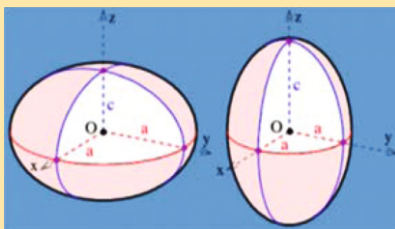
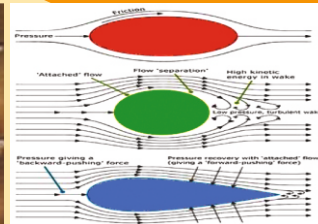
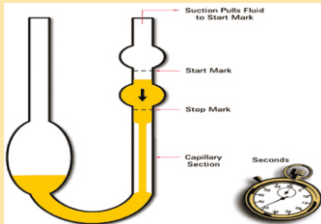
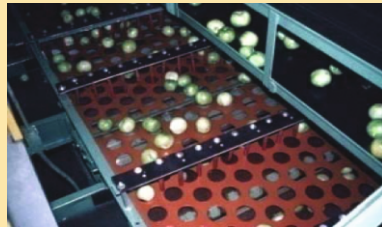


# LECTURE NOTES ON ENGINEERING PROPERTIES OF AGRICULTURAL PRODUCE



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**ON**  
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*Published by*

**Department of Agricultural Processing and Food Engineering  
College of Agricultural Engineering & Technology  
Odisha University of Agriculture & Technology  
Bhubaneswar - 751003**

**The printing of this book has been funded  
from IDP-NAHEP, OUAT, Bhubaneswar**

**Printed at  
M/S JAGANNATH PRINTERS  
Plot No.- 100, Road No. - 13, Mahavir Nagar  
Samantarapur, Bhubaneswar-751002**

**2023**

## **PREFACE**

Engineering properties of foods are useful in the design and development of various agricultural machineries for different unit operations such as cleaning, grading, drying, dehydration, milling, handling, transportation and storage. The properties are also used to monitor the textural properties and quality of different foods. In this book, the concept related to various engineering properties like physical, thermal, frictional, rheological, textural, colour and electrical properties along with their application during different stages of food processing have been discussed. Methods and instruments involved in the measurement of all these properties and their importance in relation to food quality and safety have also been narrated. Physical and frictional properties of foods have great importance in food characterization, handling, processing, and monitoring of quality food products. These properties affect the chemical and physical characteristics of foods at micro and macro levels during processing and storage. For accurate calculation of energy balance during heating and cooling process, it is important to know the behavior of thermal data of foods in terms of specific heat, thermal conductivity, and thermal diffusivity. The determinations of different thermal properties are illustrated with diagrams and formulae. Rheological properties are related with the flow and deformation of food systems. The chapter also explains the rheology of solid and liquid foods along with rheological models. Colour parameters are one of the important quality indicators of foods. Various color measurement systems like Munsell, Hunter, CIELAB, etc. have been explained. Narrations on electrical and dielectric properties of food materials have been made to enlighten the students their role in new and convenient food product development

The author expresses her gratefulness to the Dean, College of Agricultural Engineering and Technology, OUAT, Bhubaneswar for giving permission for the publication of this book. The author is also thankful to IDP-NAHEP, OUAT for providing the financial support to print this book. The authors also acknowledge all the direct and indirect help rendered by the persons while preparing this manuscript. The book is useful for both under graduate and post graduate students of Agricultural Engineering, Food Engineering and Food Technology. This can also be used as a reference material for all the researchers working in agriculture and allied fields.

**Kalpana Rayaguru**

NAME OF THE COURSE: **Engineering Properties of Agricultural produce**

COURSE NO.: **PFE 221**; CREDIT HOUR: **1+1**

**Theory Lecture outline**

| <b>Chapter</b> | <b>Major Topic (page no)</b>                           | <b>Courses to be covered</b>                                                                                                                                                                                                                                                                                  |
|----------------|--------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.             | General introduction (2)                               | Classification and importance of engineering properties of Agricultural Produce                                                                                                                                                                                                                               |
| 2.             | Physical properties (8)                                | Size, Shape, roundness, sphericity, particle and bulk Volume, density, porosity, specific gravity and surface area of grains and fruits and vegetables, methods of their measurement                                                                                                                          |
| 3.             | Thermal properties (18)                                | Basics of mode of heat transfer, Heat capacity, Specific heat, Thermal conductivity, methods of their measurement, Thermal diffusivity, Surface heat transfer co-efficient, Freezing point of depression and boiling point of elevation, Heat of respiration, Coeff of thermal expansion, Thermal Emissivity. |
| 4.             | Friction in agricultural materials (24)                | Static friction, Kinetic friction, Internal friction, Angle of repose, methods of their measurement, Rolling resistance, Flow of bulk granular materials                                                                                                                                                      |
| 5.             | Aero dynamics of agricultural products (30)            | Concept and basics of aerodynamic properties Drag coefficient and Terminal velocity, methods of their measurement                                                                                                                                                                                             |
| 6.             | Basic concepts of Rheology (34)                        | Stress, strain, shear rate, Analysis of force deformation curve, Bio-yield point, rupture point, Elasticity, Plasticity, degree of elasticity,                                                                                                                                                                |
| 7.             | Rheological properties (38)                            | Classical ideal materials, ideal elastic behaviour, elastic properties, young's modulus, shear modulus, bulk modulus, Poisson's ratio<br>Ideal plastic behaviour, Ideal viscous behaviour, viscosity (kinematic and absolute) and its measurement                                                             |
| 8.             | Visco-elastic Models and Equations (45)                | Basic mechanical elements, spring and dashpot, Maxwell model, Kelvin model, Electrical equivalence of mechanical models,                                                                                                                                                                                      |
| 9.             | Behaviour of different types of fluids (51)            | Newtonian and non-Newtonian fluid, Pseudoplastic, Dilatant, Thixotropic, Rheopectic and Bingham Plastic Foods, Flow curves                                                                                                                                                                                    |
| 10.            | Electromagnetic spectrum, determination of colour (55) | Details of electromagnetic spectrum and the use, Principle of colour measurement, Hue, chroma and value                                                                                                                                                                                                       |
| 11.            | Electrical and dielectric properties (62)              | Measurement methods of resistance, capacitance, dielectric loss factor, loss tangent, and dielectric constant,                                                                                                                                                                                                |
| 12.            | Application of engineering properties                  | Application of engineering properties in handling processing machines and storage structures.                                                                                                                                                                                                                 |

## **CHAPTER-1**

### **CLASSIFICATION AND APPLICATION OF ENGINEERING PROPERTIES**

Biological materials especially that are consumed as food or feed undergo various unit operations right from the pre-harvest to post harvest processing, preservation, packaging, and storage. Scientists and engineers need to know and understand the characteristics of the material to be processed, preserved and consumed to solve the problems while designing and selecting the means and modes of preservation, packaging, processing, storage, marketing, and consumption. Each of these unit operations has unique characteristics and need special tools and equipments. Designing and selecting of such tools and equipments require information regarding various engineering properties.

#### **A. Physical Characteristics**

1. Size, 2. Shape, 3. Weight, 4. Volume, 5. Density, 6. Specific gravity 7. Porosity, 8. Surface area, 9. Color etc

**Application of physical properties:** The knowledge of some important physical properties such as shape, size, volume, surface area, thousand grain weights, density, and porosity of different grains is necessary for the design of various separating, handling, storing and drying systems. The function of many types of machines is influenced decisively by the size and shape of the fruit participating. The size and shape are, for instance, important in their electrostatic separation from undesirable materials and in the development of sizing and grading machinery. Bulk density, true density, and porosity (the ratio of intergranular space to the total space occupied by the grain) can be useful in sizing grain hoppers and storage facilities; they can also affect the rate of heat and mass transfer of moisture during aeration and drying processes; Density is used to separate materials with different densities or specific gravities. Separation of properly matured peas can be separated from the immature and infected ones by water flotation methods. Grain bed with low porosity will have greater resistance to water vapor escape during the drying process, which may lead to higher power to drive the aeration fans. Cereal grain densities have been of interest in breakage susceptibility and hardness studies. For instance, bulk density values for raw and parboiled paddy have practical applications in the calculation of thermal properties in heat transfer problems, in determining Reynolds number in the pneumatic handling of the material, and in separating the product from undesirable materials. It plays an important role in other applications that include the design of silos and storage bins and the maturity and quality of paddy, which are essential to grain marketing. The resistance of bulk grain to airflow is in part a function of the porosity and the kernel size.



**Sorting and Grading**



## Packaging

### B. Thermal Properties

1. Specific heat, 2. Thermal conductivity, 3. Thermal capacity, 4. Thermal diffusivity
5. Boiling point elevation, 6. Freezing point depression, 7. Sensible and latent heat
8. Thermal emissivity etc

**Application of thermal properties:** These properties are involved in almost every food processing operation. Knowledge of the thermal properties of foods is essential in the analysis and design of various food processes and food processing equipment involved in heat transport, with respect to heat transfer or energy use, such as in extrusion cooking, drying, sterilization, cooking etc. The most important thermal properties in food processing such as, specific heat capacity ( $C_p$ ), thermal conductivity ( $k$ ), and thermal diffusivity ( $\alpha$ ). Specific heat has an important role in determination of energy cost and for the dimensions of machinery and equipment that are needed in thermal processes. Furthermore, specific heat ( $C_p$ ) of food materials changes according to their physical and chemical properties. The thermal conductivity ( $k$ ) of food determines how fast heat can be evenly transferred to the entire food mass, which in turn affects the quality of the final product. When heating and cooling of materials involves unsteady state or transient heat conduction, the material temperature changes with time and knowledge of the thermal diffusivity ( $\alpha$ ) is required for predicting temperature in these processes.



## Retailing and end point determination

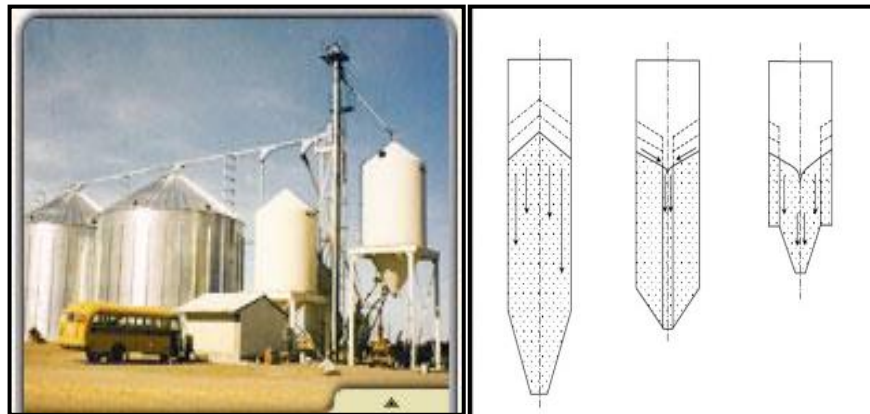
### C . Frictional properties

1. Coefficient of friction, 2. Coefficient of internal friction, 3. Angle of Repose
4. Rolling resistance etc

**Application of frictional properties:** Frictional properties such as angle of repose and coefficient of friction are important in designing equipment for solid flow and storage structures and the angle of internal friction between seed and wall in the prediction of seed pressure on walls. The coefficient of static friction plays also an important role in transports (load and unload) of goods and storage facilities. It is important in filling flat storage facility when grain is not piled at a uniform bed depth but rather is peaked. Coefficient of internal friction is important in designing storage bins, hoppers, chutes, screw conveyors, forage harvesters, and threshers. The material generally moves or slides in direct contact with trough, casing, and other components of the machine. The various parameters affect the power requirement to drive the machine. The frictional losses are one of the factors, which must be overcome by providing additional power to the machine. Hence, the knowledge of coefficient of friction of the agricultural materials is necessary.



**Elevator components**



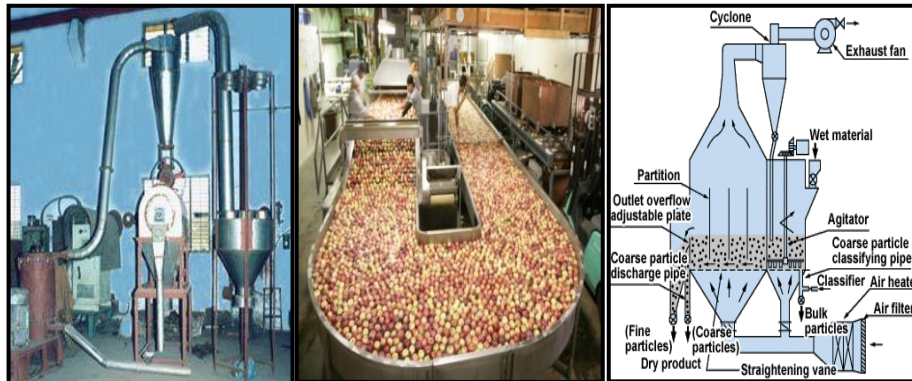
**Storage structures**

### D. Aero and Hydro dynamic properties

1. Drag coefficient, 2. Terminal velocity etc

**Application of aerodynamic properties:** The aerodynamic properties and hydrodynamic properties like terminal velocity and drag coefficient of agricultural products are important and required for the designing of air/ hydro conveying systems and the separation equipment. The physical properties, such as density, shape, size, etc., are required for calculating the terminal velocity and drag coefficient of the agricultural produce. In the handling and processing of agricultural products, air is often used as a carrier for transport or for separating the desirable

products from unwanted materials, therefore the aerodynamic properties, such as terminal velocity and drag coefficient, are needed for air conveying and pneumatic separation of materials. As the air velocity, greater than terminal velocity, lifts the particles to allow greater fall of a particle, the air velocity could be adjusted to a point just below the terminal velocity. The fluidization velocity for granular material and settling velocity are also calculated for the body immersed in viscous fluid.



**Conveying equipments**

#### **E. Mechanical and Rheological properties**

- 1 Stress, Strain, 2. Compressive strength, 3. Tensile strength, 4. Shear resistance
5. Elasticity, 6. Plasticity, 7. Flow properties, 8. Viscosity, 9. Hardness / firmness etc

**Application of rheological properties:** Knowledge of the rheological and mechanical properties of various food systems is important in the design of flow processes for quality control, in predicting storage and stability measurements, and in understanding and designing texture. The rheological behaviour under limited deformation has been widely used to obtain information on the structure and viscoelasticity of materials. An understanding of flow behaviour is necessary to determine the size of the pump and pipe and the energy requirements. The rheological models obtained from the experimental measurements can be useful in design of food engineering processes. Effects of processing on rheological properties must be known for process control. Texture is one of the most important quality characteristics of foods. The differences in textural properties are caused by inherent differences due to the variety, maturity, and differences caused by processing methods. Food texture can be evaluated by sensory or instrumental methods. Sensory methods need a taste panel containing trained panellists. It is hard to repeat the results. Instrumental methods are less expensive and less time consuming as compared to sensory methods.



**Application of mechanical and rheological properties**

## F. Electric and Dielectric Properties

1. Electrical Conductivity, 2. Electrical Resistance, 3. Capacitance, 4. Dielectric properties
5. Dielectric constant, 6. Dielectric loss factor, 7. Loss tangent

**Application of electric and dielectric properties** Dielectric properties play a major role in determining the interaction between the food material being processed and the electromagnetic energy. The degree of heating of a food material subjected to microwave or radio frequency processing is strongly influenced by the dielectric properties of the food. Dielectric heating occurs due to polarization and ionization of molecules, which are effectively used in drying, sterilization, pasteurization and other thermal processing operations. Dielectric properties consist of dielectric constant ( $\epsilon'$ ) and dielectric loss factor ( $\epsilon''$ ). Dielectric constant is a measure of the ability of a material to store electromagnetic energy whereas dielectric loss factor is a measure of the ability of a material to convert electromagnetic energy to heat. Loss tangent ( $\tan \delta$ ), a parameter used to describe how well a product absorbs microwave energy, is the ratio of  $\epsilon''$  to  $\epsilon'$ . A product with a higher loss tangent will heat faster under microwave field as compared to a product with a lower loss tangent.

Some electrical properties which are of importance in agro-processing are electrical conductance, resistance, impedance. Electrical conductance or capacitance has been used for determining the moisture content of grain. Electrostatic separation of grains is also used for separating grains, based on the ability of the grain to hold electrostatic charge. Electrical conductivity of the grain decides the ability of the material to hold electrostatic charge. Recently ohmic heating has been in use for drying, pasteurization, blanching and other thermal processing of foods, based on resistance heating. The heat distribution throughout the product is far more rapid and even, which in turn can result in better flavour retention and particulate integrity compared to conventional processes. The efficiency of ohmic heating is dependent on the conductive nature of the food to be processed and hence knowledge of the conductivity of the food as a whole and its components is essential in designing a successful heating process.



**Application of electric and dielectric properties**

## G. Optical Properties

1. Hue, 2. Chroma, 3. Value, 4. Total colour change

**Application of Optical Properties:** Light transmittance and reflectance properties of agricultural commodities are used for sorting, grading, maturity, surface colour and blemish determination. The use of hyperspectral, multispectral, infrared imaging and computer vision system have enabled even determination of moisture and other chemical composition, contamination of agro commodities to greater satisfaction of consumers and traders. This has reduced the manual inspection, which might be subjected to error due to fatigue. These systems offer the potential to automate manual grading practices and thus to standardize techniques and eliminate tedious inspection tasks. The automated inspection of produce using machine vision not only results in labour savings, but also can improve inspection, objectivity.



**Colour measurement and its application**

## CHAPTER-2

### PHYSICAL PROPERTIES

1. Size, 2. Shape, 3. Volume, 4. Density, 5. Specific Gravity, 6. Surface area

### Size

Size is the dimensional characteristics of an object. Usually measured in terms of length, breadth, thickness, diameter, height depending on the significance.

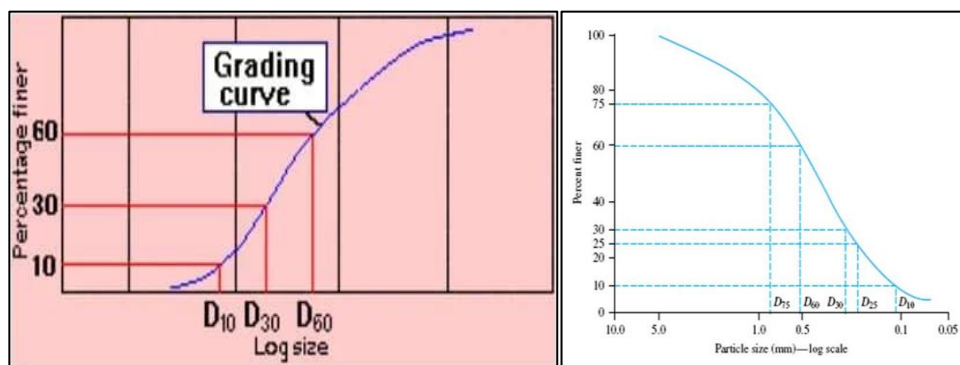
- Spherical particles like peas: defined by a single characteristic such as its diameter.
- Non-spherical objects like wheat kernels: multiple length measurements. (length,width,thickness)
- Ellipsoidal object such as grain kernel or potato: The longest diameter (major) and shorter diameter/s (minor) will adequately describe the size. The two/three dimensions are usually measured perpendicular to one another.
- Pear-shaped objects such as okra, pears, carrots, or beets: diameter or circumference of the largest part and an overall length in the direction of the stem.
- Irregular-shaped materials like bananas, requires more extensive considerations. May be given only in diameter and overall length.

#### *Methods of measurement*

- ✓ Measurement method: Micrometer and slide calipers
- ✓ Projected method: Photographic enlarger
- ✓ Electronic devices: Image analysis (Precise method)

#### *Size of Powder*

Particle size is used in grinding operations to determine the condition of the final product and determines the required power to reduce the particle's size. Small irregular-shaped objects can be sized with sieves by expressing particle size as the smallest sieve opening through which the particle passes. The size of larger objects may be expressed only in terms of its largest diameter or circumference. Fineness Modulus: Fineness Modulus is defined as an index of the mean particle size of the lot and is calculated from the sieve analysis. It is defined mathematically as the sum of the cumulative percentages retained on the standard sieves divided by 100. More fineness modulus value indicates that the aggregate is coarser.



**Particle size distribution using cumulative analysis**

### Procedure of Grain Size Analysis of Aggregates

- ✓ Take the sample of aggregates
- ✓ Arrange the sieves one over the other in descending order of the size
- ✓ Carry out the sieving for the specified time
- ✓ Find the weight of aggregate retained on each sieve taken in order. Tabulate in a table.
- ✓ Plot the Graph

Draw a graph with sieve opening to normal/log scale on the X-axis and % finer on Y-axis  
The curve is called a grading curve.

### Calculations in Grain Size Analysis

Effective size in microns (D10 sieve opening corresponding to 10% finer in the graph)

Uniformity coefficient (D60/ D10), D to be obtained from the graph)

Fineness modulus = (Sum of cumulative % weight retained /100)

## Shape

Shape describes the object in terms of a geometrical body. The shape of a food material is usually expressed in terms of its:

- ✓ Roundness,
- ✓ Sphericity,
- ✓ Slenderness ratio,
- ✓ Aspect ratio,
- ✓ Ellipsoid ratio and
- ✓ Flattening

**Sphericity** expresses the characteristic shape of a solid object relative to that of a sphere of the same volume

1. **Sphericity** =  $De/Dc$

2. **Sphericity** =  $Di/Dc$

where:  $De$  = equivalent diameter of a sphere of the same volume as the object

$Di$  = diameter of largest inscribed circle

$Dc$  = diameter of smallest circumscribed circle

3. **Sphericity** =  $(Vo / Vc)^{1/3} = (l.w.t)^{1/3} / 1$  (For Triaxial Ellipsoid)

i.e. Ratio of Geometric mean diameter to major diameter

$Vo$  = Volume of object

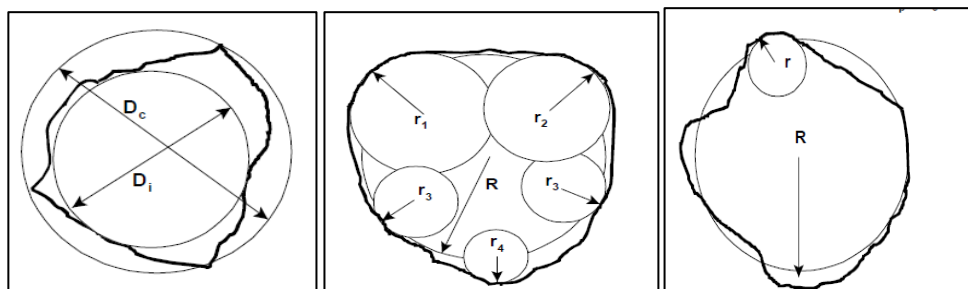
$Vc$  = Volume of smallest circumscribed sphere

$l$  = longest intercept

$w$  = longest intercept normal to 'l'

$t$  = longest intercept normal to 'l' and 'w'

Note:  $Vo = [(\pi/6) lwt]$  and  $Vc = [(\pi/6) l^3]$



Projected area of irregular objects

**Roundness** is a measure of the sharpness of the corners of the solid.

1. **Roundness** =  $A_p/A_c$

Where:  $A_p$  = largest projected area of object in natural rest position

$A_c$  = area of smallest circumscribing circle

2. **Roundness** =  $\sum r / NR_i$

Where:  $r$  = radius of curvature as defined in figure

$R_i$  = radius of maximum inscribed circle

$N$  = total number of corners summed in numerator

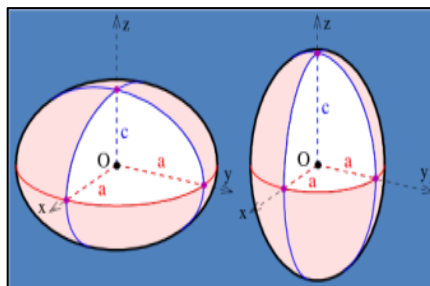
3. **Roundness Ratio** =  $\frac{\text{Radius of curvature of the sharpest corner}}{\text{Mean radius of the particle}} = r/R_m$

The use of the radius of curvature of a single corner determines the roundness of an object

- **Slenderness ratio** is the Ratio of length of rice to width of rice. Usually used for grading of rice.
- **Aspect ratio**= The aspect ratio of a geometric shape is the ratio of its sizes (longer to shorter) in different dimensions. Rectangle is the ratio of its longer side to its shorter side Ellipse, the ratio of the major axis to the minor axis.
- **Ellipsoid ratio** = Major diameter: minor diameter
- **Flattening (oblateness)** is a measure of the compression of a sphere along a diameter to form an ellipsoid of revolution. It is the ratio of difference of the major and minor semi-axes to major semi axis

**Prolate spheroid** which is formed when an ellipse rotates about its major axis. A prolate spheroid is a spheroid in which the polar axis is greater than the equatorial diameter. e.g. lemon, lime, grape etc.

**Oblate spheroid** is formed when an ellipse rotates about its minor axis. An oblate spheroid is a rotationally symmetric ellipsoid having a polar axis shorter than the diameter of the equatorial circle e.g. Orange, pumpkin, lentil (*masur dal*) etc.



**Right circular cone or cylinders** is formed when a frustum rotates about its axis e.g. carrot and okra The semi-axes on a spheroid is.

oblate if  $c < a$  (left); prolate if  $c > a$  (right);  $a=b=c$  (Sphere)

$a$  and  $b$  are the base and top side lengths of the truncated pyramid, and  $h$  is the height

# Volume

Volume is defined as the amount of three-dimensional space occupied by an object, usually expressed in units that are the cubes of linear units, or in units of liquid measure, such as litres. In the SI system, the unit of volume is m<sup>3</sup>.

**Bulk volume:** The volume of substance includes all pores within the material (internal pores) and also the void volume outside the boundary of individual particles when stacked in bulk (external pores). Bulk volume can be calculated by measuring the volume of the bulk sample by keeping the material in a container of known geometry.

**Particle volume:** This volume is the actual volume of the solid granular material, which is devoid of the volume of intergranular spaces.

**Expression and measurement of volume:** Volume, can be calculated by

- ✓ The measured dimensions (Geometrical)
- ✓ Using various methods such as liquid, gas, or solid displacement methods
- ✓ Image processing.

## Liquid Displacement Method

The volume of a sample can be measured by direct measurement of volume of liquid displaced. If the solid sample does not absorb liquid very fast, the liquid displacement method can be used to measure its volume by using a pycnometer (specific gravity bottles) or graduated cylinder or burette. The difference between the initial volume of liquid in a graduated cylinder and the volume of liquid with immersed material gives us the volume of the material. A non-wetting fluid such as mercury is better to use for displacement since in this case samples do not need coating. The use of a specific gravity bottle (Pycnometer, small necked) and toluene has been practiced for many years.

**Toluene has many advantages when used as reference liquid** (Mohsenin, 1986):

1. Little tendency to be soaked by the sample
2. Smooth flow over the surface due to surface tension
3. Low solvent action on constituents, especially fats and oils
4. Fairly high boiling point
5. Low and stable specific gravity and viscosity when exposed to the atmosphere

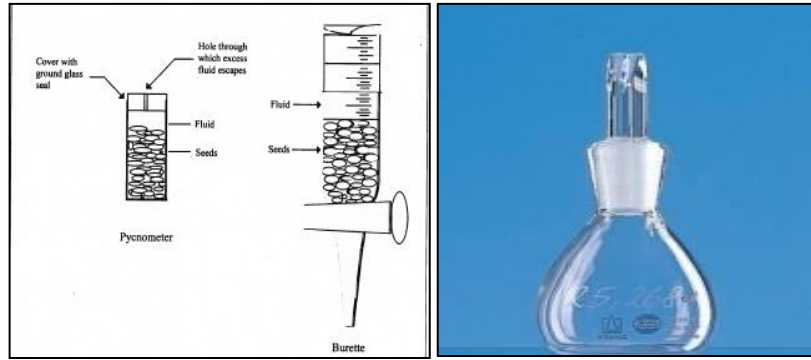
## Pycnometer method

$$\text{Volume (m}^3\text{)} = \frac{\text{Wt.of displaced water } (\frac{\text{kg}}{\text{g}})}{\text{Wt.density of water } (\frac{\text{kg}}{\text{m}^3})}$$

$$V_s = \frac{\text{Weight of the liquid displaced by solid}}{\text{Density of liquid}} = \frac{(W_{pl} - W_p) - (W_{pls} - W_{ps})}{\rho_l}$$

where

- $V_s$  = volume of the solid (m<sup>3</sup>),
- $W_{pl}$  = weight of the pycnometer filled with liquid (kg)
- $W_p$  = weight of the empty pycnometer (kg)
- $W_{pls}$  = weight of the pycnometer containing the solid sample and filled with liquid (kg)
- $W_{ps}$  = weight of the pycnometer containing solid sample with no liquid (kg)
- $\rho_l$  = density of the liquid (kg/m<sup>3</sup>).



