Air Pollution Control

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Aerosols

Definition of aerosols: nearly stable mixture of gas and particles
Change of the characteristics
- because of settling of larger particles
- because of diffusion and agglomeration of small particles
$0,01 \leq x$ [µm] ≤ 50

Type and particle sizes of particles

Dust: $x \geq 0,2$ [µm] perceptible to the eye diameter is larger than the wave length of light. Produced by breaking or attrition, abrasion, wearing of solid substances

Fume: $x \leq 1$ [µm] solid particles or fluid droplets originated from condensation or chemical reaction, in most cases chain-like structures. Produced at combustion, chemical processes.

Mist: fluid droplets originated from steam condensation or by atomization, spraying. The mist droplets and the saturated steam are in equilibrium.

Size of particles: in case off spherical particles the diameter is x. How to define the site of non-spherical particles? Geometrical, aerodynamic and optical equivalence.
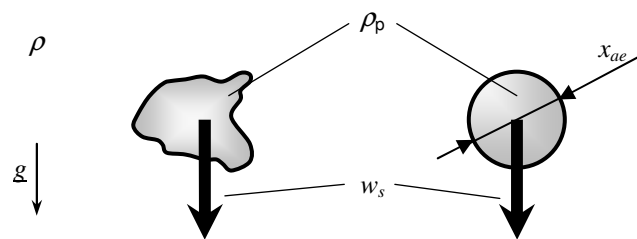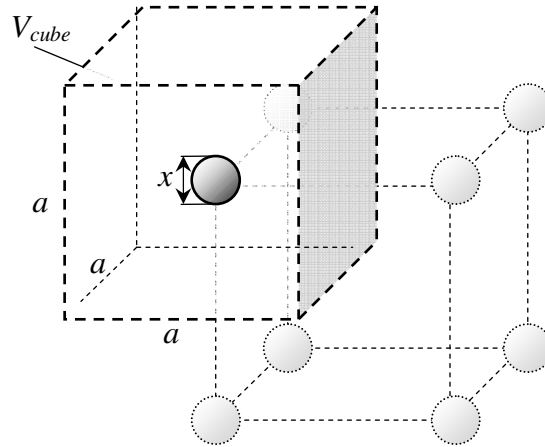

Average distance a/x between particles in gas:

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

where c [kg/m^3] a concentration, a [m] average distance between particles, ρ_p [kg/m^3] density of particles, n [db/m^3] concentration by piece.

x = 3 µm and c = 10 g/m^3 a/x = 47, in 1cm^3 350.000 particles. In 1 mm^3 37.000.000 particle of x=3µm

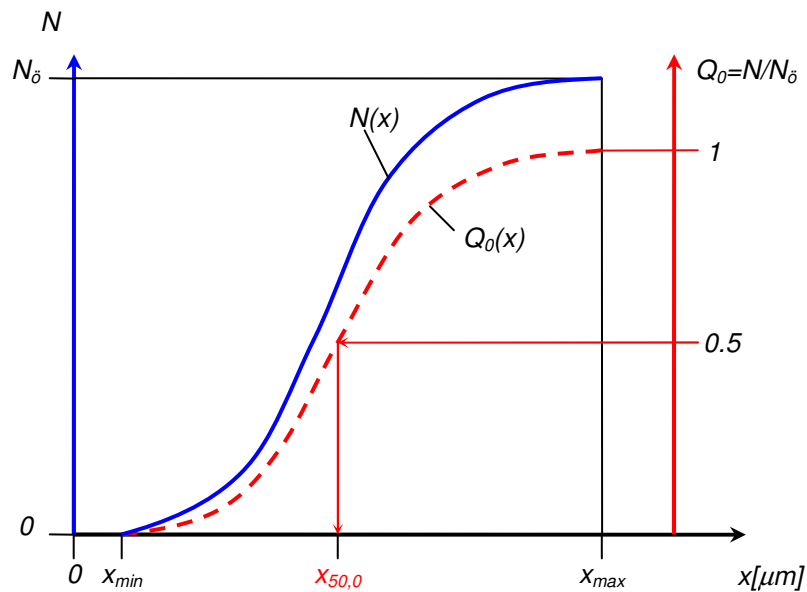| c[g/m³]	$\dfrac{a}{x}$	N [db/cm³]
10	47	350.000
1	101	35.000
0.1	218	3.500

Characterization of particle assembly:

Particle size distribution curves:
Cumulative or undersize distribution related to number of particles: $Q_0 = N/N_0$ =f(x). Q_1, Q_2, Q_3.
If $Q_0 = N/N_0$ =f(x) and the overall number of particles N_0 are known, the number of

particles in the range between x and x + Δx is $\Delta N = N_{\ddot{o}} \cdot \dfrac{dQ_0}{dx} \cdot \Delta x$.

Conversion of Q_0 to Q_3

$$Q_3(x) = \frac{\int\limits_0^x x^3 \frac{\pi}{6} N_ö \frac{dQ_0}{dx} dx}{\int\limits_0^\infty x^3 \frac{\pi}{6} N_ö \frac{dQ_0}{dx} dx} = \frac{\int\limits_0^x x^3 q_0 dx}{\int\limits_0^\infty x^3 q_0 dx}.$$

Particles in gas flow

Effect of particles on the gas flow

Navier-Stokes equation extended with considering the influence of the particles on the forces acting on gas:

$$\boxed{\frac{\partial \underline{v}}{\partial t} + \text{grad}\frac{v^2}{2} - \underline{v} \times \text{rot}\underline{v} = \underline{g} - \frac{1}{\rho}\text{grad}p + \nu\Delta\underline{v} + \underline{t}} \qquad (3.1)$$

where $\underline{t}[N/kg_{gas}]$ force to 1 kg gas from particles carried by the gas: $\underline{t} = -\frac{n\underline{F}}{\rho}$

$n[db/m^3]$: particle concentration by piece
$\underline{F}[N/db]$: aerodynamic force acting on one particle
$\rho[kg/m^3]$: gas density

The effect of particle phase on the flow field can be neglected, if $\frac{c}{\rho} \langle\langle 1$ and $\frac{d\underline{v}_p}{dt}$ is in the same order of magnitude as $\frac{d\underline{v}}{dt}$, so $\frac{c}{\rho}\frac{d\underline{v}_p}{dt} \langle\langle \frac{d\underline{v}}{dt}$.

Aerodynamic force acting on a single particle:

Particle Reynolds number: $\text{Re}_p = \frac{w\,x}{\nu}$ is small, viscosity is dominant

If $\text{Re}_p < 0.1$ Stokes relation: $\boxed{\underline{F}_e = 3\pi\mu\,x\,\underline{w} \qquad ahol\,\underline{v} = \underline{u} + \underline{w}}$

$\underline{v}$ absolute (gas) velocity
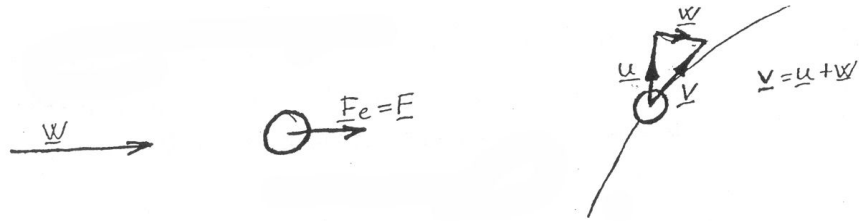$\underline{u}$ particle velocity
$\underline{w}$ relative velocity

Drag coefficient? $\boxed{c_e = \frac{|\underline{F}_e|}{\frac{\rho}{2}v^2\frac{x^2\pi}{4}}}$

Substituting Stokes relation in F_e, $c_e = 24/\text{Re}$.

