Applied Food Engineering

Managing Editors

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Foreword

The digital age has its preferences. The reading time has been encroached upon by a watching time. The access to information is easy and a plenty where Wikipedia has emerged as the most powerful encyclopedia ever. Yet, a book is a book! We wish to promote the habit of reading books. Finding books is not difficult or expensive (www.pdfdrive.com) but a local context and indigenous experiences could be missing.

The University of Agriculture, Faisalabad (UAF) has achieved global rankings of its flagship programs and acceptance as a leader in the field of agriculture and allied sciences. A competent faculty, the stimulating ecosystem and its learning environment have increasing attention. Publication of books is an important KPI for any institution of higher learning. Hence, UAF has embarked upon an ambitious ‘books project’ to provide reference texts and to occupy our space as a knowledge powerhouse. It is intended that the UAF books shall be made available in both paper and electronic versions for a wider reach and affordability.

UAF offers more than 160-degree programs where agriculture remains our priority. There are about 20 institutions other than UAF who are also offering similar degree programs. Yet, there is no strong history of indigenously produced text/reference books that students and scholars could access. The last major effort dates back to the early 1990’s when a USAID funded TIPAN project produced a few multiauthor text books. Those books are now obsoleted but still in demand because of lack of alternatives. The knowledge explosion simply demands that we undertake and expand the process anew.

Considering the significance of this project, I have personally overseen the entire process of short listing of the topics, assemblage of authors, review of contents and editorial work of 29 books being written in the first phase of this project. Each book has editor(s) who worked with a group of authors writing chapters of their choice and expertise. The draft texts were peer reviewed and language corrected as much as possible. There was a considerable consultation and revision undertaken before the final drafts were accepted for formatting and printing process.

This series of books cover a very broad range of subjects from theoretical physics and electronic image processing to hard core agricultural subjects and public policy. It is my considered opinion that the books produced here will find a wide acceptance across the country and overseas. That will serve a very important purpose of improving quality of teaching and learning. The reference texts will also be equally valued by the researchers and enthusiastic practitioners. Hopefully, this is a beginning of unleashing the knowledge potential of UAF which shall be continued. It is my dream to open a bookshop at UAF like the ones that we find in highly ranked universities across the globe.

Food engineering has recently emerged as a new interdisciplinary field that applies apply fundamental engineering principles for designing and operating the food processing equipment. The UAF is the pioneer to offer degree program in this discipline to cater the needs of growing food industry in the country. This book highlights the fundamental concepts, thermodynamics, transport phenomenon, and mathematically interpreted united operations, which are prerequisite of this quantitative discipline.

Before concluding, I wish to record my appreciation for my coworker Dr. Muhammad Farooq who worked skillfully and tirelessly towards achieving a daunting task. Equally important was the contribution of the authors and editors of this book. I also acknowledge the financial support for this project provided by the USDA endowment fund available to UAF.

Iqrar Ahmad Khan

Preface

Food Engineering is new field in Pakistan for teaching and research compared to food technology. Food engineering deals with the principle of thermodynamics to understand the process for food product and new technology development. These principles are famous in various fields of engineering i.e. chemical engineering, bioprocess engineering, etc. These fields have various books that illustrate these principles and have examples from chemical reactions and processes. These existing books of this discipline do not provide the basic concepts to food engineers and are not easily understandable.

Therefore, this book has been specifically developed for the students in the discipline of food engineering as a reference book. It contains fundamental engineering principles and how they can be applied to solve the daily life problems in food industries. This book will cover the needs of food engineers regarding basic concepts, principles and applications.

In a food industry, a series of unit of operations are required to develop or produce a food product. These operations can influence the final quality and shelf life of the product. In this book, engineering principles are described in such way that students can easily understand them and apply in food industry for proper running of the process. Besides, influence of these operations on food properties discussion is made on the techniques to reduce the waste production in the processing lines. Moreover, various new processing methods like membrane separation have been introduced.

The physical properties of food material that influence the shelf life and sensorial attributes of food product. These parameters have been discussed in detail according to engineering aspects. It will stimulate students to develop the technology/ process without influencing the physical parameters. Besides, various preservation principles have been elaborated that may be the basic for the development of a sustainable preservation technology. This book will encourage the development of sustainable food technology and products.

At the end, we would like to thank all who contributed and helped for the improvement of this book.

Muhammad Kashif Iqbal Khan

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Chapter 1

Introduction

Muhammad Iqbal and Muhammad Azam Khan[*]

Abstract

For comprehensive understanding, food engineering needs a strong background of primary sciences. Food undergoes various changes during a process that may include physical, chemical or biological. Often, it is essential to understand the kinetics of chemical or enzymatic changes. Thus, the knowledge of chemistry, physics and mathematics is essential component for food engineering field. It will ease in designing and analysing the food process to improve efficiency and develop a novel food product. This chapter summarizes the essential physical and chemical concepts related to the field of food engineering.

Keywords: Dimensions, Pressure, Moisture contents, Energy

1.1. Dimensions

A physical quantity that can be measured or observed is represented quantitatively through dimension e.g. time, area, length etc. These dimensions include length [L], mass [M], time [t], temperature [T], electric current [I], Luminous intensity [J] and amount of a substance [N]. Each dimension is represented by a symbol which is, conventionally, enclosed in a square bracket. The dimensions are measured in terms of units. A unit can be defined as definite magnitude of a physical quantity.

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Basic units in measurement system include meter (m for length), kilogram (kg for mass), kelvin or Celsius (K or ºC for temperature), second (s for time), ampere (A for electric current), candela (cd for luminous intensity) and mole (mol for amount of a substance). Some of the units are the product of various mathematical combinations of basic units known as derived units. Most commonly used derived units are as follows:

Area: It is the product of two lengths of a substance (width and length for a rectangular shape) and (for a circular shape, it is calculated through πr^2).

$$A = [L]\times[L] = m^2$$

Volume: It is the product of three lengths of the space under consideration e.g., (width) × (length) × (height).

$$V = [L] \times [L] \times [L] = m^3$$

Density: Mass per unit volume of a product/material is called its density.

$$\rho = [M]/[V] = kg/m^3$$

Velocity: Distance travelled per unit time in a specific direction is called velocity.

$$v = [L]/[t] = m/s$$

Acceleration: Rate of change of velocity is called acceleration.

$$a = [L]/[t] \times 1/[t] = (m/s) \times (1/s) = m/s^2$$

Momentum: The product of mass of an object having velocity v is known as (linear) momentum.

$$p = [M] \times [v] = kg\ m/s \text{ or } Ns$$

Force: The product of mass and acceleration is called force.

$$\begin{aligned} F &= [M] \times [a] \\ &= kg\ m/s^2 \text{ or } N \end{aligned}$$

Pressure: Force applied per unit area is called pressure.

$$P = [F]/[A] = N/m^2 = Pa$$

Units used for engineering measurements and calculations should be selected from a consistent group. System International (SI) units is internationally accepted and has been adopted by many countries. Apart from SI system, fps (foot pound second) system is also commonly used. Measurements are sometimes made in mixed units e.g. in a dairy processing plant, milk flows through the pasteurizer at a rate of 100 L/min for 15 h. Here, both minute and hour are the units of time and should be put only as minutes, hours or seconds to proceed with calculations. Conversion tables can be used for conversion of units when available data is in nonstandard units.

1.2. Systems of Measuring Units

Physical quantities are measured through various unit systems that may include English system, CGS system and MKS System (Table 1.1). These systems create confusion which has been eliminated through the development of SI units. It consists of seven base units, supplementary units, and a series of derived units.

Table 1.1 An Overview of Various Measurements Systems

Units		Systems of units			
		FPS	**CGS**	**MKS**	**SI**
Primary	Length	Foot	Centimetre	meter	Meter
	Mass	Slug	Gram	kilogram	kilogram
	Time	Second	Second	second	second
Secondary	Acceleration	ft/s^2	cm/s^2	m/s^2	m/s^2
	Force	Ibf	Dyne	Newton	Newton
	Velocity	ft/s	cm/s	m/s	m/s

1.2.1. Base units

The SI system consists of seven well defined dimensionally independent units. These units are defined as follows:

Meter: It is a unit of length that is equal to 1,650,763.73 wavelengths of the krypton 86 atom in vacuum.

Kilogram: It is unit of mass, which is equal to the mass of platinum-iridium alloy cylinder. This alloy is preserved in a vault at Sevres, France, by the International Bureau of Weights and Measures.

Second: It is a unit of time that is the duration of 9,192,631,770 periods of radiation of the cesium-133 atom.

Ampere: It is a unit of electric current. It is the constant current maintained in two straight parallel conductors having infinite length and negligible circular cross-sectional area.

Kelvin: It is a unit of temperature and denoted as K. It is the fraction (1/273.16) of the thermodynamic temperature regarding the triple point of water.

Mole: It is unit of amount and denoted as mol. It is the amount that contains the elementary entities equal to the atoms in 0.012 kg of carbon 12.

Candela: It is the unit of luminous intensity and denoted as cd. It is the intensity of a black surface having surface area 1/600,000 m^2. These base units in SI system are presented in Table 1.2.

Table 1.2 Primary units of physical quantities in SI system

Physical quantity	Name	Symbol
Electric current	Ampere	A
Intensity of light	Candela	Cd
Length	Meter	M
Mass	Kilogram	kg
Quantitative measure of substance	Mole	mol
Temperature	Kelvin	K
Time	Second	s

1.2.2. Derived Units

These units are the combinations of base units, which result of either division or multiplication process of base units. A list of frequently used derived units (Table 1.3) are described as below:

Newton: The amount of force needed to accelerate a mass of one kilo-gram with rate of one ms^{-2} (1 N = 1 kg × 1 ms^{-2}).

Joule: The quantity of work done by a force of one newton through a distance of one meter in the same direction. It can be expressed as under;

$$
\begin{aligned}
\text{I J} &= \text{N} \times \text{m} \\
&= 1\ \text{kg} \times 1\ \text{ms}^{-2} \times 1\ \text{m} \\
&= 1\ \text{kgm}^2/\text{s}^2
\end{aligned}
$$

Watt: Amount of power to produce energy at the rate of one joule per second.

$$\text{W} = \text{J/s}$$

Volt (V): The variation in the electricity potential between two points of a conducting wire carrying a constant current of one ampere (A), with one-watt (W) power dissipation between the selected points.

Ohm (Ω): It is an electrical resistance between two points of a substance that have a constant potential difference of one volt.

Coulomb (C): The quantity of electricity conveyed by a current of one ampere during a time interval of one second.

Farad (F): The capacitance quantity of a capacitor for a potential difference of one volt between two plates having equal charge of one coulomb.

Table 1.3 Few examples of derived units in the system of international units

Physical Quantity	**Name**	**Symbol**	**SI units**
Area	Square length	L^2	m^2
Capacitance	Farad	F	C/V
Conductance	Siemens	s	A/V
Density	Mass per unit volume	M/L^3	kgm^3
Dynamic viscosity	Pascal second	Pas	Nm^{-2} s
Electric charge	Columb	C	As
Electric resistance	Ohm		V/A
Electricity potential	Volt	V	W/A
Force	Newton	N	$mkgs^{-2}$
Frequency	Hertz	Hz	s^{-1}
Heat, work, energy	Joule	J	Nm
Illuminance	lux	lx	Lm/m^2
Luminance	Candela per square meter	Cd/L^2	Cd/m^2
Moment of a force	Newton meter	Nm	$Kg\ m^2\ s^{-2}$
Radiant flux, power	Watt	W	J/s
Stress or pressure	Pascal	Pa	N/m^2
Velocity	Distance per unit time	L/T	m/s
Volume	Cubic length	L^3	m^3

Example 1.1

Convert the followings in SI units:

Density = 70 $Ibmft^{-3} \times kg/m^3$?

Energy = 2 BTU into kJ?

Enthalpy = 2800 BTU/lb into kJ/kg?

Pressure = 20 psig into kPa?

Viscosity = 20 cp into Pas?

Solution

Density = 70 Ibm/ft^{3}

= [(70 lbm)/ft^{3}] (0.45359 kg)/Ibm. (1ft/ (0.3048 m))^{3}

= 104.1709 kg/m^{3}

Energy = 2 BTU

= [2 BTU]. (1.055 kJ)/ (1 BTU)

= 2.11 kJ

Enthalpy = 2800 BTU/lb

= [(2800 BTU)/lb] × (1.055 kJ/1BTU) × (1lb/0.45359kg)

= 6512.48 kJ/kg

Pressure = 20 psig

First, convert psig into psia as:

= [(20 Ib)/in^{2}] +14.69

= 34.69 psia.

Then convert psia into SI units as:

= [(34.69 Ib)/in^{2}] × (4.4482 N/Ib) × (1in / 0.0254 m)^{2} × [1Pa / (1N/m$^{2)}$]

= 23917 Pa = 239.17 kPa

Viscosity = 20 cp

= [20 cp] (0.001 Pa. s)/1cp

=0.02 Pas

1.3. System

It is a defined region in space or a fixed extent of matter enclosed through a boundary. These boundaries may be real (walls of a milk silo or house), or these can be imaginary surfaces that encircle the systems. Moreover, it can be moveable (piston, valve) or stationary (silos). The components present in the boundary describe the composition of a system. Once the boundaries of a system are chosen; the exterior of a system is converted into surroundings. A system can be classified into open (boundary of the system is vulnerable to flow of mass & heat) or closed (flow of mass is impervious). The closed systems cannot exchange mass with surroundings, however, heat exchange may occur. Similarly, a system (either closed or open) do not exchanged heat with surrounding is known as adiabatic system. Moreover, some systems do not exchange heat, mass or work with surrounding and known as isolated systems.

A process that occurs at constant temperature with exchange of heat is called as isothermal system. The state of a system describes the equilibrium conditions that help to understand about a system. State of a system can be described through the properties these can be divided into intensive and extensive categories. Extensive properties depend on the size and shape of system e.g. length, volume, energy etc. While intensive properties do not depend on size or shape. Some of these properties are discussed in the following sections.

1.4. Density

Density of a substance is mass per unit volume (kg/m^3) and an indication about the composition of a system. Density of a system depends upon the space occupied by pores. Naturally, loosely packed substance has low density compared to compact substance. Thus, density is divided into three types; bulk density, solid density and particle density. Bulk density includes the solids and all the voids (pore spaces) of a substance (Fig. 1.1). It is the property of food powders, granules and minerals (for details see chapter 2).

Bulk density may be written in mathematical model as below:

$$Bulk\ density = \frac{Mass_{total}}{Volume_{total}} \tag{1.1}$$

The bulk density of void space (space occupied by air and water), particle density and solid density are derived as below:

$$Porosity\ = V_{voids}/V_{total} \tag{1.2}$$

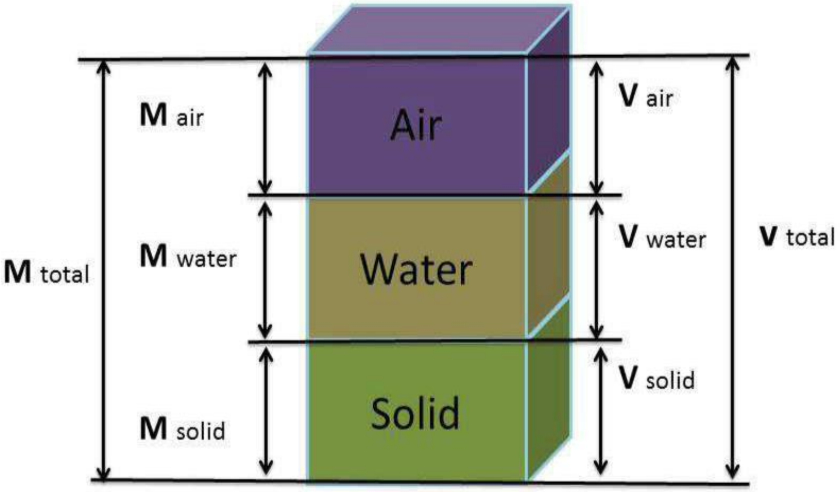

Fig. 1.1 Schematic diagram of food material as a three-phase system

1.5. Concentration of a Substance

It is the quantity of material occupied by a unit volume. Generally, it is expressed in following different forms:

Weigh by weight (w/w) or percentage: For example, a food containing 30% protein indicates that every 100 g of that food will contain 30 g of protein.

Weight by volume(w/v): It is also known as molarity form of representation. It is mass of a solute dissolved in a one litre (unit volume) of solvent e.g., 10 g salt dissolved in one-liter water. It may also be expressed in molar or molarity. A dimensionless expression is known as mole fraction (X_c) may defined as moles of a substance in total mole of a system.

$$X_c = \frac{n_c}{n_a + n_b + n_c} \tag{1.3}$$

here, n_a are the number of moles of a substance A, n_b are the number of moles of a substance B and n_c are the number of moles of a substance C.

Table 1.4 Bulk Density of Various Common Food Materials

Materials	**Bulk Density (kg/m^3)**	**Materials**	**Bulk Density (kg/m^3)**
Beans, soy whole	800	Millet	640
Butter	911	Oats	410
Coconut, shredded	320 - 352	Rice rough	580
Coffee beans, green	673	Rice, hulled	750
Coffee, ground	400	Rye	720
Coffee, roasted beans	368	Wheat	770
Corn starch	540-630	Honey	1420
Rice, clean	770	Mayonnaise	910
Corn syrup	1380	Mayonnaise, light	1000
Corn, shelled	720	Milk, whole dried	320
Barley	620	Mustard seed	720
Grain corn, ear	900	Oil	920
Sugar, Sucrose	1550	Peanuts, hulled	480 - 720
Flaxseed	770	Peas, dried	800
Salt, Sodium Chloride	2165	Rapeseed	770

Table 1.5 Solid density of some food materials

Material	**Solid density (kg/m^3)**
Cellulose	1270-1610
Citric acid	1540
Fat	900-950
Glucose	1560
Protein	1400
Salt	2160
Starch	1500
Sucrose	1590
Water	1000

1.6. Moisture Content

It is the quantity of moisture/water present in a food substance. The moisture content of a food substance may be stated on dry and wet basis.

Moisture content (wet basis): It is the mass of a component (water) in per unit mass of non-dried food sample and is expressed in equation form as:

$$MC_w = \frac{w}{w_w} \tag{1.4}$$

Where, MC_w is moisture content of substance on wet weight basis, w is weight of water in the substance in g and w_w is the weight of wet sample of substance in g.

Moisture content (dry basis): It is mass of a component per unit mass of oven dried sample weight and is expressed in equation form as:

$$MC_d = \frac{w}{w_d} \tag{1.5}$$

here, MC_d represents moisture content of substance on dry weight basis, w is the mass/weight of water in the substance in g and w_d is the weight of oven dried sample of substance in g. A relationship between dry and wet moisture content is following equation.

$$MC_w = \frac{MC_d}{MC_d + 1} \tag{1.6}$$

$$MC_d = \frac{MC_w}{MC_w + 1} \tag{1.7}$$

Example 1.2 Convert wet basis moisture contents of followings on dry basis and show their relation graphically: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60%.

Solution

MC_w (%)	MC_d (%)	MC_w (%)	MC_d (%)
5	5.26	35	53.85
10	11.11	40	66.67
15	17.65	45	81.82
20	25.00	50	100.00
25	33.33	55	122.22
30	42.86	60	150.00

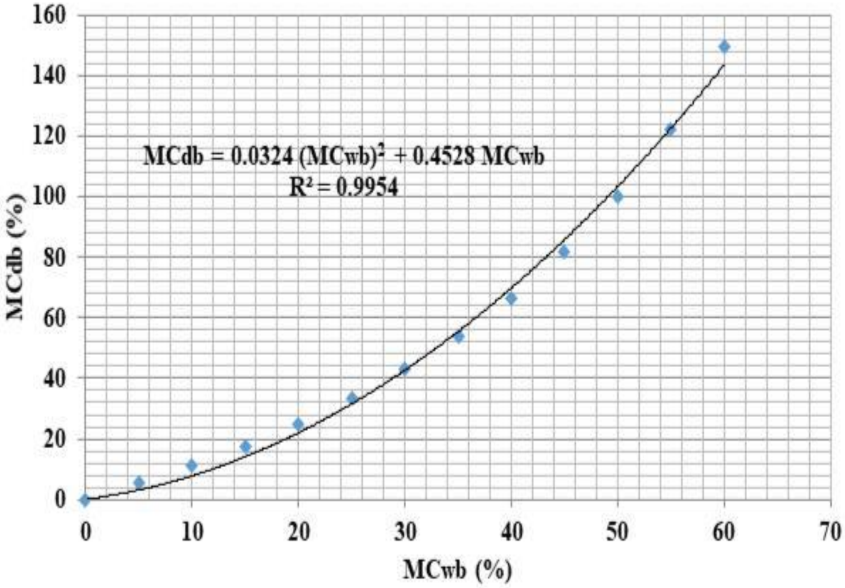

Fig. 1.2 A relationship between moisture contents on wet and dry basis

1.7. Temperature

Temperature is a measure of physiological response to hot and cold environment. The measure of temperature is a characteristic of materials owing to their sensitiveness for heat and/or coldness. It is measured in degree Celsius (°C) or degree Fahrenheit (°F) according to the SI units or English system of units, respectively. The reference point for both the systems is taken as "ice point temperature" designated as 0°C or 32°F and boiling point of water is taken as 212°F or 100°C in their respective scales. Moreover, thermodynamically independent temperature scales have been developed for standardization known as Kelvin scale with lowest temperature is 0K.

1.8. Pressure

Pressure is stated as a force exerted on a unit area of the container (Fig. 1.3) and expressed in equation form as:

$$P = dF/dA \tag{1.8}$$

here, P is the pressure, dF is the differential force perpendicular to surface area (dA). Generally, pressure exerted by a 760-mm high column of mercury is normally considered as standard pressure and known as atmospheric pressure.

1 atm = 760 mm mercury column =14.696 psi=1.01325 bar = 101.325 kPa

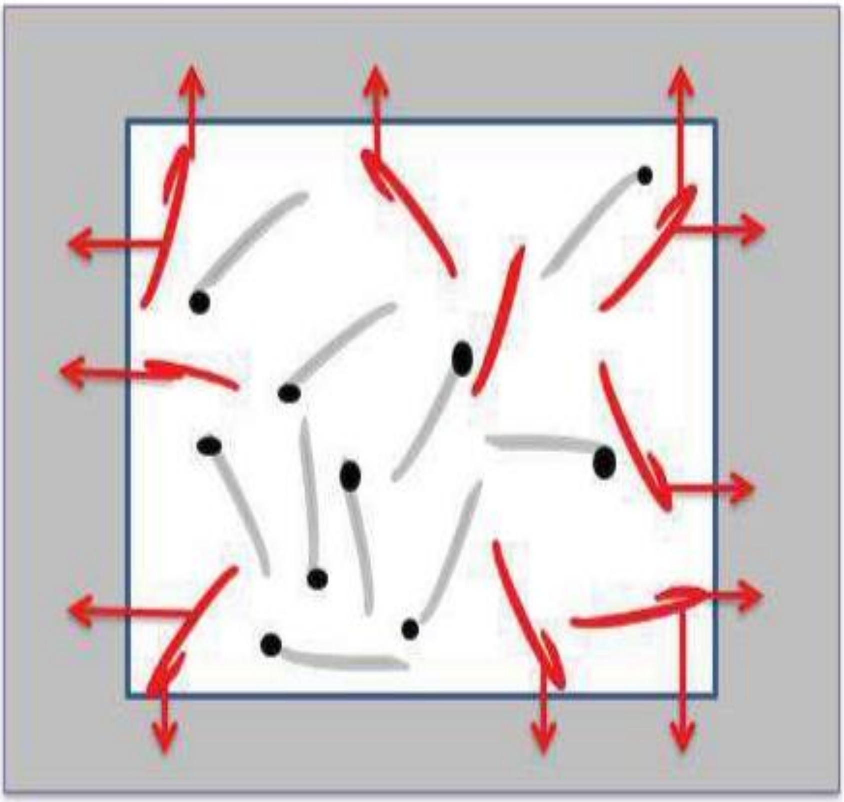

Fig. 1.3 Gas molecules exerting perpendicular force inside a closed container

Commonly, fluid pressure is measured through a gauge in relation with atmospheric pressure and presented as:

For pressure greater than atmospheric,

$P_{absolute} = P_{gauge} + P_{atmosphere}$

While, for pressure less than atmospheric,

$P_{absolute} = P_{atmosphere} - P_{gauge}$

here, $P_{absolute}$ represents absolute pressure, P_{gauge} represents the pressures measured by a gauge and $P_{atmosphere}$ is the atmospheric pressure in Pa. Negative pressure is known as vacuum. Inter conversion factors of pressure have been given in table 1.6. For solid objects, the term normal stress is employed instead of pressure.

For flow of liquids in closed pipes, the pressure of fluid is normally expressed as height or head of a fluid and is expressed by the following mathematical relationship:

$$P = \rho g h \tag{1.9}$$

here, P represent the fluid pressure in pascal (Pa), ρ represents the density of the substance (kgm^{-3}), g denotes gravitational acceleration, (9.81 m/s^{-2}) and h represent height of the object (m).

Table 1.6 Inter-Conversions of Pressure into Various Units

To convert	Into	Multiply by	To convert	Into	Multiply by
Atmosphere	Bar	1.013	kg/cm^2	inHg	28.96
Atmosphere	inHg	29.9213	kg/cm^2	inWater	393.76
Atmosphere	inWater	406.86	kg/cm^2	mbar	9.81×10^2
Atmosphere	kg/cm^2	1.033	kg/cm^2	Pa	9.81×10^4
Atmosphere	mbar	1012.95	kg/cm^2	lb/in^2	14.23
Atmosphere	Pa	1.013×10^5	kg/cm^2	mmHg	7.35×10^2
Atmosphere	PSI or lb/in^2	14.696	Pa	atm	9.87×10^{-6}
Atmosphere	mmHg	760	Pa	bar	1×10^{-5}
Bar	inHg	29.54	Pa	psi or lb/in^2	1.45×10^{-4}
Bar	kg/cm^2	1.02	Pa	inHg	2.95×10^{-4}
Bar	Pa	$1 \text{ x } 10^5$	psi or lb/in^2	bar	0.069
Bar	psi	14.5	psi or lb/in^2	kg/cm^2	7.03×10^{-2}
inHg	Pa	3385	psi or lb/in^2	N/m^2	6.89×10^3
inHg	psi	0.49	kg/cm^2	N/m^2	9.81×10^4
inWater	Pa	248.9	kg/cm^2	mmHg	7.35×10^2

Example 1.3:

The gas has been compressed by a piston in a cylinder (Fig. 1.4). It has been observed that the pressure exerted on the gas under the piston is 0-gauge in addition to extra pressure exerted by the weight. The diameter and weight of piston are 20 cm and 475 N, respectively. Piston height is 25 cm from the bottom of the cylinder and temperature is 77°C. Determine the position of piston when the system is heated to a temperature of 127°C.

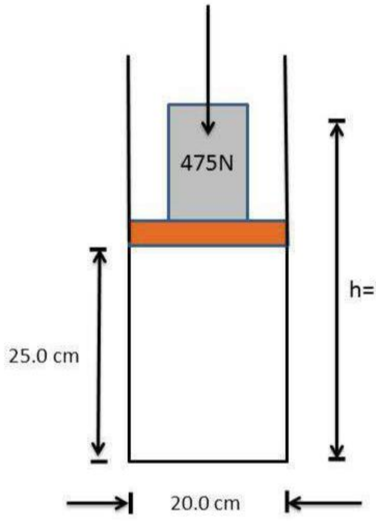

Fig. 1.4 A schematic view of gas compression inside a cylinder

Solution:

$V_1 = ((\pi D_1^2)/4) \times h_1$

$= ((\pi 20^2)/4)0.25$

$= 7854\ cm^3$

$V_2 = ((\pi D_2^2)/4) \times h_2$

$= ((\pi 20^2)/4)\ h_2$

$= 314.16 h_2\ cm^3$

$T_1 = 77\ °C + 273°C$

$= 350$ K and

$T_2 = 127\ °C + 273°C$

$= 400$ K

For isobar process (P_1=P_2), following equation builds up;

$T_2/T_1 = V_2/V_1$

$400/350 = (314.16\ h_2\ cm^3)/\ (7854\ cm^3)$

$h_2 = (400/350) \times (7854/314.16)$

$= 28.57$ cm

1.9. Energy

Energy of an object is the ability to do work. Potential energy, kinetic energy, chemical energy, and electrical energy are the diverse forms of energy.

Potential energy: This is the energy of an object with respect to its position from a reference point in the gravitational field. Mathematically this energy can be written as:

$$E_{PE} = mgh \tag{1.10}$$

Where, E_{PE} is the potential energy, m is the mass of an object at elevation of h from a reference point in the gravitational field and g is the acceleration due to gravity.

Kinetic energy: This energy is due to the velocity of an object and can mathematically be described as following:

$$E_{KE} = \frac{1}{2}mv^2 \tag{1.11}$$

Where, E_{KE} is the kinetic energy of an object with mass m and velocity

In food processing, some forms of energy may be significantly greater than the remaining others and the non-significant forms of energy may be ignored. For example, when a tomato is released into a tomato pulper, the potential and kinetic energy of tomato significantly fluctuates and the other types of energy like chemical, magnetic, and electrical energies remain the constant and therefore, can be neglected in the analysis. On the other side, as the tomato pulp is heated, the potential and kinetic energies remain the same and the internal energy changes with the increase in temperature. The mathematical relationship of total energy (E_T) of a system is as following:

$$E_T = E_{PE} + E_{KE} + E_E + E_C \ldots\ldots + E_I \tag{1.12}$$

Here, E_E is the electrical energy and E_C is the chemical energy and E_I is the internal energy of a system/object.

1.9.1. Heat Energy

Heat energy plays a key role in drying, dehydration, cooking and preservation of food. The heat transfer, from a warm body to a cold body, is due to the temperature gradient. Heat can be transferred by three approaches *viz.* conduction, convection and radiation (discussed in detail in 3rd chapter of this book). The general equation of heat transfer is as following:

$$q = c_p\dot{m}\Delta T \tag{1.13}$$

Where; q represents rate of heat transfer, or watt; c_p represents the specific heat of medium, $\dot{m}$ is the mass flow rate; ΔT is the temperature difference, K. For heating food products at constant pressure (loose lid at top of heating pot), the mathematical model can be described as following:

$$\Delta H = H_2 - H_1 = m\,[T_2 - T_1]\,c_p \tag{1.14}$$

here; ΔH = difference of final and initial heat energy, J; m = mass, kg; c_p = specific heat of substance at constant pressure; ΔT = the temperature difference, T_2 = ending temperature and T_1 = initial temperature. A phase change of ice with heating at constant pressure is given in the table 1.7.

Table 1.7 Constant Pressures Heating of Ice with Phase Change

Phase	Heat energy type	Temperature
Solid	Sensible heat for heating ice, c_{p1} = 2.05 kJ/ (kg K) Latent heat of fusion of ice for water, HL_1 = 333.2 kJ/kg	0 °C Constant at 0 °C
Liquid	Sensible heat of water, c_{p2} = 4.182 kJ/ (kg K)	0 to 100 °C
Vapor	Latent heat of vaporization of water, HL_2 = 2257.06 kJ/kg	Constant at 100 °C

Example 1.4

At one bar atmospheric pressure, determine heat energy required to vaporize 10 kg apple juice at –10 °C. Consider apple juice as a pure water.

Solution:

Stage-1. Heating juice from -10 to 0°C

Sensible heat energy, c_{p1} for apple juice = 2.05 kJ/ (kg K)

Stage-2. Heating juice in ice form to melt at 0°C

Latent heat of fusion, HL_1= 333.2 kJ/kg

Stage-3. Heating juice to melt at 0°C

Sensible heat energy of water, c_{p2} =4.182 kJ/ (kg K)

Stage 4. Heating water in juice for vaporization at 100°C,

Latent heat of vaporization of water at 100°C, HL_2 = 2257.06 kJ/kg

Details:

Stage 1. Heating apple juice (-10 to 0°C); $H_1 = mc_{p1} [T_2 - T_1]$

$H_1 = 10(2.05) [0-(-10)] = 205$ kJ

Stage 2. Juice fusion (at 0°C); $H_2 = mH_{latent}$

$H_2 = 10 [333.2] = 3332$ kJ

Stage 3. Heating juice (0 to 100°C); $H_3 = mc_{p2} [T_2 - T_1]$

$H_3 = 10[4.182] [100 - 0] = 4182$ kJ

Stage 4. Evaporation process (at 100°C); $H_4 = mH_{vaporization}$

$H_4 = 10[2257.06] = 22570.6$ kJ

Total heat required, $H = \Delta H_1 + \Delta H_2 + \Delta H_3 + \Delta H_4$

$H = 205 + 3332 + 4182 + 22570.6 = 30289.6$ kJ

1.9.2. Enthalpy

Enthalpy is the total heat content of a system. It is the summation of internal energy of the system and product of pressure and volumes. Mathematically, enthalpy is expressed as:

$$H = E_i + PV \tag{1.15}$$

Here, H represents the enthalpy of a system, E_i is the internal energy (kJ), P represents the pressure, and V represents the volume of the system.

Conservation of Mass and Energy: The law of conservation of mass: According to this law the mass can neither be created nor destroyed but its condition/phase can be transformed from one form to any other. Mathematically, mass conservation equation can be written as:

$$M_i + M_L = M_o \tag{1.16}$$

Where, M_i = Mass incoming rate, M_L = Mass leaving rate in the system and M_o = Mass outgoing rate, kg/s.

For example, milk is poured into a centrifugal machine for separating cream. Total weight of whole milk entering the centrifugal machine per unit time must be equal to the total weight of skim milk and cream going out of the centrifugal machine per unit time.

The law of conservation of energy: This law states that energy can neither be created nor destroyed. The total energy entering in the system and energy added in the system by external sources must be equal to total energy leaving the system. The energy has various forms; potential energy, kinetic energy, electrical energy, chemical energy, heat energy, etc. as discussed earlier.

1.10. Area

Surface area of a food product plays a key role for many physical and chemical entities in food engineering processes. Area of a surface is measured quantitatively in square meters. A few examples of use in food engineering are as following: Surface area of the food material required for mass and heat transfer calculations. Earlier to spray drying, a liquid food is converted to concentrated droplets to increase the surface area that boost up the drying process and reduces the time. For canning of foods, greater the ratio of surface area to volume of pot faster will be the heating of its centre that reduces the chances of overheating the product. The surface areas of some food products are provided in table 1.8.

Table 1.8 Surface Areas of Some Food Products

Food product	**Mean surface area (m^2)**
Apple, delicious	1.40×10^{-2}
Egg (60 g)	0.71×10^{-2}
Pear, Bartlett	1.45×10^{-2}
Plum, monarch	0.35×10^{-2}

Problems

1.1 Convert the followings in SI system of units.

Quantity	**From FPS system**	**To SI system**
Area	100 ft^2	m^2
Density	75 Ibm/ft^3	kg/m^3
Energy	5 BTU	kJ
Enthalpy	3000 BTU/Ib	kJ/kg
Latent heat of fusion	111 BTU/lb	J/kg
Power	100 hp	kW
Pressure	34 psig	kPa
Surface heat transfer coefficient	100 BTU/ (ft^2 °F)	W/ (m^2°C)
Thermal conductivity	0.25 BTU/ (ft °F)	W/ (m°C)
Velocity	5 mph	km/h
Viscosity	30 cp	Pas
Work	550 ftlb	Nm

1.2 Fill in the blanks by proper calculations

MC$_{wb}$ (%)	**MC$_{db}$ (%)**	**MC$_{wb}$ (%)**	**MC$_{db}$ (%)**
3	?	23	?
?	6	?	35
12	?	40	?
?	15	?	70

1.3 A food product has moisture content about 90% on wet basis. Determine its moisture content on dry basis.

1.4 10,000 kg of paddy rice having 20% moisture contents on wet basis, is required to be stored in a grain storage. The storage requires 12% moisture contents on wet basis. How many kg of freshly harvested paddy are to be procured?

1.5 A 1000 kg of wheat at MC$_{wb}$ = 14% was purchased and dried to a moisture content of $MC_{wb} = 12\%$. What will be the final weight of grain?

1.6 A food product weighing 100 kg at an initial moisture content $MC_{wb} = 80\%$ was dried to $MC_{wb} = 20\%$. Calculate the amount of dry matter and the water removed.