Pycnometer (Specific gravity bottle)

**For larger objects (F & V)**, a platform scale can be used the sample is completely submerged in liquid such that it does not make contact with the sides or bottom of the beaker. The method is based on the Archimedes principle, which states that a body immersed in a fluid will experience a weight loss in an amount equal to the weight of the fluid it displaces. The upward buoyancy force exerted on a body immersed in a liquid is equal to the weight of the displaced liquid. Weight of the liquid displaced by the solid sample is divided by its density.

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

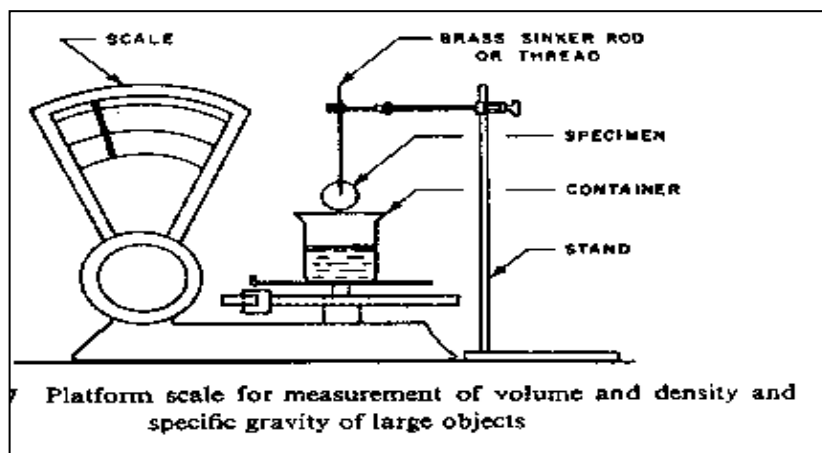
Where,  $G$  = the buoyancy force (N),

$\rho_l$  = density of the liquid ( $\text{kg/m}^3$ )

$W_{air}$  = the weight of sample in air (kg)

$W_l$  = the weight of sample in liquid (kg)

$$V_s = \frac{G(\text{sample+sinker}) - G(\text{sinker})}{\rho_l}$$



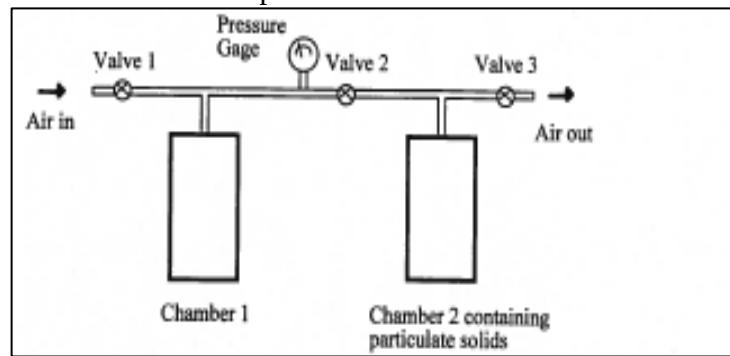
NB: The sample is forced into the liquid by means of a sinker rod if it is **lighter**. It is suspended with a string if it is **heavier** than the liquid. Liquids having a density lower than that of sample should be used if partial floating of the sample is observed.

### **Gas Displacement Method**

Volumes of particulate solids and materials with irregular shape can be determined by displacement of gas or air in pycnometer. The most commonly used gases are helium and nitrogen.

### **Solid Displacement Method**

The volume of irregular solids can also be measured by sand, glass bead, or seed displacement method. Rapeseeds are commonly used for determination of volume of baked products such as bread. Ex: Sand in puffed rice



**Schematic diagram of air comparison pycnometer for measuring volume of particulate solids**

**Working Principle:** The air comparison pycnometer consists of two airtight chambers of nearly equal volumes,  $V_1$  and  $V_2$ , that are connected with small-diameter tubing. The material to be measured is placed in the second chamber. The exhaust valve (valve 3) and the valve between the two chambers (valve 2) are closed. The inlet valve (valve 1) is opened and the gas is supplied to the first chamber until the gauge pressure is increased up to a suitable value (e.g., 700–1000 Pa). Then, the inlet valve is closed and the equilibrium pressure is recorded. Assuming that the gas behaves ideally:

$$P_1 V_1 = nRT_1$$

Where,

$P_1$  = equilibrium pressure when valve 2 is closed (Pa)

$V_1$  = volume of the first chamber ( $m^3$ )

$n$  = mole of gas (kg mol)

$R$  = gas constant (8314.34 J/kg mol K)

$T_1$  = absolute temperature (K)

After the equilibrium pressure is recorded, the valve between the two chamber is opened (valve 2) and the gas within the first chamber is allowed to fill the empty spaces (pores) in the second chamber. The new pressure ( $P_2$ ) is recorded. When valve 2 is opened, total mass of gas ( $m$ ) is divided into two, one of which fills the first tank ( $m_1$ ) and the other fills pore space of the second tank ( $m_2$ ).

$$m = m_1 + m_2$$

Assuming that 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 spaces within the second chamber and  $V_s$  is the volume of the solid and can be calculated from the following equations:

$$V_{a2} = V_2 - V_s = V_1 \frac{P_1 - P_2}{P_2} \quad V_s = V_2 - V_1 \frac{P_1 - P_2}{P_2}$$

## Density

Density of a material is the amount of that material occupying a certain space and is expressed in units of mass per unit volume. Materials consisting of particles or grains with interstitial air spaces have different values of particle density and bulk density. Materials without internal air spaces, such as fluids and solids, have equal particle and bulk density.

**Particle density (PD)** is the mass divided by the volume of the particle alone. Particle density is the density of a particle, which includes the volume of all closed pores but not the externally connected pores.

**Bulk density (BD)** is the mass of a group of individual particles divided by the space occupied by the entire mass, including the air space. Density of food materials is useful in mathematical conversion of mass to volume. Bulk density is the density of a material when packed or stacked in bulk.

**Porosity** is the percentage of air (pore space) between the particles compared to a unit bulk volume of particles.

$$\text{Porosity} = [(\text{PD} - \text{BD}) * 100] / \text{PD}$$

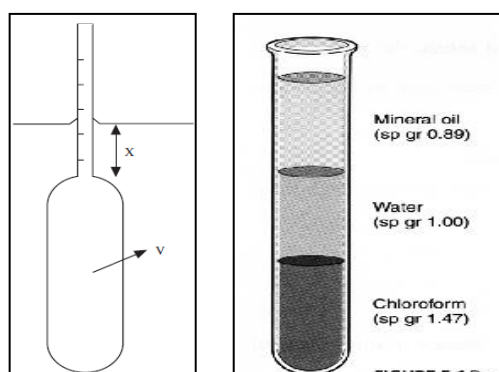
Porosity depends on-

- ✓ Shape
- ✓ Dimension/Size
- ✓ Roughness of grain surface

Porosity allows gases and liquids to flow through a mass of particles referred to as a packed bed in drying and distillation operations. Beds with low porosity (low percentage air space) are more resistant to fluid flow and thus are more difficult to dry, heat, or cool. With high porosity, air flows easily through the bed, drying is fast, and the power required by fans and pumps is low.

Density is mass per unit volume of a substance. Because the gram is defined as the mass of 1 cc of water at 4°C the density of water is 1 g/cc.

- The density of liquids can be determined by using a pycnometer.
- Wide-mouthed bottles can be used for very viscous materials such as tomato paste, batter, or honey.
- Liquid density can also be measured by placing a hydrometer in a beaker filled with the liquid sample.
  - ✓ Lactometer: milk; Oleometer: oil
- Volume measurement methods can also be used for measuring the density of solids.



**Hydrometer**

### **Specific gravity**

It is a ratio, expressed decimally, of the weight of a substance to the weight of an equal volume of a substance chosen as a standard, both substances at the same temperature. Water is used as the standard for the specific gravities of liquids and solids; The most useful standard for gases is hydrogen, although sometimes air is used.

$$\text{Specific Gravity} = \frac{\text{Weight of the substance}}{\text{Weight of an equal volume of water}} = \frac{\text{Density of the substance}}{\text{Density of water}}$$

The specific gravity is defined as the ratio of the mass of that product to the mass of an equal volume of water at 4°C, the temperature at which water density is greatest. OR, as the ratio of the density of a given solid or liquid substance to the density of water at a specific temperature and pressure, typically at 4°C (39°F) and 1 atm (760.00 mmHg), making it dimensionless.

NB: Changes in temperature will not change the weight of a substance but will change the volume of the substance by expansion or contraction, thus changing the weight per unit volume.

### **Specific gravity measurement by Pycnometer method**

Specific gravity of toluene = weight of toluene / weight of water

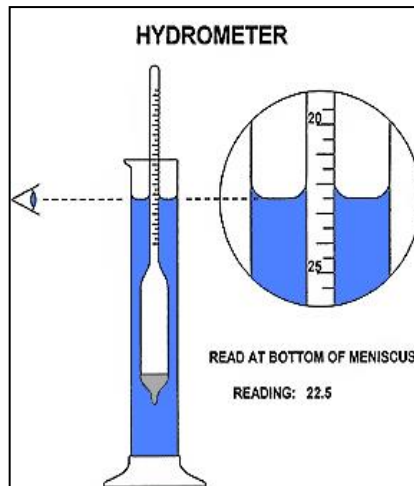
Specific gravity of grain = (specific gravity of toluene x weight of grain) / (weight of toluene displaced by the grain) = specific gravity of toluene x weight of grain / [(weight of sample) – ((weight of toluene + sample + bottle) – (weight of toluene + bottle))]

1. Determine the exact capacity of the pycnometer by weighing it when empty and likewise when filled with distilled water at 20 deg C and toluene separately
2. Determine specific gravity of toluene
3. Around 10 g of solid specimen are placed in the pycnometer with sufficient toluene to cover the sample
4. Gradually exhaust the air from the bottle by a vacuum pump to promote escape of the air trapped under the surface hairs and in the creases of the seeds or kernels
5. When air bubbles cease to be given off after several cycles of vacuuming and releasing the vacuum, fill the bottle with toluene and allow the temperature to reach 20 deg C
6. Weigh the bottle and calculate specific gravity of the seeds as given above.

### **Specific gravity measurement using hydrometer**

Fill your hydrometer jar about  $\frac{3}{4}$  with the liquid you wish to test. Insert the hydrometer slowly. Do not drop it in! Now give it a spin with your thumb and index finger, this will dislodge any bubbles that may have formed. Once the hydrometer comes to a rest, observe the plane of the liquid surface. Your eye must be horizontal to this plane. The point at which this line cuts the hydrometer scale is your reading.

A hydrometer is an instrument whose function is based on Archimedes principle. This principle states that a body (the hydrometer) immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid. The hydrometer measures the weight of the liquid displaced by the volume of the hydrometer.



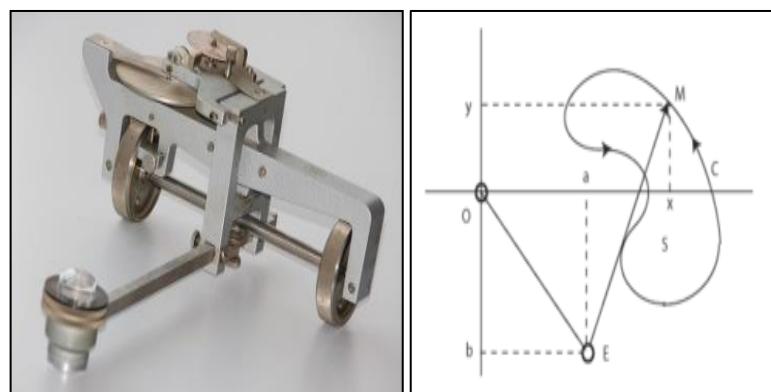
An instrument to measure the density of a liquid. The denser the liquid, the more the instrument is buoyed up (in accordance with Archimedes' principle). The scale is read at the level of the liquid's surface. Though the instrument measures density directly, it is usual to calibrate the stem in terms of specific gravity, the ratio of the density of the liquid to the density of water at that temperature.

### Surface area

Leaf area is an indicator of photosynthetic capacity and growth rate of a plant determining application rates of insecticides and fungicides. leaf area is a good indicator of yield potential. Surface areas of fruits are important in investigation related to spray coverage, removal of spray residues, respiration rate, light reflectance and color evaluation, and heat transfer studies in heating and cooling processes.

### Methods of measurement

Using planimeter: **Leaf & Stalk:** Contact printing the surface on a light sensitive paper and measuring the area by a **planimeter**, tracing the area on a graph paper and counting the squares. The planimeter is a mechanical device for measuring areas in the plane. It has the shape of a ruler with two legs. The measurement consists of dragging pointer along the boundary of the region. The wheel at pointer measures the motion in the direction orthogonal to the leg. After completing the path along the boundary of the region, the total wheel rotation indicates the area of the region.



Coating method: Small biological materials like cereals, pulses, oilseeds etc.

- ✓ Dip the irregular shape materials in molten wax having a constant sp. Gravity.
- ✓ Measure the weight gain (wt after dipping – wt before dipping).
- ✓ Divide the gain by density of wax to obtain volume of wax.
- ✓ Knowing the thickness of coating, actual surface area can be measured.

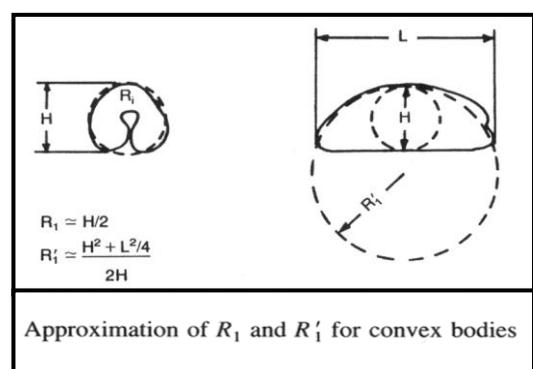
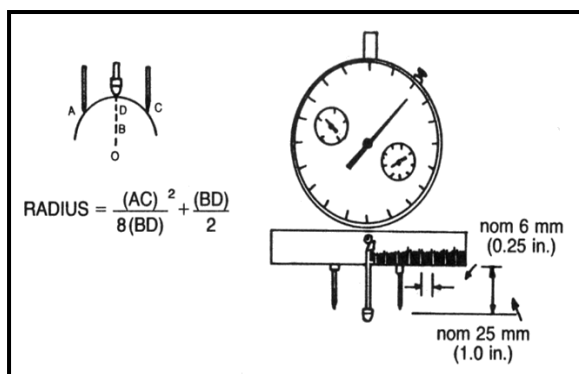
Wrapping method: Wrapping large individual objects aluminum foil precisely and measuring on a graph paper



Peeling method: Peeling the skin of **Fruits & Vegetables** and measuring the tracing of the peel by planimeter or on graph paper

Image analysis: precise measurements can be made through this method.

## Radius of Curvature measurement



## CHAPTER-3

### THERMAL PROPERTIES

#### Heat transfer occurs by

**Conduction**: is heat transfer between part of the same material or different material which are adjacent to one another.

**Convection** is heat transfer from one material to another via a medium, such as air or water.

**Radiation** is heat transfer without any medium and through electromagnetic waves, such as between the Sun and the Earth. Its efficiency is based on the texture of the receiving surface.

- These mechanisms can occur individually or simultaneously.
- In food processing, heat transfer is usually a combination of conduction and convection.
- **Conduction** heat transfer occurs when heat moves through a material (usually a solid or a viscous liquid) due to molecular action only. Conduction heat transfer may occur simultaneously in one, two, or three directions.
- One dimensional conduction heat transfer ( $J/s = W$ ) is a function of the temperature difference, the material thickness, the area through which the heat flows, and the resistance of the material to heat flow. This relationship is expressed in equation form as:

$$Q = -kA \frac{dt}{dx} = kA \frac{(t_1 - t_2)}{\Delta x} = \frac{A(t_1 - t_2)}{(\frac{1}{k})\Delta x} = \frac{A\Delta t}{R}$$

$$\text{or } q = \frac{Q}{A} = \frac{\Delta t}{R}$$

where,  $A$  = area,  $m^2$

$k$  = thermal conductivity,  $W/(m^0K)$

$Q$  = heat transfer,  $W$

$q$  = heat transfer per unit area,  $W/m^2$

$R$  = thermal resistance of the material,  $\Delta x/k$ ,  $(m^2 \text{ } ^0K)/W$

$t$  = temperature,  $^{\circ}C$  (or  $K$ )

**Convection** is the transfer of heat between solids (walls of pipes, vats, rooms) and fluids (food materials). In other cases, the food may be the solid and the fluid might be air or water. Convection heat transfer is the transfer of energy due to the movement of a heated (or cooled) fluid.

Assuming heat transfer from the fluid to the surface, the equation is:

$$Q = hA(t_b - t_s) \text{ or } Q = \frac{A(t_b - t_s)}{R_s}$$

where,

$h$  = convective (surface) heat transfer coefficient,  $W/(m^2K)$

$R_s$  = the surface resistance ( $R_s = 1/h$ ),  $(m^2K)/W$

$t_b$  = bulk temperature of the fluid,  $^{\circ}C$  or  $K$

$t_s$  = the surface temperature of the object exposed to the fluid,  $^{\circ}C$  or  $K$

Radiant heat transfer is the transfer of heat from one object directly to another without the use of an intervening medium. Thermal radiation forms a part of the electromagnetic spectrum which ranges from radio waves to gamma rays. Thermal energy can be radiated through space (solar energy) and through gases (e.g., air). The thermal energy

radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature and is given by Stefan-Boltzmann Law:

$$E = \sigma T^4$$

where,

$E$  = the energy radiated per unit time and per unit area,  $W/m^2$

$\sigma$  = the Stefan-Boltzmann constant ( $5.669 \times 10^{-8} W/m^2 K^4$ )

$T$  = the absolute temperature, (K), ( $K = 273.15 + ^\circ C$ )

For hot objects other than ideal radiators, the law is expressed in the form:

$E = \epsilon \sigma T^4$  Where  $\epsilon$  (epsilon) is called the emissivity of the particular body and is a number between 0 and 1. Bodies obeying this equation are called grey bodies

#### Important Thermal Properties

- Heat capacity
- Specific heat
- Thermal conductivity
- Thermal diffusivity
- Surface heat transfer co-efficient
- Latent heat of fusion and vaporization
- Heat of respiration
- Co-efficient of thermal expansion
- Thermal Emissivity

#### **Heat capacity**

Heat capacity may be defined as the thermal capacity, is the amount of heat required to change a substance's temperature by one degree. In the International system of units (SI), heat capacity ( $C$ ) is expressed in units of joule (J) per kelvin (K).

It is the Ratio of heat supplied ( $Q$ ) to the corresponding temp rise ( $\Delta t$ )

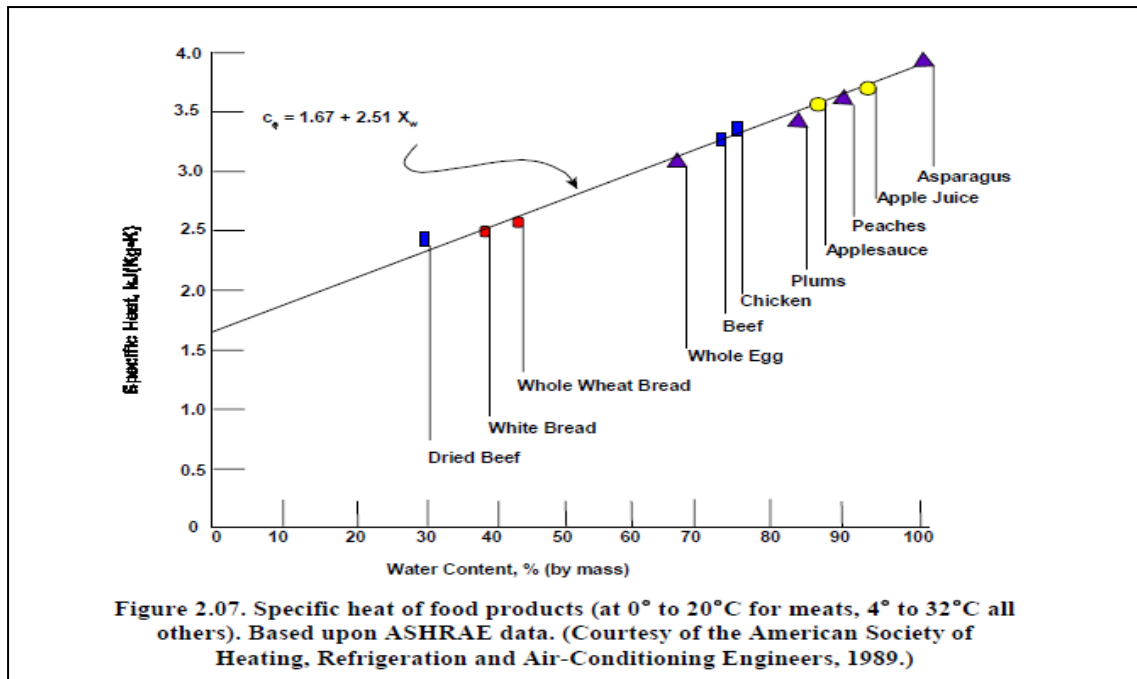
$$C = Q / \Delta t$$

#### **Specific heat**

Specific heat ( $c_p$ ) or mass heat capacity is the heat required to increase the temperature of one unit of mass by one degree. The subscript ( $p$ ) is included because specific heat of solids and liquids is determined at constant pressure

$$Q = Mc_p (T_2 - T_1)$$

The specific heat is expressed in  $kJ/(kg \cdot K)$ .



### Instrumental Methods of measurement

1. Method of mixing: Simple & suitable for food & agril material
2. Method of guarded plate: solid slab
3. Method of comparison (calorimetric): specially for liquids
4. Differential scanning calorimeter: Possible with very small sample

The thermal properties of materials vary with the composition: The empirical equation used for the specific heat of foods

$$C_p = 4.180 X_w + 1.711 X_p + 1.928 X_f + 1.547 X_c + 0.908 X_a$$

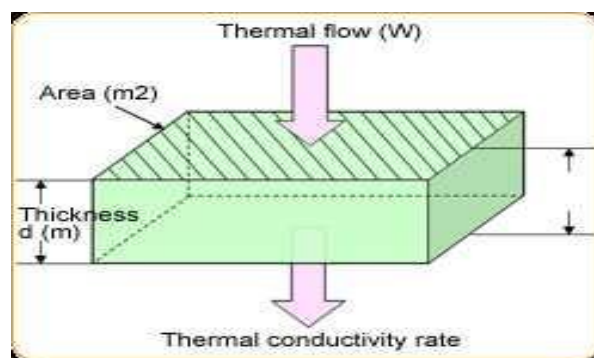
where "w" is water, "p" is protein, "f" is fat, "c" is carbohydrate, and "a" is ash and (X) the mass fraction of all the solids that make up the food.

Equations used to predict specific heats for food products based on the Wet basis moisture content, (M, decimal ) of the product.

Above freezing:  $C_p = 0.837 + 3.348M$

Below freezing:  $C_p = 0.837 + 1.256M$

These equations predict specific heat in kJ/(kg·K). Water has the greatest effect



### **Estimation of Thermal Conductivity**

In steady state conduction through a solid-like material the important thermal property is thermal conductivity ( $k$ ). Thermal conductivity is a measure of the ease with which heat flows through a material.

It is defined as the “heat flow through the material per unit of time ( $dQ/dt$ ), the cross-sectional area of the material through which the heat flows ( $A$ ), and the temperature difference per unit thickness of the conducting material ( $dT/dx$ )”.

$$(dQ/dt) = kA (dT/dx)$$

Thermal conductivity can be greatly influenced by a number of factors such as the water content, porosity, and even fiber orientation of the material.

Estimation of thermal conductivity:

The equation based upon the overall food composition:

$$k = 0.58X_w + 0.155X_p + 0.16X_f + 0.25X_c + 0.135X_a$$

where the parameters of the equations are as defined for Sp heat. The thermal conductivity of most food materials is in a relatively narrow range between 0.2 and 0.5 W/m K.

The equation based on moisture contents:

$$k = k_w X_w + k_s (1 - X_w)$$

weight fraction of water  $X_w$ , thermal conductivity of water  $k_w$ , and the thermal conductivity of the solids portion of the material  $k_s$ , which is assumed to be 0.259 W/(m·K). (thermal conductivity of ice 2.18 W/(m·K) at 0 °C) melts to form liquid water (thermal conductivity of 0.56 W/(m·K) at 0 °C).

### **Instrumental methods of measurement**

1. Guarded hot plate method: Homogenous material of slab form
2. Concentric cylinder method: Powdered granular, material
3. Concentric sphere method: Powdered granular, material
4. Probe method: Simple, fast, popular for small sample size food
5. Differential scanning calorimeter: Low to high moisture food
6. Transient hot wire method: For fluid and gases

### **Enthalpy**

Enthalpy: Total heat content of a material per unit mass. The total enthalpy of a system cannot be measured directly; the *enthalpy change* of a system is measured instead. Enthalpy change is defined by the following equation

$$H_2 - H_1 = m c_p (T_2 - T_1) + m X_w L$$

Where:  $H_2 - H_1$  = Enthalpy difference

$m$  = Mass of product

$X_w$  = Water fraction

$T_2 - T_1$  = Temperature difference

$L$  = Latent heat

### **Thermal diffusivity**

In transient heat transfer, where temperature varies with time and location, the relevant thermal property is thermal diffusivity. Thermal diffusivity ( $\alpha$ , m<sup>2</sup>/s) is a combination of three basic thermal properties, defined as “The rate at which heat is diffused out of the material. This is a quantity derived from conductivity, which is a measure of its ability to exchange thermal energy with its surroundings”.

Mathematically, Thermal diffusivity = Thermal conductivity/(density × specific heat)  
i.e.  $\alpha = k/\rho C_p$ .

When these three basic properties are known, the diffusivity can be readily computed. Values of thermal diffusivity for food products range from  $1 \times 10^{-7}$  to  $2 \times 10^{-7}$  m<sup>2</sup>/s.

**Convective heat transfer coefficient:** The thermal property associated with convection heat transfer is the convective heat *Transfer coefficient (h)*; it also goes by the names *surface heat transfer coefficient*, unit surface conductance or *film coefficient*. It is defined as the “Rate of heat transfer per degree of temp diff across the solid fluid interface per unit of the solid’s surface area”.

$$Q = h \cdot A \cdot \Delta T.$$

The convective heat transfer coefficient varies widely from about 10 to 100 W/m<sup>2</sup> · °C for still air next to a flat surface to 100,000 W/m<sup>2</sup> · °C for steam condensing on a metal pipe. The convective heat transfer coefficient depends upon fluid velocity, fluid properties, surface characteristics of the solid, and the geometry of each situation. Heat transfer may involve either sensible energy or latent energy. If the temperature of an object is changed due to the heat transfer, then the heat transfer involves a transfer of sensible heat.

