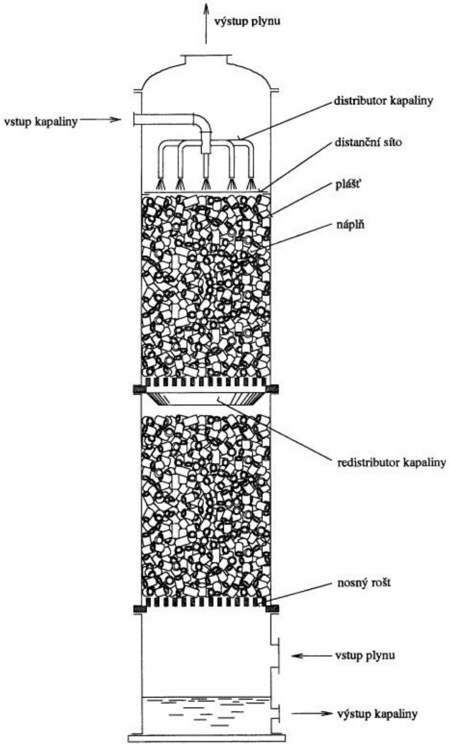
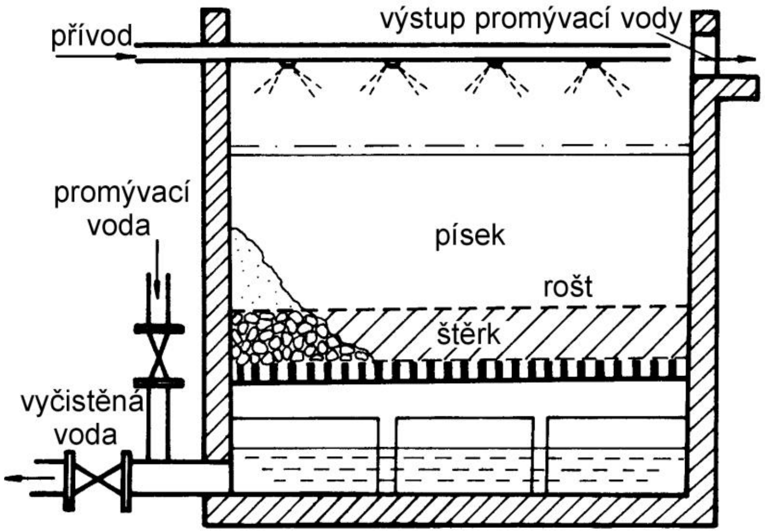
FLOW IN POROUS BEDS

Industrial application

Packed columns



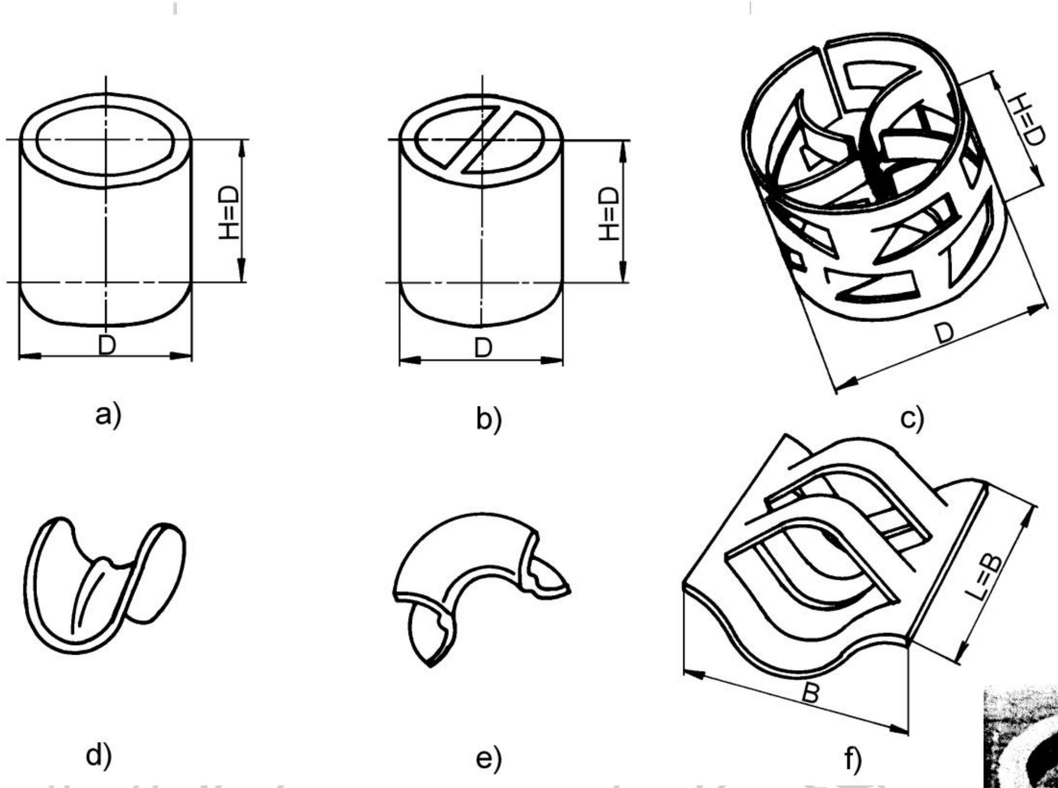
Filters



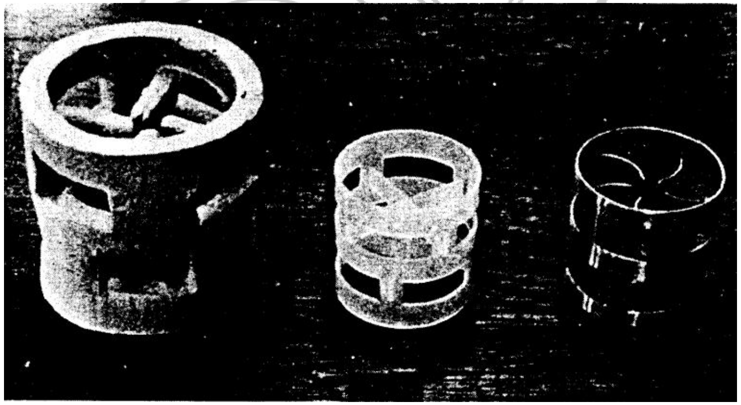
Porous bed:

- porous material (felt, ceramics, paper)
- granular bed (sand, filter cake)
- packing (spheres, rings, saddles, special packings)
- grid packings (mesh, grate, filler)

Packing – special elements

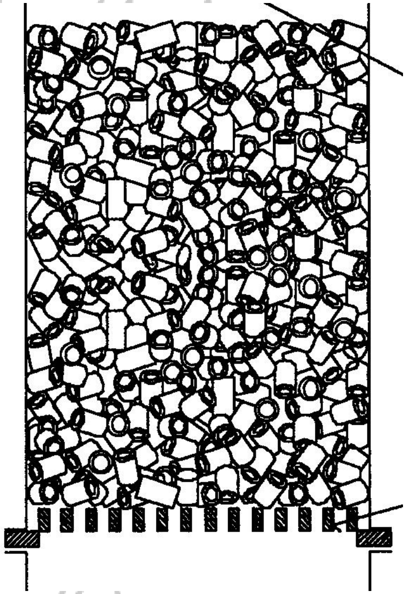


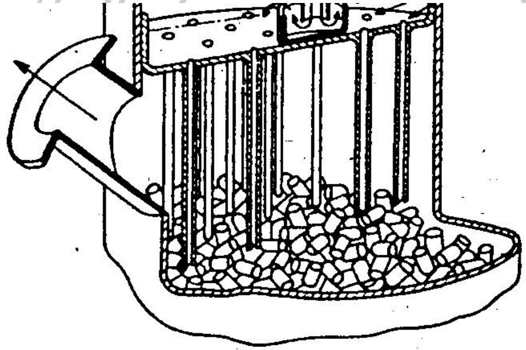
a – Raschig ring, ***b*** – Lessing ring, ***c*** – Pall ring, ***d*** – Berl saddle, ***e*** – saddle Intalox, ***f*** – element Interpack



