CHE 454A

Unit Operations Involving Particulate Solids for Chemical Engineers

Dr. Raju Kumar Gupta,
Associate Professor,
Department of Chemical Engineering,
Indian Institute of Technology Kanpur,
Kanpur 208016, India

CHE454A (Lecture 1-2)

- Unit process
- unit operation -

* upstream process:
unit operation: crushing, grinding, washing, filtration, drying mixing, etc.

* Reaction: chemical rxn takes place
raw material → products

* Downstream processes:
unit operation: Distillation, evaporation, extraction, settling, centrifugation etc.

Unit operation: physical / or mechanical procedure occurring individually or parallel to chemical rxn.

- Physical steps of preparing reactants
- separating & purifying products
- Recycling unconverted reactants
- Controlling energy transfer into or out of the reactor

Mechanical unit operations:

- purely based on physical or mechanical forces such as
  - * Gravitational force
  - * centrifugal force
  - * mechanical & kinetic forces arising from flow

* Final property of product depend on unit operation used

(a) Solid-solid operations:

- crushing, grinding, sieving, compaction, cutting, storage & transport of bulk solids etc.

(b) Solid-fluid operations:

Filtration, sedimentation, centrifugation, floatation, cyclone separators

Sphericity: $$\phi_s = \frac{6/D_p}{S_p/v_p} \quad \text{———} \quad (*)$$

D_p - nominal dia. of particle

S_p - surface area of one particle

v_p - volume of one particle

For a sample of uniform particles of dia. D_p,

$$N v_p = \frac{m}{\rho_p}$$

m - total mass of sample

ρ_p - density of particle

Total surface area of particle,

$$A = N S_p$$

$$A = \frac{m S_p}{\rho_p v_p} = \frac{m}{\rho_p v_p} \cdot \frac{6 v_p}{D_p \phi_s}$$

$$\Rightarrow \boxed{A = \frac{6m}{\phi_s \rho_p D_p}} \quad \text{———} \quad (**)$$

Specific surface area of mixture
(total surface area per mass of particles)

$$A_{ss} = A_w = \frac{6x_1}{\phi_s \rho_p \bar{D}_{p_1}} + \frac{6x_2}{\phi_s \rho_p \bar{D}_{p_2}} + \cdots + \frac{6x_n}{\phi_s \rho_p \bar{D}_{p_n}}$$

x_i - mass fraction in a given increment

n - no. of increment

D_{Pi} – Average particle dia, taken as arithmatic average of smallest & largest particle diameters in increment

	Mesh	Screen opening D_{Pi}, mm	Average particle dia, $\overline{D}_{Pi}$, mm
	4	4.699	4.699
−4+6	6	3.327	$\frac{4.699+3.327}{2} = 4.013$
−6+8	8	2.362	2.845
−8+10	10	1.651	2.007

$$\boxed{A_{ss} = \frac{6}{\phi_s \rho_p} \sum_{i=1}^{n} \frac{x_i}{\overline{D}_{Pi}}}$$

Volume surface mean dia,

$$\overline{D}_{Vs} = \frac{6}{\phi_s A_{ss} \rho_p} = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{\overline{D}_{Pi}}}$$

Problem 1:

$$\rho_p = 0.00265 \ g/mm^3$$

$$\phi_s = 0.571$$

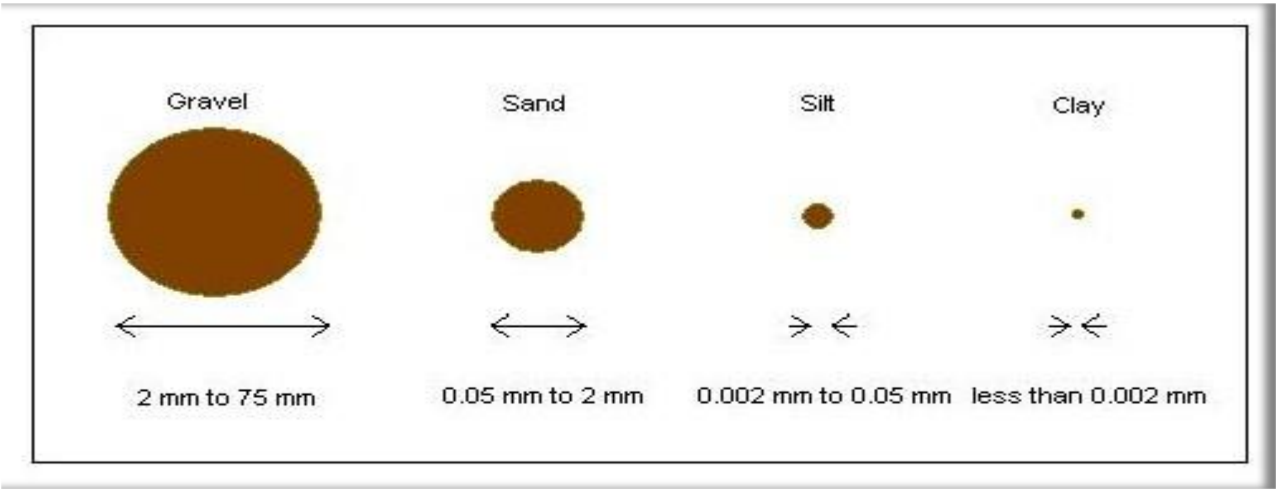
For the material b/w 4-mesh & 200 mesh in particle size, calculate specific surface area in mm^2/g.

$$A_{ss} = \frac{6}{\phi_s \rho_p} \sum_{i=1}^{n} \frac{x_i}{\bar{D}_{p_i}}$$

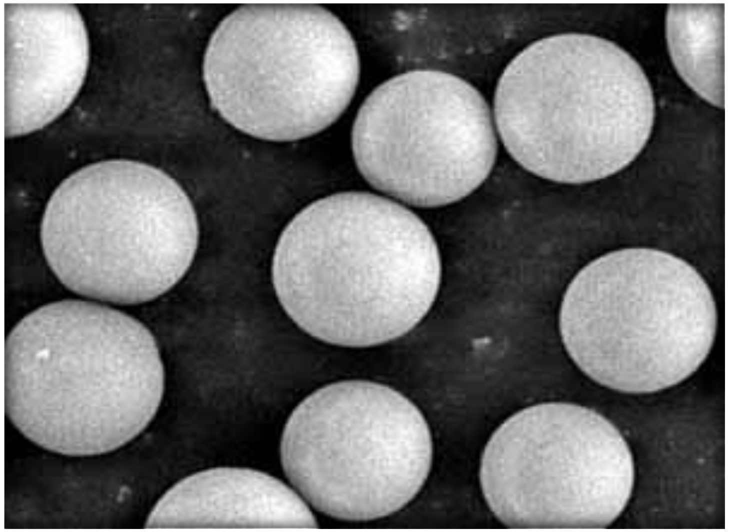
Understanding of Particle Size and Particle Shape

Particle Size

Particle size or **grain size** refers to the diameter of a grain of granular material



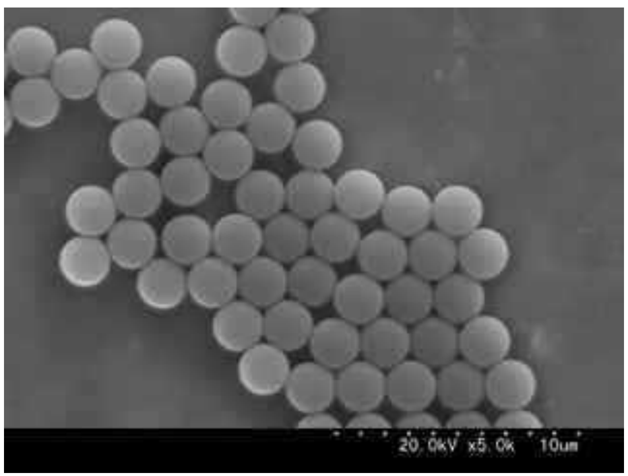
- The size of a spherical homogeneous particle is uniquely defined by its diameter.
  - For regular, compact particles such as cubes or regular tetrahedra, a single dimension can be used to define size.
  - With some regular particles it may be necessary to specify more than one dimension: For a cone the base diameter and height are required whilst for a cuboid three dimensions are needed.

