CHEMICAL ENGINEERING

Mechanical Operations

Comprehensive Theory
with Solved Examples *and* Practice Questions

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CONTENTS

Mechanical Operations

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER

1

Properties and Handling of Particulate Solids

LEARNING OBJECTIVES

The reading of this chapter will enable the students

- To understand the characterization of solid particles.
- To understand the mixed and average size analysis.
- To understand the concept of screening and screening equipment.
- To understand the concept of screen effectiveness and capacity.

1.1 INTRODUCTION

Mechanical Unit Operations are the operations which are purely based on physical or mechanical forces such as

- Gravitational force
- Centrifugal force
- Mechanical and kinetic forces arising from flow

So, the unit operations of which are purely based on mechanical or physical forces such as gravitational force, centrifugal force, mechanical or kinetic forces arising from flow, etc. they are known as the kind of mechanical unit operations.

Mechanical Unit Operations can be classified based on phases interacting as

- **Solid-Solid operations:** Crushing, grinding, sieving, compaction, cutting, storage and transport of bulk solids, etc.
- **Solid-Fluid operations:** Filtration, sedimentation, centrifugation, floatation, cyclone separators, etc.

Unit operations involving particulate solids:

- Separation of solids from a suspension by filtration.
- Fractionation of solids of wide size distribution based on size by gravity settling or differential settling methods.
- Separation of immiscible liquids by centrifugation (or decanting) and separation of solids from liquids by centrifugation.

1.2 CHARACTERIZATION OF SOLID PARTICLES

Individual solid particles are characterized by their size, shape, and density. Particles of homogeneous solids have the same density as the bulk material. Particles obtained by breaking up a composite solid, such as a metal-bearing ore, have various densities, usually different from the density of the bulk material. Size and shape are easily specified for regular particles, such as spheres and cubes, but for irregular particles (such as sand grains or mica flakes) the terms size and shape are not so clear and must be arbitrarily defined.

1.2.1 Particle Shape

The shape of an individual particle is conveniently expressed in terms of the sphericity ϕ_s, which is independent of particle size. For a spherical particle of diameter D_p, $\phi_s = 1$; for a non-spherical particle, the sphericity is defined by the relation

$$\phi_s = \frac{6v_p}{D_p s_p} \qquad \text{...(1.1)}$$

where,
D_p = Equivalent diameter or nominal diameter of particle
s_p = Surface area of one particle, v_p = Volume of one particle

The equivalent diameter is sometimes defined as the diameter of a sphere of equal volume. For fine granular materials, however, it is difficult to determine the exact volume and surface area of a particle, and D_p is usually taken to be the nominal size based on screen analyses or microscopic examination. For many crushed materials ϕ_s is between 0.6 and 0.8, as shown in table given below, but for particles rounded by abrasion ϕ_s may be as high as 0.95.

For cubes and cylinders for which the length L equals the diameter, the equivalent diameter is greater than L and ϕ_s found from the equivalent diameter would be 0.81 for cubes and 0.87 for cylinders. It is more convenient to use the nominal diameter L for these shapes since the surface-to-volume ratio is $\frac{6}{D_p}$, the same as for a sphere, and this makes ϕ_s equal to 1.0. For column packings such as rings and saddles the nominal size is also used in defining ϕ_s.

1.2.2 Particle Size

In general, “diameters” may be specified for any equidimensional particle. Particles that are not equidimensional, i.e., that are longer in one direction than in others, are often characterized by the second longest major dimension. For needlelike particles, for example, D_p would refer to the thickness of the particles, not their length.

Material	Sphericity	Material	Sphericity
Sphres, cubes, short cylinders ($L = D_p$)	1.0	Ottawa sand	0.95
		Rounded sand	0.83
Raschig rings ($L = D_p$)		Coal dust	0.73
$L = D_o$, $D_I = 0.5D_o$	0.58	Flint sand	0.65
$L = D_o$, $D_i = 0.75D_o$	0.33	Crushed glass	0.65
Berl saddles	0.3	Mica flakes	0.28

Table: *Sphericity of miscellaneous materials*

By convention, particle sizes are expressed in different units depending on the size range involved. Coarse particles are measured in inches or millimeters; fine particles in terms of screens size; very fine particles in micrometers or nanometers. Ultrafine particles are sometimes described in terms of their surface area per unit mass, usually in square meters per gram.