If Re<5 Oseen relation: $c_e = \dfrac{24}{Re}\left(1+\dfrac{3}{16}Re\right)$.

Momentum equation for particles

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

Dimensionless equation.

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

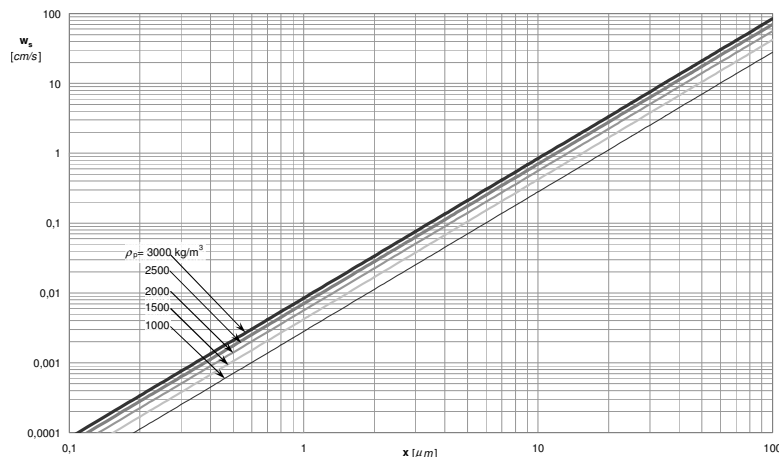Settling of particle of ρ_p density in a gas of ρ density:

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

Settling velocity: $\boxed{w_s = \dfrac{x^2(\rho_p - \rho)g}{18\mu}}$ $\qquad$ $\boxed{if\ \rho_p \rangle\rangle \rho \Rightarrow w_s = \dfrac{x^2 \rho_p g}{18\mu}}$.

Correction of settling velocity

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

$Cu = 1 + \dfrac{2\,A\,\lambda}{x}$ Cunningham coefficient, A≈1.4, λ mean free path of molecules, at room-temperature λ = 6.5 $*10^{-2}$ µm).

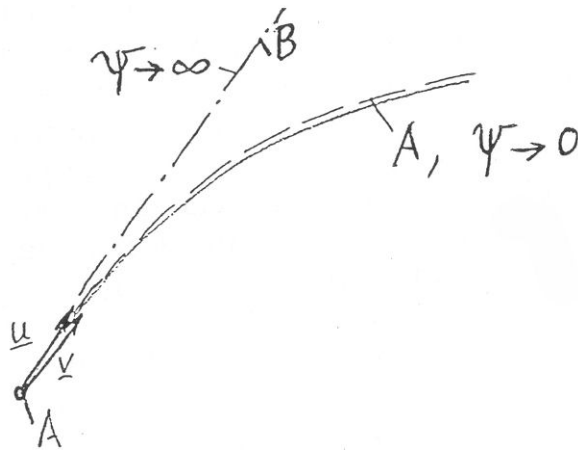Settling velocity as function of particle diameter and density

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By neglecting the field of gravity

$$\frac{\dfrac{d\underline{u}}{v_0}}{\dfrac{dt}{l_0/v_0}} = \frac{gl_0}{w_s v_0}\frac{\underline{w}}{v_0} \quad.$$

Introducing ψ inertia parameter: $\boxed{\psi = \dfrac{w_s v_0}{gl_0}}$

Dimensionless momentum equation for particles (' denotes dimensionless quantities, e.g. $u' = \dfrac{u}{v_0}$).

$$\boxed{\frac{d\underline{u}'}{dt'} = \frac{1}{\psi}\underline{w}' = \frac{1}{\psi}(\underline{v}' - \underline{u}')}$$

- If $\psi \to 0$, small particle, settling velocity $w_s \to 0$. If $(\underline{v}' - \underline{u}') \neq 0 \Rightarrow \dfrac{d\underline{u}'}{dt'} \to \infty$, the particle moves along the streamline.

- If $\psi \to \infty$, big particles, large settling velocity, $\dfrac{1}{\psi} \to 0, \, consequently \, \dfrac{d\underline{u}'}{dt'} \to 0.$ Particle moves along a straight line.

Measurement of mean dust concentration and dust mass rate in a duct.
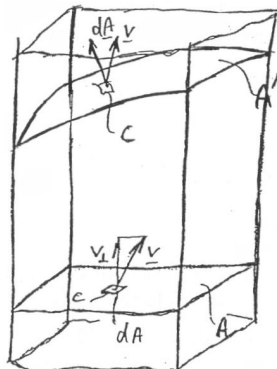
<u>Mean dust concentration</u> $\bar{c}\left[kg/m^3\right]$

$$\bar{c} = \frac{\int_{A^1} c\,\underline{v}\,d\underline{A}}{\int_{A^1} \underline{v}\,d\underline{A}}\,,\qquad \bar{c} = \frac{\int_A cv_\perp dA}{\int_A v_\perp dA}\qquad \bar{c} \approx \frac{\sum_{i=1}^{n} c_i v_{\perp i}\Delta A_i}{\sum_{i=1}^{n} v_{\perp i}\Delta A_i}$$
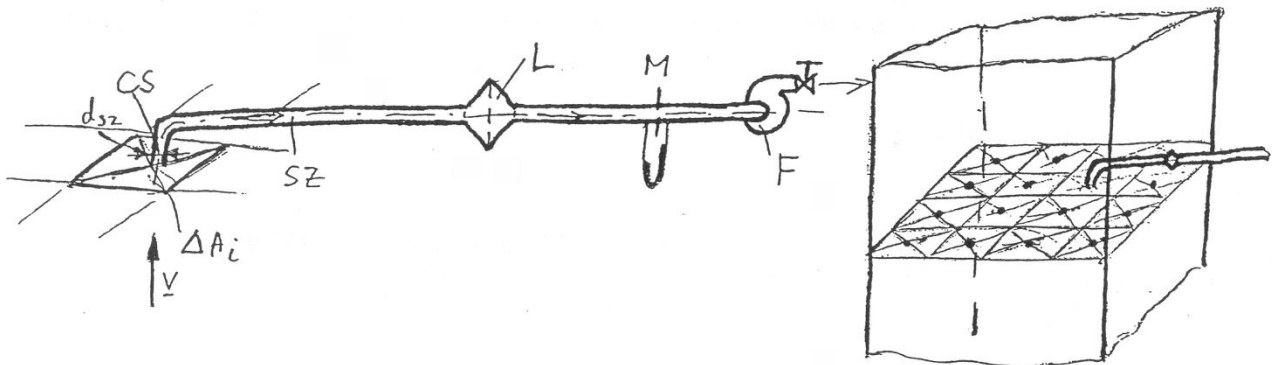
where $v_\perp$ is the velocity component perpendicular to the A cross section.