1.7 At 2 bar atmospheric pressure, determine the amount of heat energy required to vaporize 25 kg ice at -5°C.

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Chapter 2

Physical Properties

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Abstract

Physical attributes of foods such as size and size distribution, shape, density, volume, porosity etc. play a significant role in various process and quality parameters. Screening and grading of various foods, their texture, appearance and other quality parameters can all be related to general physical features. In addition to this, knowledge of rheological, textural and interfacial properties is important for various engineering calculations, process design and product development. This chapter briefly describes these general and other physical characteristics of foods in relation to their effect on food processing and end product quality.

Keywords: Size, shape, size distribution, volume, density, porosity, rheology, texture, interface

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2.1. General Physical Characteristics

2.1.1. Size and Size Distribution

These are important attributes having their role in processing as well as quality and stability of foods. Owing to their importance in various unit operations, size and size distribution are the most widely measured parameters in the industry. Various foods exist in particulate form including powders, emulsions, suspensions etc. Taste, colour, appearance, rheology and texture of such foods depend on size of the particles and their size distributions.

2.1.2. Shape

Shape is also an important characteristic which can significantly influence the food processing. For example, heating rate in Ohmic heating is influenced by the shape of the particles (Kim et al. 1996). The tendency of the particles to impart stirring and mixing depends on their shape. Spherical particles cause less stirring as compared to the irregularly shaped particles (Ramaswami et al. 2014). Defining the shape of materials is also important in screening, grading and process calculations. Shape of food materials is generally described as sphericity. Sphericity is most commonly described as the correlation of food object volume and a sphere volume having equivalent diameter. Hence, the sphericity of a spherical object having diameter D_p will be equal to one (Sahin and Sumnu 2006) and mathematically can be described as below;

$$\text{Sphericity} = \left(\frac{\text{Object Volume}}{\text{Volume of circumscribed sphere}}\right)^{1/3} = \left(\frac{V_o}{V_s}\right)^{1/3} \tag{2.1}$$

Here, V_o *and* V_s are the volumes of an object compared to circumscribed sphere, respectively. If an object volume is equal to an ellipsoid volume and diameters of ellipsoid are equal to that of the object, then;

$$\Phi = \left(\frac{V_e}{V_c}\right)^{1/3} \tag{2.2}$$

Where; Φ represents the sphericity, V_e represents the volume of ellipsoid and V_c represents the circumscribed sphere volume.

Consider an ellipsoid with minor (2x), intermediate (2y) and major (2z) diameters (Fig. 2.1). The volume of such ellipsoid can be calculated as;

$$V_e = 4/3\pi xyz \tag{2.3}$$

and sphericity can be calculated as:

$$\Phi = \frac{(xyz)^{1/3}}{z} \tag{2.4}$$

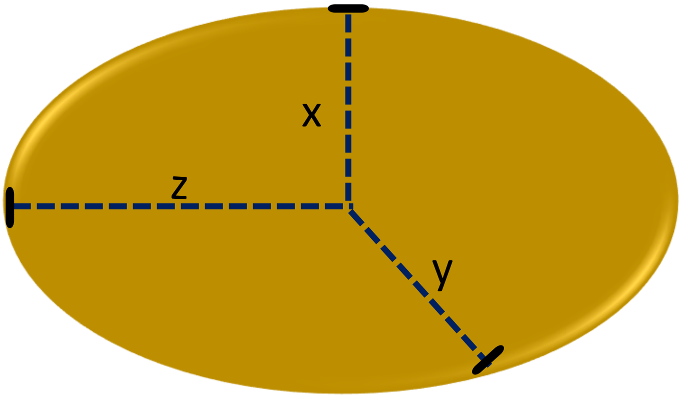

Fig. 2.1 A typical triaxial ellipsoid shape showing minor (x), intermediate (y) and major (z) diameters.

Aspect ratio is an attribute which gives the relationship between the width and length of an object. If width is 'w' and length of an object is 'l' then aspect ratio can be expressed as:

$$R_a = w/l \tag{2.5}$$

while investigating the physical characteristic of grains (e.g. rice), sphericity and aspect ratio are the important criteria to describe the shape of the grains (Ghadge and Prasad 2012).

2.1.3. Volume

Volume is the quantity of three-dimensional space occupied via entity/object or the quantity of space enclosed in a container. It is significant aspect in food processing and plays its role in measuring the loss of water, transfer of heat, amount of pesticides applied on the foods and rate of respiration etc. (Siswantoro et al. 2013). In baking industry, volume of bread serves as an indicator of gas retention of dough, protein quality and gluten development. Volume can be measured through various methods: Volume of regularly shaped objects can be obtained by measuring its characteristic dimensions. For irregular shapes, it can experimentally be calculated through solid, liquid or gas displacement procedures (Fig. 2.2).

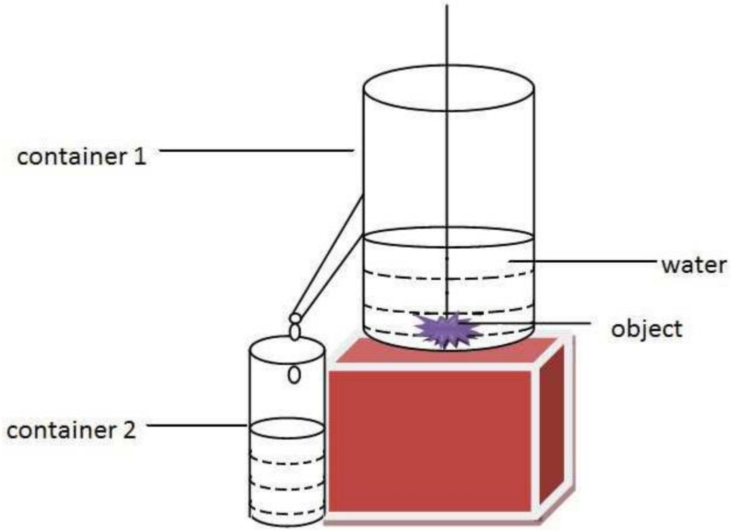

Fig. 2.2 Volume measurement through water displacement method

Traditionally it is measured through water replacement method employing Archimedes principle. An item is put in water contained in the container and the water displaced by this object is collected in another container. The volume of the displaced water is measured which is equal to the volume of the object. This method does not give accurate value for porous and fragile objects like bread. A bread sample if measured with this method will absorb water and will be destroyed. For such samples, method can be modified by replacing water with e.g. rape seeds, however merging the bread into seeds can cause the compression of the bread.

Volume can also be measured through image analysis and computer vision techniques. The technique is more accurate and non-destructive. Computer vision has been used for measuring volumes of both axisymmetric and irregularly shaped foods. Axisymmetric foods analysed through this technique include eggs, water melons, oranges, lemons and limes. Foods with irregular shapes include sliced and particulate food products (Lee et al. 2006; Koc 2007; Khojastehnazhand et al. 2009; Siswantoro et al. 2013). Cameras are used to capture the images from top and surroundings of the object with subsequent image analysis.

Volume is most commonly expressed in terms of solid, apparent and bulk volume. Solid volume (V_s) represents the solids volume of a body including water and excluding interior pores occupied by air. Apparent volume (V_{app}) is an object volume with all its interior pores. Bulk volume (V_{bulk}) reflects a packed or stacked material volume forming a bulk.

2.1.4. Density

Density is known as mass per unit volume occupied by a food commodity. It is an important parameter in creaming, sedimentation, centrifugation and (pneumatic and hydraulic) transportation of powdered and particulate food materials. Depending upon densities of disperse and continuous phases, emulsion droplets can cream up (e.g. in milk) or settle at the bottom (e.g. w/o emulsions) resulting in decreased emulsion stability. Choice of the size of container for powdered food materials depends upon their density.

Density of liquid foods is commonly measured with pycnometer or hydrometer. A hydrometer consists of a tubular bulb containing a dense material (which gives it an appropriate weight) and a stem attached to the bulb (Fig. 2.3). Density is measured by dipping the hydrometer into the liquid contained in a beaker. A hydrometer sinks into the liquid depending upon the liquid density, more the depth the lower will be the density (Sahin and Sumnu 2006). The density is calculated through measuring the ratio of hydrometer's weigh and liquid volume displaced by the hydrometer.

$$\rho_l = W/\,(ALV) \tag{2.6}$$

Where: ρ_l = Density of the liquid, W = Hydrometer weight, A = Stem cross sectional area, L = Length of stem, V = Displaced liquid volume or volume of bulb.

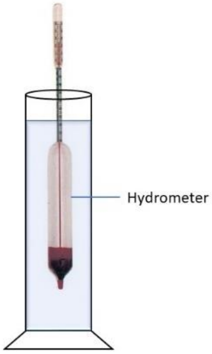

Fig. 2.3 A typical hydrometer

While evaluating a particulate food material, density may need to be measured for individual particles or for the bulk. Data presentation in such cases will need the exact form in which the density has been measured. The density is most commonly defined in following forms.

True density (ρ_T):

It is defined as the density of a pure material or a mixture derived from all densities of the constituents of the mixture considering the mass and volume conservation. It can be estimated as;

$$\rho_T = \sum_{i}^{n} X_i^v \rho_i = \frac{1}{\sum_i^n X_i^w \rho_i} \tag{2.7}$$

Where, ρ_i = Density occupied by ith component of material X_i^v = Volume fraction possessed by ith component X_i^w= ith component mass fraction and n = Components number.

Material density (ρ_m):

When a material is divided into small pieces to ensure that all closed pores are finished, the density measured is called material density.

Particle density (ρ_p):

The density of structurally unmodified particles measured with the volume addition of all packed pores.

Solid density (ρ_s):

The solid material density without interior pores occupied by air.

Apparent density (ρ_{app}):

The density measured by adding all pores within the object.

Bulk density (ρ_{bulk}):

The density measured for a substance (e.g. powder) packed in bulk form.

The density of food materials varies with temperature. Temperature (ºC) dependence of density of major food components have been described as follows (Choi and Okos 1986).

$$\rho_{Water} = 997.18 + 3.1439 \times 10^{-3}T - 3.7574 \times 10^{3}T^{2} \quad (2.8)$$

$$\rho_{CHO} = 1599.1 - 0.31046T \quad (2.9)$$

$$\rho_{Protein} = 1330 - 0.5184T \quad (2.10)$$

$$\rho_{Fat} = 925.59 - 0.41757T \quad (2.11)$$

$$\rho_{Ash} = 2423.8 - 0.28063T \quad (2.12)$$

$$\rho_{Ice} = 916.89 - 0.1307T \quad (2.13)$$

2.1.5. Porosity

Porosity is a primary attribute determining food quality as well as mechanical and textural properties. It affects the mass diffusion coefficient, thermal conductivity and thermal diffusivity of foods (Hussain et al. 2002). Crispiness of extruded and fried food products are highly related to the porosity. Oil absorption during frying process is also related to porosity (Ziaiifar and Trystram 2009). Porosity (ξ) is described as the measure of the volume of void fraction of a material and can be determined by various methods as follows.

- Direct measurement: Porosity is measured by taking the bulk volume of the sample followed by the destruction of voids through compression. The difference between volume before and after the compression is taken as porosity.
- Optical/microscopic technique: A representative sample of the porous material is viewed under microscope imaging system in order to capture images with subsequent image analysis through image analysis software.
- Calculation from density: Porosity can simply be measured from density data of the porous sample. For example, apparent porosity of a sample can be measured from density data as:

$$\xi_{app} = 1- \frac{\rho_{app}}{\rho_{s}} \quad (2.14)$$

Where ξ_{app} = Apparent porosity; ρ_{app} = Apparent density; ρ_{s}= Solid density

Similarly, bulk porosity that comprises the void volume outside the boundary of individual particles packed as bulk can be measured as;

$$\xi_{Bulk} = 1 - \frac{\rho_{bulk}}{\rho_{app}} \tag{2.15}$$

where, ξ_{Bulk}= Bulk porosity, ρ_{bulk} = Bulk density, ρ_{app} = Apparent density

- Gas pycnometer: It is used to calculate air volume fraction in a material from which porosity can be calculated.
- Porosimeter: Porosimeter is the instrument which employs the principle of liquid intrusion or extrusion to measure the porosity as well as pore size distribution. In extrusion porosimetry, some wetting liquid is filled into the pores which are then displaced from the pores using pressure and volume of extruded liquid is measured. In intrusion porosimetry, pressure is used to cause the liquid to enter the pores with subsequent measurement of intrusion volume and pressure.

2.2. Rheological Properties of Foods

The term rheology was first used by Eugene Bingham. The term originated from the word “panta rhei” given by Heraclitus (a greek philosopher of around 500 B.C.) which means “everything flows” or “everything is constantly changing” (Steffe 1992). Rheology has established as the science of flow of materials and deformation in which the materials are subjected to stress or strain with subsequent study of their response to applied stress/strain.

Food rheology depends upon its composition and is important for various engineering calculations during processing (flow through pipes, mixing, pumping, extrusion, homogenization etc.), product development, evaluation of sensory and other quality parameters and characterization of food ingredients as well as end product (Dobraszczyk and Morgenstern 2003; Nam et al. 2005; Liu et al. 2007; Innocente et al. 2009). Rheological properties determine the correlation of stress and strain of material therefore, thorough understanding of basic concepts of stress and strain is important for the study of rheological properties.

2.2.1. Stress

It is defined as force (F) applied per unit area (A). If the applied force is acting perpendicular to the plane the stress will be termed as normal stress (σ) and if force is acting tangential to the plane, then stress will be shear stress (τ) (Fig. 2.4 & 2.5). Normal stress may be tensile (causing the material to stretch) or compressive (causing the material to compress).

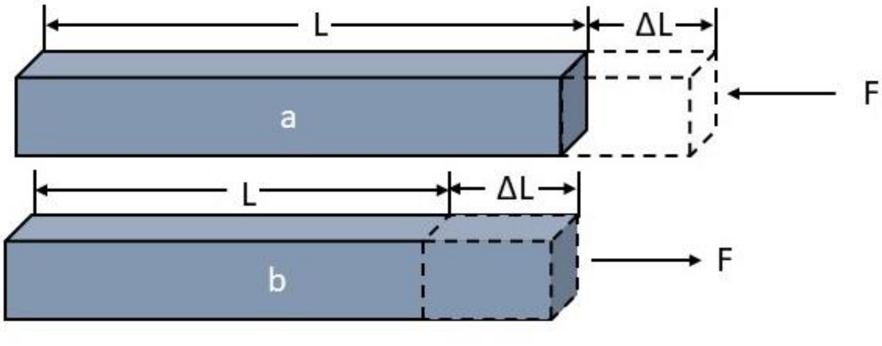

Fig. 2.4 Normal stress (a) compressive and (b) tensile

2.2.2. Strain

It is the degree of the deformation of material as unit change in size/shape relative to original size/shape of material. Strain can be normal strain (∈) if the material length changes in way of applied stress or it can be shear strain (Y) if the angle between two orthogonal planes changes because of applied stress (Fig. 2.5).

$$\in = \Delta L/L \tag{2.16}$$

$$Y = \tan\theta = x/y \tag{2.17}$$

Stress and strain may be deviatoric (resulting in shape change) or dilatational (resulting in change in volume). The ratio between normal stress and normal strain is known as Young's modulus or modulus of elasticity (E) while ratio between shear stress and shear strain is known as shear modulus or modulus of rigidity (G).

$$E = \eta / \in \tag{2.18}$$

$$G = \tau / Y \tag{2.19}$$

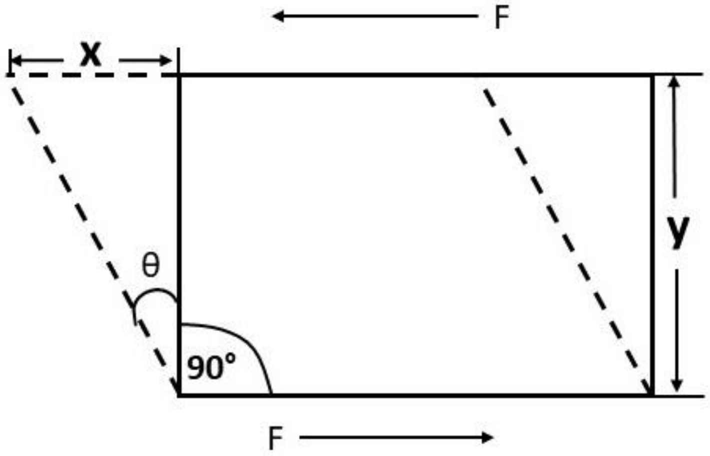

Fig. 2.5 Shear stress

2.2.3. Flow of Materials

Flow of materials can be described by following rheological parameters.

Viscosity

Viscosity is simply the resistance of a fluid to its deformation and flow and measures the internal friction of the fluid (Fig. 2.6). At constant shear stress, more viscous fluids (e.g. honey, syrups etc.) deform slowly as compared to less viscous fluids (e.g. water). The amount of force required to cause this deformation or shear increases with increasing friction. Hence, highly viscous fluids require more force for operations like pouring, mixing, spraying etc. Consider a system consisting of two parallel plates with fluid between the plates (at rest). The plates have an area "A" and are separated by a distance "Y". Force "F" is applied on lower plate at time t = 0 in the direction of z-axis which causes lower plate to move in z-direction with velocity "V" while keeping the upper plate stationery. Initially at time (t = 0) everywhere in the system velocity is zero but velocity is "V" at the lower plate. With the passage of time distribution of velocity starts and steady state is reached resulting in linear distribution of velocity from zero (top plate) to "V" (lower plate). To maintain this motion, the required force per unit area is directly related to the velocity gradient.

$$F/A = \mu V/Y \qquad (2.20)$$

here, μ is constant of proportionality and known as dynamic viscosity (Nsm^{-2} or Pas). Microscopic form of above equation is called Newtonian's law of viscosity (Sahin and Sumnu 2006) and is given as:

$$\tau_{yz} = -\mu\frac{dV_z}{dy} = -\mu\gamma_{yz} \tag{2.21}$$

Where: τ_{yz} = Shear stress μ = Viscosity of the material (Pas) γ_{yz} = Rate of shear (1/s).

Viscous Fluids

Viscous fluids are the fluids which on applying stress will deform continuously. They are distributed into two types, namely Newtonian fluids and non-Newtonian fluids.

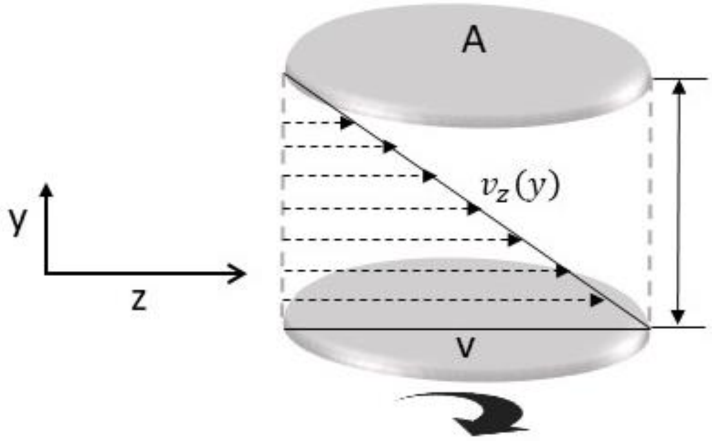

Fig. 2.6 Velocity profile of a Newtonian fluid (adapted from Sahin and Sumnu 2006)

Newtonian fluids

These are the fluids that follow Newton's law of viscosity. For such fluids, the relationship between shear rate and shear stress is a linear line and the viscosity is constant. Most of the liquid foods containing > 90% water (coffee, tea, carbonated drinks, juices etc.,) are Newtonian fluids (Fig. 2.7).

Non-Newtonian fluids

Those fluids which do not follow Newton's law of viscosity are known as non-newtion fluids (relationship between shear rate and shear stress not remains constant). Hence, viscosity fluctuates with change in shear rate. Such viscosity is called apparent viscosity and is expressed with the symbol η. To understand non-Newtonian flow, consider a fluid consisting of particles of different shapes and sizes. As the fluid flows, the molecules pass by each other and size, shape and cohesiveness of the molecules will describe the amount of force required to move them. The alignment of molecules may vary at specific shear rate and hence the required force to sustain the motion will be diverse.

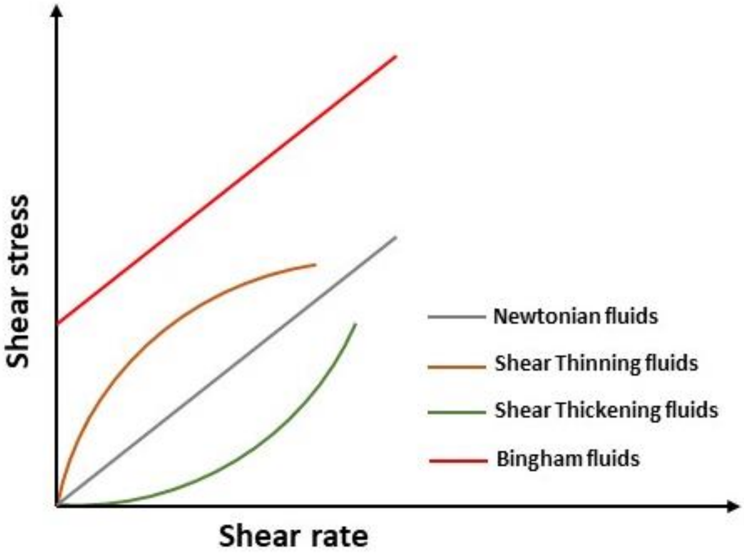

Fig. 2.7 Graphs of shear stress as a function of shear rates showing Newtonian, and non-Newtonian behaviour

In Shear thinning or pseudo-plastic fluids, shear causes the elongated chains of entangled molecules to get straight and arranged with flow resulting in decrease in friction between layers and hence the viscosity (Fig. 2.8). Most common examples of shear thinning fluids include cream, juice concentrates, salad dressings, starch paste, melted chocolate, various emulsions and dispersions (Buy Lund 2003; Rao et al. 2014). In shear thickening fluids, rise in shear rate causes increae in internal friction resulting in increased viscosity e.g., concentrated starch suspension. Moreover, volume expansion takes place together with increase in viscosity then the fluids are known as dilatant fluids.

Plastic fluids

These are the fluids which behave like solids under static conditions and some magnitude of force (yield value) is required to induce flow in the fluid. Tomato ketchup is a common example of plastic fluid. The yield value of tomato ketchup restricts it to flow out of the bottle until the bottle is shaken well to overcome its yield value. As the fluid starts flowing above yield value, it can behave as Newtonian shear thinning or thickening fluids.

Bingham plastic

Bingham plastics are those materials which remain solid when applied shear is below yield value and behave like Newtonian fluids when applied shear exceeds the yield value. Typical examples of such foods are tomato paste, mayonnaise etc (Fig. 2.8).

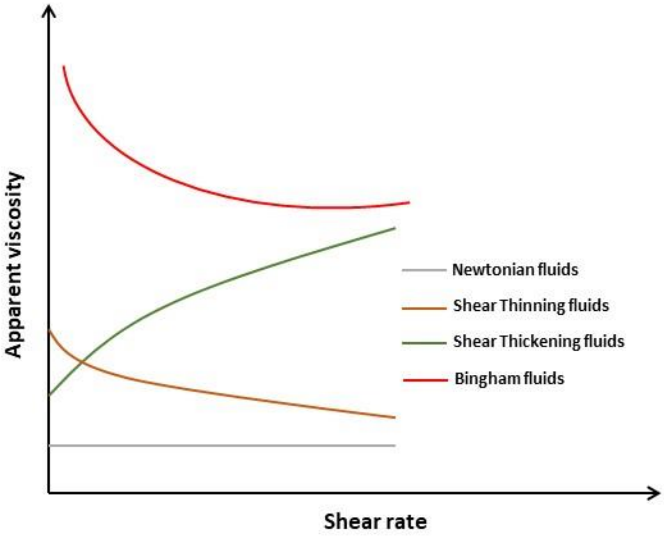

Fig. 2.8 Apparent viscosities of Newtonian and non-Newtonian fluids

Non-Bingham plastic

These plastics are those fluids in which flow does not start until the applied shear exceeds the yield value. Afterwards, a non-linear behaviour of shear rate against shear stress is observed (either shear thickening or shear thinning). Some fluids under constant shear rate show shear thickening or shear thinning expression with time. The fluids which show a reduction in viscosity under constant shear rate with time are called thixotropic fluids. Examples of such food include egg white, shortenings and gelatine. Some fluids show an increase in viscosity when sheared at constant rate. Such fluids are called rheopectic fluids. Pastes prepared from starch, milk and sugar are reported to show rheopectic behaviour (Abu-Jdayyil and Mohammed 2004).

2.2.4. Viscoelastic Behaviour

The materials which exhibit both the fluid like (viscous) and the solid like (elastic) characteristics simultaneously are known as viscoelastic materials e.g. wheat dough, ice cream mix and various gelled products. Viscoelastic materials can be studied by three different tests namely creep, stress relaxation and dynamic methods (Fig. 2.9).

Stress Relaxation Test

In this test, a constant rate of strain at time (t=0) is enforced on the substance and change in stress is measured with time. Instantaneous stress relaxation is observed for ideal viscous substances showing immediate relaxation. Ideal solids show constant stress which remains constant at t > 0 representing no relaxation. In viscoelastic materials, stress increases initially and then decreases with time. When strain is removed from viscoelastic fluids, they show complete relaxation (zero stress) while some of the stress value, stored by viscoelastic solids, is greater than zero showing partial recovery (Steffe 1992; Sahin and Sumnu 2006). Viscoelastic behaviour of various foods has recently been investigated using stress relaxation test including meat, bread, sausages and various cheese varieties (Singh et al. 2006; Nobile et al. 2007).

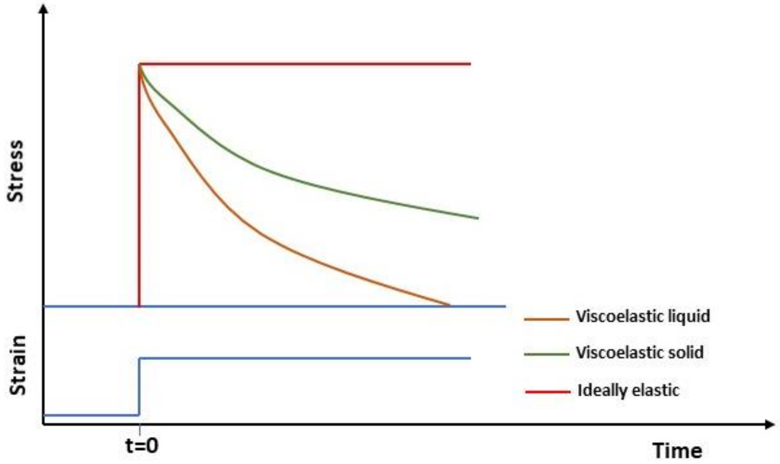

Fig. 2.9 Stress relaxation behaviour of viscous, elastic and viscoelastic materials (Sahin and Sumnu 2006)

Creep Test

In creep test, a constant load is applied on the material for a specific period after which the load is removed and corresponding strain is recorded with time. Ideal viscous materials show a linear increase in strain which becomes constant after removing load. Ideal solids show constant strain until the load is removed. Upon removing the load, the strain is completely recovered (Fig. 2.10). Viscoelastic materials show non-linear strain and partial recovery. The application of creep test in measuring food rheology can be found in low oil content food emulsions, rice dough to prepare bread and supplemented rice dough with gums and proteins for making pasta products (Sivaramakrishnan et al. 2004; Dolz et al. 2008; Sozer 2009).

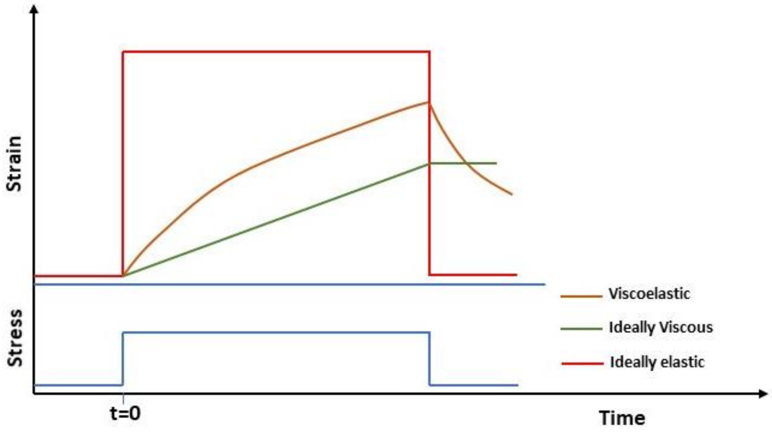

Fig. 2.10 Curves for viscous, elastic and viscoelastic materials measured through creep test (Adapted from Sahin and Sumnu 2006)

Dynamic Test

It is also known as oscillatory method. In this test, a substance is exposed to a sinusoidal oscillating stress or strain with subsequent measurement of oscillating stress or strain response (Fig. 2.11). Phase variance among oscillating stress and strain gives information about viscous, elastic and viscoelastic changes in the material. For an ideal elastic material, strain is in phase with stress while for viscous materials both stress and strain are 90° out of phase with each other. Viscoelastic materials show an intermediate phase angle. Oscillatory measurements have been described in the investigation of rice dough, dairy foods, emulsion, gels, mixtures of ketchup and cheese (Gunasekaran and Ak 2000; Yilmaz et al. 2011).

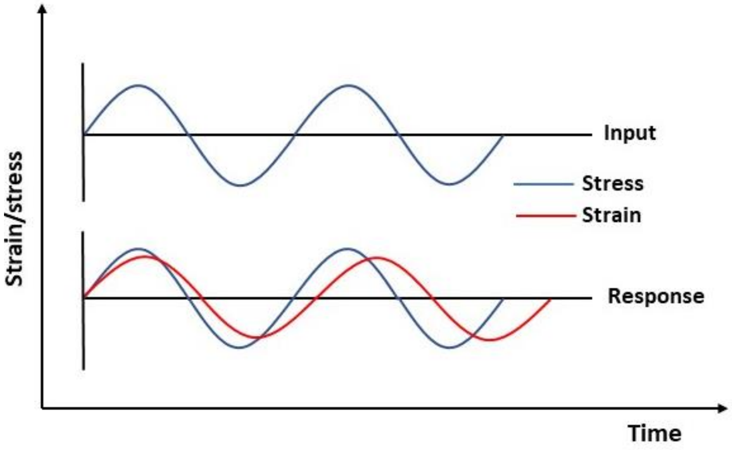

Fig. 2.11 Oscillating stress and strain responses

2.3. Textural Properties of Foods

Texture is the sensory demonstration of food structure and the way it reacts to the applied forces, involving specific senses including vision, hearing and kinesthetics. It is a group of physical properties derived from molecular, microscopic and macroscopic structure of foods (Bourne 2002). Texture can be measured by sensory methods (through a panel of trained persons) or by instrumental methods (using various instruments). Various tests performed for measurement of textural properties of foods are as follows.

2.3.1. Compression

This test measure either the distance to which material is compressed at standard force or force needed to compress the material to standard distance. It may be described in terms of softness or firmness. Other application of compression test can be found in the study of polymers for food packaging, grains, extruded snack foods etc. (Kamst et al. 1999; Anton and Luciano 2007; Siracusa et al. 2008).

2.3.2. Snapping-Bending

In this test force needed for snapping or bending of foods, which are of brittle nature, is measured. Typical examples of such foods are biscuits and crackers. The force required for snapping or bending depends upon the strength of the material and its dimensions. The test has been reported for evaluating the crispiness, freshness and stability of foods during storage (Truong and Daubert 2002; Rizzolo et al. 2013).

2.3.3. Cutting Shear

In this test, material is cut with a grid of rotating blades and the force required for cutting is measured. The test is performed to describe the texture of various vegetables and fruits at different maturity levels.

2.3.4. Puncture and Penetration

In puncture test a probe is pushed into the material and the force required is measured. It can be expressed in terms of hardness or firmness of the material. The test is generally used for texture measurement of foods with high firmness (Barrett et al. 1998). In penetration, a cone or needle can move into the material under action of gravity for a unit time. The distance covered is calculated that provides the information about spread ability of materials.

2.4. Surface and Interfacial Properties

2.4.1. Surface and Interfacial Tension

To understand surface tension, consider a molecule of water in the bulk and a molecule at the surface. The molecule in the bulk is enclocsed by other molecules from all the directions. The central molecule is attracted equally from all sides by surrounding molecules which cancel each other so that the net force is zero. While the molecule of water at surface experiences a net attractive force pulling it inward to the interior causing the liquid surface to contract and bringing it in the tension state.

In this state, water is assumed to have spherical shape with least surface area. This force which inclines to reduce the area of surface is called the surface tension. Due to surface tension, the surface of a liquid acts as an extended elastic membrane.

Surface tension is defined as the amount of work needed to extend the surface in isothermal conditions. Its unit in SI system is N/m;

$$\sigma = (work\ done)/(increase\ in\ area) = \frac{FL}{2Ld} = \frac{F}{2d} \tag{2.22}$$

Boundary of two immiscible liquids such as water and oil are called the interface and tension created by the imbalance of intermolecular forces at the interface is called the interfacial tension. In the preparation of emulsions, emulsifiers stabilize the interface by lowering the interfacial tension of the liquids (Fig. 2.13). The force due to variance in pressure between outside and inside of a drop or bubble is given as:

$$F = (P_1 - P_2)\pi r^2 \tag{2.23}$$

Due to surface tension force is described as;

$$F = 2\pi r\sigma \tag{2.24}$$

Both forces are adjusted at equilibrium

$$\delta P = P_1 - P_2 = 2\sigma/r \tag{2.25}$$

The above equation is known as Laplace equation and is used for determining the relation between rise/fall of a liquid and surface tension in a capillary.

When a capillary tube is vertically immersed in a liquid, the liquid rises or falls in the tube depending upon the surface wettability of the tube measured as surface contact angle. Liquid rises if contact angle is below 90° and falls if angle is above 90°. For capillary of very small diameter, meniscus takes the shape of a sphere and radius of curvature of surface of the liquid can be expressed as:

$$r = \frac{r_t}{cos\theta} \tag{2.26}$$

where, r_t is the radius of capillary tube.

Difference in pressure in curved and flat surfaces of the liquid can be expressed as:

$$\Delta P = \frac{2\sigma cos\theta}{r_t} \tag{2.27}$$

Liquid is pushed up by atmospheric pressure until the pressure difference is balanced by the hydrostatic pressure.

$$\frac{2\sigma cos\theta}{r_t} = hg(\rho_l - \rho_v) \tag{2.28}$$

here, ρ_l is the density of the liquid, ρ_v is the density of vapors, h is the height of the column. Since density of vapors is very small compared to the density of liquid, the equation can be written as:

$$\sigma = \frac{hg\rho_l r_t}{2cos\theta} \tag{2.29}$$

2.4.2. Surface Activity

The materials which reduce surface tension at minute concentrations are known as surface active substances. The surface-active materials (e.g. emulsifiers), owing to their amphiphilic nature, orient themselves towards interface and give a huge decrease in interfacial tension. This can be stated as:

$$\tau = \left(\frac{1}{mRT}\right)\left(\frac{d\sigma}{dlna}\right) = -\left(\frac{1}{RT}\right)\left(\frac{d\sigma}{dlnc}\right) \tag{2.30}$$

Where, τ = adsorption of solute (kgmolm^{-2}), σ = Interfacial tension (N/m), R = gas constant (J/kgmolK), T = temperature (K), m = constant, a = Solute activity in bulk solution, and c = Solute concentration in bulk solution (kgmolm^{-3})

2.4.3. Colloidal Systems in Foods

A colloidal system consists of a dispersed and a continuous phase. Particles of dispersed phase range in size from 1-1000 nm. Most of the colloidal foods comprise of hydrocolloids, which are used to improve their rheological properties and stability. Colloidal food systems can be categorized in following groups.

Sols

Sols are the dispersions in which solids are dispersed in continuous water phase e.g. gravies, stirred custard and thick sauces. It is important to control the concentration of ingredients in proper ratio to get the desired viscosity of the product which otherwise can be modified either by heating or by addition of water.

Gels

A gel is a dispersion in which liquid is scattered in continuous solid phase. The solid is concentrated to an extent so that it creates the structure to prevent the flow of the dispersion. If a cut is given in the gel structure, it causes the dispersed liquid phase to release called syneresis. The phenomena of syneresis is useful in some situations (cheese making) while in other products (e.g. jelly) it can be undesirable.

Emulsions

An emulsion defined as a dispersion in which a liquid (e.g. water) is dispersed, in the form of droplets, into another immiscible liquid (e.g. oil). Emulsions are of two types i.e. o/w (oil-in-water) in which oil droplets are dispersed into continuous water phase and w/o (water-in-oil) where water droplets are dispersed into continuous oil phase. Typical examples of o/w emulsions are mayonnaise and milk while that of w/o emulsions are cream and butter.