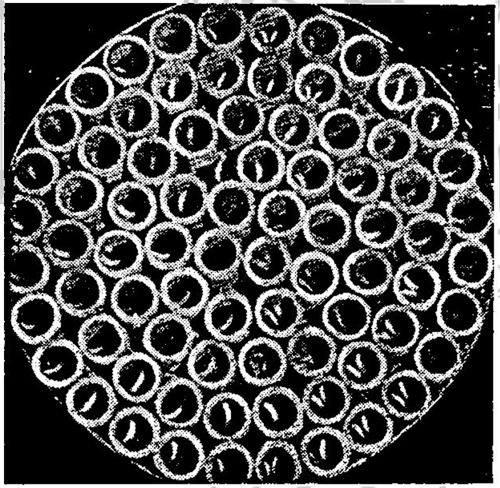
Packed beds

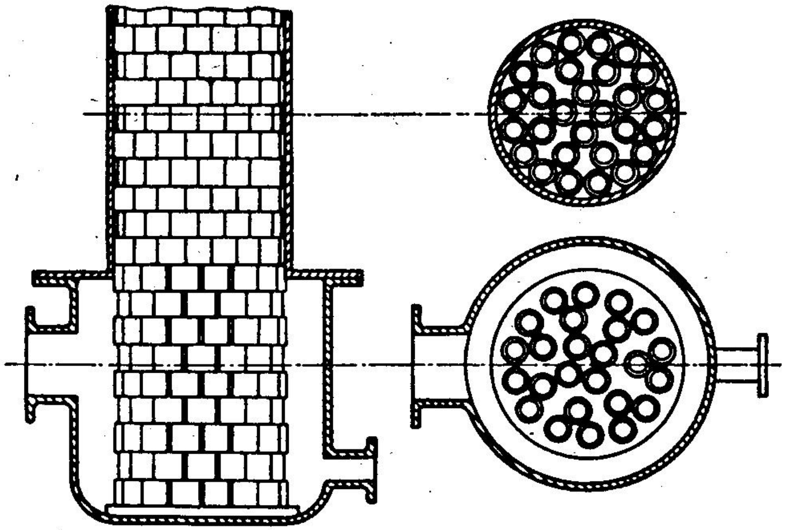
Random packing





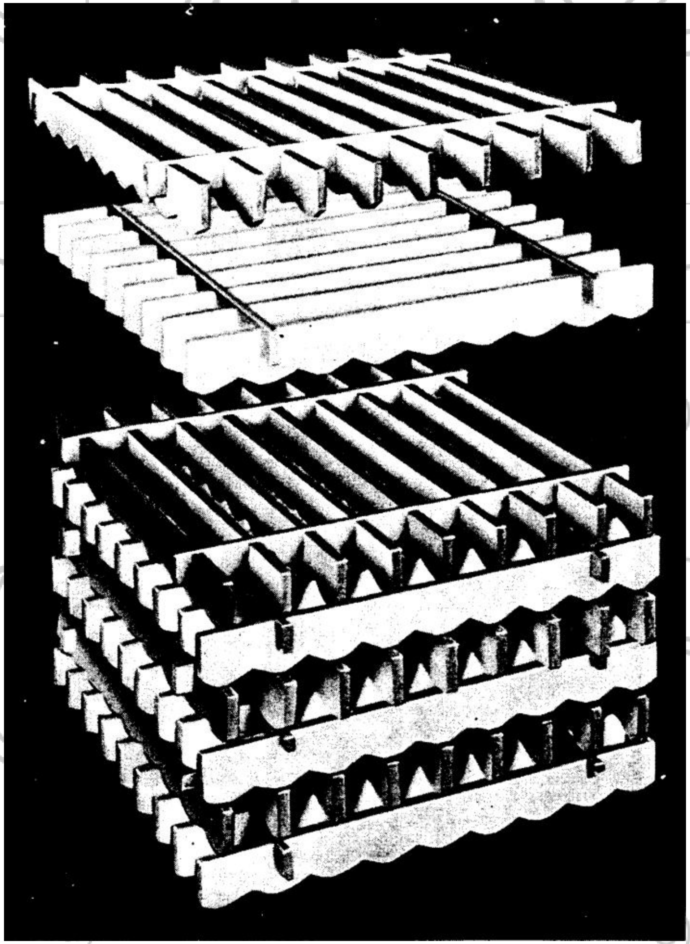
Structured packing



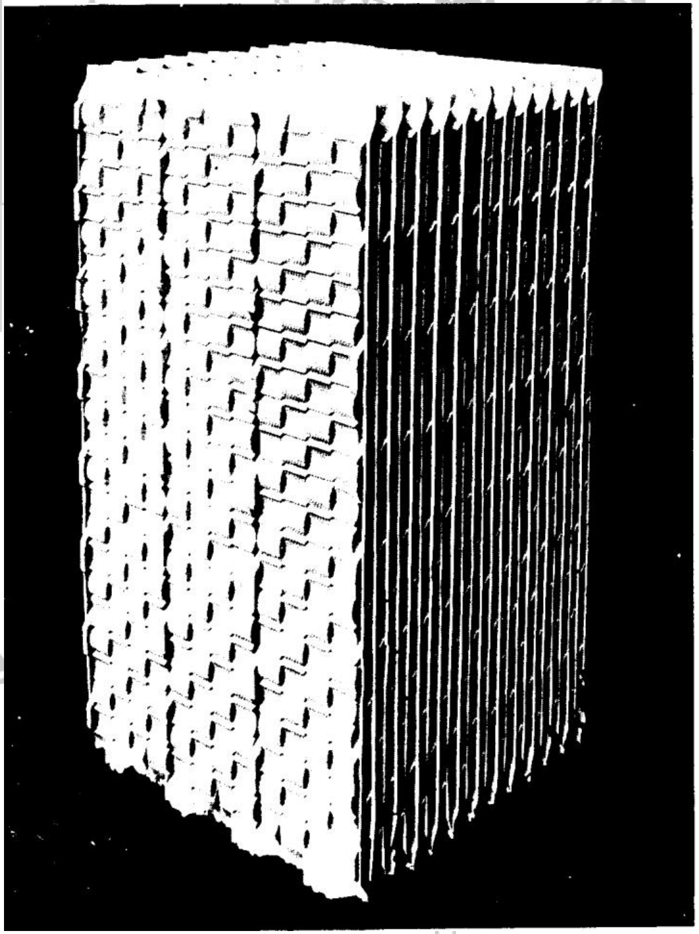


Grid packings

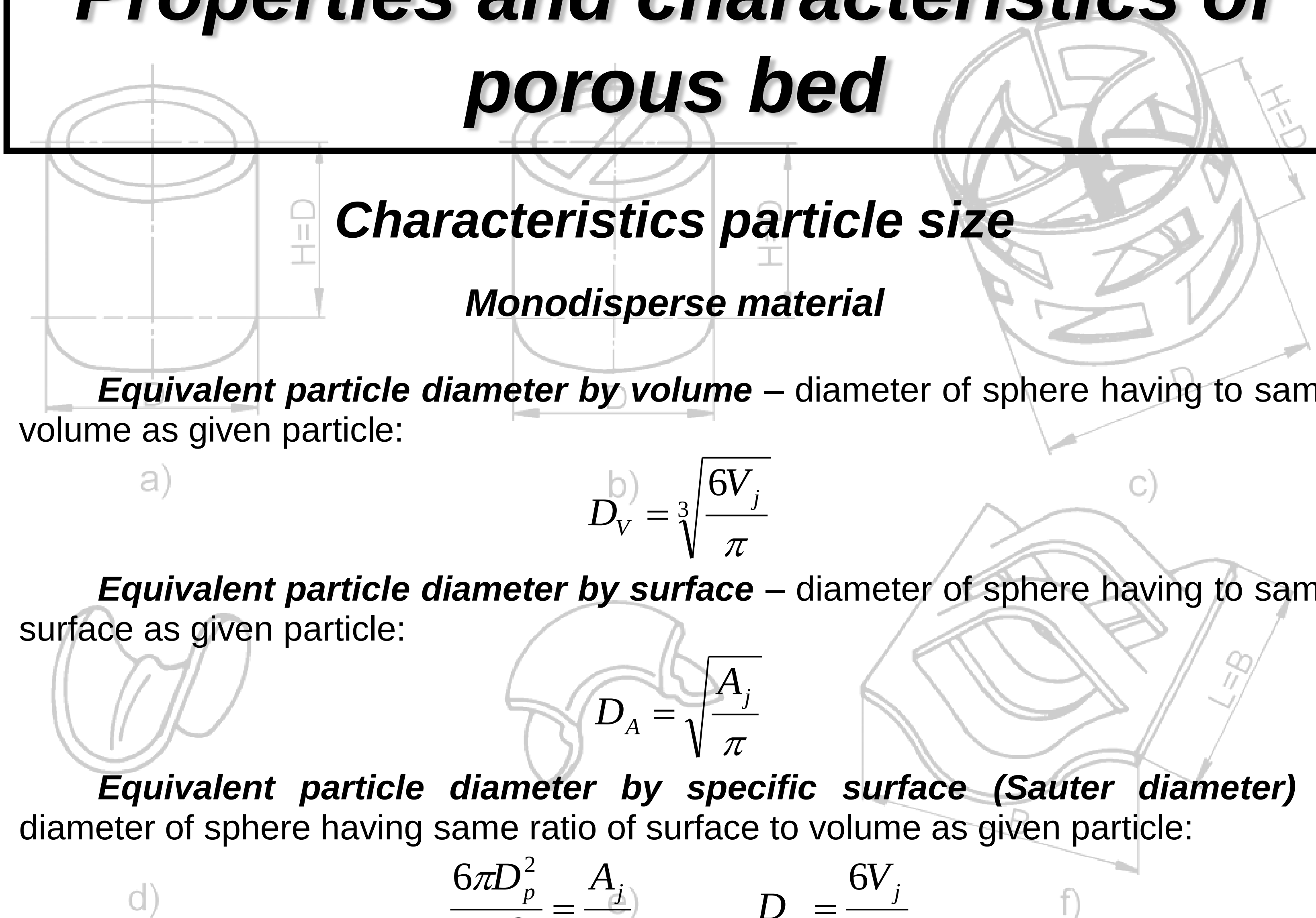
Grate



Shaped continuous filler



Properties and characteristics of porous bed



Characteristics particle size

Monodisperse material