If $\Delta A = A/n$ $\boxed{\bar{c} \approx \dfrac{\sum_{i=1}^{n} c_i v_{\perp i}}{\sum_{i=1}^{n} v_{\perp i}}}$.

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

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

<u>Measurement of concentration by sampling.</u>

Sampling rig and sampling in a stack

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

In i-th sampling point
v_{szi} and c_{szi} sampling velocity and dust concentration in the sample probe of
d_{szi} diameter, Δt_i sampling period.

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

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

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

$\bar{c}_M \approx \dfrac{\sum\limits_{i=1}^{n} c_{szi} v_{\perp i}}{\sum\limits_{i=1}^{n} v_{\perp i}}$. It is equal to $\boxed{\bar{c} \approx \dfrac{\sum\limits_{i=1}^{n} c_i v_{\perp i}}{\sum\limits_{i=1}^{n} v_{\perp i}}}$ if the concentration in sampling head is

equal to that of in front of the sampling head in the gas flow. $c_{szi} = c_i$.

Sampling velocity

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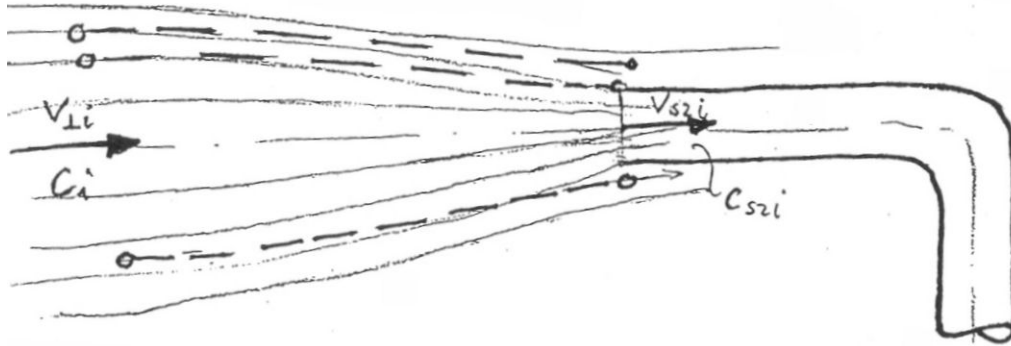
The curved streamlines in front of the sampling probe cause differences in streamlines and paths of dust particles, so if $v_{szi} \rangle v_{\perp i}$ the concentration in probe is smaller than that in front of the probe. The requirement of correct sampling is

$\dfrac{v_{szi}}{v_{\perp i}} = 1 \Rightarrow c_{szi} = c_i$ iso-kinetic sampling of gas sample.

In case of deviation from the iso-kinetic sampling the largest error (at $\psi \to \infty$)

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

Problems of sampling: deviation from iso-kinetic sampling (measuring local velocity and sample flow rate, pressures, temperatures), changing operation of the plant, deposition of the dust in the shaft of the sampling apparatus, cooling of sample gas, condensation of the steam in the shaft (shaft heating, particle separator in the stack.

Types of sample probes: simple, probe with measurement of local velocity, zero pressure probe, probe measuring velocity and flow rate.

Origin and cleaning of dusty gases.

The first task of air pollution control is to reduce the quantity of polluted gas and the concentration of pollutants.

Origin of gas-particle systems includes two steps:
a) production of particles, droplets (small enough to float in gas)
b) dispersion of particles into the gas

Both steps can be intentional or non-intentional, so there are four combinations:
  A. Both production and dispersion are intentional: e.g. pulverized-coal fired boilers, use of catalytic agent in a gas to accelerate the reaction.
      No means for reducing the amount of gas and polluting particles but change of technology (use of gas instead of coal).
  B. Production is intentional, dispersion is non-intentional: e.g. dispersion of cement at transport in production line.
      Dispersion can be reduced by reducing the particle velocity relative to air, and the air pollution in the neighborhood can be reduced by using hoods, casings, covers and exhaustion.
  C. Both production and dispersion are not intentional e.g. at explosion used in mining or at demolishing of buildings.
      Change of technology, use of water spray reducing the dispersion, covering the path of the particles, reducing the relative air velocity.
  D. The fourth combination is non-relevant.

Determination of the flow rate of exhaust gas from a hood at a given technology
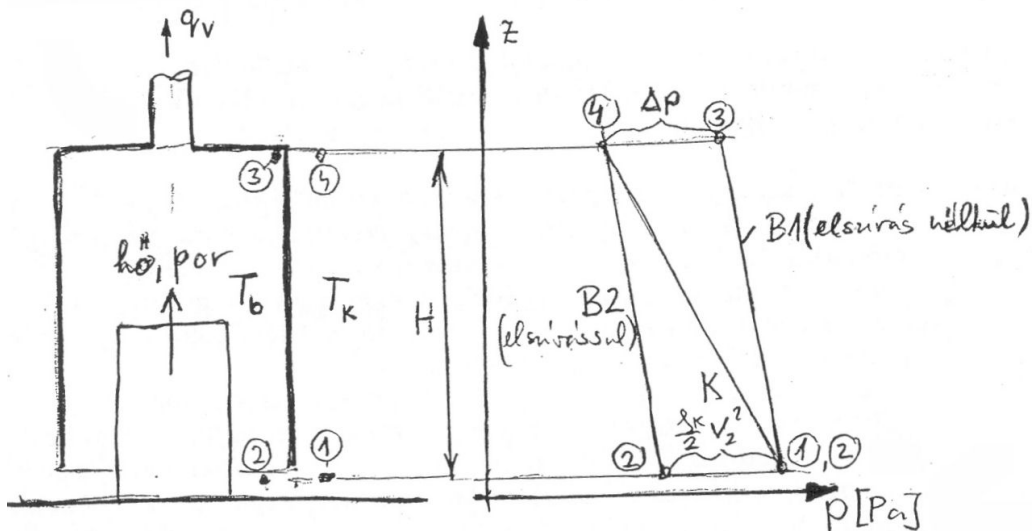
Air protection in a production hall with exhaust of polluted gas from the hood

$$\Delta p = p_1 - p_2 = \rho_k g\, H\left(1 - \frac{T_k}{T_b}\right) = \frac{\rho_k}{2} v_2^2$$

Separation of particles (gas cleaning)

Pollutant mass balance

$E = M_s/M_{in}$ efficiency of separation

$P = M_{out}/M_{in}$ penetration

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

M_{in} [kg/s] mass flow of pollutants entering the separator

M_s [kg/s] mass flow of pollutants separated

M_{out}[kg/s] mass flow of pollutants escaping the separator

Since $M_{in} = q_v\, c_{in}$, $M_{out} = q_v\, c_{out}$ és $M_s = q_v\,(c_{in} - c_{out})$

Efficiency expressed by c [kg/m^3] pollutant concentration.

$$E = \frac{M_1}{M_{ny}} = \frac{c_{ny} - c_t}{c_{ny}} = 1 - \frac{c_t}{c_{ny}}.$$

