable and instable operation of the bag filter unit:



## ADVANTAGES AND DISADVANTAGES OF THE VARIOUS SEPARATOR TYPES

(SOURCE:

“Perry’s Chemical Engineers’ Handbook”

ed. Don W. Green | 1997 | ISBN 0-07-049841-5 | McGraw-Hill)

**TABLE 25-13**

### **Advantages and Disadvantages of Cyclone Collectors**

#### *Advantages*

1. Low cost of construction
2. Relatively simple equipment with few maintenance problems
3. Relatively low operating pressure drops (for degree of particulate removal obtained) in the range of approximately 2- to 6-in water column
4. Temperature and pressure limitations imposed only by the materials of construction used
5. Collected material recovered dry for subsequent processing or disposal
6. Relatively small space requirements

#### *Disadvantages*

1. Relatively low overall particulate collection efficiencies, especially on particulates below 10  $\mu\text{m}$  in size
2. Inability to handle tacky materials

**TABLE 25-14**

### **Advantages and Disadvantages of Wet Scrubbers**

#### *Advantages*

1. No secondary dust sources
2. Relatively small space requirements
3. Ability to collect gases as well as particulates (especially “sticky” ones)
4. Ability to handle high-temperature, high-humidity gas streams
5. Capital cost low (if wastewater treatment system not required)
6. For some processes, gas stream already at high pressures (so pressure drop considerations may not be significant)
7. Ability to achieve high collection efficiencies on fine particulates (however, at the expense of pressure drop)
8. Ability to handle gas streams containing flammable or explosive materials

#### *Disadvantages*

1. Possible creation of water-disposal problem
2. Product collected wet
3. Corrosion problems more severe than with dry systems
4. Steam plume opacity and/or droplet entrainment possibly objectionable
5. Pressure-drop and horsepower requirements possibly high
6. Solids buildup at the wet-dry interface possibly a problem
7. Relatively high maintenance costs
8. Must be protected from freezing
9. Low exit gas temperature reduces exhaust plume dispersion
10. Moist exhaust gas precludes use of most additional controls



**TABLE 25-15**  
**Advantages and Disadvantages of Dry Scrubbers**

*Advantages*

1. No wet sludge to dispose of
2. Relatively small space requirements
3. Ability to collect acid gases at high efficiencies
4. Ability to handle high-temperature gas streams
5. Dry exhaust allows addition of fabric filter to control particulate

*Disadvantages*

1. Acid gas control efficiency not as high as with wet scrubber
2. No particulate collection—dry scrubber generates particulate
3. Corrosion problems more severe than with dry systems
4. Solids buildup at the wet-dry interface possibly a problem
5. Relatively high maintenance costs
6. Must be protected from freezing
7. Low exit gas temperature reduces exhaust plume dispersion

**TABLE 25-16**  
**Advantages and Disadvantages of Electrostatic Precipitators**

*Advantages*

1. Extremely high particulate (coarse and fine) collection efficiencies attainable (at a relatively low expenditure of energy)
2. Collected material recovered dry for subsequent processing or disposal
3. Low pressure drop
4. Designed for continuous operation with minimum maintenance requirements
5. Relatively low operating costs
6. Capable of operation under high pressure (to 150 lbf/in<sup>2</sup>) or vacuum conditions
7. Capable of operation at high temperatures [to 704°C(1300°F)]
8. Relatively large gas flow rates capable of effective handling

*Disadvantages*

1. High capital cost
2. Very sensitive to fluctuations in gas-stream conditions (in particular, flows, temperature, particulate and gas composition, and particulate loadings)
3. Certain particulates difficult to collect owing to extremely high- or low-resistivity characteristics
4. Relatively large space requirements required for installation
5. Explosion hazard when treating combustible gases and/or collecting combustible particulates
6. Special precautions required to safeguard personnel from the high voltage
7. Ozone produced by the negatively charged discharge electrode during gas ionisation
8. Relatively sophisticated maintenance personnel required
9. Gas ionisation may cause dissociation of gas stream constituents and result in creation of toxic by-products
10. Sticky particulates may be difficult to remove from plates
11. Not effective in capturing some contaminants that exist as vapours at high temperatures (e.g., heavy metals, dioxins)

