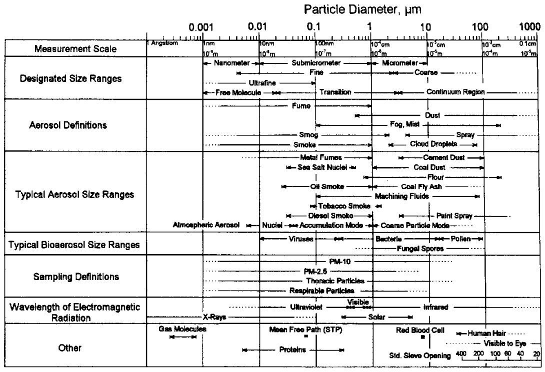
Introduction to Aerodynamics of Aerosols and related Applications

Department of Fluid Mechanics
2009



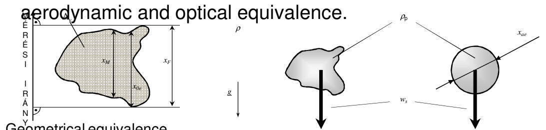
Aerosols

Definition of aerosols: approximately stable mixture of gas and particles (solid, liquid). Diameter of particles: **0,01 ≤ x [µm] ≤ 50**

Change of the characteristics of mixture caused

- by diffusion and agglomeration of small particles as consequence of diffusion of small particles (Brownian motion)
- by settling of larger particles caused by gravity.

In case off spherical particles the diameter is x [µm]. How to define the size of non-spherical particles? Geometrical, aerodynamic and optical equivalence.



Geometrical equivalence
(Feret, Martin diameters, the longest chord in direction of measurement)

aerodynamic equivalence

Types of particles in atmosphere in terms of their origin

The particles in the atmosphere can be divided in three groups:

NATURAL PARTICLES:

- Aerosols of cosmic origin (in all the Earth 10^7 t/year)
- Inorganic aerosols (e.g. vulcanic dust and ash, dust of deserts, sea salt)
- Organic aerosols (e.g. remains of vegetation, microbes, pollens)

TECHNOLOGICAL PARTICLE: They are products of technological processes like breakage, grinding, milling, classing, sizing, drying, condensation in gases.

WASTE PARTICLES:

- Particles originating from settlements (roads, particles from buildings, soil-materials)
- Originating from production processes (coal mining, ore dressing, welding, exhaust gases of motors, polishing, grinding)
- Produced during combustion (carbon black,fly-ash)

AIR POLLUTION IN HUNGARY

1.7% of the country is heavily, 6.2%-a moderately polluted by aerosols. 1/4-1/5th of population lives in these areas. Between 1980 and 2000 the aerosol emission was reduced by 75%, particularly the emission of industry and energy production, while that of traffic and transportation did not change significantly. The annual solid particle emission is in order of magnitude 100.000 tons. Industry 40%, inhabitants 25%-át, traffic and thermal power plants 13-13%.

Types of particles

- Dust: x ≥ 0,2 [µm] perceptible by light microscope (diameter is larger than the wave length of light). Produced by breaking or attrition, abrasion, wearing of solid substances.
- Fume: x ≤ 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.

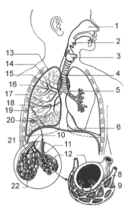
AERA	CONCENTRATION		
	mg/m³	particle/cm³	part./cm³ > 0,1 µm
mountain	0.01	200 ÷ 1.000	2
flat, open area	0.02	2.000 ÷ 10.000	15
city	0.1 ÷ 0.4	5.000 ÷ 100.000	100
industrial area	0.2 ÷ 2		1500
street, downtown	1 ÷ 3		200 ÷ 3000

Dust dispersion (deposition of dust on ground, buildings, streets) in cities: 10-100 t/km²/month.