Emulsions are unstable where coalescence of dispersed droplets can cause the two phases to separate. They can be stabilized by using emulsifiers and stabilizers. Emulsifiers are the amphiphilic compounds having both polar and non-polar parts. They decrease the interfacial tension by adsorbing at the interface thus providing short-term stability. Stabilizers are the proteins and polysaccharides which provide long term stability by modifying viscosity of the continuous phase.

Foams

Foam is a dispersion of gas in continuous liquid phase. Whipped cream, ice cream and cake batter are attributed as food foams. In such products, the dispersed gas bubbles contribute to the product volume and texture. The incorporation of gas also lowers the density of the product. The amount of foam incorporated in product is described in terms of overrun which is described as:

$$Overrun = \left(\frac{V_f - V_l}{V_l}\right)100 \tag{2.31}$$

Where, V_l is the original liquid volume and V_f is the foam volume.

Problems

1. Major, intermediate and minor diameters of average kernel of a variety of corn are 12.01, 8.15 and 5.18 mm respectively. Calculate its sphericity.
2. Major, intermediate and minor diameters of average kernel of a variety of rice are 1.5, 1.7 and 1.8 mm respectively. Calculate its sphericity.
3. Calculate true density of apple at 30°C having composition given below

Component	Amount (%)
Water	92.51
Protein	2.39
Fat	0.25
Carbohydrate	1.82
Ash	3.03

4. Two parallel plates are 0.25m apart. Bottom plate is stationary while upper plate moves with velocity ‘v’. Consider a fluid between plates with viscosity $1 \times 10^{-3}\ Pa.s$
    a. Calculate the momentum flux necessary to maintain top plate in motion at velocity of 0.25 m/sec.

   b. If the fluid between plates is replaced with a fluid of viscosity $100 \times 10^{-3} Pa.s$ and momentum flux remains constant. Find new velocity of top plate.

5. Calculate the height of rise of water in a clean capillary tube of radius 0.001 m if the density of water is 997 kg/m^3, surface tension is $7.3 \times 10^{-2} N$/m and contact angle of water with surface of capillary tube is 25°.
6. Major, intermediate and minor diameters of average kernel of a variety of grapes are 1.5, 1.7 and 1.8 cm, respectively. Calculate its sphericity.

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Chapter 3

Heat and Mass Transfer

Muhammad Shafi Sabir, Zia Ahmad and Misbah Murid*

Abstract

Transfer of heat occurs in every major unit operation in food industry. In the processing of many farm products, heat transfer is the principal part that prevents microbial and enzymatic degradation. In the food industries, the most commonly performed unit operations are thermal sterilization, evaporation, refrigeration, freezing and drying. Examples are pasteurization of milk and fruit juices, freezing of meat and vegetables, cooling of fruits and vegetables for transportation and storage and thermal sterilization of canned foods. Transfer of heat is a thermodynamic phenomenon in which from one body, heat is transferred to another body due to the temperature gradient that is the main force. The rate of heat transfer is directly related to the variation in temperatures of bodies. Greater the temperature variation, heat transfer rate will be greater. During the processing, fluctuations in the temperatures will also bring change in the heat transfer rate. Transfer of heat energy can be occurred by three mechanisms; 1) convection, 2) radiation, and 3) conduction. In many systems, all three mechanisms operate simultaneously.

Keywords: Specific heat, Thermal conductivity, Convection, Diffusion

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3.1. Thermal properties of food

In many food processing operations (baking, pasteurization and canning) thermal processing is universal method. These processes rely on heating to develop certain attributes. Heating preserve the food from microbes and deactivate the enzymes with little harm to product like the sterilization of canned food and the pasteurization of milk. During cooking of meats and vegetables, heating develops taste, flavour and changes food appearance physically. Heating process also changed the structure of the food material like in baking process. Heat transfer is known as the transition in thermal energy due to temperature difference that determines the amount of heat transfer from one object to other. In the food commodities heat transfer depends upon the various thermal properties like specific heat, viscosity, thermal conductivity and thermal diffusivity. These properties are very important for thermal analysis of food processing which are discussed as follows.

3.1.1. Specific Heat

It is described as the rate of energy that elevates the temperature by one degree of a substance. It is of two types: specific heat at constant pressure c_p and volume c_v, respectively. Value of c_p is always higher than c_v due to change in volume of system. This change consumes the energy, which is gained by the source. The following expression can be used to calculate the c_p.

$$c_p = \frac{Q}{m\Delta T} \tag{3.1}$$

here, Q is the rate of heat lost or gained (kJ), m represents the mass of substance in kg, ΔT is the difference in temperature in °C and unit of c_p is kJ/(kg °C) or kJ/(kg K). In food processing applications, the value of specific heat (c_p) at constant pressure is commonly used with exception to high pressure processing.

Example 3.1

A ball of aluminium having diameter of 10 cm is heated by increasing temperature from 40°C to 120°C in time about 30 minutes. At this temperature, specific heat of ball is 0.903 kJ/(kgK) and density is 2702 kg m^{-3}. Calculate total heat transfer rate to the aluminium ball, (ii) average rate of heat transferred to the ball and (iii) average rate of heat flux.

Solution

The change in internal energy caused by the rate of heat transferred to the aluminium ball which is determined as follows.

$Q = mc_p (T_2 - T_1)$ and

$m = \rho V$ and V=volume of sphere = $\pi D^3/6$.

So, $m = (\pi /6\ \rho) D^3$

$= \pi /6\ (2702\ \text{kg/m}^3)\ (0.12\ \text{m})^3$

$= 1.41$ kg

Substituting m,

$Q = (1.41\ \text{kg})\ (0.903\ \text{kJ/kgK})\ (120\text{-}40)\ °\text{C}$

$= 101.85$ kJ

Therefore, 101.85 kJ of heat is required to heat it from 40 to 120°C.

The average rate of heat transfer can be determined by following equation:

$q_{avg} = Q/\ t$

$= 101.85\ \text{kJ}/(30 \times 60)\ \text{s}$

$= 56.7$ W

Heat flux is defined as amount of heat transfer in unit area. Therefore

it is calculated as:

$q_{avg}/A = q_{avg}/\pi D^2$

$= 56.7\ \text{W}/\ [\pi\ (0.10\text{m})^2]$

$= 1804.8\ \text{W/m}^2$

3.1.2. Thermal conductivity

It is another important property of materials that indicates the heat transfer rate. It is defined as heat transfer rate through a unit thickness with unit area of a substance having a unit temperature difference. Higher thermal conductivity value indicates that substance is a good heat conductor and vice versa. For example, thermal conductivities (k) of water and copper are 0.607 W/mK and 401 W/mK copper at room temperature, respectively. It indicates that copper transfers heat 660 times faster than water. So, these values are the indication that copper is a good heat conductor compared to water.

Thermal conductivity (k) in SI unit can be expressed as;

$$k = \frac{J}{sm°\mathrm{C}} = \frac{W}{m°\mathrm{C}} \tag{3.2}$$

Mostly foods, which have higher moisture content (juices, tomato etc), have thermal conductivity values equal to the water thermal conductivity while the porous and dried foods have lower values due to the presence of air.

3.1.3. Thermal Diffusivity

It is the measure of heat diffusion through a material. It may be determined as the ratio of heat transfer rate (conduction) to the amount of heat stored per unit volume of substance.

$$\alpha = \frac{k}{\rho c_p} \tag{3.3}$$

here, k demonstrates the capacity of the material to transfer heat and ρc_p indicates storage ability of material per unit volume. A material with higher thermal conductivity and lower heat capacity will have higher values of thermal diffusivity. Thus, proliferation of heat in a medium is directly proportional to the thermal diffusivity. The smaller value of α shows that major portion of the heat is absorbed by the material and less amount of heat is transferred further up to the medium. Solid foods have smaller value of thermal diffusivity compared to liquid foods. Heating of liquid food may change its properties owing increase in solid contents or fouling of equipment. Therefore, designing a food process, type and state of the food determined the heat transfer.

3.2. Mechanisms of Heat Transfer

Heat Transfer occurs by three ways including conduction, convection and radiation. In many systems, all three mechanisms operate simultaneously. These mechanisms are discussed in detail in following paragraphs.

3.2.1. Conduction

In this mechanism heat is transferred through collision from high energy molecules to the neighbouring low energy molecules. Solids, liquids or gases can adopt this mechanism for heat transfer. In liquids and gases, conduction happens through collision and diffusion. While in solids, vibratory motion of molecules transfers the energy. The steady state heat transfer occurs when there is no fluctuation at any point with time within a medium. In steady state, heat conduction, time cannot affect the transfer of temperature through a material. Heat transfer depends upon the medium's geometry, its thickness, its material as well as the difference in temperature of the medium.

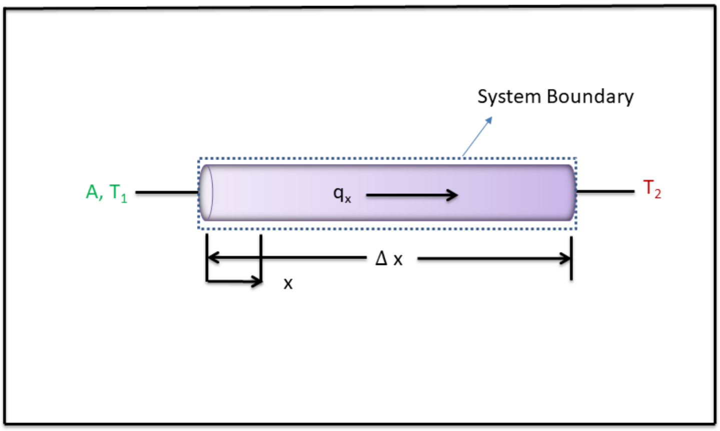

Fig. 3.1 Heat transfer through conduction process in a cylindrical object

Heat transfer rate increases with the increase in surface area and temperature gradient among the outer and inner surfaces. Similarly, the heat transfer rate is reduced with the increase in surface thickness. Thus, amount of heat transferred is directly dependent on surface area and temperature gradient and inversely proportional to surface thickness (Fig. 3.1). Mathematically, it can be expressed as;

$$\textit{Heat conduction rate } \alpha \ \frac{\text{Area (Temperature difference)}}{\text{Thickness}}$$

$$q = \frac{-kA\Delta T}{\Delta x} \tag{3.4}$$

Where, proportionality constant k is material thermal conductivity. The negative sign implies the fact that heat is transferred to the lower temperature route. Similarly, heat conduction in cylindrical objects, equation becomes as follow:

$$q = \frac{-kA\Delta T}{\Delta r} \tag{3.5}$$

where, q_r is the heat transferred in radial direction with circumference area A of a cylindrical object. Equation 3.5 may be modified by substituting value of A = 2πrL.

$$q = \frac{-k(2\pi rL)\Delta T}{\Delta r} \qquad (3.6)$$

Usually, heat transfers through many objects of varied thicknesses and thermal conductivities. Such as in a cold storage house, heat may be passes through brick, cement layer, cork and wood. Similarly, transporting of heated oil, heat will pass through pipe material and insulation layer around the pipe.

In condition of steady state transfer, time has no impact on temperature of object during heat transfer, the heat of equal quantity per unit time (heat transfer rate) must passes from each layer of the wall. Mathematically, it can be expressed as follows:

$$q = \frac{A\Delta T_1 k_1}{\Delta x_1} = \frac{A\Delta T_2 k_2}{\Delta x_2} = \frac{A\Delta T_3 k_3}{\Delta x_3} \qquad (3.7)$$

in simplified form;

$$q = U\,A\delta T \qquad (3.8)$$

Example 3.2

A slab of soft wood having a thickness of 150 mm has one face at -15 °C and the other face at 25 °C having thermal conductivity at this temperature range is 0.115 W/(mK). What is the amount of heat transfer to this slab measuring 50 cm × 500 cm.

Solution

Temperature at one face = -15 °C

Temperature at other face = 25 °C

Thickness of slab = 150 mm = 15 cm = 0.15 m

Surface area of slab = 50 cm × 500 cm

= 0.5 m × 5 m = 2.5 m^2

Thermal conductivity of soft wood = 0.115 W/mK

As $q = - kA\,(dT/dx)$

$q = - [0.115 \times 2.5]\,[25 - (-15)/ (0 - 0.15)]$

= 76.67 W

3.2.2. Transient Heat Conduction

Transient heat conduction implies variations with time or time dependence. This means that boundary conditions change suddenly or vary with time. Thus, the temperature at any given point will not remain constant. The examples of transient heat conduction include cooling of vegetables, fruits and meat and thermal processing of canned foods.

An unsteady heat transfer (transient heat conduction) occurs during cooling or heating of solid bodies made from good thermal conducting materials. Some bodies in heat transfer behave like a lump. This means that inner body temperature keeps on uniform at any time during a process of heat transfer. These bodies temperatures can be considered as time function only. The heat energy that required to elevate the temperature of the object is gained from the surroundings.

Suppose a body having mass m, density ρ, surface area As, volume V and specific heat c_p at initial temperature T_i. The body stays in a medium having temperature T_α ($T_\alpha > T_i$), at time t = 0. After time t, change in body temperature may be expressed as;

(Transfer of heat between the body in time) = (gain in the energy during the time)

$$hA_s(T_\alpha - T) = mc_p\Delta T \tag{3.9}$$

Where, m = ρ V and $\Delta T = d(T - T_\alpha)$. Here T_α is constant, equation (3.9) may be expressed as

$$\frac{d(T - T_\alpha)}{T - T_\alpha} = -(\frac{-hA_s}{\rho V c_p})dt \tag{3.10}$$

Integration may result in;

$$\frac{ln(T_t - T_\alpha)}{T_i - T_\alpha} = -(\frac{-hA_s}{\rho V c_p})t \tag{3.11}$$

Simplifying,

$$\frac{ln(T_t - T_\alpha)}{T_i - T_\alpha} = e^{-bt} \tag{3.12}$$

here, $b = hA_s/\rho Vc_p$. Equation (3.12) expresses the time required by a body having temperature (T) at a time (t) to attain the required temperature. Initially, body temperature changes rapidly until it reaches to required temperature and remains uniform. Thus, it is a common fact that heating or cooling of larger mass having large heat capacity takes a longer-time compared to smaller mass.

3.2.3. Convection

Heat transfer occurred by transportation of heated fluid material is called convection (Fig. 3.2). More the speed of fluid motion, greater will be the rate of heat transfer occurred by convection. While during conduction heat is transferred without the motion of fluid. The heated fluid transportation can be occurred through two modes (a) natural or free convection which is caused by buoyancy gradient or (b) by forced convection, attained mechanically with fans, pumps or blowers.

For convention, rate of heat may be stated through Newton's law related to cooling.

$$q_{\text{conv}} = \frac{hA_s}{T_s - T_\alpha} \tag{3.13}$$

here, q_{conv} is the amount of heat transferred by convection, h is the coefficient of convection, A_s represents the surface area of the medium, T_s and T_α are the temperature of surface and fluid, respectively.

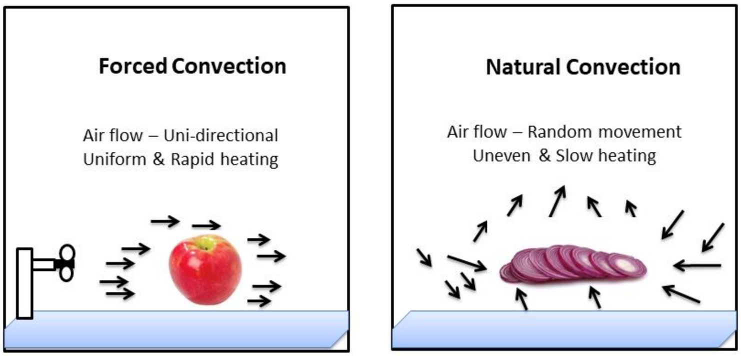

Fig. 3.2 Heat transfer through convection process in a food product

Transfer of heat by natural convection occurs when temperature of fluid is higher or lower than the contact surface. In food industry, many examples of natural convection are present. Convection is important when the hot surfaces, such as the retort is exposed with or without insulation in colder environment. When food is placed in chiller where circulation is not done by the fans, convection occurs there. Heat transfer by convection occurs when cooked food from oven is cooled in the air.

In the natural process of convection, due to the cooling or heating the fluid alter its density. Change in the density leads to the motion of the liquid and fresh liquid exchanges the heated or cooled liquids.

Methodology of Calculation of Convection

For calculating the coefficient of convection heat transfer, the following methodology is suggested.

1) Identify geometry flow. Geometric shapes in solid contact with fluid should be identified along with their dimensions. For example, inside the pipe or outside via surface, whether it is a sphere, tube, rectangular plate or rectangular channel is fluid moving.
2) Identify liquid and determine its properties. Is it water, air or liquid food calculate the mean value of temperature of the fluid equations ($T_\alpha + T_s$) / 2. Here, T_s and T_α are the liquid surface and fluid temperature far enough away from the surface, respectively.
3) Determine the Reynolds number. This number is required to evaluate the state of fluid flow whether it is laminar, turbulent or transient.
4) Select the appropriate empirical correlations. Using the information from step 1 to 3 select the appropriate empirical correlations for calculation convection heat transfer coefficient
5) Select the appropriate empirical correlation.

Natural Convection

Natural convection equation relating the characteristic dimensions of the body that may be the length of the rectangular body or the diameter of the spherical / cylindrical objects. For free convection, the general expression;

$$h_c D/k = \psi n = \frac{D_3 \rho^2 g \beta \Delta T}{\mu^2} \frac{c_p \mu}{k} \frac{L}{D} \tag{3.14}$$

stands for natural convection and has been determined experimentally. Free convection for horizontal cylinders such as steam pipes or rack having sausages on it.

Example 3.3

A 2.1meter electrical wire with 0.2 cm diameter spreads across a room which is managed at 20°C temperature. Due to resistant heating, heat is produced in the wire, and the temperature of the surface of the wire is determined in steady operation to be 180°C. The voltage drops (110V) and electric current (3A) through the wire are also calculated. Determine the heat transfer coefficient for heat transfer between the air in the room and the outer surface of the wire through convection process.

Solution

When steady operating conditions are reached, as a result of resistance heating the amount of heat loss from the wire directly proportional to the amount of heat produced in the wire.

$$q = E_{generated}$$

$$= VI = 110 \text{ x } 3$$

$$= 330 \text{ W}$$

The wire surface area is

$$As = \pi DL$$

$$= \pi \text{ (0.002 m) (2.1 m)}$$

$$= 0.01319 \text{ m}^2$$

and $q = hA_s(Ts - T_\alpha)$

If heat losses from wire occur due to convection with disregarding any heat transfer through radiation. Then, heat transfer coefficient may be calculated as;

$$h = q_{conv}/[A_s(Ts - T_\alpha)]$$

$$= 330/[(0.01319)(180 - 20)]$$

$$= 156 \text{ W/m}^2\text{k}$$

Forced Convection

In forced convection, external mechanical force including fan, pump, and wind is used to move the fluid (Fig. 3.2). Forced convection oven for baking bread, meat chillers, ice cream hardening room are the examples in the food industry. In all these mentioned techniques, surrounding fluid is to be used to heat or cool the food products. Due to continuously replacement of liquid, the rate of heat transfer is greater than the normal convection process. Experiments showed that as the growth rate of fluid increases, heat transfer rate also increases. Liquid flow can be laminar, turbulent or transient who ordered as Reynolds number.

The equation is used, for laminar flow condition when Re ≤ 2100, to determine the Nusselt number.

$$Nu = 1.86\left(\frac{Re\ Pr\ Lc}{L}\right)^{0.33}\left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (3.15)$$

Where, L indicates the length of pipe (m), the characteristic dimension L$_c$ of the inside pipe diameter. When Reynolds number is between 2100 & 10,000, then the following expression is used for calculation of Nusselt number, which can be used to find coefficient of convection heat transfer h$_c$.

$$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}(Pr^{0.67} - 1)} \tag{3.16}$$

When the Reynolds number exceeds 10,000, then the following expression may be used for determining Nusselt number.

Again, feature determines the average temperature of the fluid, except mW, which is measured at the wall, L$_c$ shows the inner pipe diameter. The above equation is effective only where the temperature of surface is constant and heat flux is uniform.

3.2.4. Radiation

It is the form of energy released from a substance in the form of photons. This emission takes place when electron moves from one shell to another shell of atoms or molecules (Fig. 3.3). The radiation process is different from other mechanisms of heat transfer because radiation does not involve the material medium for energy transfer. In fact, all three heat transfer modes occur simultaneously to varying degrees.

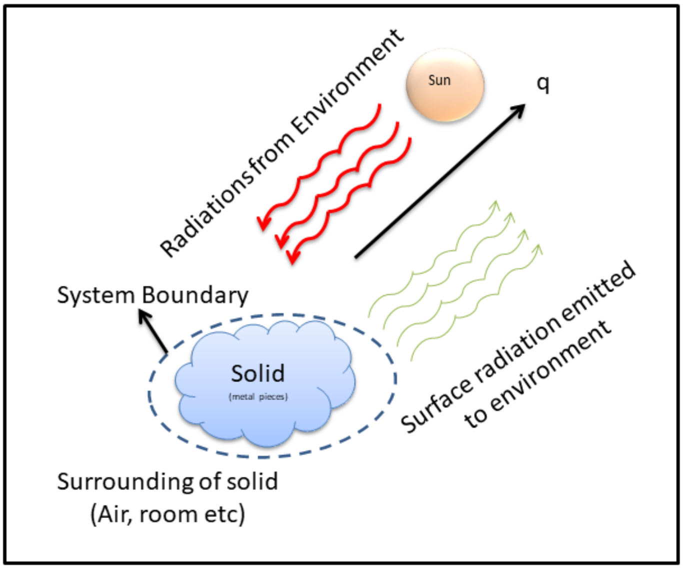

Fig. 3.3 A graphic illustration of radiation process for energy transfer

In heat conduction and convection, the heat is transferred from higher to lower temperature. However, heat by radiation may transfer among two bodies that are divided by a cooler media e.g. X-rays, microwaves, gamma rays, television waves and radio waves. All the surfaces above absolute zero, temperature, discharge thermal radiation. Maximum speed of radiation that a surface can emit is expressed as;

$$q_{emit,max} = \vartheta A_s T_s^4 \tag{3.17}$$

where, ϑ= 5.670 x 10^{-8} $Wm^{-2}k^{-4}$ indicates the Stefan-Boltzmann constant, A_s = area of body surface. A black body surface is the idealized surface for emitting radiations and the radiations emitted from black body are known as black body radiation.

The black body emits more radiations from all other real surfaces at the same temperature, and it can be expressed as,

$$q_{emit} = \vartheta \epsilon A_s T_s W \tag{3.18}$$

here, ϵ represents the surface emissivity. The emissivity of a surface may range $0 \leq \epsilon \leq 1$ that measure the closeness of surface to a black body for which ϙ = 1. An important feature of the radiation area is its absorbent α, that is part of incident radiation energy to the surface that absorbs the surface. A black surface absorbs all amount of radiation which incident on it. This is a best absorber of black (α = 1), as well as best emitter.

Example 3.4

A spherical ball at a temperature of 1000 K was suspended in air. Diameter of ball is 25 cm and is black. Calculate (i) the total emissive power (ii) the total quantity of radiation that is produced through the ball in 3 minutes.

Solution

1) The ball has taken black. The total emissive power is Stefan-Boltzmann law of Emissive power of black

$$E_b = \vartheta\, T_s^4$$
$$= (5.67 \text{ x } 10^{-8})\ (1000k)^4$$
$$= 56700\ Wm^{-2}$$

The spherical ball in the form of electromagnetic radiation produces 56.7 kJ of energy per second per surface area of the ball.

2) The ball emitted the radiation energy in 3 min. that can be calculated by multiplying the surface of the ball with emissive power and time duration:

$$A_s = \pi D^2 = \pi\,(0.25)^2$$

$$= 0.19635 m^2$$

$$Q = E_b A_s \Delta t$$

$$= (56.7)(0.19635)(3 \times 60)$$

$$= 2004 \text{ kWs} = 2004 \text{ k(J/s)s; [Since W = J/s]}$$

$$Q = 2004 \text{ kJ}$$

3.2.4.1. Application of Heat Transfer

Heat transfer plays the significant role in the development of novel food products. In food industry, it has various application i.e. pasteurization process involves heating of milk followed by cooling phenomenon. The equipment in which heating, and cooling of food materials is carried in a food processing plant called heat exchangers. There are two classifications of heat exchangers including contact and noncontact types. There is no physical separation among the cooling or heating medium and product is known as cotact type of heat exchangers. On the other hand, a thin wall is used to physically separate the food material and cooling or heating streams in noncontact-type of (indirect) heat exchangers.

Plate Type Heat Exchanger

This type of heat exchanger has broad applications in the food beverage and dairy industry. This equipment has a sequence of parallelly arranged stainless-steel plates which closely spaced in an exchanger body. To achieve better heat transfer, the turbulence in the product stream can be increased by pressing special patterns on the plates.

The intermixing of liquids can be prevented by using ‘gaskets’ which seal plate edges and ports. The flowing direction of heating/cooling medium and product stream may be same known as parallel flow or opposite nominated as counter flow. Intensive care should be taken in industrial plate heat exchangers to minimize the deposition (fouling) of solid food material like milk proteins can be deposited on the plate surface during processing. This deposition will decline the transfer rate of heat to the product through heating medium.

Tubular Type Heat Exchanger

This simplest, double-pipe, noncontact-type of heat exchangers has a long pipe situated in second pipe concentrically. Both liquid media move in the inner pipe and annular portion. The streams may be in parallel flow (same direction) or in counter flow (opposite direction). Tubular heat exchangers have some specific industrial applications such as orange juice heating 04-92°C and then cooled it up to 4°C; wash water of cottage cheese cooling with chilled water up to 18 from 46°C; and ice cream mix cooling with ammonia from 10 to 0°C.

Scraped-Surface Heat Exchanger

Due to fouling or film build up on the tube wall, heat resistance and hydraulic drag affected the heat transfer to a fluid stream in conventional types of tubular heat exchangers. If the inner side of the exchanger wall is scraped through different mechanical sources continuously then heat resistance can be minimized. Rapid heat transfer occurs due to scraping action. The scraped surfaces of cylinder (food contact areas) are constructed by corrosion free materials like stainless steel, nickel and nickel plated with chromium. The inner blades called rotor which protected by moulded plastic or plastic laminate. The product flows in the cylinder and rotor blades are packed in the outer jacket which consists of heating or cooling streams. Commonly warm water, steam, salt-water and cooling medium is used. Standard temperature ranges from -35 to 190°C used in this type of heat exchangers for products processing.

That exchangers have different applications in the food processing industry such as pasteurizing, heating, sterilizing, gelling, whipping, emulsifying, crystallizing and plasticizing. In these heat exchangers liquids are processed that can be pumped due to varied range of viscosities like soups, beverages, concentrated citrus juice, tomato paste, roasted beans, peanut butter and pie toppings.

Steam Infusion Type Heat Exchanger

In that exchanger, the product is not separated from steam and directly contacted with each other. First, material is pumped as a fluid from the upper portion of the exchanger then permitted to move through slim plates in the heating compartment. Then tiny droplets of the food made contact with steam and high rates of heat transfer can be achieved. Steam condensation raised product temperature very rapidly. Then heated products are collected at the bottom from the heating chamber. Sometimes water addition to the product is required by steam condensation, due to the water requirement of the overall process. Its application may include the processing of chocolate, thick soups, treated cheese, puddings, ice cream blends, milk and fruit pie toppings.

3.3. Mass transfer

Like the heat transfer, mass transfer occurs due to the concentration difference among the species in mixture. Here, mass transfer takes place due to the concentration gradient that is considered as driving force. This driving force is responsible of mass flow from higher concentration to lower concentration. The rate of material flow is dependent on concentration and described as;

Flow rate ∝ (Normal area) (Concentration gradient)

$$C = \frac{-\mathrm{kAdC}}{dx} \tag{3.19}$$

Here, C is the rate of mass flow rate through the surface area (A), dC/dx is the concentration gradient in a flow direction x, and k is the diffusion coefficient. For better understanding of a diffusion process, suppose a container divided into two equal halves through a wall. Initially, one half is full of nitrogen and second half is full of oxygen at the same temperature and pressure (Fig. 3.4). When the partitioning wall is detached, both gases will start to diffuse into each other. After a certain period, a homogeneous mixture of both gases will be achieved. This homogeneous mixture is due to mass diffusion process. As gas molecules move randomly, going to right or left halve is identical. Since the concentration of nitrogen molecule is higher on the left side, molecules will move toward the right side (where initial concentration of nitrogen molecule is zero). Similar phenomenon will happen for oxygen molecules but in opposite direction. After certain time, concentration of both gases will be equal in whole container.

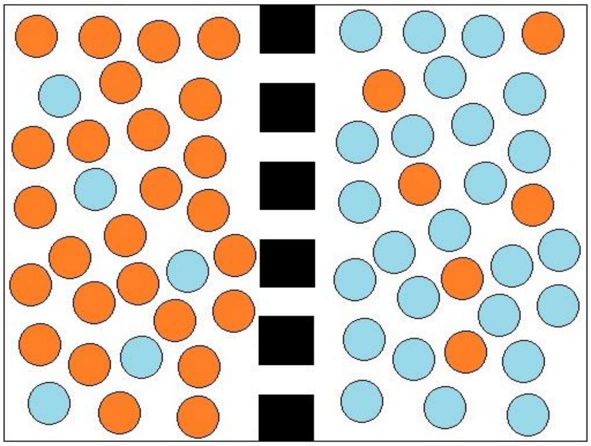

Fig. 3.4 An illustration of mass diffusion process (light colour indicates the oxygen and dark colour indicates the nitrogen gas

Similarly, mass transfer occurs in liquid and solids. For example, water evaporates from glass or cloths and diffuse into the air, it is liquid-to-gas mass transfer state. The size of dry ice gets reduced with the passage of time due to diffusion of CO_2 gas into the air; it is solid-to-gas mass transfer state. Sugar granules get slowly dissolved in a cup of tea and ultimately move upward that is solid-to-liquid mass transfer state.

Keeping in view heat transfer mechanism, a correlation can be established between mass and heat transfer. For example, for heat transfer temperature gradient in required likewise mass gradient. Heat transfer is possible through conduction, convection and radiation. Similarly, mass transfer is possible through conduction and convection collectively known as diffusion process. However, mass transfer is not possible through radiations. Following equation demonstrates the similarities among the heat and mass transfer.

$$\mathrm{q_{conduction}} = \frac{-\mathrm{kAdT}}{\mathrm{dx}}, \dot{\mathrm{C}} = \frac{-\mathrm{kAdC}}{\mathrm{dx}} \tag{3.20}$$

Mass transfer or diffusion process is first described by Fick’s law, which states that rate of diffusion of molecules at a site in a gas, liquid or solid mixture is directly related to the concentration gradient of that molecule at that site. It indicates that higher concentration for a mixture, more molecules of a mixture per unit volume. The concentration of a species is generally expressed on mole or mass basis. Concentration of a spices on mass basis is described in terms of mass per unit volume. For i^{th} specie in a mixture with volume V, partial density of species is expressed as;

$$\rho i = \frac{m_i}{V} \tag{3.21}$$

and total density of a mixture is expresses as follow;

$$\rho = \frac{\sum m_i}{V} \tag{3.22}$$

Similarly, concentration on mole basis may be described as molar concentration that is kmol of substance in unit volume. For i^{th} specie in a mixture with volume V, partial molar concentration is expressed as

$$C_i = \frac{N_i}{V} \tag{3.23}$$

and total molar concentration of a solution is expresses as follow:

$$C = \frac{\sum N_i}{V} \tag{3.24}$$

3.3.1. Diffusion Process

Two processes are involved in mass transfer including mass transport in bulk form due to convection flow and mass diffusion taking place at a molecular level. Fick's law of diffusion state it mathematically, which is defined as the mass flux per unit area is directly related to concentration gradient of component.

$$\frac{m}{A} = \frac{-\mathrm{D}\Delta \mathrm{c}}{\Delta \mathrm{x}} \tag{3.25}$$

Thus, m is mass flux of component (kg/s); c is the component concentration expresses as mass per unit volume (kg/m^{-3}); D is equal to mass diffusivity (m^2/s); and A is equal to area. Mass flux and the component concentration can be described as kmol/s and $kmol/m^3$, respectively.

3.3.2. Unsteady-State Mass Transfer

When the concentration rate increases or decreases with time, it causes the changes in component concentration in different food applications. Different examples are included in unsteady-state mass transfer like antimicrobial substance or salt diffusion in a solid food material or dispersion of a volatile flavour in a dry food matrix. Under isothermal conditions, the diffusion of water phase can occur within a food which ultimately leads to the absorption of moisture by a dry food material when stored for longer time.

3.3.3. Transient-State Diffusion

Within product mass the diffusion of the food component could be determined by following equation:

$$\frac{\Delta C}{\Delta x} = \frac{\mathrm{D}\Delta^2 \mathrm{c}}{\Delta \mathrm{t}^2} \tag{3.26}$$

Where D = mass diffusivity c = the concentration of the component which diffuses through the solid food matrix t = time.

3.3.4. Mass transfer in Moving & Stationary Medium

Mass transfer occurs simultaneously in motion and stationary medium. When a specie (A) is dissolved or diffuse in a stagnant species (B) it is known as mass transfer in stationary medium. For example, liquid or gas diffusion in a stagnant solid or liquid species. It may include the transfer of water vapor through the walls of a room. In these cases, diffusive mass and molar fluxes of specie are same as described the absolute mass and molar fluxes in equation 3.20. This may happen as concentration of specie A is less than the host or stagnant medium B.

Besides, diffusion process takes place when both species are in motion. For example, evaporation of water from river or lake, mixing of two moving liquids in a pipe. In this scenario, estimation of diffusion is quite difficult because molecules of different species show movement in various directions at various velocities. Moreover, turbulent flow may add more complexities in calculation. Therefore, a simple system consisting of two species A & B with unidirectional flow is considered for better understanding. In this case, molar concentration or total density of the mixture not changed, while the species densities (A & B) cannot remain constant in the x-direction.

The rate of mass flow (ṁ) is described as:

$$\dot{m} = \rho U A \tag{3.27}$$

here, U is equal to velocity, and A is equal to the surface area. The relation conservation of mass flux for both species A and B may be described as;

$$\dot{m} = \dot{m}_A + \dot{m}_B$$

or in terms of density,

$$\rho U \Delta A = (\rho_A U_A + \rho_B U_B) A$$

Simplifying this equation results in;

$$U = \left(\frac{\rho_A U_A + \rho_B U_B}{\rho A}\right) \tag{3.27}$$

here, U is defined as the average mass velocity of the flow.

3.3.5. Mass Transfer and Solvent Extraction

Mass transfer controls the phenomenon of solvent extraction by transferring mass of solutes to the solvent after passing the transfer interface of the material. Molecular diffusion and transport rate transfer the mass within solid and liquid materials and that rate is known as the effective diffusivity (D). That liquid diffusivity is dependent on various parameters including the interactions of molecular solvent/solute, the viscosity of the mixture or the solute molecular size. At 25°C in diluted water solutions, some solutes have distinctive values of D, such as 5×10^{-10} m^2/s (sucrose), 12×10^{-10} m^2/s (sodium chloride) and 0.7×10^{-10} m^2/s (lactalbumin). The extracted products like coffee soluble (coffee beans/water) and oil (soybean flakes/hexane) have same D value of 1×10^{-10} m^2/s. The porosity of the solid substance is directly related to diffusivity of solutes. Small molecules such as sugars have larger diffusivity values as compared to large molecules like proteins and lipids.

Various hydrothermal and mechanical pre-treatments of solid food material can be used to increase the solutes diffusion rate such as steam injection, flaking and slicing. During oil extraction, cellular structure can be modified by heating with water or steam which enhances the diffusivity. It is estimated that 22% oil recovery can be achieved from oilseeds with mechanical force (obtain over 90% oil from seeds) and leaching process with some organic solvents including alcohols, chlorinated hydrocarbons and hexane. The diffusion path (thickness) of fruits and beets can be reduced by slicing and flaking without cells injury which prevent solid and liquid separation and ultimately release components of cell into solutions.

Denaturation of protein can be done by heating thin and long slices of sugar beets at 50–60°C without the leakage of non-sugar components which enhance the diffusivity of sucrose. Roasting (thermal treatment) of coffee beans developed high porosity which facilitate the water extraction of soluble solids. The processing of soluble decaffeinated coffee can be controlled by caffeine diffusion in water (Please see chapter 10 section mass transfer in packaging).

