KARPAGAM ACADEMY OF HIGHER EDUCATION
DEPARTMENT OF BIOTECHNOLOGY (B.TECH)
B.TECH – FOOD TECHNOLOGY

LECTURE PLAN

SUBJECT CODE: 18BTFT402 **ENGINEERING PROPERTIES OF FOOD MATERIALS**

STAFFNAME: Ms.NITHIYA PRIYA.B.T
CLASS: II YEAR – IV SEMESTER; B.TECH-FOOD TECHNOLOGY

S.NO	DESCRIPTION OF TOPICS TO BE COVERED	HOURS	SUGGESTED BOOK & PAGE NOS. USED FOR TEACHING	TEACHING AIDS
UNIT-1 PHYSICAL PROPERTIES OF FOODS				
1.	Methods of estimation of Shape, Size	2	[S1] Pg: 01-08	BB+PPT
2.	Volume, Density	2	[S1] Pg: 15-24	BB+PPT
3.	Porosity and Surface area	1	[S1] Pg: 24-30; [S3] Pg: 14-16	BB+PPT
4.	Sphericity, roundness, specific gravity	2	[S4] Pg: 58-65; [S1] Pg: 3-15	BB+PPT
5.	Frictional properties-coefficient of friction	1	[W1]	BB+PPT
6.	Storage and flow pattern of agricultural crops.	1	[S2] Pg: 50-62	BB+PPT
7.	Tutorial	1	Revision	
TOTAL HOURS FOR UNIT- 1		**Theory hours : 9** **Tutorial hour : 1** **Total hours : 10**		
UNIT-2 RHEOLOGICAL PROPERTIES OF FOODS				
8.	Definition – classification – Newton's law of viscosity	2	[S1] Pg: 39-42	BB
9.	Momentum-diffusivity-kinematic viscosity – viscous fluids – Newtonian and Non Newtonian fluids	2	[S1] Pg: 42- 46	BB+PPT
10.	Viscosity Measurements- Viscometers of different types and their applications	3	[S1] Pg: 52-71	BB+PPT
11.	Texture measuring instruments- Hardness and brittleness of Food materials.	2	[S1] Pg: 91-100 [J1]	BB+PPT

12.	Tutorial	1	Revision	
TOTAL HOURS FOR UNIT- 2		**Theory hours : 9** **Tutorial hour : 1** **Total hours : 10**		
UNIT-3 THERMAL PROPERTIES OF FOODS				
13.	Definitions of Heat capacity, specific heat, enthalpy, conductivity and diffusivity, surface heat transfer coefficient,	1	[S1] Pg: 120, 142-148	BB+PPT
14.	Measurement of thermal properties like specific heat	1	[S1] Pg: 142-148	BB+PPT
15.	Enthalpy	1	[S1] Pg: 148-149	BB+PPT
16.	conductivity and diffusivity	3	[S1] Pg: 120- 138; 150-151	BB+PPT
17.	DTA, TGA, DSC.	3	[W2] [S5] Pg: 163	BB+PPT
18.	Tutorial	1	Revision	
TOTAL HOURS FOR UNIT- 3		**Theory hours : 9** **Tutorial hour : 1** **Total hours : 10**		
UNIT-4 AERODYNAMIC AND HYDRODYNAMIC PROPERTIES OF FOODS				
19.	Drag and lift coefficient, terminal velocity and their application in the handling and separation of food materials.	2	[W3] [S6] Pg: 549-559	BB+PPT
20.	Water activity- measurement-vapor pressure method –freezing point depression method	2	[S1] Pg: 200-202 [S5] Pg: 9-14	BB+PPT
21.	Effect of temperature, and pressure on water activity	1	[S1] Pg: 212 [S3] Pg: 386-389	BB+PPT
22.	Moisture sorption isotherms-models-Henderson, BET and GAB models	3	[S5] Pg: 75-79; Pg: 123	BB+PPT
23.	Tutorial	1	Revision	
TOTAL HOURS FOR UNIT- 4		**Theory hours : 8** **Tutorial hour : 1** **Total hours : 9**		
UNIT-5 ELECTRICAL PROPERTIES OF FOODS				
24.	Dielectric properties-dielectric constants	1	[S3] Pg: 572-580	BB+PPT
25.	Dielectric measurements	2	[S3] Pg:580-587	BB+PPT

26.	Ionic Interaction-Dipolar rotation	1	[S1] Pg: 173-174	BB+PPT
27.	Effect of moisture, temperature and pressure on dielectric properties	2	[S1] Pg: 177-180 [S3] Pg: 592-597	BB+PPT
28.	Microwave heating-Infrared	2	[S3] Pg: 282-308	BB+PPT
29.	Ohmic heating and Irradiation	2	[J2] [W4]	BB+PPT
30.	Tutorial	1	Revision	
TOTAL HOURS FOR UNIT- 5		**Theory hours : 10** **Tutorial hour : 1** **Total hours : 11**		
TOTAL HOURS		**50**		

SUGGESTED READINGS

S1 Sahin, S., and Sumnu, S.G. (2007). Physical Properties of Foods. Springer. USA.

S2 Mohsenin, N.N. (1990). Thermal Properties of Foods and Agricultural materials. Gordon and Reach science publishers.

S3 Rao, M.A., and Rizvi, S.S.H. (2014). Engineering Properties of Foods. 4th Edition Mercel Dekker Inc. New York.

S4 Lewis, M.J. (2006). Physical properties of foods and food processing systems. Wood head publishing Cambridge, UK.

S5 Rehman, S. (2009). Food properties Hand book. 2nd Edition. CRC press inc. New York.

S6 Ahmed, S., and Rahman, M.S., (2012). Handbook of Food Process design. Blackwell Publishing Ltd., USA.

WEBLINKS

W1 https://www.sciencedirect.com/topics/engineering/coefficient-of-friction

W2 https://www.hitachi-hightech.com/global/products/science/tech/ana/thermal/descriptions/dta.html

W3 https://link.springer.com/chapter/10.1007%2F978-94-010-1731-2_19

W4 https://apps.who.int/iris/bitstream/handle/10665/38544/9241542403_eng.pdf

JOURNALS

J1 Micheal, H.T. (2011). “Food Texture analysis in 21st century”, Journal of Agricultural and Food Chemistry, No.59, pg: 1477-1480.

J2 Soojin, J and Sudhir, S. (2005). “Modelling and optimization of Ohmic heating of foods inside a flexible package”, Journal of Food Process Engineering, No. 28, Pg: 417-436.

Faculty **Head of the Department** **Dean (FoE)**

ENGINEERING PROPERTIES OF FOOD MATERIALS

18BTFT402

Course Objectives

- Describe the physical properties of food materials
- Explain the rheology of food and use of viscometer and texture analyzer in food industry.
- Impart knowledge on thermal properties of food commodities
- Outline the aerodynamic and hydrodynamic properties of foods
- Define the electrical properties of food and its applications in food engineering.

Course Outcomes

1. Estimate the physical properties of food materials
2. Report the frictional properties and storage of agricultural crops
3. Compare and contrast the Newtonian and non-Newtonian fluids
4. Express the overall thermal properties of food materials
5. Measure the aero- and hydrodynamic characteristics and the application of frictional properties in grain handling, processing and conveying.
6. Demonstrate the dielectric and radiation heating properties of foods

UNIT I -PHYSICAL PROPERTIES OF FOODS

- Methods of estimation of Shape, Size, volume, density, porosity and surface area, sphericity, roundness specific gravity. Frictional properties-coefficient of friction, Storage and flow pattern of agricultural crops.

UNIT II -RHEOLOGICAL PROPERTIES OF FOODS

- Definition – classification – Newton’s law of viscosity – momentum-diffusivity-kinematic viscosity – viscous fluids – Newtonian and Non Newtonian fluids- Viscosity Measurements Viscometers of different types and their applications-Texture measuring instruments-Hardness and brittleness of Food materials.

UNIT III - THERMAL PROPERTIES OF FOODS

- Definitions of Heat capacity, specific heat, enthalpy, conductivity and diffusivity, surface heat transfer coefficient, Measurement of thermal properties like specific heat, enthalpy, conductivity and diffusivity, DTA, TGA, DSC.

UNIT IV - AERODYNAMIC AND HYDRODYNAMIC PROPERTIES OF FOODS

- Drag and lift coefficient, terminal velocity and their application in the handling and separation of food materials. Water activity-measurement-vapor pressure method – freezing point depression method- Effect of temperature, and pressure on water activity-moisture sorption isotherms- models-Henderson, PET and GAB models.

UNIT V - ELECTRICAL PROPERTIES OF FOODS

- Dielectric properties-dielectric constants, Dielectric measurements-Ionic Interaction-Dipolar rotation. Effect of moisture, temperature and pressure on dielectric properties. Microwave heating-Infrared and Ohmic heating, Irradiation

Introduction

- Mass–volume–area-related properties are one of five groups (acoustic, mass–volume–area related, morphological, rheological, and surface) of mechanic.
- These properties are needed in process design, for estimating other properties, and for product characterization or quality determination.
- The geometric characteristics of size, shape, volume, surface area, density, and porosity are important In many food materials handling and processing operations.
- Fruits and vegetables are usually graded depending on size, shape, and density.
- Impurities in food materials are separated by density differences between impurities and foods.

- Knowledge of the bulk density of food materials is necessary to estimate floor space during storage and transportation.

- When mixing, transportation, storing, and packaging particulate matter, it is important to know the properties of bulk material.

- The surface areas of fruits and vegetables are important in investigations related to spray coverage, removal of residues, respiration rate, light reflectance, and color evaluation, as well as in heat-transfer studies in heating and cooling processes.

- In many physical and chemical processes, the rate of reaction is proportional to the surface area; thus, it is often desirable to maximize the surface area.

- Density and porosity have a direct effect on the other physical properties.

- Volume change and porosity are important parameters in estimating the diffusion coefficient of shrinking systems.

- Porosity and tortuosity are used to calculate effective diffusivity during mass transfer processes.
- Mechanical properties of agricultural materials also vary with porosity

Size

- Size is an important physical attribute of foods used in screening solids to separate foreign materials, grading of fruits and vegetables, and evaluating the quality of food materials.
- In fluid flow, and heat and mass transfer calculations, it is necessary to know the size of the sample.
- Size of the particulate foods is also critical. For example, particle size of powdered milk must be large enough to prevent agglomeration, but small enough to allow rapid dissolution during reconstitution.
- Particle size was found to be inversely proportional to dispersion of powder and water holding capacity of whey protein powders.
- Decrease in particle size also increased the steady shear and complex viscosity of the reconstituted powder complex viscosity of the reconstituted powder.
- The size of semolina particles was found to influence mainly sorption kinetics.

- The importance of particle size measurement has been widely recognized, especially in the beverage industry, as the distribution and concentration ratio of particulates present in beverages greatly affect their flavor.
- It is easy to specify size for regular particles, but for irregular particles the term size must be arbitrarily specified.
- Particle sizes are expressed in different units depending on the size range involved.
- Coarse particles are measured in millimeters, fine particles in terms of screen size, and 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

- Size can be determined using the projected area method. In this method, three characteristic dimensions are defined
- **Major diameter**, which is the longest dimension of the maximum projected area
- **Intermediate diameter**, which is the minimum diameter of the maximum projected area or the maximum diameter of the minimum projected area; and
- **Minor diameter**, which is the shortest dimension of the minimum projected area.

- Length, width, and thickness terms are commonly used that correspond to major, intermediate, and minor diameters, respectively.
- The dimensions can be measured using a **micrometer or caliper.**
- **The micrometer** is a simple instrument used to measure distances between surfaces.
- Most **micrometers** have a frame, anvil, spindle, sleeve, thimble, and ratchet stop.

- They are used to measure the outside diameters, inside diameters, the distance between parallel surfaces, and the depth of holes.

- Particle size of particulate foods can be determined by sieve analysis, passage through an electrically charged orifice, and settling rate methods.

- Particle size distribution analyzers, which determine both the size of particles and their state of distribution, are used for production control of powders.

SHAPE

- Shape is also important in heat and mass transfer calculations, screening solids to separate foreign materials, grading of fruits and vegetables, and evaluating the quality of food materials.
- The shape of a food material is usually expressed in terms of its sphericity and aspect ratio.
- **Sphericity** is an important parameter used in fluid flow and heat and mass transfer calculations.
- Sphericity or shape factor can be defined in different ways.
- According to the most commonly used definition, sphericity is the ratio of volume of solid to the volume of a sphere that has a diameter equal to the major diameter of the object so that it can circumscribe the solid sample.
- For a spherical particle of diameter *Dp*, sphericity is equal to 1.

$$\text{Sphericity} = \left(\frac{\text{Volume of solid sample}}{\text{Volume of circumscribed sphere}}\right)^{1/3}$$

- Assuming that the volume of the solid sample is equal to the volume of the triaxial ellipsoid which has diameters equivalent to those of the sample, then:

$$\Phi = \left(\frac{V_e}{V_c}\right)^{1/3}$$

where

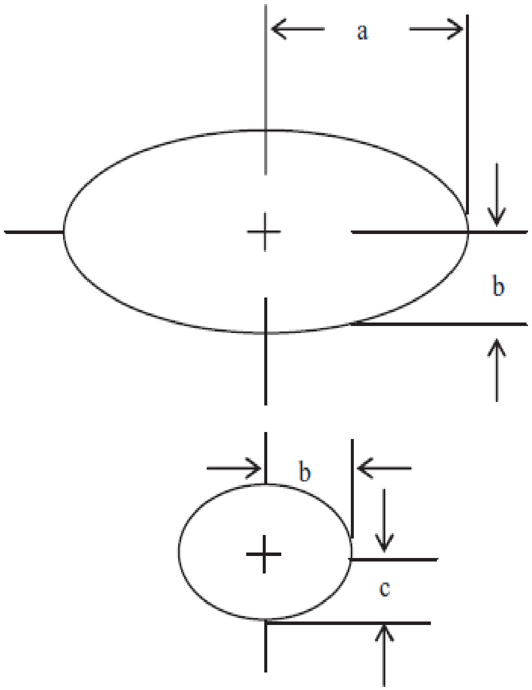
Φ = sphericity,
V_e = volume of the triaxial ellipsoid with equivalent diameters (m^3),
V_c = volume of the circumscribed sphere (m^3).

- In a triaxial ellipsoid, all three perpendicular sections are ellipses. If the major, intermediate, and minor diameters are $2a$, $2b$, and $2c$, respectively, volume of the triaxial ellipsoid can be determined from the following equation:

$$V_e = \frac{4}{3}\pi abc$$

Then, sphericity is:

$$\Phi = \frac{(abc)^{1/3}}{a}$$



- Sphericity is also defined as the ratio of surface area of a sphere having the same volume as the object to the actual surface area of the object.

$$\Phi = \frac{\pi D_p^2}{S_p} = \frac{6V_p}{D_p S_p}$$

where

D_p = equivalent diameter or nominal diameter of the particle (m),
S_p = surface area of one particle (m^2),
V_p = volume of one particle (m^3).

- The equivalent diameter is sometimes defined as the diameter of a sphere having the same volume as the particle.
- However, for fine granular materials, it is difficult to determine the exact volume and surface area of a particle.
- Therefore, equivalent diameter is usually taken to be the nominal size based on screen analysis or microscopic examination in granular materials.
- The surface area is found from adsorption measurements or from the pressure drop in a bed of particles.

- In general, diameters may be specified for any equidimensional particle.
- Particles that are not equidimensional, that is, longer in one direction than in others, are often characterized by the second longest major dimension. For example, for needle like particles, equivalent diameter refers to the thickness of the particles, not their length.
- In a sample of uniform particles of diameter *Dp*, the number of particles in the sample is:

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

where

N = the number of particles,
m = mass of the sample (kg),
ρ_p = density of the particles (kg/m^3),
V_p = volume of one particle (m^3).

- Total surface area of the particles is obtained from

$$A = N S_p = \frac{6m}{\Phi \rho_p D_p}$$

- Another definition of sphericity is the ratio of the diameter of the largest inscribed circle (*di*) to the diameter of the smallest circumscribed circle (*dc*)

$$\Phi = \frac{d_i}{d_c}$$

- Another equation to calculate sphericity as:

$$\Phi = \frac{\sum \left(D_i - \overline{D}\right)^2}{\left(\overline{D}N\right)^2}$$

where

D_i = any measured dimension (m),
$\overline{D}$ = average dimension or equivalent diameter (m),
N = number of measurements (the increase in N increases the accuracy).

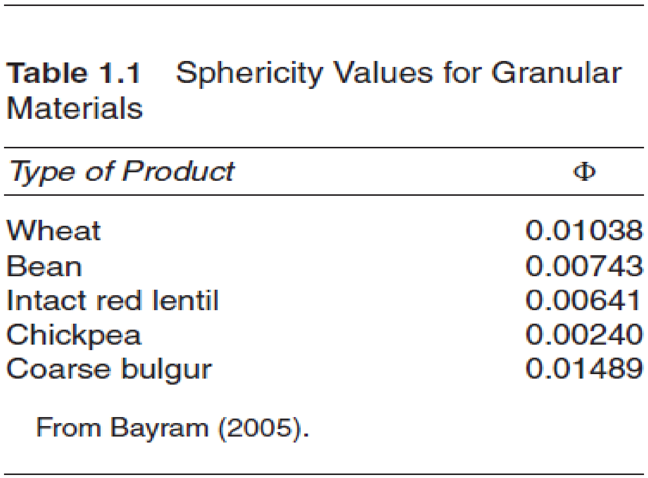


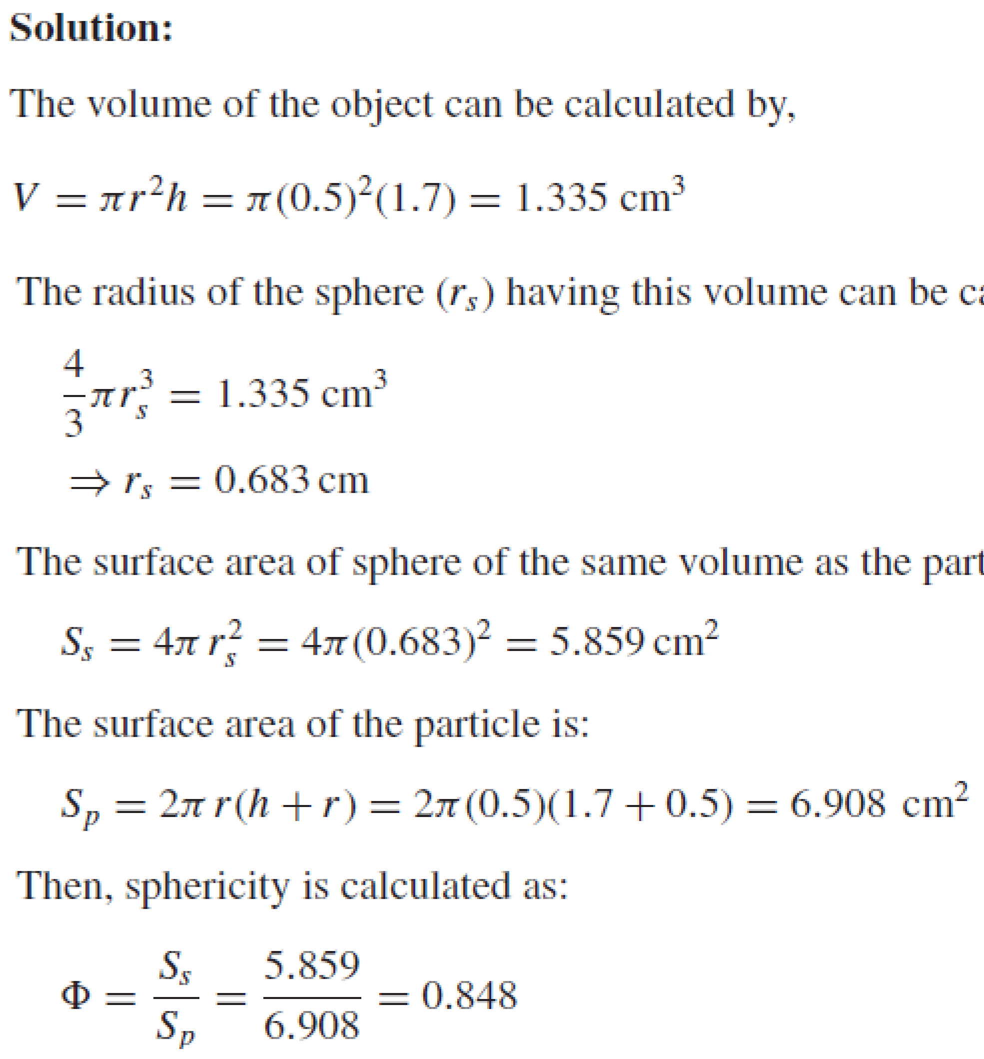
Table 1.1 Sphericity Values for Granular Materials

Type of Product	Φ
Wheat	0.01038
Bean	0.00743
Intact red lentil	0.00641
Chickpea	0.00240
Coarse bulgur	0.01489

From Bayram (2005).