Equivalent particle diameter by volume – diameter of sphere having to same volume as given particle:

$$D_V = \sqrt[3]{\frac{6V_j}{\pi}}$$

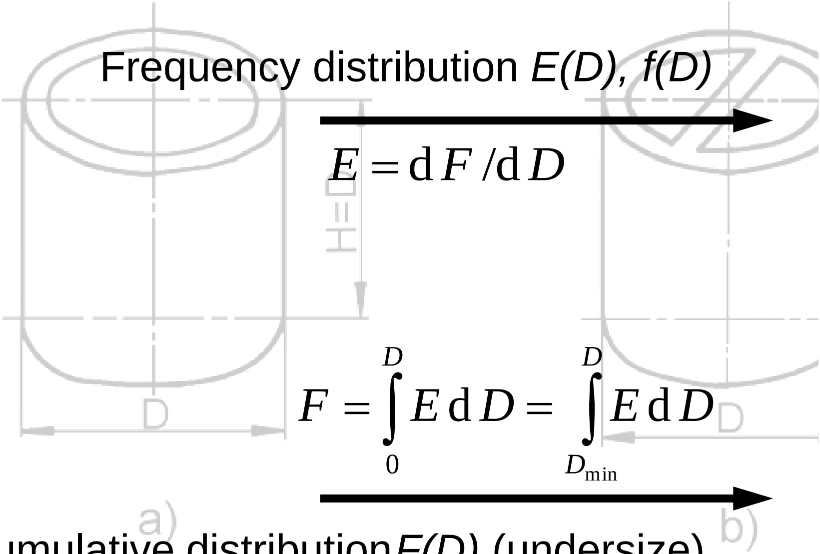
Equivalent particle diameter by surface – diameter of sphere having to same surface as given particle:

$$D_A = \sqrt{\frac{A_j}{\pi}}$$

Equivalent particle diameter by specific surface (Sauter diameter) – diameter of sphere having same ratio of surface to volume as given particle:

$$\frac{6\pi D_p^2}{\pi D_p^3} = \frac{A_j}{V_j} \qquad D_p = \frac{6V_j}{A_j}$$

Polydisperse particle size distribution



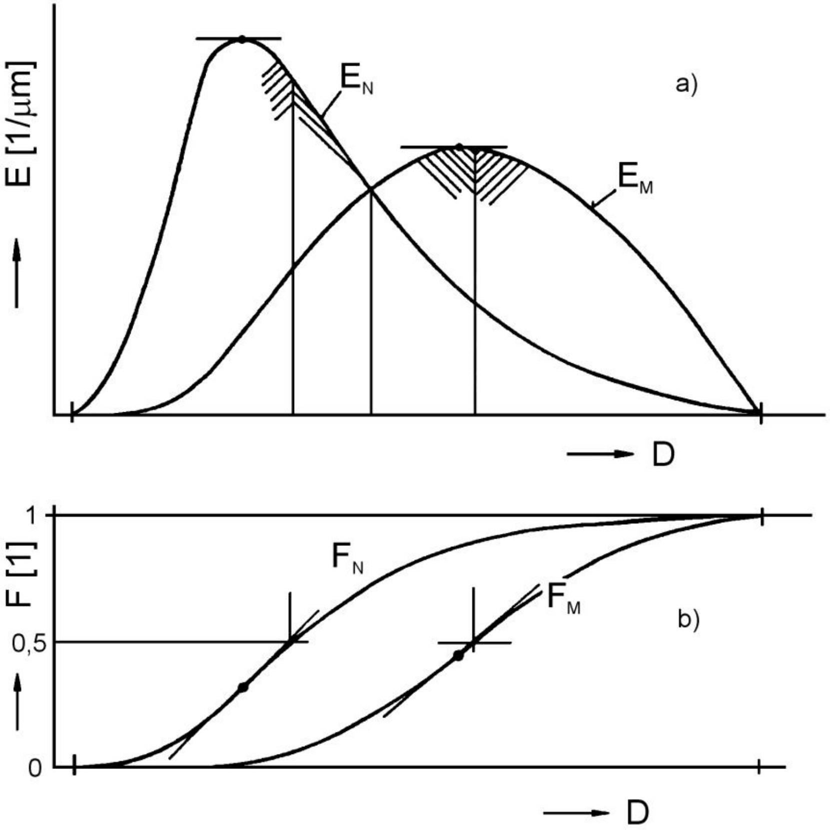
Frequency distribution *E(D), f(D)*

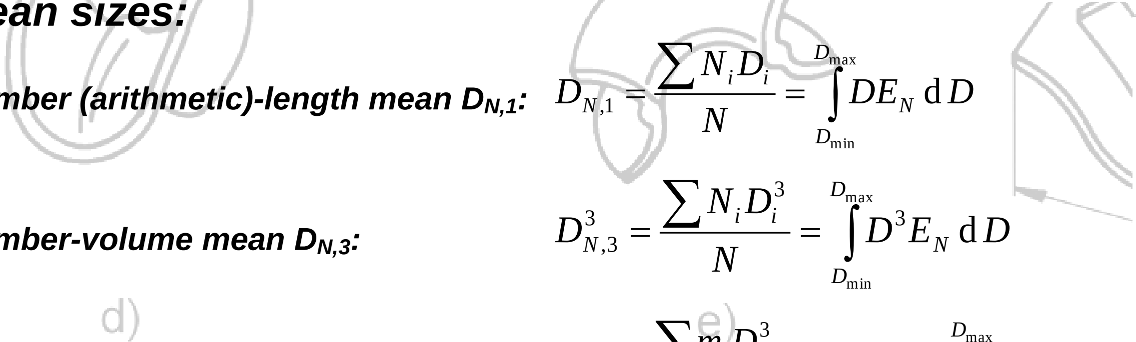
$$E = \mathrm{d}F/\mathrm{d}D$$

$$F = \int_{0}^{D} E\,\mathrm{d}D = \int_{D_{\min}}^{D} E\,\mathrm{d}D$$

Cumulative distribution *F(D)* (undersize)

R(D)=1-F (oversize)





Mean sizes:

Number (arithmetic)-length mean $D_{N,1}$:

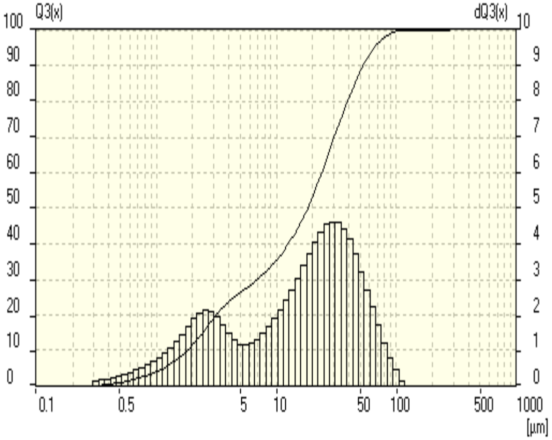
$$D_{N,1} = \frac{\sum N_i D_i}{N} = \int_{D_{\min}}^{D_{\max}} D E_N\,\mathrm{d}D$$

Number-volume mean $D_{N,3}$:

$$D_{N,3}^3 = \frac{\sum N_i D_i^3}{N} = \int_{D_{\min}}^{D_{\max}} D^3 E_N\,\mathrm{d}D$$

Cubic-volume (or mass) mean $D_{m,3}$:

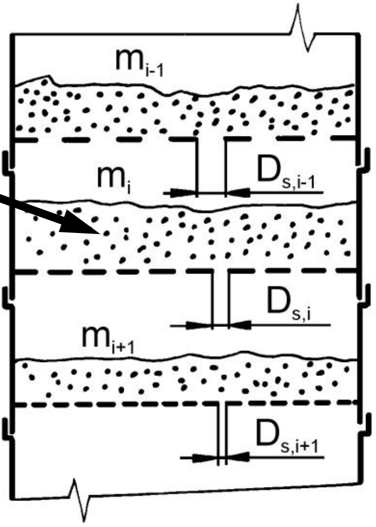
$$D_{m,3}^3 = \frac{\sum m_i D_i^3}{m} = \sum x_i D_i^3 = \int_{D_{\min}}^{D_{\max}} D^3 E_M\,\mathrm{d}D$$



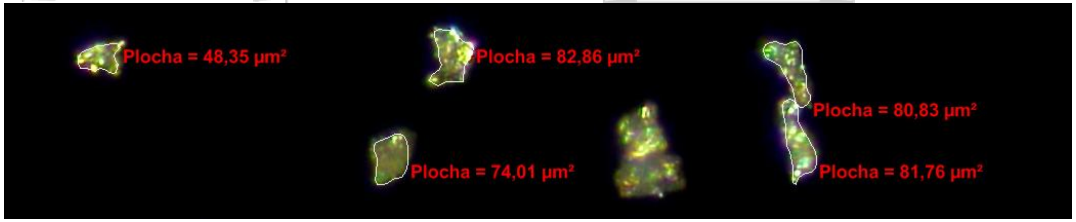
Particle size analysis (measurement)

- ***Sieving*** – for particles greater then 45 μm, adjacent sieve sizes $\sqrt[4]{2}$ (e.g. 45, 53, 63, 75,...), sieve vibrations, high accuracy for isometric particles

$$D_i = \frac{D_{s,i-1} + D_{s,i}}{2}$$



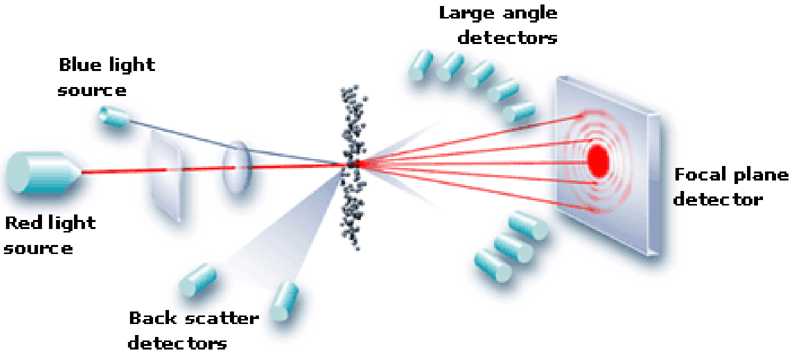
- ***Microscopy*** – computer analysis (image analysis)



- ***Sedimentation*** – 1μm ÷ 1 mm, settling (sedimentation) velocity analysis

(stop watch, sampling, sedimentation balances, light absorption - sedigraph, X-ray absorption)

