Food Engineering Unit-1

Food engineering is a significant component of the typical curriculum for undergraduate degree in Food Science or food technology. Food engineering is integral and significant component to understand theoretical aspects of food processing into practical implications.
Physics, chemistry, and mathematics are essential in gaining an understanding of the principles that govern most of the unit operations commonly found in the food industry. Foods undergo changes as a result of processing; such changes may be physical, chemical, enzymatic, or microbiological. As a food engineering student it is essential to understand the quantitative analysis of unit operations, and therefore your ability to use/apply mathematics is essential. The basic concept of units and its implications is highly significant for learning various aspects of food engineering.

This module is divided into following sub-sections.

<u>Contents</u>

(1) Concept of Unit Operations

In all the processing industries such as food, biological and chemical, there exist similarities where feed is processed into final products. These processing steps could be chemical, physical, biological, or in combination and are usually separate and distinct steps called unit operations.

Classification of Unit Operations

Unit Operations can be classified as follows:

Fluid flow: Deals with principles that determines flow or transportation of fluid (from one point to other)

Heat transfer: Deals with principles that govern accumulation and transfer of heat and energy

Evaporation: Special case of heat transfer, which deals with evaporation of a constituent from a solution

Drying: Operation where volatile liquids, usually water, are removed from solid materials

Distillation: Operation where components of a liquid mixture are separated by boiling based on vapor pressure difference.

Absorption: Process in which a component is removed from a gas stream by liquid treatment

Membrane separation: Process involving separation of a solute from a fluid by diffusion of this solute from a liquid or gas through semipermeable membrane barrier to another fluid

Liquid-Liquid extraction: Process where a solute in a liquid solution is removed by contacting with another liquid solvent which is relatively immiscible with the solution

Adsorption: Process where a component of a gas or a liquid stream is removed and adsorbed by a solid adsorbent.

Liquid-solid leaching: Process where a finely divided solid is treated with liquid that dissolves out and removes a solute contained in the solid

Crystallization: Removal of a solute such as a salt from a solution by precipitating the solute from the solution

Mechanical-physical separations: Involves separation of solids, liquids or gases by mechanical means, such as filtration, settling, and size reduction, which are often classified as separate unit operations.

(2) SI System of Basic Units

To analyze and quantify physical processes/unit operations, understanding units and dimensions of the physical quantities becomes essential.

There are three main basic unit systems employed in engineering and science.

1. **SI** (Système International d'Unités, French; International System of Units, English)

   Three basic units (i) the meter (m), (ii) the kilogram (Kg), and (iii) the second (s)

2. **FPS** system

   Three basic units (i) foot (ft) (ii) pound (lb) and (iii) second (s)

3. **CGS** system

   Three basic units (i) centimeter (cm) (ii) gram (gm) and (iii) second (s)

Presently SI, system has been adopted officially for exclusive use in engineering and science.

Table 1: SI Base and Supplementary Quantities and Units

Quantity or "dimension"	SI unit	SI unit symbol ("abbreviation")
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol

Derived Units of SI that Have Special Names

Derived units are algebraic combinations of base units expressed by means of multiplication and division. For simplicity, derived units often carry special names and symbols that may be used to obtain other derived units.

Table 2: Derived Units

Quantity	SI unit	Symbol	Formula
frequency (of a periodic phenomenon)	hertz	Hz	l/s
force	newton	N	$(kg·m)/s^2$
pressure, stress	pascal	Pa	N/m^2
energy, work, quantity of heat	joule	J	N·m
power, radiant flux	watt	W	J/s

Table 3: Additional Common Derived Units of SI

Quantity	Unit	Symbol
acceleration	meter per second squared	m/s^2
angular acceleration	radian per second squared	rad/s^2
angular velocity	radian per second	rad/s
area	square meter	m^2
concentration (of amount of substance)	mole per cubic meter	mol/m^3
density	mass kilogram per cubic meter	kg/m^3
velocity	meter per second	m/s
viscosity, dynamic	pascal-second	Pa·s
viscosity, kinematic	square meter per second	m^2/s
volume	cubic meter	m^3
entropy	joule per kelvin	J/K
heat capacity	joule per kelvin	J/K