Two steps of separation

1. The particles should be moved relative to the gas in order to establish contact with
   a) solid surfaces,
   b) fluid films, of drops much bigger than the particles,
   c) other particles
   by utilizing effects moving the particles relative to the gas in order to :
   α inertia of particle
   β gravitational force
   χ diffusion caused by thermal agitation of gas molecules
   δ electrostatic forces caused by charge of particles

2. Forces should be utilized to "stick" the particles to each other, to solid surfaces and to water films:
   A. Van der Waals force: is the attractive force between molecules
   B. electrostatic attraction
   C. a property of the surface of a liquid that causes it to behave as an elastic sheet
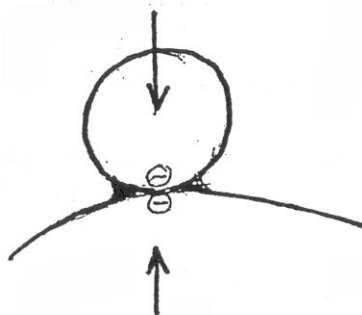
Particles "sticks" to a bigger one utilizing surface tension of water bridge

The results of moving the particles and small droplets relative to the gas and utilizing the forces are:
- conglomeration of particles or droplets of high settling velocity reaching the hopper collecting the separated dust,
- particles adhere to filters and can be removed together the filter
- particles are collected by large water drops which can be collected in an easy way, or water films.
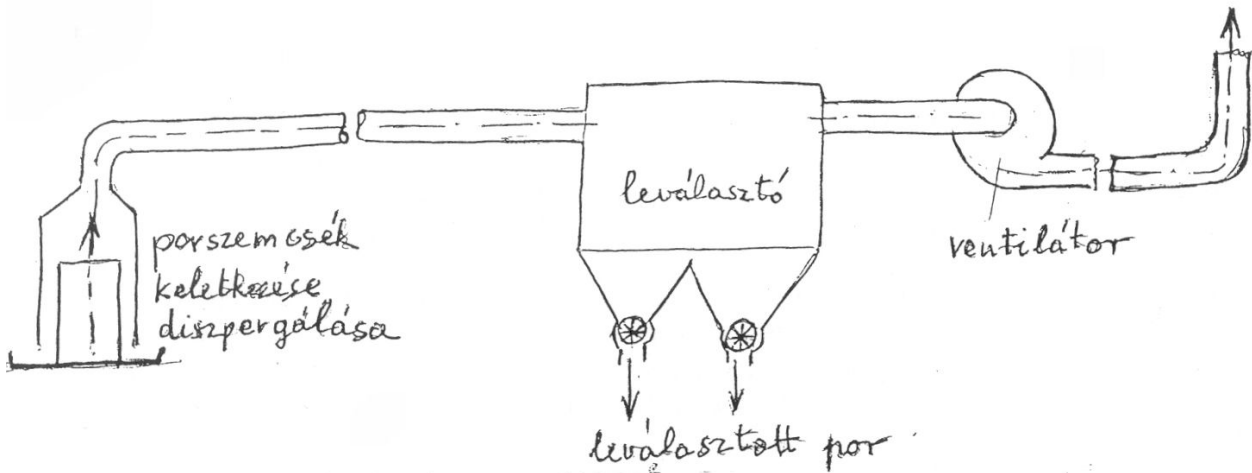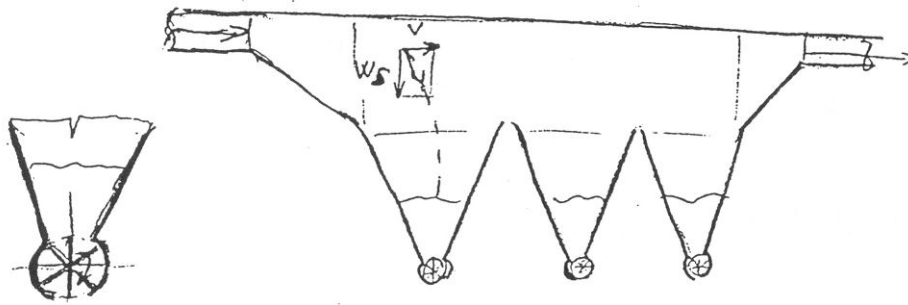

Origin, dispersion, transport and separation of pollutants

Separator types

Settling chambers

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

In general the pressure in the separators is lover 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 charging screw or rotating cells charger.

Pre-separator louvres
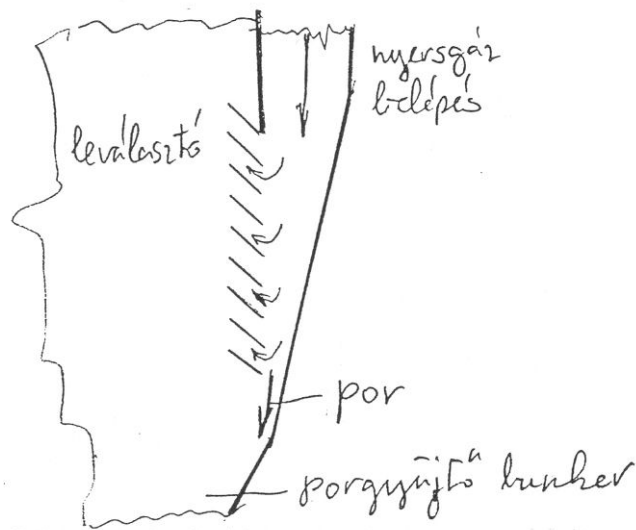
In pre-separator louvers the particles are moved relative to the gas by their inertia as well as gravitational force and Van der Waals force is utilized to "stick" the particles to each other in the hopper.

Scrubbers (washing towers)
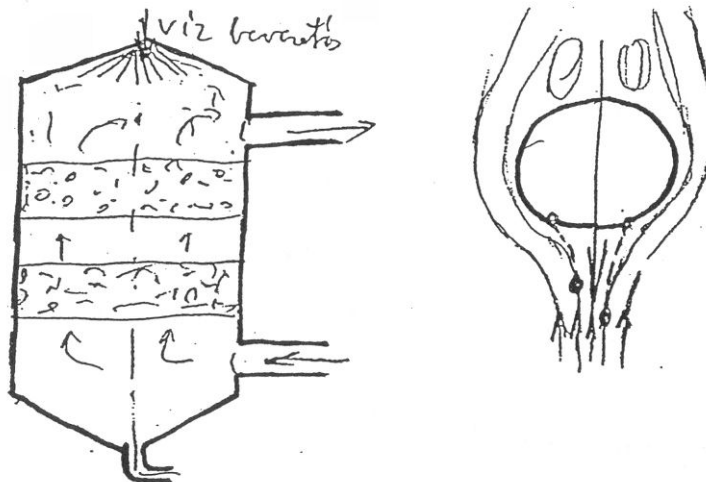
The particles are moved relative to the gas and reach the relatively large water droplets mainly by their inertia as well as diffusion and the surface tension is utilized to "stick" the particles to the droplets.