TECHNOLOGIES	c[g/m³]
Cement production	5 ÷ 30
Pulverised coal fired power plants	15 ÷ 20
Metallurgy of ferrous metals	10 ÷ 40
Metallurgy of lead, lead chamber	5 ÷ 20
Drying	10 ÷ 100
Bauxit grinding	10 ÷ 30

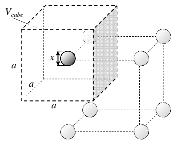
Dust fraction particularly harmful for lung:

$$0.5\mu m \leq x \leq 5\mu m$$



Upper respiratory tracts, bronchial tubes with mucous membrane and cells with cilia propelling mucus upwards (23 bifurcations),
Air cells (Alveolus pulmos) for gas metabolism: O_2 CO_2.
Demage of membran of air cells

Average distance between particles in gas



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

c [kg/m³] a concentration, a [m] average distance between particles, ρ [kg/m³] density of particles, n [db/m³] concentration by piece.

x = 3 μm

c[g/m³]	type of aerosol	a/x	n [db/cm³]
10	crude gas	47	350.000
1	after pre-separator	101	35.000
0.1	after separator	218	3.500

After transformation of the equation we get:

$$\frac{d\underline{v}}{dt} + \frac{c_p}{\rho_g}\frac{d\underline{u}_p}{dt} = (1+\frac{c_p}{\rho_g})\ \underline{g} - \frac{1}{\rho_g}\mathrm{grad}p + \nu\Delta\underline{v}$$

The effect of particle phase on the flow field can be neglected, if

$\frac{c}{\rho} \langle\langle 1$ and $\frac{d\underline{u}_p}{dt}$ and $\frac{d\underline{v}}{dt}$ are in the same order of magnitude

so $\frac{c}{\rho}\frac{d\underline{u}_p}{dt} \langle\langle \frac{d\underline{v}}{dt}$

In this case the determination of flow field can be separated from that of the particle phase. Otherwise a PDE system consisting of 11 equations should be solved to determine distributions of 3+3 velocity components, gas pressure, particulate concentration and 3 components of aerodynamic force acting on particles. 3+3 momentum, 1+1 continuity and 3 eqs. for determining the components of F aerodynamic force acting on particles.

Particles in gas flow

Effect of particles on the gas flow
Navier-Stokes equation extended by term t expressing the contribution of the particles to the forces acting on gas (the virtual mass of the particle is neglected):

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

t [N/kg] is force to 1 kg gas from particles carried by the gas:

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

n [particle/m³]: particle concentration by piece
F [N/particle] : aerodynamic force acting on a particle
ρ [kg/m³] : gas density

Drag force acting on spherical particle

Stokes: solution by linearization of NS equation and by neglecting the gravitational field of force:

$$0 = \frac{1}{\rho_g}\mathrm{grad}p + \nu\Delta\underline{v} \Rightarrow \mathrm{grad}p = -\mu\,\mathrm{rotrot}\underline{v} \Rightarrow \mathrm{div\,grad}p = \Delta p = -\mu\,\mathrm{divrotrot}\underline{v} = 0$$

Δp = 0, div $\underline{v}$ = 0 equations were solved at boundary conditions: r = R $\underline{v}$ = 0, and r ⇒ ∞ $v_x \Rightarrow v_\infty$.

$\underline{F} = 3\pi\mu x \underline{w}$ $\qquad c_e = \frac{|\underline{F}|}{\frac{\rho}{2}v^2\frac{x^2\pi}{4}}$ $\qquad Re_p < 1$ $\qquad c_e = \frac{24}{Re_p}$ $\qquad Re_p = \frac{v\ x\ \rho}{\mu}$

Oseen's less drastic linearization $\qquad v_\infty\frac{\partial v_x}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 v_x}{\partial x^2} + ...\right)$

$Re_p < 5$ $\qquad c_e = \frac{24}{Re_p}\cdot\left(1 + \frac{3}{16}Re_p\right)$

$3 < Re_p < 400$ $\qquad c_e = \frac{24}{Re_p}\cdot\left(1 + \frac{Re_p^{\frac{2}{3}}}{6}\right)$