Problems

1. A furnace wall is to be built from Firebrick 25.4 cm thickness and structural bricks of 20.32 cm thick. Thermal conductivity was 1.556 W/m K and 0.691 W/m K respectively. The inner surface of the firebrick is at 982°C, the outside surface of the brick building is at 32°C. Find the heat rate per square meter and temperature interface bricks.
2. The wall of cold storage is 3.5 m high, 12 m wide and 30 cm thick. The outermost layer of the wall of bricks 10 cm thick, then a layer of 12 cm of concrete and then 8 cm of cork. Mean temperatures of inner environment of cold storage is -10°C and the mean temperature of the outer wall surface is 20°C. Determine the heat transfer rate through the wall if the thermal conductivity of brick, concrete and cork 0.70, 0.77 and 0.043 W/mK, respectively. Set the temperature at the interface between layers of cork and concrete, concrete layers and brick.
3. A hot air supply channel is used to transport the heated air into the chamber spray drying. The channel is isolated from the 5 cm layer of glass fiber batts. The inner temperature of the surface of pipe is 150°C, external, 25 °C. Find the heat loss rate per square meter of the hot-air channel, if thermal conductivity Batts is 0.0432 W/mK.
4. A stainless-steel tube transmits high-pressurized steam. It has 6.35 cm thick insulation layer. Inner surface temperature of steel pipe is 350°C and outer temperature of insulation is at 100°C. If the thermal conductivity of the steel

tube and the insulation of 15.1 W/mK and 0.18 W/mK, respectively. Determine the rate of heat loss per meter pipe length. Inner and outer diameters of the steel tube are 2.54 and 5.08 cm, respectively. If the melting insulation is 200°C, and then the insulation be safe and maintain your integrity?

5. A 1.5 cm thick steel tube having internal diameter 5.5 cm has a covering 5.5 cm thick insulation. The temperature of inner surface of wall of steel pipe is 120°C. The insulated pipe has an ambient temperature 25°C. The coefficient of convection heat transfers on the outside of the insulated surface is 55 W/(m^2K). Determine the temperature of the steel isolation interface. Barrel length is 1 meter and the thermal conductivity of steel and insulation are 54 W/m K and 0.04 W/m K, respectively.
6. A sphere diameter 5.5 cm, length of the cube side of 5.5 cm, and a rectangular prism measuring 5.5 cm x 5.5 cm x 6.5 cm, all initially at 5°C were then kept at ambient air at 36°C on all their surface with a coefficient of heat transfer 11.5 W/m^2K. All these objects are made of pure aluminum with ρ = 2702 kg/m^3cp = 903 J/kgK and k = 237 W/mK. Determine how much will be needed for each geometry temperature rise to 20°C.
7. A brick of 205 x 105 x 60 mm in size are burned in the furnace to 1150°C, and then allowed to cool in a room with temperature of 25°C and the coefficient of convection heat transfer 5 W/m^2K. If brick has properties ρ = 1920 kg/m^3, c_p = 790 J/kgK and k = 0.90 W/mK calculate the time needed to cool the bricks on the temperature difference of 5°C from the ambient air.
8. Evaluation of the time required to center the spherical melon, 23 cm in diameter at a temperature of 6ºC upon melon, initially at 27°C, is in the refrigerator at 1.5ºC. The surface of the thermal conductivity will be 28.4 W/m^2K, density 1001 kg/m^3, specific heat of 3759 J/kgK and thermal conductivity 0.432 W/mK. You determine the mean temperature melons when the city ended 6°C.
9. The egg was considered sphere of 5.5 cm diameter and properties like water. It was kept in the water having temperature 100°C. The heat transfer coefficient on the surface of eggs is 800 W/m^2K. If the initial temperature of the eggs is 6.5°C and is cooked when the temperature reaches at 65°C center, calculate the total time required to keep in boiling water.
10. Citrus fruits destroyed if exposed to extended subfreezing temperatures. Orange 9 cm in diameter initially at 20°C faced the cold front for one night for about 5.5 h. Ambient temperature suddenly dropped to -5°C as the cold front moved from the coefficient of heat transfer 15 W/m^2K. If orange has similar properties to water, determine whether any part of the oranges will freeze that night.
11. A potato of 8 cm has the properties of ρ = 1100 kg/m^3cp = 3900 J/kgK, k = 0.6 W/mK and α = 1.4 x 10-7 m^2/s. Potatoes in the beginning of the average temperature of 22 °C to bake in oven at 180 °C until the temperature sensor

is inserted in the center indicates the reading potato 70ºC. The potatoes are then taken out of the oven and wrapped in a thick towel to protect the heat loss from baked pot that almost no heat is lost from a baked potato. Assuming the coefficient of heat transfer in the oven to 40 W/m^{2}K, determine (a) how many potatoes baked in the oven, and (b) the final equilibrium temperature of potatoes having wrapped.

12. A mother pours milk in the thin walled glass of diameter 6 cm for heating the milk for baby. Height of milk in glass is 7 cm. She then holds the glass in a large pan containing hot water of 700 °C. Due to continuously stirring, milk has a uniform temperature at all time. If the coefficient of heat transfers between the glass and the water is 120 W/m^{2}K. Calculate the time taken for increasing the temperature of milk from 30 °C to 380 °C. If properties of milk are assumed to be the same as those of water. In this case can milk be treated as a lumped system? Why?

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Chapter 4

Food Preservation Engineering

Muhammad Kashif Iqbal Khan, Abid Aslam Maan and Rana Muhammad Aadil*

Abstract

Food security is the emerging issue of the world and worsened with unequal distribution of food on earth. Therefore, it needs better transportation and food with prolonged shelf life. Natural food products have shorter shelf life. Efforts have been made to increase shelf life of food products. In this regard, food engineers have developed various principles of food preservation which resulted in new technology. This field is emerging one and still a lot of research is going on to develop novel processes for food preservation. In this chapter, traditional and basic principle of food preservation are discussed i.e. evaporation, drying, and membrane separation. Besides, various preparatory operations are also described which are essential to maintain quality, safety and shelf life of food product.

Keywords: Quality, Evaporation, Drying, Preservation, Sulphating

4.1. Need of Food Preservation

Food is the necessity for all organisms on the earth. All types of food products are not produce in the same region. Therefore, it needs transportation to other areas.

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Moreover, most of the food products have shorter shelf life owing to presence of water, microbial growth and other factors. The food quality reduces with time and consumer may not like/accept it. Thus, it should be preserved to provide quality and fresh food product. Other reasons of preservation are to produce value added products and variation in foods. Valued added products provide better quality, nutrition, and organoleptic properties. Food variation is important as consumer demands for different flavours, taste and pleasurable food. Food preservation starts from farm and ends at fork which is known as “Farm to Fork” concept. It includes the whole food chain, growing, harvesting, processing, packaging, and distribution to the consumer which requires a unified approach. Thus, knowledge of food science and engineering are the main contributors for food preservation. Food science deals with the identification of food properties that needs to be preserved and effect of processing on food. While, engineering deals with the principle of food preservation and development of various new technologies or processes for food preservation. Thereby, aim of this chapter is to introduce commonly used preservation techniques. It is important to consider following points during food preservation;

- Required quality level
- Storage time
- Consumers/target group

During storage, various biochemical reactions keep going on that reduce the food quality. Quality is an everchanging concept which may be defined as “degree of fitness for use or the conditions indicated by the satisfaction level of consumers”. When food quality is spoiled, it is considered inappropriate for eating, this stage is known as end of shelf life (Fig. 4.1). Therefore, rate of change among quality attributes determines the shelf life of food product. Food quality attributes may comprise of appearance, microbiological and sensory aspects. Loss in quality attributes can be reduced with different food preservation methods.

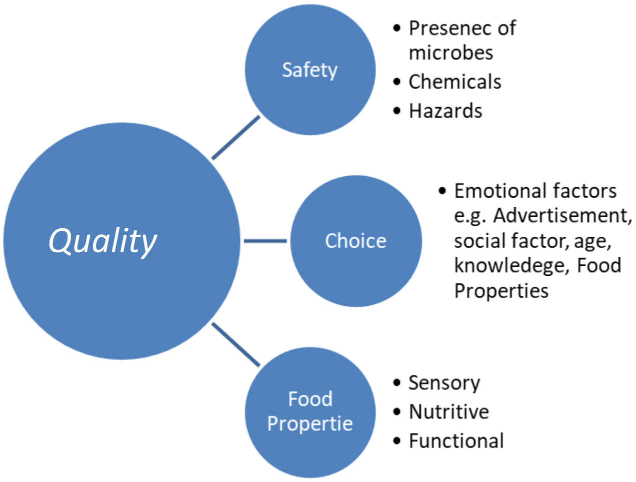


Fig. 4.1. Overview of various factors affecting quality and choice of a food product

4.1.1. Food Preservation Methods

Generally, preservation methods are divided into three groups based on their mode of action or principle of preservation.

- Inhibition or slowdown of microbial, enzymatic, and chemical spoilage
- Inactivation of microbes and enzyme
- Avoiding the re-contamination

Traditional preservation techniques use one of these three principles to increase shelf life (Fig. 4.2). To increase the quality and to meet consumer demands, use of single or combined principle and method of preservation may be achieved. Ideally, preservation starts from food harvesting; at this point food is thought to be affected more than any other stage e.g., harvesting of fruits and vegetables, meat from slaughtered animals. At this stage, microbes and dust particles may enter and reduce the quality and shelf life. Therefore, different handling and preparatory operations carried out before the application of final preservation technique / principle. These preparatory operations are useful to maintain quality, freshness, and integrity of food. Therefore, preparatory operations are discussed earlier than preservation methods. In short, this chapter provides an overview of material handling, preparatory operations and preservation techniques. These steps aim to provide safe, healthy and quality food product.

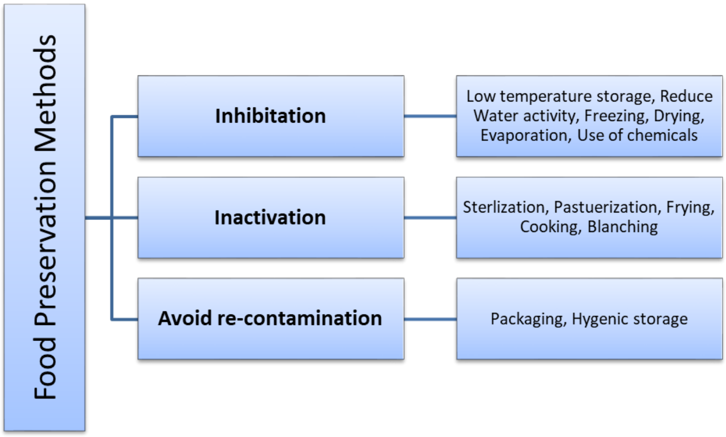


Fig. 4.2 An overview of different food preservation methods used in food industry

4.2. Preparatory Operations

The characteristics of the raw materials entering in a food industry vary significantly due to unavoidable factors. For example, in case of agricultural commodities, a combination of factors including type of variety, agricultural practices and weather conditions result in different raw material characteristics. Apart from these directly related factors, postharvest handling may be detrimental to raw material quality. The important characteristics of raw materials include geometrical shape, colour, texture, functional properties and flavour. Ideally, a food processor would like to have a uniform quality of raw materials; for example, a uniform size and shape of food will facilitate designing a heat transfer process, separation, sorting, grading, and evaporation etc. In real life, raw material with uniform quality attributes is usually not possible. Therefore, prior to main processing, preparatory operations are required to have desired food units. These preparative operations are discussed in the following separate sections.

4.2.1. Cleaning

Agricultural commodities may get heavily contaminated during pre- and postharvest handling. These contaminants range from safe to dangerous one, and include:

- Unwanted plant parts (leaves, twigs, husks, etc.)
- Contamination from growing area (soil, sand, stone, etc.)

- Physical contamination
- Biological contamination
- Chemical contamination (insecticides, pesticides, fertilizers, mineral oils)
- Microorganisms and their toxins
- Metallic pieces
- Insects, pests, animal hair and excreta

Therefore, for most of the times food is cleaned before processing. In addition to safety of the consumer, removal of contaminants always is essential for the protection of machinery and other process equipment. For example, the presence of metallic pieces may be detrimental. Broadly, cleaning may be categorized as wet or dry.

Dry cleaning

Dry cleaning is usually most appropriate for cleaning of raw materials (like grains) that should not be wetted with water. However, dry cleaning is less effective compared to wet cleaning as complete removal of contaminants is difficult. Commonly used methods for dry cleaning include:

Screening – removal of contaminants using sieves / meshes

Scalping – removal of larger contaminants, e.g., straw, husk, twigs

De-dusting – removal of dust or sand particles

Aspiration – removal of contaminants based on differences in aerodynamics of food density and unwanted material

Magnetic and electrostatic cleaning – separation based on different attractive and repulsive forces e.g., metal pieces from cereals and spices etc.

Wet cleaning

Wet cleaning is carried out in this method using a suitable liquid/solvent; usually water is used as solvent for most of the food applications. In this method, cleaning efficiency is quite high; however, the process is relatively more expensive due to a continuous supply of pure water and a continuous production of same quantity of dirty effluent. Heavily contaminated materials like root crops (potatoes, carrots, etc.) may require soaking prior to wet cleaning. The process efficiency can be further increased by using different strategies, for example, using detergents in cleaning water or by mechanical abrasion. Furthermore, a proper sanitation of the washing area is required. It may be carried out by using permissible levels of different chemicals like chlorine, citric acid, and ozone in washing water.

Spray washing is a modification of wet cleaning process where the cleaning effciency depends on water pressure and exposure time; however, care must be taken to avoid the product damage. Flotation and froth flotation are further modifications in which contaminants are removed by buoyancy and surfactant effects, respectively. To avoid re-contamination and spoilage of the raw material, dewatering must be carried out immediately after the wet cleaning. Commonly used dewatering methods include centrifugation, screens, reels and drying. A specific dewatering method should be selected keeping in view the product properties.

4.2.2. Sorting and grading

A uniform raw material is generally preferred for processing that is achieved by sorting and grading. Separation of raw material based on a single quantifiable attribute (weight, size, shape, density, or colour), is termed as sorting. However, evaluation of the complete quality of a food product with number of quality characteristics is usually referred as grading.

4.2.3. Peeling and size reduction

Unwanted or inedible material of various fruits and vegetables is usually removed by peeling. Knife peeling, caustic peeling, abrasive, flash steam peeling, and flame peeling are among the most commonly used peeling methods in food industries. Irrespective of the adopted peeling method, the main consideration while performing peeling should be the efficient removal of the unwanted materials and most importantly to minimize the wastage of the edible portions.

In numerous processing operations, it is usually required to reduce the size of raw material for different purposes. For example, size reduction improves the eating quality, and is employed to prepare a variety of products. In some cases, size reduction may facilitate other operations, e.g., a less time for cooking due to an increased surface area.

4.2.4. Blanching and sulphiting

Blanching is a mild heat treatment method that is performed earlier to final processing of food operations like freezing, dehydration, canning, concentrating, etc. The prime objective is to inactivate the enzymes responsible for reduction in quality of the processed products. Blanching is usually carried out by using boiling water or steam for few minutes. After blanching the food material is either cooled quickly or passed to the next handling / processing step.

Sulphiting is the application of sulphur dioxide (SO_2) or inorganic sulphites (SO_3), in various foods and it is usually carried out to control enzymatic and non-enzymatic browning, growth of microbes. The main objective of using sulphites also includes the preservation or prevention from the discolouration of fruit and vegetables (bleaching, reducing agents or antioxidants).

4.3. Food Preservation Techniques

Basic needs to preserve food are to remove water or reduce its availability to organisms or active ingredients. Water is present in free and bound form in a food product which determines the shelf life of a food product. Bound water may be defined as the water present in food having different properties than pure water. It is further classified into non-freezing, immobile, non-solvent, and monolayer water. Binding energy and type of bound water determine the process required to preserve food and processing cost. This can be achieved through various methods and few commonly used methods are discussed as fellow;

- Evaporation
- Drying
- Refrigeration
- Membrane separation

4.4. Evaporation

Evaporation is an important preservation technique applied to remove water from liquid food products. It increases the solid contents in food which subsequently increase shelf life and enhance/ease the transportation. Water removal increases the shelf life, microbiological stability and lower the cost of transportation and storage. For example, preparation of tomato paste is done by evaporation. In this process, water is removed from tomato juice (5-6% total solids) to achieve 35-37% total solids. This paste has longer shelf life (about a year) compared to fresh tomatoes. The prime objectives of evaporation are;

- Removal of a solvent (usually water) to increase solid contents
- To achieve it with least total process cost

The principle of evaporation is to boil solvent and separate it from the product. Water from heat sensitive food products is evaporated under vacuum conditions. Although, the latent heat of vaporization is high for water that can be reused in multiple stages or through recycling of vapours. An evaporator may consist of following important components;

- Preheater that brings food solution closer to boiling point
- Feed distributor that equally distribute the feed among the tubes
- An energy supply (electricity and steam)
- Heat transfer techniques
- A separator to separate liquid from vapours
- Condenser that extracts energy from outgoing vapours. It helps to maintain the vacuum

Efficiency of evaporator depends on the integration and optimization of its components. In evaporation, efficient use of steam and electrical energy is made by using different techniques in combinations (like multiple-effect evaporation, thermal or mechanical vapour recompression). For example, a liquid can be concentrated to 50% solids easily. Moreover, a sugar solution can also be concentrated to 98% solids (Madaeni 2010). However, limitation of evaporation includes the heat sensitivity of food product that can be concentrated through other process like freeze concentration.

4.4.1. Types of Evaporators

In food industry, numerous categories of evaporators are in practice that can be divided into two types based on physical and energy usage. The type of evaporator to be used is determined by the food material composition. Followings are the different types of evaporators based on physical properties;

- Short Tube Evaporator
- Vertical Rising Film
- Vertical Falling Film
- Forced Circulation
- Plate Evaporators
- Thin-Film Spinning Cone

A typical evaporator is made up of vessels that are connected to various tubes. In these tubes, liquid circulates around calandria more than once through and provides multi-pass effect.

Short-Tube Evaporator

This is the oldest type of evaporators which is also known as Robert evaporator. In this evaporator, tubes are vertically placed around the calandria enclosed in a shell.

Steam enters the tube and heat transfer occurs through convection. Material inside the calandria is continuously mixed with stirrer or agitator for equal distribution of heat and ease in flow of fluid with high viscosity. Sugar cane industries mainly rely on this type of evaporator. As it has advantages of higher heat transfer rates, ease in cleaning, and low cost (Madaeni 2010; Brett et al. 2013)

Vertical Rising Film Evaporator

Like short tube evaporator, feed is heated with steam which on vaporization rises and creates a film on the inner surface of tube. These evaporators effectively transfer the heat with shorter residence time. This evaporator work at higher temperature gradient only because lower temperature difference does not provide pressure required to carry the feed upwards. It will reduce the efficiency and increase the processing cost.

Vertical Falling Film Evaporator

It is the most common used evaporator that was introduced in 1953 by Wiegand Apparatebau (Dennis et al. 2006). Liquid product entered from the top and moves down in the tube which is heated from outside. Concentrates and vapours are separated; later one is reused for heating purpose. While the concentrate may be packed, reprocessed to achieve desirable solid contents or development of new products.

Forced Circulation Evaporator

In this evaporator, substance is heated; however, vaporization of liquid does not occur in heat exchanger. Vaporization of liquids take place in flash chamber where liquid and vapours are separated from each other. Advantage includes higher recirculation rates which enhance the heat transfer. More viscous liquids can easily be handled and less chance of fouling on the inner side of the tubes.

Scraped Surface Thin Film

It is used for highly viscous (20 Pas) or sticky liquid products that are heat sensitive and easily deposit on the surface. Cleaning is carried out by rotating blades which remove the fouling from the surface of tubes; increasing the heat transfer. Food products, concentrated with this evaporator, are tomato paste, gelatine, and whey.

Plate Evaporators

It works on the principle of plate heat exchangers in which liquid and heating sources are separated by plates and move side by side. Liquid may be vaporized in the plates or in flash chamber. The advantages include ease in handling, flexible operation and higher transfer of heat which reduce the holding time along with fouling of the equipment. However, capacity of this evaporator is lower as compared to others.

Thin-Film Spinning Cone

Thin film spinning cone evaporator is recently introduced. A very thin layer (100 micrometre) is produced on hollow cone, which is heated through steam. It is useful for heat sensitive products. It has higher production rate and viscous fluids with viscosity up to 20 Pas can easily be processed.

4.4.2. Types based on Energy Use

Above mentioned evaporators can be classified based on the energy use in terms of vapour flow and reuse. There are two types of evaporator based on energy use.

- Single effect evaporator
- Multiple effect evaporator

In single effect evaporators, vapours produced from food are discarded although having potential heat energy (Fig. 4.3). While, these vapours are reused to heat food products in multiple effect evaporators (Fig. 4.4). Reuse of vapours may be carried out in two or more evaporators which depend on the nature of food, required concentration of solids, and amount of water to be removed. Reuse of vapours as heating medium results in more/higher energy-efficient systems.

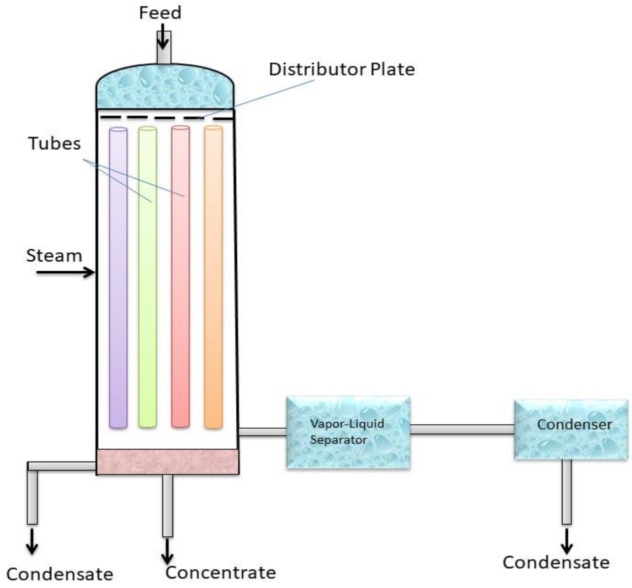


Fig. 4.3 An illustration of single effect evaporator

In multiple effect evaporators, steam is introduced into first effect only. The vapours, produced in first effect, are consumed as heating source for next (2nd) effect and this process continues. Partially concentrated food product, coming from first effect, becomes feeds of second effect. Consequently, product of second effect is the feed for third ones and continue till the last effect. Finally, product comes out with required concentration in the last effect. These specific arrays are known as forward feed system (Fig. 4.4).

In industry, other flow arrays are used which may include parallel and backward feed schemes. Aim of these different designs is to lower the energy consumption. The efficient utilization of energy can be estimated (generally known as steam economy) through following equation;

$$Steam\ economy = \frac{m_v}{m_s} \tag{4.1}$$

Where, m_v and m_s are the mass flow rates of vapours and steam, respectively. In this equation, heat losses and energy consumption for pre-heating are overlooked.

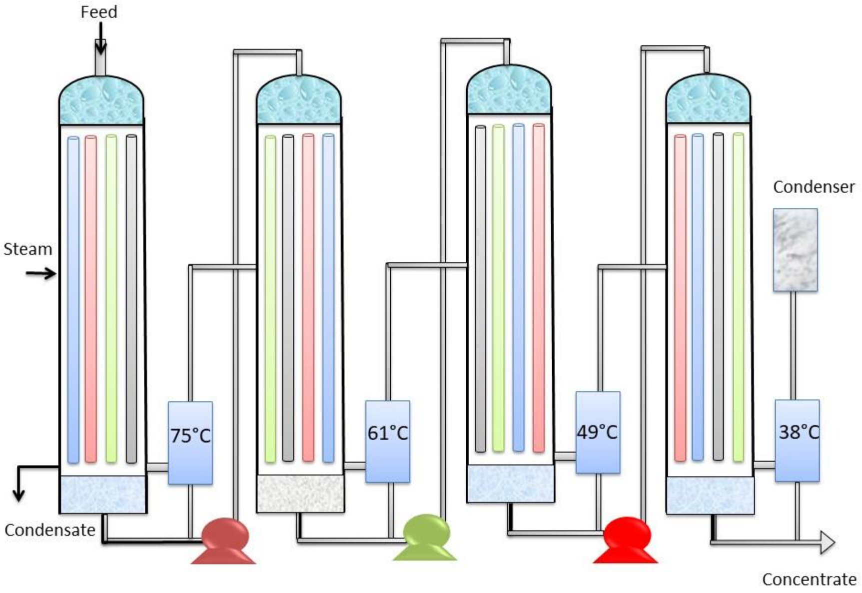


Fig. 4.4 A drawing of multiple-effect evaporator representing its working principle

4.4.3. Applications

In food industry evaporators are commonly used for following purposes;

Fruit based products

Fruit juices are concentrated to about 65% solids contents by evaporation of water. It not only facilitates transportation and storage but increases the shelf life by providing stability to the product. Other products may include jams and jellies which are concentrated product of fruits.

Milk based products

Water from milk and whey is evaporated. The concentrated products have good stability, longer shelf life and less volume with easy transportation.

Sugars

Extraction of sucrose from sugar beet and cane is carried out with hot water, which is subsequently evaporated to produce concentrated syrup. This syrup is further evaporated to get super saturated solution which is required for crystallization.

4.4.4. Designing an evaporator

As food engineering, one should keep in mind that type of food product ultimately determines the type of evaporator used. As evaporation deals with the removal of water from food product. Therefore, physical, biological, and chemical nature should be kept in mind while selecting an appropriate evaporator for a specific food product. These factors may include heat sensitivity of product, microbial growth & load, viscosity, density, thermal conductivity and boiling point of elevation. These food properties change frequently during evaporation and may limit the process. Therefore, prior information about food composition, desired capacity of evaporate, required concentration of solid in end product must be considered to design an evaporator. Two types of calculations are required for designing an evaporator which are mass and energy flow. Both also helpful to indicate the size of an evaporator.

Mass flow estimation

An evaporator may work at certain flow rate per day that need four hours of cleaning. Thus, production time is limited to twenty hours. Besides, a factory may not need to run evaporator for twenty-four hours a day or it may want to run different products through one evaporator. It limits the processing time of an evaporator. Constant flow rate through the evaporator can simply be estimated from the processing time. Use of mass balance for overall solids in feed and end product, helps to know the required amount of evaporation and flow rates. According to law of mass conversation,

$$M_f = M_v + M_p \tag{4.2}$$

Here, M_f, M_v and M_p are mass flow rates of feed, vapours & product, respectively. Moreover, total solid balance is determined from following equation;

$$M_f x_f = M_p x_p \tag{4.3}$$

Here, x_f and x_p are the mole fraction of solids in feed & product, respectively. These calculations will help to estimate the time of cleaning, total running time in a day, process time of product and flow rate of product/feed in an evaporator.

Energy flow estimation

Energy calculation is influenced by the type of evaporator hence there are various ways to calculate the energy requirement for single effect and multiple effect evaporators. In the following paragraph, energy and mass flow are calculated to for each type of evaporator. For example, we are going to concentrate apple juice with single effect evaporator. Juice is entering in evaporator at temperature T_1 and leaves it at temperature T_2 while inside evaporator temperature is maintained at T_0. Equations 4.2 & 4.3 give us the estimation of mass flow rates and mass fraction in feed and product.

For energy calculation, enthalpies input, and output should be calculated. Inputs are feed and steam, while vapours, products, and condensates are regarded as outputs during evaporation. Following equation represent the energy balance;

$$M_f H_f + M_s H_s = M_v H_v + M_p H_p + M_c H_c \tag{4.4}$$

where, H represent the enthalpy, M_s and M_c represent the mass flow rate of steam and condensate, respectively. Flows of steam and condensate are considered as same. Amount of heat transfer depends upon the area of heat exchanger, temperature variation between steam and inside the evaporator, and heat transfer coefficient. The relation of these is described in the following equation:

$$q = UA(T_s - T_1) = M_s(H_s - H_c) \tag{4.5}$$

These equations are helpful to calculate the desired size according to the required throughput of a single effect evaporator. Similarly, we can calculate the size of evaporator with multiple effects. Here, we will treat each effect as single one and finally combine into one equation to get final calculations. Thus, mass balance in n number of multiple effect evaporators will be as follow;

$$M_f = M_{v1} + M_{v2} + M_{v3} .... + M_{vn} + M_p \quad (4.6)$$

Solid fraction in the flow are as follow;

$$M_f X_f = M_p X_p \quad (4.7)$$

For energy flow, enthalpies of each effect will be written separately, thus energy equation will be as written as follow:

$$M_f H_f + M_s H_s = M_{v1} H_{v1} + M_{f1} H_{f1} + M_s H_{c1} \quad (4.8)$$

$$M_{f1} H_{f1} + M_{v1} H_{v1} = M_{v2} H_{v2} + M_{f2} H_{f2} + M_{v1} H_{c2} \quad (4.9)$$

$$M_{f2} H_{f2} + M_{v2} H_{v2} = M_{v3} H_{v3} + M_{f3} H_{f3} + M_{v2} H_{c3} \quad (4.10)$$

$$M_{f(n-1)} H_{f(n-1)} + M_{v(n-1)} H_{v(n-1)} = M_{vn} H_{vn} + M_p H_p + M_{v(n-1)} H_{cn} \quad (4.11)$$

Where, 1,2,3. . . .n represent the effect numbers.

$$q_1 = U_1 A_1 (T_s - T_1) = M_s (H_s - H_{v1}) \quad (4.12)$$

$$q_3 = U_2 A_2 (T_1 - T_2) = M_{v1} (H_{v1} - H_{v2}) \quad (4.13)$$

$$q_3 = U_3 A_3 (T_2 - T_3) = M_{v2} (H_s - H_c) \quad (4.14)$$

and

$$q_n = U_n A_n (T(n-1) - T_n) = M_{(v(n-1))} (H_s - H_c) \quad (4.15)$$

Steam economy of this evaporator is;

$$Steam\ economy = \frac{M_{v1} + M_{v2} + M_{v3} .. M_{vn}}{M_s} \quad (4.16)$$

Following example describe the use of these equations to calculate the size and efficiency of a multiple effect evaporator.

Example 4.1

A liquid is being concentrated from 11% to 50% total solids with use of double effect evaporator as shown in Fig. 4.5. It has equal size of effects and temperature gradient. Feed flows at rate of 10,000 kg/h at temperature 30 °C and vapours leaves at 1.10 kg/s. The boiling point of liquid is 70 °C in second effect and condensate leaves first and second effect at 95 and 70 °C. In first effect, steam enters at pressure of 198.5 KPa. The co-efficient of overall heat-transfer inside of both effects are 1000 W/m^2 °C and 8000 W/m^2 °C, respectively. The specific heats of the liquid at initial, intermediate, and final concentrations are 3.8, 3.0, and 2.5 kJ/(kg°C), respectively. Estimate the steam requirements and steam economy for double-effect evaporator.

Given Data

Mass flow rate of feed = M_f =10,000 kg/h = 2.78 kg/s

Mass flow rate of vapours = M_v = 1.10 kg/s

Solid fraction in feed =X_f = 0.11

Solid fraction in product =X_p = 0.11

Steam pressure = 198.5 kPa

Feed temperature = 30 °C

Boiling temperature in second effect = T_2 =70 °C

Coefficient of Heat transfer in first effect = 1000 W/m^2 °C

Coefficient of Heat transfer in second effect = 800 W/m^2 °C

Specific heat of feed = C_f = 3.8 kJ/(kg °C)

At intermediate concentration;

Specific heat of feed = C_{pf} = 3 kJ/(kg °C)

Specific heat of product = C_p = 2.5 kJ/(kg °C)

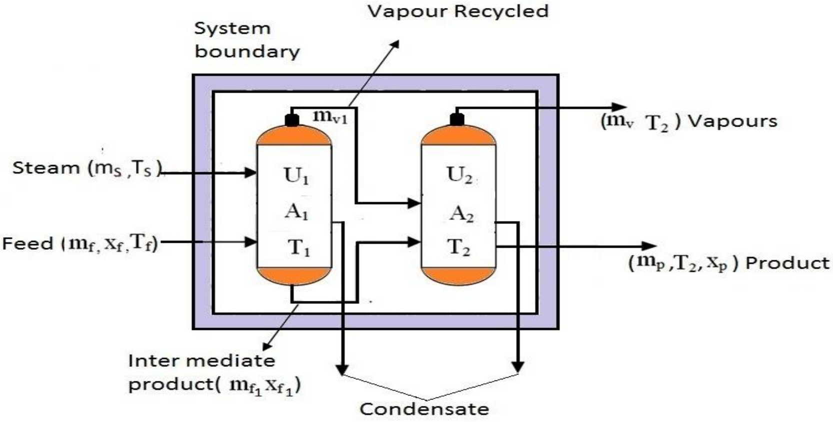


Fig. 4.5 A representation of double effect evaporator

Solution

First, we will calculate;

Product flow rate = (0.11)×(2.78) = $0.75M_p$,

and $M_p = 0.61$ kg/s

The total amount of water evaporated; 2.78 = 1 .10 + M_{v2} + 0.61

and $M_{v2} = 1.07$ kg/s

Temperature gradient is 50ºC that means each effect will have 25ºC.

Thus, heat transfer will be equal in both effect and calculated as;

$q_1/(U_1A_1(T_s - T_1)) = q_2/(U_2A_2(T_1 - T_2))$

Now enthalpies of the systems are as below;

$H_{f1} = C_p (T_f - 0) = 3.8(20\text{-}0) = 76$ kJ/kg

$H_{f2} = C_{fp} (T_1 - 0) =3(95\text{-}0) = 285$ kJ/kg

$H_{f3} = C_p (T_2 - 0) =2.5 (70\text{-}0) = 175$ kJ/kg

add these values in heat transfer will result in following

$(2205.59M_s)/25000 = (2270.14M_{v1})/20000$

$0.088M_s = 0.124M_{v1} \Rightarrow M_{v1} = 1.41$kg/s

Steam efficiency is calculated as:

$(M_{v1} + M_{v2})/M_s = 1.5$

Thus, 1.5 kg water is being evaporated with the use of one kg steam.

4.5. Drying

Drying is one of the oldest methods of food protection and has been practiced by man for thousands of years. Still today, drying is an important food preservation technique around the globe. Dried foods can be stored for longer periods as the available moisture or water activity of dried foods is reduced to a level where spoilage microorganisms cease to grow and enzymatic activities (responsible for undesirable changes) are reduced. In addition, drying reduces weight and volume of the product which reduce transportation, storage, and packaging costs.

During drying, influence of heating on microbes and enzyme activity is a vital part to enhance the shelf life. For food preservation with drying, maximum microbial growth and minimum enzymatic activity is required. It will increase the shelf life and reduce the food deterioration. Therefore, adverse influence of drying process may be beneficial or detrimental, dependent on the drying purpose of a food product. Drying is generally associated with changes detrimental to the quality of the product. These changes include the size, shape, colour, flavour and nutritional value (loss of vitamins A and C, denaturation of proteins etc.). Drying process can be divided into three categories.

1) Air/contact drying in which heat is supplied to the food stuff through heated air or surface and drying is performed at atmospheric pressure
2) Vacuum drying in which heat is transferred through conduction or radiation and water is evaporated at low pressure
3) Freeze drying in which water is removed from frozen food stuff through sublimation under suitable temperature and pressure conditions necessary for sublimation to occur

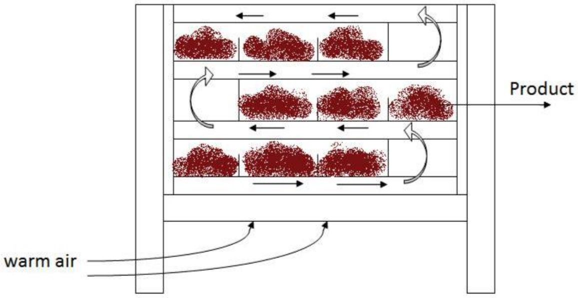
4.5.1. Drying systems

The efficiency of a drying system depends upon vapour pressure and temperature gradients between drying air and the product to be dried. More the gradient, higher will be the efficiency. Such conditions can be maintained in dryers of various designs as discussed below.

Cabinet/tray dryers

In this type of dryers, the product is held in trays enclosed in a cabinet and is exposed to hot air (Fig. 4.6). To get efficient heat and mass transfer, air is moved over the product surface at higher velocities. Temperature gradient cause the water removal and drying of the surface. Along with temperature, vacuum can be incorporated within the cabinet which reduces the temperature required to evaporate the moisture from the product, hence improving the product quality. Cabinet drying generally results in non-uniform drying of the product which can be improved by rotating the trays during drying process. In a typical dryer, drying time depends upon air temperature, water contents and product dimensions.