- According to this formula, equivalent diameter for irregular shape material is accepted as the average dimension.
- Differences between average diameter and measured dimensions are determined by the sum of square of differences.
- When this difference is divided by the square of product of the average diameter and number of measurements, it gives a fraction for the approach of the slope to an equivalent sphere, which is sphericity.
- According to the above equation, if the sample sphericity value is close to zero it can be considered as spherical.

- Calculate the sphericity of a cylindrical object of diameter 1.0 cm and height 1.7 cm.



Solution:

The volume of the object can be calculated by,

$$V = \pi r^2 h = \pi (0.5)^2 (1.7) = 1.335 \text{ cm}^3$$

The radius of the sphere (r_s) having this volume can be calculated as:

$$\frac{4}{3}\pi r_s^3 = 1.335 \text{ cm}^3$$

$$\Rightarrow r_s = 0.683 \text{ cm}$$

The surface area of sphere of the same volume as the particle is:

$$S_s = 4\pi r_s^2 = 4\pi (0.683)^2 = 5.859 \text{ cm}^2$$

The surface area of the particle is:

$$S_p = 2\pi r(h + r) = 2\pi (0.5)(1.7 + 0.5) = 6.908 \text{ cm}^2$$

Then, sphericity is calculated as:

$$\Phi = \frac{S_s}{S_p} = \frac{5.859}{6.908} = 0.848$$

- **The aspect ratio (*Ra*)** is another term used to express the shape of a material. It is calculated using the length (*a*) and the width (*b*) of the sample as

$$R_a = \frac{b}{a}$$

- Certain parameters are important for the design of conveyors for particulate foods, such as radius of curvature, roundness, and angle of repose.
- **Radius of curvature** is important to determine how easily the object will roll.
- The more sharply rounded the surface of contact, the greater will be the stresses
- developed.
- A simple device for measuring the radius of curvature is shown in figure below.
- It consists of a metal base that has a dial indicator and holes into which pins are placed.
- Two pins are placed within these holes according to the size of the object.
- When the two pins make contact with the surface, the tip of the dial indicator is pushed upwards.
- Then, the dial indicator reads the sagittal height (*S*).
- The radius of curvature is calculated from the measured distances using this simple device and the following formula:

$$\text{Radius of curvature} = \frac{(D/2)^2 + S^2}{2S}$$

where

D = spacing between the pins (m),
S = sagittal height (m).

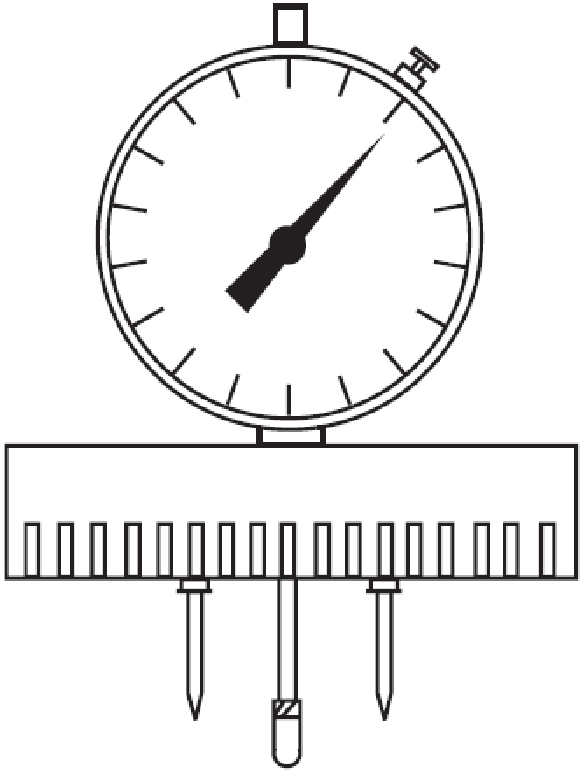
- The minimum and the maximum radii of curvature for larger objects such as apples are calculated using the larger and smaller dial indicator readings, respectively.
- For smaller objects of relatively uniform shape, the radius of curvature can be calculated using the major diameter and either the minor or intermediate diameter.

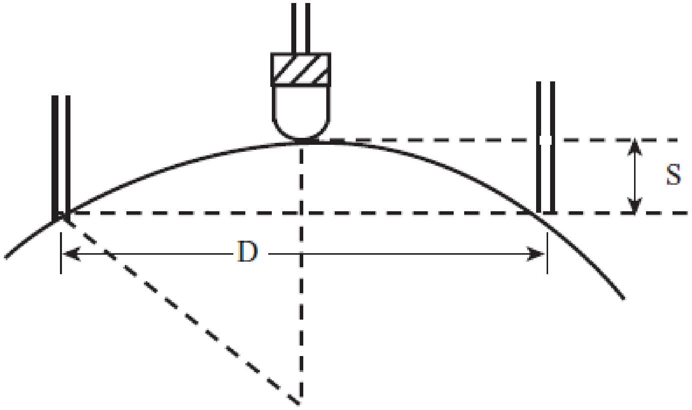
$$R_{\min} = \frac{H}{2}$$

$$R_{\max} = \frac{H^2 + \frac{L^2}{4}}{2H}$$

where

$R_{\min}$ = Minimum radius of curvature (m),
$R_{\max}$ = Maximum radius of curvature (m),
H = intermediate diameter or the average of minor and major diameters (m),
L = major diameter (m).





The major diameter (*L*) and the average of the minor and major diameters (*H*) of barley are measured as 8.76 mm and 2.83 mm, respectively. Calculate the minimum and maximum radii of curvature for the barley.

Solution: The minimum and maximum radius of curvatures can be calculated

$$R_{\text{min}} = \frac{H}{2} = \frac{2.83}{2} = 1.415 \text{ mm}$$

$$R_{\text{max}} = \frac{H^2 + \dfrac{L^2}{4}}{2H} = \frac{(2.83)^2 + \dfrac{(8.76)^2}{4}}{2(2.83)} = 4.804 \text{ mm}$$

- **Roundness** is a measure of the sharpness of the corners of the solid. Several methods are available for estimating roundness.

$$\text{Roundness} = \frac{A_p}{A_c}$$

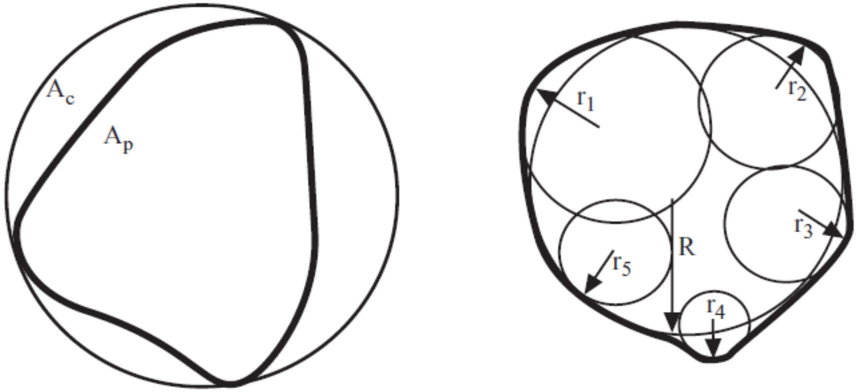
where

Ap = largest projected area of object in natural rest position (m^2),

Ac = Area of the smallest circumscribing circle

- **Roundness can also be estimated**

$$\text{Roundness} = \frac{\sum_{i=1}^{N} r}{NR}$$



(a) (b)

Roundness definitions.

where

r = radius of curvature (m),

R = radius of the maximum inscribed circle (m),

N = total number of corners summed in numerator.

Angle of repose

- **Angle of repose** is another important physical property used in particulate foods such as seeds, grains, and fruits.
- When granular solids are piled on a flat surface, the sides of the pile are at a definite reproducible angle with the horizontal.
- This angle is called the angle of repose of the material.
- The angle of repose is important for the design of processing, storage, and conveying systems of particulate material.
- When the grains are smooth and rounded, the angle of repose is low.
- For very fine and sticky materials the angle of repose is high.
- For determination of this property, a box with open sides at the top and bottom is placed on a surface.
- The angle of repose is determined by filling the box with sample and lifting up the box gradually, allowing the sample to accumulate and form a conical heap on the surface.
- Then, the angle of repose is calculated from the ratio of the height to the base radius of the heap formed.

9 Friction of Solids and Flow of Granular Solids

During the handling, harvesting, processing and storage of grains, seeds, fruits, vegetables, forage and biomass, the products exert frictional forces on machinery components or storage structures. Knowledge of the magnitude of these frictional forces becomes important in design of equipment and processes. This chapter will discuss the basic principles of friction as they apply to the interaction of agricultural materials and food products with surfaces. This type of interaction occurs in an enclosed auger as the rotating screw of the auger pushes the material along the surface of the enclosing steel tube. The magnitude of this friction force affects the amount of power required to convey the material. Friction between a particulate solid and a conveyor belt affects the maximum angle with the horizontal which the conveyor can assume when transporting the solid. The forces which particles exert on the walls of bins and other storage structures, under both static and quasi-static conditions, are also affected by friction among particles and the friction between the particles and the structure.

A second topic discussed in this chapter is the flow of particulate solids through orifices and their flow pattern during emptying of bins and enclosures. Internal friction among particles influences the flow pattern. Many granular materials are metered through orifices during handling. Therefore, it is often necessary to estimate the flow rate of the material. The manner in which particulate materials flow from a bin is affected by both particle interaction and the angle which the bottom of the bin makes with the horizontal.

9.1 Friction -Basic Definitions and Properties

The force of friction acts to resist relative motion between two solid objects in contact. When two solid objects are in contact, the relationship between the tangential force required to move the objects relative to each other and the normal force pressing the objects together is given by Coulomb's law. For example, if a block of wood is resting on a flat metal surface, the tangential force, F_t, required to move the block across the surface of the metal is given by:

$$F_t = \mu F_n \tag{9.1}$$

where F_n is the normal force exerted by the block on the metal surface, and μ is the static or dynamic coefficient of friction. F_t acts in the direction opposite to the direction of relative motion. The static coefficient of friction, μ_s , predicts the force at the point in time when motion is initiated, and the dynamic coefficient of friction, μ_d predicts the force required to maintain motion once it has been initiated. For a given applied normal force, F_n, the force required to maintain motion is less than or equal to the force required to initiate motion. Therefore, $\mu_d \leq \mu_s$. In fact, as a tangential force is applied to the block of wood, the static friction increases up to the point when relative motion begins, and then it drops off rapidly to the level of dynamic friction. Coulomb's law, which is empirical, assumes that F_t is independent of the apparent area of contact between the two surfaces. In the case of sliding friction, it is also assumed to be independent of the relative velocity of the two surfaces. However, it is dependent on the nature of the materials in contact. For example, the coefficient of friction for two blocks of wood in contact differs from the coefficient for two blocks of steel in contact.

Another way of visualizing the static coefficient of friction μ_s in the example in the preceding paragraph is to imagine that the metal surface is a long strip which is hinged at one end. If the opposite end of the strip is lifted, the wooden block will now be resting on an incline. When the incline is sufficiently steep, the block will begin to slide down the incline. Assume that when sliding begins the angle which the incline makes with the horizontal is α. The gravitational force F_g acts downward on the block. It can be resolved into two components acting on the inclined metal strip. One component acts normal to the surface of the block and is equal to $F_g \cos \alpha$. The other acts in a tangential direction and is $F_g \sin \alpha$. If these forces are substituted into equation 9.1 and the equation is solved for μ, then $\mu_s = \tan \alpha$. Therefore, the static coefficient can be determined from the angle of the incline when motion is initiated.

The values of μ_s and μ_d are dependent on the characteristics of the materials. Typical values for some agricultural materials are given in Table 9.1. Note that for a given type of grain, the coefficient is greater for contact with wood than for contact with teflon. The moisture content of the grain also affects the magnitude of the friction force.

9.1.1 A Microscopic View of Interaction Between Surfaces

Tribology is the study of friction and the interaction between solids which occurs when there is relative motion between two surfaces in contact with each other. Two surfaces which appear quite smooth to the naked eye may be quite irregular if viewed on a microscopic level. At the microscopic level, it is possible to make a distinction between A_o, the apparent area of contact between two surfaces and A_a the actual area of contact. This is illustrated in Figure 9.1A. The apparent area of contact between the two blocks, A_o is a b. However, at the microscopic level, both of the surfaces are irregular, even in the case of polished steel. Therefore, the surfaces are only in contact at points where the asperities, which are "peaks" of the irregular surfaces, make contact. Thus, the actual area of contact between the two surfaces, A_a, might be represented by the shaded area on the surface of the lower block (Fig. 9.1A, right). In most cases $A_0 \gg A_a$

It is also instructive to consider the interaction between two asperities when there is relative motion between two contacting surfaces. This interaction is illustrated in Figure 9.1B. When contact is first initiated, the two asperities will exert forces on each other which will cause elastic deformation. Depending on the types of surfaces which are in contact, the forces may increase to the point where some plastic deformation occurs. If one asperity is much "harder" than the other, ploughing may occur. In this type of interaction, a portion of the softer surface may be sheared away. This can be illustrated by an extreme example of a macroscopic interaction: a metal file being dragged across the surface of a slab of butter. The ridges on the file dig into the soft butter, quickly shearing it away.

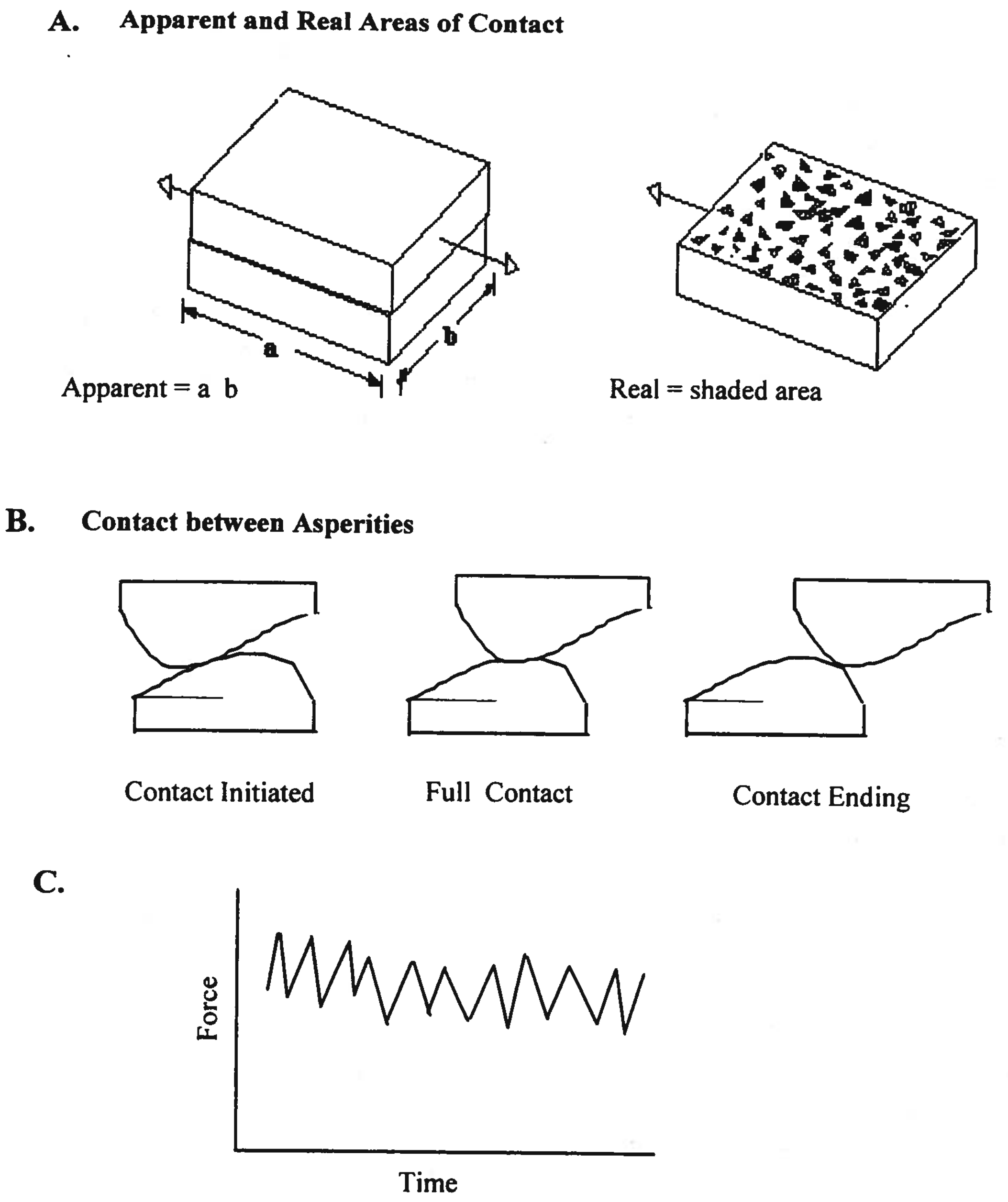


Figure 9.1. Microscopic aspects of friction of solids. **A.** Apparent and actual areas of contact between two surfaces. **B.** Tribological interaction between two solids as an asperity on one solid moves over an asperity on the second solid. **C.** Stick-slip motion.

As the interaction continues, the two crests of the asperities move across each other. This motion will be resisted by adhesion bonding or "welding" between the two surfaces. The bonding occurs because of interaction at the molecular level. Molecular forces include those involved in chemical bonding such as metallic bonds and Van der Waals forces. This type of interaction is affected by surface composition, which is in turn influenced by surface contaminants, absorbed layers (e.g. metal soaps), and oxides (e.g. rust) which may have formed on the surface. One common surface contaminant is water. Anyone who walks on ice covered by water quickly becomes familiar with the marked reduction in friction which water can create. In the case of grains and seeds, the adhesion between the surfaces actually increases when the outer layers of the seed are wet. Therefore the coefficient of friction of wet grain is also greater. The surfaces of many grains and seeds are covered by a waxy layer of cutin. When corn slides across a metal surface, this cutin can form a thin layer on the surface which in turn increases the coefficient of friction.

As sliding contact continues, the two asperities begin to separate. If welding has occurred between the asperities, a shearing force will be needed to break apart the welded surfaces. Elastic recovery will also occur. When two surfaces are in contact, thousands of these asperities are interacting in one of these ways at any given instant of time. This gives rise to the potential for "stick-slip" motion in which the net force required to pull one surface across the other varies erratically with time (Fig. 9.1C).

9.1.2 Coefficients of Friction

Values of the static coefficient of friction, μ_s, of grains and seeds and several granular or powdered food products are given in Table 9.1. Coefficients can be affected by properties of the material, such as moisture content, as well as the type of surface over which the material is moving. For example, one source (Table 9.1) gave μ_s of alfalfa pellets on wood as 0.39 and μ_s on steel as 0.22. Similarly, another researcher gave two values for μ_s of shelled corn on concrete. The coefficient was reported as 0.54 for a relatively rough wood float finish but only 0.35 on the plastic smooth finish. Similarly, μ_s was 0.12 for shelled corn on teflon but 0.44 for shelled corn on rubber. In general, the μ_s of a given type of granular material is greater at higher moistures. For example, Brubacker and Pos (1965) report that μ_s of wheat on galvanized sheet steel is 0.33 at 15.9% m.c., 0.27 at 15.0% m.c., 0.14 at 13.0% m.c., and 0.10 at 11.2% m.c. Note that the effect of a given change in moisture on μ_s is more pronounced at the higher moistures.