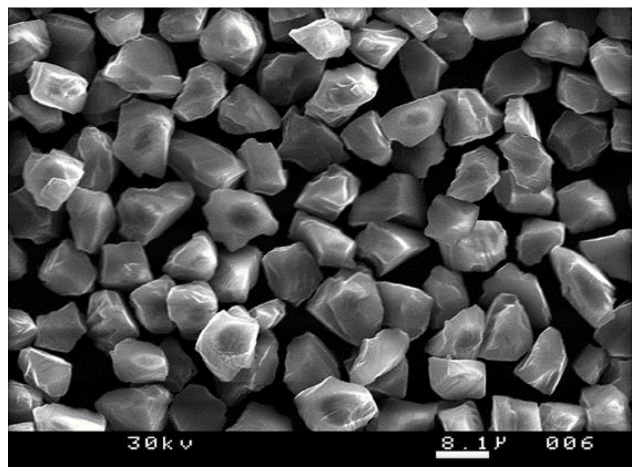


- For irregular particles, it is desirable to quote the size of a particle in terms of a single quantity, and the expression most often used is the "equivalent diameter".

  - The assigned equivalent diameter usually depends on the method of measurement.

  - Several equivalent diameters are commonly encountered. For example, the Stokes' diameter is measured by sedimentation and elutriation techniques; the projected area diameter is measured microscopically and the sieve-aperture diameter is measured by means of sieving.





Influences of Particle Size

- Particle size influences dissolution

Small particles dissolve more rapidly than large ones, which is important in various manufacturing processes.

- Particle size influences flow properties of powders

The flow properties of powders are strongly dependent on particle size and, in particular, particle shape. Since most powders are moved from one place to another by flowing, control of flow behavior is highly important. Generally, coarse, roughly spherical particles flow much more easily than small or elongated particles.

- Particle size influences stability of dispersions

The stability of dispersions, such as suspensions and emulsions, depends on the size of the dispersed material. The forces between colloidal particles depend on their dimensions, and the settling.

Effect of Particle Shape

- Particle shape influences such properties as:
    - Flowability of powders
    - Packing
    - Interaction with fluids
- The variation between the diameters increases as the particles diverge more from the spherical shape.
- Different results from different techniques can be compared by applying shape factors and shape coefficients.

Particle Size Distribution

- The particle size distribution (PSD) may be defined as

"Particle size distribution (PSD) of a powder, or granular material, or particles dispersed in fluid, is a list of values or a mathematical function that defines the relative amounts of particles present, sorted according to size."

Significance of Particle Size Distribution (PSD)

- The PSD of a material can be important in understanding its physical and chemical properties.

- It affects the strength and load-bearing properties of rocks and soils.

- It affects the reactivity of solids participating in chemical reactions, and needs to be tightly controlled in many industrial products such as the manufacture of printer toner and cosmetics.

Sieve Analysis

- Sieve analysis is one of the oldest methods of size analysis.

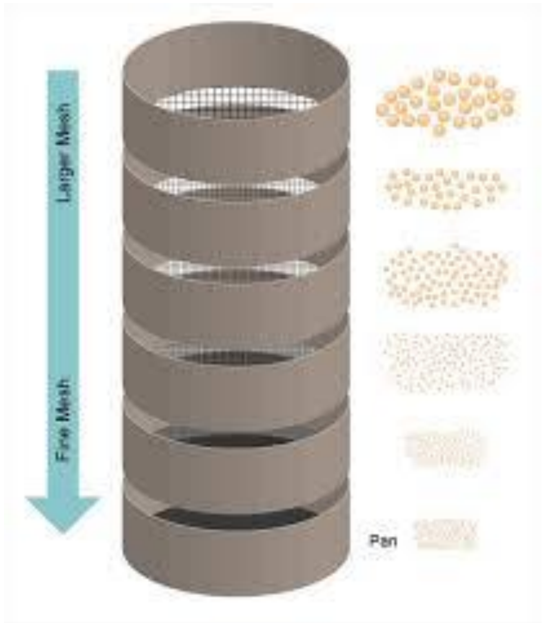
- Sieve analysis is accomplished by passing a known weight of sample material successively through finer sieves and weighing the amount collected on each sieve to determine the percentage weight in each size fraction.