Momentum equation of solid (particle) phase regarded as continuum (Eulerian approach)

$$\frac{d\underline{u}_p}{dt} = \underline{g} - \frac{1}{\rho_p}\mathrm{grad}p + \frac{\underline{F}}{m_p}$$

$\underline{u}_p$ [*m/s*] velocity field of particle phase
m_p [*kg*] mass of a particle
ρ_p [*kg/m³*] density of particle phase,
g [*N/kg*] gravitational field of force
$\underline{F}_p$[N] aerodynamic force acting on a particle

Pressure force can be neglected, so: $\frac{d\underline{u}_p}{dt} = \underline{g} + \frac{\underline{F}}{m_p}$

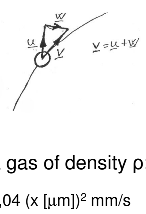
By expressing F_p and inserting it in the momentum equation of gas we obtain:

$$\frac{d\underline{v}}{dt} = \underline{g} - \frac{1}{\rho}\mathrm{grad}p + \nu\,\Delta\underline{v} - \frac{n \cdot m_p}{\rho_g}\cdot\left(\frac{d\underline{u}_p}{dt} - \underline{g}\right)$$

where $n \cdot m_p = c_p$[kg/m³] is solid concentration

Momentum equation for particles 1.

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



Dimensionless equation:

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

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

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

$w_s \cong 0{,}04\ (x\ [\mu m])^2$ mm/s

Settling velocity: $w_s = \frac{x^2(\rho_p - \rho)g}{18\mu}$ Correction: $w_{s,corr}$= Cu $\mathbf{w_s}$

$Cu = 1 + \frac{2A\lambda}{x}$ Cunningham coefficient, A=1,4, λ mean free path of gas molecules. (At room-temperature $\lambda = 6.5 \cdot 10^{-2}$ μm).

Momentum equation for particles 2.

By neglecting the field of gravity $\dfrac{\dfrac{d\underline{u}}{v_0}}{\dfrac{dt}{l_0 / v_0}} = \dfrac{g l_0}{w_s v_0} \dfrac{\underline{w}}{v_0}$

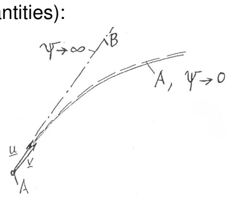
and by introducing the inertia parameter: $\psi = \dfrac{w_s v_0}{g l_0} = \dfrac{s}{l_0}$,

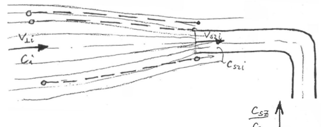
where s [m] stopping distance.

Dimensionless momentum equation for particles
(' denotes dimensionless quantities):

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

Motion of particle in case of curved streamlines: due to their momentum particles move along path of larger radius of curvature than that of the streamline

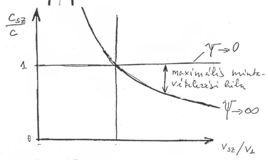


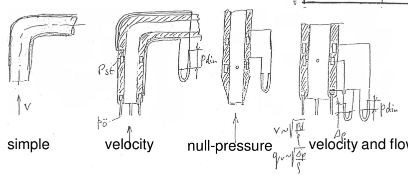


c_{szi}=c_i if v_{szi}=$v_{\perp i}$

isokinetic sampling

In case of non-isokinetic sampling the error of sampling (c/c_{sz}) depends of the Ψ inertia parameter.

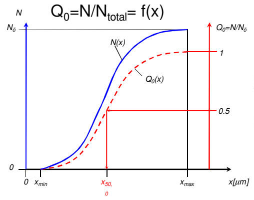




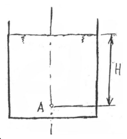
simple velocity null-pressure velocity and flow rate

Application 1: determining of cumulative (undersize) distribution of particle assembly related to mass of particles by using sedimentation

Q_0=N/N_{total}= f(x)



Q_3=M/M_{total} = f(x) = ?