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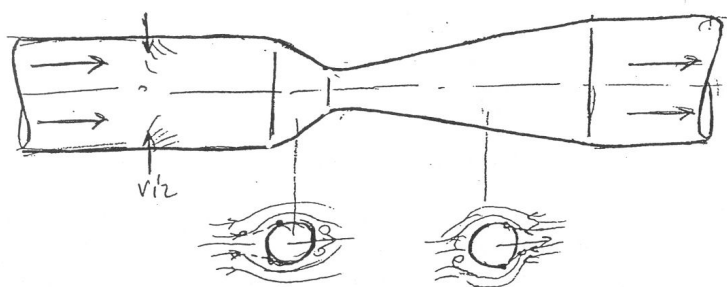
The particles are moved relative to the gas and reach the relatively large water droplets mainly by their inertia as well as diffusion and the surface tension is utilized to "stick" the particles to the droplets. The large droplets are separated by a cyclone separator.

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 utilized to "stick" the particles to each other in the hopper.

Simple considerations results in estimation of the limit particle diameter (x_h):É diameter of 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 acting on the particle: $F_c = \dfrac{x_h^3 \pi}{6} \rho_p \dfrac{v_{1t}^2}{r_1}$. Here the radial velocity of gas is v_{1r}:

$$\frac{x_h^3 \pi}{6} \rho_p \frac{v_{1t}^2}{r_1} = 3\pi \mu\, x_h v_{1r}, \text{ where } \bar{v}_{1r} \cong \frac{q_v}{2 r_1 \pi M}.$$
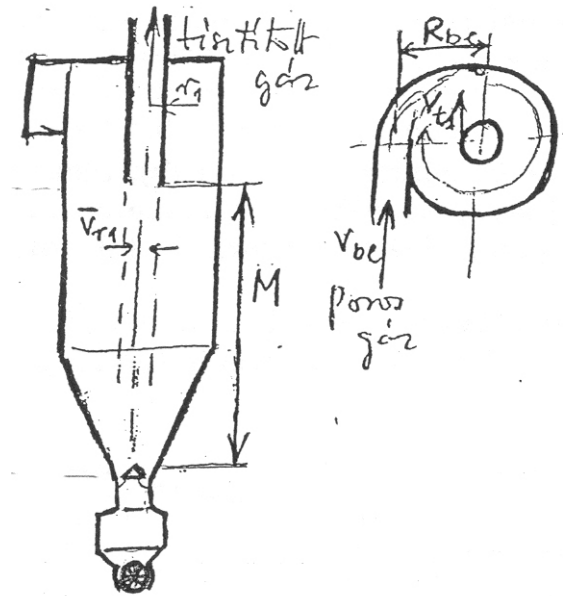

Tangential velocity can be calculated by assuming a potential vortex in the cyclone: $v_{1t} = \dfrac{R_{be} v_{be}}{r_1}$, where R_{be} is the radius of air tangential introduction of polluted gas into the cyclone, with inlet velocity v_{be}. By expressing v_{1r} and substituting it we get: $\dfrac{v_{be}^2 R_{be}^2}{r_1 r_1^2} \dfrac{x_h^2}{18\mu} \rho_p = v_{1r} = \dfrac{q_v}{2 r_1 \pi M}$. The expression for limit particle diameter (x_h) is:

$$x_h = \sqrt{\frac{9}{\pi} \frac{r_1}{R_{be} v_{be}}} \sqrt{\frac{\mu\, q_v}{\rho_p M}}$$

Electrostatic precipitators

Venturi scrubbers,
electrostatic precipitators and
filters
meet the most rigorous environmental protection requirements.
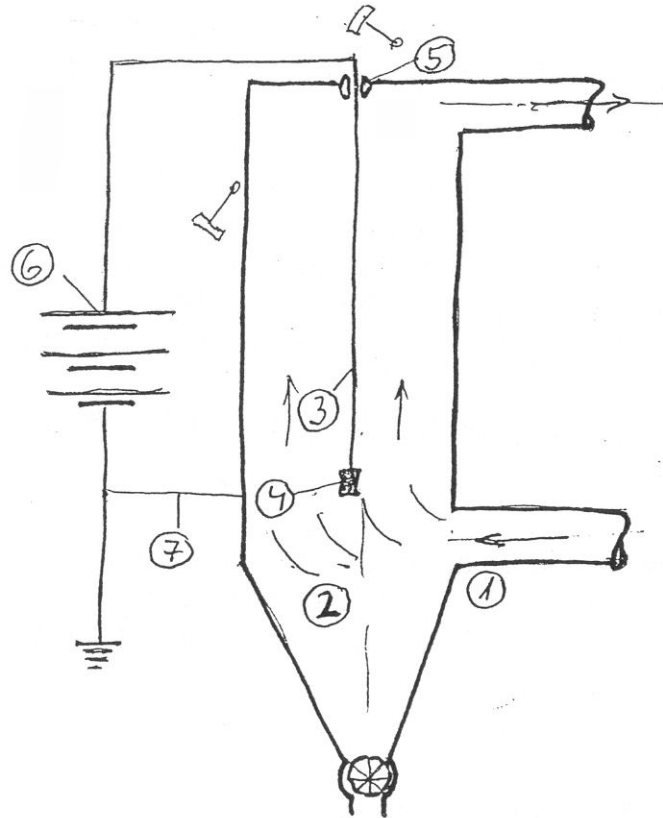
1. Inflow of dusty gas
2. Turning vanes, perforated plates for providing uniform flow
3. High voltage electrode
4. Weight spanning the electrode
5. Insulator
6. High voltage direct current
7. Grounding, collecting electrode

At 10-30 kV voltage corona discharge – electrons moving in direction of collecting electrode and ionize 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 utilized 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.
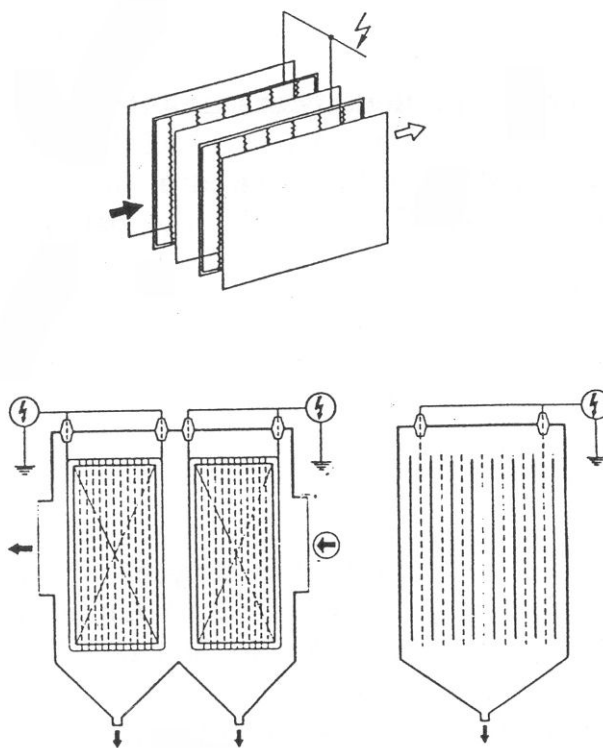
Problems: in case of particles of small electric conductivity (high electric resistance) instable operation, leakage, considerable reduction of efficiency. Difficulties of cleaning of collecting electrode. Electric breakdown voltage corona. Particles can escape the separator easily.