Sphericity of some regular particle:

Particle Shape	Sphericity
Cylinder (L = D)	0.87
Cylinder (L = 2D)	0.82
Cylinder (L = 3D)	0.78
Cube	0.80
Cuboid (1 : 2 : 3)	0.725

1.3 MIXED AND AVERAGE SIZE ANALYSIS

In a sample of uniform particles of diameter D_p, the total volume of the particles is $\frac{m}{\rho_p}$, where m and ρ_p are the total mass of the sample and the density of the particles, respectively. Since the volume of one particle is v_p, the number of particles in the sample N is

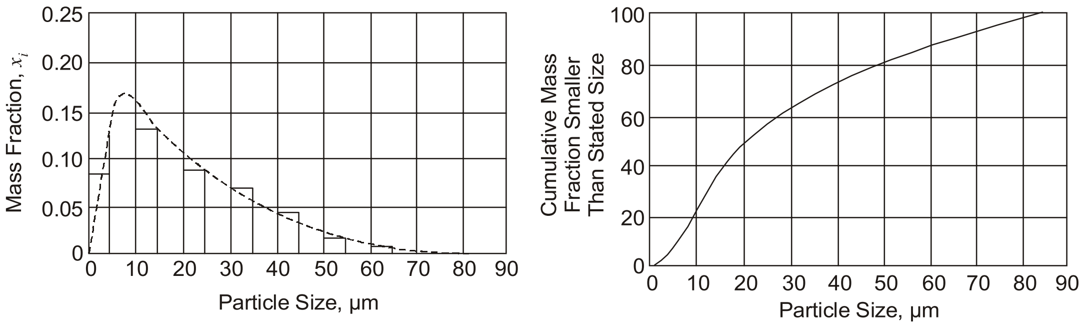
$$N = \frac{m}{\rho_p v_p} \qquad ...(1.2)$$

The total surface area of the particles is, from eqs. (1.1) and (1.2),

$$A = Ns_p = \frac{6m}{\phi_s \rho_p D_p} \qquad ...(1.3)$$

To apply Eqs. (1.2) and (1.3) to mixtures of particles having various sizes and densities, the mixture is sorted into fractions, each of constant density and approximately constant size. Each fraction can then be weighed, or the individual particles in it can be counted or measured by any one of a number of methods. Equations (1.2) and (1.3) can then be applied to each fraction and the results added.

Information from such a particle-size analysis is tabulated to show the mass or number fraction in each size increment as a function of the average particle size (or size range) in the increment. An analysis tabulated in this way is called a **differential analysis**. The results are often presented as a histogram, as shown in fig. (a), with a continuous curve like the dashed line used to approximate the distribution. A second way to present the information is through a cumulative analysis obtained by adding, consecutively, the individual increments, starting with that containing the smallest particles, and tabulating or plotting the cumulative sums against the maximum particle diameter in the increment. Fig. (b) is a cumulative-analysis plot of the distribution shown in fig. (a). In a cumulative analysis the data may appropriately be represented by a continuous curve.



(a) (b)

Fig. *Particle-size distribution for powder: (a) differential analysis; (b) cumulative analysis*

Student's Assignments

Q.1 What is the sphericity of a cuboid whose length, breadth and depth are in the ratio 5 : 4 : 1?
(a) 0.726 (b) 0.614
(c) 0.81 (d) 0.563

Q.2 Find the shape factor of a cylindrical particle of 3 mm diameter and 3 mm length?
(a) 0.873 (b) 1.145
(c) 1 (d) 1.375

Q.3 What is the sphericity of a cylindrical particle whose length is equal to its diameter?
(a) 0.873 (b) 0.673
(c) 0.573 (d) 0.81

Q.4 For a cylindrical particle of height equal to twice the diameter, the sphericity value is
(a) 0.655 (b) 0.728
(c) 0.832 (d) 0.915

Q.5 The shape factor for a hemisphere is
(a) equal to 1 (b) greater than 1
(c) less than 1 (d) None of the above

Q.6 Find the sphericity of a cube of dimension $a \times a \times a$.

Q.7 Finely divided clay is used as a catalyst in the petroleum industry. It has a density of 1.2 g/cc and a sphericity of 0.5. The size analysis is as follows :

Average diameter, $D_{pi,avg}$(cm)	0.0252	0.0178	0.0126	0.0089	0.0038
Mass fraction, x_i (g/g)	0.088	0.178	0.293	0.194	0.247

Find the specific surface area and the sauter mean diameter of the clay material.

Q.8 Calculate the volume-surface mean diameter for the following particulate material.

Size range, μm	Mass of particles in the range, g
$-710+300$	30
$-300+180$	35
$-180+90$	65
$-90+38$	70
Pan	55

Q.9 Which of the following particle has the lowest value of sphericity?
(a) Rounded sand
(b) Pulverized coat
(c) Tungsten powder
(d) Mica flakes

Q.10 The following table gives the size distribution of a dust measured by micro scope. Convert these figures to obtain distribution on mass basis and calculate the specific surface in μm. Assuming spherical particle of specific gravity 2.65.