- Sieving is carried out with wet or dry materials and the sieves are usually agitated to expose all the particles to the openings.

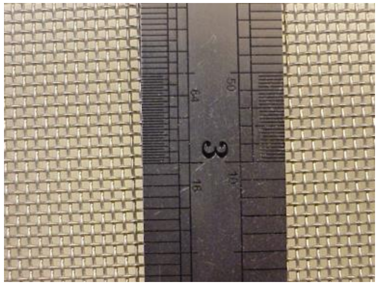
Process of Sieving

- The process of sieving may be divided into two stages.
- First, the elimination of particles considerably smaller than the screen apertures, which should occur rapidly and, second, the separation of the so-called "near-size" particles, which is a gradual process rarely reaching final completion.
- The effectiveness of a sieving test depends on the amount of material put on the sieve (the "charge") and the type of movement imparted to the sieve.

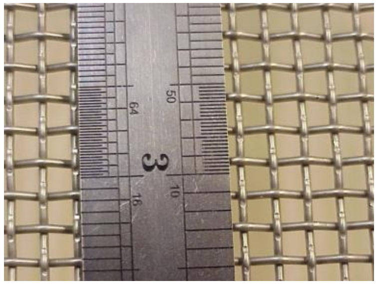
- The woven sieve is the oldest design, and it is normally made by weaving fine metal wire into a square pattern, then soldering the edges securely into a flattish cylindrical Container.
- Woven-wire sieves were originally designated by a **mesh number** (the *number of wires per inch or* the *number of square apertures per square inch)*



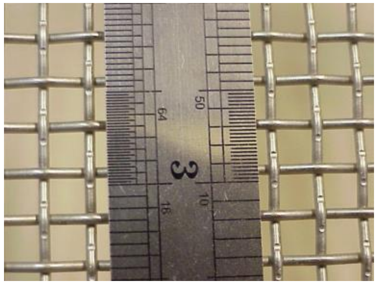
16 Mesh



6 Mesh



3 Mesh



Screen Analysis & Standard Screen Series

- Testing sieves are made of woven wire screens, the mesh and dimensions of which are carefully standardized. The openings are square. Each screen is identified in meshes per inch.

- The actual openings are smaller than those corresponding to mesh numbers because of thickness of the wires.

Tyler standard screen scale

This screen scale has as its base an opening of 0.0029 in., which is the opening in 200-mesh 0.0021-in. wire, the standard sieve, as adopted by the National Bureau of Standards.

Mesh	Clear opening, in.	Clear opening, mm	Approximate opening, in.	Wire diameter, in.
	1.050	26.67	1	0.148
†	0.883	22.43	$\frac{7}{8}$	0.135
	0.742	18.85	$\frac{3}{4}$	0.135
†	0.624	15.85	$\frac{5}{8}$	0.120
	0.525	13.33	$\frac{1}{2}$	0.105
†	0.441	11.20	$\frac{7}{16}$	0.105
	0.371	9.423	$\frac{3}{8}$	0.092
$2\frac{1}{2}$†	0.312	7.925	$\frac{5}{16}$	0.088
3	0.263	6.680	$\frac{1}{4}$	0.070
$3\frac{1}{2}$†	0.221	5.613	$\frac{7}{32}$	0.065
4	0.185	4.699	$\frac{3}{16}$	0.065
5†	0.156	3.962	$\frac{5}{32}$	0.044
6	0.131	3.327	$\frac{1}{8}$	0.036
7†	0.110	2.794	$\frac{7}{64}$	0.0328
8	0.093	2.362	$\frac{3}{32}$	0.032
9†	0.078	1.981	$\frac{5}{64}$	0.033
10	0.065	1.651	$\frac{1}{16}$	0.035
12†	0.055	1.397		0.028