Filters

Filters: porous sheets (woven fabrics or flieses) of elementary fibres (filter mats). Example: mass of $1\,m^2$ filter: $m_f = 0.4\,kg/m^2$, thickness: s=0.004 m, diameter and density of fibres $d_f = 20\mu m$ and ρ_f = 1000 kg/m³.

Solidity: $\alpha = \dfrac{V_f}{V} = 1-\varepsilon$, (8.1)

V_f and V[m³] volume of fibres and filter, ε porosity. $\alpha = \dfrac{m_f}{\rho_f\,s} = 0.1$. Usual values for

α 0,01 - 0.3-ig terjed.

Length of the fibres in 1m² filter sheet: $L_{f1m^2} = \dfrac{V_f}{d^2\pi/4} = 1.27\cdot 10^6\,m/m^2$,

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

$\alpha = \dfrac{d_f^2\pi}{4a^2} \Rightarrow \dfrac{a}{d_f} = \sqrt{\dfrac{\pi}{4\alpha}} = 2.8$.

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

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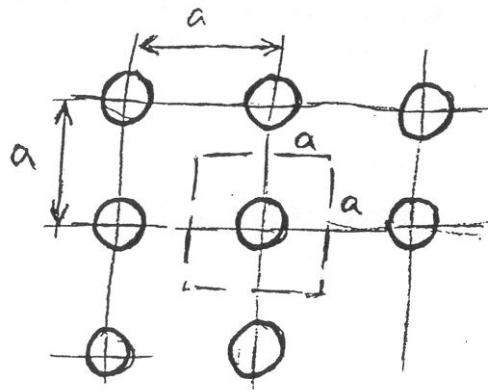
The separated particles are of diameter of several microns, so the particles are not filtered in a conventional way. The collection of particles occures in another way: Δp pressure difference across the filter induces flow of dusty gas across the filter mat: v_f [m/s] filtration velocity. In the flow past fibres viscosity is the dominant.
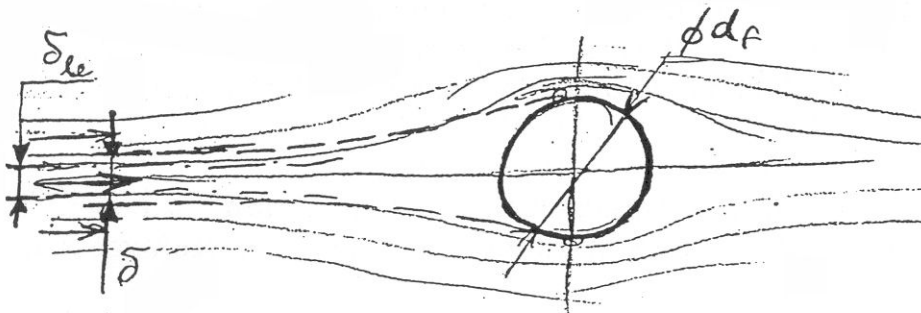
There are a number of mechanisms moving the particles relative to the gas towards the fibres and causes collision of particles on the fibre:.
- curved streamlines: inertia of particles
- weight
- diffusion
- electrostatic forces
- blocking
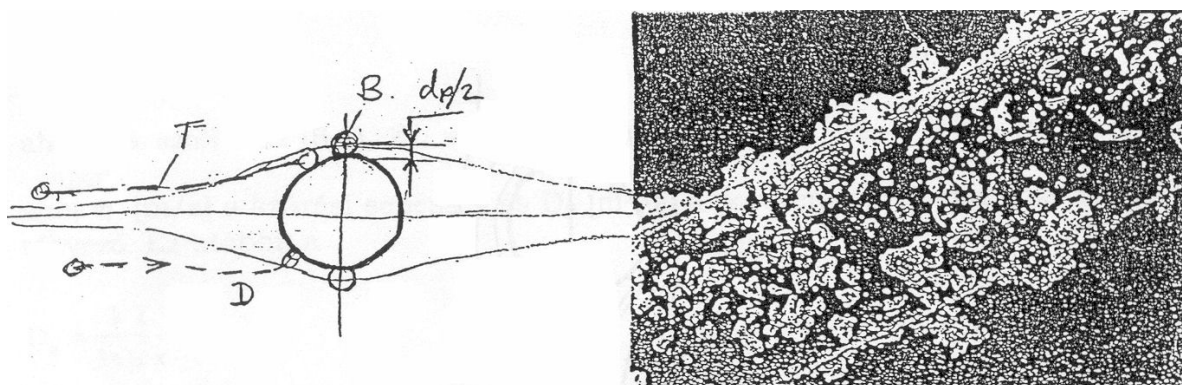
T inertia, B blocking, D diffusion

Collision efficiency of single fibre: $\varphi = \dfrac{\delta}{d_f}$, where δ is the thicknes of 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 utilized to "stick" the particles to the fibres and to each other.
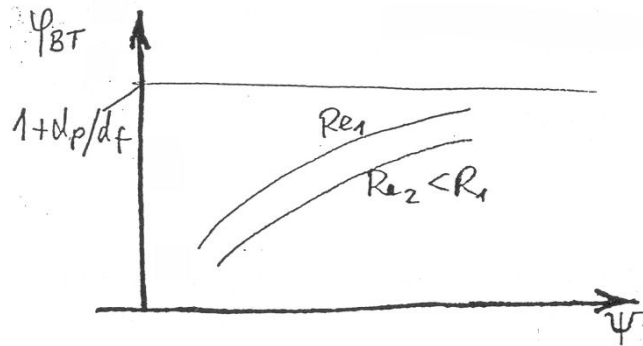
Collision efficiency as function of ψ inertia parameter: $\Psi = \dfrac{v_f w_s}{g\, d_f} = \dfrac{v_f \rho_p x^2}{18 \mu d_f}$

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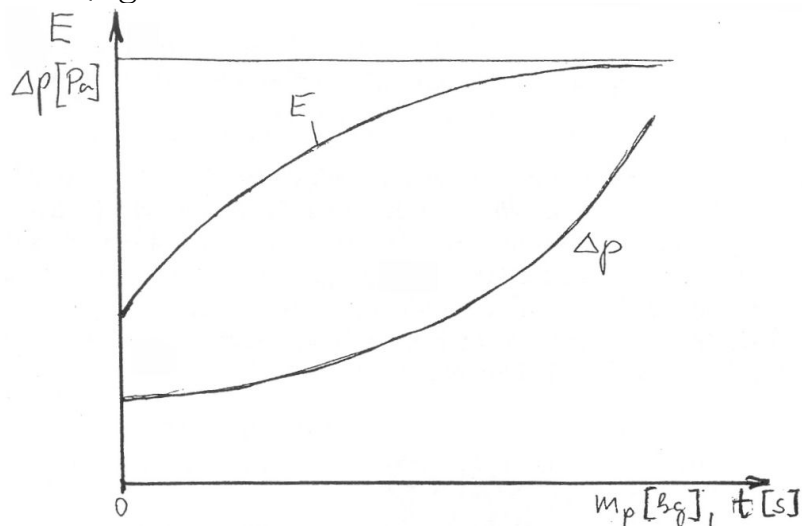
Change of pressure drop and filtration efficiency in time (separated dust mass)