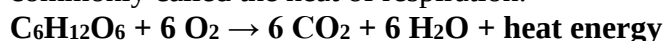
- **Latent heat (L)** is the heat that is exchanged with a material during a phase change, when the heat exchanged does not result in a change in the temperature of the material. The units for latent heat are kJ/kg. Latent heat is usually subdivided into latent heat of freezing and latent heat of vaporization.
- **Latent heat of freezing** is the 335 kJ that 1 kg of water releases while maintaining its temperature at 0 °C when changing from the liquid to the solid state. **Latent heat of vaporization** is represented by the 2257 kJ that 1 kg of water must absorb while temperature remains constant at 100 °C to evaporate from liquid into vapor.
- Latent heat is best determined through experimentation, but it also can be estimated based on the mass fraction of water in the product.

$$L_f = 335X_w$$

$$L_v = 2257X_w$$

- Differential scanning calorimeter is most suitable for latent heat measurement of food material.
- **Freezing point depression:** It is the lowering of freezing temperature of food. Pure water freezes at 0°C, while food products freeze at lower temperatures. The **freezing point** is lowered due to the presence of solutes, solids, in the water. The change in the freezing point temperature is primarily dependent on the concentration or amount of solids.
- **Boiling point elevation:** Boiling point is elevated by the presence of solute in the liquid phase as found in most foods. This is useful in evaporation and drying operations. Examples: The depression of the freezing point for high salt products i.e., processed meats, the boiling point rise with sugar content in candy making.

**Heat of Respiration:** Fruit and vegetable products are living organisms. To maintain their life processes, they must consume energy. They do this by a “combustion” process that “burns” sugar to produce CO<sub>2</sub> and heat. The heat produced by this process is commonly called the heat of respiration.



Heats of respiration

- ✓ Vary greatly among products (Sugar content)
- ✓ Increase exponentially with temperature.
- ✓ Affected by maturity and storage time.
- ✓ High respiration rates also cause rapid deterioration in food quality.

Measurement

- ✓ A commodity's rate of carbon dioxide production is related to its temperature. The carbon dioxide production rate can then be related to the commodity's heat generation rate from respiration

### **Coefficient of thermal expansion**

When a material is heated, it leads to density difference. Solids mostly expand in response to heating and contract on cooling. This response to temperature change is expressed as its coefficient of thermal expansion. The physical property relating to this is called Coefficient of thermal expansion ( $\beta$ ,  $K^{-1}$ ).

$$\beta = \Delta V / (V * \Delta T)$$

$\Delta V$ : Change in volume,  $\Delta T$ : Change in Temp

**Thermal emissivity:** The emissivity coefficient -  $\epsilon$  - is the ratio of total emissive power of anybody to the total emissive power of a black body at the same temperature. it indicates the radiation of heat from a '**grey body**' according the **Stefan-Boltzmann Law**, compared with the radiation of heat from an ideal '**black body**' with the emissivity coefficient  $\epsilon = 1$ .

If a hot object is radiating energy to its cooler surroundings, the net radiation heat loss rate can be expressed as

$$Q = A \epsilon \sigma (T_h^4 - T_c^4)$$

Q= rate heat transfer

A= surface area

$\epsilon = 1$  black body and  $<1$  real object

(This thermal constant is associated with the rate of heat transfer by radiation from a hot body to a cold body & is dependent on angle factor of the body & emissivity factor)

$\sigma$  = Stefan Boltzmann constant

$T_h$  &  $T_c$  = Absolute temperature of hot and cold body respectively

Specific Heat Measurement (Practical)

Amount of heat required to raise/lower the unit mass by  $1^\circ C$

## CHAPTER-4

### FRICTIONAL PROPERTIES

The frictional properties of granular materials are important in designing

- Storage bins, hoppers, chutes,
- Pneumatic conveying system, screw threshers and conveyors,
- Forage harvesters,
- Fruits and Vegetables grader
- Friction is a force that resists motion between two objects that are in contact with each other. Smoother surfaces exhibit less friction, while rougher surfaces exhibit more friction

**Static friction** arises between two objects that are not in motion with respect to each other. It is measured as the maximum force the bodies will sustain before motion occurs.

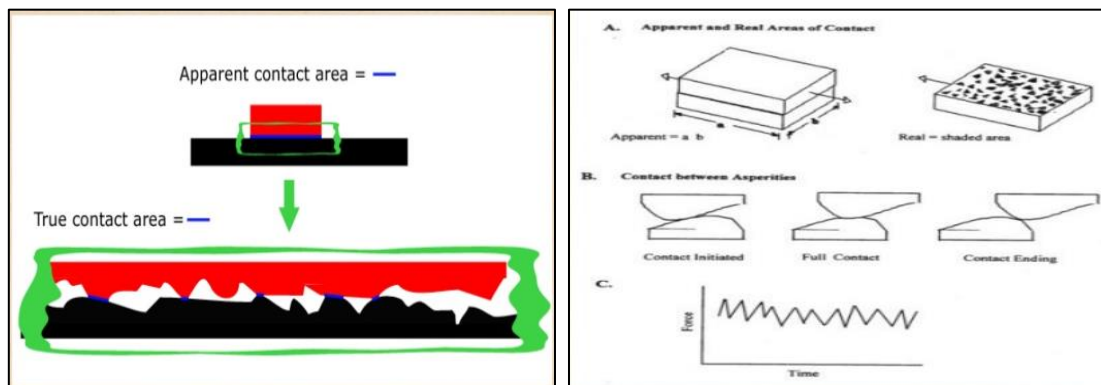
**Kinetic friction** arises between bodies that are in motion with respect to each other, It is measured as the maximum force the bodies will require to keep them in motion

- Frictional force can be expressed as

$$F_f = \mu N, \text{ where, } F_f = \text{frictional force (N)}$$

$\mu$  = static ( $\mu_s$ ) or kinetic ( $\mu_k$ ) frictional coefficient

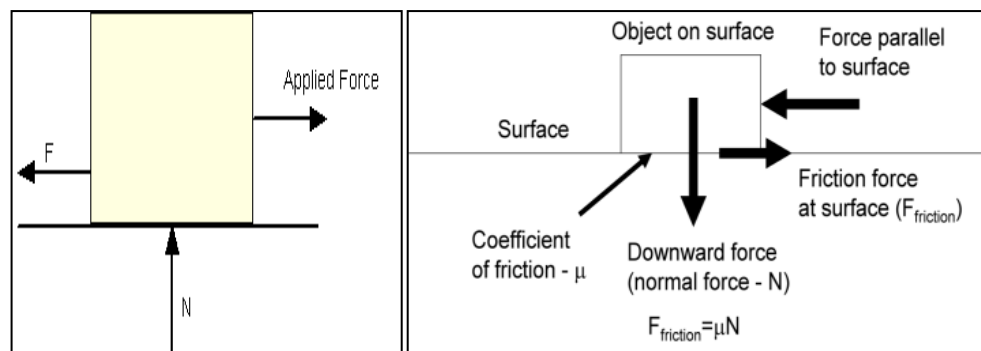
$N$  = normal force (N)



For an object pulled or pushed **horizontally**, the normal force -  $N$  - is the weight

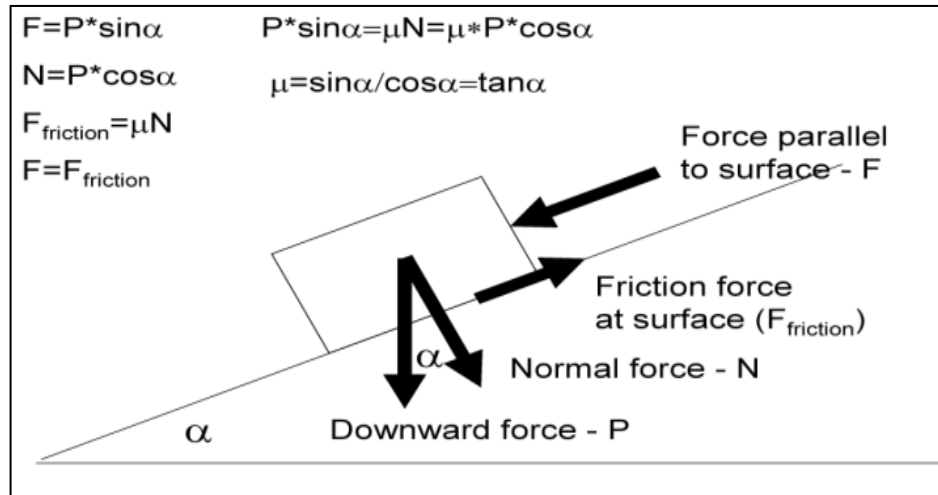
$N = m g$  Where,  $m$  = mass of the object (kg),  $g$  = acceleration of gravity ( $9.81 \text{ m/s}^2$ )

**Coefficient of friction:** The ratio of the frictional force to the force, normal to the surface of contact. The coefficient of kinetic friction is usually less than the coefficient of static friction for the same materials.



If the object is on a tilted surface such as an inclined plane, the normal force is less, because less of the force of gravity is perpendicular to the face of the plane. Therefore, the normal force, and ultimately the frictional force, is determined using vector analysis

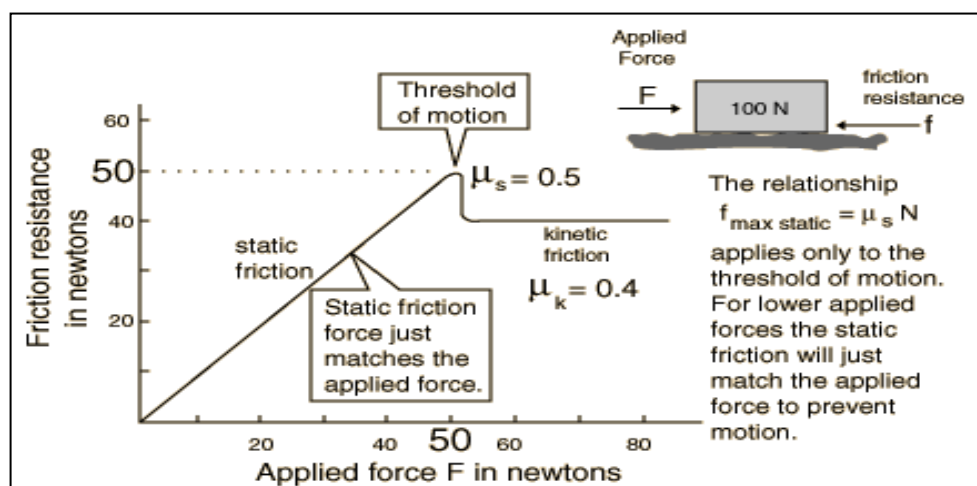
$$\text{Coefficient of friction} = \tan \alpha$$

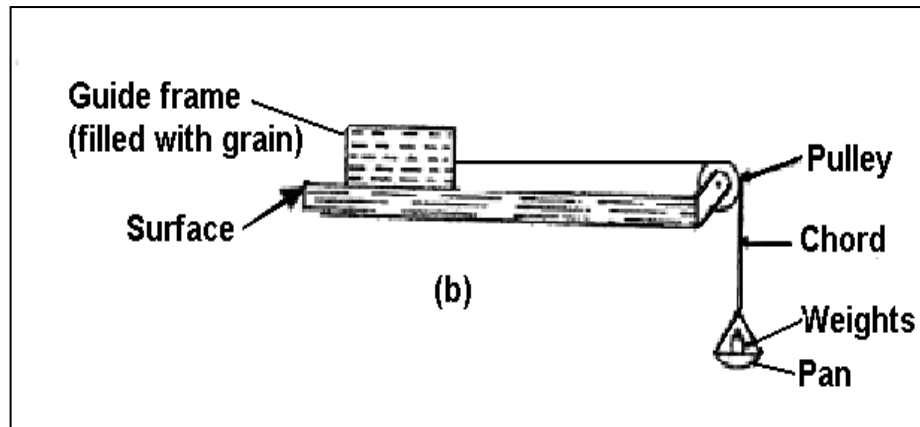


### Factors affecting frictional force

1. Load
2. Actual contact area
3. Sliding velocity
4. Nature of material in contact
5. Moisture content
6. Static vs Dynamic (kinetic) Friction

The coefficient of friction for a pair of materials is often quoted as Static and Dynamic values. From the typical diagram below, dynamic friction is usually lower than static any force larger than the force of static friction causes sliding to occur. The instant the sliding occurs, static friction is no longer applicable—the friction between the two surfaces is then called kinetic friction.





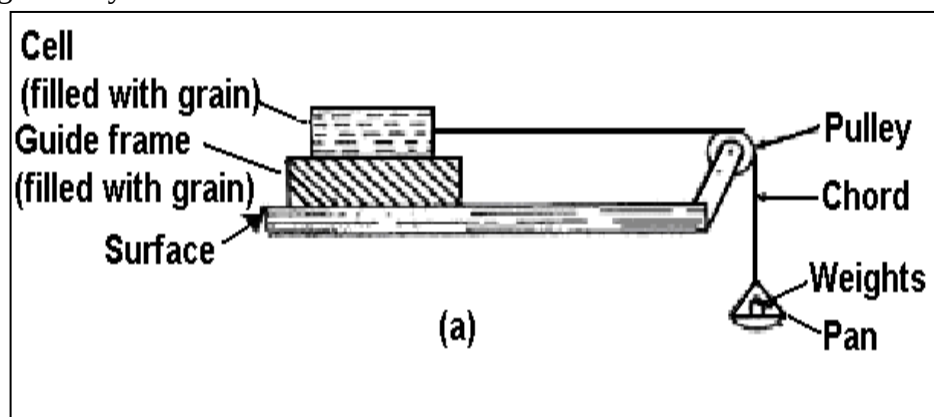
**Experimental set-up Coefficient of friction on material surface**

### ***Coefficient of internal friction***

The friction of the kernels or grains against each other is known as internal friction where as the friction between the grain mass and the contact surface is known as static friction. The coefficient of the internal friction of the grains is required in predicting the lateral pressure on a retaining wall in silos or design of silos and hoppers for gravity flow.

### ***Factors affecting internal frictional force***

1. Moisture content
2. Shape and size of material
3. Amount of consolidation or settling
4. Load
5. Sliding velocity

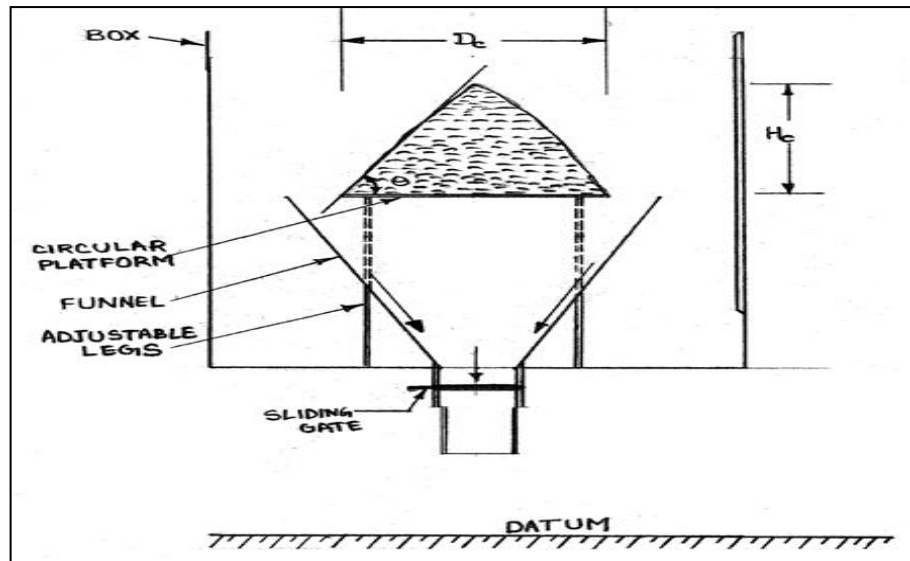


**Experimental set-up Coefficient of internal friction**

### ***Angle of repose***

Angle of repose is important in designing a structure for storage of food grains in bulk. When a granular material is allowed to flow freely from a point into a pile, the angle which the side of the pile makes with horizontal plane is called the angle of repose (IS: 6663-1972). The angle of repose is influenced by size, shape, moisture content and orientation of the particles. It has been found that the angle of repose increases with the increase in moisture content. The cohesive materials have larger angle of repose. Lower

angle of repose represents easier flowability. Angle of repose of the grain can be calculated experimentally using the following formulae:



*Line diagram of Experimental Set up for Angle of Repose*

$$\theta = \tan^{-1}\left(\frac{2H_c}{D_c}\right)$$

where,

$H_c$ =height of the cone formed measured with depth gauge

$D_c$ =diameter of the platform on which the cone formed

#### **Indicator of flow ability of product.**

Lower angle of repose: easy flow ability

Cohesive material has larger angle of repose.

Factors affecting angle of repose:

Size, shape, moisture content and orientation of the grains.

Each product has its own angle of repose.

Examples: Barley (13% mc): 31°; (20% mc): 34°

#### **Flow characteristics with respect to angle of repose**

| <b>Flow characteristics</b> | <b>Angle of repose, degree</b> |
|-----------------------------|--------------------------------|
| Very, free flowing          | 25-30                          |
| Free flowing                | 30-38                          |
| Cohesive                    | 45-55                          |
| Very cohesive               | Beyond 55                      |

Easy flowing materials: Examples: Wheat, barley, corn, soya beans

Bulk products with less advantageous flow pattern are called non easy flowing/cohesive materials. Examples: soya meal, tapioca

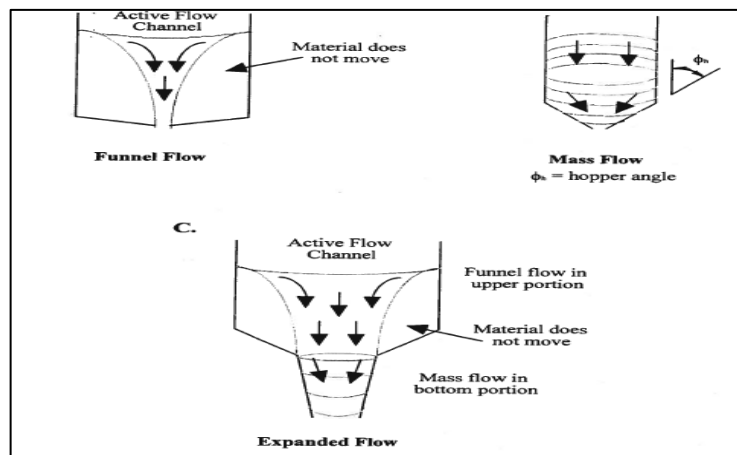
Angle of repose is greater than angle of internal friction.

### Major problems associated with the flows

1. Piping: When bulk solid above the outlet is flowing out remaining bulk solids stays in place. called dead regions.
2. Arching: It is a stable obstruction that forms over the point of narrowest cross section of the storage vessel (usually the discharge outlet).

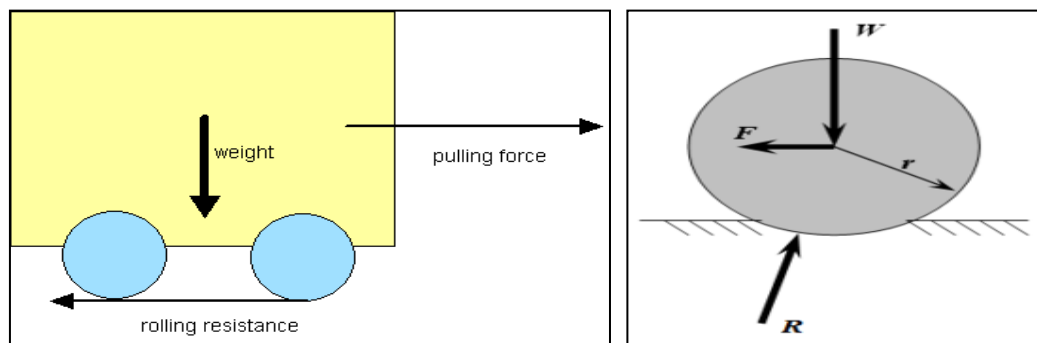
### To obtain mass flow: Requirements

1. Outlet dimensions increased (to avoid arching).
2. Slope of silos: Steeper, Hopper slope-60 or 70°
3. Material selection: That cause less friction to the material.



### Rolling resistance

Rolling resistance is the force that resists the rolling of a wheel or other circular (rounded) object along a surface caused by deformations in the object and/or surface. Generally the force of rolling resistance is less than that associated with kinetic friction.



Rolling resistance is a measure of the retarding effect of a floor surface at the tread/floor interface of the rounded objects. It is normally expressed in units of force and is a measure of the energy dissipated per unit of distance rolled.

The rolling resistance can be expressed as

$$F_r = c W \quad (1)$$

where

$F_r$  = rolling friction (N,)

$c$  = rolling resistance coefficient - dimensionless (coefficient of rolling friction - CRF)

$W = m g$  = normal force or weight of body (N,)

$m$  = mass of body (kg,)

$g$  = acceleration of gravity ( $9.81 \text{ m/s}^2$ ,)

The rolling resistance can alternatively be expressed as

$$F_r = c_l W / r \quad (2)$$

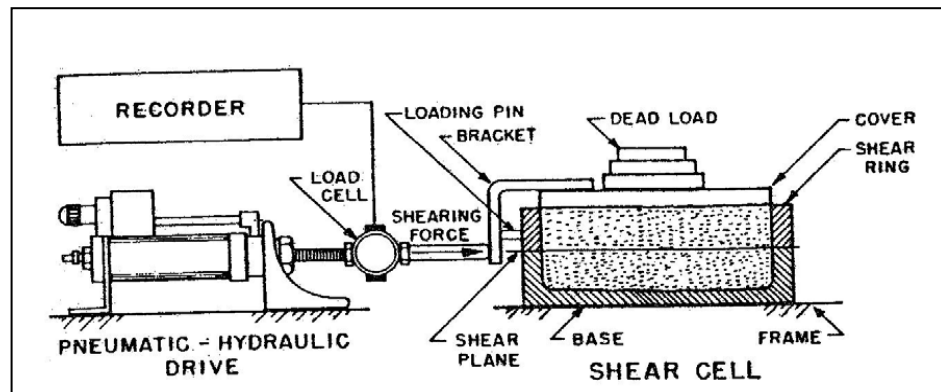
Where,

$c_l$  = rolling resistance coefficient with dimension length (coefficient of rolling friction) (mm,)

$r$  = radius of rounded object (mm,)

**Rolling resistance** is directly proportional to weight of the rolling object; inversely proportional to the effective radius and directly proportional to the coefficient of rolling resistance which is dependent on supporting surface rigidity.

NB: More rigid is the surface, lower is the 'c' in rolling resistance. Sand is a good example of a soft, rolling-resistant surface. Bicycling across a paved roadway is much easier than across a white sandy beach.



**Tri-axial compression test apparatus for coefficients of internal friction**

Tri-axial compression test apparatus or Shear test apparatus: The direct shear test apparatus consists of a shear cell, a controlled loading device and a recorder. The normal load is applied by weights acting vertically. The shearing action is provided by means of an electrical or mechanical drive with a load cell or dynamometer in line for force measurement. The shearing force acts in the plane of contact between the base and the ring. The shear cell assures a uniform stress distribution across the specimen sample and shear of solid in the plane between the ring and base.

## CHAPTER-5

### AERO AND HYDRODYNAMIC PROPERTIES

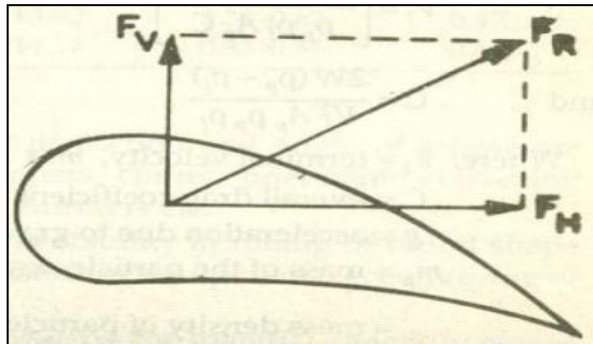
When particle is immersed in stagnant fluid,

1. Buoyant forces (weight of displaced fluid)

When particle is immersed in fluid in motion Along with buoyant force other significant force, drag refers to air resistance or fluid resistance (force) that oppose the relative motion of an object through a fluid (a liquid or gas).

These forces acting are

1. Normal to the surface of the object due to fluid flow (Pressure)
2. Shear stresses, acting tangential to the surface in the direction of flow and resulting from frictional effects.



**1. Skin friction/Frictional drag:-** drag force exerted on one side of a smooth flat plate aligned with flow. (Shear drag)

**2. Profile/pressure drag:-** drag force on blunt object. (Form Drag)

The total drag force is sum of Frictional drag and pressure drag.

- ✓ At higher velocity and blunt or spherical object like grain etc the frictional drag can be neglected because of the small surface area on which frictional effects can work.
  - ✓ In case of plant leaves, chaff etc frictional effects may be important
- In most agricultural engineering applications the moving object is usually free to assume its own random orientation. For this reason the net resistance force  $F_r$  (resultant force) can be given in terms of the Resultant drag force which is a function of following

$$F_r = f_1 (A_p, \rho_f, \mu, E, V)$$

- the smooth object having a projected area, ( $A_p$ )
- moving through a fluid of mass density, ( $\rho_f$ )
- viscosity, ( $\mu$ )
- modulus of elasticity, ( $E$ )
- velocity, ( $V$ )

Employing the methods of dimensional analysis, resultant drag may be derived as:

$$F_r = \frac{1}{2} C A_p \rho_f V^2$$

Where,

$F_r$  = Resistance drag force or weight of particle at terminal velocity, N

$C_d$  = overall drag coefficient (dimensionless)

$A_p$  = projected area of the particle normal to direction of motion,  $m^2$

$\rho_f$  = mass density of the fluid,  $kg/m^3$

$V$  = relative velocity between main body of fluid and object,  $m/s$

- The drag coefficient of the material and its resistance to air flow depend upon,
- (1) the bed thickness of the material,
  - (2) type, shape and size of grain,
  - (3) the air velocity and
  - (4) orientation and packing of the material.