As noted in Section 9.1, the force required to maintain motion is less than (or equal to) the force required to initiate motion. Therefore, the dynamic coefficient of friction, μ_d is less than or equal to μ_s. Values of μ_d for several agricultural materials are given in Table 9.2. A comparison (Tables 9.1, 9.2) for alfalfa pellets on wood shows that μ_d and μ_s are 0.28 and 0.39, respectively. Values for alfalfa pellets on steel are more nearly the same. As in the case of μ_s one would expect μ_d to decrease with a decrease in moisture. In some cases, normal force may affect μ_d. In data reported by Richter (1954) μ_d of corn silage (73% m.c.) on polished galvanized steel measure at a velocity of 0.10 m/s decreased from 0.70 at a normal pressure of 426 Pa to 0.66 at a normal pressure of 1360 Pa. This same trend is apparent for values of μ_d averaged over a range of velocities (Table 9.2). However, for the same conditions (surface, velocity, normal pressure) μ_d of grass silage (73% m.c.) increased from 0.65 to 0.71. Similarly, μ_d of chopped straw (same surface and velocity) remained relatively constant. It was 0.29, 0.30 and 0.30 for normal pressures of 680, 1365, and 2730 Pa, respectively. Richter also reported fluctuations in μ_d with velocity.

Table 9.1. Static Coefficients of Friction for Agricultural Materials.

Material	Type Surface & Characteristics	Moisture content	Coef.	Reference
Alfalfa Pellets	Steel	n.r.[a]	0.22	Kososki (1976)
	Wood	n.r.	0.39	"
Alfalfa, Chopped	Steel	n.r.	0.37	Kososki (1976)
	Wood	n.r.	0.49	"
Barley	Concrete, wood float finish	12.3	0.52	Brubaker and Pos
	Wood, Douglas fir, grain	12.3	0.31	(1965)
	parallel	12.3	0.17	"
	Galvanized Sheet metal			"
Canola Meal	Concrete, wood float finish	12.7	0.61	Kukelko et al.
	Plywood, parallel to grain	12.7	0.49	(1988)
	Galvanized Steel	12.7	0.31	"
				"
Corn, Shelled	Concrete, wood float finish	13.9	0.54	Brubaker and Pos
	Concrete, plastic smooth finish	13.9	0.35	(1965)
	Wood, Douglas fir, grain	13.9	0.37	"
	parallel			"
	Galvanized sheet metal	13.9	0.37	"
	Polyethylene	13.9	0.38	"
	Teflon	13.9	0.12	"
	Rubber	13.8	0.44	Chung et al. (1982)
Corn silage	Steel, polished galv.[b] 960 Pa	74.	0.60	Richter (1954)
Fish Meal	Steel	n.r.	0.38	Kososki (1976)
Limestone	Steel	n.r.	0.45	Kososki (1976)
Meat Scraps	Steel	n.r.	0.32	Kososki (1976)
Oats	Concrete, wood float finish	13.0	0.44	Brubaker and Pos
	Wood, Douglas fir, grain par	13.0	0.29	(1965)
	Galvanized sheet metal	13.0	0.24	"
Oyster Shells	Steel	n.r.	0.38	Kososki (1976)
	Wood	n.r.	0.60	"
Rice (rough)	Wood, Douglas fir, grain par.	≈14.	0.44	Kososki (1976)
	Galvanized sheet metal	≈14.	≈0.45	"
Soybeans	Concrete, wood float finish	12.2	0.52	Brubaker and Pos
	Wood, Douglas fir, grain par.	12.2	0.35	(1976)
	Galvanized sheet metal	12.2	0.20	"
	Rubber	11.6	0.22	Chung et al. (1982)
Straw (chop)	Steel, polished galv.[b], 960 Pa	n.r.	0.20	Richter (1954)
Wheat	Concrete, wood float finish	11.2	0.51	Brubaker and Pos
	Wood, Douglas fir, grain pr.	11.2	0.31	(1976)
	Galvanized sheet metal	11.2	0.10	"

[a] n.r. indicates that moisture contents were not reported.

[b] Coefficient varied with normal force. Values given are for normal force indicated

μ_d

Table 9.2. Dynamic (sliding) Coefficients of Friction for Agricultural Materials.

Material	Type Surface & Characteristics	Moisture Content	Coef.	Reference
Alfalfa Pellets	Steel	n.r. [a]	0.17	Kososki (1965)
	Wood	n.r.	0.28	"
Alfalfa, Chopped	Steel	n.r.	0.34	Kososki (1965)
	Wood	n.r.	0.37	"
Corn Silage	Polished Galv. Steel[b], 426 Pa	73%	0.70	Richter (1954)
	Polished Galv. Steel, 680 Pa	73%	0.68	"
	Polished Galv. Steel, 1360 Pa	73%	0.66	"
Fish Meal	Steel	n.r.	0.35	Kososki (1965)
Limestone	Steel	n.r.	0.43	Kososki (1965)
Oyster Shells	Steel	n.r.	0.35	Kososki (1965)
Straw	Polished Galv. Steel[b], 680 Pa	n.r.	0.30	Richter (1954)
	Polished Galv. Steel, 1360 Pa		0.30	"

[a] n.r. indicates that moisture contents were not reported.

[b] Average values for velocities between 0.025 and 1.62 m/s. The coefficient varied with normal force and therefore the normal force at which the measurements were taken is included.

9.1.3 Angle of Repose of Granular Material

When granular material is removed from a opening in the bottom of a bin, or when it is dropped into bins or allowed to form a pile, the coefficient of friction between individual particles will affect the angle which the surface of the material assumes with the horizontal. This angle is called the **angle of repose**. In general, the angle of repose in situations where the material is being emptied from a bin, called the angle of repose for **emptying** or **funneling**, will be greater than the angle of repose for **filling** or **piling**, which is the angle formed when material is allowed to flow from a spout or elevator outlet so as to form a pile. These angles are particularly useful for calculating the quantity of granular materials that can be placed in piles or on storage structures with flat floors. Angles of repose for some agricultural materials and for coal and glass beads are given in Table 9.3. As moisture content increases, the emptying or funneling angle of repose increases. For example, the angle of repose (emptying) of shelled corn at 13.0% m.c. was reported as 28° while at 23% m.c. it was reported as 38°. Note also that the angles of repose of shelled corn for emptying and filling were, respectively, 27° and 16°.

Table 9.3. Angles of Repose for Agricultural Materials and Selected Granular Materials.

Material	Moisture Content[a]	Angle of Repose		Reference
		Emptying or Funneling	Filling or Piling	
Barley	n.r.	28	16	Stahl (1950)
	7.9	29.6		Lorenzen (1957)
	13.3	31.0		"
	16.6	31.6		"
	19.5	34.0		"
	23.2	34.6		"
Canola Meat	5.2	34.3[b]	34.5	Kukelko et al (1988)
	9.9	32.2	35.5	"
	12.6	33.1	34.4	"
	17.8	39.5	33.5	"
Canola Meal Pellets	10.5	31.5[b]	26.7	Kukelko et al. (1988)
Coal 16-28 mesh	n.r.	31		Franklin & Johanson (1955)
Corn (shelled)	n.r.	27	16	Stahl (1950)
	7.3	27.7		Lorenzen (1957)
	13.0	28.3		"
	16.2	30.3		"
	19.5	34.0		"
	23.1	38.0		"
Flaxseed	n.r.	25	14	Stahl (1950)
Glass Beads (5 mm)	n.r.	22.5		Franklin & Johanson (1955)
Oats	n.r.	32	18	Stahl (1950)
Rice (Rough)	n.r.	36	20	Stahl (1950)
	9.6	34.0		Lorenzen (1957)
	12.1	35.0		"
	17.6	38.7		"
Rice (Puffed)	n.r.	31.5		Franklin & Johanson (1955)
Soybeans	n.r.	29	16	Stahl (1950)
Wheat (winter)	n.r.	27	16	Stahl (1950)
	7.3	29.6		Lorenzen (1957)
	11.0	29.3		"
	14.1	31.0		"
	17.1	35.6		"
	19.3	41.0		"
Vetch	n.r.	25	14	Stahl (1950)

[a] n.r. indicates that moisture content was not reported in the reference

[b] The authors reported that there were two distinct angles observed--a steeper upper angle and a flatter lower angle. The value reported here is the lower angle.

9.1.4 Friction in Granular Material

When the individual particles which comprise granular materials move in relation to each other, the relative motion of the particles is resisted by the friction between particles. Figure 9.2A illustrates the measurement of this resistance by means of a direct shear cell. The resistance to motion is quantified by the **angle of internal friction,** ϕ_i or the **coefficient of internal friction,** μ_i. The two quantities are related by the equation:

$$\mu_i = \tan \phi_i . \tag{9.2}$$

The value of μ_i is determined by applying various normal loads, F_n, to the material in the retaining cup and ring (Figure 9.2A) and measuring F_t, the force required to move the ring in relationship to the retaining cup. If the internal diameters of the retaining cup and ring are D_i, their cross sectional areas, A_j, are $\pi D_i^2 / 4$ and the normal stress, σ, and shear stress, τ, can be calculated as follows:

$$\sigma = \frac{F_n}{A_i} \quad \text{and} \quad \tau = \frac{F_t}{A_i} \tag{9.3}$$

For an ideal material, the plot of τ versus σ gives a straight line with slope μ_i, as shown in Figure 9.2B and τ and σ are related by the following equation:

$$\tau = \sigma \tan \phi_i = \sigma \mu_i \tag{9.4}$$

For some materials, the shearing stress τ will be nonzero, τ_0, when the normal stress σ is zero. This is the case with cohesive granular materials such as heavy soils. The relationship between τ and σ (Fig. 9.2B) is as follows:

$$\tau = \tau_0 + \sigma \tan \phi_i \tag{9.5}$$

In some cases the relationship between τ and σ is nonlinear and follows an exponential relationship:

$$\tau = [(\sigma + b) \lambda_0]^{\frac{1}{m}} \tag{9.6}$$

where b, m and λ_0 are constants. In these types of material, an "effective" angle of internal friction can be defined for a given value of σ. In Fig. 9.2 the effective angle at point A would be σ_A/τ_A and is the same as the angle for an ideal bulk material in which the straight line defining the relationship between τ and σ passes through the origin and point A. Sitkei (1986) reported that cereals behave in this manner when σ exceeds 4 N/cm^2. In other cases the relationship between τ and σ becomes linear after σ exceeds a certain value (Fig. 9.2B). Sitkei (1986) gives equations for calculating the various constants which define the curve and states that this curve describes cereal grains when σ does not exceed 2 to 4 N/cm^2.

Like the coefficient of friction, the angle of internal friction is influenced by moisture content and the shape and size of the particles. In addition it can vary with the amount of consolidation or settling which the material has experienced. Values for ϕ_i for several materials are given in Table 9.4.

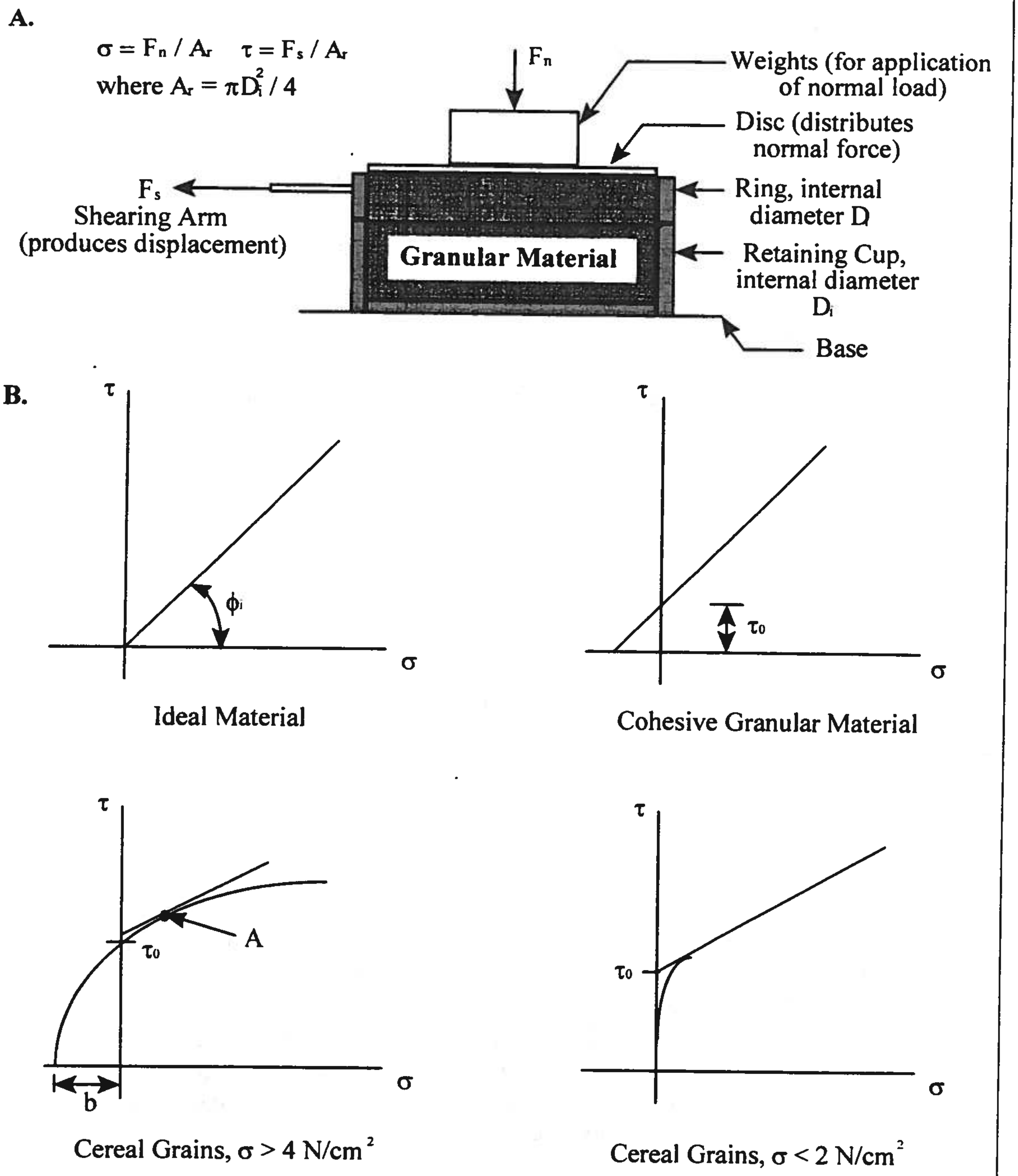


Figure 9.2. Angle of internal friction, ϕ_i, of granular material. **A.** Direct shear cell used for measurement of ϕ_i (Kamath et al., 1991). **B.** Relationshi between τ and σ for various types of granular materials (adapted from Sitkei, 1986).

Table 9.4. Angle of internal friction and density of agricultural materials and food products.

Material	Moisture Content (% w.b.)	Angle of Internal Friction	Bulk Density (kg/m^3)	Method of Measurement	Reference
Flour (Wheat)	10.6	29.6	842.	Direct Shear	Kamanth et al. (1991)
Milk (non-fat, Powdered)	2.7	26.	507.	Direct Shear	Hayashi et al. (1968)
	4.2	33.5	671.	"	"
	4.8	36.0	772.	"	"
Sand	n.r.	24.1	1730.	"	"
Sorghum	13.0	25.5	801.	Triaxial Test	Stewart (1968)
	17.7	26.0	801.	"	"
Sugar	0.014	34.0	1025.	Direct Shear	Hayashi et al. (1968)
Wheat	11.0	24.5	790.	?	Lorenzen (1957)
	17.1	27.3	727.	?	"

9.2 Friction - Measurement Techniques

9.3 Flow of Granular Materials

Many agricultural materials and food products are granular in nature and relatively dry. Examples of such dry granular materials are grains and seeds, soybean and cottonseed meals, wheat and corn flour, and breakfast cereals. These materials are often stored in bulk bins or containers from which they are metered onto belts or conveyors or poured into boxes. Both the manner in which these materials flow from the containers and the rate at which they flow through an orifice of a given size and shape can be of great importance in the design and operation of processing facilities. This section first describes flow patterns for these materials and then gives equations which can be used to predict flow through orifices of various sizes.

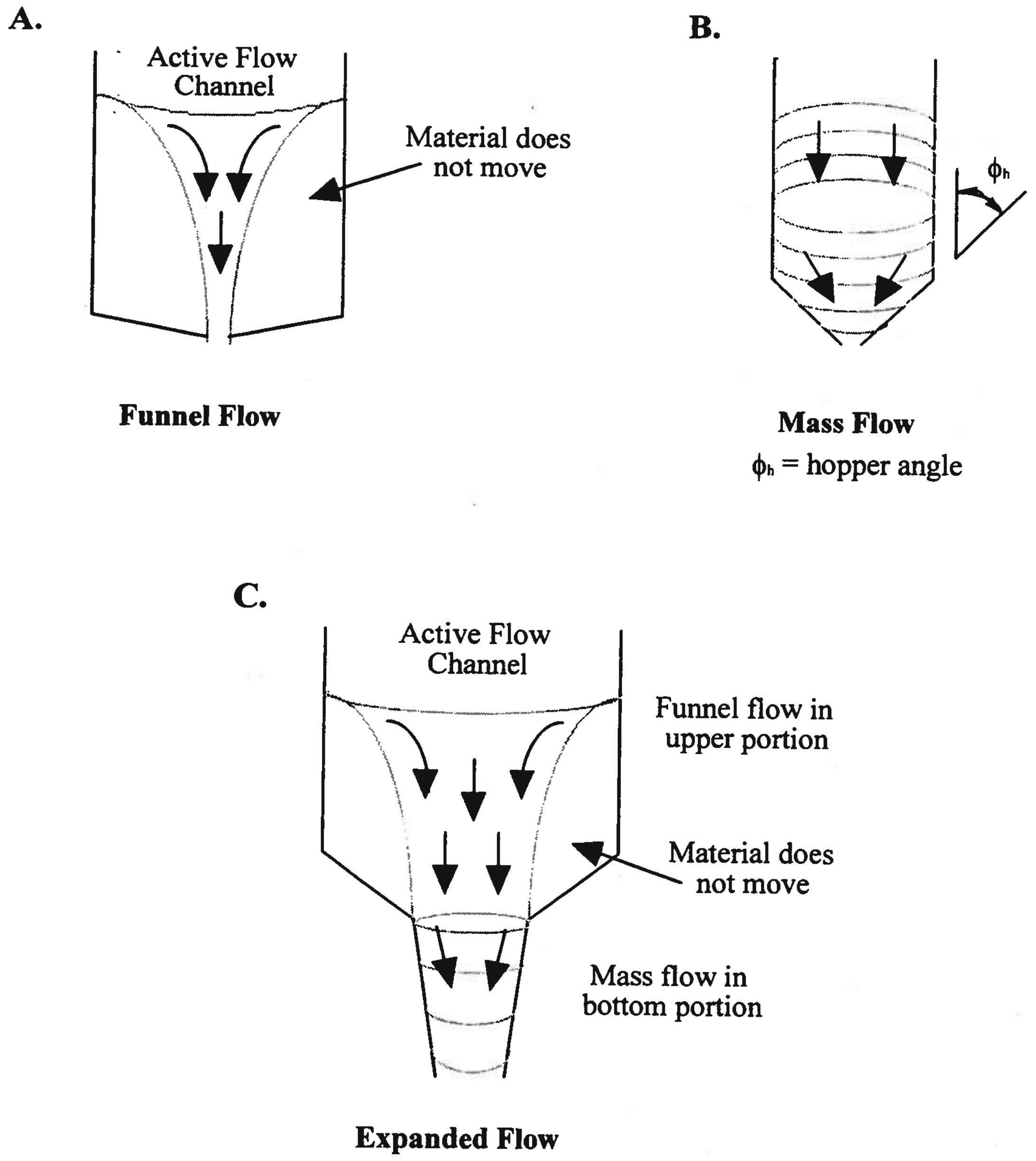
9.3.1 Flow Patterns

In most situations where granular materials are stored in bins, the material is removed from the bins through an opening in the center of the bottom. If the material is free flowing, it usually flows from the bin in one of the three types of patterns shown in Figure 9.3: funnel flow, mass flow, and expanded flow. These patterns are explained in more detail in the following paragraphs. Examples of free flowing granular materials include dry, clean whole grain and pelleted feeds. Materials which are high in moisture and/or contain fibrous materials (e.g. high moisture ground ear corn containing shredded husks), irregularly shaped materials and finely ground feeds may not be free-flowing. Other materials may not be free-flowing because they bind together as a result of the effects of temperature, moisture, and pressure. Examples of such materials are some types of dry fertilizer (e.g. ammonium nitrate), salt and sugar.