(3) Common Units and Conversion Factors

Unit conversion is a multi-step process that involves multiplication or division by a numerical factor.
For instance 12 feet 5 inches in converted to inches as follows
As 1 foot = 12 inches
12 feet = 12 x 12 inches = 144 inches
Hence 12 feet 5 inches = (144 + 5) inches = 149 inches

Table 4: Some of the common conversion factors

Mass (M)	1 pound mass = 453.5924 grams = 0.45359 kilograms = 7000 grains 1 slug = 32.174 pounds mass 1 ton (short) = 2000 pounds mass 1 ton (long) = 2240 pounds mass 1 ton (metric) = 1000 kilograms = 2204.62 pounds mass 1 pound mole = 453.59 gram moles
Length (L)	1 foot = 30.480 centimeters = 0.3048 meters 1 inch = 2.54 centimeters = 0.0254 meters 1 mile (U.S.) = 1.60935 kilometers 1 yard = 0.9144 meters
Area (L^2)	1 square foot = 929.0304 square centimeters = 0.09290304 square meters 1 square inch = 6.4516 square centimeters 1 square yard = 0.836127 square meters
Volume (L^3)	1 cubic foot = 28,316.85 cubic centimeters = 0.02831685 cubic meters = 28.31685 liters = 7.481 gallons (U.S.) 1 gallon = 3.7853 liters = 231 cubic inches
Time (θ)	1 hour = 60 minutes = 3600 seconds
Temperature (T)	1 centigrade or Celsius degree = 1.8 Fahrenheit degree Temperature, Kelvin = T°C + 273.15 Temperature, Rankine = T°F + 459.7 Temperature, Fahrenheit = 9/5 T°C + 32 Temperature, centigrade or Celsius = 5/9 (T°F − 32) Temperature, Rankine = 1.8 T K

Force (F)	1 pound force = 444,822.2 dynes = 4.448222 Newtons = 32.174 poundals
Pressure (F/L^2)	Normal atmospheric pressure 1 atm = 760 millimeters of mercury at 0°C (density 13.5951 g/cm^3) = 29.921 inches of mercury at 32°F = 14.696 pounds force/square inch = 33.899 feet of water at 39.1°F = 1.01325×10^6 dynes/square centimeter = 1.01325×10^5 Newtons/square meter
Density (M/L^3)	1 pound mass/cubic foot = 0.01601846 grams/cubic centimeter = 16.01846 kilogram/cubic meter
Energy (H or FL)	1 British thermal unit= 251.98 calories = 1054.4 joules = 777.97 foot-pounds force = 10.409 liter-atmospheres = 0.2930 watt-hour
Gas constant	1.987 Btu/lbm mole °R = 1.987 cal/mol K = 82.057 atm cm3/mol K = 0.7302 atm ft3/lb mole °F = 10.73 (lb*f* /in.2) (ft3)/lb mole °R = 1545 (lb*f* /ft2) (ft3)/lb mole °R = 8.314 (N/m2) (m3)/mol K

(4) Dimensional Analysis

Dimensional analysis is a tool to represent the relevant data and how to depict the same. It is a useful technique for experiment based engineering fields. It is a means of simplifying a physical problem by appealing to dimensional homogeneity to reduce the number of relevant variables.

(4.1)Dimensional Analysis is particularly useful for:

- presenting and interpreting experimental data
- attacking problems not amenable to a direct theoretical solution
- checking equations
- establishing the relative importance of particular physical phenomena
- physical modelling

In dimensional analysis we are only concerned with the nature of the dimension i.e. its quality not its quantity. The following common abbreviation used are:

length = L
mass = M
time = T
temperature = θ

We can represent all the physical properties we are interested in with L, M and T.

The following table lists dimensions of some common physical quantities:

Table 5: Representation of physical quantities in L, M, T dimensions

Quantity	SI Unit	SI Unit	Dimension
velocity	m/s	ms^{-1}	LT^{-1}
acceleration	m/s^2	ms^{-2}	LT^{-2}
force	N $kg\ m/s^2$	$kg\ ms^{-2}$	$M\ LT^{-2}$
energy (or work)	Joule J N m, $kg\ m^2/s^2$	$kg\ m^2s^{-2}$	ML^2T^{-2}
power	Watt W N m/s $kg\ m^2/s^3$	Nms^{-1} $kg\ m^2s^{-3}$	ML^2T^{-3}
pressure (or stress)	Pascal P, N/m^2, $kg/m/s^2$	Nm^{-2} $kg\ m^{-1}s^{-2}$	$ML^{-1}T^{-2}$
density	kg/m^3	$kg\ m^{-3}$	ML^{-3}
specific weight	N/m^3 $kg/m^2/s^2$	$kg\ m^{-2}s^{-2}$	$ML^{-2}T^{-2}$
relative density	a ratio no units		1 no dimension
viscosity	$N\ s/m^2$ kg/m s	$N\ sm^{-2}$ $kg\ m^{-1}s^{-1}$	$M\ L^{-1}T^{-1}$
surface tension	N/m $kg\ /s^2$	Nm^{-1} $kg\ s^{-2}$	MT^{-2}

(4.2) Dimensional Homogeneity

Any equation describing a physical situation will only be true if both sides have the same dimensions. That is it must be **dimensionally homogenous**.

For example the Bernoulli's equation:

$$p + \frac{1}{2}\rho V^2 + \rho g h = \text{constant}$$

Where p is the pressure, ρ is the density, V is the velocity, h is the elevation and g is the gravitational acceleration

The SI units for each term on the left hand side should be consistent and equal.

$P = ML^{-1}T^{-2}$

$\rho V^2 = ML^{-3}\,(LT^{-1})^2 = ML^{-3+2}T^{-2} = ML^{-1}T^{-2}$

$\rho gh = ML^{-3}\,LT^{-2}\,L = ML^{-3+2}T^{-2} = \; = ML^{-1}T^{-2}$

The units of the right hand side must be the same. Hence the constant will also have dimensions of $ML^{-1}T^{-2}$

i.e. the units are consistent.

Dimensional homogeneity is a useful tool for **checking** formulae. For this reason, it is useful when analyzing a physical problem to retain algebraic symbols for as long as possible, only substituting numbers right at the end. However, dimensional analysis cannot determine numerical factors; e.g. it cannot distinguish between $\frac{1}{2}at^2$ and at^2

This property of dimensional homogeneity can be useful for:

- Checking units of equations
- Converting between two sets of units
- Defining dimensionless relationships

(5) CONSERVATION OF MASS

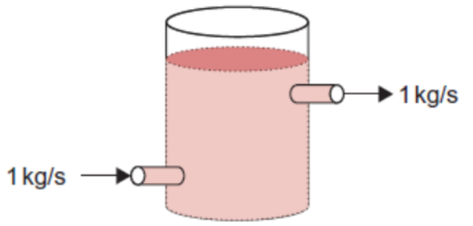
The principle of conservation of mass states that: Mass can be neither created nor destroyed. However, its composition can be altered from one form to another.

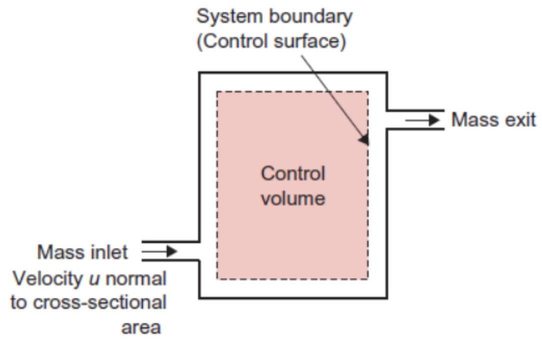
Conservation of mass principle

Rate of mass entering through the boundary of a system	-	Rate of mass exiting through the boundary of a system	=	Rate of mass accumulation within the system

-------- Eq. 1.1

	If the rate of mass accumulation within a system is zero, then the rate of mass entering must equal rate of mass leaving the system. For example, as shown in Figure 1.1, if the level of milk in a tank remains constant, and the milk flow rate at the inlet is 1 kg/s, then the flow rate of milk at the exit must also be 1

 Fig. 1.1: Liquid flow in and out of a tank	kg/s.