- ***Laser diffraction*** – 1nm ÷ 1 mm



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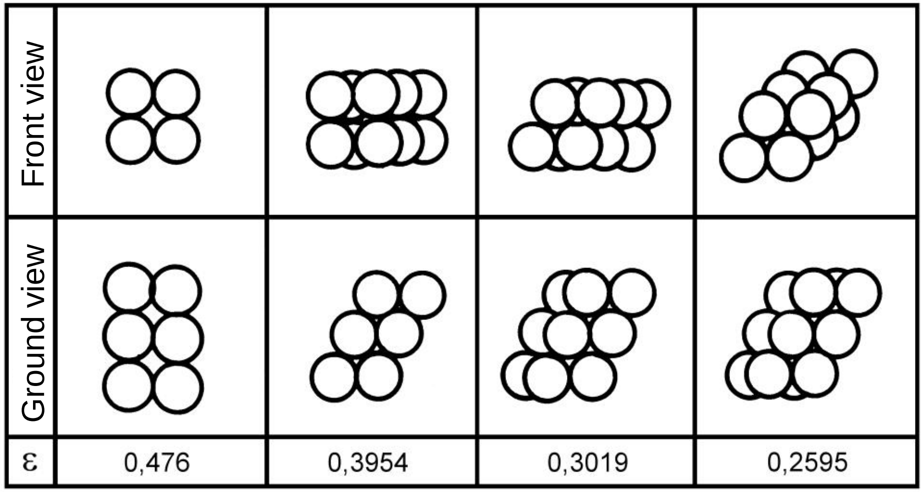
Porosity (voidage) of porous bed

Porosity (voidage) ε is defined by ratio of volume of voids in bed to total volume of bed:

$$\varepsilon = \frac{V_p}{V} = \frac{V - V_s}{V}$$

$$\varepsilon = \frac{\text{volume of voids in bed}}{\text{total volume of bed (voids + solids)}}$$



Specific surface of particle

Absolute specific surface (density of bed surface) a is surface area of all particles *A* in all volume of bed *V*:

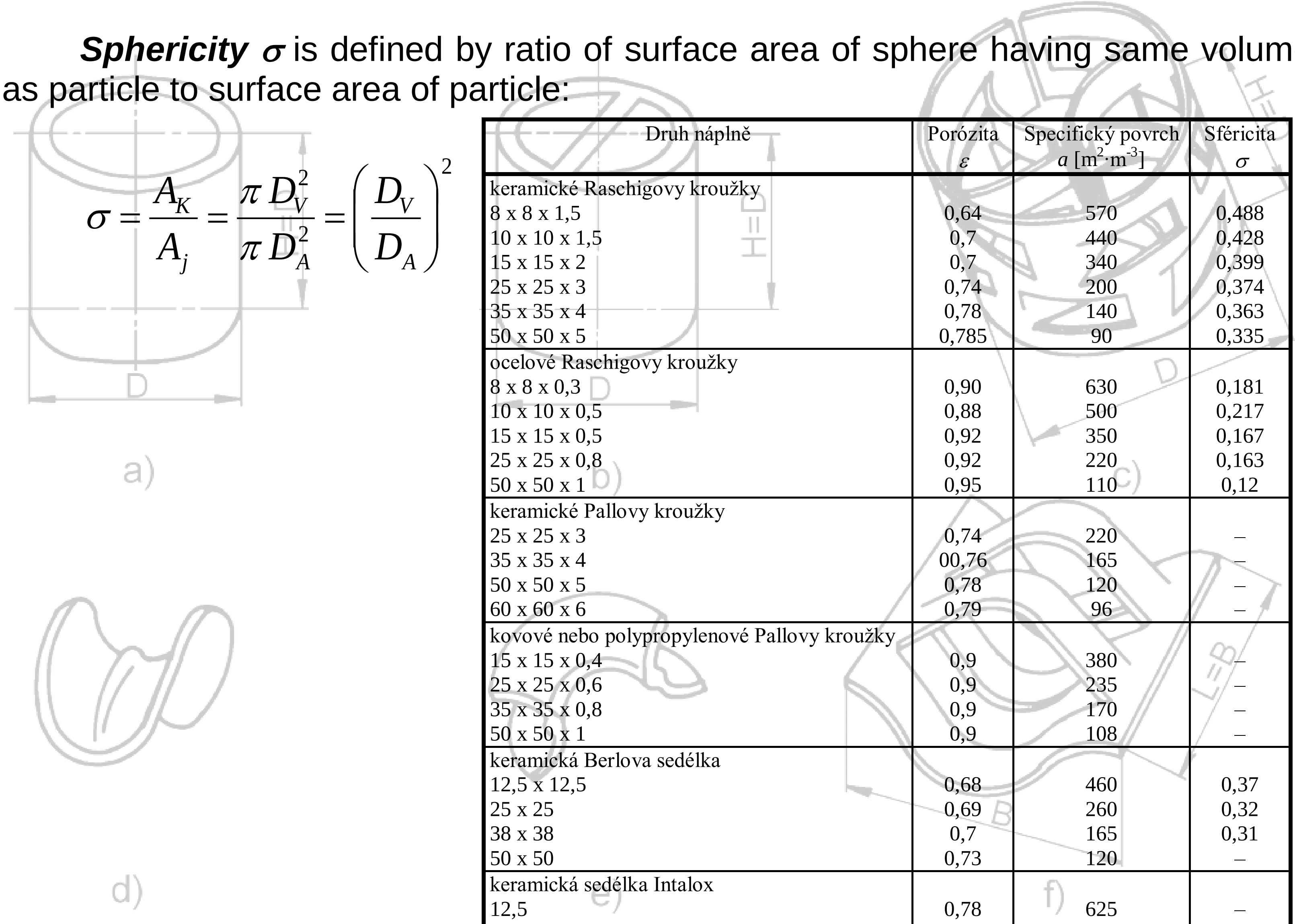
$$a = \frac{A}{V}$$

Own specific surface a*$_V$* is ratio of particle surface area *A* to volume of particle V_s:

$$a_V = \frac{A}{V_s}$$

Sphericity

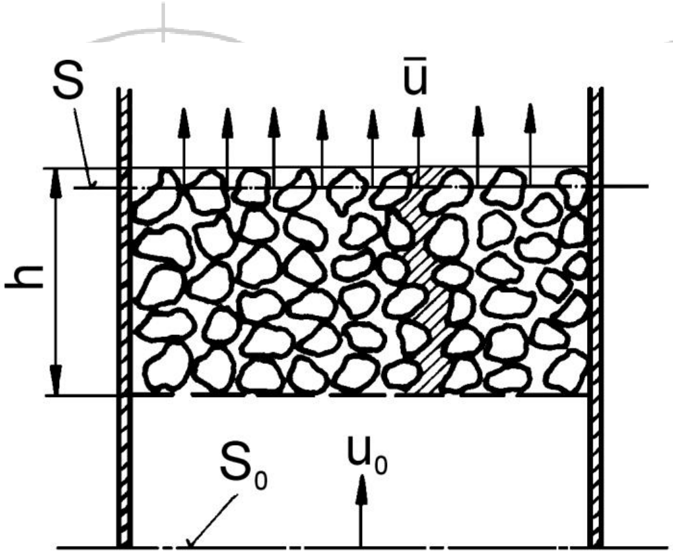
Sphericity $\boldsymbol{\sigma}$ is defined by ratio of surface area of sphere having same volume as particle to surface area of particle:



$$\sigma = \frac{A_K}{A_j} = \frac{\pi D_V^2}{\pi D_A^2} = \left(\frac{D_V}{D_A}\right)^2$$