Fig. 4.6 A schematic representation of cabinet drier



Tunnel dryers

A tunnel dryer consists of a tunnel through which the product trays are moved in small trucks at some specific rate to ensure the residence time necessary for drying the product. The heated air enters from one end of the tunnel and moves through the product trays. Both air and product can move in the same direction (co-current dehydration) or in opposite directions (counter-current dehydration) depending upon the type of the product and desired characteristics.

In co-current system, a product with higher moisture content is exposed to the air with high temperature (at the entrance of tunnel) while a low moisture product is exposed to the low temperature air (near tunnel exit). In counter-current system, low moisture product is exposed to high temperature air (near tunnel entrance). Despite the higher efficiency of the counter-current system, its application may be limited owing to product quality characteristics.

Roller dryer

It consists of one or more rotating cylinders heated generally with steam (from inside). Liquid product is applied in thin films (30 to 300 micrometre) on the surface of rollers and dried product is scraped from the roller surface. It can also be operated under vacuum conditions.

Puff drying

In this process, the product consisting of small pieces (generally 2 cm cube shapes) is exposed to high pressure and temperature with subsequent release of pressure to atmospheric pressure. This results in rapid removal of moisture from inside of the product resulting in porous structure. Such products are characterized by rapid rate of rehydration.

Fluidized bed drying

Fluidized bed drying involves the suspension of the pieces of the product in heated air. As moisture evaporates, mass of the individual product pieces decreases which results in increased movement of the product. This movement results in identical drying of all product surfaces.

Spray drying

Liquid foods are generally spray dried which involves spraying of a liquid into a chamber containing dry air. Droplets of the sprayed liquid move with heated air and evaporation takes place. The dried product particles are then separated from air in a cyclone separator and packed at moisture contents less than 5%. Cooling effect of the evaporation protects the product solids which help to maintain the product quality. A typical example is milk powder, in which concentrated liquid milk is sprayed through a nozzle along hot air. Both move downward with certain velocity and dried on the way.

Freeze drying

Freeze drying is preferred for temperature sensitive foods, where the loss of nutrients and quality characteristics are important concerns. During this process, temperature of the product is reduced to freeze the product and water/moisture freezes to ice. Afterwards, surrounding pressure is reduced to support the sublimation process of the ice. In this process, water from frozen phase, move to gaseous phase and leave the product. In this way, product is dried; however, this process is quite expensive that limit its application on industrial scale.

4.5.2. Heat and Mass transfer in drying

In drying process, heat and mass transfer occur simultaneously. Heat transfer occur inwards (inside the product surface), which depends upon temperature gradient between the heating medium and product. Heat transfer occurs at molecular level and influenced by the thermal conductivity of the product.

Heat and mass transfer take place due to convective process at product surface. In this regard, vapour pressure governs the transportation of vapours from product surface to air. While heat transfer from air to product is attributed to the temperature gradient. Besides, convective coefficients at product surface determine the both rate of heat and mass transfer. Moreover, food structure is the rate limiting factor in heat and mass transfer. The rate of drying is determined through rate of heat transferred to the moisture to be evaporated. While, rate of heat transfer is given by;

$$q = h_a A(T_a - T_S) \tag{4.17}$$

where, q is the rate of heat transfer is the surface heat transfer coefficient, A is the area through which heat transfer takes place, T_a is the temperature of the air and T_s is the temperature of the food surface which is being dried.

4.5.3. Dryer efficiency

Drier efficiency is important to calculate as energy consumed for drying is a major component of the drying cost. Drying efficiency is simply a ratio of the minimum energy required for drying to the energy which is actually consumed during drying process. The efficiency of a drier can be defined as;

$$E = (T_1 - T_2)/ (T_1 - T_a) \tag{4.18}$$

where T_1 is the air temperature arriving the dryer, T_2 is air temperature leaving the dryer and T_a is the ambient air temperature.

4.6. Membrane Separation

Traditionally, liquid foods are concentrated by evaporation process involving huge amount of thermal energy. In addition to high cost of operation, evaporation process also causes detrimental changes to the product quality. However, water is separated from feed deprived of heating as there is no phase change involved through membrane separation. It is the use of membranes which allow selective transmission of some species in a mixture. In a food industry, membranes are used for various operations like purification of water, to produce juice concentrates, to clarify fruit juices & milk products and wastewater treatment (chapter 5 provides a detailed discussion on this topic).

Problems

1. Vita cons wants to concentrate apple juice through a natural-circulated single-effect evaporator. Juice is being fed at 0.7 kg/s rate having temperature of 45 °C. Initial total solids contents in juice are 10% while final concentrated juice contains 70%. The specific heats of feed and end product are 4 & 2.5 kJ/(kg °C), respectively. Steam enters at 305 kPa into evaporator. The boiling temperature of product is 60 °C inside the evaporator. Overall coefficient of heat transfer is 900 W/(m^2°C). Compute the end product flow rate, quantity of steam required, efficiency of evaporator, and area for heat transfer.
2. Nestle is interested to concentrate citrus juice through a single-effect evaporator. Juice is being fed at 0.7 kg/s rate having temperature of 20 °C. Initial total solids contents in juice are 5% while final concentrated juice contains 50%. The specific heats of feed and end product are 4 & 2.5 kJ/(kg°C), respectively. Steam enters into evaporator at 170 kPa having 85% quality. The boiling temperature of product is 80 °C. Co-efficient of heat transfer is 1000 W/(m^2°C). Compute flow rate of end product, quantity of steam required, efficiency of evaporator, and area for heat transfer.
3. Engro is using a single-effect evaporator to concentrate a fluid food product which enters 10,000 kg/h rate having temperature of 25 °C. Initial total solids

contents in juice are 5% while final concentrated juice contains 30%. The specific heats of feed and end product are 5 and 4 kJ/(kg °C), respectively. The steam enters into evaporator at 130 kPa having 80% quality. The boiling temperature of product is 70 °C. Coefficient of heat transfer is 800 W/(m^2°C). Determine flow rate of end product, quantity of steam required, efficiency of evaporator, and area for heat transfer.

4. Millac Foods requires a four-effect evaporator to concentrate fruit juice up to 20% total solid contents. Steam is available at 143.27 kPa for dehydration of juice which has no appreciable boiling point of elevation. Product boils at 45 °C in the 4th effect, however, its boiling points in 1st, 2nd, and 3rd are yet not known. Coefficient of heat transfer of the effects are 300, 2500, 2100, and 1800 W/(m^2°C) in the ascending orders and all effect have similar area of heat transfer (40 m^2). Juice enters at 1500 kg/h which has 5% total solids, while steam enters in the 1st effect at 2400 kg/h. Concentrates leaves at 6.25%, 8.82%, and 10%, from 1st, 2nd, and 3rd effect. Calculate the unknown temperatures, and steam economy of evaporator.
5. Sugar juice enters into the tunnel dryer at a rate of 100 g/min which have 60% water content on wet basis. Juice is dehydrated with dry air and it enters into tunnel at 1500 kg/min at 60 °C & 15% RH. It leaves drier at 50% RH and 30 °C in equilibrium with concentrated juice. Calculate amount of water contents and final water activity in the end product.
6. Haleeb is trying to optimize the cabinet dryer for the drying of a new milk-based product. Initially, product contains of 85% moisture contents on wet basis and half an hour is needed to reduce the moisture content to a critical level of 25% (wet basis). Calculate the moisture present in final product when product is dried for 20 minutes.

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Chapter 5

Membrane Separation

Akmal Nazir, Muhammad Kashif Iqbal Khan and Muhammad Tahir Nadeem*

Abstract

Membrane is a thin film that separates two bulk phases by creating barrier and allows a selective passage of the dissolved constituents between the two phases. In a food industry, membranes are used for various operations like purification of water, concentration & clarification of different liquid foods and wastewater treatment. Traditionally, liquid foods are concentrated by evaporation process that requires higher energy consumption, higher operational costs and additionally, can damage the product quality. However, in membrane separation, water is removed from the feed without heating and no phase change occurs. The present chapter is aimed to provide an overview of membrane technology and its various applications in food processing industry.

Keywords: Membrane separation; Reverse osmosis; Microfiltration; Ultrafiltration; Nanofiltration; Electrodialysis

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5.1. Introduction

Membrane is a thin film that separates two bulk phases by creating a barrier and allows only a selective passage of the dissolved constituents across it. In nature, membranes exist as an integral part of the living organisms, e.g., cell membrane and are usually termed as biological membranes. These biological membranes are specialized to carry out several complex transport phenomena in living creatures. The separation processes across these membranes are frequently carried out through active transport and therefore require very low energy.

Contrary to biological membranes, man-made, artificial or synthetic membranes are being used commercially for several separation processes, e.g., sea and brackish water desalination, separation or concentration of food and bioproducts, separation of gases and vapours. Additionally, these artificial membranes have successfully been applied in medical sector, e.g., artificial kidneys, artificial lungs, and for the controlled drug delivery inside the body. However, synthetic membranes are simpler ones in terms of structure or function compared to bio-membranes. They perform only passive transport that is usually less selective and energy efficient. Generally, these membranes are highly stable (chemically and mechanically) at elevated temperature (Strathmann et al. 2011).

In a food industry, membranes are used for various operations like purification of water, concentration and clarification of different liquid foods (such as fruit juices, milk and milk products) and wastewater treatment. Traditionally, liquid foods are concentrated by evaporation process involving huge amount of thermal energy. In addition to high cost of operation, evaporation process causes detrimental changes to the product quality. In membrane separation, water is separated from feed in the absence of heat and no phase change is involved.

In a membrane separation process, the solution that needs to be purified, concentrated or fractionated is usually termed as feed. The permeate or filtrate is the material that has passed through the membrane while the retentate does not pass through and rejected by the membrane. The rate of filtration is usually termed as flux and expressed as volume that passes in a unit time through a unit area of the membrane. As this phase separation is usually against the concentration gradient, there must be a driving force to carry out the process. Thus, pressures driven and charge-driven are the two commonly known modes of membrane operations and will be the focus of this chapter.

5.2. Pressure-based Membrane Processes

In membrane-based procedures, which are normally pressure driven separations, a vital driving force is hydrostatic pressure. It is inversely linked to membrane's pore size, i.e., smaller pores require higher pressure. Here, we can identify three different pressure points that need to be considered (Fig. 5.1). The pressure on the retentate side is not uniform; usually decreases in the flow direction and along the length of membrane. Therefore, P_1 and P_2 are the pressures on the retentate side at the inlet and outlet of the membrane, respectively. However, the pressure on the permeate side (P_3) is rather uniform. Hence, the transmembrane pressure or the pressure drop across the membrane can be defined as:

$$\Delta P_{TM} = \frac{P_1 + P_2}{2} - P_3 \tag{5.1}$$

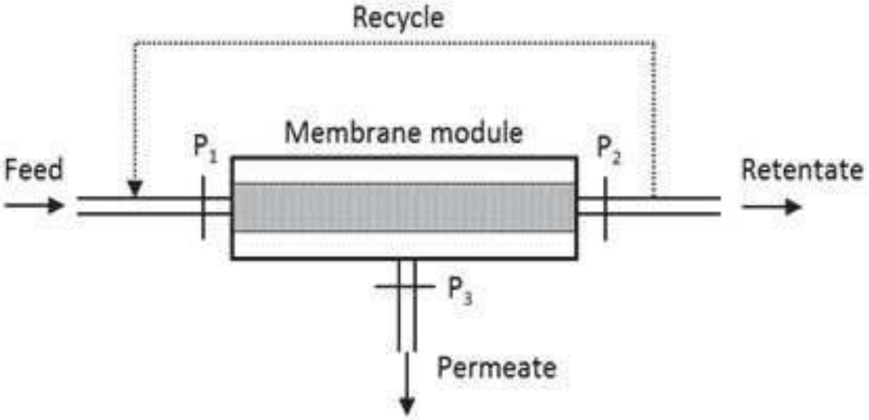

Fig. 5.1 A schematic representation of membrane separation process

In conventional or traditional filtration, feed flows vertically to the membrane surface, which is usually termed as dead-end filtration (Fig. 5.2). As the filtration continues, the retained particles pile up on membrane surface in the form of a cake layer. This increases the resistance to filtration and reduces flux at a constant pressure drop. Consequently, the process must be stopped at intervals to replace or to clean fouled membrane. An important development in the membrane technology is the cross-flow filtration process. In this process, feed stream flows parallel to the surface of membrane. The flowing feed stream prevents excessive deposition of cake layer at the membrane surface, which results in higher permeation fluxes. The filtration setup shown in Fig. 5.1 & 5.3 is a cross-flow membrane filtration.

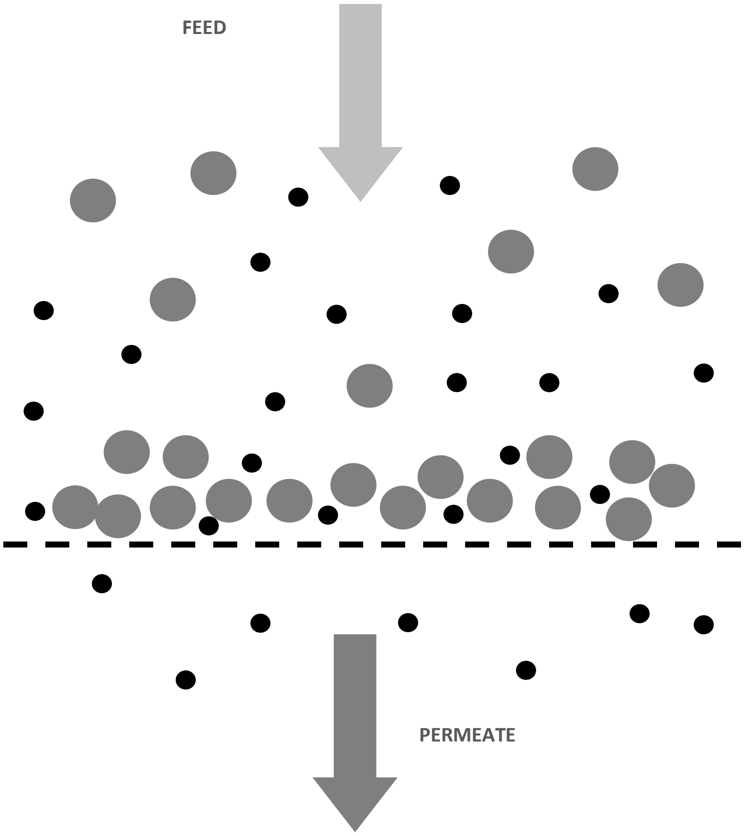

Fig. 5.2 Dead-end membrane filtration process

In pressure-driven membrane separation, the pore size governs the extent of separation while trans-membrane pressure being the main driving force. As the filtration process continues, the feed (retentate) concentration will continue to increase, resulting in a gradual flux decline. A reduced or a zero flux in this case is an indication of the extent of separation. Hence, the membrane pore size is an important factor that defines the rejection limit of a membrane separation process. Membrane pore size determines the process type; microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) or reverse osmosis (RO). Apart from pore size, other properties like pore size distribution, pore tortuosity, membrane thickness, membrane strength, membrane interactions affect the separation process.

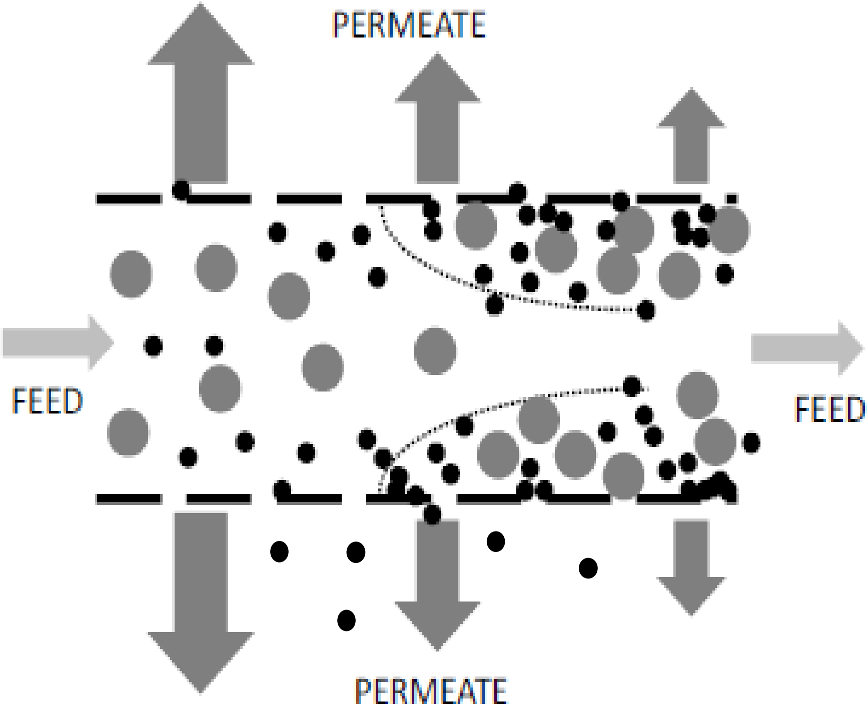

Fig. 5.3 Cross-flow membrane filtration process

As shown in Fig. 5.3, a microfiltration membrane separates suspended particulates having dimensions in the range from < 1 μm to > 1000 nm. An ultra-filtration membrane is useful in fractionating components by rejecting macromolecules. A nano-filtration membrane allows undissociated acids and monovalent salts to pass through while rejecting dissociated acids, divalent salts and sugars. Finally, a reverse-osmosis membrane separates water as permeate and rejects salts & sugars (Singh and Heldman 2008). This top to bottom filtration spectrum may be regarded as a continuous process without any distinct boundary. This filtration spectrum has several interesting applications in food sector. A comparative depiction of these four membrane-based filtration processes is provided in Table 5.1.

Table 5.1 A comparative depiction of pressure-driven membrane separation processes.

Membrane Process	**Pressure range (MPa)**	**Separation range**	**Examples**
Microfiltration	0.1 – 0.3	100 – 10 000 nm	Bacteria, milk fat globules
Ultrafiltration	0.2 – 1	1 – 100 nm (10^2 – 10^6)	Casein micelles, whey proteins, vitamins, viruses
Nanofiltration	1 – 4	0.5 – 5 nm (10^2 – 10^3 Dalton)	Divalent salts, sugars, dissociated acids, part of monovalent ions like sodium and chlorine
Reverse Osmosis	3 – 10	10^1 – 10^2 Dalton	Separates everything except pure water

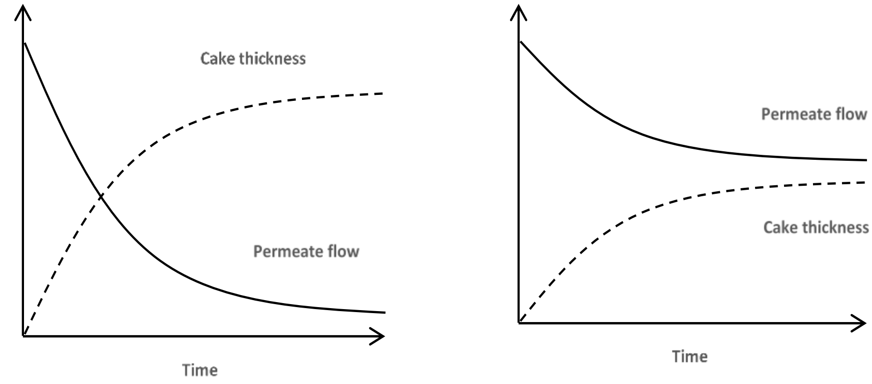

Fig. 5.4 A graphical representation/comparison of dead-end and cross-flow membrane filtration processes

5.2.1. Transport theory

The commonly used models to describe the permeation in pressure-driven membrane processes are pore-flow model and solution-diffusion model (Fig. 5.5). The pore-flow model was more popular to describe fluid permeation in general in the early nineteenth century whereas, during 1940s, the permeation of gasses through polymeric films was preferably described through the solution-diffusion model. A pore flow model is closer to physical understanding as the materials are separated while the fluid flows through membrane pores. Due to size-based exclusion, separation is carried out i.e., particles larger than the pore size stay on the membrane surface while smaller pass through it.

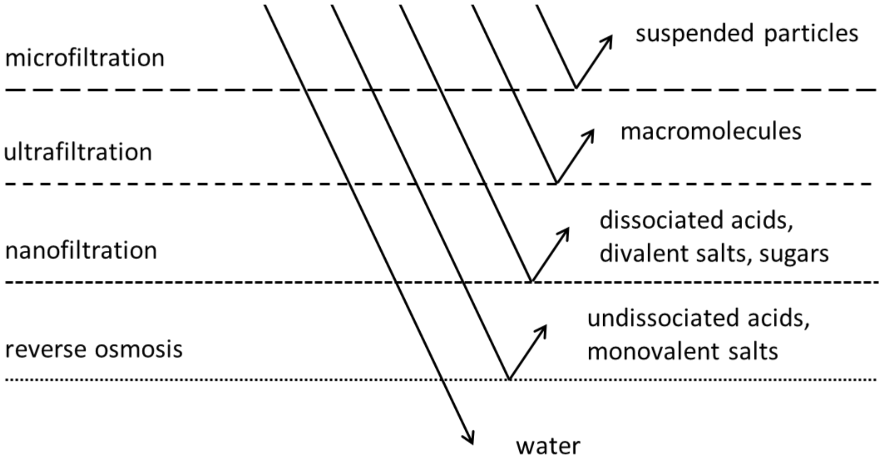

Fig. 5.5 The pressure-driven membrane filtration spectrum

In pore-flow model, the permeation rate (J_i, expressed as g/cm^2s) of i^{th} component is usually described by Darcy's law as follows;

$$J_i = K' c_i \frac{\mathrm{d}p}{\mathrm{d}x} \tag{5.2}$$

where K is a medium coefficient used to describe nature, dp/dx is equal to pressure gradient across the membrane and c_i is the i^{th} component's concentration in the medium. In terms of resistance to flow, R, the flow of permeate flux, J, through the membrane can be defined through Darcy's law as follows;

$$J = \frac{\Delta P}{\eta R} \tag{5.3}$$

where ΔP is the pressure of trans-membrane and η is the viscosity of feed. The resistance to flow is usually provided by the membrane itself and by the cake layer that is formed due to feed particles deposition on the surface of membrane. On the other hand, in solution diffusion model, the permeable components first get mixed in membrane then ultimately transported to permeate by diffusion through the membrane. The permeation in this case is toward the concentration gradient that depends upon the amount of dissolved material and rate of diffusion through the membrane (Wijmans and Baker 1995). In a solution-based diffusion model, the rate of permeation of component (i^{th}) is calculated through Fick's law of diffusion that follows;

$$J_i = -D_i \frac{\mathrm{d}c_i}{\mathrm{d}x} \tag{5.4}$$

where D is equal to coefficient of diffusion (cm^2/s) and dc / dx describes the concentration gradient. The minus sign here represents that permeation is toward concentration gradient.

5.2.2. Microfiltration and Ultrafiltration membranes

Both membranes (microfiltration and ultrafiltration) are microporous and permeation is carried out purely based on pore flow model. For these membrane processes, the particle size limit for rejection or permeation through the membrane is not so sharp because of several factors related to membrane, including type of membrane, pore size distribution, pore tortuosity, etc. This might result into rejection of particles with diameter even less than pores of membrane. The microfiltration membranes are usually characterized by mean pore diameter (in micrometres); however, the ultrafiltration membranes are specified as molecular weight cut-off (MWCO)[†]. The commonly used materials used for commercial production of these membranes are polysulfone, cellulose acetate, polyether sulfone, polyvinylidene fluoride, polyacylonitrite, polypropylene, polyvinyl chloride and polyethylene.

5.2.3. Reverse Osmosis

In the absence of any externally applied force, the movement of water through the membrane (placed between two bulk phases) will be governed by osmotic pressure. In this case the water will move from low concentration to high concentrated solution. However, in most of membrane operations the desired separation or concentration processes are carried out to overcome the osmotic pressure by applying an external (transmembrane) pressure; this process is known as reverse osmosis (Fig. 5.5 & 5.6). Therefore, it is important to know the osmotic pressure of the feed mixture to have an idea of the required operating pressure. The osmotic pressure of a diluted mixture is expressed by Van't Hoff's equation as follows;

[†] MWCO is defined as the lowest molecular weight of solute (in daltons) in which more than 90% of the solute is reserved by a membrane.

$$\Pi = \frac{cRT}{M} \tag{5.5}$$

Where, π denoted the osmotic pressure in Pa, R is a gas constant, c is concentration of solute (kg/m^3) of solution, T is the temperature (K) of solution and M represents the molecular weight of solute. This equation usually results in a higher osmotic pressure in the presence of small molecules. To overcome this problem, Gibb's equation can be used that has been found more precise over a broader range of concentrations of solute and is given as;

$$\pi = -\frac{RT \ln X_a}{V_m} \tag{5.6}$$

where, X_a is molar fraction of pure liquid and V_m is the molar volume of pure liquid.

Contrary to MF/UF membranes, the reverse osmosis membranes do not possess distinct pores and are basically homogeneous. Therefore, the pore-flow model is not accurately applicable to describe the permeation through RO membranes (Fig. 5.5). In this case, the filtration is perfectly represented by solution diffusion model. The molecules permeate through the membrane between the polymer chains by diffusion process (Wijmans and Baker 1995). The overall driving force is the gradient in chemical potential (a thermodynamic parameter) that is collectively affected by pressure, temperature, concentration and electromotive forces. In addition to reverse osmosis process, the appropriate transport equations can be derived for other processes like gas infiltration, dialysis and evaporation by using the solution-diffusion model.

The commercially used RO membrane is usually made of aromatic polyamide or cellulose acetate. The RO membranes are the basis of water purification technology where they are used to remove minerals from drinking water. The areas that have either no, or limited surface water or groundwater may have adopted for seawater desalination. In this process, reverse osmosis is applied to produce pure water from a highly saline feed stream.

This method is quite economical because of its relatively low energy consumption as compared to the evaporation process. Typically, 50% of the seawater can be recovered as fresh water through reverse osmosis; however, the membrane fouling, and energy consumption are the factors that are directly linked with the fresh water recovery. In addition to water purification, reverse osmosis is used in many industrial processes such as fruit juice and whey concentration, ice making, and wastewater treatment. Hence, the objective of any reverse osmosis process may be either to get pure water (filtrate) or to concentrate the feed stream.

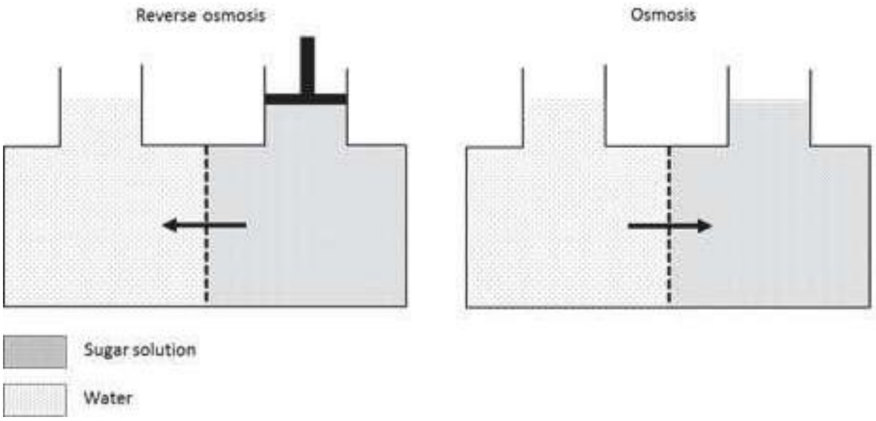

Fig. 5.6 A schematic representation of osmosis and reverse osmosis process

5.2.4. Nanofiltration

The pore-flow and solution-diffusion mechanisms can be differentiated by comparative pore size, its permeance and transition exists in the range of 5-10 ºA diameter. The nanofiltration membranes are the third group of membranes with their pore size falling in this transition range. Therefore, the filtration cannot be truly described by either pore-flow or solution diffusion model. These membranes have ability to fractionate or separate ionic or relatively lower molecular weight organic species, e.g., di- and trisaccharide sucrose and raffinose that have molecular diameter in the range of 10-13ºA. The commercial nanofiltration membranes are usually made of different polymers such as polyamide, polyamines, cellulose acetate, polyether sulfone, polysulfone, polydimethyl siloxane, polyvinyl alcohol, polyethylene terephthalate etc.

5.2.5. Concentration Polarization

In membrane filtration, as the separation continues, the permeable components are withdrawn from the sample at bottom layer of membrane (Fig. 5.7). This results in depletion of permeable components and gradual build-up of concentration of slow or non-permeable components in a very small region close to the membrane, termed as boundary layer. The development of this boundary layer is usually regarded as concentration polarization.

The concentration polarization is a characteristic of all the pressure-based membrane separation processes, electrodialysis and some pervaporation processes. However, its implication may vary in different processes. For example, in reverse osmosis process, reduction in concentration of permeable components in the boundary layer reduces the concentration gradient across membrane that causes permeate flux decline.

Moreover, retention of non-permeable components on the surface of membrane increases osmotic pressure on boundary layer. This results in back diffusion that acts against the forward convective flow (Fig. 5.8) and thus plays its role in lowering of the flux. On the other hand, in ultra-filtration the larger particles do not concentrate near the membrane surface but instead are retained on the surface of membrane. In this way, osmotic pressure is less affected by larger molecules; however, the retention of larger molecules on the surface of membrane can cause deposition of a solid material (also termed as gel formation) at the membrane surface which is responsible for flux decline in ultra-filtration processes.

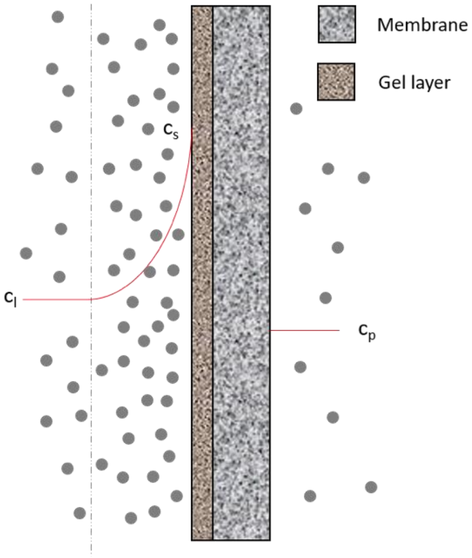

Fig. 5.7 A schematic representation of concentration polarization process

This is clear by now that extent of concentration polarization varies according to membrane processes. The degree of concentration polarization may be described quantitatively as concentration polarization modulus that is a relation of permeable material's concentration at the surface of membrane (c_s) and its bulk concentration (c_l). The concentration profiles of solutes at both layers of membrane and adjacent to the membrane surface is shown in Fig. 5.8. The convective transport rate of solute expressed as $J_{s(f)}$ can be calculated by following expression;

$$J_{s(f)} = J_v c \tag{5.7}$$

where J_p is the permeate flux rate in m^3/m^2s; and c is solute concentration (kg/m^3). The rejected solute at the wall by membrane transfers backward into the bulk liquid. The rate of back-transport flux of solute denoted as $J_{s(b)}$ can be calculated through the following relationship:

$$J_{\mathrm{s(b)}} = D\frac{\mathrm{d}c}{\mathrm{d}x} \tag{5.8}$$

where D is solute diffusion coefficient expressed in m^2/s. The convective transport of a solute under steady-state situations equals to the back transport done by concentration gradient; therefore,

$$J_{\mathrm{v}}c = D\frac{\mathrm{d}c}{\mathrm{d}x} \tag{5.9}$$

Boundary conditions can be used after separation and integration of variables ($c = c_s$ at $x = 0$, and $c = c_l$ at $x = \delta$), the Eq. 5.9 becomes

$$J_{\mathrm{v}} = \frac{D}{\delta}\ln\left[\frac{c_{\mathrm{w}}}{c_{\mathrm{b}}}\right] \tag{5.10}$$

the term D/δ may be replaced with mass transfer coefficient, k_m ($Lm^{-2}\,h^{-1}$) when the flux is no more influenced by the pressure. Furthermore, the term c_s/c_l is represented as the concentration polarization modulus, so after rearranging the Eq. 5.10, we obtain;

$$\frac{c_{\mathrm{w}}}{c_{\mathrm{b}}} = \exp\left[\frac{J_{\mathrm{v}}\delta}{D}\right] \tag{5.11}$$

This expression shows that the concentration polarization modulus rises exponentially with the thickness of the boundary layer and transmembrane flux and it declines exponentially by enhancing rate of solute diffusivity. A modulus value of 1.0 represents that there is no sign of concentration polarization; however, as the modulus value deviates farther from 1.0, the effect of concentration polarization on flux and membrane selection becomes gradually important.

For reverse osmosis membranes, the modulus value is normally between 1.1 and 1.5. In case of ultrafiltration separation, the modulus of concentration polarization can be large (5-10) or small (0.2-0.1). It can extremely affect the working of membranes (Baker 2004). The Eq. 5.9 is applicable to both reverse osmosis as well as ultrafiltration; however, in case of ultrafiltration due to formation of gel layer (as explained earlier) the concentration of solute at surface of membrane (c_s) should be replaced with concentration of solute at the surface of gel layer (c_g), and this expression can then be regarded as gel polarization model. In such situation, the gel layer resistance may turn out to be more significant as compared to the membrane resistance.

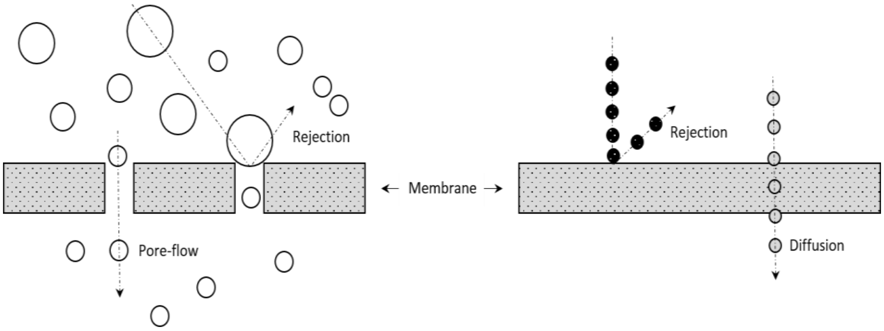

Fig. 5.8 The schematic representation of pore-flow and solution-diffusion models

As the development of concentration polarization layer seriously affects the membrane performance during the separation processes, several strategies may be adopted to avoid or reduce the concentration polarization. One of the simplest approaches is to apply turbulent mixing at the surface of membrane, which may be achieved for instance by increasing the fluid flow velocity over membrane surface or by use of different shaped turbulence promoters in the flow channels.

5.2.6. Applications

The membranes are being used extensively in dairy industry because the membrane operations are more economical and energy efficient as compared to conventional technologies. For example, milk concentration through reverse osmosis is quite advantageous over milk evaporation. Moreover, the membranes have been applied for the recovery of valuable components from whey, which is a by-product of cheese processing industry. The juice industry is next to dairy industry where the membranes have found a lot of applications, for instance, in juice clarification, filtration, and concentration. The application of membranes in dairy and juice industry constitutes the major part of their applications in food industry.

5.3. Charge-based Membrane Separation Process

Electrodialysis is a charge-based membrane separation technique that separates ions according to their charge by the membranes, i.e., positive ions move towards negatively charged membranes and vice versa. The electro-dialysis is principally applied in food industry for demineralization, desalting, acidification or de-acidification of liquid foods. A schematic diagram of an electrodialysis system is shown in Fig. 5.9, which consists of alternating anionic and cationic membranes.