Receiver filled with fluid in which particle distribution is uniform at t = 0, solid concentration c_0.
Samples are collected at H depth in A at t_1,t_2…time.
Solid phase concentrations in samples are determined: c_0, c_1, c_2…

Relation between t_i sampling time and size of particles x ≥ x_i that – because of settling – are not present in the sample.

$$t_i = \frac{H}{w_{si}} = \frac{18\,\mu\,H}{x_i^2(\rho_p - \rho_g)\,g}$$

The ratio of M mass of particle fractions existing in the sample (and in and above point A) and the M_{total} mass of all fractions is equal to c_i/c_0. Knowing from sampling time x_1, x_2, … x_i and c_1/c_0, c_2/c_0,…c_i/c_0 Q_3 = M/M_{total} = f(x) can be constructed.
Problems: uniform distribution at t = 0, interaction of settling particles of different sizes.

$$x_i = \sqrt{\frac{18\,\mu\,H}{t_i\,g\,(\rho_p - \rho_g)}}$$

Separation of particles

Origin of technological aerosols, what to do in a given case?

Two steps of originating aerosol: Production of particles and their dispersion.
a) Production of particles: a1 intentional – a2 not-intentional
b) Dispersion of particles: b1 intentional – b2 not-intentional

3 variations:

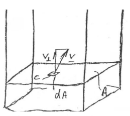
I. a1 – b1 Both production and dispersion are intentional: e.g. pulverized-coal fired boilers, use of catalytic agent in a gas to accelerate the reaction. No means for reducing the amount of gas and polluting particles so gas should be removed and cleaned or technology can be changed (use of gas instead of coal).

II. a1 – b2 Production is intentional, dispersion is non-intentional: e.g. dispersion of cement powder 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 and removal and cleaning of particle laden air (development of transport system),

III. a2 – b2 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.

IV. a2 – b1 Not relevant

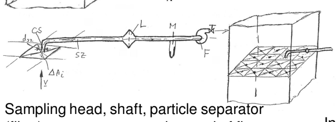
Application 2: Measurement of mean dust concentration and dust mass rate in a duct.



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

$$\bar{c} = \frac{\int_A c v_\perp dA}{\int_A v_\perp dA} \qquad \bar{c} \approx \frac{\sum_{i=1}^{n} c_i v_{\perp i} \Delta A_i}{\sum_{i=1}^{n} v_{\perp i} \Delta A_i}$$

if ΔA_i=const. $\bar{c} \approx \dfrac{\sum_{i=1}^{n} c_i v_{\perp i}}{\sum_{i=1}^{n} v_{\perp i}}$



Sampling head, shaft, particle separator (filter), measurement and control of flow rate (volume) of gas sample

Measured concentration:

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

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

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

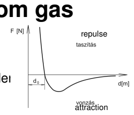
If $d_{szi}^2 \dfrac{v_{szi}}{v_{\perp i}} \Delta t_i \equiv const.$ $\bar{c}_M \approx \dfrac{\sum_{i=1}^{n} c_{szi} v_{\perp i}}{\sum_{i=1}^{n} v_{\perp i}} = \bar{c}$ if c_{szi}=c_i

Separation of particles from gas

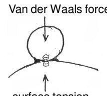
Two steps of separation

1. The particles should be moved relative to the gas in orde[r] to establish contact with
- solid surfaces,
- fluid films, of drops much bigger than the particles,
- other particles

by utilizing effects moving the particles relative to the gas:
- α **inertia of particle**
- β gravitational force
- χ diffusion caused by thermal agitation of gas molecules
- δ electrostatic forces caused by charge of particles

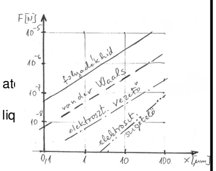


Van der Waals force



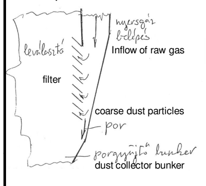
surface tension

2. Forces should be utilized to “stick” the particles
- to each other,
- to solid surfaces and
- to surface of liquid (e.g. water films) by
- A. Van der Waals force (attractive force between at[…]
- B. electrostatic attraction
- C. surface tension (a property of the surface of a liq[…]
- causes it to behave as an elastic membrane.