Funnel flow occurs in bins with flat bottoms or bins with sloping bottoms in which the angle which the bottom of the bin makes with the vertical is less than a critical angle termed the hopper angle. In this type of flow the material first flows from a center "core" which is approximately the size of the opening at the bottom of the bin and which, like a funnel, slowly expands in diameter with height above the opening (Fig. 9.3A). A large ring of material is supported by the floor and remains stagnant. As flow proceeds, material from the top surface flows into the "funnel" of flowing particles. Thus the majority of the bin unloads from the top to the bottom. This is the type of design that is used for most grain bins. The major advantages are that it is a simple design and it is easy to build. Therefore, construction costs are relatively low. However, there are disadvantages which include the "top down" unloading pattern in which first material placed in the bin is the last to be removed. If additional material is placed in the bin after some has been removed, the material around the bottom of the bin and near the walls may remain "in storage" for an excessive period of time. In some cases the material in the stagnant regions will be consolidated by the force of the material above it and will therefore cake. When cohesive materials such as ground animal feeds or fine powders are placed in this type of bin arching may occur and the material will flow erratically from the bin. (Note: when mold develops in grain that has been placed in bins the material becomes cohesive and this same type of arching can occur. As a result, many farm workers have lost their lives when they have gone into bins in which arching has occurred and the arch has collapsed, burying them beneath the surface of the grain.)

In **mass flow** all of the material flows towards the exit at the same time and, ideally, at the same rate (Fig. 9.3B). This type of flow is well suited for processing facilities where additional material is being periodically added to the top of the bin while material is also being withdrawn from the bottom. This is the type of bin used for storage of animal feeds at livestock facilities. The flow is uniform rather than erratic (as is sometimes the case for funnel flow). Furthermore, the material can act as a gas seal because the air entrapped between the particles moves downwards with the material. The major disadvantage is that, for a given capacity, the bin must be higher to accommodate the sloping bottom. Furthermore, beams/columns must be used to support the structure. Mass flow is achieved when the hopper angle, ϕ_h (Figure 9.3b) is less than a specified value. Charts for determining ϕ_h are given by Jenike (1964)

An alternative to the two types of flow already discussed is **expanded flow**. By constructing the bottom of the bin with two regions having different slopes, mass flow is achieved in a larger portion of the bin (Fig. 9.3C) and the size of the stagnant region is decreased. This expands the active flow region and permits a smaller discharge orifice. It is sometimes possible to achieve this type of flow by modifying existing bins in which funnel flow has been occurring. However, the design of this type of bin is relatively expensive and the construction costs are greater than for the funnel flow bins.



Funnel Flow

Mass Flow

φh = hopper angle

Expanded Flow

Figure 9.3. Flow patterns for granular materials flowing from bins. Note the effect of the inclination of the bottom (A versus B) on the flow pattern.

9.3.2 Flow Rates

Equations have been developed which describe the flow of granular materials through horizontal and vertical orifices. Horizontal orifices are parallel to the ground and vertical orifices are perpendicular to the ground. An example of a horizontal orifice would be a circular or square hole in the flat surface of the bottom of a bin and an example of a vertical orifice would be a hole in the side of the bin. As would be expected, orifice characteristics affect the flow rate. One of these characteristics is the **hydraulic**

diameter, which is defined as 4 times the orifice area divided by the orifice perimeter. In the case of a circular hole and a square hole the hydraulic diameter is equal to the diameter. Another important characteristic is the **aspect ratio** of a rectangular orifice which is the ratio of the length of the longer sides to the length of the shorter sides. It can also be anticipated that if the diameter of the orifice through which granular material is flowing is only several multiples of the particle diameter, the flow of that particulate material through the orifice would be restricted because the particles would tend to bridge the open area made by the orifice. A **small orifice** is defined as an orifice that has a hydraulic diameter less than 15 times the minor diameter of the particle and a **large orifice** has a diameter ≥ 15 times the minor diameter of the particle.

The flow rates of grains and seeds through horizontal and vertical orifices have been summarized in ASAE Data D274 (ASAE, 1992). The data presented in the 1992 edition applies to large orifices (see definition above). D274 includes the following equation which can be used to predict the volume flowrate, in m^3/hr, for mass flow from an orifice having hydraulic diameter D, in units of cm, and area A, in units of cm^2:

$$Q = c_0 A D^n \tag{9.2}$$

where values of the coefficient c_0 with units of $m^3 cm^{-(n+2)} h^{-1}$ and the exponent n are given in Table 9.5. The range in orifice diameters and moisture contents for which the equation was validated are listed in the Table. For rectangular orifices, the equation has been validated only for horizontal orifices with aspect ratios of 1.33 to 2.67. However, data reported by Chang et al. (1990b) suggest that the equations can also be used for vertical orifices. A simplification of the equation in which the exponent n is assumed to be 0.7 is described by Moysey et al. (1988).

9.4 Applications

This section will summarize several applications of the information presented in the previous sections. One example shows how the forces applied to the sides and bottom of bins containing granular materials can be predicted. Two others illustrate the forces applied to metal surfaces such as a sheet of metal suspended in a bin or a chute used to direct the grain or seed. The last example describes how power requirements for belt and screw conveyors can be estimated.

9.4.1 Forces on Bins - the Rankine and Janssen Equations

When granular materials are stored in bins, the forces which the material exerts on the bin are much different from those exerted by liquids. The lateral pressures, i.e. the pressures exerted on the sides of the bin, can become very significant. Two equations are used to predict lateral pressures: the Rankine equation, which is used for "shallow" bins and the Janssen equation, which is used for deep bins. A **shallow bin** is a bin in which the diameter exceeds the height while in a **deep bin**, the height significantly exceeds the equivalent diameter. The equivalent diameter is four times the hydraulic radius (see Section 9.3.2). The equations presented below can be used to estimate the forces on bins

Table 9.5. Values of Constants C and n for the equation predicting flow of grain through orifices.

Grain	Moisture Content (% w.b.)	Orifice Size (cm) Validated	Horizontal		Vertical		Reference
			c	n	c	n	
Corn	12 to 15	13 to 25	0.0277	0.823	0.0155	0.791	Chang et al, 1984; 1990a
	20 to 22	13 to 25	0.0466	0.646	0.0185	0.702	Chang et al, 1984; 1990a
Wheat	13 to 15	10 to 25	0.0503	0.693	0.0380[a]	0.542[a]	Chang & Converse, 1988; Chang et al, 1990a
Sorghum	11 to 14	10 to 25	0.0922	0.461	0.0245[b]	0.626[b]	Chang & Converse, 1988; Chang et al, 1990a
	16 to 18	10 to 25	0.0784	0.532	-	-	Chang & Converse, 1988
Canola	6 to 12	7 to 20	0.055	0.7	-	-	Fast and Moysey, 1988
Flaxseed	4 to 13	7 to 20	0.0415	0.7	-	-	Fast and Moysey, 1988
Black Eyed Peas		4 to 8	0.0148	1.0	-	-	Gregory & Fedler, 1987
Soybeans	12	10 to 30	-	-	0.0182	0.730	Chang et al., 1990a

[a] Valid for 10 to 15% m.c. for vertical orifices.

[b] Valid for 12 to 18% m.c. for vertical orifices.

during static conditions. During bin loading and unloading, the bin may be subjected to dynamic loads which exceed these static loads.

The Rankine equation predicts the lateral pressure on the wall of a shallow bin, σ^3 as a function of the angle of internal friction, ϕ_1, and y, the distance below the free surface (the upper surface) of the material:

$$\sigma_3 = \frac{g}{g_c} \, w \, y \tan^2 (45 - \frac{\phi_i}{2})$$

where w = the weight density of the material, kg/m^3 (or lb/ft^3), and g/g_c = 9.81 N/kg or 1 lbf/lb.

When estimating pressure in deep bins, the Janssen equation is used. It includes a term called the pressure ratio, k. This is defined as the ratio of the lateral pressure, σ_3, to the vertical pressure, σ_1. It is dependent on the angle of internal friction, ϕ_1, and is given by the following equation:

$$k = \frac{\sigma_3}{\sigma_1} = \frac{1 - \sin \phi_i}{1 + \sin \phi_i}$$

The Janssen equation predicts σ_3 as a function of y, the distance from the free surface of the material in the bin (usually the top surface of the material in the bin):

$$\sigma_3 = \frac{g}{g_c} \frac{w R}{\mu_s} \left\{1 - \exp\left(\frac{- k \mu_s y}{R}\right)\right\}$$

where R is the bin hydraulic radius, defined as the ratio of the cross sectional area of the bin to its circumference; w is the weight density of the material; and μ is the static coefficient of friction of the material. As y decreases, the exponential term becomes relatively small. This means that σ_3 is greatest at the bottom of the bin (when y = h, the height of the bin). For a given height, w, k, and μ_s, the greater the hydraulic radius, R, of the bin, the lower the value of σ_3, the lateral pressure on the wall. Although other theories have been developed for prediction of static loads on bins, the Janssen equation is the basis of many design codes and bin specifications.

EXAMPLE PROBLEM 9.1: Estimate the lateral and vertical forces at the bottom of the wall of a bin 9.1 m (20 ft) in diameter filled to a depth of 30 m (98.4 ft) with wheat at 11% m.c. The bin is made of concrete (wood float finish).

SOLUTION: The Janssen equation applies. The angle of internal friction is given in Table 9.4 as 24.5°. The pressure ratio can be calculated as:

$$k = \frac{\sigma_3}{\sigma_1} = \frac{1 - \sin \phi_i}{1 + \sin \phi_i} = \frac{1 - \sin 24.5°}{1 + \sin 24.5°} = \frac{0.585}{1.414} = 0.413$$

The coefficient of friction for wheat on concrete is 0.51 (Table 9.1) and the grain bulk density is 790 kg/m^3 (Table 9.4). For a circular bin, the hydraulic radius is equal to the radius, 4.55 m (10 ft). Substituting these values into Janssen's equation for y = 30 m gives:

$$\sigma_3 = \frac{g}{g_c} \frac{w R}{\mu_s} \left\{1 - \exp\left(\frac{-k \mu_s y}{R}\right)\right\} = \frac{9.81 \text{ N/kg} (790 \text{ kg/m}^3) (4.55 \text{ m})}{0.51}$$

$$\left\{1 - \exp\left(\frac{- 0.413 (0.51) 30 \text{ m}}{4.55 \text{ m}}\right)\right\}$$

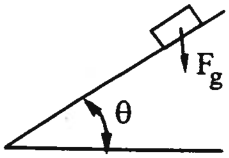
$$= 69.1 \text{ kN/m}^2 \left\{1 - \exp(- 1.39)\right\} = 51.9 \text{ kN/m}^2 \text{ or } 51.8 \text{ kPa}$$

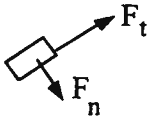
The vertical force can be calculated from the definition of the pressure ratio:

$$\sigma_1 = \frac{\sigma_3}{k} = \frac{51.8 \text{ kN/m}^2}{0.413} = 125.4 \text{ kN/m}^2 \text{ or } 125.4 \text{ kPa}$$

Homework

9.1 Alfalfa pellets are placed on a horizontal plywood surface and the plywood is gradually tilted until the pellets begin to slide across the surface. Sketches of the forces acting on a single pellet are shown below.





a. Develop expressions for the magnitudes of the forces F_n and F_t as a function of the gravitational force on the pellet, F_g and the angle θ at which the plywood is inclined. If the weight of a pellet is 0.35 g (0.00343 Newtons), evaluate the magnitudes of F_g and F_t when $\theta = 10°$.

b. Estimate the angle θ_c at which the pellets will begin to slide.

9.2 A round steel bin is filled with wheat at 17.1% m.c. (w.b.). The bin has a diameter of 7.31 m (24 ft) and is filled to a depth of 3.0 m (10 ft).

a. Calculate the increase in lateral pressure at the base of the bin wall when the wheat is dried from 17.1% to 11.0% m.c. Estimate density using the appropriate formula (chap 2). Assume the depth will remain the same after drying.

b. The bin is unloaded through a square orifice 20.3 cm x 20.3 cm (8 in x 8 in) located on the side of the bottom of the bin (i.e. it will be a vertical orifice). Assume the flow rate will be constant during unloading. Estimate the rate at which grain flows from the bin and the total time required to unload the bin.

c. The wheat is conveyed away from the orifice on a flat (no slope on the sides) horizontal belt conveyor moving at 15.2 m/s (50 ft/s). Neglecting the effects of inertia (i.e. assuming effectively static conditions), estimate the minimum width required for the belt.

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03/12/19

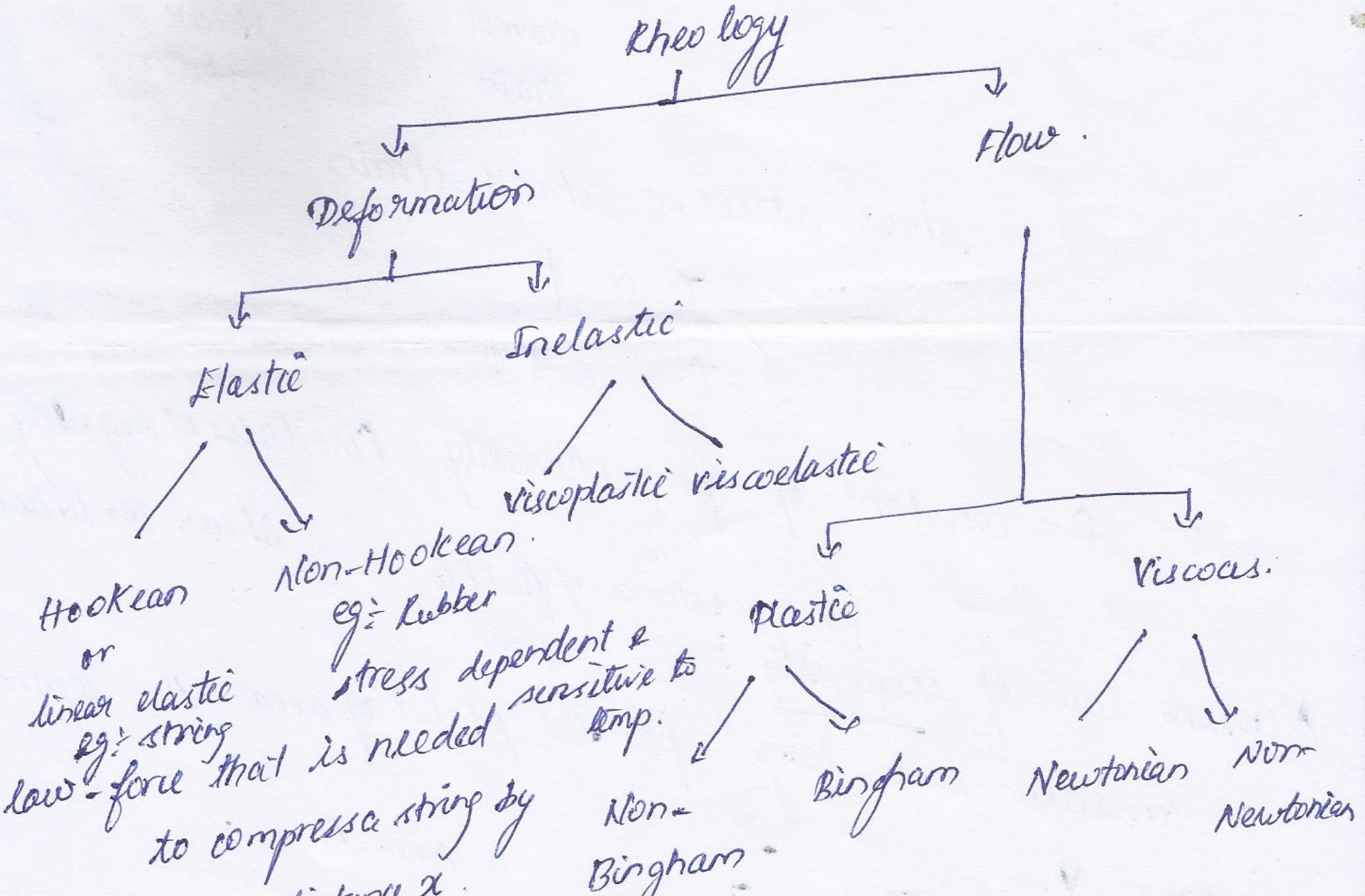
ENGINEERING PROPERTIES OF FOOD MATERIAL. ①

UNIT-2:- RHEOLOGICAL PROPERTIES OF FOOD. (39-43) S1

→ Definition - science that studies abt the deformation of materials including flow.

Need:-
- rheological data - quality evaluation, eng. calculation, process design
- Rheological models is used for designing food eng. processes
- Rheological properties must be known for process control.

Classification of rheology.



→ Hooke's law - force that is needed to compress a string by some distance x.

$$\underbrace{F_s}_{\text{force}} = \underbrace{k}_{\text{constant factor}}\underbrace{x}_{\text{deformation}}$$

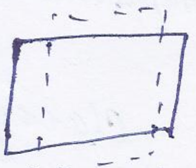
→ Viscoplastic - rate-dependent inelastic behaviour of solids.
- deformation depends on the rate ~~of~~ at which loads are applied.
- the deformation is unrecoverable.

→ viscoelasticity - both viscous & elastic characteristics when undergoing deformation

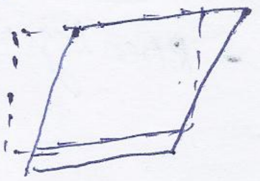
- water (viscous fluid), resist shear flow & strain linerly with time when stress is applied.

→ shear stress - force tending to cause deformation

→ shear strain - length of deformation divided by ⊥r length in plane of force applied.



Normal strain



Shear strain.

shear stress ∝ shear strain

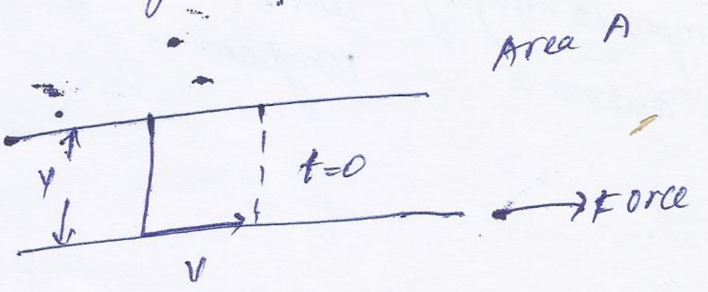
$$\tau \propto \phi$$

$$\tau = c * \phi$$

c = constant of proportionality (Modules of rigidity or Shear Modulus).

Newton's law of viscosity : ↳ resistance of fluid to flow.

consider two large parallel plates of area A, separated by distance Y.



→ The lower plate is initially at rest but at t=0, the lower plate is set in motion in Z-direction at constant velocity V by applying force F in Z-direction.

→ Upper plate is stationary.

→ At $t = 0$, $V = 0$ everywhere except lower plate V.

$t = \infty\uparrow$, velocity distribution starts to develop.

Finally steady state is achieved, a linear velocity is obtained.

→ Experimental result:

Force required to maintain the motion of lower plate / unit area is $\propto$ to the velocity gradient & proportionality constant μ - viscosity of fluid.

$$\frac{F}{A} = \mu \frac{V}{Y}$$

→ microscopic form of this eqn is Newton's law of viscosity.

$$\tau_{yz} = -\mu \frac{dv_z}{dy} = -\mu \dot{\gamma}_{yz}.$$

↓

shear stress (N/m^2)

μ - viscosity (Pa·s)

$\dot{\gamma}$ - shear rate (1/s)

z- direction of force

y- direction of force normal to the surface.

→ -ve sign indicates the velocity gradient is -ve, when velocity ↓ in the direction of transfer of momentum.

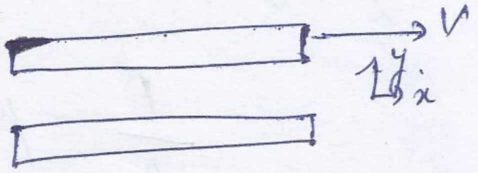
↳ quantity of motion that an object has.