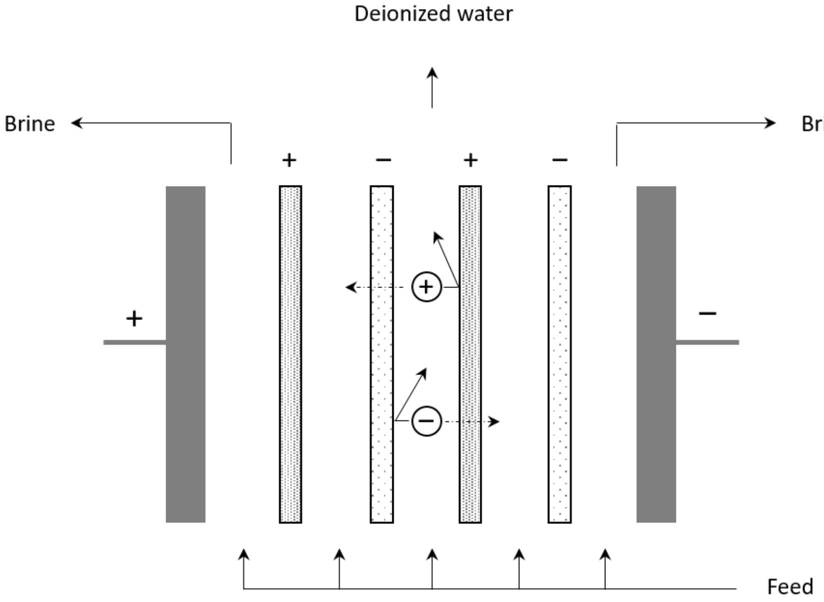

Fig. 5.9 A schematic diagram of an electro-dialysis system

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Chapter 6

Food Packaging

Muhammad Azam Khan and Mudassir Arif*

Abstract

In the modern world, with ascending demand for food products, increasing consumer expectations for convenience, food safety, enhanced shelf life and high-quality product make the food packaging role as inevitable and pervasive ones. Packaging is a socio-economic discipline that works in a society ensuring the delivery of products to the end user in the best conditions. Packaging functions to protect and contain the goods from processing and manufacturing to their final delivery to the ultimate consumer. Materials handling without packaging would be inefficient, and inadequate. The concepts of profit enhancement and customer satisfaction would merely be a dream. This chapter contains the basic concept of food packaging, an elaboration of various environments for food packaging to work in, a brief overview of packaging materials, recent advances in the field of food packaging and environmental impacts of food packaging.

Keywords: Bio-switch, Active packaging, Modified Atmospheric Packaging,

6.1. Introduction

Packaging in the modern era is an inevitable element of consumption with wide range of benefits for consumers and multiple functionalities. Packaging is playing a major role on the consumer-packaged goods (CPG) markets. These are highly

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dependent on the packaging elements to fulfil the packaging functions but on the other hand they have certain adverse impacts on the environment (Bovea et al. 2006).

Despite the significant role of packaging, it is commonly considered as a compulsory evil or an excessive addition to a process cost. Such views develop because role that packaging plays is unknown or not considered in full at the level of consumer. But the modern consumer is more inclined towards sustainable packaging, so the trend is rapidly shifting towards sustainability in packaging (Bemporad et al. 2012).

Sustainable packaging is a packaging that possesses a low environmental impact which can be estimated through life cycle assessment models (Glavic and Lukman 2007). From the consumer point of view; “a packaging that evokes explicitly or implicitly the eco-friendliness of the packaging” can be deemed as sustainable packaging (Magnier and Crie 2015). Food packaging has become an inevitable need for the present era in which research is being conducted to balance the scale of the pros and cons. Some of the important terminologies frequently used in the field of food packaging are mentioned below;

Package: A physical body or object, in which the product is contained, is called a package

Packaging: Packaging is a ‘coordinated system’ that prepares goods for the purposes of transportation, storage, distribution, retail services, and end consumption. Hence, it is a way of delivering the product to the end user safely and in good conditions ensuring minimum cost

Packing: It constitutes an individual item, or several items enclosed in a package

Primary Package: It is the package that is directly in contact with the product. It provides the very first and major protective coating/barrier. Normally, primary packages are purchased by us at the retail outlets. Examples are, a bottle of juice, metal can have sliced pineapple

Secondary Package: Several primary packages formulate a secondary package. It is designed to act as a physical distribution carrier and for the display of the primary packages at retail outlets. Examples are a corrugated case, a box of chocolates

Tertiary Package: A tertiary package contains many secondary packages or corrugated boxes

Quaternary Package: This package comprises a long container that has the capacity to hold many pallets

These are of intermodal nature and are transported by ships, trains and trucks. Some containers have controlled temperature, gas atmosphere and humidity that are necessary to transport certain types of foods.

6.2. Function of Packaging

Food packaging plays many significant roles, the major among them being the protection of the food products from the environmental factors, their containment, ease of transportation, convenience of handling, maintenance of product quality, enhancement of shelf life, providing labels aiming at advertising of the product along with nutrients and ingredients information (Coles et al. 2003). The primary functions of packaging can be categorized into four major types as shown in Fig. 6.1.

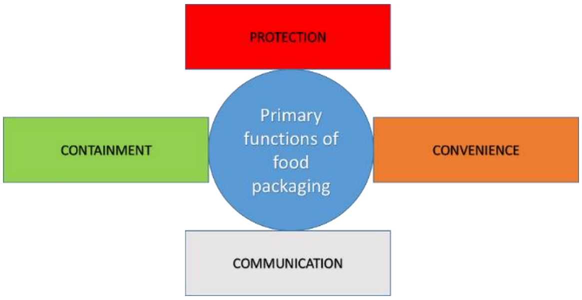

Fig. 6.1 A schematic representation of primary functions of food packaging

6.2.1. Product Protection

Product protection is commonly considered to be the primary function of the package. It involves protecting the product from external environmental influences like odours, water vapor, water, microorganisms, shocks, dust, vibration and compressive forces. Protection is an essential part of the preservation process. Very simple examples are the aseptically packaged drinks like juices and milk that only maintain aseptic behaviour as long as the protection is provided by the package.

Similarly, the shelf life of vacuum-packaged meat is not ensured if its integrity is breached by entrance of oxygen. The food package provides chemical protection, biological protection and physical protection to the product contained in it. In case of the chemical protection, the food product inside the package is prevented from any alteration in composition which may be caused by the moisture, gases or light; biological protection acts as a barrier to pathogens, microorganisms and disease-causing agents. While, physical protection prevents the food products form any mechanical damage.

Along with protection; packaging also plays a significant role in the conservation of energy consumed during the production and processing stages of the product. For instance, it takes 15.8 MJ of energy in producing 1kg of bread. These 15.8 MJ are needed in the form of transportation, heating processes in industry, power and refrigeration, wheat milling and in distribution of the finished product. Energy of 1.4 MJ is required to make low density polyethylene (LDPE) bag for a loaf of 1kg bread. Now 1.4 MJ energy is meant to conserve 15.8 MJ. Without the LDPE bag, this energy may be conserved but would result in the spoilage of 15.8 MJ energy of the product rapidly i.e. reduce shelf life. A schematic representation of the packaging function is shown in Fig. 6.2.

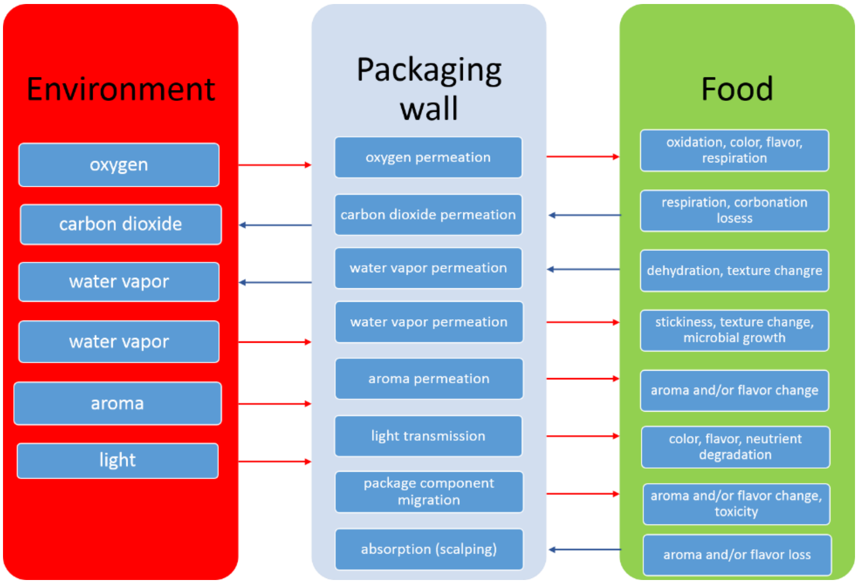

Fig. 6.2 A schematic representation of packaging function

6.2.2. Product Containment

Containment functions prevents product loss and pollution / contamination. It prevents the environment's damages to products that are transported from one place to another. Even in the modern world, containment function is not addressed properly as witnessed by the number of packaged foods that leak their contents, especially around the closures and seals. The containment area should be separate from the production area, but close enough to allow efficient communication between these two processes. The material leaving the containment area should be properly labelled to ease for the ingredients inspection.

6.2.3. Product Convenience

Advancement in industrialization has brought great changes in the life styles. The packaging industry has responded to these changes i.e. satisfying the demand for wide variety of snack type meals and outdoor drinks for events like sports and office consumption. Therefore, the designing of products now a day aims at enhancing convenience which includes pre-prepared foods that require a very short reheating or cooking time even without removing them from their primary packages. There are also sauces, condiments and dressings that can be applied on the desired surface using aerosol or pump action packages. Convenience plays an important role in promoting sales.

The large-scale output from industrial level is reduced to a manageable and desirable 'consumer size'. Thus, we can see some carbonated drinks 'apportioned' into 500 ml, 1 L, 1.5L and 2.25 L bottles; in a similar way a churn of butter is 'apportioned' into 25g mini pats, a batch of ice cream is 'apportioned' by filling in 2 L plastic tubs. For all those products which can't be consumed at once, the package is resealable.

Second factor is the design of the package. Shape/design of the package is attributed to the convenience of the consumer and its efficiency in building secondary and tertiary packages. This factor widely contributes towards the accommodation of primary packages into secondary and secondary packages into tertiary packages. This not only saves space, but it attracts the consumers of different genders, age, cultures and believes. It is one of the fundamental considerations during package design.

6.2.4. Package Communication

A package, itself, is a "silent salesman". It must protect what it sells and sell what it protects. Presently, the supermarkets work on self-service basis as the consumer is able to choose their desired products due to different shapes, brands and labels. Fast and error free ways of payment for the products have become common as package possess a universal product code (UPC) which is rapidly and accurately read. In many countries it has become inevitable to provide nutritional information on the packaging and the larger labels usually depict the ingredients included in the product.

Package communications includes display and inform aspects. Display is related to the advertising of the product and inform is attributed to the terms of use and nutritional information. The communication function of the package holds cardinal significance in stores and warehouse management. The use of symbols is imperative on the packages when international trade is involved so that the difference of languages could be removed and overcome. There are three basic environments in which a package must perform its functions. These environments are ambient environment, physical environment and human environment.

Ambient environment is the one surrounding the package. The contained product can be damaged by gases particularly O_2, water and water vapours, light, UV radiations, temperature, microorganisms and microorganisms such as rodents, insects, mites and birds that are frequent in warehouses and retail outlets.

In any physical environment, a physical damage may occur to the product. This damage can occur due to falling of packages or bumps on the way or additionally, due to vibrations occurring because of various modes of transportation and crushing or compression as a result of stalking.

In human environment, the package comes in interaction and communication with the humans. As the communication function of the package is of cardinal significance therefore, it is imperative that the package massage such as nutritional contents and net weight etc. should be clearly conveyed to the consumer. To designing packages for human environment a profound knowledge of the differences in consumers including their vision, weakness, strength, memory, dexterity and cognitive behaviour is required.

Some of the secondary functions that packaging serves includes; traceability which can be defined as “the ability to follow the movement of a food through specified stage(s) of production, processing and distribution”.

6.3. Packaging Materials

Various materials are used for different food stuffs. These packaging materials may include glass, plastic, metals, flexible films, paper and paper board.

6.3.1. Metals

Metals have many advantages as compared to other packaging materials. The most commonly used metals in packaging industry are steel, tin and aluminium. They possess the following advantages and disadvantages:

Advantages

- Protect the contents ultimately
- Convenient for ambient presentation and storage
- Temper proof

Disadvantages

- They have high manufacturing and transportation costs

6.3.2. Glass

Glass is used in the packaging industry due to its following attributes:

Advantages

- Gases, moisture, odours and micro-organisms can't permeate through it
- It is inert therefore there is no chance of reaction with food
- When hermetically sealed, it can be heat processed.
- It can be reused and recycled
- It is transparent, and contents are clearly displayed
- It is rigid to allow stalking without damage to container

Disadvantages

- It increases higher transport costs due to higher weight
- It possesses lower resistance to thermal shock and fracture
- Serious hazard from glass splinters and fragments in food

6.3.3. Flexible films

Various types of flexible films are used in food packaging such as cellulose, polypropylene, polyethylene and other films. Properties of films are listed as:

- They have a relatively low cost
- They act as an effective barrier against gases and moisture
- They are heat sealable to stop content leakage
- They are easy to handle
- They add little weight to the product

6.4. Packaging Selection

The structural, material and graphical components of a package integrate to form a package design. The structural and material components comprise the functions of packaging and facilitation regarding transport and distribution as well as provide the physical surface on which packaging design exists. The graphic components are attributed to the display and inform functions of the package. It is responsible to convince the consumer to purchase an item. For successful packaging, following factors must be brought under consideration.

6.4.1. What is the product?

The producer must know what the product is and must be well aware of the product types and its nature, its competition, and it user acceptability and utility, marketing goal & distribution methods. It is necessary that the integrity of package is not breached under changing conditions during the storage time, transport & consumption. Also, the contained product in the above environments must be protected. By law in many countries the identity, weight, volume, content, and location of the manufacturer of any product must be given and mentioned on the product so that it may describe itself to the purchaser. For example, when the packages contain dangerous products, it must state the hazardous nature; methods to prevent and off set injuries. If such a package is liable to be used in household, then it must ensure the hindrance of children efforts to gain access to it.

6.4.2. Communication

Practical requirements of mass production must be brought under consideration by the designer. Professional packaging developers always develop measurements of their keeping in view the needs of procurement and manufacturing, storage, shipment and sales to ensure that no potential trouble spots the left behind. A compromise is always necessary when various requirements conflict. Therefore, a capable designer must know how to prioritize conflicting requirements and make factual and logical judgments.

6.4.3. Market Analysis

Market analysis aims at capturing the target consumer. The information about gender, age, affordability and social set up are among the most significant considerations for this purpose. There are various social norms and eating habits that varies within a country and across the globe. It may alter use of product with the change of borders or countries. Therefore, the trend of packaging differs from country to country or culture to culture. For example, milk consumption style varies from individual to individuals;

1) In Australia, milk is sold in 2–4 L plastic bottle convenient for milk shakes & coffee.

2) In India, milk is sold in PVC 500 mL & 1L pouches convenient for making tea.

3) In China, milk is sold in 200 mL & 1L tetra packs to be drunk as it is.

Methods of trading, techniques adopted for displaying, and advertising any product influence the final design significantly. A package may totally appear different on a clients' desk or on a drawing board as compared to its appearance on the shelf. Before the finalization of a package design it is also necessary to simulate the package in a completion environment with other packages competing in it. It is good to view a new package in a trade situation surrounded by competing products before finalizing the design.

A contrasting format must be chosen to distinguish one's product from competing brands. For example, China's best dairy brand named Yili, aimed at capturing good consumer insight in the beverage side, by introducing a new high-end milk shake. This package was designed by Tetra Pak which gave it a Scandinavian touch in the design, to make it prominent and distinguished on the shelves in the market. The design has white and clean surfaces, elegant hand-created typography, photography and illustrations tailored for the various package panels, and beautiful metallic details in addition to that. Two delicious flavours are provided in the packaging, named, chocolate and papaya and has been a big hit on the Chinese market since spring 2012.

6.4.4. Style

Style is attributed towards value addition to the product. Besides projecting the contents of the product visually, style adds value to the product by depicting its mood and appearance. Shape, size, colour, texture, tone and line combine to form style.

Shape: it is an illustrative outline or text body. There are both negative / positive shapes. Length-to-width proportions of 2:3 & 3:5 are the most pleasing; while 1:1 & 1:2 are do not attract attention.

Size: How large or small the package or design is. Size can be physical or perceptual.

Colour: Colour helps in attracting attention & the mood or persona of a package is also affected by it. Expense addition is also due to colour of the package.

Texture: Perceived of real smoothness or roughness. It involves the sense of touch. Texture can be created using graphic patterns or textured substrates.

Tone: It accounts for the lightness or darkness. Darker colours appear heavier than lighter ones.

Line: Lines can be straight or curved, heavy or light, rough or smooth, continuous or broken. Certain line orientations can create different feelings:

Horizontal: calm . . . . Vertical: dignity

Diagonal: vitality. . . . . Curved: grace

Converging: distance. . . . . Shadow: suggest volume.

6.4.5. Copy

Original graphic material including art & text, submitted for reproduction can be classed as:

- Line copy-image composed of solid lines or blocks of colours
- Tone-image will in varied tones and shades of selected colours
- Process copy-colour photographic reproduction that will be reproduced using CMYK inks.

In the main panel a promise should be implied, to get attention of the viewer. For example, trade name, supporting phrases and subtitles must attract the purchaser by appealing to its natural desires.

On the package a careful handling of the text should be done by conducting a profound study with a priority of minimum usage of copy. The total effect of the package is weakened when more amount of copy is done to put descriptions, trademarks subtitles quantity designation, manufacturer name and address which compete for the customer attention.

6.4.6. Product Liability

A number of injuries can occur to the consumer while using various packages. For example, mostly metal cans possess sharp edges, broken glass containers produce jagged edges. Similarly, hand-holes in a corrugated box provide easiness to carry, but heavier contents may result in tearing of the paperboard resulting in smashed toes of the consumer. Therefore, a package designer must bring under consideration any potential hazards and must anticipate all of them to avoid unfavourable publicity and litigation. In case if the manufacturer cannot provide necessary protection into the package then it is mandatory to provide relevant warnings in a prominent place to catch consumers attention.

6.4.7. Export Considerations

A food product that is to be exported from a country, various factors must be kept in mind. For example, hazards of transportation, in general practice packages are made 1.5-2 times stronger so that they are not damaged when piled up for transportation. Wooden crates may be used as substitutes for corrugated boxes and in some cases textile bags can replace multi walled paper bags.

As there are different laws, traditions and customs in different countries more complexity was added to copy and graphics e.g. in Islamic countries illustrations of dogs, pigs and inadequately dressed women are discouraged and avoided. Whereas in Taiwan, Korea and Hong Kong triangles are perceived to be negative and ‘four’ is considered an unlucky number in Japan. Similarly, colours and combinations must be selected in accordance with the regional traditions and norms. For example, in Japan and Korea white colour is considered the colour of death but represents purity in many Western countries. In Pakistan, black & saffron, is considered as the colour of hell.

6.4.8. Vending

If any item is intended to be used in vending machines, then it must be considered during the design stage so that it could possess all necessary characteristics to serve the purpose. For example, rigid packages do not have a lot of flexibility and are more practical instead, but pouched products are also possible if they possess a combination of stronger films and heat seals with added improvement in structures for both the packages and dispensing machines can be designed.

6.4.9. Material Selection

Packaging is used to provide adequate protection to the product from exposure to the environment and physical damage during storage, shipping and general use While selecting the material the following considerations must be kept in mind.

1) Nature of product & the kind of packaging needed to contain the product
2) Material’s availability / cost
3) Transportation modes, handling techniques and storage conditions

Moreover, essential technical information is the production line for various processes used in packaging operations, e.g. cleaning, filling, closing, labelling, wrapping, sealing etc. Regardless of the position anyone possesses in the packaging industry, basic knowledge of packaging machinery & functions it performs is inevitable.

6.4.10. Consumer Expectations and Requirements

One of the most important aspects brought under consideration while designing a package; what are the expectations and requirements of a user from the packaging. For example, Japan produces smaller bottles of coke as compared to Australia because of the availability of small refrigerators in the market. In this case, the manufacturers never compel the consumer but rather their packaging decisions would be driven by feedback on consumer expectations.

6.4.11. Retail Space

As the retail space is shrinking and getting costlier day by day, retail space has emerged as an important factor; leading manufacturer towards making innovative and space efficient packages. For example, PVC pouches are being frequently used to provide pickles as compared glass bottles and plastic jars because PVC takes less space on the shelves.

6.4.12. Specifications

This is a concluding phase of development process and it becomes a record of results of the work that has gone on before. If the specifications are prepared properly, they result in enhanced efficiency, error prevention and cost minimization which are the top priority in any industrial operation. So, it serves and a bridge establishing communication with purchasing department, manufacturing units, quality control cells & all other departments with direct involvement to satisfy the designer's attentions. While ordering the package components maximum information regarding the requirements should be provided to the vendor. Tolerance attributes such as size, colour, density etc., should be agreed upon by both sides and the conditions of acceptance or rejection should be clarified before ordering. Limits should be placed on overruns or under runs; penalties for late delivery, extra inspection, and rework need to be established before the order is placed.

6.4.13. Cost

Packaging represents a significant portion of the products selling price. Ideally, packaging cost should be 10% less than that of the product cost. Therefore, it is essential to possess an intelligent understanding of the different elements that add up into the cost of package. Other than labour and material costs there are many fixed elements that constitute or contribute towards the overall cost of doing business e.g. control costs for inspection and testing, operational cost e.g. sterilization etc., maintenance, supervision, and anticipated spoilage. In case of a manufacturing operation, its efficiency can be measured by the standard cost in terms of plus or minus variances from the standard.

6.4.14. Testing

An adequate testing program is important in packaging development. Failure of testing can be very costly when the effects are multiplied by the large number of inadequate packages. It might produce an extra cost of correcting errors, increased waste rates and loss of consumer satisfaction due to damaged goods.

6.5. Packaging Testing

To check the durability and prevent cross contamination, the packages should be tested accordingly. All packages must be tested under controlled atmosphere i.e. 23ºC temperature and a relative humidity of 50%. ISO 2206 provides the standard conditions under which the package must be tested. While dealing with package testing the following terms must be kept in mind: Thickness, Density of paper, Burst strength, Tear resistance, Grease resistance Gas transmission rate (GTR), and Water vapor transmission rate (WVTR).

6.5.1. Thickness

It can be defined as the distance when taken perpendicularly between the two surfaces on the outer side of any package or material. In case of packaging materials, the water vapor transmission rate (WVTR) and gas transmission rate (GTR) are inversely proportional to thickness. For measurement of thickness, dial gauges, micro meter screw gauges and Vernier callipers can be used.

Paperboards: In case of paper boards the thickness is taken in points or in millimetres (1 point=1/1000th of an inch).

Papers: In case of papers the thickness is in millimetres or in inches.

Films: In case of films the thickness is taken in micron, mils or in gauge (25 micron = 1 mil= 1/1000th of an inch= 100 gauge= 0.25 mm).

Paper density: It is the ratio of the mass and the unit area of the paper or pulp and is also known as basis weight or grammage. It is a common term in the paper and pulp industry.

Grammage: Paper density is also known as grammage when it is represented in grams per square meter (gm^{-2}).

Basis weight: Paper density is also called as basis weight when expressed in mass per number of sheets.

6.5.2. Burst Strength

It is a test that is used to measure the capability of the paper or paperboard to withstand hydraulic or pneumatic pressure build up. It is used for films, foils, laminates and paper. A combined assessment is given by the test for the properties such as tensile and tears. It is a reliable index to show the quality in which the packaging material is fabricated.

6.5.3. Tear resistance

There are two ways to test the tear resistance of the papers.

Internal tearing: The energy needed to transmit an internal tear is measured.

Edge tearing: In this case measurement for the energy which can cause the tear is performed. The test is done on both directions of the paper.

Tear factor = tearing resistance in grams/basic weight in g/m^2.

6.5.4. Tensile Strength

The tensile strength is the force that is applied to the paper of predefined width and length in the parallel direction of the specimen plane at specified condition of loading. This test is conducted to indicate and estimate the serviceability and durability of the selected paper during operations such as bagging, wrapping, printing etc. Due to their higher extensibility, the plastic films are tested at higher speeds.

6.5.5. Grease Resistance

Grease containing red dye is applied to one of the sides of the specimen. The measure of this property is basically the time which is required for the red stain to show on the unexposed side of the specimen. In case of plastic films, groundnut oil coloured with red Sudan dye can directly be exposed to the pouches.

6.5.6. Gas Transmission Rate

Keeping the volume constant, the pressure is measured to determine GTR. The amount of the gas that flows through the film is taken as volume. The barrier properties and the permeability of the packages are studied using this property.

6.5.7. Water Vapor Transmission Rate

It is the quantity of the water vapor that enters or penetrates (permeates) form one side of a film of one square meter area to the other side in a time span of 24 hours with a RH gradient of 90% between the two sides at a temperature of 37.8ºC. WVTR is usually measured in grams. This property assists in selecting barrier materials for hygroscopic foods.

6.5.8. Impact Strength

Impact strength test of any package is done to investigate the ability of the package/film to withstand fracture by shock. It is aimed to measure the toughness of the material. It is a combination of deformation and breaking properties.

6.5.9. Abrasion Resistance

The ability of any material to withstand rubbing and surface wear is measured using this property. Some mechanical properties like hard resilience are measured. The procedure consists of abrading the sample with a wheel of standard abrade for a definite number of revolutions and finding the weight loss of the sample.

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Chapter 7

Innovative Food Processing Technologies

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Abstract

Food is being preserved through thermal and non-thermal treatments. Both processes have limitation in application. In thermal treatment, limitations may include overheating, non-efficient heating, CIP issues in dairy industry and loss of vitamins or other ingredients. While, nonthermal may be expensive ones, and improper inactivation / killing of the microorganisms. Thus, there is a need for new technologies development that can overcome these drawbacks. This chapter provides an overview of novel processing technologies.

Keywords: Higher Pressure Processing, Pulse Electric Field, Ohmic Heating, Hybrid Technology

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7.1. Emerging Trends in Food Industry

Food product development is now based on the consumer demands and food industry needs to convert plant and animal raw material into valuable and acceptable food products. This processing prevents them from the undesirable changes and adverse effects that may alter shelf life and consumer acceptability. This can be achieved through thermal processing of food like pasteurization, drying, baking, etc. these conventional methods have adverse effect on food components especially vitamins and other nutritive values. Thus, there is a need for alternate methods that should overcome these drawbacks, provide food with fresh like attributes and increase the shelf life (Patras et al. 2009).

The major objectives that needs to be addressed for novel processing methods are; food safety (free from microorganism, no enzymes activity) and minimizing the loss of essential nutrients, with reduced physico-chemical losses. These technologies particularly include pulse electric filed (PEF), high pressure processing (HPP) and Ohmic heating.

7.2. Ohmic Heating

In food processing, heating is used for cooking, preservation, inactivation of enzyme and evaporation purposes. In traditional processing methods, heat is transferred through conduction, convection and radiations which are dependent on internal and external resistance of food product. It is a limiting factor for homogenous heating and result in loss of food quality. Ohmic heating is promising one to overcome these drawbacks with quality products. Ohmic heating offers rapid and uniform heating of material along with reduced loss of material. It ensures the high-quality products which have higher values of nutritional and sensorial constituents.

In Ohmic heating, current is conceded in food product for heating purposes. Heat is produce due to the transformation of electrical energy to thermal inside the material. It does not depend on the heat transfer mechanism through solid-liquid interface or solid particles. Heat production process is rapid and takes only few seconds / minutes. Thereby, high temperature short time and ultra-high treatment is possible for liquids and solid products. This mechanism is difficult to achieve through conventional heating methods. Therefore, preparation of food blend exhibiting good electrical and rheological properties determined the ease of Ohmic heat application in food industry. Moreover, care should be done to avoid problem created by the particle / liquid interface having similar electrical conductivity. A comparison of ohmic heating with other technique is described in Table 7.1.

Table 7.1. Comparison between Ohmic heating and other heating methods

Technique	Principle	Efficiency	Operating parameters
Ohmic heating	An electric current is passed through the heating sample, resulting in a temperature rise due to the conversion of the electric energy into heat	Energy efficiency close to 100% and uniform temperature distribution.	Electrical conductivity Solid pH of heating sample, Voltage gradient
Heat resistance heating	An electric current flowing through a resistor converts electrical energy into heat energy	Converts nearly 100% of the energy in the electricity to heat	Depends on conductive, convective and radioactive heat transfer coefficient
Microwave heating	Energy is delivered directly to materials through molecular interaction with the electromagnetic field	Up to 65% at 2.45 GHz	Depends on internal dielectric properties, electromagnetic field distribution and the shape of the heating piece
Heat pump heating	An electrically driven vapour-compression cycle and pumps energy from the air in its surroundings to water in a storage tank	Depends on operating conditions	Condenser inlet temperature, Condenser outlet temperature, Dryness fraction at evaporator inlet

7.2.1. Design

An Ohmic heating system consists of electrodes for the conduction of electric current to the product. Electrodes may be used as plate or in rod form and the arrangement of electrode is a major factor for efficient heating. The most commonly used design of Ohmic heating system is shown in Fig. 7.1.

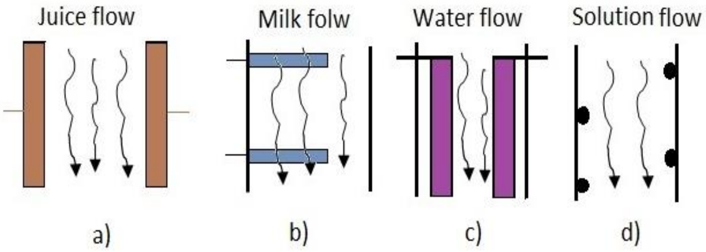

Fig. 7.1 A schematic representation of electrode arrangements in Ohmic heating: a) Parallel plates, b) Collinear plates, c) Parallel rod and d) Staggered rod (Sakr and Liu 2014).

Factors

Product composition determines the efficiency of Ohmic heating. In food composition, presence of liquid and solid parts influences the Ohmic heating process. Both parts determine the conductivity of food products that should be properly managed for effective Ohmic heating. In liquids, heating rate is dependent on volume and conductivity of the liquid phase. Presence of less conductive solid particle in liquid phase will influence more than volume size on the conductivity of overall product system. However, with the increase of such solid material, a rapid heating occurs. This process may occur due to the change in route of electric current. As solid particles increase flow of current in liquid part is tortuous which force the current to pass through solid. It results in higher energy generation; ultimately higher heating production. In general, electrical conductivity of food product determine the efficiency of Ohmic hating that mainly influenced by the ions and conductivity of solid - liquid portions.

7.2.2. Applications

In last two decades, application of Ohmic heating has significantly increased in food industry. Its major application is microbial inactivation. Heat produce through Ohmic heating can inactive the microbes. However, it can be done in non-thermal conditions through use of electrical current (Cho et al. 1999; Pereira et al. 2007; Sun et al. 2008). During Ohmic treatment, low frequency (50-60 Hz) creates charge and causes pore formation on the cell wall / membrane. This result in microbial inactivation (*Bacillus licheniformis, Escherichia coli, Streptococcus thermophiles, Bacillus subtilis, Byssochlamys fulva*) and D value for Ohmic heating reduces in comparison with traditional thermal approaches (Cho et al. 1999; Pereira et al. 2007; Sun et al. 2008). Milk microbes especially S. thermophilus were more prone to inactivation through Ohmic heating compared with traditional heating (Sun et al. 2008). Similarly, destruction of yeast cells was higher with Ohmic heating compared to conventional ones (Yoon et al. 2002). An overview of Ohmic heating is given below;

Advantages

- Instant heating and ease in attaining required temperature
- Rapid and uniform heating
- No residual heat transfer after shutting off the current
- Lower maintenance costs
- Energy efficient
- Environmentally friendly processing system
- Reduced the chance of fouling

Disadvantages

- Lack of generalized information which need more research
- Narrow frequency band
- A complex process for monitoring and control
- Difficulties in coupling the temperature and electrical filed distribution among the product

7.3. High Pressure Processing

High pressure (HP) processing is famous as non-thermal process to extend the food shelf life. It is mainly used to inactivate pathogens and destroy the vegetative spore of microorganisms present the products. In HPP, an intense pressure (ranging from 400 to 600 MPa or 58,000 to 87,000 psi) is applied at mild temperatures. This process enhances the foods to preserve with minimal effects on various attributes like fresh like, nutritional value, flavour, appearance or texture. This technique is popular as high hydrostatic pressure (HHP) processing and ultra-high-pressure processing (UHP).

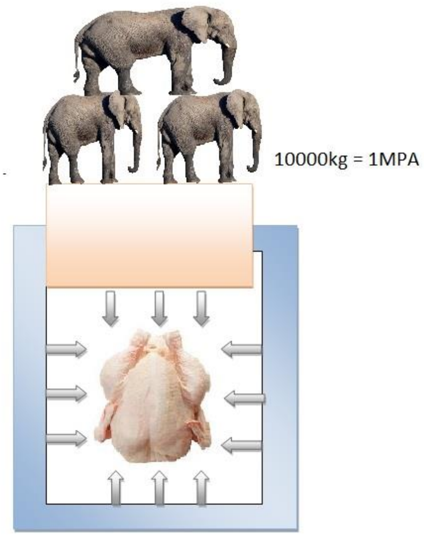

Fig. 7.2 A schematic diagram of high pressure processing principle

In HPP, a packed product is placed into chamber which contains pressure transferring liquid (Fig. 7.2). Water is commonly used fluid in HPP. Pressure is applied on fluid through pump which is transmitted to the packed product. Pressure application may increase the temperature depending upon the product constituents. After small interval, pressure is released quickly on the product; subsequently it returns to the initial temperature. In case of pathogen bacteria, pressure is maintained for 30 seconds to 15 minutes. After depressurization, product is taken out and stored or distributed in traditional ways. In this process, pressure is homogenously transmitted to the product which helps to retain the shape and structure of food. Absence of thermal treatment ensures the sensory and nutritional values of original food product.

In HPP under uniform pressure, food molecules follow Le Chatelier–Braun law and their volumes are reduced. This action influences the structure of large molecules; having tertiary structure as functionality like proteins. During this process, partial unfolding occurs that may encourage non-covalent interactions resulting in the denaturation. In this way inactivation of enzymes and microbes is achieved. However, pressure did not influence significantly on smaller molecules like vitamin, flavour, amino acid and aroma compounds (Cheftel 1995). Generally, HPP offers numerous benefits in food protection:

- Uniform pressure distribution ensures homogeneity of treatment around and inside the product

- Nominal heat impression
- Shelf life is comparable to conventional pasteurization process in addition to maintain natural attributes like texture, appearance and nutrients etc.
- Reduction in energy requirement; Less energy is required to achieved 500 MPa pressure in comparison with achieving 100ºC (Tewari 2008).

Apart from reduction in energy requirement and consumer benefits, one fundamental benefit is the prevention of recontamination as it is applied on packaged foods. HPP is quite popular in Japan, America and Europe. There are about 82 food products processed with HPP and are in use globally. Some examples of HHP processed products are seafood, fruit juices, vegetables, fish and cooked meats (Norton and Sun 2008).

7.3.1. Effects of HPP on Foods

Juices

The effect of HP on food nutrients and other properties has been studied which is described in following paragraphs. Fruit juices are rich source of vitamins and minerals. In thermal processing, loss vitamins and taste attribute are very common. In this regard, Barba et al. (2013) evaluated the physical, chemical and nutritional status of HP processed blueberry juice at varying pressure and time regimes (200, 400, 600 MPa and 5, 9, 15 minutes, respectively). The HPP did not influence the vitamin C content of juice however, total phenolic contents especially the anthocyanin was increased. Other attributed of juice (antioxidant capacity, brix and pH) remained unaffected in HP processed samples and have fresh like attributes.

Water soluble vitamins

These vitamins are sensitive to heat and lost during thermal processing. Ascorbic acid (AA) stability depends upon the varying pressure and temperature combinations. AA is readily lost under the effect of adiabatic heat consequently produced even due to the lower pressure of 100 MPa. In iso-processing condition (keeping pressure and temperature constant e.g. 50ºC, 850 MPa, 1 h), degradation is lesser compared to longer time exposure up to 8 hours. Other vitamins B1, B2, B6 and niacin are generally stable under HP processing at room temperature as reported in numerous studies. During HPP vitamins may disintegrate due to oxidation or breakage of covalent bond due to pressure.

Fat soluble vitamins

There is a few information available about effects of HP processing on fat soluble vitamins. Generally, these vitamins are quite stable at high pressures. For example, vitamin K showed stability at 650 MPa pressure and 70ºC temperature for three hours. Similarly, carotene exhibited higher stability during HP treatments.

Enzymes

Enzymes are proteins in nature and behave similarly in structural changes under applied high pressure consequently losing their activity. Enzyme structure changes in two different ways;

- At low pressure (100 MPa), reversible inactivation of enzyme take place.
- At higher pressure, enzymes may be of four types;
    - Incomplete with reversible inactivation.
    - Incomplete with irreversible inactivation
    - Complete but still with reversible inactivation
    - Complete and irreversible inactivation

Food quality

Conventional heat treatment (sterilization) involves slower heat penetration to the cold-point of food product hence induce undesirable changes including off-flavour, textural degradation, colour and vitamins destruction. HP treatment devoid such alteration among processed foods and protects the sensory profile of products. Higher pressure generally increases microbial inactivation in a shorter time but may denature protein to some extent.