This is quantified using Reynolds number ( $N_{Re}$ )

i.e Ratio of inertia forces tend to produce velocity change To viscous forces, tend to resist velocity change)

$$N_{Re} = V d_p \rho_f / \mu$$

- $V$ : the mean velocity of the fluid ( m/s).
- $\mu$  : is the dynamic viscosity of the fluid ( $\text{Pa}\cdot\text{s} = \text{N}\cdot\text{s}/\text{m}^2 = \text{kg}/(\text{m}\cdot\text{s})$ ).
- $\rho_f$  : is the density of the fluid ( $\text{kg}/\text{m}^3$ ).
- $d_p$  : is the effective dimension of the object (length of a plate or dia of a sphere)
- $V$ : the mean velocity of the fluid ( m/s).
- $\mu$  : is the dynamic viscosity of the fluid ( $\text{Pa}\cdot\text{s} = \text{N}\cdot\text{s}/\text{m}^2 = \text{kg}/(\text{m}\cdot\text{s})$ ).
- $\rho_f$  : is the density of the fluid ( $\text{kg}/\text{m}^3$ ).
- $d_p$  : is the effective dimension of the object (length of a plate or dia of a sphere)

From Mathematics;  $F_d = 3\pi d_p \mu V$  for laminar flow and spherical particle

So equating this with,

$$F_r = \frac{1}{2} C A_p \rho_f V^2$$

We have,  $C_d = 24 / N_{Re}$

When the value of  $N_{Re}$  is less than 0.2, the flow is laminar and the drag coefficient can be determined from  $C_d = 24 / N_{Re}$

In excess of 200,000, where the flow is turbulent

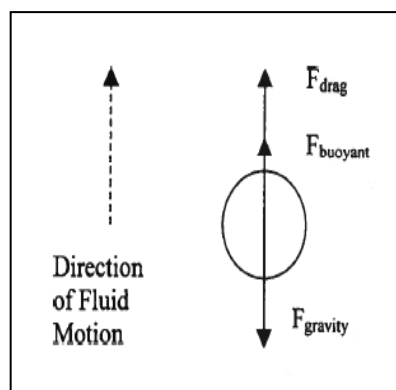
$$C_d = 0.44$$

Finally, for the values of between 500 and 200,000

$$C_d = [24 / N_{Re}] [1.0 + 0.15(N_{Re})^{0.687}]$$

### Terminal velocity

The terminal velocity of a particle may be defined as equal to the air velocity at which a particle remains in suspended state in a vertical pipe. In the condition of free fall, the particle attains a constant terminal velocity ( $V_t$ ), when the net gravitational accelerating force ( $F_g$ ), equals the resisting upward drag force ( $F_r$ ). If  $V=V_t$ ,  $F_g= F_r$



By substituting the value of  $F_g$  and  $F_r$  the terminal velocity can be expressed as;

$$m_p g \left[ \frac{(\rho_p - \rho_f)}{\rho_p} \right] = \frac{1}{2} C A_p \rho_f V_t^2$$

$$V_t = \left[ \frac{2W(\rho_p - \rho_f)}{\rho_p \rho_f A_p C} \right]$$

$$\text{and } C = \frac{2W(\rho_p - \rho_f)}{V_t A_p \rho_p \rho_f}$$

Where,  $V_t$  = the terminal velocity, m/s;  $m_p$  = mass of the particle, kg

- $\rho_f$  = mass density of the fluid, kg/m<sup>3</sup>;  $\rho_p$  = mass density of the fluid, kg/m<sup>3</sup>
- $g$  = Acceleration due to gravity, m/s<sup>2</sup>;  $C$  = Overall drag coefficient
- $W$  = Weight of the particle, N;
- $A_p$  = projected area of the particle normal to direction of motion, m<sup>2</sup>
- $F_g = Fr$ , Without Buoyancy;  $F_g = Fr + F_b$  With Buoyancy

Terminal velocity—without buoyancy effect,  $F_g = Fr$ ,

At equilibrium, the net force is zero ( $F = 0$ );

Therefore,  $mg = (C_d A_p V_t^2 \rho_f)/2$

Solving for  $V_t$  yields  $V_t = \sqrt{(2mg/C_d A_p \rho_f)}$

Terminal velocity—with buoyancy effect,  $F_g = Fr + F_b$

Spherical Particles,  $A_p = (\pi/4) d^2$

$$W = (\pi/6) d^3 \rho_p g$$

$$C_D \frac{\pi d^2}{4} \frac{\rho_f V_t^2}{2} + \frac{\rho_f g \pi d^3}{6} = \frac{\rho_p g \pi d^3}{6}$$

$$V_t = \sqrt{\frac{4d(\rho_p - \rho_f)g}{3\rho_f C_d}}$$

For Laminar Flow,  $C_d = 24 / N_{Re}$  Therefore,  $V_t = gd^2 (\rho_p - \rho_f)/18\mu$

In the steady state conditions, after attaining the terminal velocity, If the density of the particle is greater than the density of the fluid, the particle will move downward. If the density of the particle is lesser than the density of the fluid, the particle will rise upward. If the separation of mixture of grain and foreign matters is to be achieved by air stream, the terminal velocities of each component of mixture decide the range of air velocity to be used for a definite extent of separation.

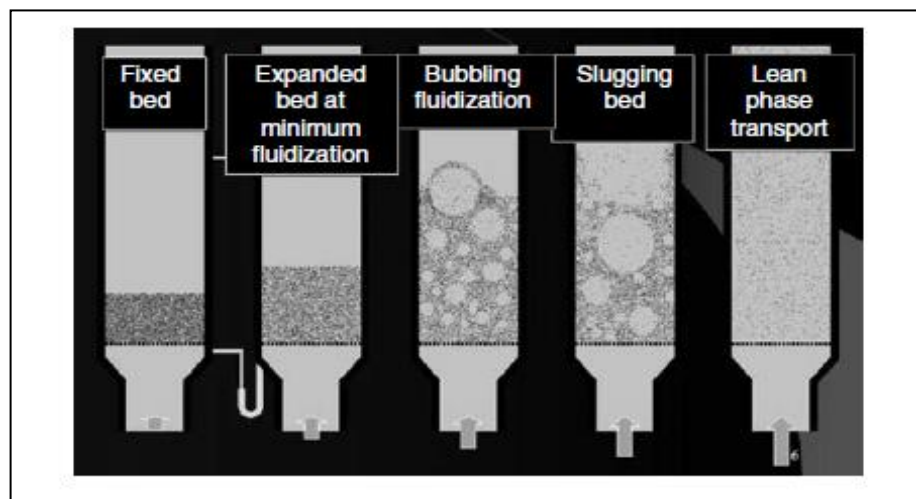
## Fluidization of bulk granular material

In the food industry, processes based on fluidized beds are finding increasing use:

- ✓ By virtue of the large fluid–solid contact area and the vigorous agitation created by the random movement of the particles, the fluidized bed is an ideal system for rapid heat and mass transfer.
- ✓ Another advantage of the fluidized bed is uniformity of conditions throughout the material. A fluidized bed is practically isothermal.

Some of the applications of the fluidized bed in food process technology:

- ✓ Fluidized bed drying
- ✓ Individual quick freezing (IQF)
- ✓ Coating of particulate solids
- ✓ Rapid heating or cooling of solids.



The minimum fluid velocity required for fluidization,  $v_{mf}$  (m/s), can be calculated by equating the pressure drop with the apparent weight of the bed.

$$V_{mf} \approx d_p^2 \frac{(\rho_p - \rho_f)}{150\mu} \cdot \frac{\varepsilon^3}{1-\varepsilon} \cdot g \quad V_t = \frac{d_p^2 (\rho_p - \rho_f) g}{18\mu} \quad Re_p = \frac{d_p V_p \rho}{\mu(1-\varepsilon)}$$

$\rho_f, \mu$  = density and viscosity of the fluid,  $\text{kg.m}^{-3}$  and  $\text{Pa.s}$  respectively

$\varepsilon$  = porosity (void fraction) of the bed

$d_p$  = particle diameter, m;  $V_t$  : settling velocity;  $Re_p$  : Reynolds Number

## CHAPTER-6

### BASICS Of RHEOLOGY

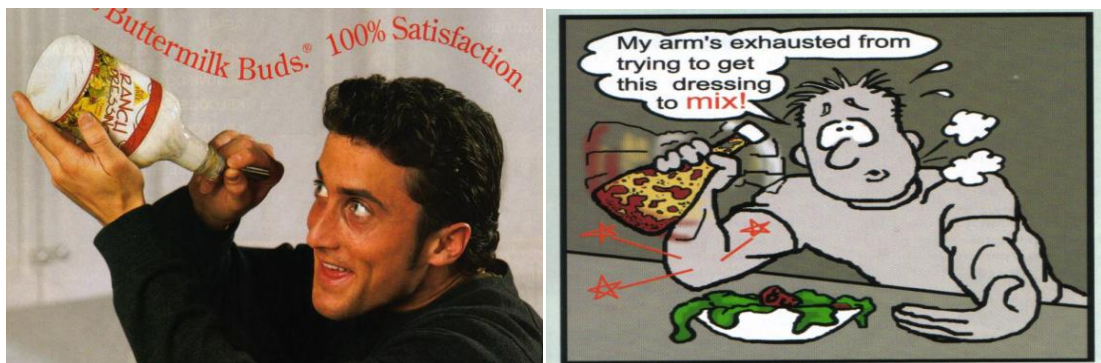
Consumers use *subjective tests* to perceive texture of food. Rheology is used to *objectify these perceptions*



*Rheology in Daily Life*



*Exhibiting “desirable” flow property*



*When the products are not correctly formulated rheologically”?*

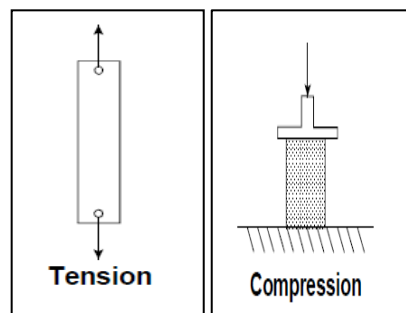
### Let's define Rheology

"Rheology" comes from Greek *rheos*, meaning 'to flow'. Rheology is "a science devoted to the study of deformation and flow." When subjected to external forces, Solids will deform, whereas Liquids will flow. Rheology considers the time effect during the loading of a body.

### Application

- Knowledge of rheology is important for a better understanding of how process variables and ingredients influence specific textural characteristics, such as pourability and mouthfeel
- Rheological measurements can aid in the understanding of how the viscosity and elasticity of foods are influenced by changes in composition, processing and storage parameters Stress. The intensity of force that act on a given plane. Stress is expressed in force per unit of area.

**Normal stress:** The stress component perpendicular to a plane on which the forces act. Normal stress may be either:



**Tensile stress:** Normal stress due to forces directed away from the plane on which they act, or

**Compressive stress:** Normal stress due to forces directed towards the plane on which they act.

**Shear stress** is the component of stress coplanar with a material cross section. It is the stress that is tangential to the plane on which the forces act tending to change the sample's shape.

### ASTM standard definition of terms

(American Society for Testing and Materials)

#### Strain

The unit change in the size or shape of a body to its original size or shape due to action of force. Strain is dimensionless quantity, but it is frequently expressed centimeters per centimeter, m/m, mm/mm etc.

**a. Linear (tensile or compressive) strain:** The change per unit length due to force in an original linear dimension.

**i. Axial strain:** Linear strain in a plane parallel to the longitudinal axis of the specimen.

**ii. Transverse strain:** Linear strain in a plane perpendicular to the axis of the specimen.

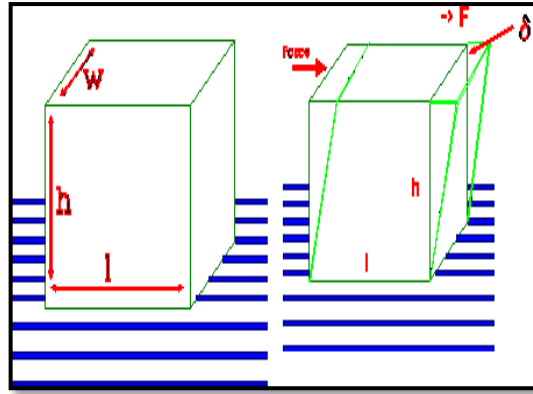
**b. Shear strain (angular strain):** The tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body.

Mathematically

**Shear Stress** is  $F/A$  ( $A$  is the area of the upper surface of the cube  $l \times w$ ). The unit is Pascal (i.e.  $1 \text{ N/m}^2 = 1 \text{ Pascal}$ ) and is denoted by the symbol  $\sigma$ .

**Shear strain** is ratio of two lengths (displacement / original) So unitless

**Shear deformation ( $\delta u$ ) ; Shear Strain =  $\delta u/h$**



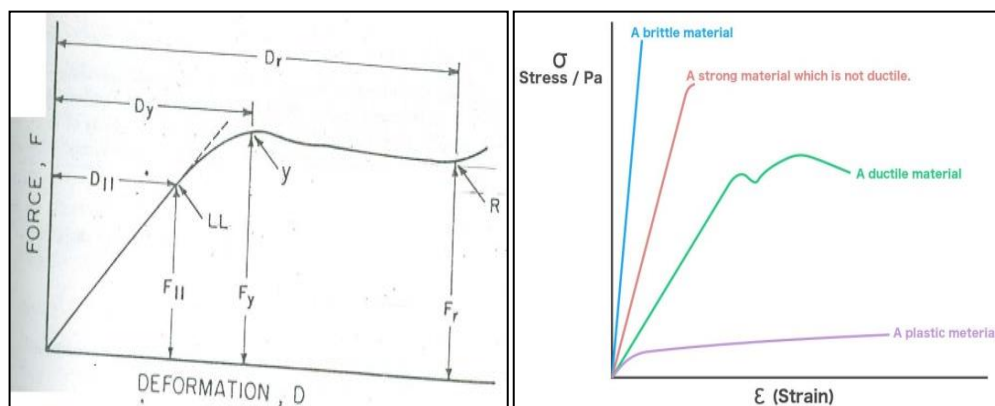
**Shear Rate:** The rate of change of strain is referred to as the SHEAR STRAIN RATE often abbreviated to SHEAR RATE and is found by the rate of change of strain as a function of time i.e. the ratio of differential SHEAR STRAIN to differential TIME

#### **Bioyield point (y)**

A point on the stress-strain or force-deformation curve at which there occurs an increase in deformation with a decrease or no change of force. In some agricultural products, the presence of this bioyield point is an indication of initial cell rupture in the cellular structure of the material.

#### **Rupture point (R)**

A point on the stress-strain or force-deformation curve at which the axially loaded specimen ruptures under a load. In biological materials, rupture may cause puncture of shell or skin, cracking, or fracture planes.



(a)

(b)

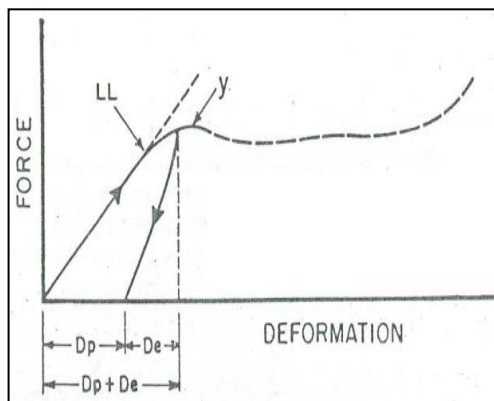
a) Force-Deformation curve for an agricultural product

b) Stress-strain curve of different types of materials

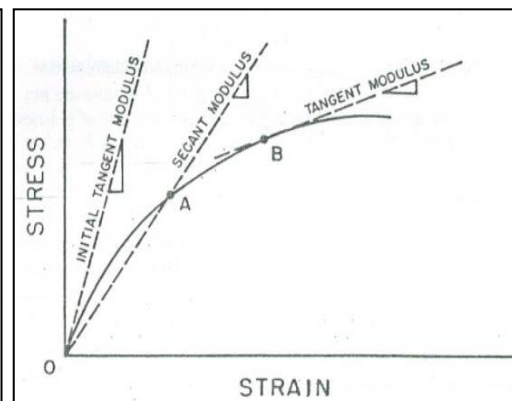
#### **Difference**

- ✓ It may be stated that a "bioyield point" in these materials corresponds to a failure in the microstructure while a "rupture point" corresponds to a failure in the macrostructure of the specimen.
- ✓ In a force-deformation curve, the bioyield point may occur at any point beyond linear limit LL, where the curve deviates from the initial straight-line portion. The point of rupture of the specimen may occur at any-point on the curve beyond the bioyield point.
- ✓ In a "brittle" material, rupture may occur in the early portion of the curve. In a "tough" material, rupture may take place after considerable plastic flow at such point as R.

- **Elastic Limit:** The greatest stress which a material is capable of sustaining without any permanent strain remaining upon complete release of the stress.
- **Proportional Limit:** The greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law).
- **Ultimate stress:** The stress corresponding to the rupture point.
- **Bioyield stress:** The stress corresponding to the bioyield point.
- **Elasticity:** The capacity of a material for taking elastic or recoverable deformation. The portion of the curve before the point LL is reached, if elongation is recoverable, it is a measure of elastic deformation.
- **Plasticity:** The capacity of a material for taking plastic or permanent deformation. Since deformations from the bioyield point to the point of rupture are not all recoverable, the unrecoverable part can be taken as a measure of plastic deformation.
- **Degree of elasticity:** The ratio of elastic deformation to the sum of elastic and plastic deformation when a material is loaded to a certain load and then unloaded to zero load.



Loading-unloading curve



Stress-strain diagram modulus in non-linear

#### **Degree of elasticity from a loading-unloading curve.**

De = elastic or recoverable deformation;

Dp = plastic or residual deformation;

Degree of elasticity =  $De / (De + Dp)$

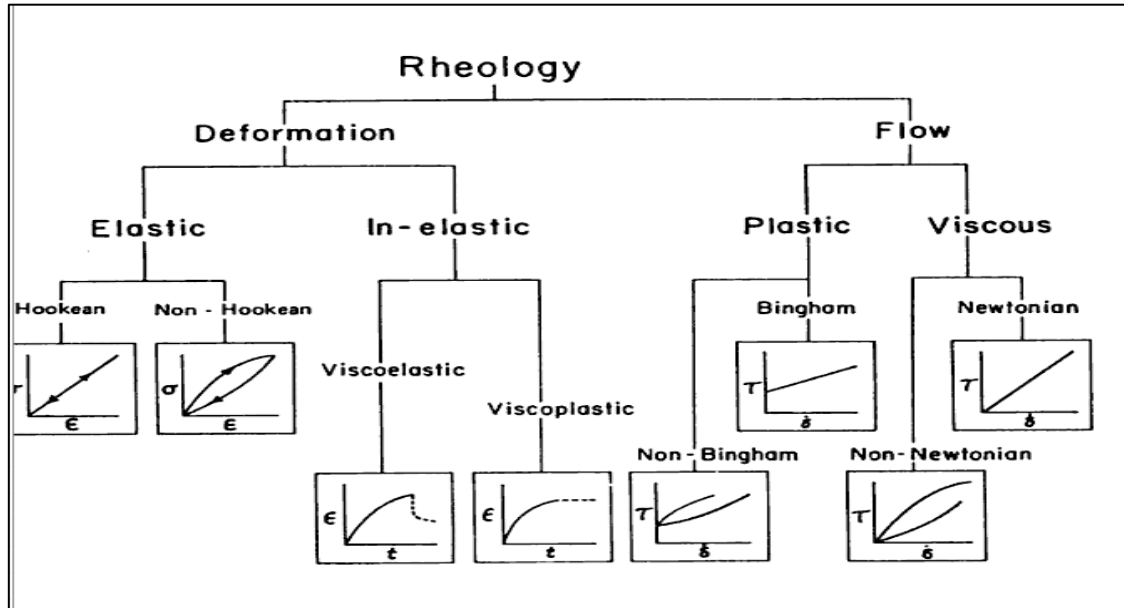
**Toughness:** The work required to cause rupture in the material (Unit: Energy per volume). This can be approximated by the area under the stress-strain or force-deformation curve up to the point selected as the rupture point. If in estimating toughness, a force-deformation curve is used, the size of the specimen should be specified.

**Resilience:** The capacity of a material for storage of strain energy in the elastic range. Thus, the area under the unloading curve is a measure of resilience of the material. When a force-deformation curve is used, the size of the specimen and the loaded area should be specified.

**Stiffness:** Stiffness or rigidity is indicated by the slope of the initial straight-line portion of the curve. The ratio of stress to strain of the curve may be referred to as the "modulus of elasticity" or "Young's modulus" ( $\text{kg/cm}^2$ ). In the case of nonlinear stress-strain behavior, stiffness or "apparent modulus" can be defined in terms of Initial tangent modulus, Secant modulus and Tangent modulus

## CHAPTER-7

### RHEOLOGICAL PROPERTIES (CLASSICAL MATERIAL)



$\sigma$ : Stress  $\epsilon$ : Strain  $t$ : Time  $\dot{\epsilon}$ : Shear rate : Shear stress

#### **Classical ideal materials**

Elasticity, Plasticity and Viscosity are three fundamental properties by which the rheological behavior of a material can be described.

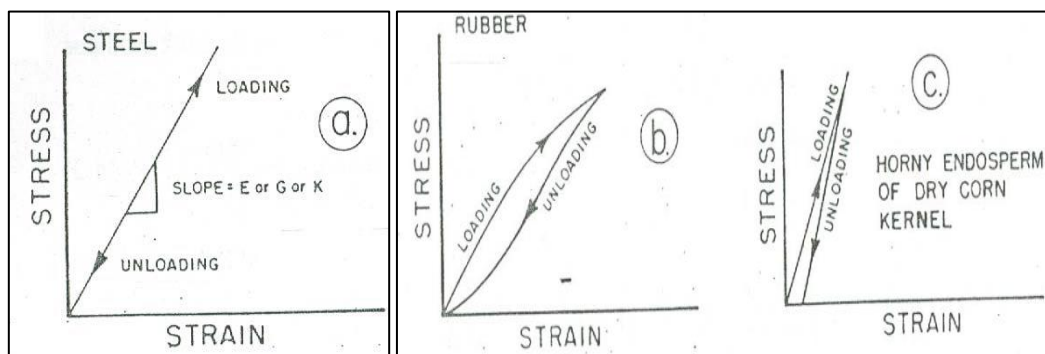
**The three classical ideal bodies representing these properties are**

1. Ideal elastic behavior (hookean body),
2. Ideal plastic behavior (st. Venant body),
3. Ideal viscous behavior (newtonian liquid)

Since no real material behaves perfectly elastic or perfectly plastic, the three ideal bodies have been chosen to serve as standards of comparison in the analysis of the behavior of any real material.

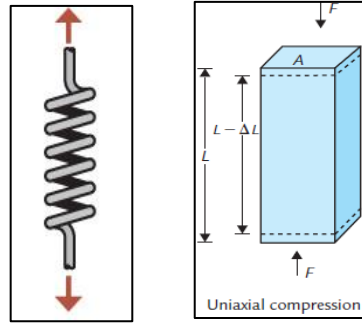
#### ***Ideal elastic behaviour (Hookean body)***

In a Hookean body, stress is directly proportional to strain. The relationship is known as the Hooke's law and the behavior is referred to as Hookean behavior (Elastic spring).



a) Linear elasticity in steel, (b) non-linear elasticity in rubber, (c) inelasticity in corn

## Elastic Properties



1. Young's Modulus
2. Shear Modulus
3. Bulk Modulus
4. Poisson's Ratio

### **Young's Modulus**

(modulus of elasticity)

*Young's modulus* of elasticity is the ratio of tensile or compressive stress to tensile or compressive strain. It is a measure of stiffness and is described by equation:

$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{F/A}{\Delta L/L}$$

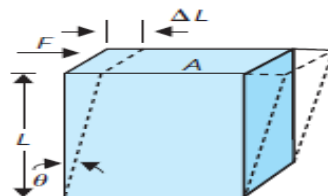
where  $E$  is Young's modulus,  $F$  is the applied force perpendicular to the area defined by the stress,  $A$  is the cross-sectional area of the test material,  $L$  is the length or height of the test specimen and  $\Delta L$  the change in length resulting from the application of force  $F$ .

### **Shear Modulus**

(modulus of rigidity)

*Shear modulus* is the ratio of shearing stress to shearing strain and is described by the equation:

$$G = \frac{\text{shearing stress}}{\text{shearing strain}} = \frac{F/A}{\gamma/L}$$



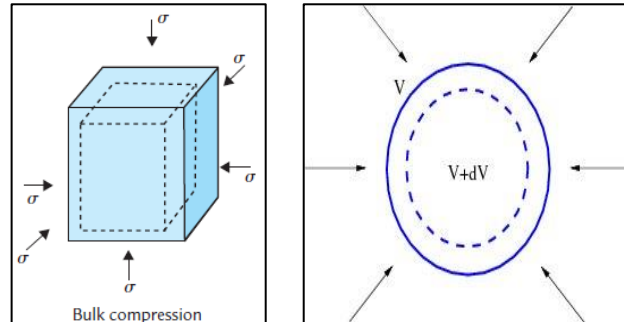
Shear

Where,  $G$  is the shear modulus,  $F$  is the applied force parallel to the area defined by the stress,  $\gamma$  (or  $\Delta L$ ) is the greatest distance of movement in the test material, and  $L$  is the length.

### **Bulk Modulus (Compressibility)**

*Bulk modulus* is the ratio of the stress to the change in volume with respect to original volume:

$$K = \frac{\text{hydrostatic pressure}}{\text{volumetric strain}} = \frac{P}{\Delta V/V}$$

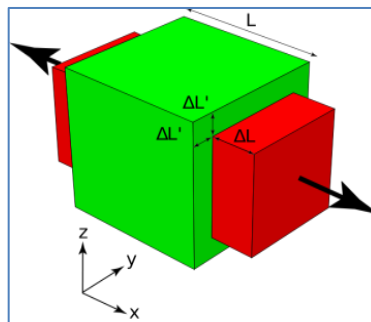


where  $K$  is the bulk modulus,  $P$  the force per unit area (pressure) applied from all directions (isotropically),  $V$  is the original volume of the unstressed material and  $\Delta V$  the change in volume resulting from the application of pressure  $P$ .

### **Poisson's Ratio**

When a sample of material is stretched in one direction it tends to get thinner in the other two directions. Poisson's ratio is the ratio of the relative contraction strain, or transverse strain normal to the applied load, to the axial strain in the direction of the applied load.

$$\mu = \frac{\text{lateral strain}}{\text{axial strain}} = \frac{\text{change in width per unit width}}{\text{change in length per unit length}} = \frac{\Delta D/D}{\Delta L/L}$$



where  $\mu$  is Poisson's ratio,  $D$  is the width of the test specimen and  $L$  its length,  $\Delta D$  and  $\Delta L$  the changes caused by the application of a stress.

NB: If the volume is unchanged when the stress is applied, Poisson's ratio is 0.5. It is less than 0.5 if the volume changes. Since water is essentially incompressible, foods containing high water content such as fruits and vegetables have a Poisson's ratio close to 0.5 unless they also contain gas.

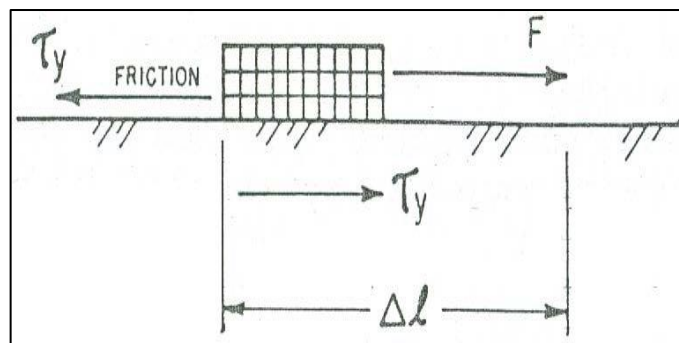
### **Interrelations Between Moduli**

$E$ ,  $G$ ,  $K$  and  $\mu$  are called 'material constants' because they are inherent to the material. Rheological theory shows that for elastic materials these four moduli are interrelated as follows:

$$\frac{1}{E} = \frac{1}{3G} + \frac{1}{9K} \quad E = 3K(1-2\mu) \quad E = 2G(1+\mu)$$
$$\mu = \frac{(3K-E)}{6K} \quad \mu = \frac{(E-2G)}{2G}$$

### **Ideal plastic behaviour (St. Venant body)**

A friction block can be used as the mechanical model for St. Venant Body representing ideal plasticity. The material does not flow until a limiting value of shearing stress  $\tau_y$ , called the "yield-stress," is reached. The material can sustain no stress greater than this value and flows indefinitely under this stress.

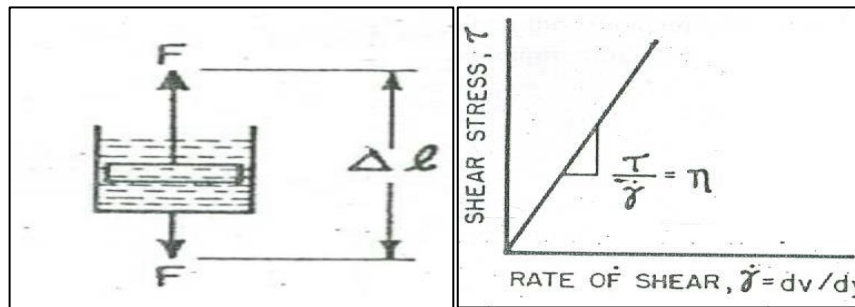


Friction block representing St. Venant Body for ideal plasticity



### **Ideal viscous behaviour (Newtonian liquid)**

In liquid, flow begins as soon as a shear stress is applied, and when the stress is removed, it will not return to its original state. In a liquid, strain is a function not only of stress but of time as well. The mechanical model simple dashpot (damper), called the viscous element, is supposed to be a weightless, loosely fitted piston moving in a medium filled with the liquid.