Druh náplně	Porózita ε	Specifický povrch a [m^2·m^{-3}]	Sféricita σ
keramické Raschigovy kroužky			
8 x 8 x 1,5	0,64	570	0,488
10 x 10 x 1,5	0,7	440	0,428
15 x 15 x 2	0,7	340	0,399
25 x 25 x 3	0,74	200	0,374
35 x 35 x 4	0,78	140	0,363
50 x 50 x 5	0,785	90	0,335
ocelové Raschigovy kroužky			
8 x 8 x 0,3	0,90	630	0,181
10 x 10 x 0,5	0,88	500	0,217
15 x 15 x 0,5	0,92	350	0,167
25 x 25 x 0,8	0,92	220	0,163
50 x 50 x 1	0,95	110	0,12
keramické Pallovy kroužky			
25 x 25 x 3	0,74	220	–
35 x 35 x 4	00,76	165	–
50 x 50 x 5	0,78	120	–
60 x 60 x 6	0,79	96	–
kovové nebo polypropylenové Pallovy kroužky			
15 x 15 x 0,4	0,9	380	–
25 x 25 x 0,6	0,9	235	–
35 x 35 x 0,8	0,9	170	–
50 x 50 x 1	0,9	108	–
keramická Berlova sedélka			
12,5 x 12,5	0,68	460	0,37
25 x 25	0,69	260	0,32
38 x 38	0,7	165	0,31
50 x 50	0,73	120	–
keramická sedélka Intalox			
12,5	0,78	625	–
19	0,77	335	–
25	0,775	255	–
38	0,81	195	–
50	0,79	118	–

Single phase flow in porous bed



$$e_z = \lambda \frac{h}{d_e}\frac{\bar{u}^2}{2}$$

$$d_e = 4\frac{S}{O} = 4\frac{Sh}{Oh} \approx 4\frac{V_p}{A}$$

$$u_o S_o = \bar{u} S \Rightarrow \bar{u} = \frac{S_o}{S}u_o$$

$$d_e = 4\frac{\frac{V_p}{V}}{\frac{A}{V}} = 4\frac{\varepsilon}{a}$$

$$\bar{u} = \frac{S_o h}{Sh}u_o = \frac{V}{V_p}u_o = \frac{u_o}{\varepsilon}$$

modified Reynolds number:

$$Re = \frac{\bar{u} d_e \rho}{\mu} = \frac{u_0 \cdot 4\varepsilon\rho}{\varepsilon\mu a} = \frac{2}{3}\frac{u_0 D_p \rho}{(1-\varepsilon)\mu} = \frac{2}{3}Re'$$

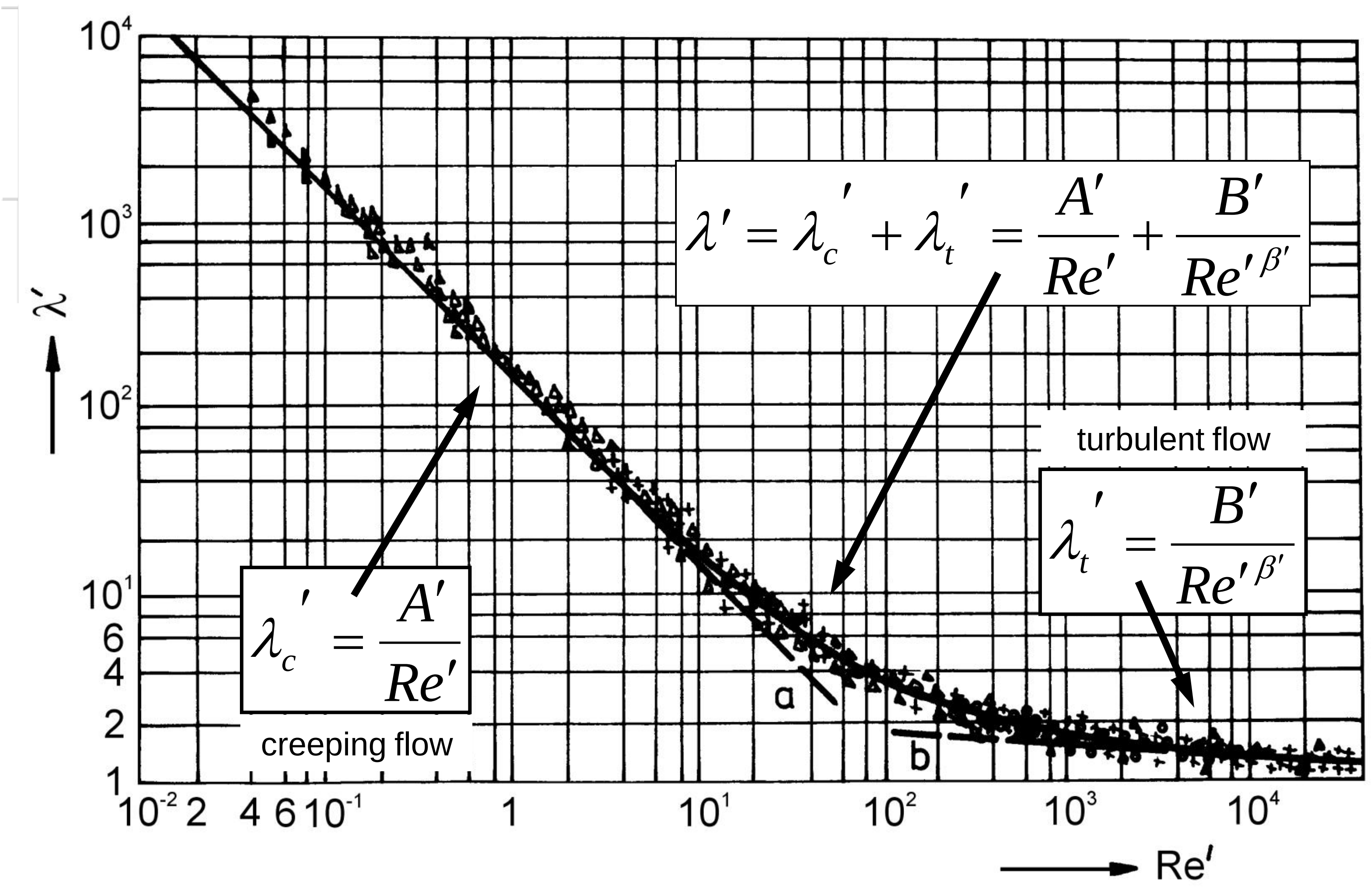
$$Re' = \frac{u_0 D_p \rho}{(1-\varepsilon)\mu}$$

$$\boxed{e_z = \lambda' \frac{1-\varepsilon}{\varepsilon^3}\frac{h}{D_p}u_0^2}$$

$$\lambda' = f\left(Re', \text{particle shape}\right)$$

Dependence of friction factor λ' for single phase flow in monodisperse bed with spherical particles on modified Reynolds number Re´