Prob :-

Two parallel plates are 0.1m apart. The bottom plate is stationary while the upper one is moving with a velocity V. The fluid b/w the plates is water, which has viscocity of 1CP.

a.) calculate the momentum flux neassary to maintain the top plate in motion at a velocity of 0.30 m/s.

b.) If water is replaced with a fluid of viscosity 100 CP & momentum flux remains constant, find the new velocity of the top plate.



a.) $\mu = 1CP = 1 \times 10^{-3}$ Pa.s.

$$\tau_{yx} = -\mu \frac{dV_x}{dy}$$

$$\tau_{yx} = -1 \times 10^{-3} \text{ (Pa.s)} \times \frac{(0 - 0.3) \text{ m/s}}{(0.1 - 0)} = 0.003 \text{ Pa.}$$

b.) $\mu = 100 \text{ CP} = 100 \times 10^{-3} = 10^{-1} = 0.1 \text{ Pa.s.}$

$$0.003 = 0.1 \text{(Pa.s)} \frac{(0 - V) \text{ m/s}}{(0.1 - 0) \text{ m}} = 0.003 \text{ m/s.}$$

04/12/19 Viscosity → resistance of a fluid to flow. (42 - 46) S1.

→ Unit (Pa.s) - SI ③

g/cm.s - CGS

→ It varies with temp. due to its diff. in molecular structure

Temp effect on viscosity is gn by Arrhenius type eqn.

$$\mu = \mu_\infty \exp\left(\frac{E_a}{RT}\right)$$

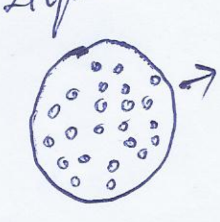
E_a → activation energy. (J/kg mol)

R → gas constant (8314.34 J/kg mol K)

T → absolute temp. (K)

μ_∞ = constant (Pa.s)

→ Liquid molecules are closely spaced with strong cohesive force.



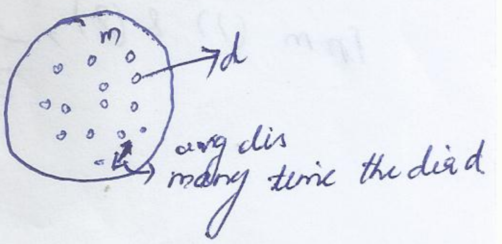
→ temp↑, these forces b/w molecules ↓ & flow become free.

viscosity of liquids ↓ as temp ↑.

→ Gases the viscosity is expressed in terms of kinetic theory.

→ Consider a pure gas, composed of rigid, non attracting spherical molecules of dia d. & mass m.

present in
→ concentration of N molecules / unit volume.
is small



→ According to kinetic theory, the avg. mole transverses a distance equal to the mean free path λ.

→ Two sides of gas layer thickness of λ,

velocity difference $\lambda \frac{dv}{dz}$.

velocity gradient normal to the motion of the gas $\Big\} = \frac{dv}{dz}$.

molecules from upper to lower carry excess momentum $\Big\} = m\lambda \frac{dv}{dz}$

no. of molecules going upper to lower with speed $(\bar{c})$ $\Big\} = N\bar{c}$.

The momentum transferred across this layer up & down by the molecule

$$F = \frac{1}{3} N \bar{c} m \lambda \frac{dv}{dz} \quad \text{———} (1)$$

↳ one third of molecules are moving up or down.

From Newton's law of viscosity,

$$F = \mu \frac{dv}{dz} \quad \text{———} (2)$$

from (1) & (2), $\frac{1}{3} \cancel{N} \bar{c}\, m \lambda \cancel{\frac{dv}{dz}} = \mu \cancel{\frac{dv}{dz}}$

$$\mu = \frac{1}{3} N \bar{c} m \lambda \quad \text{———} (3)$$

mean path length, is gn by $\lambda = \cancel{\frac{1}{\sqrt{2\pi d^2 N}}}$ ~~(4)~~ $\left[\lambda = \frac{1}{\sqrt{2}\,\pi d^2 N}\right]$ (4)

sub λ in (3), $\mu = \frac{1 \cancel{N} \bar{c} m}{3 \sqrt{2} \pi d^2 \cancel{N}}$

$$\mu = \frac{1}{3} \frac{\bar{c} m}{\sqrt{2} \pi d^2} \quad \text{———} (5)$$

According to kinetic theory, molecular velocities relative to fluid velocit

$$\bar{c} = \sqrt{\frac{8RT}{\pi N_A m}}.$$

N_A - Avogadro no, m - mass, R - gas constant, T - abs. temp.

$$\mu = \frac{2}{3\pi^{3/2} d^2} \sqrt{mKT}$$ → predicts as velocity ↑ with square root of Temp.

→ velocity ↑ with temp more rapidly

K - Boltzmann constant ($K = R/N_A$).

→ Gases has lowest viscosity.

→ viscosity of gases is constant up to 1MPa pressure & it ↑ as pressure ↑

Momentum diffusivity or kinematic viscosity.

↳ it is defined to make transport properties analogous.

→ unit m^2/s - SI (or) cm^2/s.

→ Ratio of dynamic viscosity to density of fluid.

$$\nu = \frac{\mu}{\rho}.$$

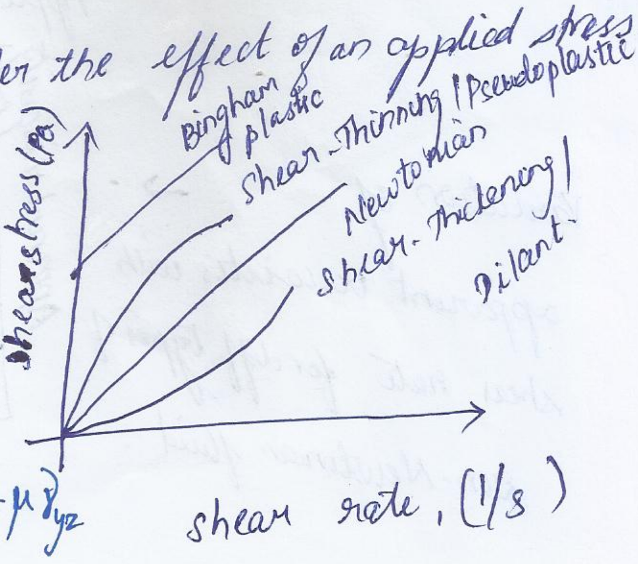
*Viscous fluids :

↳ tends to deform continuously under the effect of an applied stress.

→ Newtonian & Non-newtonian.

Newtonian fluid:

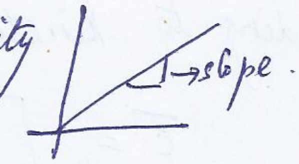
↳ follows Newton's law of viscosity.



↳ $\tau = -\mu \frac{dv}{dy} = -\mu \gamma_{yz}$

→

→ slope of shear stress vs shear rate, viscosity is constant & independent of shear rate in Newtonian fluid.



→ Eg. Gases, oils, water & most liquids contain more than 90% of water such as tea, coffee, beverages, fruit juice, milk show Newtonian behaviour.

Non-Newtonian fluids. →eg :- sauce, ketchup.

→ donot follow Newton's law of viscosity.

→ Shear thinning or shear thickening fluids obey Ostwald-de Waele eqn. (power law model) :

$$\tau_{yz} = \overset{K}{\cancel{\mu}}\left(\frac{dv_z}{dy}\right)^n = \overset{K}{\cancel{\mu}}(\dot{\gamma}_{yz})^n \text{ —— (1)}$$

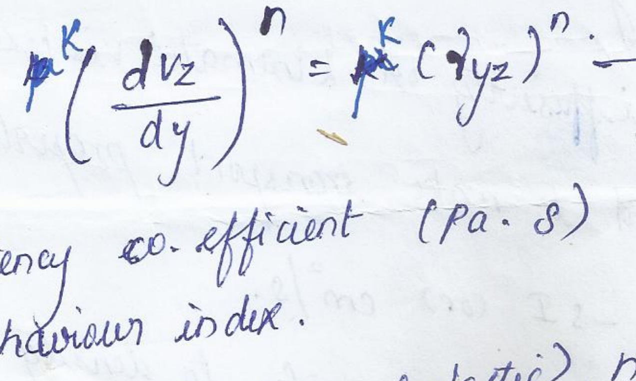
where K = consistency co-efficient (Pa · s)

n = flow behaviour index.

For shear thinning (Pseudoplastic), $n<1$

For " thickening (Dilant), $n>1$

Apparent viscosities of time-independent fluids.



Variation of → apparent viscosities with shear rate for diff types of Non-Newtonian fluid.

→ For newtonian fluid $n=1$ & $k=\mu$.

→ The slope of shear rates stress vs shear rate is not constant for non-newtonean fluid.

→ For diff. shear rates, diff. viscosities are observed.

→ Apparent viscosity is given by η.
where Newtonian viscosity " " μ.

→ Ratio of shear stress to shear rate is apparent viscosity at that shear rate.

$$\eta(\underset{\downarrow}{\gamma}) = \frac{\tau}{\gamma} \longleftarrow (2)$$

shear rate.

→ Apparent viscosity & Newtonian viscosity as same for Newtonian fluid., but apparent viscosity for power law fluid is:

$$\eta(\gamma) = \frac{k(\gamma)^{n}}{\gamma} \overset{\Rightarrow \tau = k(\gamma)^n}{=} k(\gamma)^{n-1} \longrightarrow (3)$$

Pseudoplastic fluids

→ Shear thinning fluids

→ For these fluids, when viscosity ↓ the shear rate ↑.

→ eg:- quicksand, blood, paints ⇒ when V in brush, V ↑, shear V ↓, nail polish, ketchup.

→ Shearing causes the long-chain molecule to straighten out & become aligned with flow ↓ viscosity.

Shear Thickening Fluids :-

→ Dilatant fluids

→ Apparent viscosity ↑ as shear rate ↑.

→ Eg :- Wet sand & mixture of cornstarch & water

→ ↑ in viscosity accompanied by volume expansion, shear thickening fluid is called dilatent fluid.

2,4,6,8,12,13

09/12/19

①

Porosity :

→ Porosity is an ⊗ property (physical) characterizing the texture & quality of dry & intermediate foods.

→ Required for modeling & design of various heat & mass transfer process like drying, frying, baking, heating, cooling & extrusion

→ defined as volume fraction of air or void fraction of sample.

$$\text{Porosity} = \frac{\text{Void volume}}{\text{Total Volume.}}$$

METHODS FOR DETERMINATION OF POROSITY :-

*1.) Direct method :- Determined by difference of bulk volume of a piece of porous material & its volume after destruction of all voids by means of compression.

- used if material is very soft & no attractive or repulsive force is present b/w the particles.

*2) Optical method :- determined from the microscopic view of a section of the porous material.

- used if the porosity is uniform throughout the sample ie sectional porosity represents porosity of whole sample.

- suitable software to analyze the image.

→ Image J is a software is used to analyze the pores & to determine area based on pore size distribution, median pore diameter & % area fraction of pores.

→ Software uses contrast b/w two phases(pores & solid part). 1st scanned colour image → converted to grey scale by software

→ using bars of known length, pixel values are converted to distance unit.

*3) Density method :→ calculated from the measured densities.

Apparent porosity (ε_{app})/ Internal porosity - porosity due to enclosed air space within the particle.

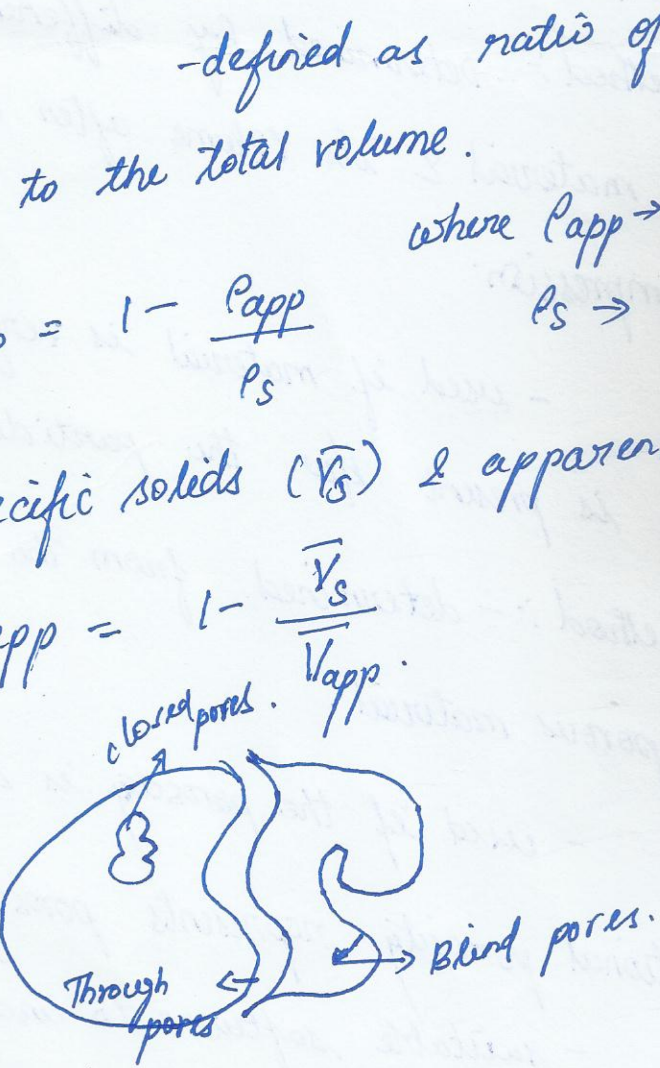
-defined as ratio of enclosed air space or voids volume to the total volume.

$$\varepsilon_{app} = 1 - \frac{\rho_{app}}{\rho_s}$$

where ρ_{app} → apparent density.
ρ_s → density of solids.

(or) from specific solids ($\bar{V}_s$) & apparent ($\bar{V}_{app}$) volumes as:

$$\varepsilon_{app} = 1 - \frac{\bar{V}_s}{\bar{V}_{app}}.$$



Bulk porosity : → also called external or interparticle porosity.

- includes void volume outside the boundary of individual particles when stacked (↳ completely empty) as bulk.

$$\varepsilon_{bulk} = 1 - \frac{\rho_{bulk}}{\rho_{app.}}$$

where

ρ_{bulk} → bulk density

ρ_{app} → apparent density.

(or)

$$\varepsilon_{bulk} = 1 - \frac{\bar{V}_{app}}{\bar{V}_{bulk}}$$

$\bar{V}_{app}$ - apparent Volume.

$\bar{V}_{bulk}$ - specific bulk.

Total porosity when materials is packed or stacked as bulk :-

$$\varepsilon_{TOT} = \varepsilon_{app} + \varepsilon_{bulk}.$$

Pores within the material

→ Closed pores - closed from all sides

→ Blind pores - one end closed

→ Open or flow through pores - flow takes place.

$$\varepsilon_{op} = \frac{\bar{V}_{op} \rightarrow \text{Vol. of open pore}}{\bar{V}_s \quad \text{Total volume}} = 1 - \frac{\rho_a}{\rho_p}$$

$$\varepsilon_{cp} = \frac{\bar{V}_{CP}}{\bar{V}_S} = 1 - \frac{\rho_p}{\rho_m}.$$

$$\varepsilon_{app} = \frac{\bar{V}_{app}}{\bar{V}_s} = 1 - \frac{\rho_a}{\rho_m}$$

→ ∴ apparent porosity is due to the enclosed air space within the particles & 3 diff. forms of pores :-

$$\varepsilon_{app} = \varepsilon_{CP} + \varepsilon_{OP} + \varepsilon_{BP}.$$

where ε_{CP} - porosity due to closed pores.

ε_{OP} - " " " Open pores.

ε_{BP} - " " " Blind pores.

→ Then porosity can be written as,

$$\varepsilon_{TOT} = \varepsilon_{cp} + \varepsilon_{op} + \varepsilon_{Bp} + \varepsilon_{bulk}.$$

*4.) Gas pycnometer method :- → measured dire dty by measuring volume fraction of air using the air comparison pycnometer.

$$V_{a_2} = V_2 - V_s = V_1 \frac{P_1 - P_2}{P_2}.$$

$$\varepsilon = \frac{V_{a2}}{V_1} = \frac{P_1 - P_2}{P_2}$$

*5.) Using porosimeters :→ porosity & pore size distribution are measured by porosimeters.

→ principle of either liquid intrusion into pores or liquid extrusion from the pores.

→ pressure is applied to force the liquids such as water, oil, or mercury into pores since liquids cannot flow spontaneously into pores.

→ Extrusion porosity metoye, 1st wetting liquids are used used to fill the pores of the porous materials.

→ Next, the liquid is displaced by applying differential pressure on the sample & the volume of extruded liquid is measured.

→ In intrusion porosimetry, liquid mercury, water, oil are used.

→ Here liquid is forced into the pores under pressure & intrusion volume & pressure is measured.

→ Mercury porosimetry – size range 0.03 to 200 μm.

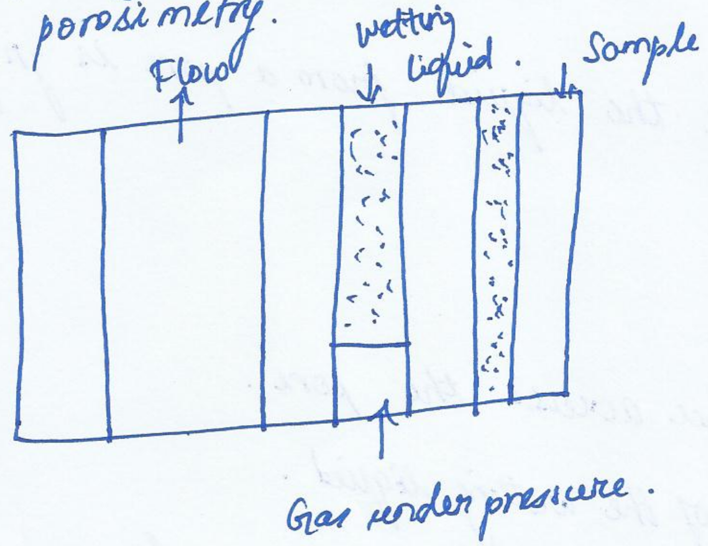
→ Non-mercury " – " " 0.001 to 20 μm.

→ direct measure of pore volume, pore diameter & surface area of through & blind pores can be found.

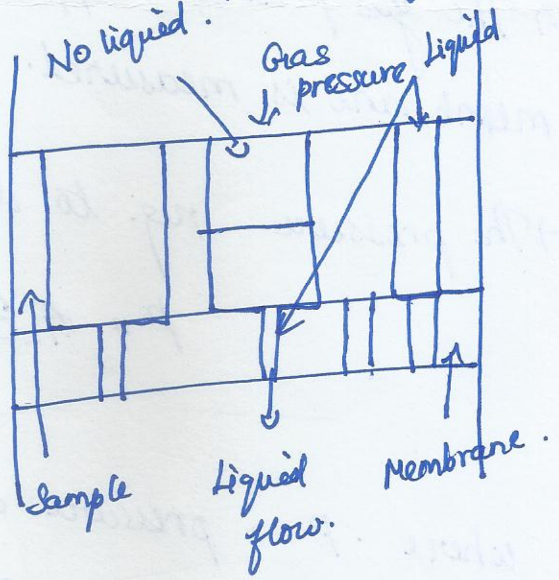
Extrusion method → capillary flow porosimetry

Extrusion method → Liquid extrusion porosimetry.

Capillary flow porosimetry.



Liquid extrusion porosimetry.



Capillary flow porosimetry:

→ Liquid extrusion method where differential gas pressure & flow rate thr' wet & dry samples are measured.

→ A wet sample in the chamber & sealed & gas flows behind the sample.

→ The pt when the pressure can overcome. the capillary action of the fluid within the largest pore is recorded as the bubble pt.

→ The largest pore should open up under lower pressure.

→ So, The pressure at the bubble pt is determined & pore diameter is calculated.

→ After bubble pt is found, pressure is ↑ & the flow rate is measured until all pores are empty.

→ Can measure pore size b/w 0.013 & 500μm.

Liquid extrusion porosimetry :

→ Larger pores size, of 0.06 to 1000μm.

→ The gas pressure applied & the amt. of liquid flowing out of a membrane is measured.

→ The pressure req. to displace the liquid from a pore is gn by,

$$p = \frac{4 \sigma \cos\theta}{D}$$

where P → pressure difference across the pore.

σ → surface tension of the wetting liquid.

θ → contact angle of the liquid with the sample.

D → pore diameter.

→ The membranes are chosen such that the pores are smaller than the smaller pore in the sample.

→ Gas pressure req. to empty the pores of the sample cannot remove the liquid from the pores of the membrane while the liq. is pushed out of the sample can pass thro' the membrane.

+ From pressure & corresponding volume of liquid collected, the distribution of pore volume as a functn of diameter is calculated.