(Continued)

Tyler standard screen scale

Mesh	Clear opening, in.	Clear opening, mm	Approximate opening, in.	Wire diameter, in.
14	0.046	1.168	$\frac{3}{64}$	0.025
16†	0.0390	0.991		0.0235
20	0.0328	0.833	$\frac{1}{32}$	0.0172
24†	0.0276	0.701		0.0141
28	0.0232	0.589		0.0125
32†	0.0195	0.495		0.0118
35	0.0164	0.417	$\frac{1}{64}$	0.0122
42†	0.0138	0.351		0.0100
48	0.0116	0.295		0.0092
60†	0.0097	0.246		0.0070
65	0.0082	0.208		0.0072
80†	0.0069	0.175		0.0056
100	0.0058	0.147		0.0042
115†	0.0049	0.124		0.0038
150	0.0041	0.104		0.0026
170†	0.0035	0.088		0.0024
200	0.0029	0.074		0.0021
For coarser sizing: 3- to $1\frac{1}{2}$-in. opening				
			3	0.207
			2	0.192
			$1\frac{1}{2}$	0.148

† These screens, for closer sizing, are inserted between the sizes usually considered as the standard series. With the inclusion of these screens the ratio of diameters of openings in two successive screens is as $1:\sqrt[4]{2}$ instead of $1:\sqrt{2}$.