Food colour

Protein denaturation may result in alteration of functionality or colour in comparison to raw products. Among meat group, colour changes due to applied pressure depend upon temperature, time and pressure. Due to these factors, myoglobin undergoes 'heme' displacement, denaturation and ferrous atom oxidation ultimately results in cooked-like appearance (Mor-Mor and Yuste 2003).

Food texture

Among high moisture food products, physical structure remains intact due to the absence of pressure assisted shear forces while in gas-containing foods, gas displacement and liquid infiltration may induce texturally and colour change under exposure to HP. Due to anisotropic behaviour, the mechanical collapse of air pockets may induce physical shrinkage. HP does not change the textural profile of foods having no air voids. Considering specific foods, HP has the potential of inducing textural modification to attain desirable structure and texture to increase product functionality or develop new food products. Recently, HP treatment modified

Mozzarella cheese in developing desired functional properties upon melting (Hugas et al. 2002).

Food yield

Food yield is one of the greatest economic issues encountered by food manufacturers using HP treatment. Food yield depends upon product type and treatment intensity as HP can provide with greater food yield in comparison to heat processing. Like, Mor-Mor and Yuste (2003) mentioned about higher weight loss in heat processed sausages than in HPP controls also preventing any taste deviation, ropiness, off-flavour or colour changes (Hugas et al. 2002). Conclusively, HPP and thermal treatment inactivate microorganisms, increase shelf life and denature protein fraction of food products. Still, heat processing may compromise food sensory and textural outlook and nutritional status in comparison to HP processing which provides natural like processed foods.

Product safety and stability

Primarily, food preservation technique is evaluated in terms of its ability to eliminate pathogenic microbes so to enhance product's safety; secondly, inactivating spoilage microbes to enhance shelf stability of the food product. Presence of microorganisms in foods initiates spoilage mechanism due to unacceptable modifications in odour, taste, texture and appearance. Microorganisms belong to a heterogeneous group of organisms, capable of growing at different temperature ranges between below freezing to temperatures above 100°C (extreme psychrophiles to extreme thermophiles respectively).

Yet, every different species has optimum growing temperature range at which it grows best; temperature influence is a major factor in determining this optimum growth range which affects enzymes and cell membrane beyond this temperature range growth are hampered. Different strains of same species can exhibit variable pressure resistance. Microbes are eliminated by sublethal injury caused by HPP, which is a major consideration for any of the preservation mode. Under favourable conditions of a suitable substrate and prolonged storage, injured cells may recover. Additionally, irreversible damage to essential growth and reproductive components is associated with cell death.

Micro-organisms

Pressure-assisted microbial inactivation primarily involves cell membrane modification ultimately altering ion-exchange and permeability. Due to cell membrane modifications, microbial resistance is lost. High pressure also changes cell morphology and biochemical status, denaturing the protein and inhibiting genetic mechanism. Destruction of key enzyme and ribosomes may also be considered as other possible mechanisms of action responsible for microbial inactivation (Linton and Patterson 2000).

Temperature, pressure and holding time

Generally, an increase in treatment pressure will increase microbial inactivation (with bacterial spores as an exception). Most HP treatments are carried out at ambient temperatures, increase or decrease in temperature mostly increases microbial inactivation (Kalchayanand et al. 1998). Pathogenic and spoilage microorganisms are rapidly inactivated by an increase in temperature above 45-50ºC. Using higher temperature in food processing may pose a microbial inactivation advantage but the temperature may also rise due to adiabatic heating. When pressure is 100 MPa, at 3ºC temperature rise can be observed due to adiabatic compressions in a transient mode which in some cases may be resisted by sample insulation.

Pressure transmitting equipment will also be dependent upon the selection of processing temperature. Considerable factors during HP treatment are the come-up times (time required to reach desired pressure) and pressure release times. Conclusively, longer come up times will increase processing time and product throughput but will affect microbial inactivation kinetics. So, these parameters must be consistent and controlled while developing HP process. Table 7.2 shows different applications of HPP in food processing.

Table 7.2. Food products that are commercially produced using High Pressure Processing technique (Balasubramaniam et al. 2008).

Cooked and ready to eat meat products	Salsa
Apple sauce, apple cider and apple juice	Orange juice
Oysters	Apple, kiwi Jams and Jellies
Sea foods	Chicken

7.4. Pulsed Electric Field

In recent decade, consumer demand for nutritional and fresh food products. It needs to develop the new mild process. Pulsed electric field technique is one of the non-thermal pasteurization methods of food. It is successful method to reduce the microbial population in foods. In this method, electric filed is applied on the food system which disintegrates the microbial cell and this method is known as electroporation in the field of genetics. Electric field strength can be adjusted to achieve final goal of food preservation.

In PEF processing, cell membrane act as a capacitor with lower conductivity and dielectric constant in the range of 2. It facilitates the charge accumulation on membrane. When this membrane is exposed to electrical field resulting in charges movement along the electric field lines. It induces the viscoelastic deformation in cell membrane. When electric potential surpasses the critical value (1V), it ruptures the cell membrane. The critical electric value depends upon size of cell, compressibility, permittivity and thickness of the membrane. Thus, electric field requirement varies from organism to organism and final purpose of the application.

A pulsed electric field system consists of a treatment chamber connected to an impulse generation module. In treatment chamber, food is fed and exposed to the electric field. The electric field is supplied by impulse generation system. The temperature inside the treatment chamber can varied according to the treatment and product. Heat exchangers may be used for preheating of sample and cooling of products. It will reduce the processing time in treatment chamber.

7.4.1. Treatment Chamber

It consists of two electrodes; one electrode is connected to high voltage and the other one is grounded to create potential differences. These electrodes may have different configurations i.e. co-linear, parallel and co-axial. Among these, parallel plates deliver uniform electric field in most of the treatment area. However, boundary region receives less electric field; resulting in untreated food products. It can be overcome with several treatment zones in line or baffled flow channels. All the component of treatment chambers should be food grade and auto- cleavable.

7.4.2. Processing parameters

Electric field

Field strength is highly dependent on microbial cell size and its location in the field. The requirement of electric filed increases with the decrease in cell size while change in shape may increases the amount of required filed strength. Besides electric field, pulse width and pulse number determine the intensity of electric field. The pulse width is the time during which peak field is maintained or time in which 37% decay is obtained. Naturally, increasing pulse numbers cause the increase in treatment time resulting in increased inactivation.

Treatment temperature

Higher temperature exhibited a synergetic influence on treatment efficiency (Fig. 7.3). Phospholipids are tightly packed at low temperatures and become wobbly with increasing in temperature. The S. Dublin microbes present in milk were successfully inactivated from 1 to 4 log cycles with the increase in temperature from 40 - 50ºC. Similarly, L. brevis was efficiently inactivated at 60ºC compared to treatment temperature at 24ºC.

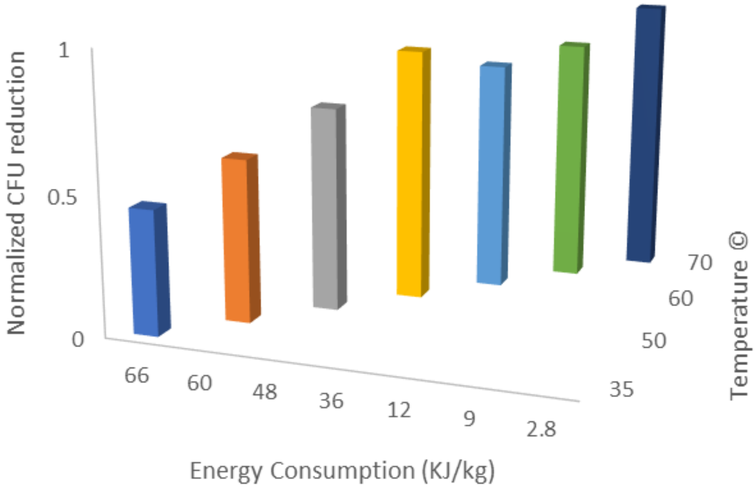

Fig. 7.3 Influence of various temperature values on energy requirement to inactivate microbes through PEF treatment

Treatment medium factors

The product parameters like pH, water activity, conductivity and presence of bubbles influence the efficiency of pulse electric field. Conductivity of the medium is the key parameter which is influenced by the temperature. A medium contains ions (tomato juice) creates problem in achieving required electric field strength. Subsequently, it will reduce the efficiency of microbial inactivation. Conductivity determine the ionic strength between the medium and cytoplasm of cell. This difference may lead toward the weakening of cell membrane and make it susceptible to electric field; resulting in disintegrated cells. For effective inactivation, lower ionic strength along with less conductivity is required. Moreover, presence of air in product or medium reduces the inactivation efficiency.

7.4.3. Effect of PEF on Food Products

Juices

Fruit or vegetable juices are rich source of nutrients as they contain prominent level of bioactive compounds. That’s why, it rapidly deteriorates the microorganisms and enzymatic activities. So, it is necessary to apply treatments to combat this issue to ensure the stability and sensory characteristics of juices. PEF, as one of the non-thermal preservation technologies, can successfully has applied on liquid foods for the pasteurization purposes as it is a continuous process and not valid for solid foods. These include many fruit juices which have low viscosity like apple, cranberry, orange juice etc. This treatment increases the juice extraction rate from the plant cells by improvement of biological tissues disintegration to release the intracellular compound, industrially profitable and produce less waste. It improves flavour and textural properties and increase the shelf life of juices by inactivation of deteriorative enzymatic reactions and spoilage microorganisms.

PEF applied at lower temperature and short residence time for quality enhancement purposes of the liquid juices, to be preserved its freshness characteristics. Numerous comparative studies have been showed the difference between intensive heat treatments and non-thermal techniques and proved that mild PEF processing with different EFS, treatment times and energies, did not cause any degradation of the quality attributes specially some sensitive nutrients like ascorbic acid in orange juice.

It is proved that PEF potentially effective for enhancing shelf life of juices while compared to the other heat treatments with better quality and enzyme inactivation. Other studies that were linked to the storage period and organoleptic properties of orange juice demonstrated that PEF treatments significantly extend the storage period acceptability of orange juice even after the 180th day when it was stored at 4ºC.

This treatment basically applied to deactivate the pathogenic microbial effects and reducing the risk of food-borne illness caused by unpasteurized juices consumption as well as provides juice manufacturers an innovative approach for enhancing the safety and extending the shelf life of juice products. Other than the use of PEF for microbial inactivation, it can be applied for various quality purposes in juice industry as for increasing the extraction processes yield, textural modifications of the products to reduce downstream losses. Besides its use alone, PEF has been successfully combined with other non-thermal technologies such as UV irradiation, sonication, microwave, high intensity light pulses and HHP to achieve higher quality final product.

Food nutrients

Due to PEF treatment, nutritional characteristics of juices are seeming to be improved, because it induces disintegration in plant cells that extracted more valuable components within juices. If we generally talking about the cell permeabilization process that is induce by application of PEF treatment, so it may be reversible or irreversible depending upon the intensity of pulse energy (field strength) and timing of action of treatment. In the case of reversible cell permeabilization process, low PEF treatment is needed to induce stress in plant cellular system. Plant metabolism activated and produce secondary metabolites that drives many valuable components with them like secondary metabolite production together with extractability of plant pigments from wine grapes have been reported.

Studies showed that low PEF treatment potentially increase total polyphenolic contents in fresh pressed grape juice that was enhanced by increasing EFS. There is a fact that should also be noted that higher PEF treatment proved to have no adverse effects on other quality characteristics of juices e.g. no change in pH, Brix values was noticed after PEF treatment PEF induced cell permeabilization and release of intracellular pigments while 65% of the total membrane area was permeabilized, which resulted in three-fold increase of the total anthocyanin content. In case of beets, higher yield of sucrose was obtained by easy pressing of PEF pre-treated beets as compared to the conventional thermal process that have less residual sugar. PEF also evaluated for extraction of β-carotene content of carrot juice, vitamin C content in bell peppers, higher amounts of tocopherols and polyphenols in oil and important antioxidants in rapeseed.

Enzymes

PEF treatment was familiarized to inactivate enzyme and microorganism activity by increasing the physico-chemical properties, colour, flavour, taste quality attributes, healthy components and quality attributes, which were founded in cranberry, orange and apple juices. There are some enzymes which are quite sensitive, and some shows much resistant after PEF treatment than some microorganisms. Enzymes are basically proteins that effected by temperature fluctuations (heat labile enzymes) and pH changes that may occur during PEF treatments due to electrochemical reactions on electrode surface and partial electrolysis cause the change in pH.

It is also stated that there may be the reason of protein unfolding and denaturation, breakdown of covalent bonds and oxidation reduction reactions, like those between sulphide groups and disulphide bonds, because of the charge separation due to short field pulses, which created morphological changes in enzymes. So, these lose their active sites for binding of substrates and they lose their activity. Moreover, electric field pulses generate charges that influence the chemical stability of proteins or enzymes while some researchers demonstrated that PEF causes entire globular configuration changes in enzymes structure.

A study reveals the inactivation of various enzyme through PEF. These enzymes are; PPO in apple juice, POD in milk, lipoxygenase in green pea juice & tomato juice. Besides, PEF treatment may contribute to increased pectin extraction due to inactivation of PME ultimately increases juice extraction yield from plant tissues.

Research showed that PEF treatment might be supportive of radical formation due to the high energy input, leading to a rise in antioxidative capacity. PEF can inactivate enzymes or even can increase the activity of enzymes depending upon intensities of EFS and width of generating pulses that can influence on enzyme structure.

Effects of PEF on microbes

There are various factors that play important role in microbial inactivation through PEF. These factors may include type of product & microbes along with processing methods. In PEF treatment, effect of temperature, energy consumption to inactive microbes indicated in Fig. 7.4. Besides these, treatment time, pulse polarity, width and shape contribute in microbial inactivation (Abram et al. 2003).

When an electric field was induced at a certain membrane potential, then mechanical volatility was occurred in membranes and the membrane was broken down when this influences on dynamic worth with strong electric field. Due to PEF treatment, electro-permeabilization was verified to be reversible or irreversible depending upon the changes occurred in the membrane. Previously, some researchers confirmed the theory that the effect of PEF plays significant role in the death of microbes which might be attributed to the electroporation and electromechanical compression provoked after the PEF treatment (Weaver et al. 1988). Microbial inactivation through PEF is termed as Cavitation, which effect on bacterial cell membrane. This process induces the cell wall breakdown of microbe through electroporation ultimately, changes the cell morphology. Thus, a cell loses it components and integrity (Grahl and Märk 1996; Gonzalez and Barrett 2010; Maskooki and Eshtiaghi 2012; Pillet et al. 2016).

Nutritional Quality

Nowadays, consumers are the emphasis to get fresh-like fruit and vegetable juices with minimum loss in the form of nutrients during processing. So, food scientists are paying some attention to expand such product and new techniques which can fulfil the expectation of consumer demand. Researchers are giving their attention to control the enzymes and microbes but there is a need to focus that some research should be done on PEF regarding different liquid products with nutritional and sensory properties, and minimal impact on the quality of the foods, which recommends that it is feasible to get safe, healthy and good quality PEF treated liquid products with a sensible shelf life.

7.4.4. Applications

Disintegration of biological material

In various food operations, thermal treatment, grinding or enzymatic action is necessary to destroy the cellular material. These operations needs higher energy (Fig. 7.4), more time or storage silos to complete the enzymatic maceration. It may result in loss of quality, nutrition and physical properties of food product. However, PEF offer an alternate to these conventional processes and overcome these drawbacks.

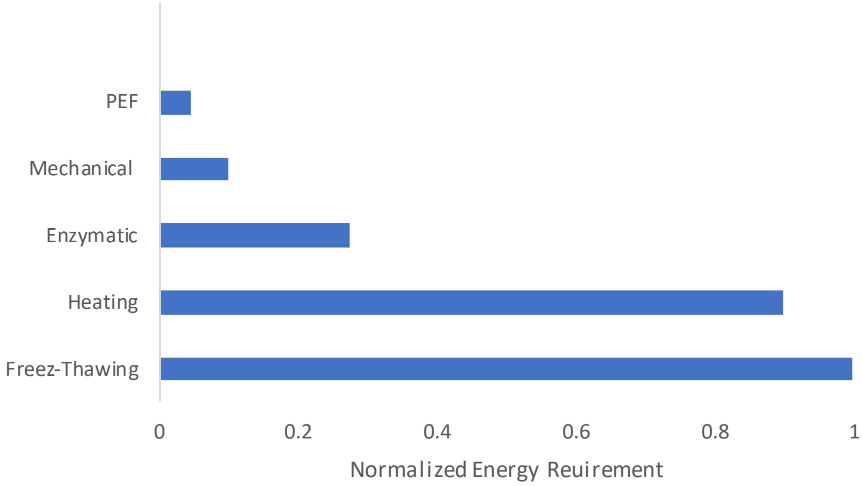

Fig. 7.4 A comparison of energy requirement to disintegrate the microbial cell through different processing techniques (Stefan et al. 2005).

PEF working at ambient temperature, result in retained quality and fresh like attributes of food product compared to thermal treatments. The juice processed with PEF has fresh-like sensory attributes and retain its natural nutritional values. The carrot juice yield was increased from 60.1 to 66.4% compared to traditional methods. Similarly, grape juice was significantly increase through cell fragmentation by PEF. Juice and pectin extraction from fruit with PEF and conventional method is compared in Fig. 7.5.

Drying

Drying is the most energy consuming process as enormous volume of moisture is required. PEF treatment reduce the energy requirement by facilitating the transport mechanism increasing the surface area for dehydration. In case of PEF treated red pepper slices, the drying time was reduced from 6 hours to 3.7 hrs (Ade-Omowaye et al. 2001). Similarly, higher drying rate and enhanced rehydration ratio were exhibited by PEF treated apples. Thereby, reduced drying temperature and time will reduce the cost and increase the production capability. Apart from these benefits, there is chance of reaction may occur at electrodes. Therefore, it still an open area for research to avoid the reaction or to produce electrode where food could not stick and react.

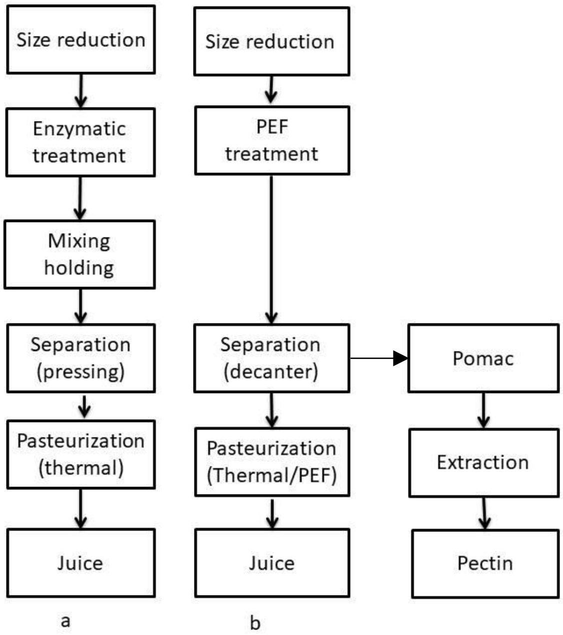

Fig. 7.5 A graphical representation of juice extraction process through (a) thermal and (b) PEF techniques (Stefan et al. 2005).

7.5. Hybrid Technology

In many agricultural countries, large quantities of food products are dried to improve shelf life, reduce packaging costs, lower shipping weights, enhance appearance, encapsulate original flavour and maintain nutritional value. According to Okos et al. (2006), the goals of drying process research in food industry are three-fold:

- Economic considerations: To reduce cost and improve capacity per unit amount of drying equipment, to develop simple drying equipment that is reliable and requires minimal labour, to minimize off-specification product and develop a stable process that is capable of continuous operation.

- Environmental concerns: To minimize energy consumption during the drying operation and to reduce environmental impact by reducing product loss in waste streams.
- Product quality aspects: To have precise control of the product moisture content at the end of the drying process, to minimise chemical degradation reactions, to reduce change in product structure and texture, to obtain the desired product colour, to control the product density and to develop a flexible drying process that can yield products of different physical structures for various end users.

The principle motivation in developing hybrid drying technologies is to minimize product degradation and yet produce a product with the desired moisture content. The characteristics of food quality parameters are paramount considerations during the employment of different drying mechanisms to yield quality dried products.

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Chapter 8

Supplemental Processes

Amna Sahar, Ubaid ur Rahman and Eric Dufour[†]

Abstract

Recent advances in centrifugation, mixing, sedimentation, distillation, extraction and crystallization have contributed to the growing success of food industries, meeting their requirements for consistency and developing new products while also lowering the production costs. In process engineering, these processes involve manipulation of a heterogeneous physical system with the intent to make it more homogeneous. This chapter discusses the principles involved behind these processes and their applications in different food processing industries. Some applications are presented as well to illustrate certain processing challenges and how these technologies are being used in food industries. This chapter mainly deals with various supplemental processes used in the food industry. Among these processes, mixing is known as universal process because it is an integral part of processing lines. For each process, mathematical relationships are useful in their designing and operations are considered in this chapter.

Keywords: Centrifugation, Mixing, Sedimentation, Distillation, Extraction, Crystallization,

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8.1. Centrifugation

Centrifugation is a procedure that includes the use of the centrifugal power for the separation of heterogeneous mixtures based on their densities. This process is used to separate two immiscible fluids. More dense elements of the mixture move away from the axis of the centrifuge, while less-dense elements of the mixture move towards the axis. The basic principle that governing the centrifugation process is decantation of particles under the effect of earth's gravity. In food industry, centrifugation process is mainly used for milk separation, cheese production, and fruit pulp separation etc. The rate of centrifugation is specified by the angular speed calculated in revolution per minute (RPM), or acceleration indicated as g. The particle settling speed in centrifugation is dependent on their size, shape, centrifugal acceleration, quantity of solids in samples, and the viscosity. In the food and chemical sectors, unique centrifuges are used that allow continuous flow of particle laden fluid.

8.1.1. Principle of Centrifugation

In centrifugation procedure, there are only two forces acting on the particles. Newton's second law states that the acceleration of the food components moving in the pipe is directly proportionate to the forces acting on the particles, but inversely related to the mass of the pipe. These two forces can be settled into x and y vectors with the up and down route taken as y and the side-to-side route as x. With these presumptions, the power of the stress in the y route is equivalent and reverse to the power of the bodyweight. Since these forces terminate each other, there is no change in speed in the y route while the centrifuge is in movement. The x part of the stress, however, shows that the pipe is accelerating up towards the left side, or in this situation towards the middle of the spinning movement. This acceleration is known as the centripetal acceleration (Babior and Stossel 1994).

8.1.2. Mechanical Separation

The separation of two immiscible liquids, or fluid and solid, relies on the effect of gravity on the elements. Sometimes separation occurs very slowly because the gravitational forces of the elements do not differ significantly, or because of forces having the elements in organization. In sedimentation, an obvious separation between the elements did not occur rather it is a consolidation of the levels. For example, if milk is allowed to stay in a pan for some period, the cream of milk will be collected on the upper layer of milk and can be separated from the milk. This process is time consuming and usually suitable at domestic level, not for commercial purposes.

At commercial level, the effect of gravitational force is usually neglected during the analysis because the centrifugal force is much greater than the force of gravity. The centrifugal force on a particle is given by;

$$F_c = mr\omega \tag{8.1}$$

Where F_c is the centrifugal force that acts on the particle to maintain the rotation in a circular path, whereas r is the radius of circular path, m is mass of the particle, and ω is the angular velocity of the particle. Since ω = v/r, where v is the tangential velocity of the particle.

$$F_c = mv^2/r \tag{8.2}$$

Rotational speed is usually expressed in revolutions per minute, so the equation 8.2 can also be written as:

$$\omega = 2\ \omega N/60 \tag{8.3}$$

Where N is the rotational speed measured in rpm. In comparison with gravitational force (Fg = mg), the centrifugal acceleration replaced the gravitational acceleration, which is usually expressed in g.

8.1.3. Applications

The centrifugation process has been widely used in the food industry for the separation of different phases having different specific gravity. The most common use of centrifuges in the food industry is the clarification of liquids. Cylindrical rotating bowls are used to separate the suspended solids from the liquids. These solids are collected at the bottom of the bowl and removed by internal conveyors. The separation efficiency can be improved by introducing different polyelectrolytes having specific characteristics. The added polyelectrolytes enhance the accumulation of solid particles and they can easily be separated. However, polyelectrolytes are normally added during the purification of sludge and not commonly used in the processing of foods. Some common applications of centrifugation process in the food industries are discussed in the following lines.

Recycling

Centrifuges are widely used for the treatment and recycling of industrial fluids, polymers and their respective recyclables. The centrifugation process is also used for the recycling and treatment of water in different food processing plants.

Animal-Based Products

This method is also used for the treatment of different by-products obtained from meat and fish processing industries. Different bioactive compounds can be separated from the animal blood and viscera, which have wide applications in different food, feed and pharmaceutical industries. Additionally, separation of finally dispersed components of an immiscible liquid-liquid mixture is commonly practiced in food industries. This process is commonly used in dairy industries for the separation of milk and cream by using centrifuges. Milk is continuously fed to the rotating bowl of centrifuge and the skim milk and cream is discharged through specific points.

Food and Beverage Production

This process is widely used in the processing of non-liquid food products, fruit and vegetable processing, juice manufacturing, wine and sugar processing, and recycling of food-related products.

Oleo-Chemistry

Centrifuges are also used in the production processes for oleo-chemistry derivatives and refining of edible vegetable oils.

Formation of Multilayer Emulsions

Different strategies have been adopted to develop stable multilayer emulsions for food applications to prevent the aggregation of droplets due to free polyelectrolyte (Voigt et al. 1999). In this method, the excess polyelectrolytes are removed from the colloidal solutions by applying centrifugal forces. The non-adsorbed molecules of polyelectrolyte are then separated from the colloidal suspension, collected and resuspended in some appropriate buffer solution. The complete removal of free polyelectrolyte is ensured by repeating the process several times and then the new polyelectrolyte solution is added. A pictorial representation of multi-layer emulsion formation is described in Fig. 8.1.

Centrifugal Separation of Oil and Water

A dispersion of oil in water is to be separated by using a centrifuge. Oil droplets are dispersed in water as globules having a diameter density. During centrifugation, the oil droplets are separated by rotating at a specific speed. Oil and water droplets rotate with different speeds due to the difference in their densities. The velocity of centrifugation can be calculated by using Stokes' Law that determines the rate of sedimentation.

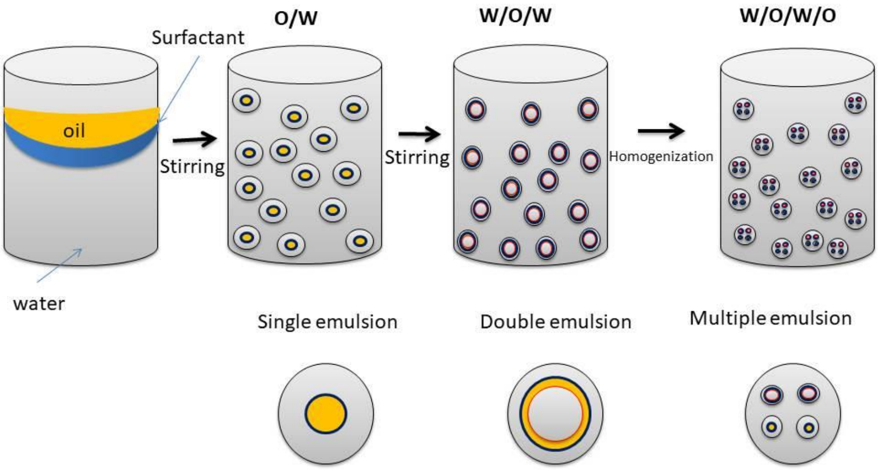

Fig. 8.1 A graphical representation of multilayers emulsion formation process

8.2. Sedimentation

Sedimentation is the process of separating solid particles from fluids through gravitational force. Sedimentation is one of the most commonly used processes in the food industries for the removal of solid particles from liquids or gases. This process has considerable applications in food industry. Rate of sedimentation process depends on the concentration of solid contents in a suspension. Sedimentation flux is quite different in low-concentration and in high-concentration suspensions.

8.2.1. Low-Concentration Suspensions

In low-concentration suspensions, particles settle down with respect to the terminal velocity. In this type, no interaction between suspension and particles exists hence known as free settling. The terminal velocity of particles depends on the force exerting on the particles called drag force. Drag force in low-concentration suspension can be described as follows:

$$F_D = 3\pi\mu du \tag{8.4}$$

In this expression, u is the relative velocity between particle and the fluid, d represents the particle diameter and µ is the viscosity of fluid. Equation (8.4) is valid for Reynolds number less than 0.2. It is suitable for food applications because in most of the food processing applications, Reynolds number is usually less than 0.2. The gravitational force can be expressed as a function of difference between particle volume and density along with acceleration. This relation can be mathematically stated as:

$$F_G = 1/6\pi d^3(\rho_p - \rho_f)g \tag{8.5}$$

In this equation, d is the particle diameter having spherical shape, ρ_p is the density of particles and ρ_f is the density of fluids. By comparing the equation (8.4) and (8.5), the terminal velocity can be calculated with the help of following equation:

$$u_t = [4d(\rho_p - \rho_f)/3C_d\rho_f]^{1/2} \tag{8.6}$$

Thus, terminal velocity is directly related with the diameter of particle, particle density and fluid properties are also related to terminal velocity. Equation (8.6) is the simplest form of Stoke's law and this equation is only applicable for spherical shaped particles and streamlines flow of fluid. In some cases, particles are not of spherical shape. For these kinds of irregular shaped particles, a shape factor is usually introduced to account for the irregular particle shape and effect of this factor on terminal velocity. However, if Reynolds numbers are above 1000, laminar flow does not exist, so the equation can be modified and described as follows:

$$u_t = d^2g/18\mu(\rho_p - \rho_f)g \tag{8.7}$$

In this equation C_d is the drag coefficient and is a function of the Reynolds number.

8.2.2. High-Concentration Suspensions

In these suspensions particle size varies from 6 to 10 microns, and it is assumed that all these particles fall approximately at the same rate during sedimentation. This sedimentation rate of particles corresponds to the velocity prophesied by Stoke's law, using the mean particle size in the suspension. The physical phenomenon involved is the velocity of larger particles during settling is reduced due to the smaller particles of fluid. Contrarily, the rate of movement of smaller particles' fall is enhanced due to the supportive movement of larger particles.

The settling of particles with a uniform rate results in the development of well-defined zones of solid concentrations. This movement of particles with a constant rate results a clear liquid at the top of the column suspension and there is a continuous layer of solids moving with a uniform velocity. Zones of different concentrations of solids are developed below the layer of solids. Largest particles are settled at the bottom of the suspension column. The sizes and levels of different zones are affected the size of particles and their respective ranges.

The settling rate of suspensions can be expressed by introducing some modifications in the Stoke's law. Stoke's law can be modified by introducing the velocity and density of suspension instead of viscosity and density of the fluid. In this case, the new expression for calculating the settling rate of suspension will be illustrated as:

$$u_s = Kd^2(\rho_p - \rho_f)g/\mu_s \tag{8.8}$$

In this expression, K is the experimental constant. In most cases, viscosity of the solution and density of the particles is predicted on the basis of composition of suspension. Another approach for estimating the velocity of suspended particles is to account for the void between suspension particles. This allows the fluid to move towards the top of the suspension column. The modified expression for calculating the velocity of particle settling can be depicted as follows:

$$u_p = d^2(\rho_p - \rho_f)gf_e/18\mu \tag{8.9}$$

Where f_e is a function of the void in a suspension. In this case viscosity of fluid and particle density is used in the calculation. The function of the void space in the suspension must be determined experimentally for each situation in which the expression is utilized. There are certain associated limitations with equations (8.8) and (8.9). The major hitch is that these equations are only applicable to determine the rate of sedimentation in high concentration suspensions having large particle size.

Considerable errors have seen in the values if these equations are used in the suspensions having low concentration of suspended solids. So, there is a need to develop some new and more reliable mathematical expressions that can be used for both types of suspensions. Another important factor that influences the rate of sedimentation is the diameter of sedimentation column. If the diameter of column is less than 100 cm, the walls impose a retarding effect on sedimentation rate.

Sedimentation process can also be used for the removal of solid particles from air, such as after spray drying processes. These solid particles can be settled to the floor surface by introducing the suspension into a static air column. In this type of sedimentation, usually simple and straightforward computations are used. But a major drawback of these processes is that these are quite slow and relatively impractical (Singh and Heldman 2009). Thus, sedimentation is not recommended for these processes. Therefore, several other types of forces can be used to accelerate removal of suspended particles in air.

8.3. Mixing Process

It is one of the extensively used processes for the preparation of food products. Many foods need mixing procedure to attain the features that are essential for the final product such as texture, homogeneity and structure. Mixing can start as early as the preparation of components can be consistently used until the end of the procedure. Food mixing can range from nano-emulsions to large particle suspensions and extremely sticky pastes to dry grains (Canovas et al. 2009).

The primary purpose of mixing is to create homogeneity (uniform distribution) in the product. In homogenization, shearing effect of force causes reduction in the dimensions of compound. It is frequently used in the food processing; liquid milk products, emulsification of healthy salad dressing and sauces, mashing of baby meals and stabilizing concentrates. Food products development have various roles depending upon their use, for example, creams and margarines have to transform liquid stage to constant emulsion; ice creams and chocolates should integrate gas pockets as a component into liquid or viscoelastic materials.

The components being mixed have direct impact on the types of devices that should be used in mixing (solid-solid combining, solid-liquid combining (coffee, sugar) or liquid-solid combining (butters, pastes and dough), liquid-liquid combining (emulsions: margarines and spreads) and gas-liquid combining (fermentation or chlorination). It is essential to consider a balance between the device and component qualities in order to obtain an effective dimension production without using a variety of time and power consumption; this would backslide in a better process and energy efficiency. Another essential parameter for sizing the devices is the rheology.

In the food industry sanitary design and relevance of cleaning are very important factors to consider because of the repercussions that could result from a poor sanitary standard, for example the contamination of the item by bacterial growth. For the mixing of liquids some types that are being used are: the paddle mixer, anchor mixers, turbine mixers, propeller mixers and the new generation of static mixers (Berk 2009).

8.3.1. Applications

Mixing in food industry is used mainly to acquire homogeneity with the best possible devices. The fact that some viscoelastic items should maintain the gas generated during the procedure and some other items should prevent gas distribution. Lastly it is necessary to underline the most important variations between the food mixing, hygiene and sanitation, where formal rules are involved. Food mixing can occur between liquid-liquid, gas-liquid and solid-liquid (Kutz 2007).

Emulsions

Emulsions play a dynamic role to develop a variety of food products. For example, several emulsified products including creams, fluid milk, ice creams, fermented milk, butter and other dairy products are manufactured from milk by using this technique. Raw milk is an example of oil-in-water emulsion with roughly 4% fat existing in dispersed phase. The droplet diameter ranges between 1-4 µm that is enclosed by a membrane. If the milk is not homogenized, the fat droplets would be aggregated to produce cream. In mayonnaise, phospholipids and egg yolk are used as emulsifier to stabilize oil and acidified aqueous phase. A number of factors including pressure and applied force are involved in the modification of size, droplet diameter and solidity of emulsions after homogenization.

One of the major categories of mixing is Liquid-Liquid mixing (emulsions). Many food products in the market are emulsions. They are very complex in their composition and structure. An emulsion is a combination of two immiscible fluids; one is dispersed in the other fluid. Some examples of food emulsions are milk, butter, confectionary products, mayonnaise, salad creams and sauces.

Emulsions’ quality depends on type of emulsifier, process, packaging and storage (Gerald et al. 2008). The quality of food depends on the qualities of the emulsion, concentration, distribution droplets and their size. The physiochemical aspects of an emulsion are described by its type, concentration, structure and interaction of elements. Usually emulsions are polydisperse; dimensions of the drops differ from each other.

Moreover, if the properties of the individual particles of the emulsion are not known, the real behaviour of the emulsion cannot be understood because of the complicated interaction of elements. These bonding interactions are accountable for the rheological properties, stability, overall look, and certain other features of the emulsions. Several other factors including temperature, pH and concentration of emulsifier modify the properties of emulsion (McClements 2005).