Size range (mm)	Number of Particles
0 – 2	2000
2 – 4	600
4 – 8	140
8 – 12	40
12 – 16	15
16 – 20	5
20 – 24	2

Q.11 The cumulative mass fraction of particles smaller than size d_j for a collection of N_i particles of diameter d_i and mass m_i (i = 1, 2, 3, ..., ∞) is given by

(a) $\dfrac{\sum_{i=1}^{j} N_i d_i^3}{\sum_{i=1}^{\infty} N_i d_i^3}$ (b) $\dfrac{\sum_{i=1}^{j} N_i m_i d_i^3}{\sum_{i=1}^{\infty} N_i m_i d_i^3}$

(c) $\dfrac{\sum_{i=1}^{j} N_i m_i d_j^2}{\sum_{i=1}^{\infty} N_i m_i d_i^2}$ (d) $\dfrac{\sum_{i=1}^{j} N_i m_i d_j}{\sum_{i=1}^{\infty} N_i m_i d_i}$

Q.12 Weight mean diameter is given by

(a) $\frac{\Sigma n_i d_i^4}{\Sigma n_i d_i^3}$ (b) $\left(\frac{\Sigma n_i d_i^3}{\Sigma n_i}\right)^{1/3}$

(c) $\frac{\Sigma n_i d_i^3}{\Sigma n_i d_i^2}$ (d) $\frac{\Sigma n_i d_i^2}{\Sigma n_i d_i}$

ANSWERS

1. (b) **2.** (b) **3.** (a) **4.** (c)

5. (b) **6.** (0.81) **7.** (1235.43, 8.094×10^{-3})

8. (79.11) **9.** (d) **10.** (0.726×10^6)

11. (b) **12.** (c)

Explanation

1. (b)

The volume of cuboid is $5 \times 4 \times 1 = 20\ \text{m}^3$

and surface area of this cuboid

$$= 2[(5 \times 4) + (4 \times 1) + (5 \times 1)]$$
$$= 2(20 + 4 + 5)$$
$$= 2 \times 29 = 58\ \text{m}^2$$

Let, D_P = Diameter of the equivalent sphere

Then, $\frac{\pi}{6}D_P^3 = 20$

$$D_P = 3.36\ \text{m}$$

Area of sphere $= \pi D_P^2 = 35.63\ \text{m}^2$

Thus, Sphericity $= \frac{35.63}{58} = 0.614$

2. (b)

For a non-spherical particle, the sphericity (ϕ)

$$= \frac{6}{D_P}\left(\frac{V_P}{S_P}\right)_{\text{Particle}}$$

Volume of sphere $= \frac{\pi}{6}D_P^3$

Volume of cylindrical particle $= \frac{\pi}{4}D^2 \times l$

where, $l = D$

$$\frac{\pi}{4}D_P^3 = \frac{\pi}{4}D^3$$

$$D_P = \left(\frac{6}{4}\right)^{1/3} D$$

$$\left(\frac{V_P}{S_P}\right)_{\text{Particle}} = \frac{\frac{\pi}{4}D^3}{\frac{\pi}{2}D^2 + \pi D^2} = \frac{D}{6}$$

$$\phi = \frac{6}{D_P} \times \frac{D}{6} = \left(\frac{4}{6}\right)^{1/3} = 0.873$$

Shape factor, $\phi' = \frac{1}{\phi} = \frac{1}{0.873} = 1.145$

3. (a)

For a non-spherical particle, the sphericity (ϕ)

$$= \frac{6}{D_P}\left(\frac{V_P}{S_P}\right)_{\text{Particle}}$$

Volume of sphere $= \frac{\pi}{6}D_P^3$

Volume of cylindrical particle $= \frac{\pi}{4}D^2 \times l$

where, $l = D$

$$\frac{\pi}{6}D_P^3 = \frac{\pi}{4}D^3$$

$$D_P = \left(\frac{6}{4}\right)^{1/3} D$$

$$\left(\frac{V_P}{S_P}\right)_{\text{Particle}} = \frac{\frac{\pi}{4}D^3}{\frac{\pi}{2}D^2 + \pi D^2} = \frac{D}{6}$$

$$\phi = \frac{6}{D_P} \times \frac{D}{6} = \left(\frac{4}{6}\right)^{1/3}$$

$$\phi = 0.873$$

4. (c)

Sphericity $\phi = \frac{6}{D_p}\left(\frac{V_p}{S_p}\right)_{\text{particle}}$

Volume of sphere = Volume of cylindrical particle

$$\frac{\pi}{6}D_p^3 = \frac{\pi}{4}D^2 \times l$$

where, $l = 2D$

$$\frac{\pi}{6}D_p^3 = \frac{\pi}{4} \times 2D^3$$

$$D_p = (3)^{1/3}D$$