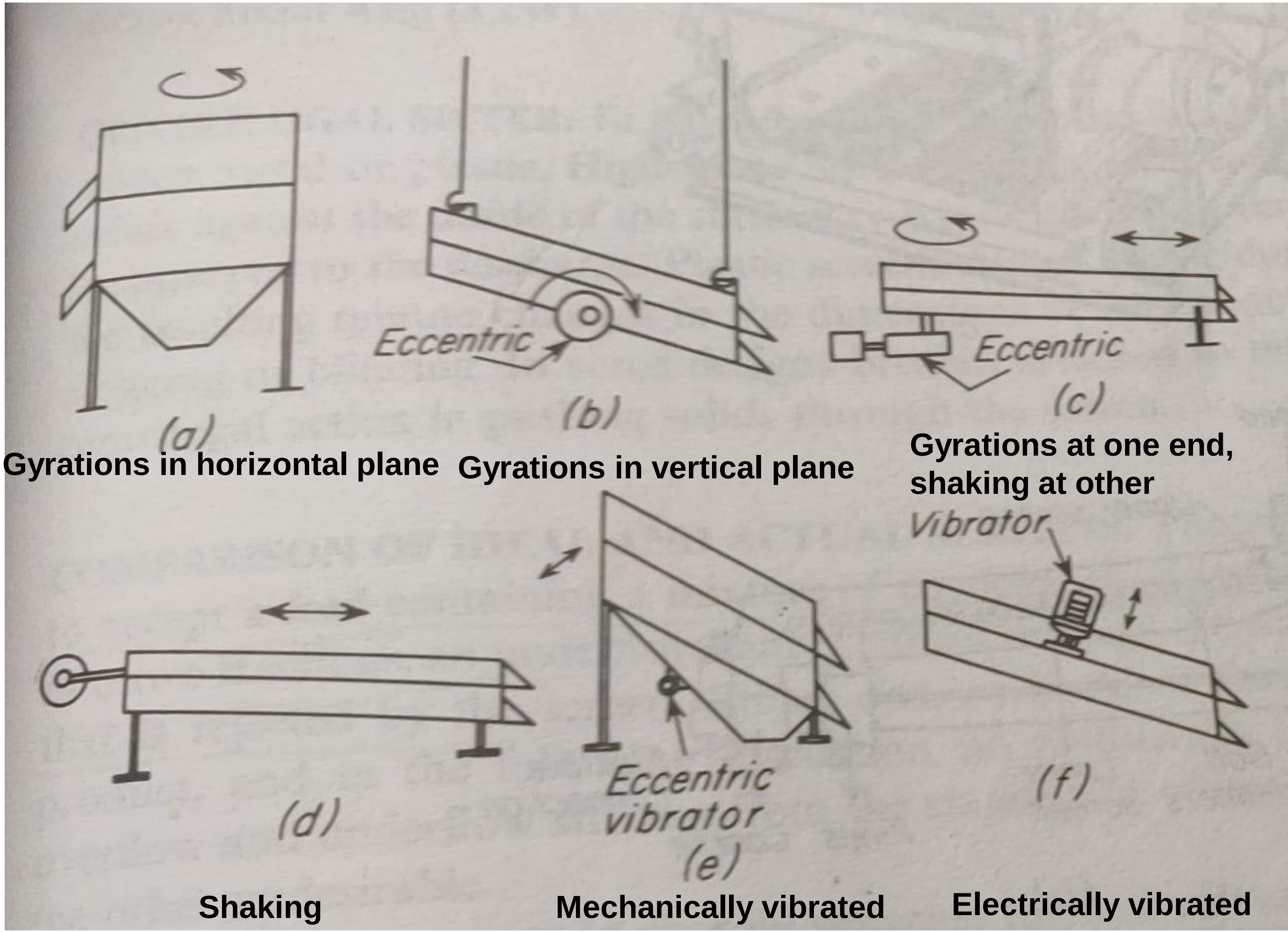
Typical Screen Analysis

Mesh	Screen opening D_{pi}, mm	Mass fraction retained, x_i,	Average particle diameter in increment, $\bar{D}_{pi}$, mm	Cumulative fraction smaller than D_{pi}
4	4.699	0.0000	—	1.0000
6	3.327	0.0251	4.013	0.9749
8	2.362	0.1250	2.845	0.8499
10	1.651	0.3207	2.007	0.5292
14	1.168	0.2570	1.409	0.2722
20	0.833	0.1590	1.001	0.1132
28	0.589	0.0538	0.711	0.0594
35	0.417	0.0210	0.503	0.0384
48	0.295	0.0102	0.356	0.0282
65	0.208	0.0077	0.252	0.0205
100	0.147	0.0058	0.178	0.0147
150	0.104	0.0041	0.126	0.0106
200	0.074	0.0031	0.089	0.0075
Pan	—	0.0075	0.037	0.0000

The notation 14/20 means ‘through 14 mesh and on 20 mesh’

D_{pi} means the particle diameter equal to the mesh opening of screen i

Screening equipment



(a) Gyrations in horizontal plane
(b) Gyrations in vertical plane
(c) Gyrations at one end, shaking at other
(d) Shaking
(e) Mechanically vibrated
(f) Electrically vibrated

Sieve test results

Results of typical sieve test

(1) Sieve size range (µm)	(2) Sieve fractions wt (g)	(3) wt %	(4) Nominal aperture size (µm)	(5) Cumulative % undersize	(6) oversize
+250	0.02	0.1	250	99.9	0.1
−250 to +180	1.32	2.9	180	97.0	3.0
−180 to +125	4.23	9.5	125	87.5	12.5
−125 to +90	9.44	21.2	90	66.3	33.7
−90 to +63	13.10	29.4	63	36.9	63.1
−63 to +45	11.56	26.0	45	10.9	89.1
−45	4.87	10.9			

Table shows:

(1) The sieve size ranges used in the test.

(2) The weight of material in each size range, e.g. 1.32 g of material passed through the 250 μm sieve, but was retained on the 180 μm sieve: the material therefore is in the size range -250 to +180 μm.

(3) The weight of material in each size range expressed as a percentage of the total weight.

(4) The nominal aperture sizes of the sieves used in the test.

(5) The cumulative percentage of material passing through the sieves, e.g. 87.5% of the material is less than 125 μm in size.

(6) The cumulative percentage of material retained on the sieves.