 Fig. 1.2: A Control volume	Next, let us convert the previous word equation into a mathematical form. To do this, we will refer to Figure 1.2, which shows a system with mass inlet and exit streams. Although only one inlet and one exit stream is shown, there may be more than one stream entering and exiting a control volume. Therefore, for a general case, the rate of mass flow entering the system is $$\dot{m}_{inlet} = \sum_{i=1}^{n} \dot{m}_i \qquad \text{Eq. 1.2}$$

where subscript ***i*** denotes the inlet, and ***n*** is the number of inlets to a system. The rate of mass flow exiting the system is

$$\dot{m}_{exit} = \sum_{e=1}^{p} \dot{m}_e \qquad \text{Eq. 1.3}$$

where subscript ***e*** denotes the exit, and ***p*** is the number of exits from a system. The rate of mass accumulation within the system boundary, expressed as a function of time, is

$$\dot{m}_{accumulation} = \frac{dm_{system}}{dt} \qquad \text{Eq. 1.4}$$

Then substituting into the word we obtain Equation (1.1)

$$\sum_{i=1}^{n} \dot{m}_i - \sum_{e=1}^{p} \dot{m}_e = \frac{dm_{system}}{dt} \qquad \text{Eq. 1.5}$$

Typically, mass flow rate is easier to measure than other flow properties such as velocity. When instead of mass flow rate, we may measure velocity of the flow along with the density of the fluid, the mathematical analysis involves integral expressions. There are two systems for conservation of mass i.e Open system and closed system .Let's discuss them now

(5.1) Conservation of Mass for an Open System

Consider a section of a pipe used in transporting a fluid. For a control volume shown, for this open system a fluid with a velocity, ***u***, is entering the system across a differential area ***dA***. Velocity is a vector quantity, possessing both magnitude and direction. As seen in Figure 1.2, only the component of velocity vector normal to the area ***d***A will cross the system boundary. The other component, $\boldsymbol{u_{tan}}$, (tangent to the area) has no influence on our derivation. Thus, if the fluid particle crossing the boundary has a velocity $\boldsymbol{u_n}$, then the rate of mass flow into the system may be expressed as

$$d\dot{m} = \rho u_n dA \qquad \text{Eq. 1.6}$$

Integrating over a finite area

$$\dot{m} = \int_A \rho u_n dA \qquad \text{Eq. 1.7}$$

The previous equation for mass flow rate will apply for inlet and exit cases. The total mass of the system may be expressed as a product of its volume and density, or

$$m = \int_V \rho dV \qquad \text{Eq. 1.8}$$

Substituting this quantity in the word Equation (1.1), we obtain

$$\int_{A_{inlet}} \rho u_n dA - \int_{A_{exit}} \rho u_n dA = \frac{d}{dt}\int_V \rho dV \qquad \text{Eq. 1.9}$$

The previous equation is somewhat complicated because of the integral and differential operators. However, this expression may be simplified for two common situations encountered in engineering systems. First, if the flow is uniform, then all measurable properties of the fluid are uniform throughout the cross-sectional area. These properties may vary from one cross-sectional area to another, but at the same cross-section they are the same in the radial direction.

For example, fruit juice flowing in a pipe has the same value of its properties at the center and the inside surface of the pipe. These properties may be density, pressure, or temperature. For a uniform flow, we can replace the integral signs with simple summations, or

$$\sum_{inlet} \rho u_n dA - \sum_{outlet} \rho u_n dA = \frac{d}{dt} \int_V \rho dV \qquad \text{Eq. 1.10}$$

The second assumption we will make is that of steady state—that is, the flow rate does not change with time, although it may be different from one location to another. If there is no change with time, then the right-hand term must drop out. Thus, we have

$$\sum_{inlet} \rho u_n dA = \sum_{outlet} \rho u_n dA \qquad \text{Eq. 1.11}$$

Furthermore, if we are dealing with an incompressible fluid—a good assumption for most liquids—there is no change in density. Thus

$$\sum_{inlet} u_n dA = \sum_{outlet} u_n dA \qquad \text{Eq. 1.12}$$

The product of velocity and area is the volumetric flow rate. Thus, according to the conservation of mass principle, for a steady, uniform, and incompressible flow, the volumetric flow remains unchanged. For compressible fluids such as steam and gases, the inlet mass flow rate will be the same as the exit mass flow rate.