Median pore diameter is the diameter of volume is equal to half of Total extruded liquid volume.

$$\text{Volume} = \frac{\text{Total extruded liq. volume}}{2.}$$

1.) Calculate the true density of spinach at 20°C having the composition given:

Component	composition (%)
Water	91.57
protein	2.86
Fat	0.35
Carbohydrate	1.72.
Ash	3.50.

Soln: Choi & Okos (1986)

$$\rho_{water} = 997.18 + 3.1439 \times 10^{-3} T - 3.7574 \times 10^{-3} T^2$$

$$\rho_{CHO} = 1599.1 - 0.31046 T.$$

$$\rho_{protein} = 1330 - 0.5184 T$$

$$\rho_{fat} = 925.59 - 0.41757 T$$

$$\rho_{ash} = 2423.8 - 0.28063 T$$

$$\rho_{ice} = 916.89 - 0.1307 T$$

2|11 - 1, 6, 7, 8, 11, 14
3|11 - 3-14, 6-14

Component	Density (kg/m3)	X_i^w.
Water	995.74	0.9157
Protein	1319.63	0.0286.
Fat	917.24	0.0035
CHO	1592.89	0.0172.
Ash	2418.19	0.0350.

$$\text{True density} = \frac{1}{\sum_{i=1}^{n} \frac{X_i^w}{\rho_i}}$$

$$\rho_T = \frac{1}{\frac{0.9157}{995.74} + \frac{0.0286}{1319.63} + \frac{0.035}{917.24} + \frac{0.0172}{1592.89} + \frac{0.035}{2418.19}}$$

$$= 1030.53 \text{ kg/m}^3.$$

Surface area :-

→ The surface area of a solid object is a measure of total area of that the surface of the object occupies.

→ ↑ the surface area of a substance generally ↑ the rate of chemical reaction.

→ For process calculations, two types of surface area are used
  ↳ outer boundary surface of a particle or object.
  ↳ pore surface area for a porous material.

→ Object can be characterized by using
  → Euclidian
  ↳ Non-Euclidian geometries.

→ Euclidian geometric shapes have characteristic dimensions & have a ⓧ common peculiarity of smoothness of surface. eg: spheres, cubes & ellipsoids.

Boundary Surface Area :-

→ estimated from geometric dimensions or measured by image analysis or contour analysis.

→ Leaf & stalk surface area can be measured by contact - printing the surface on a light sensitive paper.

→ And then estimating the area with a planimeter, or by tracing the area on a graph paper & counting the surface or determining the mass of the paper.

→ Planimeter - measuring instrument used to determine the area of an arbitrary 2-D shape.

→ Planimeter - Two bar linkage

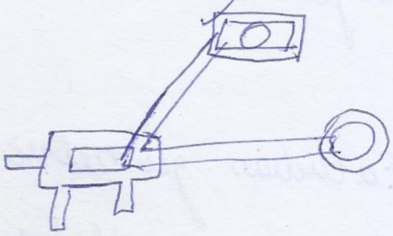
↳ one link is a pointer, used to trace around the boundary of the shape to be measured.

↳ other end linkage pivots freely on a weight that keeps it from moving.

→ Near junction of two links is the measuring wheel of calibrated diameter, with scale.

→ After area outline is traced, this wheels rolls on the surface of the drawing.

→ When tracing is complete, the scales at the measuring wheel show shape's area.



→ Here mass-area relationship of the paper must be developed 1st.

→ Air-flow planimeter - area as a function of the surface obstructing the flow of air.

→ Surface area of fruits & vegetables, found by estimating the peeled or skin area.

→ The simplest method of obtaining surface area of a symmetrical convex body such as egg is the projection method using a shadow-graph or photographic enlarger.

→ using profile of egg, equally spaced ‖el & ⊥r lines can be drawn from the axis of symmetry to the intersection with the profile.

→ Then using integration, the surface area can be obtained by summing up the surfaces.

* Pore surface area :-

→ defined as the surface of the pores in the porous medium exposed to fluid flow per unit volume or per unit mass of the solid particles.

1) Methods based on adsorption :-

→ The quantity of inert vapour that can be adsorbed on the poresurface is dependent on the surface area.

Quantity of gas or vapour adsorbed ∝ surface area of the porous material.

2) Methods based on fluid flow :-

- Mohsenin noted that Carman-Kozeny eqn. can be used to measure the specific surface of non-uniform pore surface.

- Kozeny showed the permeability can be written for steady state & steam line flow (Re<2.0), thr' porous medium:

$$k = \frac{f\,\varepsilon_{op}^{3}}{A^{2}}$$

$$Re = \frac{\rho a \cancel{u}}{\;}$$

$$Re = \frac{\rho a u}{\mu (1-\varepsilon_{op}) A}$$

where f - dimensionless constant.

ε_{op} - open pore porosity.

A - specific surface area.

u - approach or velocity of the fluid in the empty column (m/s)

→ Later Carman modified the eqn with $f = 1/5$, then it is known as

Carman - kozeny eqn,

$$k = \frac{\varepsilon_{op}^3}{5A^2 (1-\varepsilon_{op})^2}$$

→ The value of f depends on the particle shape, porosity & particle size range & lies b/w 3.5 & 5.5.

→ The value of A can be calculated by knowing the porosity & permeability.

→ permeability can be calculated by Darcy's eqn as:-

$$q = k \left[\frac{A (\Delta P)}{\mu L}\right]$$

→ Inert fluid should be used. Commonly used for rocks.

3) Mercury Intrusion :-

→ It measures the characteristics of pores.

→ Surface area is determined by the intruded volume using geometric dimensions of a preassumed geometric shape of the pores.

4.) Cross - sectional area :-

→ It is the area of surface after longitudinal or transverse section of amaterial.

→ Necessary whena fluid is flowing over an object.

→ method of boundary surface area can be used.

Specific gravity :-

→ Specific gravity of liquids and solids is defined as a dimensionless unit which is the ratio of density of the material to the density of water at a given temperature, where density is defined as the materials mass per unit volume and it is measured in kg/m^3.

$$SG = \frac{\text{mass of liquid}}{\text{mass of equal volume of water}}$$

$$= \frac{\text{density } \rho_L \text{ of liquid}}{\text{density } \rho_w \text{ of water}}.$$

→ The specific gravity of a fluid changes less than the density, as temperature changes.

→ For example, maize oil has densities of 927 kg/m^3 & 893 kg/m^3 at 10°C & 60°C. Their specific graivity only decreases from 0.927 to 0.908.

→ If the temperature of the material is known at a temperature T°C, its density at T°C will be given by,

$$\rho_L = (SG)_T \times \rho_w.$$

where ρ_L - density of liquid at T°C

$(SG)_T$ - specific graivity at T°C

ρ_w - density of water at T°C

→ The temperature & pressure of both the material and water need to be the same as these factors influence the density & hence the specific gravity.

→ Specific gravity is unique to every material & has a wide range of application.

→ Water has a density of 1kg/l at 4°C or 39.2 F

→ The specific gravities of gases usually are compared to dry air which generally has a density of 1.29g/l.

→ The specific gravity of all other materials is compared to water.

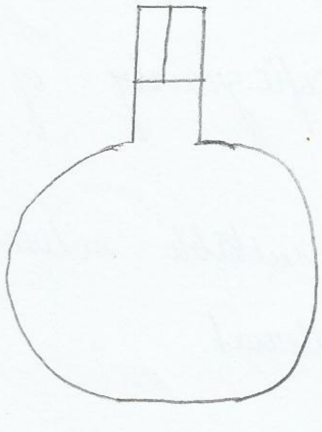
The reference density of water at 4°C (39.2F) is used as the reference

→ Specific gravities are conveniently measured using density bottles, pycnometers or hydrometers.

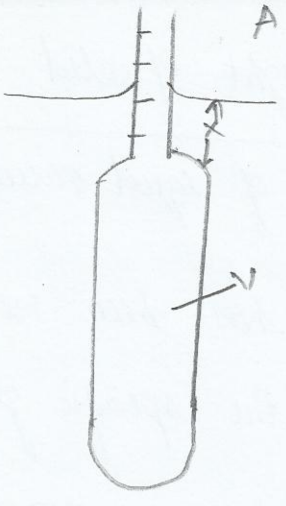
DENSITY BOTTLES:-

→ A density bottles can be used to determine the specific gravity of an unknown liquid & a particulate solid provided that the solid is insoluble in the liquid.

→ Care should be taken that all air is removed from the bottle when the liquid is added to the solid.



a.) SPECIFIC GRAVITY BOTTLE



b.) A HYDROMETER.

The following readings are taken:

W_1 - weight of the specific gravity bottle empty;

W_2 - weight of the bottle full of water.

W_3 - weight of the bottle full of liquid.

W_4 - weight of bottle plus solid

W_5 = weight of the bottle plus solid plus liquid to fill.

The specific gravity of the liquid is equal to

$$\frac{W_3 - W_1}{W_2 - W_1}$$

Now the weight of the solid is $W_4 - W_1$ &

weight of liquid having same volume of solid is $W_3 - W_1 - (W_5 - W_4)$

∴ The specific gravity of the solid is equal to

$$\frac{W_4 - W_1}{W_3 - W_1 - (W_5 - W_4)} \cdot \frac{W_3 - W_1}{W_2 - W_1}.$$

ie $$\frac{\text{weight of solid}}{\text{weight of equal volume liquid}} \times \text{specific gravity of liquid.}$$

→ Toluene has been recommended as a suitable solvent for determining the specific gravity of food material.

HYDROMETERS AND HYDROMETER SCALES:-

→ The constant weight hydrometer works on the principle that a floating body displaces its own weight of fluid.

→ The instrument is placed in the fluid & the density of the fluid is read from the scale on the stem.

→ Let the volume to the base of stem be V, the cross-sectional area of stem be A and the weight of the hydrometer be W.

→ When immersed in a liquid of density ρ, the length of the stem immersed be x.

→ Thus the volume of liquid displaced is $Ax + V$.

→ The weight of liquid displaced equals $\rho(Ax+V)$, which by the principle of floatation equals. W.

→ Therefore, $$\rho = \frac{W}{Ax+V}$$

HYDROMETER SCALES:-

→ Examples of special hydrometers or hydrometer scales.

* Alcoholometer - testing alcoholic solution, the scale shows the amount of alcohol by volume (0-100%)

* Brix saccharometer - directly shows the percentage of sucrose by weight in the solution, at the temperature indicated on the instrument. Degree Brix is the percentage of sugar w/w.

* Density hydrometer / lactometer - determining the density of milk. The instrument has scale divisions ranging from 25 to 35. If the fat content is known, then by reference to appropriate tables, the hydrometer reading can be used to give MSNF (Milk solids but not fat).

* Twaddell hydrometer - used for liquids that are more dense than water. The scales are so arranged that the readings multiplied by five and added to 1000 gives the specific gravity with reference to water as 1000.

* Baume scale - There are two scales, one for use of fluids heavier than water and one with lighter fluids.

Equation gives the mean conversion on this scale:

$$SG = \frac{m_B}{m_B - d}$$

m_B - constant equal to 145 in the USA & equal to 146.78 on the new scale.

d - Baume reading

* Oleometer - used for vegetable & sperm oil.
The scale is from 50 to 0 & corresponds to specific gravity from 0.870 to 0.970.

VISCOSITY MEASUREMENTS AND DIFFERENT TYPES OF VISCOMETER

INTRODUCTION

- Viscosity is the resistance of a fluid (liquid or gas) to a change in shape, or movement of neighboring portions relative to one another. Viscosity denotes opposition to flow.
- Viscosity is a major factor in determining the forces that must be overcome when fluids are used in lubrication and transported in pipelines.
- It controls the liquid flow in such processes as spraying, injection molding, and surface coating.
- For liquids, it corresponds to the informal concept of "thickness": for example, syrup has a higher viscosity than water.

MEASUREMENT OF VISCOSITY

The most commonly used viscosity measurement devices are

- capillary flow viscometers
- Orifice type viscometers
- falling ball viscometers and
- rotational viscometers.

CAPILLARY FLOW VISCOMETERS

- Capillary flow viscometers are generally in the form of a U-tube. These types of viscometers are very simple, inexpensive, and suitable for low-viscosity fluids.
- In capillary flow viscometers, the time for a standard volume of fluid to pass through a known length of capillary tubing is measured.
- The flow rate of material due to a known pressure gradient is determined.
- The driving pressure is usually generated by the force of gravity acting on a column of the liquid although it can be generated by the application of compressed air or by mechanical means.

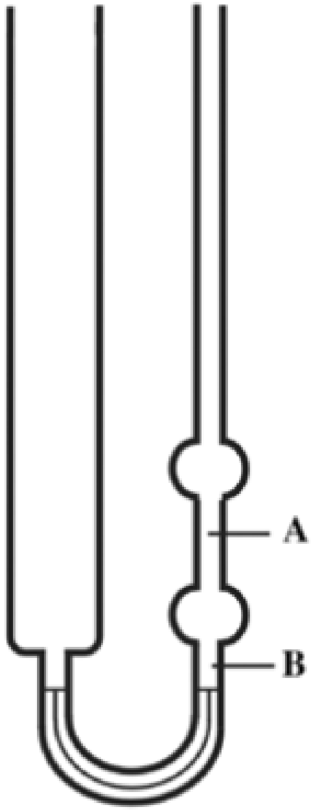


Fig 1 Cannon-Fenske capillary flow viscometer

- Gravity-operated glass capillaries are suitable only for Newtonian fluids having viscosities in the range of 0.4 to 20,000 mPa·s.
- To measure the viscosities of more viscous fluids, external pressure may be applied.
- For non-Newtonian fluids, this device is less suitable because the measurement cannot be done at a constant shear rate.

- The diameter of a capillary viscometer should be small enough to provide laminar flow.
- Capillary viscometers are calibrated with Newtonian oils of known viscosities since the flow rate depends on the capillary radius, which is difficult to measure.
- For the viscosity measurement, the viscometer is accurately filled with an accurately known volume of test fluid and the apparatus is immersed in a constant temperature bath until equilibrium is reached.
- Then, fluid is sucked up from the other limb through the capillary tube until it is above the marked level (A).
- Then, suction is removed and fluid flows through the capillary tube under the influence of gravity or the induced pressure head and the time for the fluid to flow from mark A to B is recorded.

- This time is a direct measure of the kinematic viscosity since it depends on both viscosity and density of fluid. This can be written as:

$$v = Ct$$

where C is the calibration constant.

- Assuming that the flow is laminar, fluid is incompressible, velocity of the fluid at the wall is zero and end effects are negligible, making a macroscopic force balance for a fluid flowing through a horizontal cylindrical tube of length (L) and inner radius (r), the following equation is obtained:

$$\Delta P\pi r^2 = \tau 2\pi r L$$

where P is the pressure drop causing flow and τ is the shear stress resisting flow.

- This equation can be solved for shear stress:

$$\tau = \frac{\Delta P r}{2L}$$

- For a Newtonian fluid, both shear stress and shear rate vary linearly from zero at the center ($r = 0$) of the capillary to a maximum at the wall ($r = R$).
- For a Newtonian fluid, this results in the parabolic velocity profile. Then, the shear stress on the fluid at the wall (τ_W) is related to the pressure drop along the length of the tube:

$$\tau_W = \frac{\Delta P R}{2L} \ldots\ldots\ldots\ldots\ldots\ (1)$$

- The flow in capillary viscometers is described by the Hagen Poiseuille equation:

$$\Delta P = \frac{8\mu v L}{\mathrm{R}^2} \quad \text{………………….(2)}$$

- Substituting Eq. (2) into Eq. (1), shear stress can also be expressed as:

$$\tau_W = \mu \frac{4v}{R} \text{………………….(3)}$$

- Then, shear rate at the wall (γw) for a Newtonian fluid is given by:

$$\gamma w = \frac{4v}{R} = \frac{4Q}{\pi \mathrm{R}^3} \text{………….. (4)}$$

where Q is the volumetric flow rate.

- Newton's law of viscosity can be written in terms of pressure gradient and volumetric flow rate as:

$$\frac{\Delta P r}{2L} = \mu \frac{4Q}{\pi \mathrm{R}^3} \quad \text{………………..(5)}$$

and viscosity of the fluid can be determined from the pressure drop and volumetric flow rate or velocity data.

- For non-Newtonian fluids, the relation between shear stress and shear rate has to be known to derive these equations.
- Compared to the parabolic profile for a Newtonian fluid, the profile for a shear thinning fluid is more blunted.
- The shear rate at the wall can be determined from the Rabinowitsch-Mooney equation:

$$\dot{\gamma}_w = \left(\frac{3Q}{\pi R^3}\right) + \tau_w \left[\frac{d(Q/\pi R^3)}{d\tau_w}\right] \quad \text{.......................................} \ (6)$$

- This equation can be expressed in terms of apparent value shear stress as:

$$\dot{\gamma}_{\mathrm{app}} = {}^{4Q}/_{\pi R^3}$$

$$\dot{\gamma}_w = \left(\frac{3}{4}\right)\dot{\gamma}_{\mathrm{app}} + \left(\frac{\tau_w}{4}\right)\left(\frac{d\dot{\gamma}_{\mathrm{app}}}{d\tau_w}\right) \quad \text{......................}(7)$$

- Equation (7) can also be written as:

$$\dot{\gamma}_w = \left[\left(\frac{3}{4}\right) + \left(\frac{1}{4}\right)\left(\frac{d(\ln \dot{\gamma}_{\text{app}})}{d(\ln \tau_w)}\right)\right]\dot{\gamma}_{\text{app}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

- Equation (8) can be written in the following simplified format:

$$\dot{\gamma}_w = \left(\frac{3n' + 1}{4n'}\right)\dot{\gamma}_{\text{app}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (9)$$

where n' is the point slope of the ln (τ_w) versus ln$(\dot{\gamma}_{\text{app}})$. That is:

$$n' = \frac{d(\ln \tau_w)}{d(\ln \dot{\gamma}_{\text{app}})}$$

- If the fluid behaves as a power law fluid, the slope of the derivative is a straight line and $n' = n$.

ORIFICE TYPE VISCOMETERS

- In orifice type viscometers, the time for a standard volume of fluid to flow through an orifice is measured.
- They are used for Newtonian or near-Newtonian fluids when extreme accuracy is not required.
- Orifice viscometers are mainly adopted by the oil industry due to their simplicity and easy operation. They are also known as efflux type viscometers.
- Orifice viscometers essentially consist of a reservoir, an orifice and a receiver.
- The orifice length does not exceed 10 times the diameter of the orifice.
- Although the original design concept of these viscometers was based on the Hagen-Poiseuille Law which states that the efflux of a fixed volume of liquid through a capillary is proportional to the viscosity of the fluid but the actual design of the instrument failed to meet the requirement of the Hagen-Poiseuille Law.

- The friction loss at the orifice entrance and the varying hydrostatic head during the experiment are needed to be considered when calculating the viscosity.
- The friction loss was found to be a function of cross sectional area ratio of cup to orifice, velocity of fluid, and the shape of the orifice entrance.
- Because of these reasons, the efflux time no longer remains proportional to the viscosity.
- Conversion formulas or tables must be used for comparing results which are generally not very accurate. Absolute measurements cannot be carried out using this type of equipment.
- The general method of operation of most of the orifice viscometers is basically the same.
- The sample liquid is poured into a cup which is maintained at a constant temperature by a water or oil bath.
- The level of the liquid in the cup is adjusted to a definite height, and the liquid is allowed to attain the temperature of the bath.

- Once the desired temperature is reached, a valve at the base of the cup is opened and the time required for a specific volume of liquid to discharge through the orifice is measured.
- The viscosity is calculated using an empirical expression that is specific to each instrument and has the general form as follows:

$$\upsilon = \frac{\eta}{\rho} = kt - \frac{K}{t}$$

where

t is the viscometer second

k and K are instrument specific constants and must be determined for each instrument.

- In the food industry, the most commonly used one is a **dipping type Zahn viscometer**.

ZAHN VISCOSITY CUP

- The General Electric (or "Zahn") viscometer consists of a bullet-shaped steel cup with a small orifice in the bottom.
- Zahn viscosity cup is also known as Dip-Type viscosity cup because of the manner in which viscosity of a test sample is determined.
- It can be used to determine the viscosity of Newtonian paints, varnishes, lacquers, ink, and related liquids.
- For measuring viscosity, the cup is completely immersed in the liquid, withdrawn and the time for the flow of the liquids through the orifice at the bottom of the cup is measured.
- Zahn viscosity cups are available in 5 sizes that can measure the oil viscosity in the range of 20 to 1600 cSt.
- The cups are made of corrosion and solvent resistance materials.
- The volume of a cup can vary from 43 to 49 mL depending on the manufacturer.