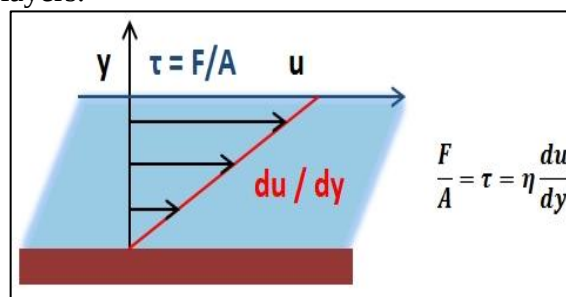
Newton's law of viscosity, The plot is a straight line passing through the origin. The slope of the line is by definition the viscosity.

### Viscosity

Viscosity is a measure of a fluid's resistance to flow and is a measure of the adhesive/cohesive or frictional fluid property. The resistance is caused by intermolecular friction exerted when layers of fluids attempt to slide by one another. The knowledge of viscosity is needed for proper design of structures for storage, pumping or flow of fluids at required temperatures. Thus, water and honey are "thin," having a lower viscosity, while ghee is "thick" having a higher viscosity.



In general, in any flow, layers move at different velocities and the fluid's viscosity arises from the shear stress between the layers that ultimately opposes any applied force. Isaac Newton postulated that, for straight, parallel and uniform flow, the shear stress,  $\tau$ , between layers is proportional to the velocity gradient,  $\partial u / \partial y$ , in the direction perpendicular to the layers.



$$\tau \propto (du/dy); \quad \tau = \eta (du/dy); \quad ; \quad \tau = (1/\phi) (du/dy)$$

Where,  $\phi$ : Fluidity, or  $1/\phi = \eta$ : Viscosity

### Dynamic (absolute) Viscosity

SI system:  $\text{N s/m}^2$ ,  $\text{Pa s}$  or  $\text{kg/m s}$  where

$1 \text{ Pa s} = 1 \text{ N s/m}^2 = 1 \text{ kg/m s} = 10 \text{ poise}$

CGS system:  $\text{g/cm.s}$ ,  $\text{dyne.s/cm}^2$  or poise (p) where

$1 \text{ poise} = \text{dyne s/cm}^2 = \text{g/cm s} = 1/10 \text{ Pa s}$

$1 \text{ p} = 100 \text{ cP}$  (centiPoise)

Kinematic Viscosity (is the ratio of dynamic viscosity to density)

$\nu = \mu / \rho$  Where,  $\nu$  = kinematic viscosity,  $\mu$  = absolute viscosity,  $\rho$  = density

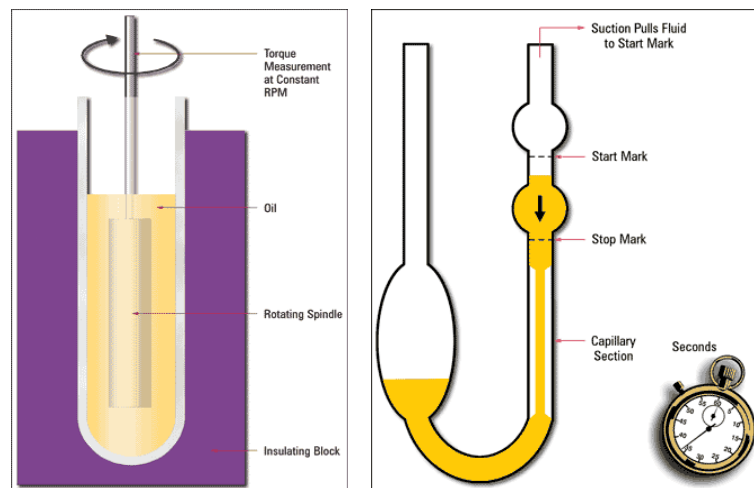
SI-system the unit is  $\text{m}^2/\text{s}$  or commonly used Stoke (St) where

- $1 \text{ St} = 10^{-4} \text{ m}^2/\text{s}$  ,
- $1 \text{ St} = 100 \text{ cSt}$  (Centistokes) , So  $1 \text{ cSt} = 10^{-6} \text{ m}^2/\text{s}$

Viscosity of a fluid is temperature dependent and reference temperature must be quoted.

Water at (20.2°C) has an absolute viscosity 1 centiPoise and kinematic viscosity 1.0 cSt.

- ✓ For a liquid - the kinematic viscosity will decrease with higher temperature
- ✓ For a gas - the kinematic viscosity will increase with higher temperature



**Viscosity measuring instruments**

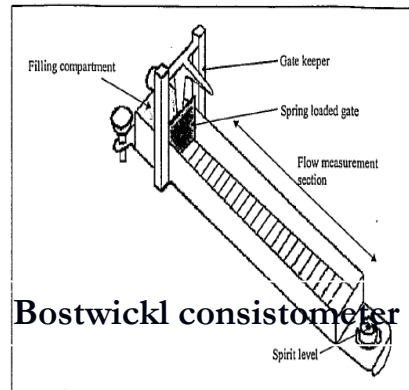
**Absolute viscosity** is measured as the resistance to flow when a body is forced through the fluid by an external and controlled force such as a spindle driven by a motor. In this case, the rpm (or shear) as a function of the input force is measured, which reflects the internal resistance of the sample to the applied force, or its dynamic viscosity.

**Kinematic viscosity** is traditionally measured by noting the time it takes the liquid to travel through the orifice of a capillary under the force of gravity. The orifice of the kinematic viscometer tube produces a fixed resistance to flow. Different sized capillaries are available to support fluids of varying viscosity. The time taken for the fluid to flow through the capillary tube can be converted directly to a kinematic viscosity using a simple calibration constant provided for each tube

## Consistency

It gives the flow properties of semi solid materials relates to firmness or thickness.

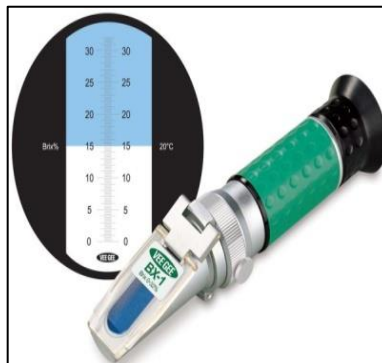
**1.The Bostwick consistometer** is used to determine sample consistency by measuring the distance in centimeters that a material flows under its own weight during a given time interval, which is 30 sec at 25°C.



**2.Cone penetrometer:** The instrument is used for determining the consistency and penetration properties of semi-solid substances.



**3.Refractometry** Reads the natural variation of soluble solids in fruit juices. The instrument measures the percent of soluble solids at the temperature indicated on the instrument. The scale used is the Brix scale ( $^{\circ}\text{B}$ ), which is equivalent to percent sucrose concentration.



NB: Like viscosity, consistency is also temperature dependent

## CHAPTER-8

### VISCOELASTIC MODELS AND EQUATIONS

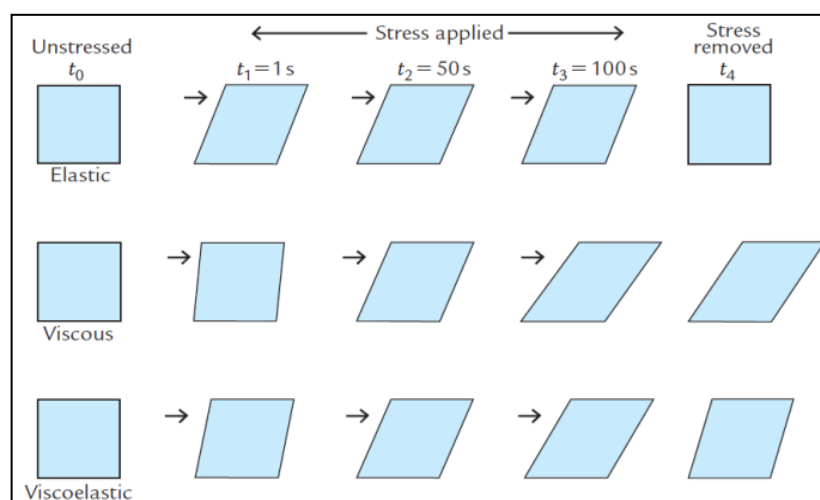
#### **Viscoelasticity**

The word 'viscoelastic' means that the material simultaneously exhibits some of the elastic properties of an ideal solid and some of the flow properties of an ideal liquid. A combined solid-like and liquid-like behavior in which the stress-strain relationship is time dependent.

#### ***Examples of viscoelastic foods***

Almost all solid foods and fluid foods containing long chain biopolymers

- ✓ Food starch, gums, gels
- ✓ Grains
- ✓ Most solid foods (fruits, vegetables, tubers)
- ✓ Cheese
- ✓ Pasta, cookies, breakfast cereals



#### **Elastic solid:**

There is an instantaneous deformation when the deforming force is applied and no further deformation with time. There is complete recovery of the original shape when the force is removed.

#### **Newtonian (Viscous) liquid:**

The material begins to flow as soon as the deforming force is applied and it continues to flow as long as the force is being applied. There is no recovery of shape when the force is removed.

#### **Viscoelastic solid:**

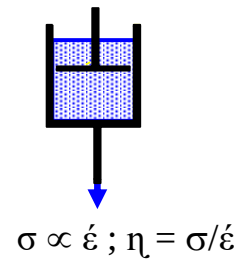
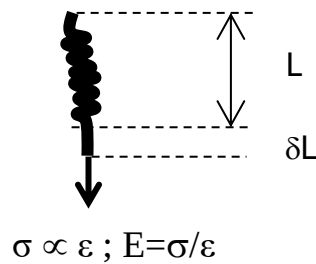
There is an instantaneous deformation when the deforming force is first applied, and then the material continues to deform so long as the force is applied. When the force is removed there is some recovery of the original shape (elastic component) but not a full recovery (viscous component).

#### **Basic mechanical elements**

##### **The two basic mechanical elements used in mechanical models**

1. Spring (ideal elastic body) obeys Hooke's law: Stress  $\propto$  Strain
2. Dashpot (Newtonian liquid) obeys law of Newton. Stress  $\propto$  Shear Rate

Strain:  $\epsilon = \delta L/L$       Stress:  $\sigma$

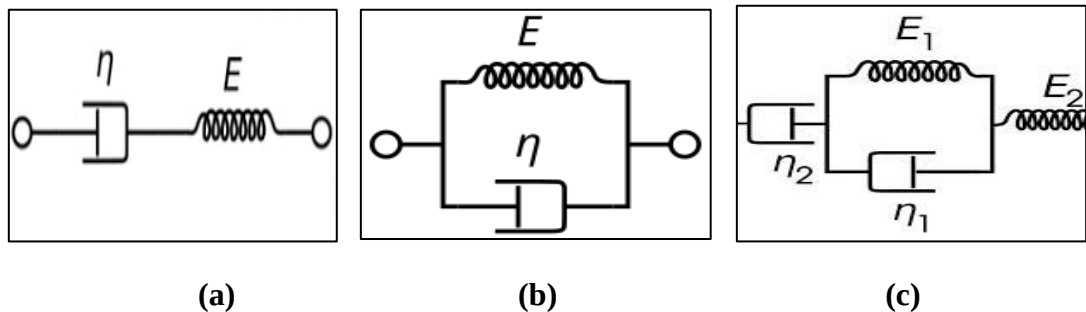


### Mechanical models

**Maxwell model (a)**- The behaviour of agricultural materials under stress can be represented by any of these three models Maxwell model - States that the behaviour of agricultural materials under stress can be represented by a spring (representing elastic behaviour) and a dashpot (representing viscous behaviour) in series.

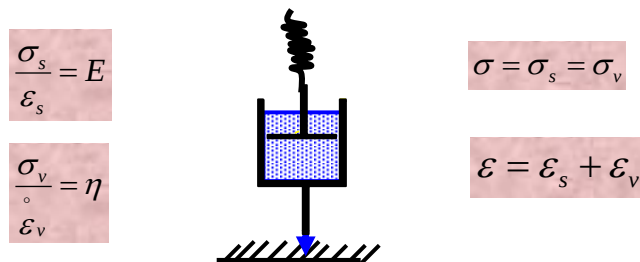
**Kelvin model (b)**- States that the behaviour of agricultural materials under stress can be represented by a spring (representing elastic behaviour) and a dashpot (representing viscous behaviour) in parallel.

**Burger's model (c)**- States that the behaviour of agricultural materials under stress can be represented by a spring (representing elastic behaviour) in series with a dashpot and a combined spring and a dashpot (representing viscous behaviour) in parallel.

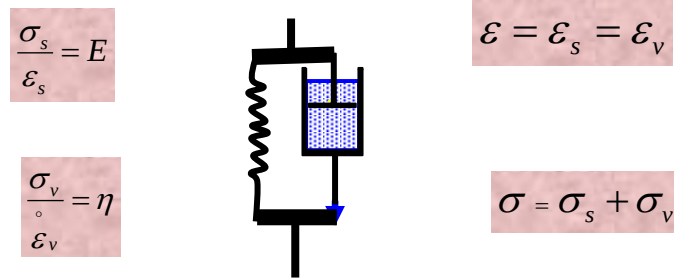


### Viscoelastic models and equations

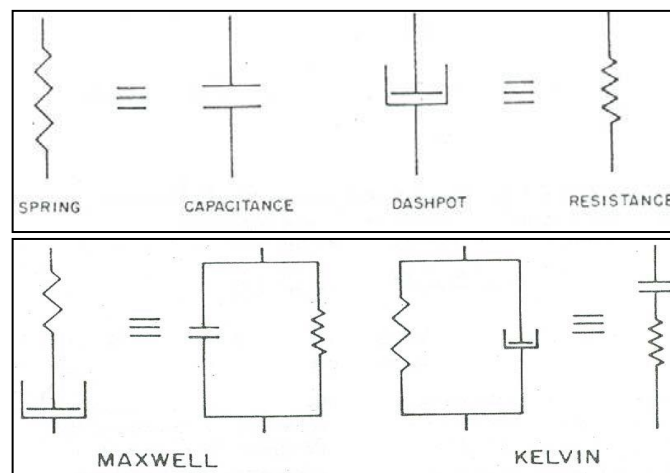
**Maxwell Model: Used for stress relaxation tests**



### ***Kelvin Model: Used for creep tests***



### ***Electrical equivalence of mechanical models***



Spring → elasticity → capacitance → dashpot → viscosity → resistance

The tension and compression of the spring corresponds to charging and discharging of the capacitor. When elements are coupled in parallel in the mechanical model, its equivalent in the electrical network is a series coupling. Similarly, a series coupling in the mechanical system has a parallel equivalence in the electrical system. In the electrical network, the stress is represented by the electric potential (voltage) and the strain by electric current.

### **CREEP STRESS RELAXATION**

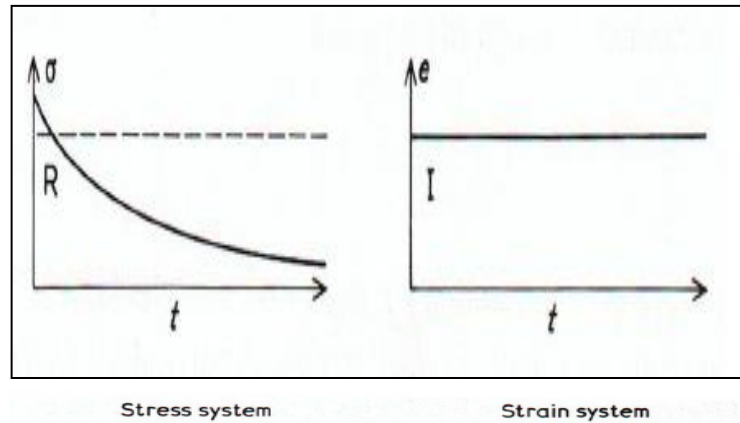
#### **Application**

- ✓ From these tests the material's elastic behavior can be obtained which is important to keep the shape of the bread dough, dairy products, and pharmaceutical creams after extruding to avoid variations in product size.
- ✓ The food industry uses this knowledge to predict how the soft food structure and texture would behave before large-scale production processes such as compression, stretching, extrusion, high pressure and electric field processing.
- ✓ To predict the deformation of agricultural products such as fruits and vegetables under dead load
- ✓ Overloading of stress in a material can cause damage at microstructural level and failure in later use

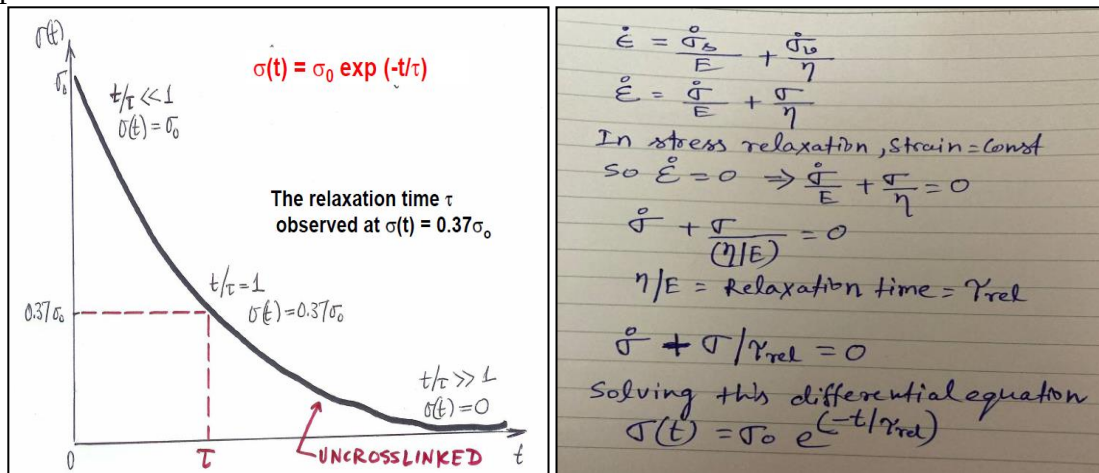
## Stress relaxation

- ✓ In stress relaxation test the specimen is suddenly brought to a given deformation (strain), and the stress required to hold the deformation constant is measured as a function of time.

**Relaxation time:** It is the time required for the stress in the Maxwell model, representing stress relaxation behavior, to decay to  $(1/e)$  or approximately 37 percent of its original value.



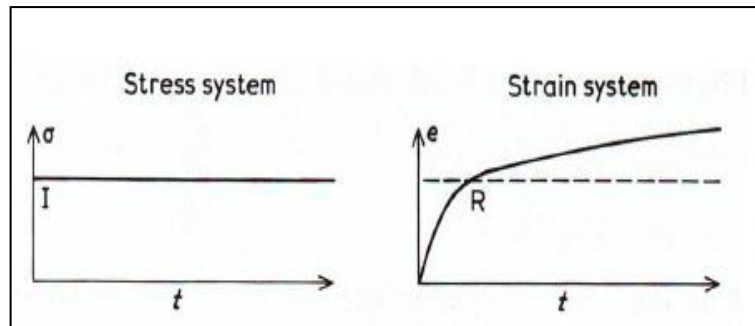
Relaxation time is a measure of the rate at which a material dissipates stress after receiving a sudden force. Time required for a chemical reaction to take place such as bond interchange, degradation, hydrolysis & oxidation. The shorter the relaxation time, the more rapid the stress relaxation.



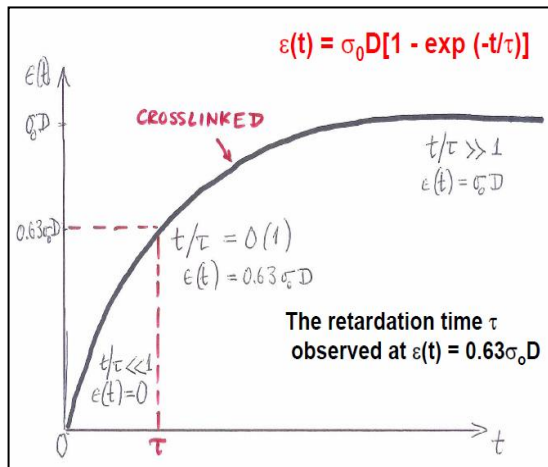
## Creep

In this test the stress is suddenly applied and held constant, and strain is measured as a function of time.

**Retardation time:** The rate at which the retarded elastic deformation takes place in a material creeping under dead load. It is the time required for the Kelvin model, representing creep behavior, to deform to  $(1 - (1/e))$  or about 63 percent of its total deformation.



The retardation time of the material is a measure of the time taken for the creep strain to accumulate; the shorter the retardation time, the more rapid the creep straining.



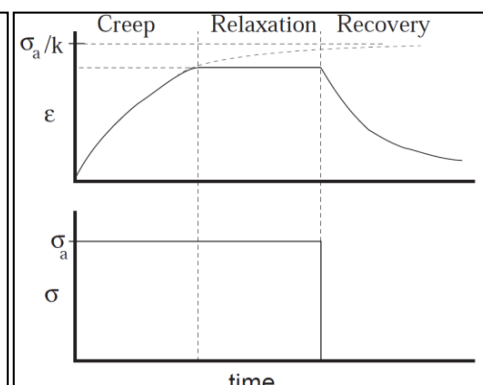
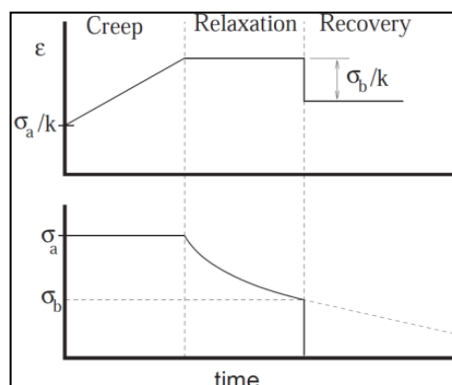
$$\begin{aligned}\sigma &= \sigma_s + \sigma_0 \\ \sigma &= E\varepsilon + \eta \dot{\varepsilon} \\ \frac{\sigma}{E} &= \varepsilon + \dot{\varepsilon} \frac{\eta}{E} \quad \left( \frac{\eta}{E} = \text{retardation time} \right) \\ \frac{\sigma}{E} &= \varepsilon + \dot{\varepsilon} \gamma_{\text{ret}} \\ \frac{\sigma}{E} &= \varepsilon + \dot{\varepsilon} \gamma_{\text{ret}} \\ \text{In creep phenomena, stress constant} \\ \dot{\varepsilon} \gamma_{\text{ret}} + \varepsilon &= 0 \\ \text{on integration, solving differential eqn} \\ \varepsilon(t) &= \frac{\sigma_0}{E} (1 - e^{-t/\gamma_{\text{ret}}})\end{aligned}$$

### Maxwell model

- Spring & dashpot are in series
- Combine Hooke's and Newton's laws
- Both elements have the same stress
- Strain is additive
- Handles stress relaxation fairly well

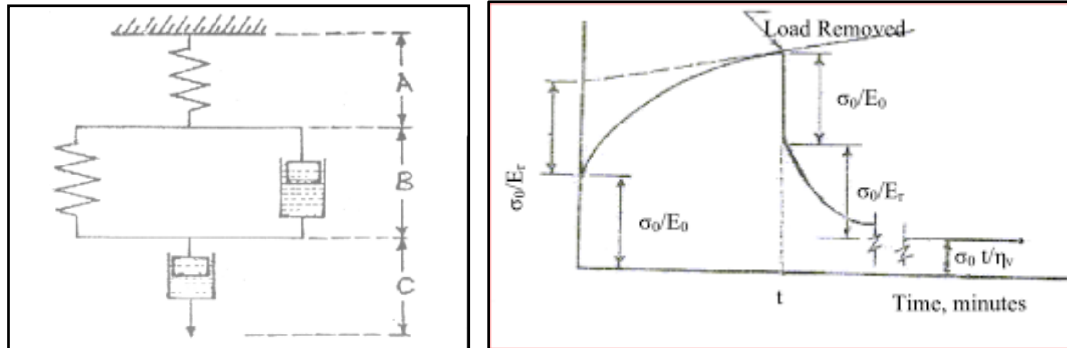
### Kelvin (voigt) element

- Spring & dashpot are in parallel
- Combine Hooke's and Newton's laws
- Both elements have the same strain
- Stress is additive
- Handles Creep fairly well



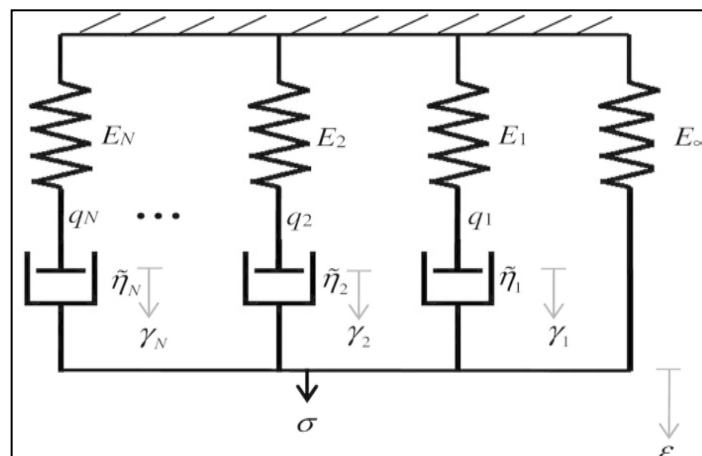
#### 4-element model (Burgers model)

Burger's model - States that the behaviour of agricultural materials under stress can be represented by a spring (representing elastic behaviour) in series with a dashpot and a combined spring and a dashpot (representing viscous behaviour) in parallel.

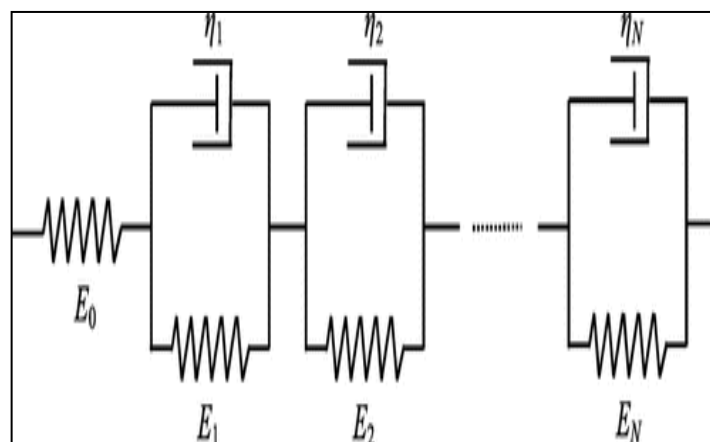


#### 4-element model (Burgers model)

$$\epsilon_t = \sigma_0 / E_0 + \sigma_0 / E_t (1 - e^{(-t/T_{ret})}) + \sigma_0 t / \eta_v$$



**Generalized Maxwell model**



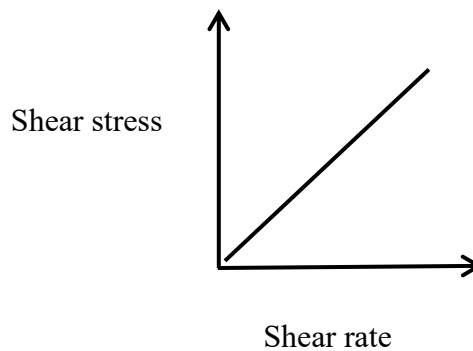
**Generalized Kelvin model**

## CHAPTER-9

### RHEOLOGICAL BEHAVIOR OF FLUID MATERIALS

**Newton's law of viscosity** for straight, parallel and uniform flow, the shear stress between layers is proportional to the velocity gradient in the direction perpendicular to the layers:

The viscosity is given by the slope of the shear stress–shear rate curve.