**TABLE 25-17**  
**Advantages and Disadvantages of Fabric-Filter Systems**

*Advantages*

1. Extremely high collection efficiency on both coarse and fine (sub-micrometer) particles
2. Relatively insensitive to gas-stream fluctuation; efficiency and pressure drop relatively unaffected by large changes in inlet dust loadings for continuously cleaned filters
3. Filter outlet air capable of being recirculated within the plant in many cases (for energy conservation)
4. Collected material recovered dry for subsequent processing or disposal
5. No problems with liquid-waste disposal, water pollution, or liquid freezing
6. Corrosion and rusting of components usually not problems
7. No hazard of high voltage, simplifying maintenance and repair and permitting collection of flammable dusts
8. Use of selected fibrous or granular filter aids (precoating), permitting the high-efficiency collection of submicrometer smokes and gaseous contaminants
9. Filter collectors available in a large number of configurations, resulting in a range of dimensions and inlet and outlet flange locations to suit installment requirements
10. Relatively simple operation

*Disadvantages*

1. Temperatures much in excess of 288°C (550°F) requiring special refractory mineral or metallic fabrics that are still in the developmental stage and can be very expensive
2. Certain dusts possibly requiring fabric treatments to reduce dust seeping or, in other cases, assist in the removal of the collected dust
3. Concentrations of some dusts in the collector (~50 g/m<sup>3</sup>) forming a possible fire or explosion hazard if a spark or flame is admitted by accident; possibility of fabrics burning if readily oxidisable dust is being collected
4. Relatively high maintenance requirements (bag replacement, etc.)
5. Fabric life possibly shortened at elevated temperatures and in the presence of acid or alkaline particulate or gas constituents
6. Hygroscopic materials, condensation of moisture, or tarry adhesive components possibly causing crusty caking or plugging of the fabric or requiring special additives
7. Replacement of fabric, possibly requiring respiratory protection for maintenance personnel
8. Medium pressure-drop requirements, typically in the range 4- to 10-in water column

**TABLE 25-18**  
**Advantages and Disadvantages of Absorption Systems (Packed and Plate Columns)**

*Advantages*

1. Relatively low pressure drop
2. Standardisation in fiberglass-reinforced plastic (FRP) construction permitting operation in highly corrosive atmospheres
3. Capable of achieving relatively high mass-transfer efficiencies
4. Increasing the height and/or type of packing or number of plates capable of improving mass transfer without purchasing a new piece of equipment
5. Relatively low capital cost
6. Relatively small space requirements
7. Ability to collect particulates as well as gases
8. Collected substances may be recovered by distillation

*Disadvantages*

1. Possibility of creating water (or liquid) disposal problem
2. Product collected wet
3. Particulates deposition possibly causing plugging of the bed or plates
4. When FRP construction is used, sensitive to temperature
5. Relatively high maintenance costs
6. Must be protected from freezing

**TABLE 25-19**  
**Comparison of Plate and Packed Columns**

*Packed column*

1. Lower pressure drop
2. Simpler and cheaper to construct
3. Preferable for liquids with high-foaming tendencies

*Plate column*

1. Less susceptible to plugging
2. Less weight
3. Less of a problem with channeling
4. Temperature surge resulting in less damage

## Control questions

The control questions cover the lecture topics. Mid-term test questions are based on the oral lectures, presented slides and this lecture handout.

1. Definition of aerosols. Types of aerosols. Evaluation & Conclusions.
2. Equivalent diameter of non-spherical particles. Types of equivalences. Evaluation & Conclusions.
3. Characterisation of particle-laden flows. Average relative distance between particles in gas. Volume ratio and mass loading ratio. Evaluation & Conclusions.
4. Characterisation of particle assembly ( $Q_0$ ,  $q_0$ ) Evaluation & Conclusions.
5. Navier-Stokes equation including effect of particles. Conditions for neglect of the effect of particles on the gas flow field. Evaluation & Conclusions.
6. Aerodynamic drag force (Stokes' drag form) acting on a single particle, drag coefficient. Evaluation & Conclusions.
7. Momentum equation for particles in gas flow. Evaluation & Conclusions.
8. Calculation of settling velocity. Evaluation & Conclusions.
9. Determination of particle path based on the inertia parameter ( $\Psi_p$ ) / particle Stokes number ( $St_p$ ) in case of a curved gas streamline of carrier flow. Evaluation & Conclusions.
10. Mass balance of a separator, overall efficiency, penetration. Ideal / real separation: fractional efficiency. Evaluation & Conclusions.
11. Main conditions of proper sampling during the measurement of particle concentration in a duct. Evaluation & Conclusions.
12. Steps of separation, forces and effects acting on the particles, relative to the gas & forces adhering the particles to each other, to solid surfaces and to water droplets of films. Evaluation & Conclusions.
13. Settling chambers / pre-separator louvres / washing tower / Venturi scrubber / cyclone / electrostatic precipitator / filters (one of your choice): sketch of the facility, operational basics, main forces & effects in the separation process, efficiency, costs etc.).