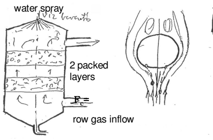


Separators of significant role of inertia of particles

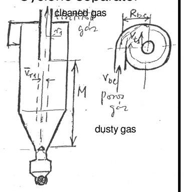
Pre-separator louvre of a filter



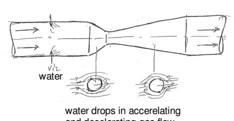
Scrubber (washing towers)



Cyclone separator



Venturi scrubber

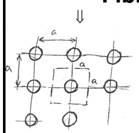


$$F_c = \frac{x_h^3 \pi}{6} \rho_p \frac{v_{1t}^2}{r_1} = 3\pi \mu x_h v_{1r}$$

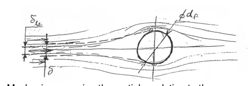
$$\bar{v}_{1r} \cong \frac{q_v}{2 r_1 \pi M} \qquad v_{1t} = \frac{R_{be} v_{be}}{r_1}$$

$$\frac{v_{be}^2 R_{be}^2}{r_1 r_1^2} \frac{x_h^2}{18\mu} \rho_p = v_{1r} = \frac{q_v}{2 r_1 \pi M} \qquad x_h = \sqrt{\frac{9}{\pi} \frac{r_1}{R_{be} v_{be}}} \sqrt{\frac{\mu q_v}{\rho_p M}}$$

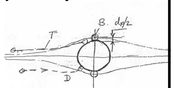
Fibrous filters (wowen fabrics, felts)



α= 0,01 - 0.3 solidity
$d_f \cong$ 10-30 μm
$a/d_f \cong$ 1,6 - 9



Mechanisms moving the particles relative to the gas towards fibres and causes collision of particles on fibre:.
- curved streamlines: **inertia of particles**
- weight
- diffusion
- electrostatic forces
- blocking

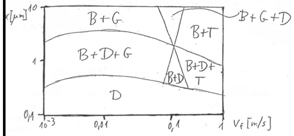


Inertia (T) blocking (B) and diffusion (D)

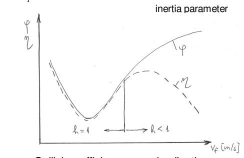
$$\varphi = \frac{\delta}{d_f}$$ collision efficiency

$$\Psi = \frac{v_f w_s}{g d_f} = \frac{v_f \rho_p x^2}{18 \mu d_f}$$ inertia parameter

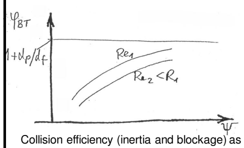
α= 0,1, a/df = 2,6, d_f = 20μm, a = 52 μm,
Fabric width s = 4 mm $\Rightarrow$ 76 rows of fibres



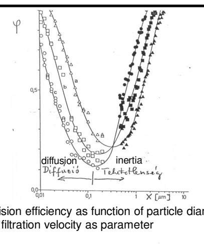
Domains of dominant effects influencing the collision Efficiency: T inertia, G weight, D diffusion, B blocking



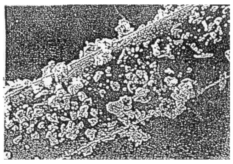
Collision efficiency φ and collection efficiency η as function of filtration velocity
Particle rebounding, bouncing
h = collected/colliding particles



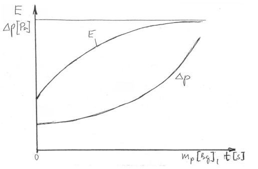
Collision efficiency (inertia and blockage) as function of inertia parameter and Reynolds number



Collision efficiency as function of particle diameter and filtration velocity as parameter



Single fibre as particle separator



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