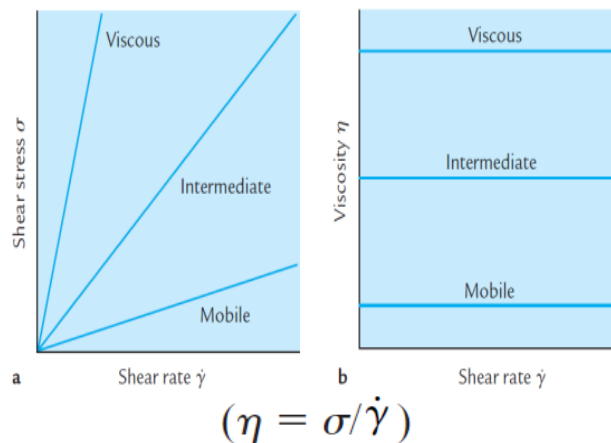


#### **Different types of fluids**

**Newtonian Fluid:** The shear rate is directly proportional to the shear stress and the flow behaviour curve passes through the origin. Fluids, such as water and most gases have a constant viscosity.

**Non-Newtonian Fluid:** If there is no linear relationship between shear stress and shear rate or if the flow behavior curve does not pass through the origin on the shear stress–shear rate diagram. Thus there exist a number of forms of viscosity.

#### **Newtonian Foods**



Examples:

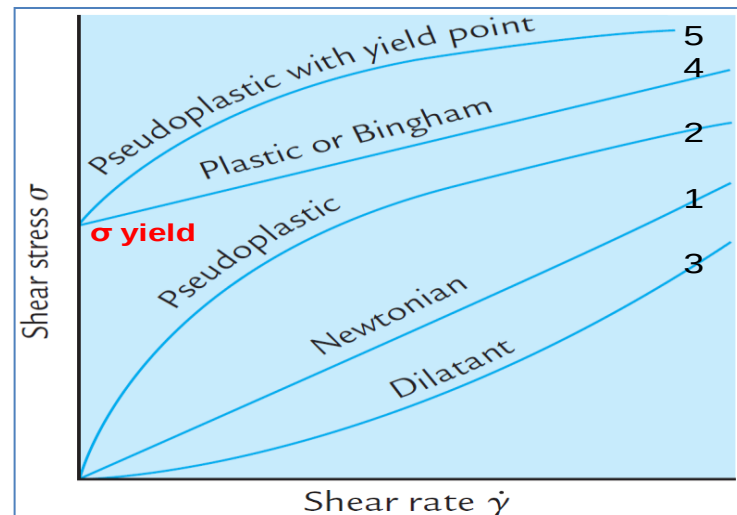
- Water
- Milk
- Vegetable oils
- Fruit juices
- Sugar and salt solutions

#### **Newtonian flow:**

1. shear stress versus shear rate (note that the straight lines begin at the origin)
2. viscosity versus shear rate (the viscosity remains constant with changing shear rate).

## Non-Newtonian fluids

1. **Pseudoplastic** : viscosity decreases with increase in shear stress.
2. **Dilatant** : viscosity increases with increase in shear stress.
3. Thixotropic: materials which become less viscous over time when shaken, agitated, or otherwise stressed.
4. **Rheoplectic**: materials which become more viscous over time when shaken, agitated, or otherwise stressed.
5. **Bingham plastic** is a material that behaves as a solid at low stresses but flows as a viscous fluid at high stresses.



**Graphical classification of rheological behavior of fluids**

- (1) Newtonian liquid
- (2) shear thinning behavior (Pseudoplastic)
- (3) shear thickening behavior (Dilatant)
- (4) Bingham (plastic) liquid
- (5) Plastic fluid behavior

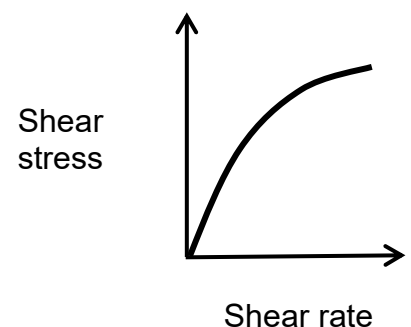
### ***Pseudoplastic (Shear thinning) Foods***

In this type of flow an increasing shear force gives a more than proportional increase in shear rate, but the curve begins at the origin. On a shear stress–shear rate diagram, the tangential slope is decreasing with increasing shear rate. This means the viscosity is decreasing with increasing shear rate.

Examples:

- sauce
- Banana puree
- Orange juice concentrate
- Oyster sauce

Sometimes this observation is referred to as “shear-thinning” behavior.

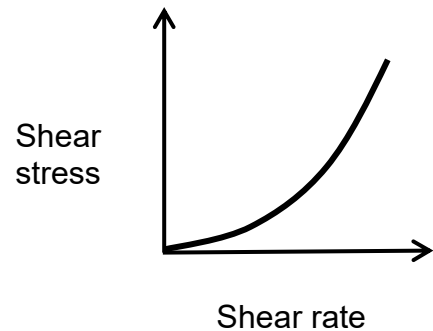


### ***Dilatant (Shear thickening) Foods***

Dilatant flow behavior occurs when we observe shear stress increasing at an increasing rate with increasing shear rate. On a shear stress–shear rate diagram, the tangential slope is increasing with increasing shear rate. This means the viscosity is also increasing with increasing shear rate. Sometimes this observation is referred to as “shear-thickening” behavior.

Examples:

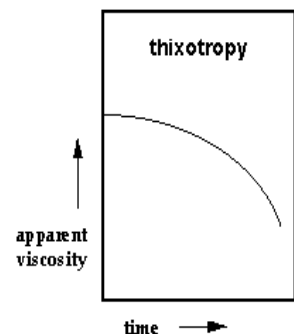
- Chocolate syrups.
- 40% Corn starch solution
- CMC solution (carboxy methyl cellulose) This type of flow is only found in liquids that contain a high proportion of insoluble rigid particles in suspension.



### **Thixotropy and Rheopexy (Time dependent viscosity)**

Thixotropic flow behavior is observed when shear stress or viscosity decreases over time at a constant shear rate. A thixotropic material becomes more fluid with increasing time of applied force. This effect is sometimes called ‘work softening’. It is often reversible, so that if left undisturbed for some time a thixotropic slurry regains its viscosity.

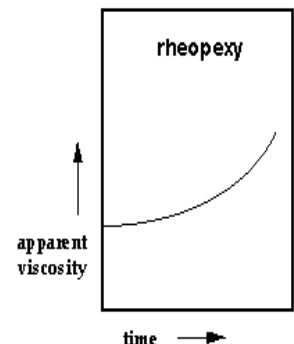
Ex: honey, yoghurt, mayonnaise, margarine, ice-cream, paint (on stirring, and solid honey becomes liquid)



Rheoplectic flow behavior is observed when shear stress or viscosity increases over time at a constant shear rate. A rheoplectic material becomes more viscous with increasing time of applied force. This effect is the opposite of thixotropy, and is sometimes called ‘work hardening’.

Ex: Cream, cucumber gum (the longer you whip it the thicker it gets)

The applied force could be stirring, pumping or shaking.



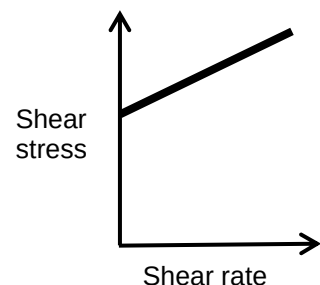
### **Bingham Plastic Foods**

When a solid material keeps its deformation as a permanent set after taking away the shear stress, we call that plastic deformation.

Liquids will demonstrate plastic behavior when they will not begin to flow until a minimum shear stress is exceeded that allows them to yield and begin to flow. This initial stress that must be overcome before the liquid will yield to begin flow is called the yield stress.

Examples:

- Cheese spread,
- Tomato paste
- Pickle
- Butter, which looks like a solid, but can be deformed, and keeps its deformation as a permanent set



## Model parameters for different types of fluids

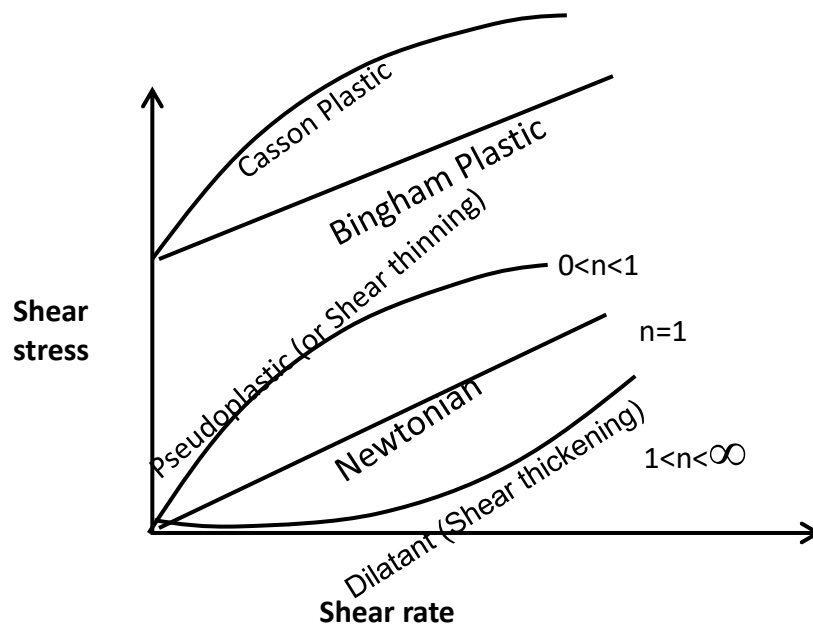
$$\eta = \sigma / \dot{\gamma}$$

$$\tau = K \dot{\gamma}^n + \tau_0$$

The power law model (also known as the Herschel-Bulkley model) with or without a yield term has been employed extensively to describe the flow behavior of viscous foods over wide ranges of shear rates where

‘K’ is the consistency coefficient (consistent index, Pa.s<sup>n</sup>),

‘n’ is the flow behavior index (dimensionless)



**Deborah number** is defined as the ratio of the relaxation time characterizing the time it takes for a material to adjust to applied stresses or deformations, and the characteristic time scale of an experiment of the material:

$$De = T_c / T_p$$

where  $T_c$  refers to the stress relaxation time, and  $T_p$  refers to the time scale of observation.

This incorporates both the elasticity and viscosity of the material. At lower Deborah numbers, the material behaves in a more fluidlike manner, with an associated Newtonian viscous flow. At higher Deborah numbers, the material behaviour enters the non-Newtonian regime, increasingly dominated by elasticity and demonstrating solid like behaviour.

### **Deborah number range**

Hookean elastic solid: 1

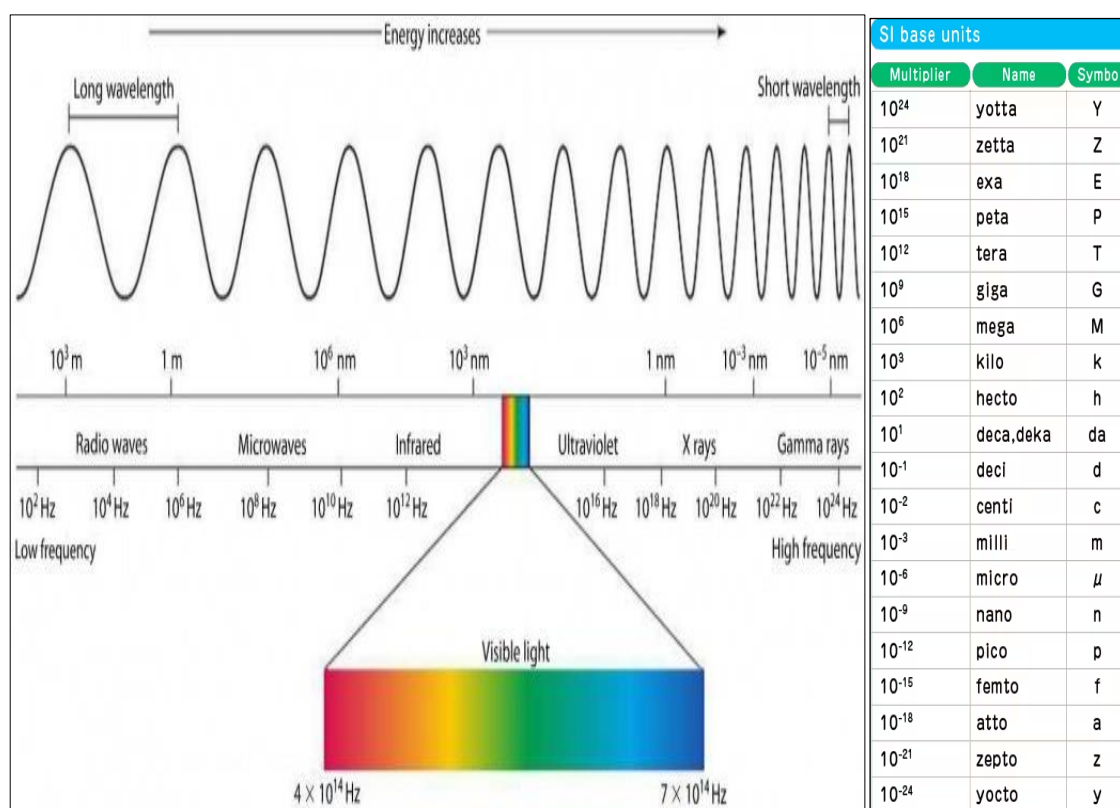
Newtonian viscous fluid: 0

## CHAPTER-10

### ELECTROMAGNETIC SPECTRUM AND COLOUR OF FOOD MATERIALS

#### **ELECTROMAGNETIC SPECTRUM**

- Electromagnetic spectrum is the graphical representation of frequency attained by the electromagnetic radiations along with their respective wavelength and photon energies.
- If we move along the ascending energy of the spectrum, the sequence is as follows:  
Radio waves – Micro–Infrared –Visible light –Ultraviolet rays –X-rays – Gamma rays
- Extremities:
  1. Radio waves: Low frequency, low energy, longer wavelength
  2. Gamma rays: High frequency, high energy, shorter wavelength
  3. Visible light: Wavelength range is 400 – 700 nm. Red is the starting spectrum of visible range and violet is the end spectrum. So, the sequence is: Red – Orange–Yellow–Green–Blue–Indigo–Violet (i.e., VIBGYOR in reverse order).



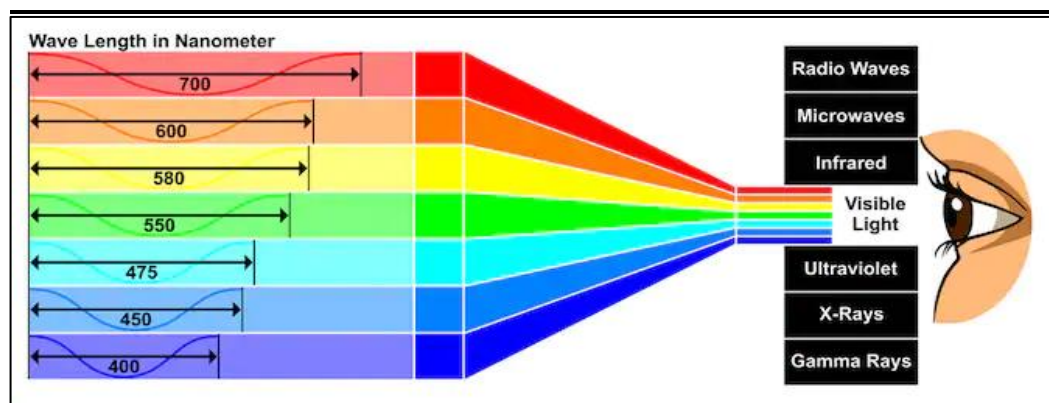
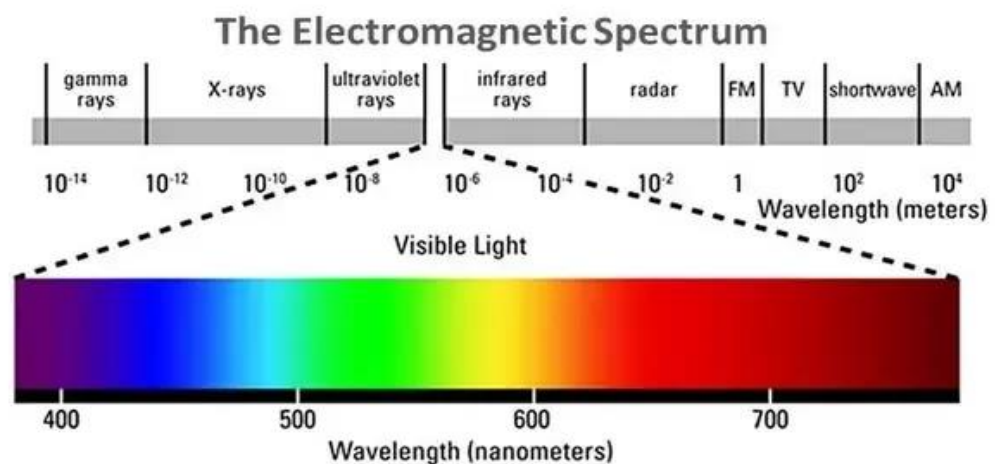
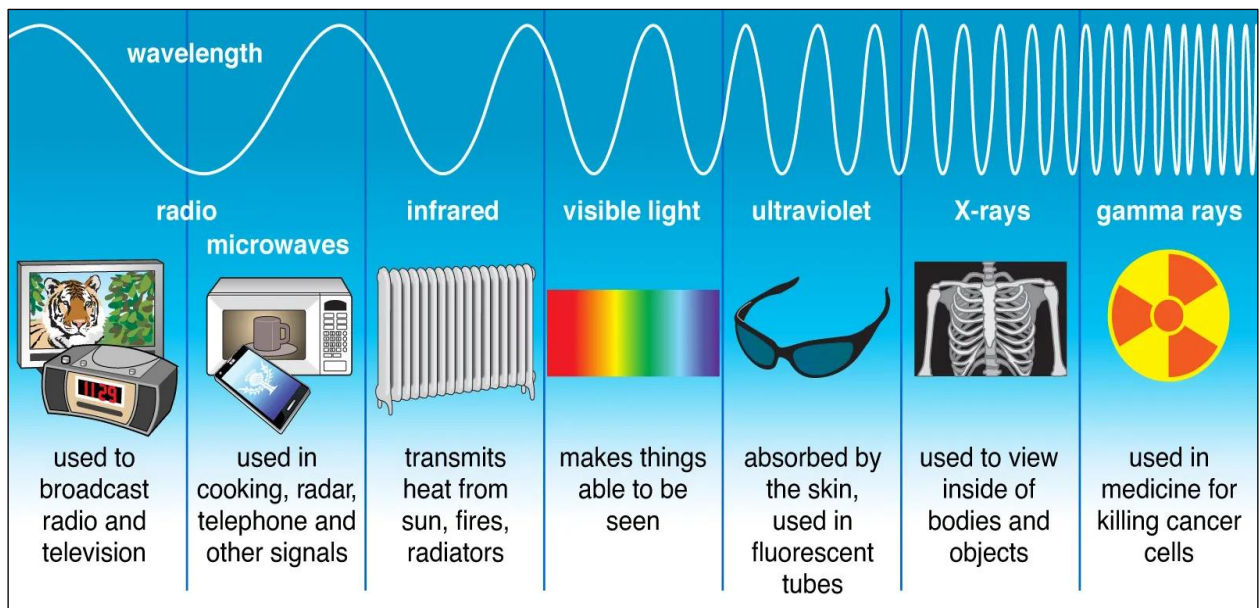
- For ultraviolet (UV), X-rays and Gamma rays are called ionizing radiations, because their photons have enough to ionize atoms, causing chemical reactions.
- These radiations cause health hazards like radiation sickness, DNA damage & even cancer.
- Radiation of visible spectrum and longer wavelength have lower energy and come under non-ionizing radiations.
- Frequency is inversely proportional to wavelength, and is directly proportional to energy.

$$f = \frac{c}{\lambda}, f = \frac{E}{h}, \text{ So, } E = \frac{hc}{\lambda}$$

where,  $f$  = frequency (Hz);  $E$  = energy (J);  $c$  = speed of light =  $3 \times 10^8 \frac{m}{s}$

$h$  = Planck's constant =  $6.62 \times 10^{-34} \text{ J.s}$ ;  $\lambda$  = wavelength (m)

Examples.



- **Visual methods of specifying colour is Subjective**
- **Measuring colour using an instrument gives objective results**

The visible spectrum is the portion of the electromagnetic spectrum that is visible to the human eye. Electromagnetic radiation in this range of wavelengths is called visible light /simply light. A typical human eye responds to wavelengths from about 400 to 700 nm.

### **Food color is very important**

- Effects of raw ingredients in the colour of the finished product
- Changes due to processing; need to ensure a consistent color
- Some naturally occurring colors also degrade based on
  - ✓ Exposure to heat,
  - ✓ Sunlight,
  - ✓ Processing conditions and storage.

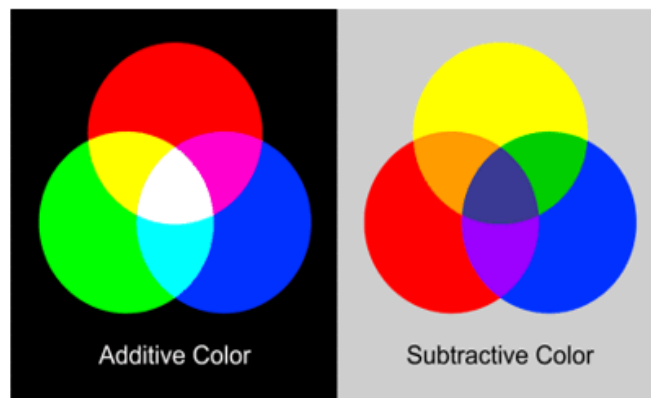
This adds complexity to the color consistency expectations.

### ***Classification of Foods depending on how light acts***

- ✓ **Opaque foods**, such as fruit, crackers, corn flakes, cheese puffs, flour, tomato juice, cheese, and meat, are seen wholly by reflected light.
- ✓ **Translucent foods**, such as fruit juices, jams, and custards, are seen partially by reflected light and partially by transmitted light. Translucent foods are typically in liquid or semi-solid form,
- ✓ **Transparent foods** are typically liquids or semisolids, such as clear juices, wines, jellies, gelatins, vegetable oil, and soft drinks, are seen wholly by transmitted light. Products such as clear juice, soft drink, vegetable oil, and brewed tea are poured into a transmission cell for sampling.

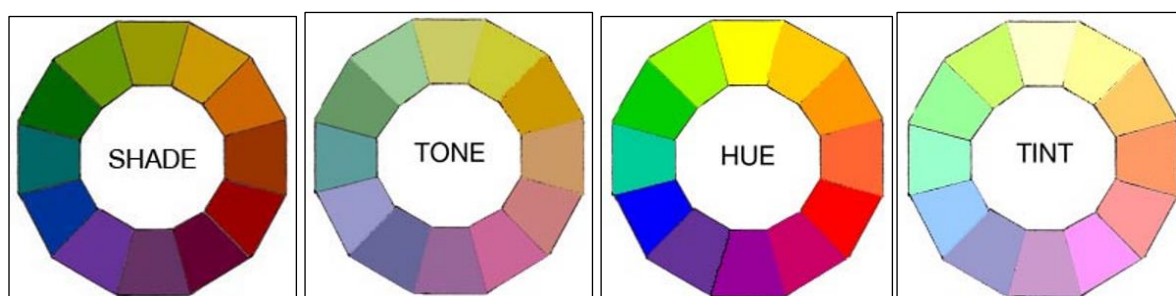
### **Science of Colour**

- Food colour provides an objective index of food quality. It determines the acceptance or rejection of a food in terms of its visual appeal.
- Every colour combination is derived from a set of primary colours, as human colour vision is trichromatic (i.e., red, green and blue). The combinations are again classified as additive or subtractive colour combination.
- Additive colour combination considers mixing of red, green and blue (RGB) as primary colours. An example is cathode ray tube (CRT) used in colour television. Munsell colour system is based on this principle.
- Subtractive colour combination mixes red, yellow and blue (RYB) as primary colours. Examples include mixing of pigments and dyes. Lovibond colour system is based on this principle.



## Terminologies

- **Hue:** Defines pure colour in terms of red, green and magenta. Hue also defines mixture of two pure colours like red-yellow(=orange), or yellow-green. Hue ranges from 0-359 Å
- **Tint:** A tint is a mixing result of an original colour to which white colour has been added. A tint is lighter than the original colour.
- **Shade:** A shade is a result of an original colour to which black colour has been added. A shade is darker than the original colour.
- **Tone:** A tone is defined as a result of mixing a pure colour with any greyscale colour. A tone is softer than the original colour.



## Principle of color measurement

Beer-Lambert law: It states that, the amount of energy absorbed or transmitted by a solution is proportional to the path length and concentration of the solute.

$$\text{Absorbance} \propto \text{path length (b)} \cdot \text{Concentration (C)}$$
$$A \propto b \cdot C \text{ or } A = \epsilon b C$$

Where A = absorbance of the solution (unitless)

b = path length (m) of the sample

C = concentration of solute (moles) of the compound in sample

$\epsilon$  = proportionality constant called molar absorption coefficient ( $\text{mol}^{-1}\text{m}^{-1}$ ).  $\epsilon$  is the proportionality constant, is called the molar extinction coefficient or molar absorptivity. It is a constant for a given substance provided the temperature and wavelength are constant. It has units of litre/mol.cm ( $\text{mol}^{-1}\text{m}^{-1}$ ). b and C have the usual units of length (cm) and concentration (mol/lit), path length and concentration

- It relates the attenuation of light to the properties of the material through which light is travelling.
- This principle is followed in spectrophotometer to measure the absorbance of different samples.

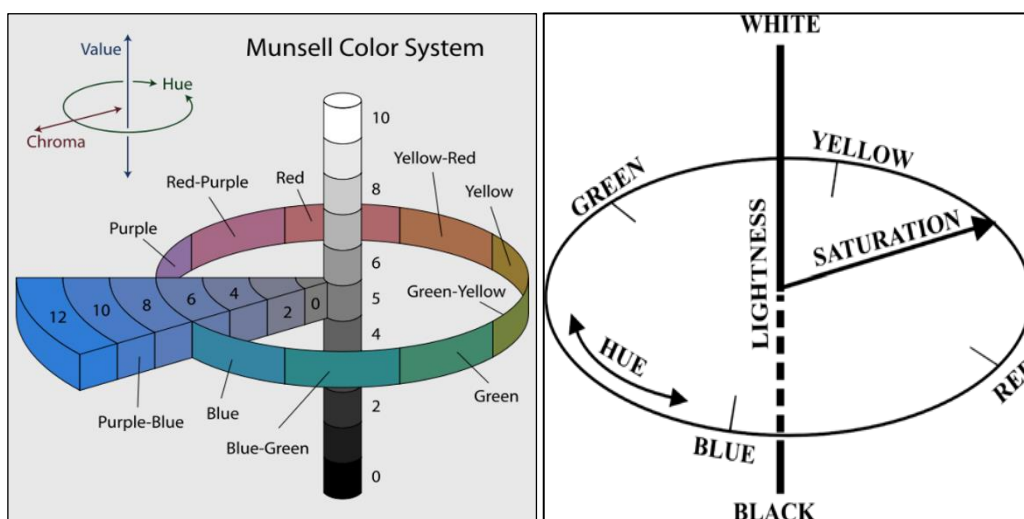
**Working Principle:** The colorimeter is based on Beer-Lambert's law, according to which the absorption of light transmitted through the medium is directly proportional to the medium concentration. Higher the concentration higher is absorbance value. The main difference between colorimeter and spectrophotometer is that colorimeter is a device which measures absorbance of specific colours, whereas a spectrophotometer measures transmittance or reflectance as a function of wavelength.