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*.
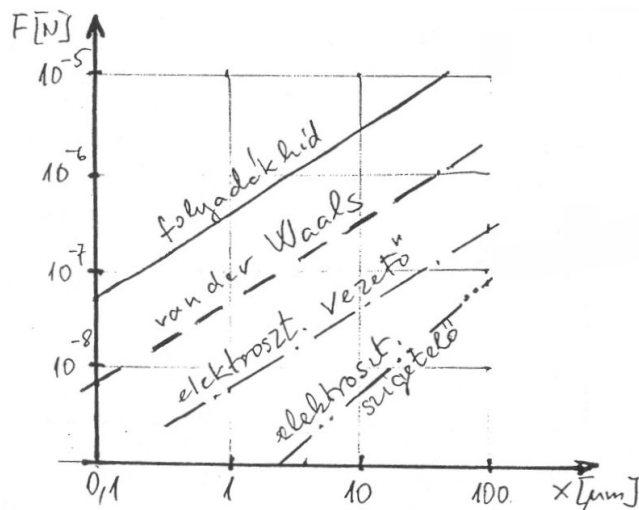
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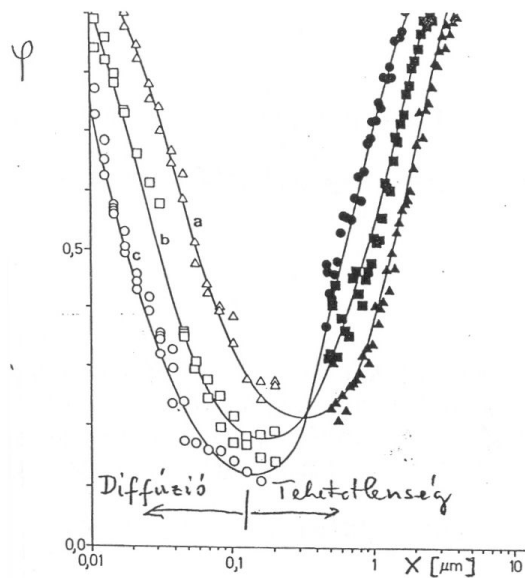
Collision efficiency as function of particle diameter and filtration velocity
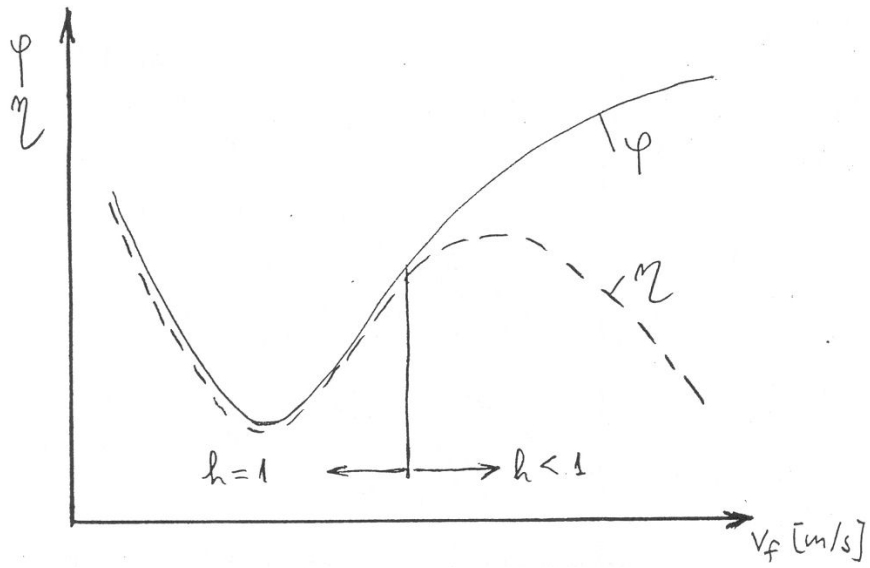
$v_c > v_b > v_a$
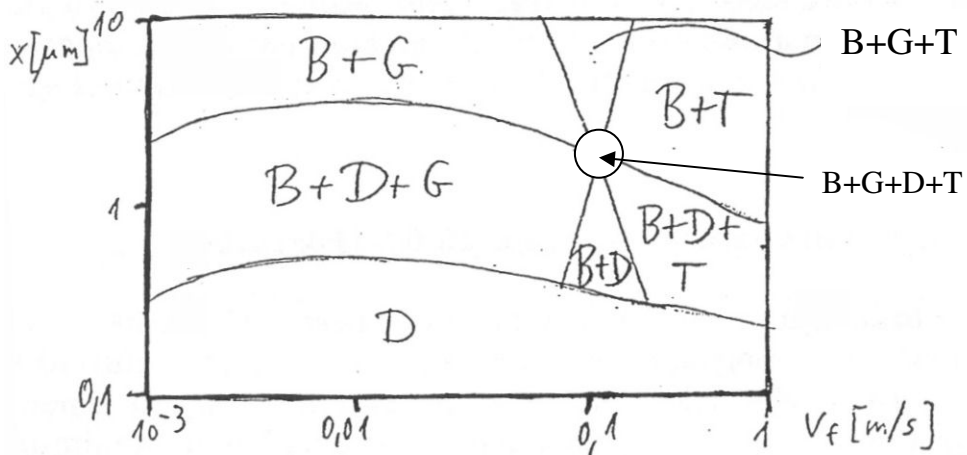
The domain of dominant effects influencing the collision efficiency
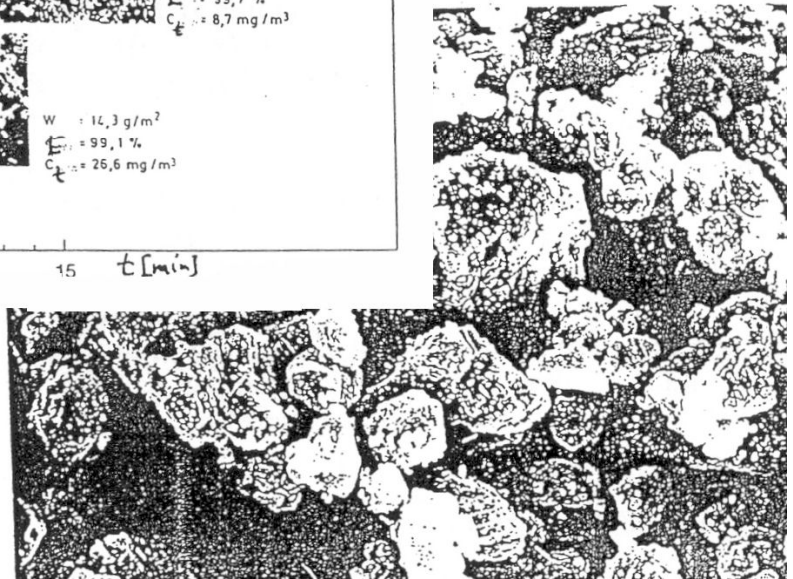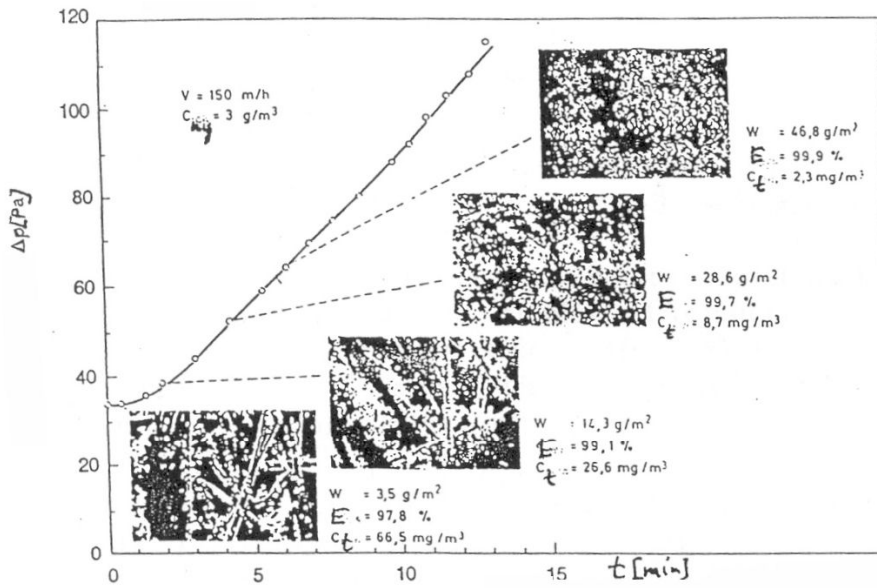
T inertia, G weight, D diffusion, B blocking
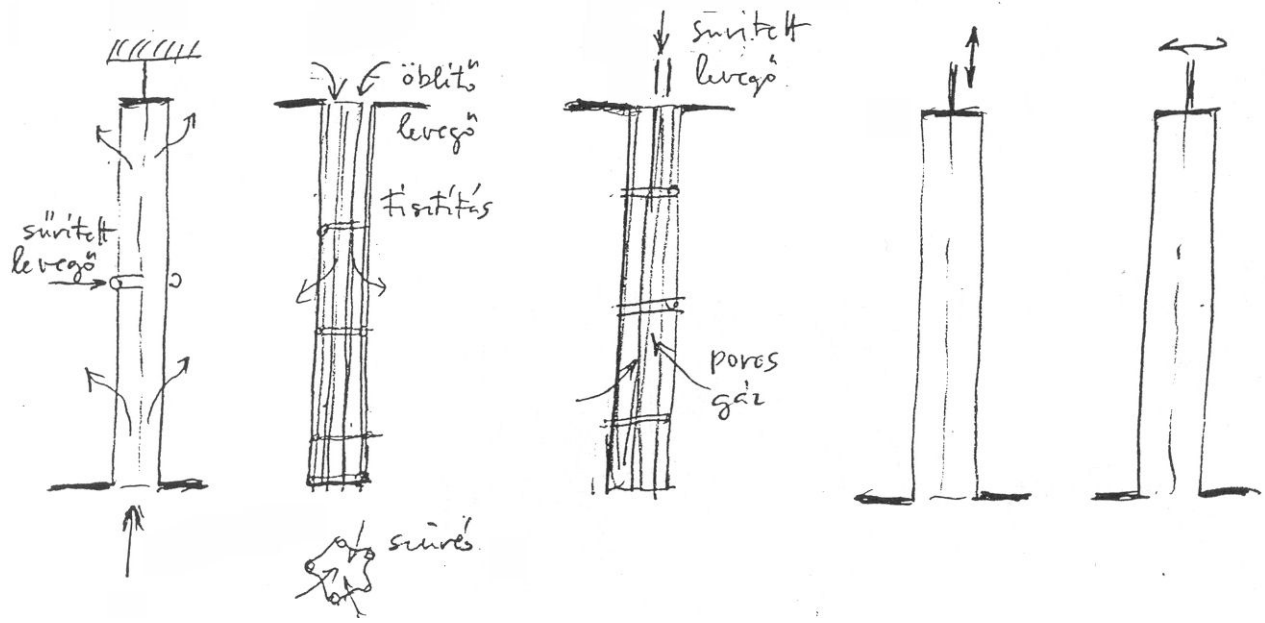