Table 2.17. Zahn viscosity cup orifice diameter.

Cup Number	*Nominal Orifice Diameter, (mm)*	*Approximate Viscosity Range, (cSt)*	*Approximate Oil Viscosity at 25°C, (cSt)*
1	2.0	5 – 60	20
2	2.7	20 – 250	120
3	3.8	100 – 800	480
4	4.3	200 – 1,200	480
5	5.3	400 – 1,800	900, 1600

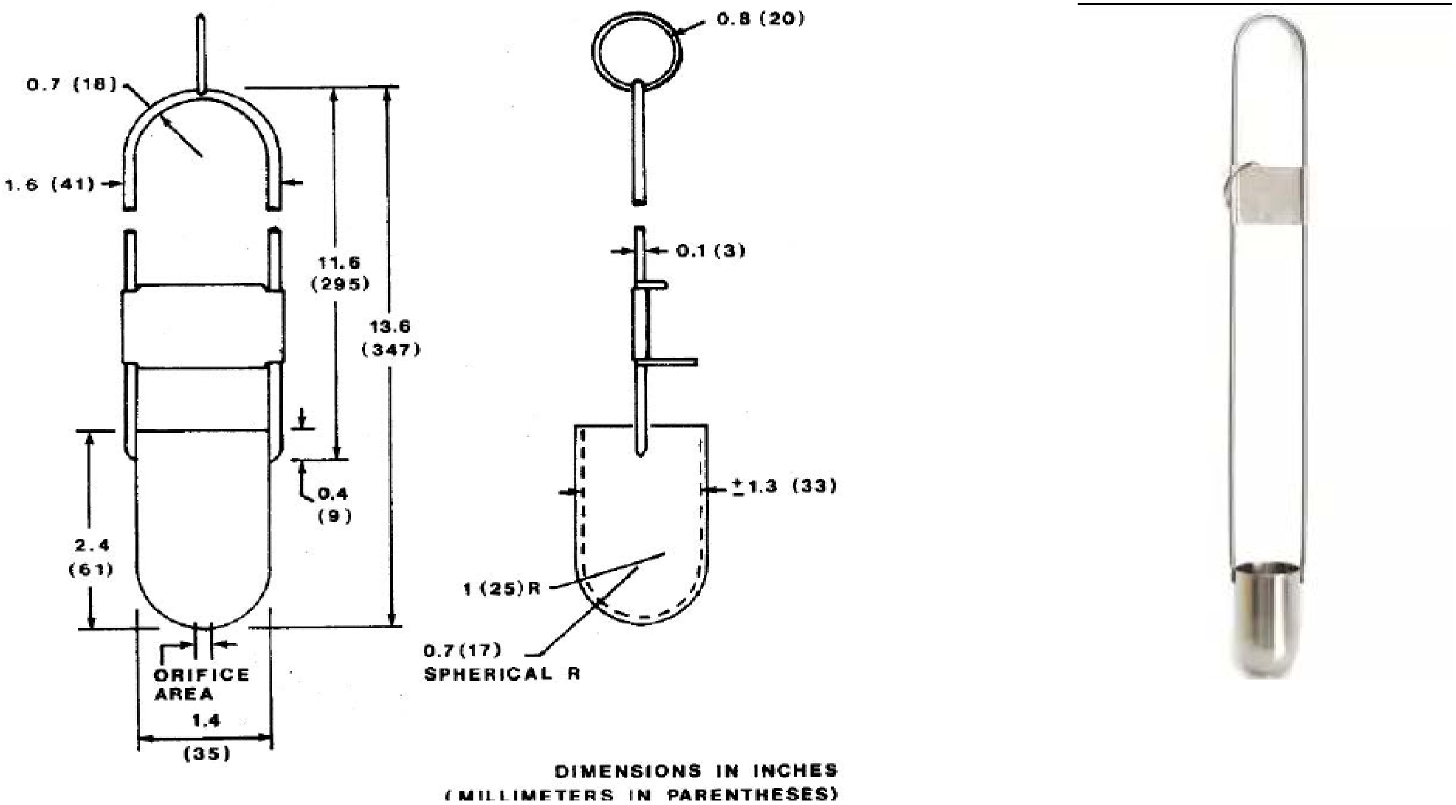


Fig 2 Zahn type viscometer

- Viscosity measurement using Zahn viscosity cups is generally made at 25º C.
- For viscosity determination at other temperature, a temperature correction curve or factor needs to be determined for each liquid.
- The choice of cup for measuring viscosity depends on the efflux time which should be between 20 to 80 s.
- The container holding the test liquid should be stirred well to provide a uniform temperature and density.
- The cup is immersed in the container and is kept there for 1 to 5 minutes to allow thermal equilibration.
- The cup is lifted vertically from the container in a quick steady motion.
- As the top edge of the cup breaks the surface, the timer is started and the cup is held about 6 in (15.2 cm) above the level of the liquid.
- When the liquid stream breaks at the base of the cup, the timer is stopped and the efflux time in seconds is noted.
- The efflux time in seconds is converted to kinematic viscosity using the following expression: $\upsilon = At - B$.

FALLING BALL VISCOMETERS

- These types of viscometers involve a vertical tube where a ball is allowed to fall under the influence of gravity.
- It operates on the principle of measuring the time for a ball to fall through a liquid under the influence of gravity.
- When the ball falls through the fluid, it is subjected to gravitational force, drag force, and buoyancy force.
- In falling ball viscometers, a solid body is allowed to fall under gravity through a viscous medium.
- After a period of initial acceleration, the solid body attains a uniform terminal velocity when the gravitational force is balanced by the viscous resistance of the fluid.
- By measuring the terminal velocity of the falling body, the viscosity can be determined.
- Although a solid body of any shape and size can be used, a spherical geometry is preferable due to the simplicity involved in deriving the theory.

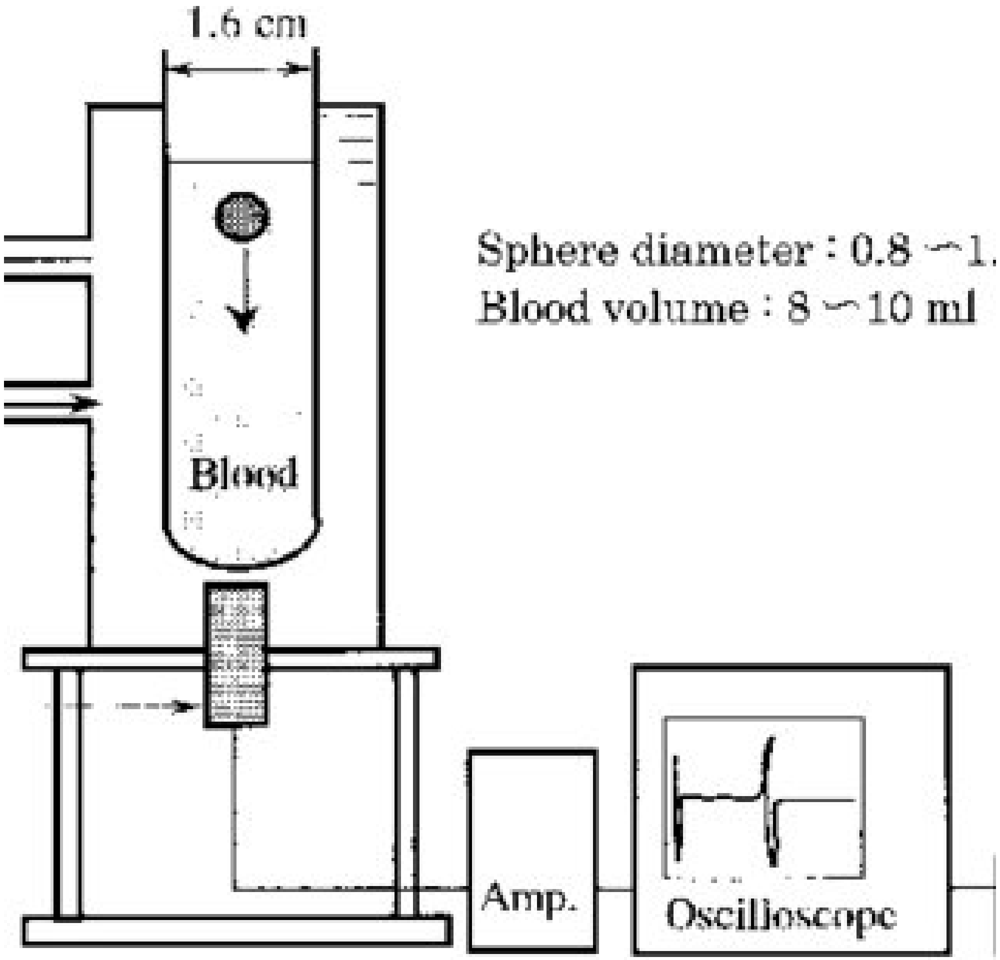


Fig 3 FALLING BALL VISCOMETER

- Consider the system shown in Figure in which a sphere is falling through a homogeneous fluid.
- If the motion of the sphere is sufficiently slow, the inertia terms become negligible.
- Under this condition and assuming that the fluid medium has an infinite extension, the viscous resistance to the motion of the sphere moving with a velocity *v* is equal to the driving force due to the difference in density between the sphere and the fluid.
- Making a force balance:

Net force (F_{Net}) = Gravitational force (F_G)– Buoyancy force (F_B)–
Drag force (F_D)

$$\frac{\pi D_p^3 \rho_p}{6}\frac{d\mathrm{v}}{dt} = \frac{\pi D_p^3 \rho_p g}{6} - \frac{\pi D_p^3 \rho_f g}{6} - \frac{c_D \pi D_p^2 \rho_f \mathrm{v}^2}{8} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(10)$$

where

D_p = diameter of the ball (m),
ρ_p = density of the ball (kg/m^3),
ρ_f = density of the fluid (kg/m^3),
c_D = drag coefficient,
v = velocity of the ball (m/s).

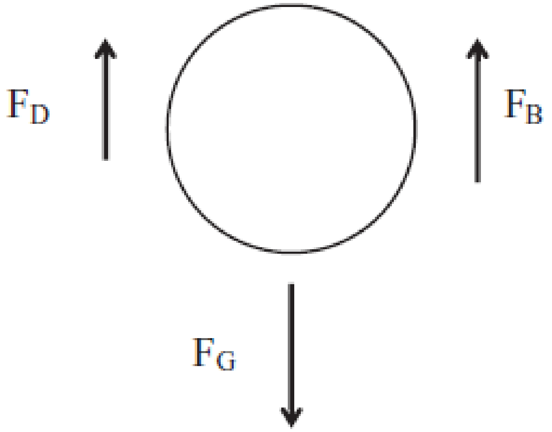


Fig 4 Forces acting on a ball in falling ball viscometer

- When equilibrium is attained, the upward and downward forces are balanced and the ball moves at a constant velocity.
- That is, the falling ball reaches a terminal velocity (v_t) when the acceleration due to the force of gravity is exactly compensated by the friction of the fluid on the ball.

$$\frac{dv}{dt} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

- In the Stoke’s region, the drag coefficient is:

$$C_D = \frac{24}{Re} \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

- Substituting Equation (11) and (12) in Equation (10),

$$\frac{\pi D_p^3 \rho_p g}{6} = \frac{\pi D_p^3 \rho_f g}{6} + \frac{6\pi D_p \mu v_t}{2}$$

$$\Rightarrow \mu = \frac{D_p^2(\rho_p - \rho_f)g}{18 v_t}$$

- If the terminal velocity of the ball is calculated, it is possible to determine the dynamic viscosity of the fluid.
- Falling ball viscometers are more suitable for viscous fluids where the terminal velocity is low.
- Stoke’s law applies when the diameter of the ball is so much smaller than the diameter of the tube through which it is falling.
- Thus, there is no effect of the wall on the rate of fall of the ball.
- If the tube diameter is 10 times the ball diameter, wall effects can be neglected.

- The larger the ball, the faster it falls.
- Therefore, it is necessary to select the diameter of ball small enough to fall at a rate that can be measured with some degree of accuracy.
- This method is not suitable for opaque fluids.

Example 2.4. To determine the viscosity of sunflower oil, a falling ball viscometer was used. Viscometer has a tube length of 10 cm and its ball has a diameter of 0.68 mm. Oil and the ball have densities of 921 kg/m^{3}and 2420 kg/m^3, respectively. If it takes 44.5 s for the ball to fall from the top of the tube, calculate the viscosity of the oil.

Solution:

Terminal velocity is:

$$v_t = \frac{L}{t}$$

$$= \frac{0.1\,\text{m}}{44.5\,\text{s}}$$

$$= 0.0022 \text{ m/s}$$

Then, viscosity can be calculated using Eq. (2.44):

$$\Rightarrow \mu = \frac{D_p^2(\rho_p - \rho_f)g}{18v_t} \tag{2.44}$$

$$\mu = \frac{(0.68 \times 10^{-3}\,\text{m})^2(2420\,\text{kg/m}^3 - 921\,\text{kg/m}^3)(9.81\,\text{m/s}^2)}{(18)(0.0022\,\text{m/s})} = 0.172 \text{ Pa} \cdot \text{s}$$

06/12/19

VOLUME :- (15-20) Si

→ Volume is defined as the amt of 3-D space occupied by an object, which is expressed as cubic units ie cubic inches or cubic centrimeters.

→ For liquids measure it is expressed as litres & gallons.

→ SI system - unit of volume is m^3.

→ It is the quality attribute in food industry.

Volume of solids are determined by following methods :-

* For solids with regular ~~spac~~ shape, volume can be calculated from its dimensions.

* Solid volume can be experimentally found out by liquid, gas ~~or~~ or solid displacement method.

* Image processing methods - recent development to measure volume of ellipsoidal agricultural prdts such as eggs lemons, limes & peaches.

$V = m/D$

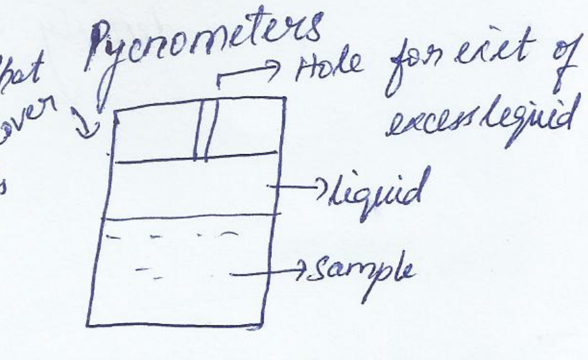
$D = m/V$

LIQUID DISPLACEMENT METHOD :-

→ used for solid samples that does not absorb liquid very fast

→ volume of food materials is measured ~~by~~ by pycnometers (specific gravity bottles) or graduated cylinders.

→ Pycnometer has a small hole in the lid that allow excess fluid to escape as the lid is fitted into the neck of the bottle.



→ The bottle is weighed & filled with the liq. of known density.

→ The lid is placed & escape water is removed or wiped out of the capillary.

→ Then the bottle is weighted again.

→ Next the bottle is emptied & dried & solids particles are placed in the bottle & weighted.

→ The bottle is completely filled with liquids & bottle is reweighted.

→ The volume of solid particles can be determined using the formula

$$V_s = \frac{\text{weight of the liquid displaced by solid}}{\text{Density of liquid}}$$

$$V_s = \frac{(W_{pe} - W_p) - (W_{pls} - W_{ps})}{\rho_l}$$

where V_s - volume of solid (m^3)

W_{pe} = wt of the pycnometer filled with liquid (kg)

W_p - weight of empty pycnometer (kg)

W_{pls} - wt. of pycnometer containing the solid sample & filled with liquid (kg)

W_{ps} - wt. of pycnometer containing solid with no liquid (kg)

ρ_l - density of the liquid (kg/m³)

→ For direct measurement of volume of liquid displaced is by using graduated cylinder or burette.

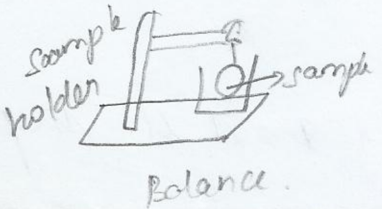
→ (Initial volume of liquid in graduated cylinder) − (Final volume of liq. with immersed material) = Volume of the material.

→ Liquids with low surface Tension & should be absorbed very slowly must be used.

→ generally water, alcohol, toluene & tetrachloroethylene.

→ some non-wetting fluids like mercury can be used for displacement.

→ or samples can be coated with a film or paint to prevent liquid absorption.



→ For larger objects, platform scale is used.

→ The samples is completely immersed in a liq. such that it does not touch the sides & bottom of the tube.

→ wt. of liq displaced by the solid is ÷ by its density

→ It is based on Archimedes principle, body immersed in a fluid will experience a wt loss in an amt equal to the weight of the fluid it displaces.

→ upward buoyancy force exerted by the liq. on the body in a liq. is equal to wt. of the displaced liq.

$$\therefore V_s = \frac{G}{\rho_l} = \frac{W_{air} - W_l}{\rho_l}$$

where G - bueoyancy force (N)
ρ_l - density of liquid (kg/m3)
W_{air} - wt. of sample in air (kg)
W_l - wt. of sample in liquid (kg)

→ Liquid having density lower than that of sample must be used if partial floating of sample is observed.

→ The sample is forced into the liquid by means of sinker rod if it is lighter.

$$V_s = \frac{G_{sample+sinker} - G_{sinker}}{\rho_l}$$

→ & it is suspened with a string if it is heavier.

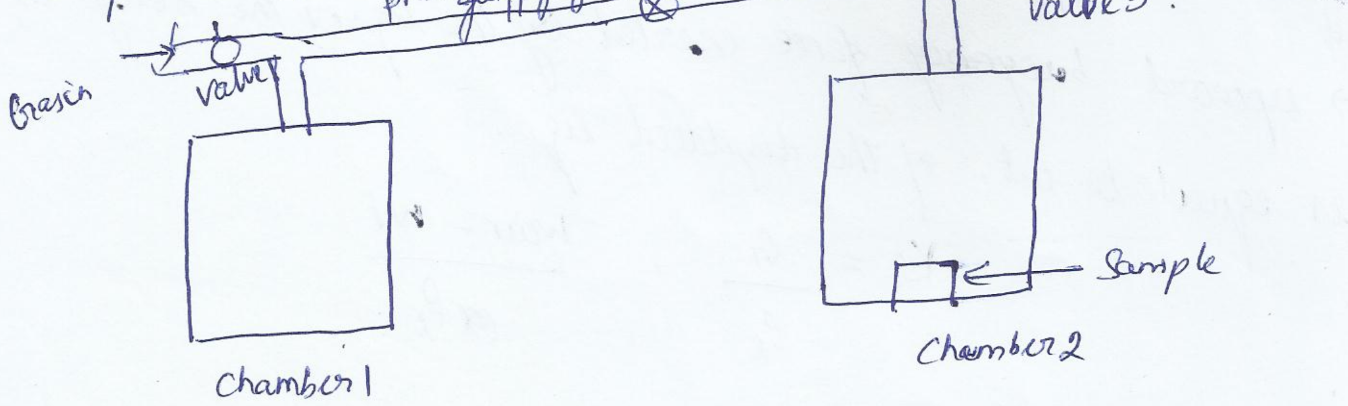
GAS DISPLACEMENT METHOD:-

→ volumes of particulate solids & materials of irregular space can be determined by displacement of gas or air in pycnometer.

→ used gases N_2 & Helium.

→ Two air tight chambers of equal volume, V_1 & V_2 connected by small diameter tube.

→ The sample is placed in the second chamber.



⑤

→ Exhaust Value & valve b/w two chambers are closed.

→ The inlet valve is opened & the gas is supplied to the first chamber until gauge pressure is ↑ (700-1000 Pa).

→ The inlet valve is closed & equilibrium. pressure is recorded.

Assuming gas behaves ideally,

$$P_1 V_1 = n R T_1$$

where P_1 - equilibrium pressure when valve 2 is closed (Pa).

V_1 - volume of the 1st champer (m3)

n - moles of gas (kg mol)

R-gas constant (8314.34 J/kg molk)

T_1 - absolute temp. (K)

→ Next the valve b/w two chambers is opened. & the gas b/w the 1st chamber is allowed to fill the free space in the 2nd chamber.

→ New pressure is recorded.