(5.2) Conservation of Mass for a Closed System

We have learnt that, in a closed system, mass cannot cross system boundaries. Therefore, there is no time rate of change of mass in the system, or

$$\frac{dm_{system}}{dt} = 0 \qquad \text{Eq. 1.13}$$

$$m_{system} = \text{constant}$$

(5.3) Material Balances

Material balances are useful in evaluating individual pieces of equipment, such as a pump or a homogenizer, as well as overall plant operations consisting of several processing units—for example, a tomato paste manufacturing. Compositions of raw-materials, product streams, and by-product streams can be evaluated by using material balances.

The following steps should be useful in conducting a material balance in an organized manner.

1. Collect all known data on mass and composition of all inlet and exit streams from the statement of the problem.
2. Draw a block diagram, indicating the process, with inlet and exit streams properly identified. Draw the system boundary.
3. Write all available data on the block diagram.
4. Select a suitable basis (such as mass or time) for calculations. The selection of basis depends on the convenience of computations.
5. Using Equation (1.5), write material balances in terms of the selected basis for calculating unknowns. For each unknown, an independent material balance is required.
6. Solve material balances to determine the unknowns.

(1) Conservation of Energy

Conservation of energy and energy balances are based on laws of thermodynamics.

First Law: Energy can be neither created nor destroyed but can be transformed from one form to another.
Second Law: No process is possible whose sole result is the abstraction of heat from a single reservoir and the performance of an equivalent amount of work.

These concepts are dealt in detail in an exclusive thermodynamics course and not under the purview of present module.

Energy Balance is based on first law of thermodynamics and is depicted as follows

Total energy entering the system	-	Total energy exiting the system	=	Change in total energy of the system

Therefore, when a system is undergoing any process, the energy entering the system minus that leaving the system must equal any change in the energy of the system, or

$$E_{in} - E_{out} = \Delta E_{system}$$

We can also write the energy balance per unit time as a rate expression:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}$$

Heat transfer between a system and its surroundings is probably the most prevalent form of energy that we observe in many food engineering systems. Heat plays a major role in cooking, preservation, and creating new food products with unique properties. We will denote heat with a symbol Q, with units of joule (J). If heat transfer is from a system to its surroundings, then Q is negative. On the other hand, if heat is transferring into a system from its surroundings (such as in heating of a potato), then heat transfer Q is positive.

If we consider heat transfer per unit time, then we express it as rate of heat transfer, q, with the units J/s or watts (W). Thermal energy, Q, can be determined if the heat capacity c is known. Thus,

$$Q = m\int_{T_1}^{T_2} c\,dT$$

If the path for energy transfer is under constant pressure, then

$$Q = m\int_{T_1}^{T_2} c_p\,dT$$

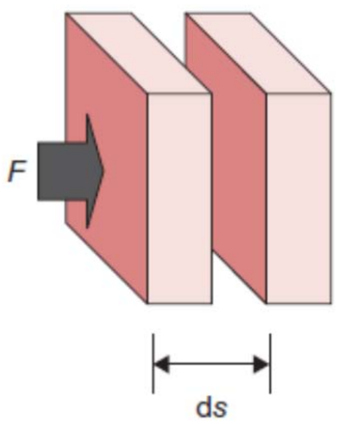
where c_p is the specific heat capacity at constant pressure, J/(kg K). Under constant volume conditions,

$$Q = m\int_{T_1}^{T_2} c_v\,dT$$

where c_v is the specific heat capacity at constant volume, J/(kg K). The numeric values of c_p and c_v are similar for solids and liquids; however, they may be considerably different for gases.

Work encompasses all interactions between a system and its surroundings that are not a result of temperature difference. Eg: Shaft transmitting energy from a motor to another piece of equipment that is enclosed in the system boundary

The symbol used for work is W, and its units are joules (J). The sign convention used for work (W) is that any time work is done by a system, W is positive; when work is done on a system, W is negative. This is opposite to that of heat transfer.



As shown in Figure 1.3, consider a case where an object moves a small distance ds due to the application of force ***F***. The work done on the system may then be calculated as the product of force and distance, or

$$dW = -Fds$$

The negative sign reflects the sign convention stated earlier. We can calculate the total work done in moving the object from location 1 to 2 as

$$W_{1-2} = -\int_{1}^{2} Fds = F(s_1 - s_2)$$

Fig. 1.3: Work associated with movement of an object.	The work interaction between a system and its surroundings can be attributed to several mechanisms, such as a moving boundary, gravitational forces, acceleration, and shaft rotation.