## HUE, VALUE AND CHROMA

The Munsell colour system explains these three colour parameters.

1. **Hue** (pure color): Quality by which one color is distinguished from another. measured by degrees around horizontal circles
2. **Value** (lightness/brightness), measured vertically from 0(black) to 10(white)
3. **Chroma** (Saturation/ Intensity of purity): quality that distinguishes a pure hue from a gray shade. The chroma (saturation or) axis extends from the value (lightness) axis toward the pure hue measured radially outward from the neutral (gray) vertical. Saturation defines a range **from pure color** (100%) **to gray** (0%) at a constant lightness level. A pure color is fully saturated.

$$\text{Chroma} = (a^{*2} + b^{*2})^{1/2}$$



*Evaluation system includes matching the colors*

## Principle and Instruments

Generally, four types of instruments are used for colour measurement, which are:

- **Monochromatic colorimeter** measures the amount of light reflected in relative units in a narrow zone of red, green, blue or yellow region of colour.
- **Tristimulus colorimeter** measures true color and correlates with what the eyes see. This is a trichromatic system, where any colour is matched with a combination of three primary colours, i.e., red, green and blue (RGB).
- **Colorimetric spectrophotometer** measures true colour by measuring a ratio of light reflected (or transmitted) from a food product to that of a reference (which is the standard for the instrument).
- **Hunter Lab colorimeter** (also called *CIE Lab colorimeter*) gives the most complete color specification.
- $L^*$  represents lightness, (0 for black to 100 for white).
- $a^*$  represents chromaticity on a green (-50) to red (+50) axis and
- $b^*$  represents chromaticity on a blue (-50) to yellow (+50) axis.

## Measurement of Colour Parameters

- a) Total colour difference ( $\Delta E^*$ ): It is the net change in colour of a sample from a reference. Higher value of  $\Delta E^*$  shows more variation of colour from the reference sample, and a smaller change is desirable.

$L_1^*$ ,  $a_1^*$  and  $b_1^*$  = lightness, red/green and yellow/blue colour value of the sample being analysed

$L_0^*$ ,  $a_0^*$ ,  $b_0^*$  = lightness, red/green and yellow/blue colour value of the reference sample.

$$\Delta E^* = \sqrt{(L_1^* - L_0^*)^2 + (a_1^* - a_0^*)^2 + (b_1^* - b_0^*)^2}$$

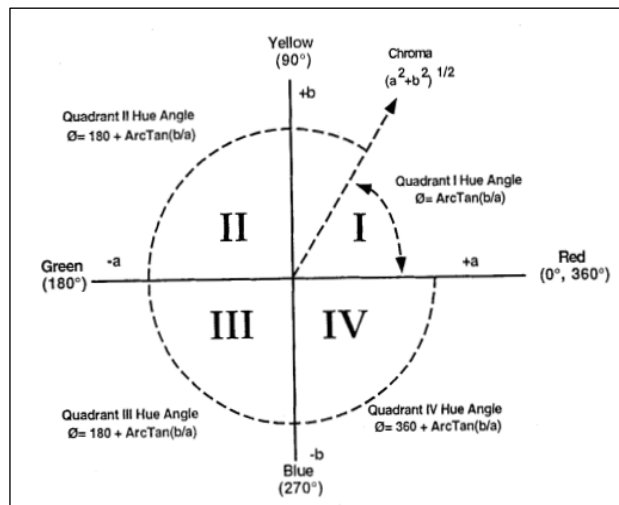
- b) Chroma: It is the quantitative attribute of colour. It generally shows the intensity of the sample colour.

$$\text{Chroma (C)} = \sqrt{(a_1^*)^2 + (b_1^*)^2}$$

$$\text{Hue angle} = \arctan (b^*/a^*)$$



- c) Hue angle: It shows the dominating color of the sample. It is measured in a scale of 360°. As per the location of the angle in the following four quadrants, the hue angle is calculated



d) Whiteness Index (WI): It represents the overall whiteness of the food products, which indicates the extent of discoloration due to processing conditions.

e) Yellowness Index (YI): YI is generally used to quantify different types of degradation of food products which may be caused due to exposure to light, chemicals or processing conditions.

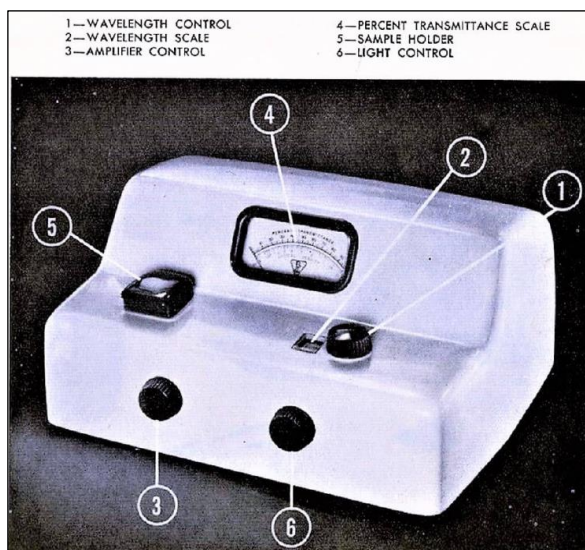
f) Browning Index (BI): BI is used to characterize the overall changes in brown color of the sample, which may include either or both enzymatic and non-enzymatic browning.

$$\text{Whiteness index (WI)} = L^* - 3b^* + 3a^*$$

$$\text{Yellowness index (YI)} = \frac{142.86 \times b^*}{L^*}$$

$$\text{Browning index (BI)} = \left( \frac{X - 0.31}{0.17} \right) \times 100$$

$$\text{Where } X = \frac{(a^* + 1.75 L^*)}{(5.645 L^* + a^* - 3.012 b^*)}$$



**Monochromatic colorimeter**



**Tristimulus colorimeter**



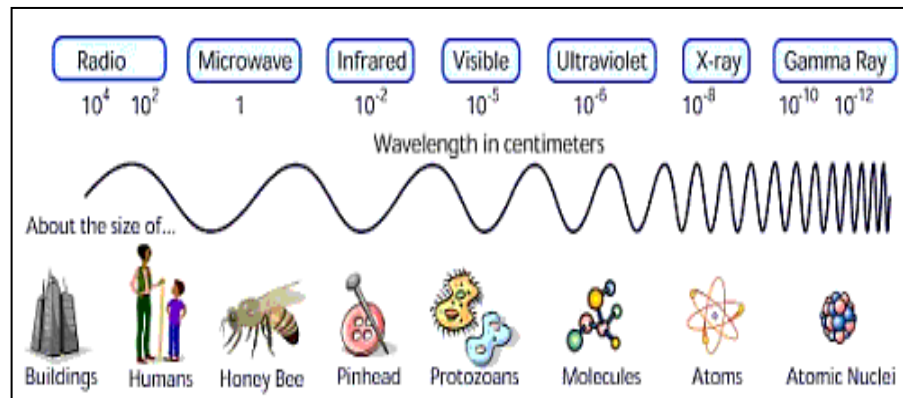
**Colorimetric spectrophotometer**



**Hunter Lab colorimeter**

## CHAPTER-11

### ELECTRIC AND DIELECTRIC PROPERTIES

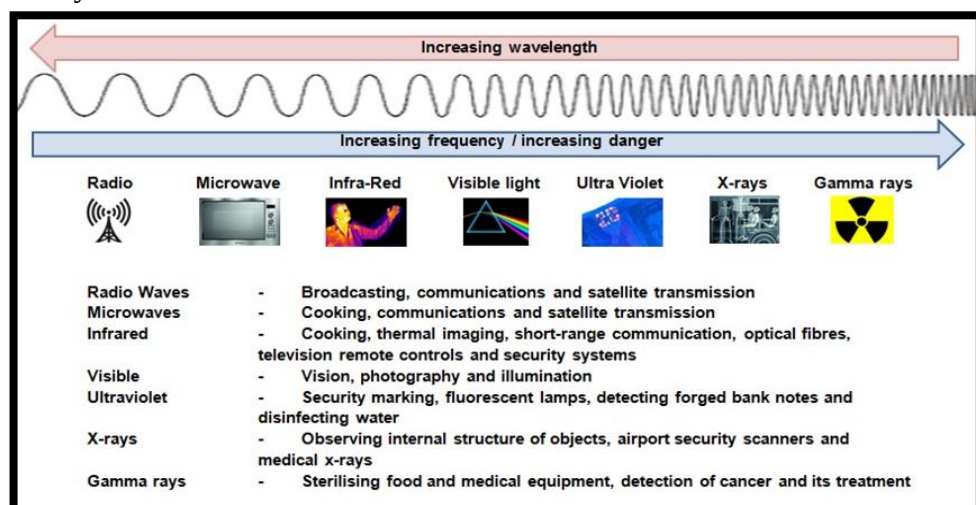


**Electromagnetic spectrum**

- Electromagnetic radiation encompasses a wide variety of phenomena as represented by the various regions along its broad spectrum.

| Region      | Frequency                                  | Wavelength           |
|-------------|--------------------------------------------|----------------------|
| Radio       | $< 3 \times 10^9$ Hz                       | $> 10$ cm            |
| Microwave   | $3 \times 10^9 - 3 \times 10^{11}$ Hz      | $10 - 0.1$ cm        |
| Infrared    | $3 \times 10^{11} - 4 \times 10^{14}$ Hz   | $1000 - 0.7$ $\mu$ m |
| Visible     | $4 \times 10^{14} - 7.5 \times 10^{14}$ Hz | $700 - 400$ nm       |
| Ultraviolet | $7.5 \times 10^{14} - 3 \times 10^{16}$ Hz | $400 - 10$ nm        |
| X-ray       | $3 \times 10^{16} - 3 \times 10^{19}$ Hz   | $10 - 0.01$ nm       |
| y-ray       | $> 3 \times 10^{19}$ Hz                    | $< 0.01$ nm          |

- The EM **spectrum** is generally divided into **seven** regions, in order of decreasing wavelength and increasing energy and frequency. The common designations are: radio **waves**, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma rays.



Only a few specialized, narrow regions are utilized in food applications. These include light, infrared, and microwave frequencies.

## Electrical and dielectric properties

- Non-destructive methods are highly encouraged for quality and safety assessment of foods.
- A dielectric material is an electrical insulator which can be polarized by an applied electric field.
- When the material is placed within an electric field, there is a shift of electric charges due to the resistance offered by the food material, and this causes dielectric polarization.
- Electrical and dielectric properties are used to explain interactions of foods with electric fields.
- Major factors affecting these properties of electrical materials are:
  - i. Frequency of the applied radio frequency or microwave electric fields
  - ii. Water content
  - iii. Temperature
  - iv. Density of the materials
  - v. Structural composition of the materials

### Electrical properties:

#### i) Resistance

Resistance plays a vital role in ohmic heating, when electricity in transformed energy when an alternating current (AC) flows through the food.

This property is important to determine food characteristics like frost sensitiveness, chilling and freezing tolerance, moisture content, seeds germination, mechanical stress, pasteurization etc..

$$R = \rho \frac{L}{A} = \frac{L}{\sigma A}$$

Where R = resistance offered by the foodstuff ( $\Omega$ )

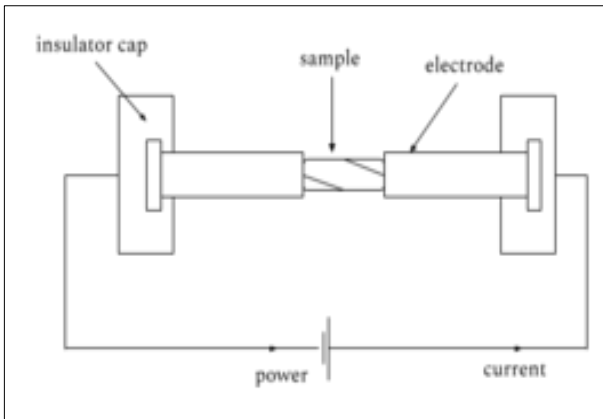
$\rho$  = resistivity of the foodstuff ( $\Omega\text{m}$ )

L = length (or thickness) of the food material (m)

A = cross-sectional area through which electricity passes ( $\text{m}^2$ )

$\sigma$  = conductivity of the foodstuff ( $\text{S|m}$ ) =  $\frac{1}{\rho}$

- Generally, the conductivity of the material is measured by passing a known current at constant voltage through a known volume of material and by determining resistance.
- Due to this effect, the internal structure of agricultural products changes substantially.
- The electrical conductivity of foods increases with increase in temperature and moisture content, so resistance decreases.



## ii) Capacitance

- Capacitance is defined as the ratio of a capacitor to the potential difference across the capacitor.

$$C = \frac{Q}{V}$$

where  $C$  = capacitance of the material (farad, F) (1 F = 1 coulomb/volt)

$Q$  = charge held by the material (coulomb)

$V$  = potential difference across the capacitor (V)

- Capacitive sensing technique has been used as chemical quality indicator and for measuring viscosity of oils to check their deterioration due to heating and frying.
- It has also found applications as sensors for quality detection of stored grains, flour, powdered milk, etc.
- ✓ **Electrical properties** are important in processing **foods** with
  - Pulsed electric fields, ohmic heating, induction heating,
  - Radio frequency, and microwave heating.
- ✓ These **properties** are also useful in the detection of processing conditions or the quality of **foods**.
- ✓ Standard methods and commercial conductivity meters are available for electrical conductivity measurements.
- ✓ The electrical conductivity increases with increase in:
  - ✓ 1. Temperature of product
  - ✓ 2. Food Ingredient
  - ✓ 3. Electrical field strength
- ✓ The electrical conductivity of foods is strongly affected by ionic content, moisture mobility, and physical structure, as well as the heating process.

## Dielectric Properties

### *Application of Dielectric Properties of Foods*

- Electromagnetic heating processes are governed by the material properties called dielectric properties.
- A **dielectric** is an electrical insulator that can be polarized by an applied electric field.

- Electromagnetic heating such as microwave and radiofrequency (RF) heating are used in many processes such as reheating, precooking, tempering, baking, drying, pasteurization, and sterilization in industry and at home.
- Although microwaves cover a wide range of frequencies (300MHz to 300GHz), their use is restricted to some frequencies owing to the possibility of interference of microwaves with radar or other communication devices.
- Absorption of microwave energy in the food involves primarily two mechanisms: ionic interaction and dipolar rotation.
- Since microwave heating is common in many food processes, determination of dielectric properties becomes significant to understand the heating profiles of foods in a microwave oven, and to develop equipment and microwaveable foods.

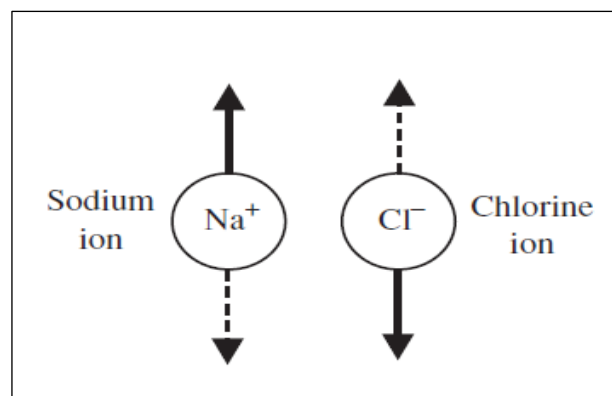
#### ***Facts on Microwave Heating***

- ✓ Microwaves are electromagnetic waves that cover a spectrum of frequencies ranging from 300 MHz to 30 GHz.
- ✓ Like light waves, these are reflected by metallic objects, absorbed by dielectric materials, or transmitted through glass.
- ✓ Although microwaves cover a wide range of frequencies, their use is restricted to some frequencies owing to the possibility of interference of microwaves with radar or other communication devices.
- ✓ The typical frequencies used in microwaves are 2450 MHz for home type ovens and 915 MHz for industrial use.
- ✓ Absorption of microwave energy in the food involves primarily two mechanisms: ionic interaction and dipolar rotation.
- ✓

#### **Basic Principles of Microwave Heating**

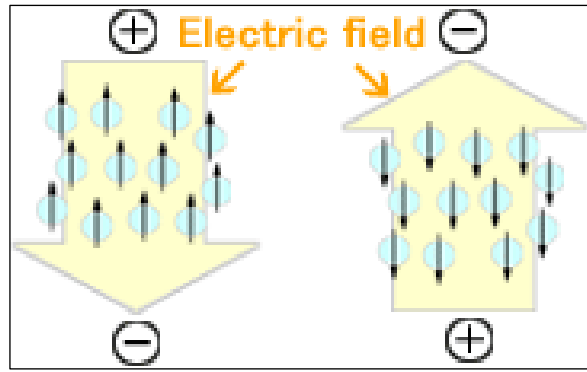
##### **Ionic Interaction (Ionic Conduction)**

Ions, such as those present in a salty food, migrate under the influence of the electric field, generating heat. If the accelerating particle collides with an adjacent particle, it will impart kinetic energy to it and set it into more agitated motion. As a result of agitation, the temperature of the particle increases.



##### **Dipolar Rotation**

If polar molecules are placed in an alternating electric field, they will experience a rotational force attempting to orient them in the direction of the field. When the field reverses its direction, they try to line up with the reversed direction and further collisions occur. This causes thermal agitation and heating takes place.



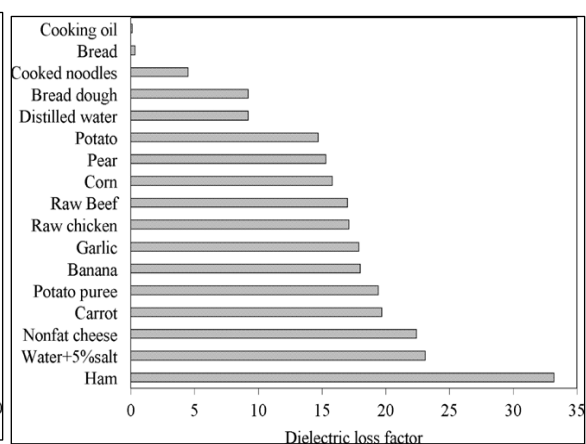
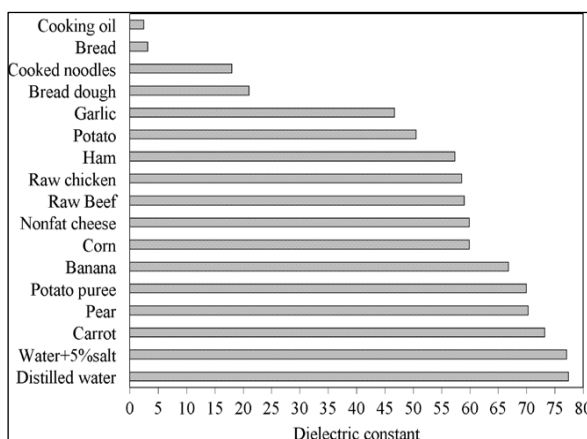
## Dielectric Properties

Dielectric properties can be categorized into two dimensionless quantities:

- **Dielectric constant ( $\epsilon'$ )** is related to the capacitance of a substance and its ability to store electrical energy. It is useful in microwave treatment. Higher  $\epsilon'$  of the material results in quicker heating. This helps in better drying and better extraction with minimum consumption of energy.
- **Dielectric loss factor ( $\epsilon''$ )** shows the ability of the material to dissipate microwave energy into heat. Here, energy is lost in heating the dielectric material. Hence, a low value of  $\epsilon''$  is desirable.
- **The loss tangent:  $\tan \delta = \epsilon'' / \epsilon'$** 
  - The values of dielectric constant and loss factor will play important roles in determining the interaction of microwaves with food.
  - The rate of heat generation per unit volume ( $Q$ ) at a location inside the food during microwave heating can be characterized by:

$$Q = 2 \pi f \epsilon_0 \epsilon'' E^2$$

$f$  is the frequency,  $\epsilon_0$  is the dielectric constant of free space ( $8.854 \times 10^{-12}$  F/m),  $\epsilon''$  is the dielectric loss factor, and  $E$  is the electric field (v/m)



Dielectric constant of various food materials at 25°C.

Dielectric loss factor of various food materials at 25°C.

Dielectric properties of cooking oil are very low because of its nonpolar characteristic. Dielectric properties of water and high-moisture-containing foods such as fruits, vegetables, and meat are high because of dipolar rotation. The highest loss factor is observed in the case of

salt-containing foods. The distance that microwaves will penetrate into the material before it is reduced to a certain fraction of its initial value is power penetration depth ( $\delta_p$ ), which is defined as the depth at which power density (level) decreases to 1/e or (36.8%) of its original value. It depends on both dielectric constant and loss factor of food.

$$\delta_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon''}} (\sqrt{1 + (\varepsilon''/\varepsilon')^2} - 1)^{-\frac{1}{2}}$$

where  $\lambda_0$  is wavelength of the microwave in free space (for 2450 MHz,  $\lambda_0 = 122$  mm).

Wavelength, frequency and velocity of electromagnetic waves are related by

$\lambda = v / f$ , where,  $\lambda$  is wavelength, m;  $f$  is frequency in Hz;  $v$  is velocity of light,  $3 \times 10^8$  m/s.

$\lambda_{915} = 3 \times 10^8 \text{ (m/s)} / 915 \times 10^6 \text{ (1/s)} = 0.328 \text{ m}$ ;  $\lambda_{2450} = 3 \times 10^8 \text{ (m/s)} / 2450 \times 10^6 \text{ (1/s)} = 0.122 \text{ m}$

### **Factors affecting Dielectric Properties**

**1. Moisture Content:** The increase in water increases the polarization, which increases both dielectric constant and loss factor.

**2. Temperature:** Since dielectric loss and dielectric constant are temperature dependent, thus the dissipation factor (loss parameters of microwave applications) will increase with temperature.

**3. Composition of Foods:** Water and high moisture foods are excellent absorbers of microwave energy while dry materials and ice are poor absorbers. Microwave heating, therefore, works best to heat unfrozen foods of high moisture.

### **Measurement steps of Dielectric Properties**

1. A microwave signal is generated at the frequency of interest.
2. Signal is directed through the sample.
3. Changes in the signal caused by the sample are measured.
4. From these changes the dielectric constant and loss factor are determined

### **Microwave Heating**

#### ***The characteristics of microwave heating***

There are some characteristics of microwave heating that other heating methods (conventional heating method) do not have.

**The internal heating:** Microwave will reach the object to be heated at the same speed of light. Then it enters into the object as a wave, and by getting absorbed, the object generates heat.

**Rapid heating:** The object will generate heat on their own by the penetration of the microwave.

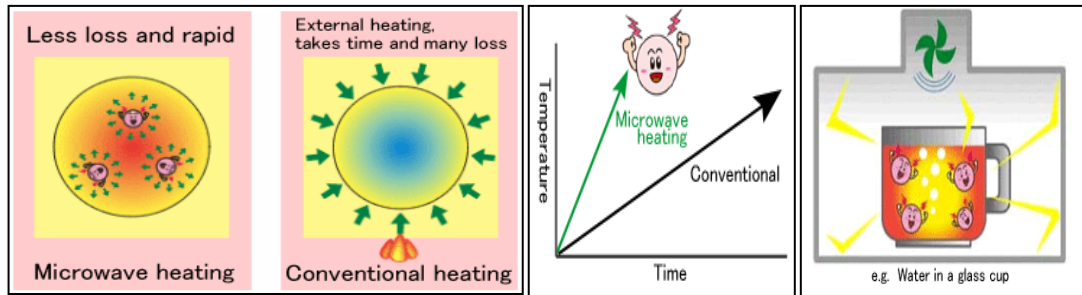
**Selected heating:** There is a difference in microwave power absorption depending on the material. When a good material of container is selected, microwave can only heat the object not container.

**High heating efficiency:** No need to consider the heating losses of air inside the heating furnace.

**Rapid response:** One can start and stop the heating instantly as microwave penetrates into the object at the speed of light

**Clean energy:** Microwave doesn't require a medium. It doesn't heat the air during process.

**Good operation and work environment:** The temperature of the object only rises, not the furnace. And there is no radiant heat, so it's possible to keep operational and good working environment.



### The basic structure and components of microwave oven

**Power supply and control:** it controls the power to be fed to the magnetron as well as the cooking time.

**Magnetron:** it is a vacuum tube in which electrical energy is converted to an oscillating electromagnetic field. Frequency of 2450 MHz has been set aside for microwave oven for home use.

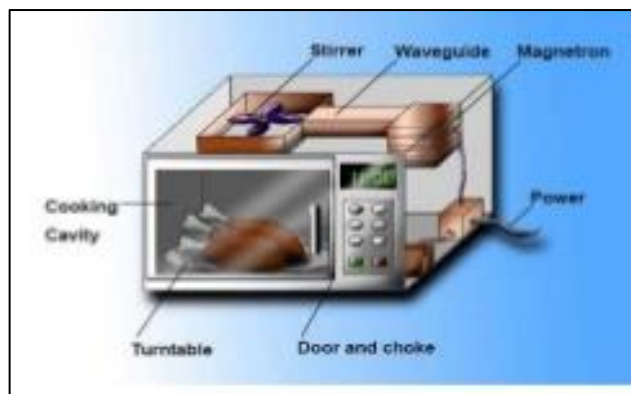
**Waveguide:** it is a rectangular metal tube which directs the microwaves generated from the magnetron to the cooking cavity. It helps prevent direct exposure of the magnetron to any spattered food which would interfere with function of the magnetron.

**Stirrer:** it is commonly used to distribute microwaves from the waveguide and allow more uniform heating of food.

**Turntable:** it rotates the food products through the fixed hot and cold spots inside the cooking cavity allows the food products to be evenly exposed to microwaves.

**Cooking cavity:** it is a space inside which the food is heated when exposed to microwaves.

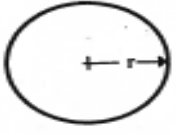
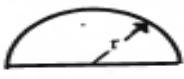
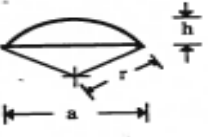
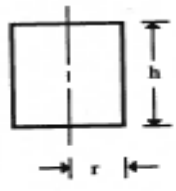
**Door and choke:** it allows the access of food to the cooking cavity. The door and choke are specially engineered that they prevent microwaves from leaking through the gap between the door and the cooking cavity.