Forces fixing the particles on the fibre

Collision efficiency φ and collection efficiency η as function of filtration velocity

Surface filters

Development of dust layer (cake) over the surface of the filter
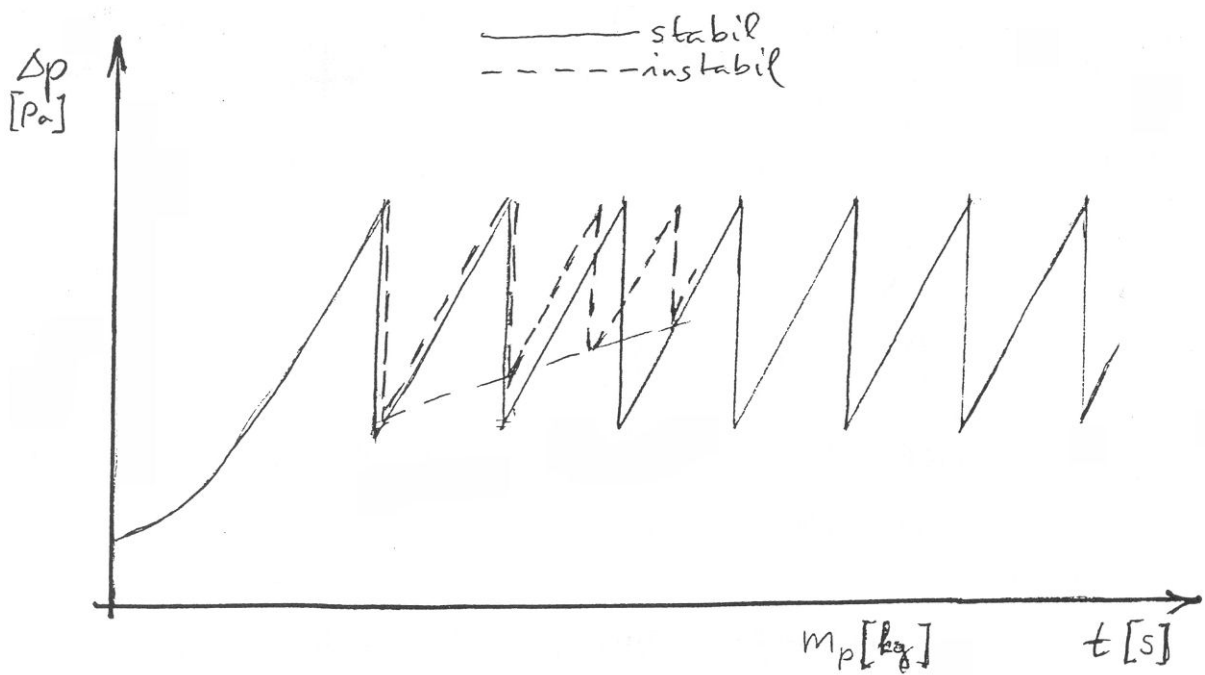
reversed
compressed
air jet   reverse air flow   compressed air jet   mechanical regeneration
knocking   shaking
of bag filters

Methods of regeneration of bag filtes

Stable and instable operation of the bag filter unit