→ when value 2 is opened, mass of gas is ÷ into two ie

$$m = m_1 + m_2$$

Assuming the system is isothermal,

$$P_1 V_1 = P_2 V_1 + P_2 V_{a2}$$

where V_{a2} is the volume of the empty space in 2nd chamber.

& can expressed as:

$$V_{a2} = V_2 - V_s = V_1\left(\frac{P_1-P_2}{P_2}\right)$$

where V_s is the volume of solids (m^3) & can be found by

$$V_s = V_2 - V_1\left(\frac{P_1-P_2}{P_2}\right)$$

↓

volume of the gas present in the chamber 1 after valve 2 is opened.

→ Disadvantages :

→ Error for not accounting the volume of the tubing connecting the chambers.

→ Calculation assumes ideal gas law, air does not exactly follow ideal gas law.

→ Equalization of pressure is not isothermal.

SOLID DISPLACEMENT METHOD:-

→ For irregular solids ~~like~~ by using sand, glass bead or seed displacement method.

→ Rape seed is used for determining volume of baked pdts such as bread.

→ 1st bulk density of rapeseed is determined by filling the seed in a glass container & weight is noted.

→ From this density is found by using weight of the seed & volume of container.

→ Sample & rapeseeds are placed together in a container & weighted.

Volume of sample is calculated as

$$W_{seeds} = W_{total} - W_{container} - W_{sample}$$

$$V_{seeds} = \frac{W_{seeds}}{\rho_{seeds}}$$

$$V_{sample} = V_{container} - V_{seeds}$$

where W- weight (kg), V- volume (m3), ρ- density (kg/m³)

Expression of volumes:-

* Solid volume - * volume of solids excluding interior pores that are filled with air

* determined by gas displacement method in which the gas is capable of penetrating the pores up to the diameter of the gas molecules.

* Apparent volume - volume of substance including all pores within the material.

- Liquid or solid displacement method.
- apparent volume of regular geometries can be found by characteristic dimension.

* Bulk volume - volume of material when packed or stacked in bulk.

- it includes both external & internal pores.

DENSITY :- (20-23) S1

→ Quality of food materials can be assessed by measuring their densities.

→ It is required for separation process & centrifugation & in pneumatic & hydraulic transport of powders & particulates.

→ Density of liquid is req.. to measure the power req. for pumping.

→ Density - mass per unit volume.

- unit (SI) - kg/m³

→ In incompressible fluids, the density is hardly affected by moderate changes in T & P.

→ In compressible fluid such as Gases, the density is affected by changes in T & P.

→ Density of gases ↓ as temp ↑ &

" " " ↑ as pressure ↑

→ Under moderate condition, gases obey ideal gas law.

→ Mol wt of any gas in kg occupies 22.4 m³ at 273K & 1atm.

$$\text{Density of air } \rho_{air} = \frac{29 \text{ kg/kg mole}}{22.4 \text{ m}^3\text{/kg mole}}$$

→ Density of liq is determined by pycnometer.

→ wide mouthed bottles can be used for samples with ↑ viscosity like paste, honey & ketchup, batter.

→ Liquid density can be found using hydrometer. in a beaker filled with liquid.

→ Hydrometer has a stem that extends from a tubular Hydrometer. shaped bulb.

→ The dia of the bulb is equal to the dia of the thermometer

→ Bulb is filled with the dense material, & the hydrometer sinks in the liq upto the marked level.

→ The depth the hydrometer sinks depends on the density of the liq.

→ Deeper the hydrometer sinks, lower the density of the soln.

$$\text{Density of liquid} = \frac{\text{wt of hydrometer}}{\text{Volume of liq displaced}}$$

$$\rho_l = \frac{W}{Ax+V}.$$

where W - wt. of hydrometer (kg)

A - cross-sectional area of stem (m^2)

x - Length of the stem immersed (m)

V - Volume of the bulb.

→ Density hydrometer are used for narrow range app. & ∴ is sensitive to small change.

→ kinds of hydrometer → Lactometers for milk.
Oleometers for oil.
Twaddell hydrometer for liq. denser than water.
Baume scale → one for fluids heavier than water
second for lighter fluids.

→ Density of solids can be measured by their weight & volume.

→ Density are expressed in diff. forms.

* True density (ρ_T) - density of pure substance or a composite material calculated from densities of its components.

- if densities, volume or mass fraction of constituents is known

density can be determined from.

$$\rho_T = \sum_{i=1}^{n} x_i^v \rho_i = \frac{1}{\sum_{i=1}^{n} x_i^w / \rho_i}$$

ρ_i = density of i^{th} component (kg/m³).

x_i^v - volume fraction of ith component.

x_i^w - mass fraction of ith component.

n - no. of components.

* Solid density (ρ_s) - density of solid materials, excluding interior pores that are filled with air.

- ~~solid~~ do gas displacement method.

$$\text{Solid density} = \frac{\text{Sample wt}}{\text{Solid volume}}$$

* Material (substance) density (ρ_m) - density of material when the material is broken into pieces small enough that no closed pores remain.

* Particle density (ρ_p) - density of particles that has not been structurally modified.

- Includes volume of all closed pores.
- gas pychometer.

$$\text{Particle density} = \frac{\text{Sample wt}}{\text{Particle volume.}}$$

* Apparent density (ρ_{app}) - density of a substance including all pores within the material (internal pores)

- ρ_{app} for irregularly shaped samples may be determined by solid or liq displacement method.
- ρ_{app} for regular geometries can be found by measuring characteristics dimensions & mass.

* Bulk density (ρ_{bulk}) - density of a material when packed or stacked in bulk.

- Bulk density is found out for particulate solids by allowing it to pour into a container of known dimensions.
- It depends on solid density, geometry, size, surface properties, & method of measurement.

$$\rho_{bulk} = \frac{\text{sample wt}}{\text{Bulk volume.}}$$

MCQs

1. Coarse particle size is measured in

a) mm
b) cm
c) m
d) nm

2. Very fine size particle is measured in terms of

a) micrometer
b) nanometer
c) picometer
d) Both a and b

3. The ratio of the width to length of the sample is known as

a) radius of curvature
b) aspect ratio
c) angle of repose
d) sphericity

4. For very fine and sticky materials the angle of repose is

a) high
b) low
c) constant
d) None of the above

5. **Which fluid does not experience shearing stress during flow?**

a) Pseudoplastic
b) Dilatant
c) Newtonian
d) Inviscid

6. **Stress strain relationship for Newtonian fluid is**

a) Parabolic
b) Hyperbolic
c) Linear
d) Inverse type

7. What happens to viscosity of liquid and gas when temperature is increased?

a) For liquid increases and for gas decreases
b) For liquid decreases and for gas increases
c) Both increases
d) Both decreases

8. Which acceleration has a nonzero value in uniform flow?

a) Local acceleration
b) Convective acceleration
c) Both local as well as convective acceleration
d) unpredictable

9. Thermal conductivity in polymers increases with

a) Increase in crystallinity
b) Decrease in crystallinity
c) Either
d) None

10. Find the wrong statement: Specific heat of a material

a) Constant for a material
b) Heat capacity per unit mass
c) Extrinsic property
d) Has units as J/kg-K.

11. Differential scanning calorimeter is a technique to measure

a) Electrical conductivity
b) Impact energy
c) Thermal expansion
d) Specific heat

12. What is the graph that is represented in the airfoil section?
a) Lift-moment ratio
b) Coefficient of lift-coefficient of drag ratio
c) Angle of attack-drag ratio
d) Lift–angle of attack ratio

13. The relative humidity of food can be determined by measuring the
a) wet and dry bulb temperature of air
b) wet bulb temperature
c) dry bulb temperature
d) wet and dry bulb temperature of water

14. Water activity of most salt solution decreases with
a) **increase in temperature**
b) decrease in temperature
c) no temperature change
d) None of the above

15. Which of the following are used for the preparation of sorption isotherm?
a) hot air oven
b) desicattor
c) Laminar air flow chamber
d) muffle furnace

16. Raoult’s law is not valid for macromolecular solute due to
a) very high molecular weight of water and solute
b) very low molecular weight of water and solute
c) low molecular weight of water and solute
d) same molecular weight of water and solute

17. What is the process of producing electric dipoles inside the dielectric by an external electric field?
a) Polarisation
b) Dipole moment
c) Susceptibility
d) Magnetisation

18. Dielectric material's atoms and molecules are microscopically
a) positive
b) negative
c) neutral
d) None of these

19. Which of the following is correct about beta particles?
a) High specific ionization ability
b) Low penetrating power
c) Higher ionization ability than gamma radiation
d) All of the mentioned

20. Materials whose dominant charges in molecules are bound negative and positive charges that are held in place by atomic and molecular forces are known as
a) dielectrics
b) semiconductors
c) super conductors
d) conductors

21. The size of semolina particles was found to influence mainly

a) physical kinetics
b) chemical kinetics
c) absorption kinetics
d) sorption kinetics

22. The ratio of the diameter of the largest inscribed circle (di) to the diameter of the smallest circumscribed circle (dc)

a) sphericity
b) aspect ratio
c) radius of curvature
d) angle of repose

23. Major diameter is the longest diameter of the

a) projected area
b) minimum projected area
c) maximum projected area
d) None of the above

24. The instrument which is used to measure distance between surfaces is known as

a) viscometer
b)micrometer
c) porosimeter
d) hydrometer

25. **The unit of pressure one bar is**

a) 1 Pa
b) 1 kPa
c) 100 kPa
d) 1000 kPa

26. **Property of fluid that describes its internal resistance is known as**

a) Viscosity
b) Friction
c) Resistance
d) Internal energy

27. Which of the following represents Newtonain fluid?

a) Honey
b) Synthetic oil
c) Lubricating oil
d) Rubber suspension

28. Which of the following represents slow motion of layers of fluids in one direction?

a) Viscous fluid
b) laminar fluid
c) Turbulent fluid
d) laminar and viscous fluid

29. Heat capacity of most materials is approximately equal to

a) R
b) 2R
c) 3R
d) R/2

30. With increase in temperature, thermal conductivity of a metal

a) Increases
b) Decreases
c) Both increases and decreases
d) depends on the material

31. Change in enthalpy when 1 mol of compound is formed under standard conditions is called

a) reaction
c) combustion

b) formation
d) neutralization

32. Metals have thermal conductivities in the range of
a) < 1
b) 1-5
c) 5-25
d) 20-400

33. The manometric fluid used in vapour pressure method must be with
a) low density and low vapour pressure
b) high density and low vapour pressure
c) high density and high vapour pressure
d) high density and low vapour pressure

34. The determination of water activity by freezing point depression method is very accurate at water activities
a) below 0.85
b) 0.85
c) below 0.65
d) above 0.85

35. The relative humidity of food can be determined by measuring the
a) wet and dry bulb temperature of air
b) wet bulb temperature
c) dry bulb temperature
d) wet and dry bulb temperature of water

36. Water activity acts as
a) a processing factor
b) an intrinsic factor determining the likelihood of microbial population
c) an extrinsic factoe
d) All the above

37. If the loss tangent is very less, then the material will be a
a) Conductor
b) Lossless dielectric
c) Lossy dielectric
d) Insulator

38. Materials whose dominant charges in molecules are bound negative and positive charges that are held in place by atomic and molecular forces are known as
a) dielectrics
b) semiconductors
c) super conductors
d) conductors

39. Which of the following fact about radiation/ irradiation is true?
a) All food items consumed by man are radioactive
b) Alpha and beta particles and gamma photons are the radiations available for food preservation applications
c) Energy lost per ion pair formed is greater than the ionization energy
d) All the above

40. The relative viscosity of albumin in solution on irradiation

a) increases c) remain constant
b) decreases d) none of the above

41. Decrease in particle size increases
a) steady shear and complex density **c) steady shear and complex viscosity**
b) strain and complex density d) strain and complex viscosity

42. The shape of a food material is usually expressed in terms of its
a) sphericity **c) sphericity and aspect ratio**
b) aspect ratio d) angle of repose

43. The diameter of a sphere having the same volume as the particle is
a) equivalent diameter c) sphericity
b) diameter d) aspect ratio

44. The measure of the sharpness of the solids is known as
a) aspect ratio c) angle of repose
b) Roundness d) sphericity

45. The component of acceleration due to change in the direction of velocity vector is called as
a) direction acceleration **c) normal acceleration**
b) tangential acceleration d) parallel acceleration

46. **A Newtonian fluid is defined as the fluid which**
a) Obeys Hook's law c) Is incompressible
b) Is compressible **d) Obeys Newton's law of viscosity**

47. Which of the following represents Newton's equation for viscosity?
a) $\tau= \mu$ (dv/dt) c) τ = dv/dt
b) $\mu= \tau$ (dv/dt) d) $\tau= \mu^2$ (dv/dt)

48. If shear stress is proportional to the velocity gradient, the fluid is known as
a) Non- Newtonain fluid c) viscous fluid
b) laminar fluid **d) Newtonian fluid**

49. Thermal expansion of a material has units as
a) J/kg-K **c) 1/°C**
b) J/mol-K **d)** J.ohm/sec.K^2

50. Metals have thermal conductivities in the range of
a) < 1 **c)** 5-25
b) 1-5 **d) 20-400**

51. Exothermic enthalpy changes are shown as
a) negative values c) neutral

b) positive values

d) constant

52. Heat capacity of most materials is approximately equal to

a) R

b) 2R

c) 3R

d) R/2

53. Raoult’s law is not valid for macromolecular solute due to

a) very high molecular weight of water and solute

b) very low molecular weight of water and solute

c) low molecular weight of water and solute

d) same molecular weight of water and solute

54. How lift and drag ratio can be expressed in a relation?

a) Dividing the lift coefficient by the drag coefficient

b) Dividing the lift coefficient by the moment coefficient

c) Dividing the drag coefficient by the lift coefficient

d) Dividing the drag coefficient by the moment coefficient

55. Water activity of most salt solution decreases with

a) **increase in temperature**

b) decrease in temperature

c) no temperature change

d) None of the above

56. Type- III isotherm is observed in the case of

a) antifoaming agent

b) anticoagulant

c) anticaking agent

d) All the above

57. For a dielectric which of the following properties hold good?

a) They are superconductors at high temperatures

b) They are superconductors at low temperatures

c) They can never become a superconductor

d) They have very less dielectric breakdown voltage

58. Dielectrics are basically

a) insulators

b) semiconductors

c) super conductors

d) conductors

59. Low dose irradiation has a potential to

a) reduce the shelf life

b) extend the shelf life

c) does not have any influence on shelf life

d) None of the above

60. Which of the following is correct about beta particles?

a) High specific ionization ability

b) Low penetrating power

c) Higher ionization ability than gamma radiation

d) All of the mentioned

61. The particle size of powdered milk must be large enough to prevent

a) agglutination
b) agglomeration
c) crystal formation
d) emulsion formation

62. Major diameter is the longest diameter of the

a) projected area
b) minimum projected area
c) maximum projected area
d) None of the above

63. The ratio of surface area of a sphere having the same volume as the object to the actual surface area of the object is

a) radius of curvature
b) angle of repose
c) aspect ratio
d) sphericity

64. When the grains are smooth and rounded, the angle of repose is

a) constant
b) low
c) high
d) none of the above

65. Which acceleration has a nonzero value in uniform flow?

a) Local acceleration
b) Convective acceleration
c) Both local as well as convective acceleration
d) unpredictable

66. Viscous forces are not present in

a) rotational flow
b) irrotational flow
c) laminar flow
d) turbulent flow

67. Orifice type viscometer convert viscosity to

a) Force
b) Pressure
c) Displacement
d) Potential difference

68. Which of the following represents the relation for kinematic viscosity?

a) Absolute density X mass density
b) Absolute density X (mass density)^2
c) Absolute density/ mass density
d) Absolute density/(mass density)^2

69. Units for thermal conductivity

a) J/kg.K
b) J/mol.K
c) J.ohm/sec.K^2
d) W/m.K

70. Polymers have thermal conductivities in the range of

a) < 1
b) 1-10
c) 10-100
d) >100

71. Amount of energy required to break a specific covalent bond is called

a) bond dissociation energy
c) bond enthalpy

b) bond energy
d) All the above

72. Thermal conductivity in polymers increases with
a) Increase in crystallinity
b) Decrease in crystallinity
c) Either
d) None

73. What is the graph that is represented in the airfoil section?
a) Lift-moment ratio
b) Coefficient of lift-coefficient of drag ratio
c) Angle of attack-drag ratio
d) Lift–angle of attack ratio

74. The basic equation for the determination of water activity of ideal solution is
a) Newton's law
b) Dalton's law
c) Raoult's law
d) Henry's law

75. How lift and drag ratio can be expressed in a relation?
a) Dividing the lift coefficient by the drag coefficient
b) Dividing the lift coefficient by the moment coefficient
c) Dividing the drag coefficient by the lift coefficient
d) Dividing the drag coefficient by the moment coefficient

76. Water activity of most salt solution decreases with
a) **increase in temperature**
b) decrease in temperature
c) no temperature change
d) None of the above

77. Materials whose bounded dominant charges that are not free to travel are
a) dielectrics
b) semiconductors
c) super conductors
d) conductors

78. Dielectric don't contain any
a) bound charge
b) proton
c) free charge
d) neutron

79. With respect to which of the following properties of food does food irradiation prove a disadvantage?
a) flavor
b) tenderness
c) microbial growth
d) juiciness

80. Which of the following is correct about alpha particles?
a) High ionization due to relative size and carrying of double positive charge
b) Low penetration power
c) In air, they have a range of few centimeters
d) All the above

81. Size is an important physical attribute of foods used in
a) screening solids
c) separating foreign materials

b) grading of fruits and vegetables
d) All the above

82. The instrument which is used to measure distance between surfaces is known as

a) viscometer
c) porosimeter
b) micrometer
d) hydrometer

83. The ratio of volume of solid to the volume of a sphere that has a diameter equal to the major diameter of the object so that it can circumscribe the solid sample is

a) aspect ratio
c) sphericity
b) angle of repose
d) radius of curvature

84. The amount of three-dimensional space occupied by an object is known as

a) porosity
c) surface area
b) density
d) volume

85. Newton’s law of viscosity relates

a) pressure velocity and viscosity
c) temperature viscosity and velocity
b) shear stress and rate of angular deformation in a fluid
d) pressure temperature viscosity and rate of angular deformation in a fluid.

86. The shear stress applied to the fluid is directly proportional to the velocity gradient is known as

a) Newton's law of viscosity
c) Arrhenius equation
b) Newton’s law of cooling
d) Stefan-Boltzmann equation

87. What is an ideal fluid?

a) A fluid which has no viscosity
c) A fluid which has no surface tension
b) A fluid which is incompressible
d) All of the above

88. Which of the following is not converting viscosity into pressure?

a) Redwood viscometer
c) Orifice viscometer
b) Rotameter viscometer
d) Saybolt viscometer

89. Find the wrong statement: Specific heat of a material

a) Constant for a material
c) Extrinsic property
b) Heat capacity per unit mass
d) Has units as J/kg-K.

90. Heat capacity has units as

a) J/kg.K
c) J.ohm/sec.K^2
b) J/mol.K
d) W/m.K

91. Enthalpy changes which cannot be found by calorimeter can be found by help of

a) Newton's Law
c) Krebs's Law
b) Hess's Law
d) Ohm’s Law

92. Units for thermal conductivity

a) J/kg.K
b) J/mol.K
c) J.ohm/sec.K^2
d) W/m.K

93. Water activity acts as
a) a processing factor
b) an intrinsic factor determining the likelihood of microbial population
c) an extrinsic factoe
d) All the above

94. How lift and drag ratio can be expressed in a relation?
a) Dividing the lift coefficient by the drag coefficient
b) Dividing the lift coefficient by the moment coefficient
c) Dividing the drag coefficient by the lift coefficient
d) Dividing the drag coefficient by the moment coefficient

95. To increase or decrease water activity
a) increase or decrease temperature
b) increase or decrease pressure
c) increase pressure
d) Both a and b

96. Water activity of foods can be measured by using methods based on
a) colligative property
b) heteroscopicity of salts
c) moisture level
d) none of the above

97. Identify a good dielectric.
a) Iron
b) Ceramics
c) Plastic
d) Magnesium

98. A dielectric can be made a conductor by
a) Compression
b) Doping
c) Heating
d) Freezing

99. The relative viscosity of albumin in solution on irradiation
a) increases
b) decreases
c) remain constant
d) none of the above

100. With respect to which of the following properties of food does food irradiation prove a disadvantage?
a) flavor
b) tenderness
c) microbial growth
d) juiciness