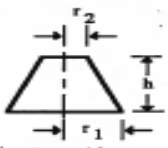
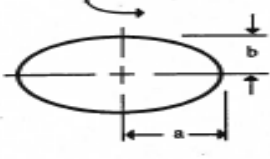


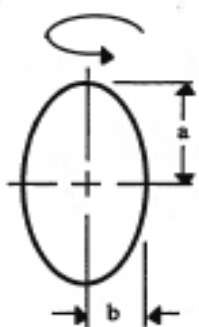
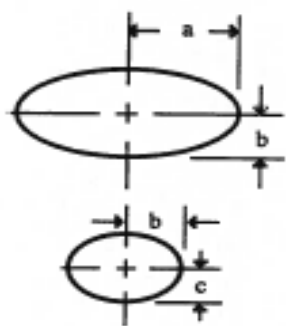
The basic structure and components of microwave oven

# ANNEXURE

## VOLUME AND SURFACE AREA OF SOME COMMON REGULAR SHAPES

| SHAPE                                                                                                              | SURFACE AREA                                                 | VOLUME                                                                         |
|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------------------------------------|
| <p>Sphere</p>                     | $S = 4 \pi r^2$                                              | $V = \frac{4}{3} \pi r^3$                                                      |
| <p>Hemisphere</p>                 | $S = 3 \pi r^2$<br>(not including circular bottom)           | $V = \frac{2}{3} \pi r^3$                                                      |
| <p>Spherical Segment</p>          | $S = 2 \pi r h$<br>(not including circular bottom)           | $V = \frac{1}{3} \pi h^2 (3r - h)$<br>where $r = \frac{h}{2} + \frac{a^2}{8h}$ |
| <p>Right Circular Cylinder:</p>  | $S = 2 \pi r (h + r)$<br>(including circular bottom and top) | $V = \pi r^2 h$                                                                |

| SHAPE                                                                                                                                    | SURFACE AREA                                                                                                                                        | VOLUME                                                    |
|------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|
| <p>Right Circular Cone</p>                            | $S = \pi r \sqrt{r^2 + h^2}$<br>(not including circular bottom)                                                                                     | $V = \frac{1}{3} \pi r^2 h$                               |
| <p>Truncated Right Circular Cone</p>                  | Area of curved surface (top and bottom excluded)<br>$S = \pi (r_1 + r_2) \sqrt{h^2 + (r_1 - r_2)^2}$                                                | $V = \frac{\pi h}{3} (r_1^2 + r_1 r_2 + \frac{r_2^2}{2})$ |
| <p>Pyramid:</p>                                       | $S = a L + \frac{1}{2} a^2$<br>(bottom excluded)                                                                                                    | $V = \frac{1}{3} a^2 h$                                   |
| <p>Oblate Spheroid (rotation around minor axis):</p>  | $S = 2 \pi a^2 + \frac{\pi b^2}{e} \ln \left( \frac{1+e}{1-e} \right)$<br>where $e = \left( 1 - \left( \frac{b}{a} \right)^2 \right)^{\frac{1}{2}}$ | $V = \frac{4 \pi}{3} a^2 b$                               |

| SHAPE                                                                                                                                                            | SURFACE AREA                                                                                                                                                                                                                 | VOLUME                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| <p>Prolate Spheroid<br/>(rotation about major axis):</p>                        | $S = 2\pi b^2 + \frac{2\pi ab}{e} \sin^{-1}(e)$ <p>where <math>e = \left(1 - \left(\frac{b}{a}\right)^2\right)^{\frac{1}{2}}</math><br/> and <math>\sin^{-1}(e)</math> is expressed in radians,<br/> 1 radian = 57.2988°</p> | $V = \frac{4\pi}{3} ab^2$ |
| <p>Triaxial Ellipsoid<br/>all three perpendicular sections are ellipses):</p>  |                                                                                                                                                                                                                              | $V = \frac{4\pi}{3} abc$  |

| Paddy Shape | L/W ratio   | Paddy Size                                                                                                                                        |
|-------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Slender     | Over 3.0    | <ul style="list-style-type: none"> <li>• Extra-long &gt;7.5</li> <li>• Long 6.5-7.5</li> <li>• Medium 5.5-6.5</li> <li>• Short &lt;5.5</li> </ul> |
| Medium      | 2.1 – 3.0   |                                                                                                                                                   |
| Bold        | 1.1 – 2.0   |                                                                                                                                                   |
| Round       | 1.0 or less |                                                                                                                                                   |

Sphere

$$V = \frac{4}{3}\pi r^3 \quad \text{and} \quad A = 4\pi r^2$$

Cylinder

$$V = \pi r^2 L \quad \text{and} \quad A = 2\pi r^2 + 2\pi r L$$

Cube

$$V = a^3 \quad \text{and} \quad A = 6a^2$$

Brick

$$V = abc \quad \text{and} \quad A = 2(ab + bc + ca)$$

Prolate spheroid

$$V = \frac{4}{3}(\pi a b^2) \quad \text{and} \quad A = 2\pi b^2 + \frac{2\pi a b}{e} \sin^{-1} e$$

Oblate spheroid

$$V = \frac{4}{3}(\pi a^2 b) \quad \text{and} \quad A = 2\pi a^2 + \frac{\pi b^2}{e} \ln \left( \frac{1+e}{1-e} \right)$$

Frustum right cone

$$V = \frac{\pi}{3} L (r_1^2 + r_1 r_2 + r_2^2) \quad \text{and} \quad A = \pi (r_1 + r_2) \sqrt{L^2 + (r_1 - r_2)^2}$$

---

\* Where  $a$  and  $b$ , respectively, are major and minor semiaxes of the ellipse of rotation,  $e$  is the eccentricity given by  $e = \sqrt{1 - (b/a)^2}$ ,  $r_1$  and  $r_2$ , respectively, are the radii of base and top, and  $L$  is the altitude.

## Shape and description of various agro commodities

| Shape      | Description                                        | Examples                                      |
|------------|----------------------------------------------------|-----------------------------------------------|
| Round      | Approaching Spheroid                               | sapota, cherry tomato, pea                    |
| Oblate     | Flattened at the stem end and apex                 | orange, pumpkin                               |
| Prolate    | Elongated along a line                             | Lemon, grape                                  |
| Oblong     | Vertical diameter greater than horizontal diameter | some apple varieties, capsicum, brinjal, rice |
| Conic      | Tapered toward the apex                            | ladies finger, carrot, radish                 |
| Ovate      | Egg shaped & broad at stem end                     | Brinjal, apple and guava.                     |
| Oblique    | Axis connecting stem and apex slanted              | some apple varieties, tomato.                 |
| Obovate    | Inverted ovate-broad at apex                       | Mango, papaya                                 |
| Elliptical | Approaching ellipsoid                              | rice, wheat, pointed guard                    |
| Truncate   | Having both ends squared or flattened              | capsicum                                      |
| Unequal    | One half larger than the other                     | mango                                         |
| Ribbed:    | In cross section, sides are more or less angular   | plantain, ladies finger                       |
| Regular    | Horizontal section approaches a circle             | orange, apple, guava etc                      |
| Irregular  | Horizontal section dearts materially from a circle | mango, ladies finger, capsicum                |

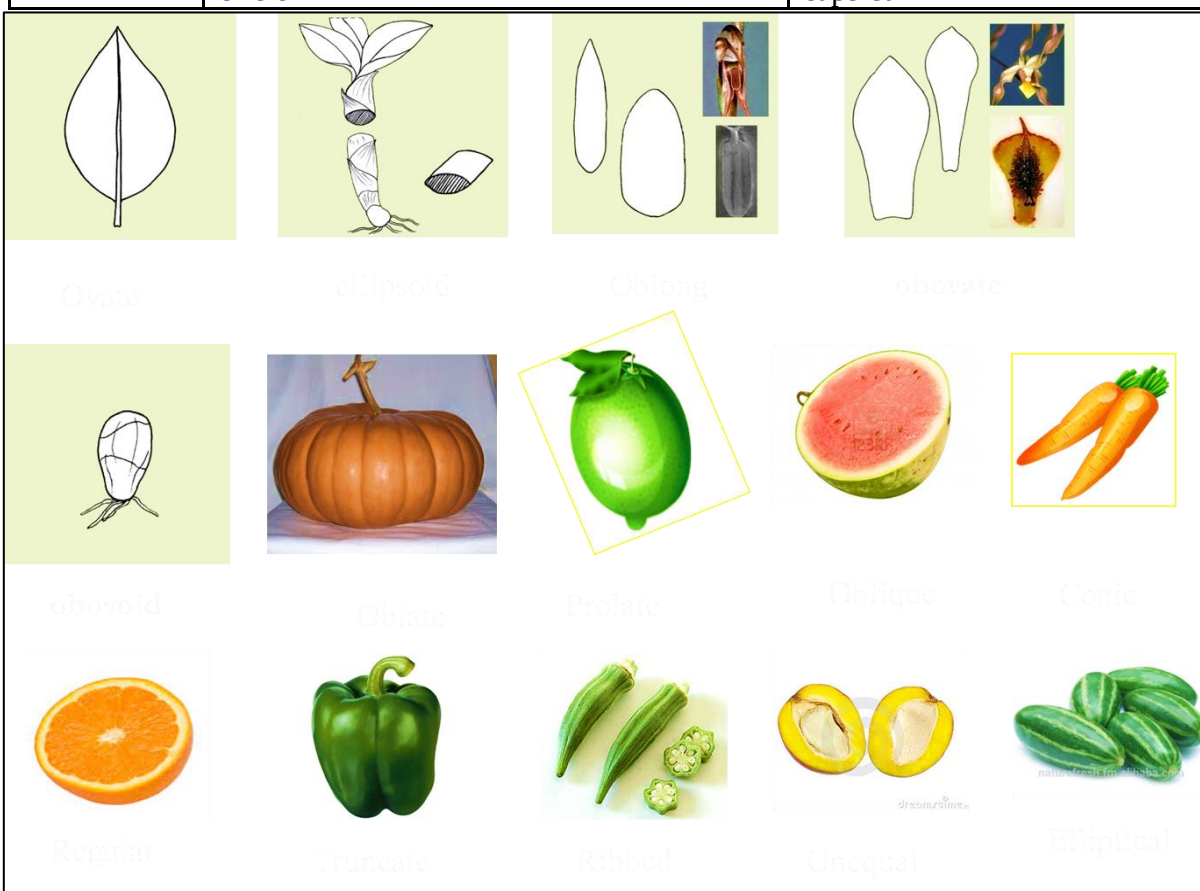
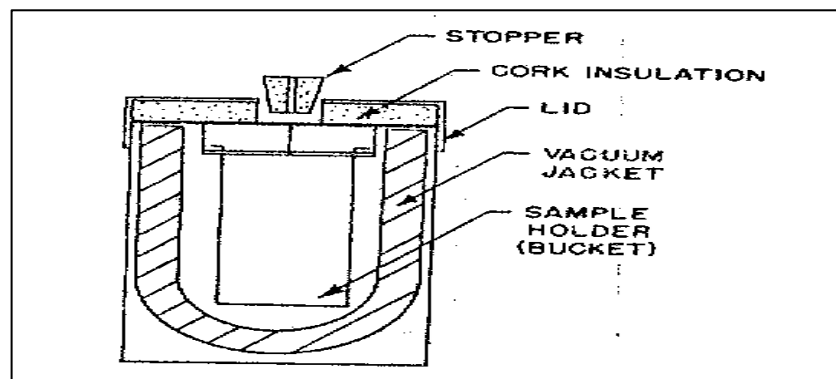


**Table 4.3: Some physical and mechanical properties of the grains**

| Grains     | Moisture content (% , wb) | Bulk Density (Kg/m <sup>3</sup> ) | True Density (Kg/m <sup>3</sup> ) | Porosity | Angle of repose (Degree) | Friction coefficient on sheet metal |
|------------|---------------------------|-----------------------------------|-----------------------------------|----------|--------------------------|-------------------------------------|
| Wheat      | 8-14                      | 790-700                           | 1390-1400                         | 40       | 26-28                    | 0.40                                |
| Rice       | 9-11                      | 610-580                           | 1200-1240                         | 54       | 27-30                    | 0.48                                |
| Corn       | 10                        | 820                               | 1393                              | 41       | 26-28                    | 0.23                                |
| Soya bean  | 10-11                     | 680                               | 1180                              | 42       | 24-25                    | 0.34                                |
| Pigeon pea | 9-10                      | 815                               | 1330                              | 39       | 19                       | 0.29                                |
| Gram       | 8-9                       | 815                               | 1340                              | 39       | 17                       | 0.35                                |

**Source:** Engg. properties of Food material (1980) CIAR Publication /80/15



**Vacuum jacketed calorimeter**

$$C = \left( \frac{m}{100} \right) C_w + \left( \frac{100 - m}{100} \right) C_d \text{ k cal/kg}^\circ\text{C}$$

It depends on the nature of the process of heat addition: (i) constant pressure process, (ii) constant volume process.

For biological materials constant pressure process is generally used.

Determination of Sp. Heat by Method of mixtures

If change in heat of calorimeter =  $q_c$ , water =  $q_w$ , sample =  $q_s$

Then heat gain by sample = heat lost by calorimeter & water

$$C_s W_s (t_e - t_{is}) = C_c W_c (t_i - t_e) + C_w W_w (t_i - t_e)$$

Other Methods: Method of guarded plate, Comparison calorimeter

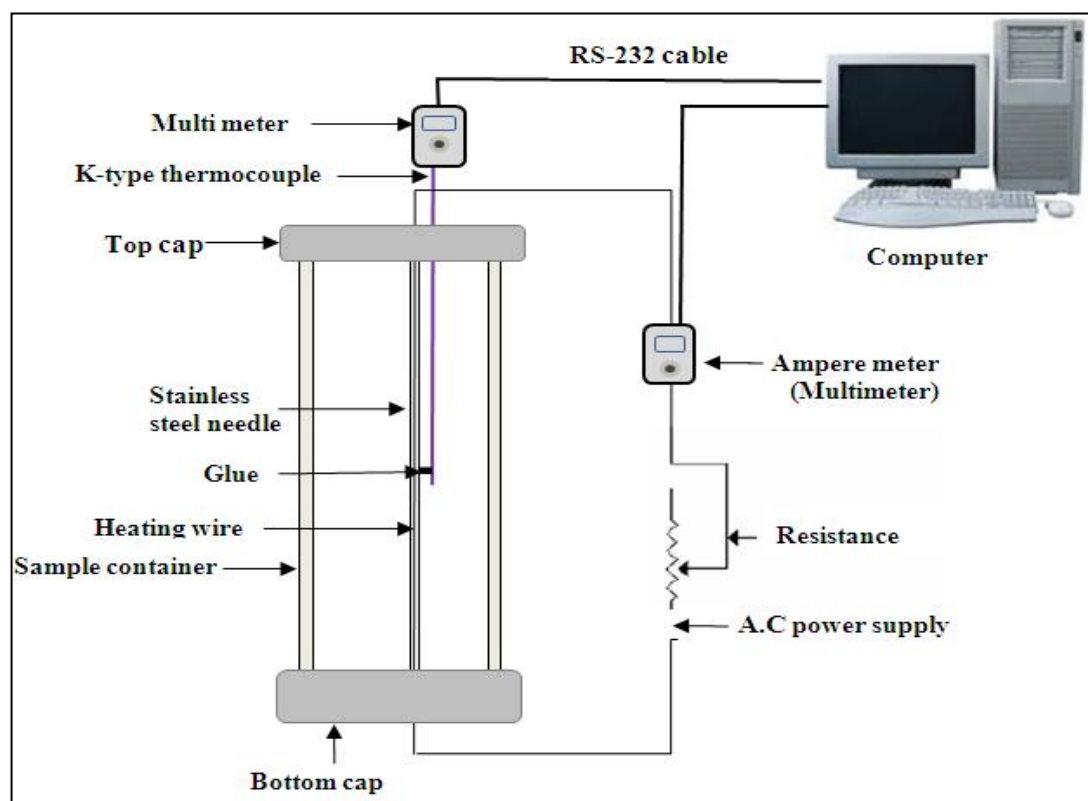
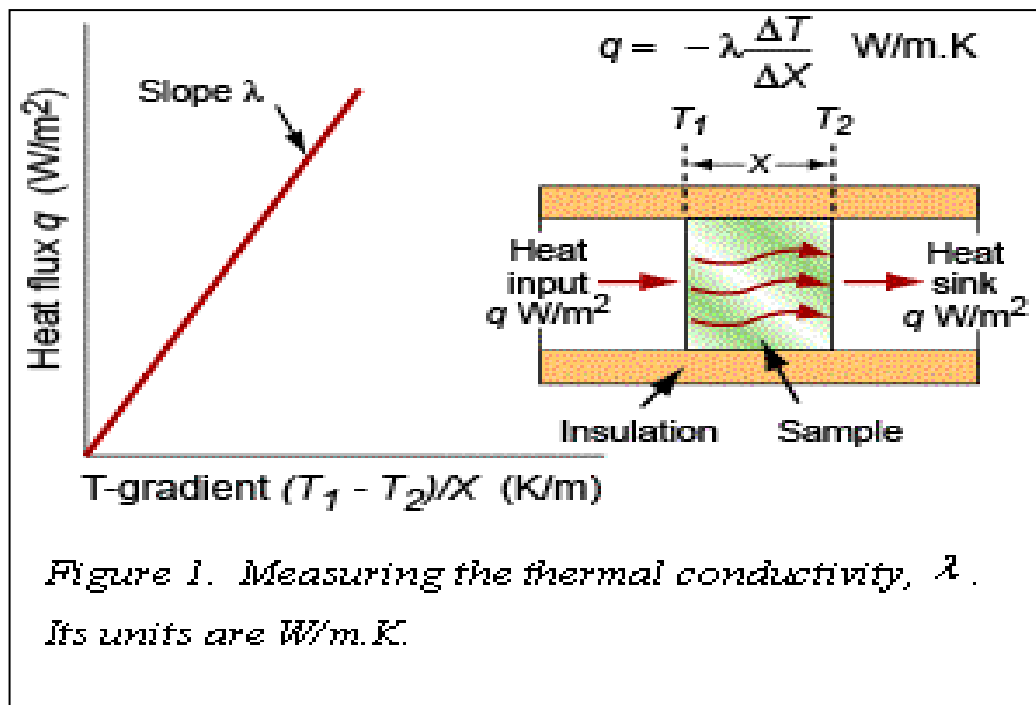


**Table 4.4: Thermal properties of grains**

| Grains      | Moisture content (% db) | Specific heat (KJ / Kg K) | Thermal conductivity (W / m K) | Thermal Diffusivity ( $10^{-7} \text{ m}^2 / \text{s}$ ) |
|-------------|-------------------------|---------------------------|--------------------------------|----------------------------------------------------------|
| Wheat       | 10-20                   | 1.09                      | 0.139                          | 0.91                                                     |
| Rice        | 10-20                   | 1.33                      | 0.087                          | 1.00                                                     |
| Corn        | 10-20                   | 1.20                      | 0.165                          | 0.89                                                     |
| Pigeon pea  | 8-22                    | 1.50                      | 0.153                          | 0.94                                                     |
| Soyabean    | 8-10                    | 2.01                      | 0.116                          | 0.54                                                     |
| Bengal gram | 10-20                   |                           |                                | 17.1                                                     |
| Mustard     | 8-12                    | 2.56                      | 0.175                          | 0.73                                                     |
| Sorghum     | 8-12                    | 1.69                      | 0.124                          | 0.85                                                     |

**Source:** Engg. properties of Food materials (1980) CIAE Publication /80/15

**Table 9.1. Static Coefficients of Friction for Agricultural Materials.**

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

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

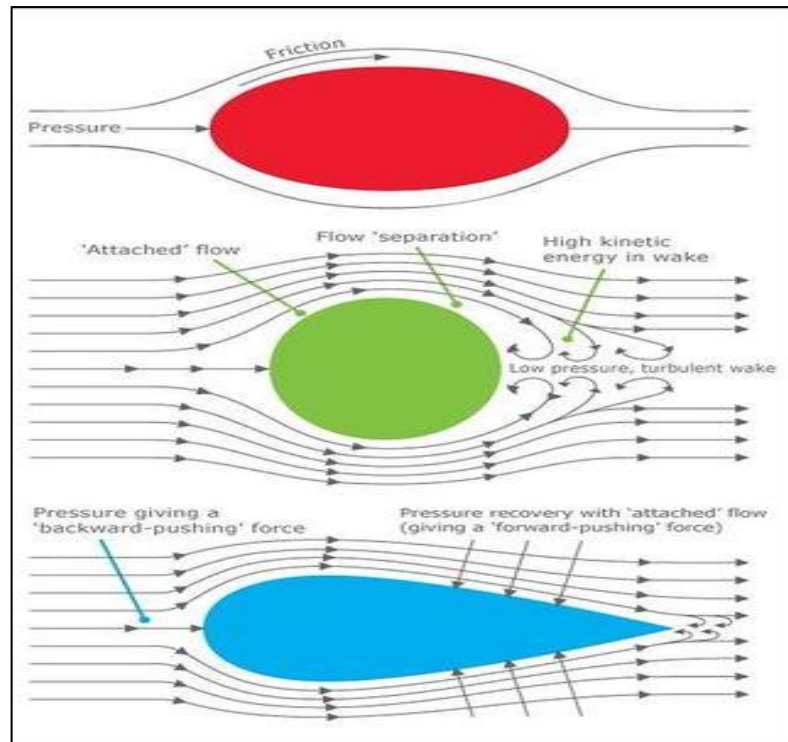
| Material         | Type Surface & Characteristics             | Moisture Content  | Coef. | Reference       |
|------------------|--------------------------------------------|-------------------|-------|-----------------|
| Alfalfa Pellets  | Steel                                      | n.r. <sup>a</sup> | 0.17  | Kosowski (1965) |
|                  | Wood                                       | n.r.              | 0.28  | "               |
| Alfalfa, Chopped | Steel                                      | n.r.              | 0.34  | Kosowski (1965) |
|                  | Wood                                       | n.r.              | 0.37  | "               |
| Corn Silage      | Polished Galv. Steel <sup>b</sup> , 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  | Kosowski (1965) |
| Limestone        | Steel                                      | n.r.              | 0.43  | Kosowski (1965) |
| Oyster Shells    | Steel                                      | n.r.              | 0.35  | Kosowski (1965) |
| Straw            | Polished Galv. Steel <sup>b</sup> , 680 Pa | n.r.              | 0.30  | Richter (1954)  |
|                  | Polished Galv. Steel, 1360 Pa              |                   | 0.30  | "               |

<sup>a</sup> n.r. indicates that moisture contents were not reported.

<sup>b</sup> 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.

**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 <sup>3</sup> ) | 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.                              | ?                     | "                     |



| Shape                      |   |                                                                                      | Drag Coefficient |
|----------------------------|---|--------------------------------------------------------------------------------------|------------------|
| Sphere                     | → |   | 0.47             |
| Half-sphere                | → |   | 0.42             |
| Cone                       | → |   | 0.50             |
| Cube                       | → |   | 1.05             |
| Angled Cube                | → |   | 0.80             |
| Long Cylinder              | → |   | 0.82             |
| Short Cylinder             | → |   | 1.15             |
| Streamlined Body           | → |   | 0.04             |
| Streamlined Half-body      | → |  | 0.09             |
| Measured Drag Coefficients |   |                                                                                      |                  |

**TABLE 2.3 Rheological Properties of Fruit Products**

| Product                  | Concentration<br>(% solids) | Method        | Temperature<br>(°C) | K<br>(Pa s <sup>n</sup> ) | n    | Yield<br>stress<br>(Pa) | Reference                       |
|--------------------------|-----------------------------|---------------|---------------------|---------------------------|------|-------------------------|---------------------------------|
| Tomato juice<br>(pH 4.3) | 5.80                        | Conc cylinder | 32.2                | 0.22                      | 0.59 |                         | Harper and<br>El Sahrigi (1965) |
|                          |                             |               | 48.9                | 0.27                      | 0.54 |                         |                                 |
|                          |                             |               | 65.6                | 0.37                      | 0.47 |                         |                                 |
|                          | 12.80                       |               | 32.3                | 2.10                      | 0.43 |                         |                                 |
|                          |                             |               | 48.9                | 1.18                      | 0.43 |                         |                                 |
|                          |                             |               | 65.6                | 2.28                      | 0.34 |                         |                                 |
|                          | 16.00                       |               | 82.2                | 2.12                      | 0.35 |                         |                                 |
|                          |                             |               | 32.3                | 3.16                      | 0.45 |                         |                                 |
|                          |                             |               | 48.9                | 2.27                      | 0.45 |                         |                                 |
|                          | 25.00                       |               | 65.6                | 3.18                      | 0.40 |                         |                                 |
|                          |                             |               | 82.2                | 3.27                      | 0.38 |                         |                                 |
|                          |                             |               | 32.3                | 12.9                      | 0.41 |                         |                                 |
|                          |                             |               | 48.9                | 10.5                      | 0.42 |                         |                                 |
|                          |                             |               | 65.6                | 8.0                       | 0.43 |                         |                                 |
|                          |                             |               | 82.2                | 6.1                       | 0.44 |                         |                                 |
|                          | Tomato paste                |               | 29.7 °Brix          | Haake mixer               | 32.0 | 208.0                   |                                 |
| 29.7 °Brix               |                             | 39.0          | 179.0               |                           | 0.31 | 180                     |                                 |
| 23.8 °Brix               |                             | 33.0          | 48.0                |                           | 0.47 | 40                      |                                 |
| 23.8 °Brix               |                             | 39.0          | 34.0                |                           | 0.52 | 29                      |                                 |
| 16.3 °Brix               |                             | 25.0          | 24.0                |                           | 0.23 | 38                      |                                 |

|                                           |            |                            |       |       |      |     |                       |
|-------------------------------------------|------------|----------------------------|-------|-------|------|-----|-----------------------|
| Applesauce                                |            | Haake mixer                | 32.0  | 200.0 | 0.42 | 240 | Rao et al.,1993       |
| Apple juice                               | 69.8 °Brix | Haake RV2/                 | 25.0  | 0.24  | 1.00 |     | Rao et al.,1993       |
|                                           | 65.3 Brix  | Deer Rheom.                | 23.0  | 0.09  | 1.00 |     |                       |
|                                           | 69.8 Brix  |                            | 43.0  | 0.03  | 1.00 |     |                       |
|                                           | 51.1 Brix  |                            | 25.0  | 0.02  | 1.00 |     |                       |
| Orange juice<br>Pera orange,<br>3.4% pulp | 64.9 Brix  | Haake RV2<br>Conc cylinder | -18.0 | 18.3  | 0.80 |     | Vitali and Rao, 1984b |
|                                           |            |                            | -14.0 | 10.6  | 0.81 |     |                       |
|                                           |            |                            | -10.0 | 7.1   | 0.79 |     |                       |
|                                           |            |                            | -5.0  | 4.9   | 0.78 |     |                       |
|                                           |            |                            | 0.0   | 3.2   | 0.79 |     |                       |
|                                           |            |                            | 10.0  | 1.6   | 0.79 |     |                       |
|                                           |            |                            | 20.0  | 0.7   | 0.83 |     |                       |
|                                           |            |                            | 30.0  | 0.4   | 0.82 |     |                       |
| Valencia orange<br>21.2% pulp             | 65.3 Brix  |                            | -18.3 | 109.9 | 0.55 |     |                       |
|                                           |            |                            | -14.2 | 59.7  | 0.61 |     |                       |
|                                           |            |                            | -9.7  | 40.6  | 0.60 |     |                       |
|                                           |            |                            | -5.1  | 24.5  | 0.63 |     |                       |
|                                           |            |                            | -0.4  | 18.5  | 0.62 |     |                       |
|                                           |            |                            | 10.2  | 8.3   | 0.65 |     |                       |
|                                           |            |                            | 19.7  | 6.1   | 0.61 |     |                       |
|                                           |            |                            | 29.6  | 2.5   | 0.68 |     |                       |

**Table 1. SI and equivalent rheometric units.**

| Quantity            | SI Units                         | Equivalent CGS Units                                           |
|---------------------|----------------------------------|----------------------------------------------------------------|
| viscosity           | Pa • s                           | 10 P (poise) or 1000 cP (centipoise)                           |
| kinematic viscosity | m <sup>2</sup> • s <sup>-1</sup> | 10 <sup>4</sup> St (stoke) or 10 <sup>6</sup> cSt (centistoke) |
| shear stress        | Pa                               | 0.1 dyn • cm <sup>-2</sup>                                     |
| strain              | unitless                         |                                                                |
| shear rate          | s <sup>-1</sup>                  | s <sup>-1</sup>                                                |
| modulus             | Pa                               | 0.1 dyn • cm <sup>-2</sup>                                     |
| compliance          | Pa <sup>-1</sup>                 | 10 cm <sup>2</sup> • dyn <sup>-1</sup>                         |
| frequency           | Hz                               |                                                                |
| angular frequency   | 2 • f                            |                                                                |
| phase angle         | rad                              |                                                                |

**Table 2. SI derived units expressed in terms of SI base units.**

| Symbol | Special Name | Other SI Units      | SI Base Units                          |
|--------|--------------|---------------------|----------------------------------------|
| Pa     | Pascal       | N • m <sup>-2</sup> | kg • m <sup>-1</sup> • s <sup>-2</sup> |
| Hz     | Hertz        |                     | s <sup>-1</sup>                        |
| rad    | radian       |                     | m • m <sup>-1</sup> =1                 |