(spherical particles: A´ = 160; B´ = 3,1; β' = 0,1)



$$\lambda' = \lambda_c{}' + \lambda_t{}' = \frac{A'}{Re'} + \frac{B'}{Re'^{\beta'}}$$

turbulent flow

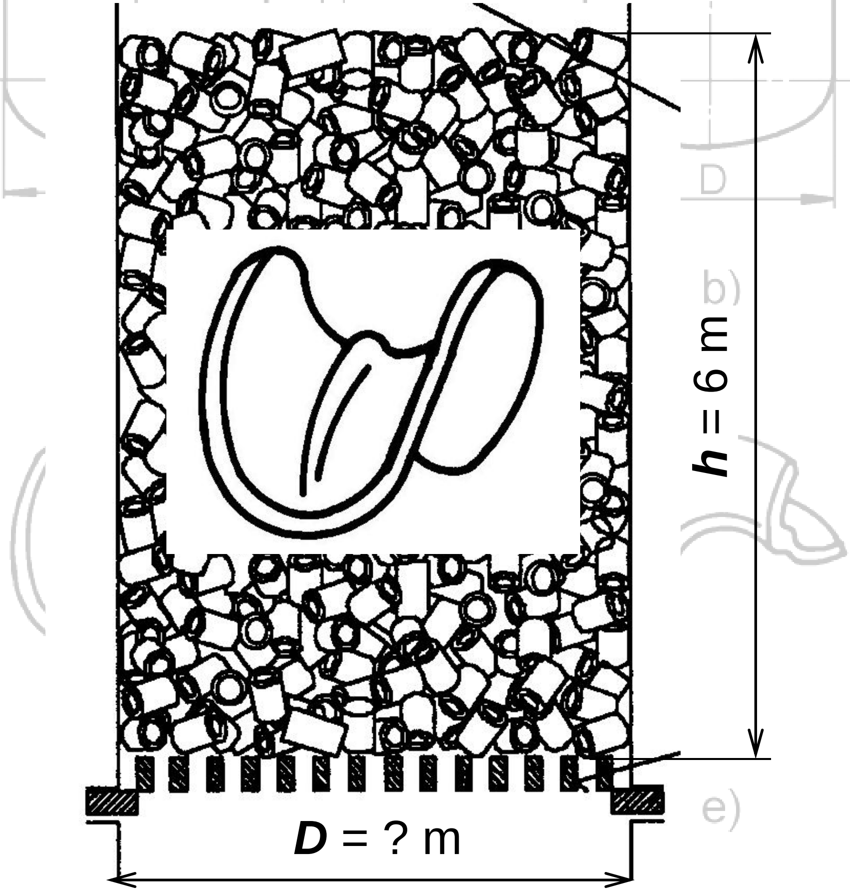
$$\lambda_t{}' = \frac{B'}{Re'^{\beta'}}$$

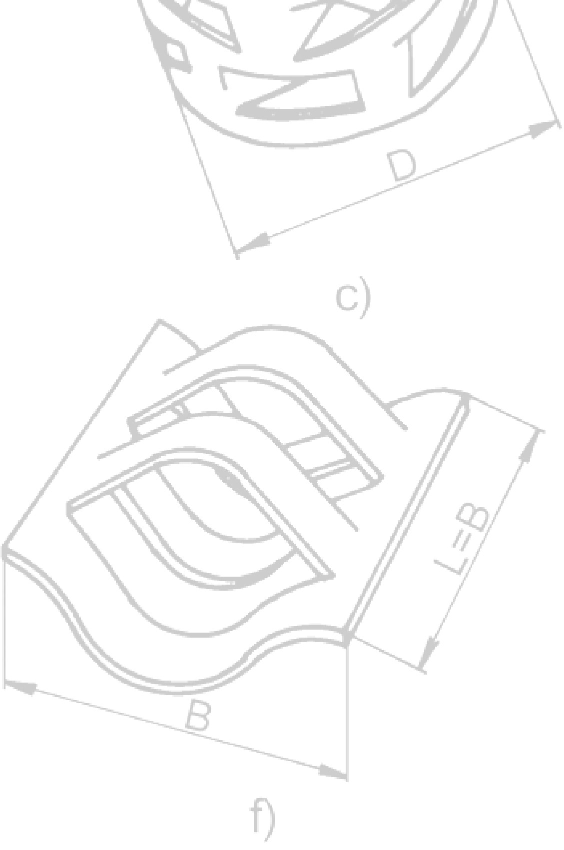
$$\lambda_c{}' = \frac{A'}{Re'}$$

creeping flow

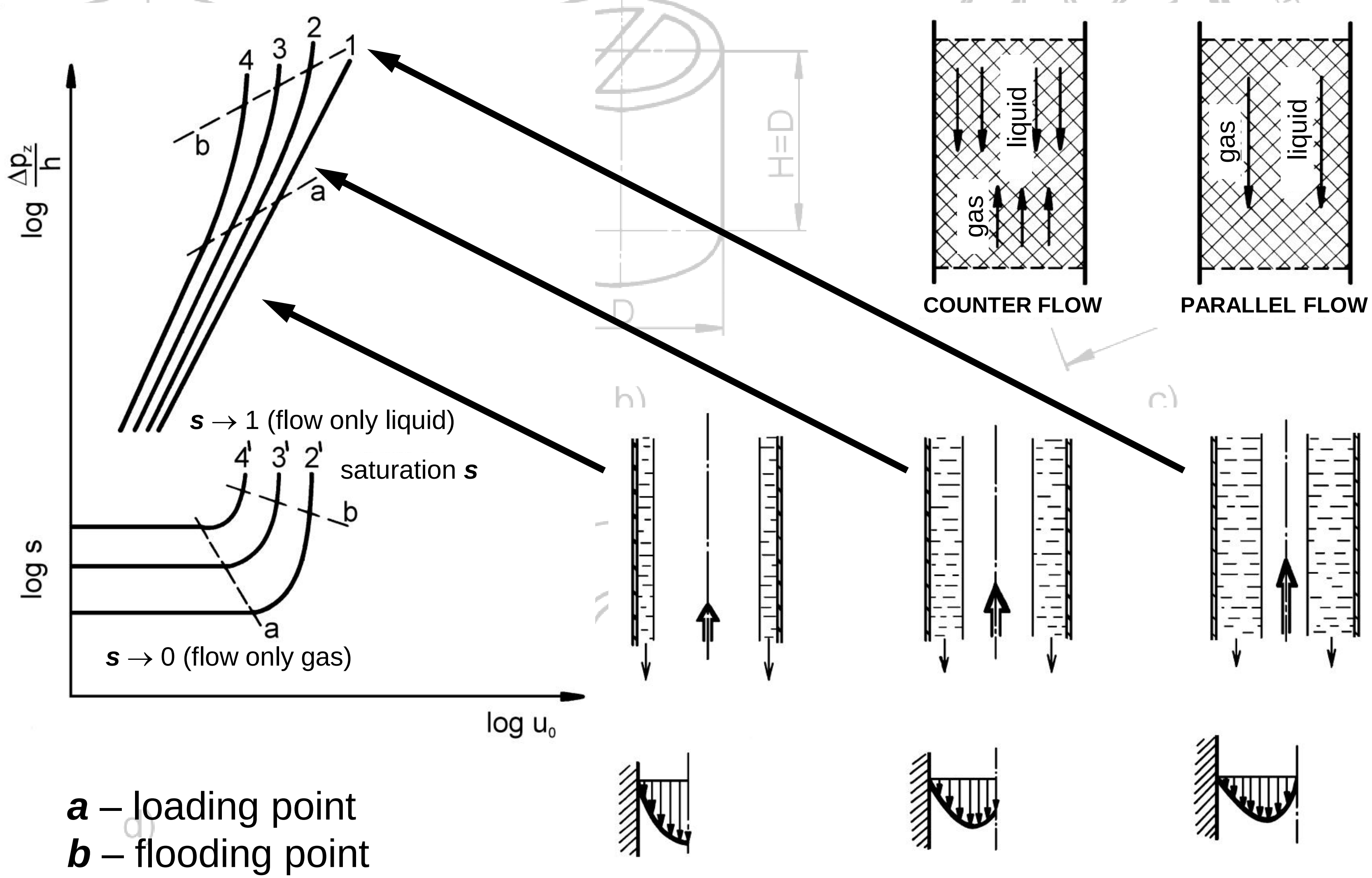
EXAMPLE: *Single phase flow in adsorption tower*

Gas with mean density $\rho = 3.35$ kg·m^{-3} and viscosity $\mu = 3 \cdot 10^{-5}$ Pa·s flow in packed bed of adsorption tower with height $h = 6$ m. Tower is random packed with Berl saddle with dimension 25 x 25 mm. Determinate inside diameter of tower for pressure drop $\Delta p = 150$ kPa.





Two phase flow in porous bed



$s \rightarrow 1$ (flow only liquid)

saturation s

$s \rightarrow 0$ (flow only gas)

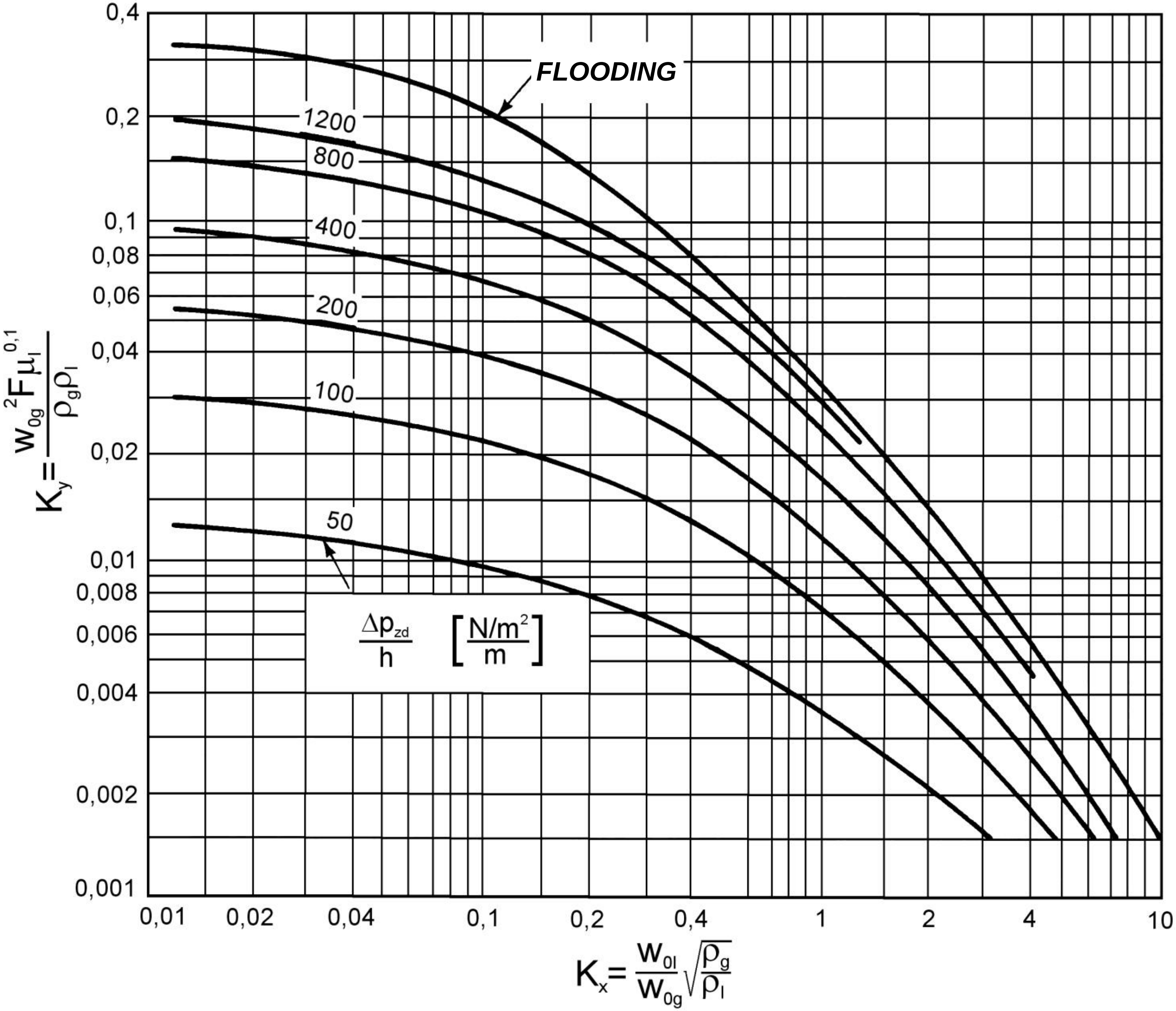
COUNTER FLOW

PARALLEL FLOW

a – loading point

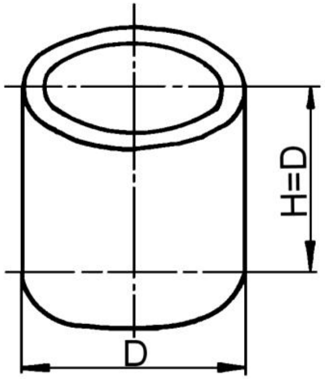
b – flooding point

Determination of flooding velocity and pressure drop for two phase flow in porous bed



EXAMPLE: *Two phase flow in absorption tower*

Sulphure dioxide SO_2 clean up from compound with air (ρ_g = 1.1 kg·m^{-3} and μ = 1.4·10^{-5} Pa·s). Tower is packed random packed with ceramic Raschig rings with dimension 25 x 25x 3 mm (packing factor *F* see table) and with height *h* = 5 m. Gas with mass flow rate 4400 kg·h^{-1} is absorbed to counter flow water. Design inside diameter of tower for their optimal working under flooding. Determinate pressure drop for gas. Choose mass ratio of spraying w_{0l}/w_{0g} = 2.



Typ náplně			Jmenovitý rozměr [mm]										
			6	9,5	13	16	19	**25**	32	38	50	76	89
Raschigovy kroužky keramické	tl. stěny [mm]	s	0,8	1,6	2,4	2,4	2,4	**3**	4,8	4,8	6	9,5	
		F	1600	1000	580	380	255	**155**	125	95	65	37	
Raschigovy kroužky kovové	tl. stěny 0,8 mm	F	700	390	300	170	155	115					
	tl. stěny 1,6 mm	F			410	290	220	137	110	83	57	32	
Kroužky PALL	plast	F				97		52		40	25		16
	kovové	F				70		48		28	20		16
Berlova sedla keram.		F			240		170	110		65	45		
Sedla Intalox	keram.	F		330	200		145	98		52	40	22	
	plast	F						33			21	16	
Flexiring, plast		F				78		45		28	22		18