Type of Emulsifier

The emulsifiers are the surface-active compounds that are present on the outer lining of the droplet and prevent reunification. Both natural and synthetic emulsifiers have been extensively used for the development of emulsions. Emulsifiers reduce the interfacial tension between the fluids but do not enhance the interruption due to mechanical agitation. Mixture of different emulsifiers is commonly used in the food industry to protect several features of the final product such as texture, rheological characteristics, stability and sensory attributes. Using these kinds of emulsifiers in the food industry allow a smooth, fluffy and moist product. These emulsifiers are usually prepared by mixing surfactants, necessary proteins, polysaccharides and phospholipids. Sometimes mono-glycerol and its derivatives are also added in the emulsifiers.

Importance of Stability and Type of Emulsion

Emulsion type and stability are also considered while developing some suitable emulsions for a particular product. Emulsions are categorized by their comparative distribution in the greasy and aqueous phases. Besides the traditional emulsion of oil-in-water (O/W) and water-in-oil (W/O), some multiple emulsions including water-in-oil-in-water (W/O/W) and oil-in-water-in-oil (O/W/O) are also developed.

Some food emulsions contain other ingredients including vitamins, fat, proteins, and glucose in addition to emulsifier at water & oil interphase. Emulsion stability is an important factor which maintains emulsion's properties. Stability of emulsions also keeps the diameter of particles constant. Emulsifier also plays an important role to enhance the stability of emulsion. Without the addition of emulsifier, oil and water will be separated instantly when the mixing will be stopped. By using an emulsifier, emulsions are stabilized kinetically for a certain time period. Several chemical reactions such as oxidative rancidity adversely affect the emulsion stability. This problem can be tackled by using antioxidants.

Light is another important factor which contributes to instability of an emulsion. Moreover, viscosity of the continuous phase also determines the stability of the emulsion. If the viscosity of continuous phase of the emulsion is improved, the drops will not shift quickly, and the stability will be improved. Different gelling and thickening agents are added to increase the viscosity of an emulsion. The most commonly used thickening agents include alginates, pectin, cellulose derivatives, starchy foods, gelatine and other jam developing ingredients.

Devices/Equipment Used to Develop Emulsions

Mechanical agitation is required to mix the immiscible fluids with a suitable emulsifier. This can be achieved through high speed mixers or high-pressure valve homogenizers. Moreover, membrane based micro structured systems and ultrasound waves are used to prepare emulsions. Homogenizers are also extensively used to produce emulsions on commercial scale. It decreases the droplet diameter by applying high shear force and pressure. High pressure mixers are used to mix extremely sticky immiscible fluids by providing higher spinning time at low rate. High pressure homogenization is commonly used in different food industries. For example, in dairy industries creaming of milk is reduced in the formulations of different soups, sauces and salad dressings.

Gas-Liquid Mixing

Besides liquid-liquid mixing, gas-liquid mixing is an important part of food industry. Gas-Liquid mixing has wide applications and development of the new products is based on air as the most numerous component. Gas development is essential for food mixing because, so many items use air for desired product appearance. Steam induced mixing is used for puffed grain, snacks and coffee. Gas development is an essential procedure in the food industry, as many foods such as breads, alcohol, sparkling wine, ice creams and even some sweets contain air pockets. The addition of air cells in foods allows development of very novel components (Cullen 2009).

Foams are typical in many foodstuffs such as alcohol, morning meal, and ice creams. The two major techniques for combining gas into fluids are mechanical agitation and steam induced mixing. The technique of mixing the phase is not the only essential part of the Gas-Liquid mixing but the quantity of gas integrated should also be examined. Gas keep-up evaluates the level of gas pockets in liquid food. Gas hold-up in bubble containing liquid meals range from 15% to 20%; for example, in milkshakes, to over 90% in extruded items such as snacks and rice cakes (Cullen 2009). Gas hold-up can be defined by the following equation:

$$\varphi = [1 - (m_f / m_i)] * 100 \tag{8.10}$$

Where, φ is the gas keeps up, m_i is the mass of the continuous phase in kg and m_f is the mass of the froth in kg. This formula can be used for fluids and pastes having medium to high viscosities such as ice creams and whipping creams. For strong foams such as aerated chocolates, it is complex to perfectly obtain perfect volume. The flotation technique is more appropriate for these cases (Haedelt et al. 2005). For systems that are less viscous (alcohol and cappuccino), the gas keeps up is measured using the size of the froth and the size of the fluid.

Using agitation under beneficial stress is a very typical technique and can be seen in almost every kitchen with an electric whisker. This procedure successfully surpasses air into the content to generate air pockets in the fluid. Larger air pockets are originally integrated from the head space and their dimensions reduce as agitation continues. Another typical beneficial stress in gas fluid system is a carbonator. A carbonator depends on mass transfer concepts and allows close get in touch with the gas (carbon dioxide) and the fluid. Other key elements to impact the level of carbonation consist of the pressure of the system, gas solubility, time and area of get in touch with (Cullen 2009). Steam induced mixing is used in cereals products, puffed grain and snacks.

The framework of these products is established by presenting pellets into a toasting stove, where the content is revealed to a heat range of up to 300ºC for up to 90 seconds. This causes the water in the permeable structure to disappear into vapor, which then causes its way out of the pellet developing the extended item (Cullen 2009). Steam induced mixing can also be found in every restaurant. Steam is induced into the milk products and air is entrained in the headspace of the coffee cup.

8.4. Distillation

Distillation involves the separation of different components in a mixture based on their densities. When a mixture comprising, substances having different volatility is subjected to high temperature, the vapours that are released because of ebullition will have different composition in comparison of the boiling mixture. After the condensation process, vapours constitute distillate whereas the remaining liquid will be termed as residues or bottoms. Distillation is the oldest and simplest separation technique with prime importance for chemical process industries. Distillation process has vibrant applications in food processing.

It can be used to produce alcoholic beverages and ethanol from fermented liquids. It can also be used for the recovery of organic acids as well as for recovery, concentration and fractionation of volatile aroma compounds. This process may also be used for manufacturing edible oils by using the process of solvent extraction and for deodorization of cream (Berk 2009).

8.4.1. Vapor-Liquid Equilibrium

To understand the phenomenon of distillation, suppose an ideal binary solution with components A and B. Then, pressure exerts on the substance A is p_A and given by Raoult's law as follows:

$$p_A = x_a \rho_A \tag{8.11}$$

In this equation x_a is the mole concentration of substance A in the solution calculated in mole fraction whereas ρ_A is the vapor pressure of substance A in its pure form at a given temperature. In vapor phase, Dalton's law will be applied and expression for partial pressure of substance A will be modified as:

$$pA = P\bar{y}_A \tag{8.12}$$

Here, $\bar{y}_A$ represent the concentration of the substance A in the vapor phase and P represents the pressure exerted on the gas mixture. At equilibrium stage, partial pressure exerted substance A in gaseous state should be same as vapor pressure of component A in the solution. Under these circumstances, the concentration of substance A is given by the following formula:

$$Y_A^* = \frac{x_a\, p_a}{P} \tag{8.13}$$

The hypothesis of ideal gas combination only occurs if the total pressure of ideal gas mixture is high. Contrarily, in food processing some liquids act as an ideal solution. For instance, the behaviour of vapor pressure of ethanol-water mixture shows considerable deviation from Raoult's law. In these cases, vapor pressure of component A over a non-ideal solution can be explained by the following expression:

$$p_A = P\gamma_A X_A \rho_A^o \tag{8.14}$$

In the above equation, γ_A depicts the activity coefficient of substance A. This coefficient is not a constant value but depends on the temperature of the solution and nature of the mixture. The equilibrium concentration of substance A in the vapor phase is given by:

$$Y_x^* = \frac{\gamma_A X_A \rho_A^o}{P} \tag{8.15}$$

The use of equation (8.15) for the calculation of vapor-liquid equilibrium (VLE) is difficult because activity coefficient of mixtures with respect to temperature and chemical composition of mixture is different. To overcome this problem, another expression may be used based on the relative volatility of the components of a mixture and can be described as:

$$\alpha_{A\to B} = \frac{Y_A^*(1 - x_A)}{x_A(1 - Y_A^*)} \tag{8.16}$$

In this equation, $\alpha_{A\to B}$ represents the volatility of component A comparative to component B. In case of ideal solutions, relative volatility can be described as the ratio of the vapor pressures of the pure components A and B. Relative volatility can also be kept constant in a limited range of concentrations of pure components in the mixture.

However, formation of azeotrope in ethanol-water mixture at 0.894 mol fraction ethanol concentration is one of the idiosyncrasies of the ethanol water solution. An azeotrope can be described as a homogeneous mixture having same chemical composition in vapor and liquid phase at its boiling point. Consequently, an azeotrope always performs like a pure constituent rather than a mixture in the distillation process. Thus, simple distillation cannot be used to distribute an azeotrope into its individual constituents. In case of solution of water and ethanol, boiling point of azeotrope is 78.15ºC at atmospheric pressure and this temperature is lower as compared to the boiling point of pure ethanol. Many mixtures containing two or three substances are known to form azeotropes (Petlyuk 2004).

8.4.2. Types

Most common types of distillation that are commonly used in the food processing industries include:

1) Continuous flash distillation
2) Batch distillation
3) Fractional distillation
4) Steam distillation
5) Distillation of wines and spirits

Continuous Flash Distillation

This process is commonly used for the recovery of aromatic compounds from fruit juices for deodorization. In distillation process, preheating of feed mixture followed by vaporization is carried out at lower pressure than that of saturation pressure. In the vaporization chamber, feed immediately boils and becomes partially evaporated. The vapours are later condensed, and distillate is formed. It is presumed that there is equilibrium between the vapours and liquid sending-off the chamber.

Let F be the quantity of feed, V be the vapours and B represents the bottoms or liquid in moles, then the overall material balance can be expressed as:

$$F = B + V \tag{8.17}$$

Additionally, equation for the material balance of volatile components can be stated as:

$$Fx_F = V_y^* + B_{xb} \tag{8.18}$$

By substitution and elimination of F following equation will be obtained.

$$y^* = \frac{-B}{V\,(xB - xF\,) + xF} \tag{8.19}$$

Equation (8.19) is completely depends on the material balance and is linear on the x, y plane. The straight line in Fig. 8.2 is referred as operating line which is in correspondence with material balance. The operating line of equation (8.19) has a deep slope (-B/V) that passes through the point x = y x_F. The sloppiness of the line depends on the quantity of vapours produced by F moles of feed. It can be determined by writing an energy balance based on the enthalpies of reaction for feed, vapours and liquid & assuming adiabatic evaporation. So, vaporization ratio depends on the temperature of feed and can be adjusted accordingly.

Continuous flash distillation is normally considered as simple and cost-effective process. However, several disadvantages are associated with this process. For example, this process is completed in single step that results in poor yield and inadequate enrichment. Therefore, this process is primarily applied for the solutions comprising of components having dissimilar volatilities (Berk 2009).

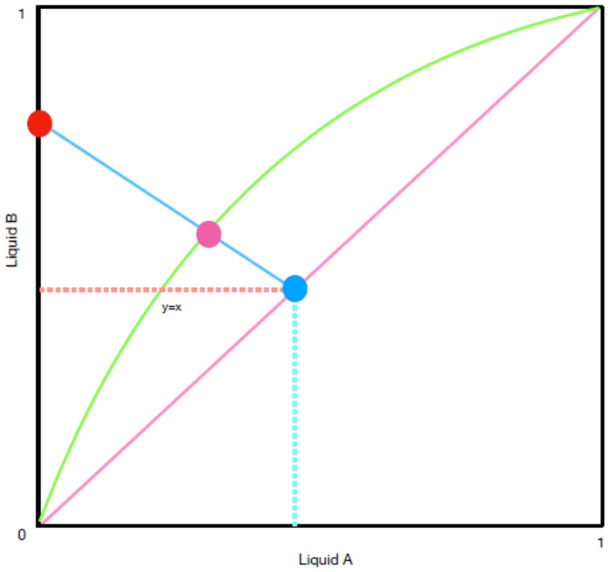

Fig. 8.2 A graphical representation of flash distillation process of two liquids

Batch Distillation

Batch distillation process is claimed as the simplest distillation method which is widely used in almost all laboratory exercises. In batch distillation, mixture is subjected to boiling in a closed container. Vapours generated during the boiling process are condensed and distillate is collected. Batch distillation differs from continuous flash distillation because it cannot be performed at a constant state. Additionally, in batch distillation, composition of the solution, vapours and distillate keeps on changing in a continuous manner (Petlyuk 2004).

Suppose that L is the total amount of solution in the vessel, x designates the concentration of volatile component in the mixture and dL is the amount of liquid evaporated. Since equilibrium exists between the number of vapours generated during distillation and liquid, then y* will be the concentration of more volatile component in that solution. In this situation, a material balance equation can be stated as:

$$xL = (L - dL)(x - dx) + y^{*}dL \tag{8.20}$$

Besides being a standard procedure for distillation in laboratories, this process is also considered as the standard method for the distillation of aroma compounds, brandy and perfumes at small scale. For these processes, the vessel containing batch is equipped with a reflux condenser.

Fractional Distillation

Likewise, batch distillation process, the recovery of distillate with highly volatile substance needs a multistage distillation process for higher recovery. For this purpose, fractional distillation process is applied to improve the process of recovery of more volatile substance from the mixture. In this method, distillation column has multiple contact stages, called trays or plates, for the movement of liquid and vapours in opposite directions. Through these plates liquid moves downward while vapours move upward. The mixture of which the distillation required is incorporated at a certain point.

There are two zones above and below the column. The upper portion is called rectification zone, while the lower zone is termed as the stripping zone. The column is further attached with a boiler to supply the heat for vaporization and a condenser for condensation of generated vapours (Berk 2009).

During the process, vapours are cooled down by the moving liquid whereas the liquid is heated by up-traveling vapours. In this way, heat is exchanged between the vapours and liquid which condenses less volatile substance and evaporates the component with high volatility. Thus, gas has become saturated with more volatile substance and the liquid has given up the more volatile component during its downward movement. The liquid which is acquired in the condenser during condensation process is further divided into two parts. One portion is called reflux which is sent back to the column for re-distillation while the other portion is known as distillate. Major advantage of fractional distillation is that we can obtain vapours and distillate with varied compositions at any stage of process.

Steam Distillation

This process of distillation is thought to be among the most promising methods that can be used for manufacturing fragrances and essential oils. Essential oils are mainly composed of different kinds of terpenoids having comparatively high boiling points usually more than 200ºC. Essential oils are highly volatile compounds and susceptible to higher temperatures. Therefore, ordinary distillation methods are generally not recommended for their recovery because they suffer from thermal degradation at elevated temperatures. However, vacuum distillation can be effectively used for the recovery of essential oils at normal temperature and pressure, but its applications are limited due to high cost. Hence, steam distillation process is considered as the most economical method for the retrieval of these kinds of volatile components from a mixture.

Essential oils are completely insoluble in water under normal conditions. It is usually hypothesized that vapor pressure of immiscible substances present in a solution is equal to that of pure components. Accordingly, this mixture is boiled at a lower temperature as compared to the boiling temperature of individual constituents present in a mixture. So, the mixture containing water and essential oils is usually boiled at atmospheric pressure below the boiling point of water. Hence, steam distillation is based on this basic phenomenon.

Steam is bubbled out from the solution holding essential oils like spices, extracts, basils and juices. Essential oils from these materials are volatilized and mixed with steam and then sent to the condenser. After condensation process, a liquid is obtained having two immiscible layers. From this liquid essential oil are alienated by decantation or centrifugation.

Distillation of Wines and Spirits

Alcoholic beverages like brandies whisky, vodka and rum are manufactured by distillation of fermented provisions such as wines, beers and fruit juices. This process can be explained by a simple equation which shows the reaction that involves the fermentation of hexose which results in the formation of ethyl alcohol.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{8.21}$$

Perceptibly, ethyl alcohol is not a single volatile substance produced during fermentation process but some other volatile compounds such as higher alcohols, methyl alcohol and several aldehydes are also produced in fermented materials which are responsible for flavour. Some of these additional volatile components are undesirable due to their off-flavour and toxicity & their removal from the material is necessary (Faundez et al. 2006).

Scotch and Cognac whisky are conventionally produced by batch distillation process. Cognac is generally manufactured by grape wine in pot-stills by a process called double distillation. After first distillation, bouilli is obtained that contains about 25% alcoholic compounds. This distillate is then subjected to another distillation step which results in the production of another distillate containing 70% ethanol. After that water is added in second distillate and it is poured in oak barrels for ageing.

Scotch malt whisky is also manufactured by double distillation. For this purpose, copper pot-stills are used that are firstly pre-heated by using peat or coke. Other alcoholic beverages like brandies, vodka and whiskies are manufactured by fractional distillation process. Normally, bubble-cap columns are used for the distillation of these alcoholic beverages but sometimes sieve plate columns can also be used in this regard. During the manufacturing of alcohol, fraction of higher alcohols is removed from the mixture and is called as fusel oil.

8.5. Extraction

Extraction is the process of getting something out from any material. It is used to perform various functions in food processing industries, for example, to get some health promoting substances from a food component or to obtain juices from fruits. Extraction is generally defined as a separation procedure based on differences in the solubility of various constituents present in a particular sample. Usually, solvents are utilized to aid solubilization and separation of least soluble solute from other components of a mixture.

Extraction process is generally classified into two broad categories namely solid-liquid extraction and liquid-liquid extraction. In solid-liquid extraction, a solvent is used for the removal of a solute from a solid phase. For example, salt is separated from rocks with the help of water, soluble coffee is produced by extracting coffee soluble from roasted coffee beans; recovery of edible oil from oilseeds with the help of solvents and production of detached soybean by extraction of proteins from soybean with solvents (Berk 2009). Solid-liquid extraction process involves solvent infiltration into solid phase that causes disintegration of extractable, transfer of solutes to the surface of solid particles by dispersion and scattering of solutes into solvent by dissemination and agitation.

In liquid-liquid extraction, another solvent is used for the extraction of solute in which solute is more miscible as compared to the first one. Some common examples of liquid-liquid extraction include extraction of essential oils from citrus peel by ethanol and penicillin extraction from fermented broths by using butanol as solvent. Liquid-liquid extraction has very important role in pharmaceutical and chemical industry as well in biotechnology. Like adsorption, refining and crystallization, extraction is a partition process in view of molecular transfer, in which particles undergo phase transition under the influence of difference in their chemical potential. Typical design of extraction process requires the knowledge of three main areas:

8.5.1. Equilibrium

Net atomic transfer seizes when balance occur between the phases, i.e. at the point when equilibrium exists between chemical potential of the extractable substance and other phases. A large number of such partition procedures comprise of various back to back steps, through which phases move, take place after different flow designs. The common methodology is the establishment of standard procedure to a progression of hypothetical equilibrium stages and to remedy the nonconformity from hypothetical conduct with the assistance of experimental or semi-experimental efficiency elements. Equilibrium information may be given as comparisons, tables or diagrams.

8.5.2. Solid-Liquid Extraction

This process involves the extraction of soluble components from a solid or semisolid with the help of suitable solvents. Solid-liquid extraction is an extraction procedure considering the special dissolution of solid segments blended in the liquid solvent. As a rule, the physical condition of the segment to be removed from the crude material is not generally solid. For intense, oil is present in liquid state in oilseeds before solvent extraction. In sugar beet, sugar is in the form of solution (juice) before solvent reaches. Washing process is important for the removal of undesirable solutes from sugar however, extraction is used to get desirable components (juice) from the material. Coffee soluble extraction for production of instant coffee is a very common example of extraction while lactose removal from cheese curd and low molecular weight compounds are removed from soybean flour by washing process.

8.5.3. Solid-Liquid Extraction Systems

Both continuous and semi-continuous forms of solid-liquid extraction are used in food industry. Batch process is utilized in specific cases, for example, the separation of colour pigments from plants, protein extraction from seeds and preparation of meat extracts. In batch systems, a vessel is used to mix solids with solvents which is further equipped with a separation device. Decanter rotators are generally utilized to separate solid components from a liquid solution. The main problem which is usually faced in continuous extraction is the transport of solids due to pressure gradient. Different systems of extraction vary in their solid movement systems.

Fixed Bed Extractors

This type of extractors is mainly used for the extraction of coffee. Fixed bed extractors are commonly composed of an extraction column along with six percolators as shown in Fig. 8.3. At the start, five percolators are filled with fresh roasted coffee beans and sixth one is filled with fresh coffee. After that, hot water is poured into first percolator which streams down to the bed. The concentrate is then transferred to the second percolator where it is further enhanced in soluble contents, thus on taking after the sequence from a series of extractors. The most accumulated concentrate exits at fifth percolator. The coffee present in first percolator is extracted with the pure water and contains minimum quantity of extractable. At the point when its substances are completely depleted, first percolator is detached, purged by gusting out the solids, washed and filled with fresh coffee.

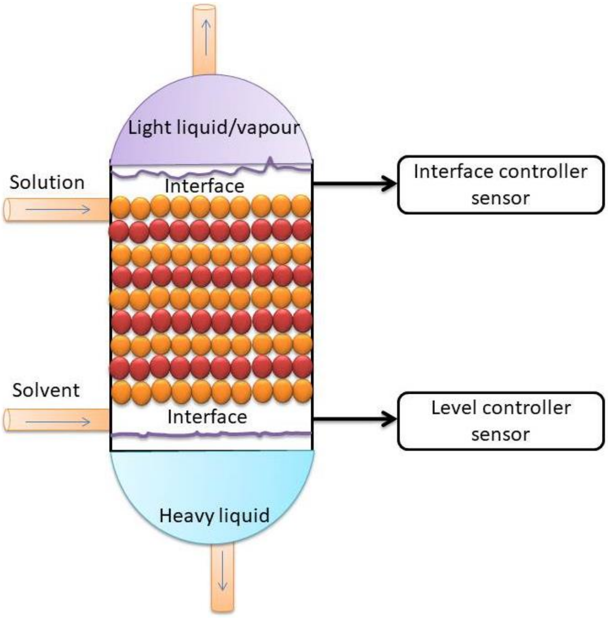

Fig. 8.3 A schematic drawing of fixed bed extraction process (Chassagnez-Méndez et al. 2000)

Boiling water is introduced to second percolator and the fluid flow sequence turns into 2-3-4-5-6. At this stage, first percolator is turned into a stand-by unit. At the following stage, percolator no. 2 is purged, and then first one is associated, and the arrangement of fluid stream turns into 3-4-5-6-1, etc. Consequently, the counter current impact is accomplished without movement of solids.

Belt Extractors

These extractors are mostly utilized for extraction of edible oils and sugar. The component to be separated is consistently introduced by a container to shape a thick tangle on a gradually moving perforated belt. Length of the bed is kept steady by controlling the rate of feeding. Solvent is splashed on solid at the last portion of the extractor closest to the outlet. The first concentrate is gathered at the base of segment and propelled over the preceding segment. This procedure of splashing of solvent, permeation of fluid through bed, fluid collection underneath the belt and pumping of concentrate rehashed in the opposite direction of belt. The highly concentrated fluid (called micella), is then accumulated at the bottom of first segment (Fig. 8.4).

In case of volatile solvent, whole framework is encased in an air-tight container having a little bit pressure to avoid spillage of solvent. In case of two-stage extractor, two belts are used in combination. Solids are exchanged and blended between these belts. Belt extractors are usually preferred for large scale production such as 2000-3000 tons.

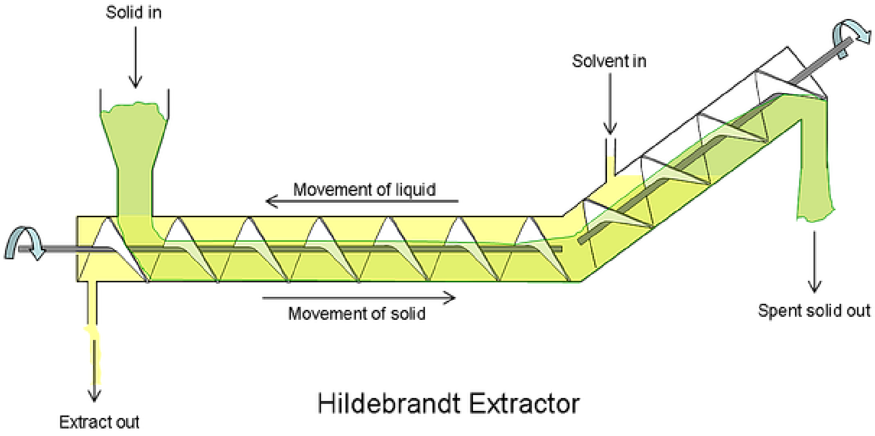

Fig. 8.4 A schematic drawing of Belt extractor. (reprinted with permission from Shantanu 2017)

Carrousel Extractors

Carrousel extractors are mostly utilized for the extraction of edible oils (Weber 1970). These extractors comprise of a vertical cylinder and hollow vessel with a gradually rotating concentric rotor. The rotor is further divided into sections by outspread segment dividers and turns over an opened base. These sections are filled with solid to be extracted. The fluid extractant is poured from the upper end and passes through the solid bed while the concentrate exits through the open-ended base, gathered in chambers and pumped back. The processes of gathering and moving back of fluid are run in the opposite directions to the revolution. After the completion of one revolution, the section passes through an opening in the base plate. After that, new material is fed to the chamber and the cycle repeats. Carrousel extractors are intended for limits like the belt extractors.

Auger Extractors

These are twisted drill extractors in which the solids are passed in vertical direction by a substantial screw transport, pivoting inside a tube shaped walled in area, against a stream of extractant fluid. Certain modifications are performed in wood screw extractors for the extraction of sugar from sugar beet with boiling water.

Basket Extractors

In basket extractors, special crates are used to carry the material. These crates have perforated bottom thorough which the extracted components leave the material. In this system, baskets are moved in upward direction or on a plane level. Another modified system which involves the use of basin lift extractors is also used for the extraction of desired components from a material. In this type of extractors, solvent flows through the pails and is accumulated at the bottom side of chain. However, vertical type extractors are preferably used for large scale extraction in a continuous system (Berk 1992).

8.5.4. Supercritical Fluid Extraction

Any substance having temperature and pressure above its critical point is called supercritical fluid. The critical temperature is that value of a gaseous substance over which it cannot be condensed. Thus, critical point of any substance is considered as the end of the gas fluid balance at a particular temperature and pressure. The thickness of a supercritical fluid is quite closer to the fluid whereas consistency of a supercritical fluid is lower than or similar to the gas. These two major properties of SCF extraction are used to derive SFC extractors. The moderately high thickness of supercritical fluids provides great force for solubilization whereas lower consistency of these fluids helps in quick penetration of solvent into solid material (King 2000).

Supercritical Extraction Systems

At laboratory and industrial scale, mostly batch process of supercritical fluid extraction is used. As a result of the restricted solubilization, it is important to apply higher concentration of solvents to sustain proportions. Supercritical fluid is continuously recovered and recycled for reuse. The essential components of supercritical fluid extraction are described in the following lines and illustrated in Fig. 8.5.

- An extraction vessel in which supercritical fluid is used to treat food material
- An evaporator, where the solute is precipitated by reducing pressure
- A separator where the product is separated from carbon dioxide
- A condenser where carbon dioxide is cooled and condensed
- A supply tank for fluid and CO_2 storage and addition of CO_2 according to the requirement
- A CO_2 compressor where the liquid carbon dioxide is pressurized above critical pressure
- A heater is used to rise the temperature above critical value before bringing supercritical fluid into the extraction vessel

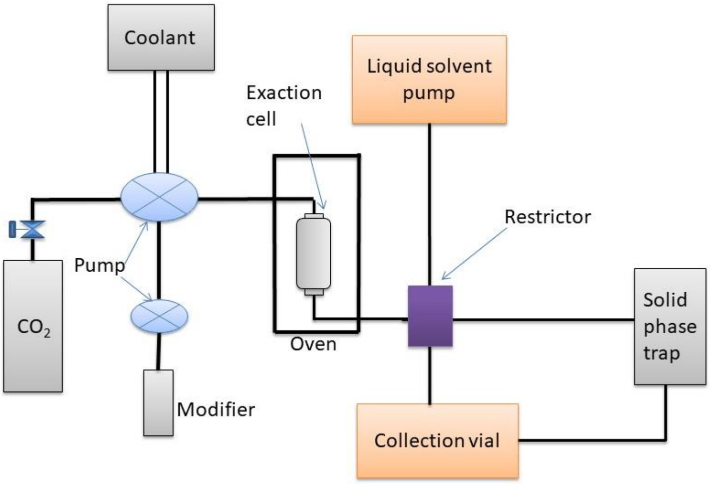

Fig. 8.5 An overview of supercritical fluid extraction system.

The process is further classified into two categories; a zone of high pressure from compressor to expansion valve and a zone of low pressure from expansion valve to the compressor. Pressure decrease is not very large between two zones because solvent is very susceptible to pressure change. The separated components are constantly precipitated due to a minute decrement in the pressure. Thus, the pressure range and energy utilization of compressor are kept moderate. Sometimes separation of the extracted components from supercritical CO_2 is done by providing a washing treatment to CO_2 with another solvent. A typical example of this process is the separation of caffeine from CO_2 by washing with water.

The potential benefits of SCF extraction in comparison with traditional methods include:

- Extraction process is carried out at moderate temperature
- Solvents are Non-dangerous, non-flammable and environmental friendly
- No residues of solvent are found in the final product because solvent is very volatile
- Great mass exchange, because of the low solvent viscosity
- Specific dissolution
- Conservation of energy because no energy is required for de-solventizing.

The disadvantages associated with SCF include:

- Require large amount of solvent because of limited solvation power
- High pressure is required. Process equipment is very expensive
- Continuous operation of process is very difficult

Commercial Applications

The main commercial scale applications of SCF are described in the following section.

Extraction of Hops; Advances in brewery increase the use of hop extract. Solvent extraction is used at large scale in industrial hop extraction. The major advantage of SCF is the efficient extraction of attractive flavour compounds without undesirable substantial resins. Likewise, hop extracts of desired aroma and flavour can also be extracted by modifying the conditions of extraction process (Rossi et al. 1990).

Decaffeination of Espresso; Application of SCF effectively replaces the other solvents used for extraction due to absence of undesirable residues. The extraction is done by coffee beans. Both extricated caffeine and decaffeinated coffee are important products.

Other Applications; SCF extraction has a wide range of application in food processing industries such as extraction of flavours (Sankar and Manohar 1994), colours and food bioactive substances (Zeidler et al. 1996; Higuera-Ciapara et al. 2005). As demand for nutraceutical food products has been enormously increased these years so, SCF extraction can be used to extract several functional components for the development of novel functional foods (Nguyen et al. 1994). In addition to that, SCF extraction can also be employed in laboratories procedure for extraction and separation.

8.5.5. Liquid-Liquid Extraction

it is known as portioning and it is the exchange of a solute starting with one solvent then onto the next, the two solvents might be immiscible or some-what miscible with one another. Mostly, water is used as one of the solvents and the other solvent is usually a non-polar liquid. Like other extraction types, this type of extraction also possesses a stage of blending, trailed by partition phase. However, important thing to consider in both steps is the selection of suitable solvents and standard procedures of extraction. Hence, while vigorous blending transfer of extractable results in the impairment of phase separation by emulsion formation.

Liquid-liquid extraction has a broad range of applications for exploring new bioactive compounds and other chemical analyses. It can also be used to recover several products of fermentation such as amino acids, antibiotics and steroids. Use of this technique in food industry is confined to isolation processes such as exchange of carotenoid to edible oils and terpene free production of essential oils from citrus by using ethanol as solvent.

8.6. Crystallization

Crystallization process involves the formation of solid crystals of solute in a solution. A liquid layer is obtained after crystal formation which is termed as mother liquor (Hartel 2001; Decloux 2002). In food processing industries, crystallization has a wide range of applications. This process is commonly used for the recovery of several crystalline products like sugar, salt, glucose, citric acid and lactose, to remove undesirable components.

Crystallization has also been used during the chilling of edible oils, a process called winterizing, for the separation of waxes and other undesirable compounds through solidification. It can also be used for the structural modifications of food products particularly in confectionary for sugar crystallization to make marzipan and fondant.

Another application of this process is the crystallization of fat in the manufacturing of margarine and chocolate. Contrarily, sometimes crystallization is also considered as an undesirable change in the structure of food products that should be controlled in order to maintain the desirable quality of a particular food product.

Some common examples of crystallization as an undesirable process in the food products are formation of sugar crystals in jams and preserves, lactose crystallization in ice cream and formation of white crystals on the surface of chocolates. Crystallization process is limited to supersaturated solutions.

Supersaturation can cause by a number of methods as follows:

- Solvent removal from a solution by different methods like evaporation, freeze concentration and membrane separation
- Cooling of solution
- Modifying the ionic strength of a solution
- Addition of another solvent in the solution which is miscible and reduces the solubility of solute
- Chemical precipitation and complexion.

Among these methods, removal of solvent and cooling are considered as the major factors that cause crystallization of food products.

The mechanistic approach involved behind the process of crystallization is nucleation followed by crystal growth. Both of these phenomena only occur in supersaturated solutions. In case of inorganic crystals, ionic bonds are involved in the formation of these crystals so strong forces of attraction are found between the molecules. On the other node, organic crystals are made up of van der Waals forces or weak dipole forces so weak forces of attraction are present between the molecules. Consequently, crystallization occurs in organic compounds as polymorphism i.e. in different forms. As organic crystals hold weak intermolecular forces, so these are quite unstable and convertible to other forms.

In food processing, the phenomenon of polymorphism is very important in the crystallization of fats during the fabrication of chocolate and stabilization of peanut butter. In desirable or intentional crystallization, care should be taken into account that size and shape of crystals is adequately controlled because proper shape and size of crystals is essential to facilitate the filtration and centrifugation process during the processing of food (Berk 2009).

8.6.1. Nucleation

Consider a solution containing a pure solute and a pure solvent. By definition, the term saturation describes the maximum amount of a solute that a solvent can hold at a particular temperature. Studies reveal that if we continue to concentrate the solution after saturation, the solute may still stay in the solution. At this point, the solution is termed as supersaturated solution. Supersaturation is not thermodynamically stable, and the degree of supersaturation can be mathematically expressed as:

$$\beta = C/C_s \tag{8.22}$$

In this expression, C represents the actual concentration (kg solute/kg solvent) and C_s shows the degree of saturation at the same temperature. It is commonly observed that solute starts to aggregate in the form of clusters with increase in degree of supersaturation. At earlier stage, small sized clusters are formed but as the rate of super saturation increases, larger lumps of solute are formed as crystal lattice.

At this stage these clusters are turned into large solid particles that have the ability to attach more solute particles called nuclei with them which ultimately results in the formation of crystals. This type of nucleation is known as homogeneous nucleation because the nuclei are formed from the solute which is formerly present in the solution (Berk 2009).

8.6.2. Crystal Growth

After the formation of nuclei, crystals start to form around them due to accumulation of solute molecules. The rate of crystal growth is denoted by G and is defined as increase in the mass of solute (dm) build-up per unit surface area, per unit time. This relation can be expressed mathematically as:

$$G = dm/Adt \tag{8.23}$$

Following empirical formula can also be used to express the rate of crystal growth.

$$G = k\sigma^g \tag{8.24}$$

In equation (8.24) k is known as empirical coeffcient that depends on extent of agitation and temperature, σ shows the driving force needed for deposition of solute and g is a numerical value called growth order. If the driving force for solute deposition is taken as the difference between the chemical potential of solute at the crystal solution interface and chemical potential at a particular temperature, and pressure is considered to be proportional to the concentration, then σ can be expressed as the difference between the concentration of solution and the equilibrium concentration at the solid surface. This relation can be depicted in the following manner:

$$G = K' (C - C_s)^g \tag{8.25}$$

In the above expression, K' is the empirical constant that depends on several factors like concentration and type of solute, quantity and type of solvent, impurities exist in the solution, rate of agitation and temperature. C represents the concentration of the supersaturated solution and C_s shows the concentration at saturation. Crystal growth consists of two stages:

- Transportation of solute from solution to the crystal surface

- Arrangement of incoming molecules in a regular pattern on crystal

Crystallization process also depends on several other factors. For example, transport of solute depends on the diffusion coefficient, temperature of the system and viscosity of the solution. Solutions having very high viscosity are unable to carry crystallization process in an effective manner. Moreover, if transport rate of solute molecules towards the solid phase is high during the growth of crystals, concentration of the liquid phase and the rate of crystal growth will decrease in a significant way.

Equation (8.25) reveals that maintaining a high degree of super-saturation is essential for constant growth of crystals. It can be achieved by continuous evaporation of some quantity of the solvent during crystallization process. This process is technically called evaporative crystallization and has been widely used for the production of salt and sugar.

8.6.3. Crystallization in Food Industry

Equipment

Crystallizers are commonly used for crystallization in industry. They are locally called pans and of types i.e., batch type or continuous type. Evaporation and cooling processes are performed simultaneously to maintain super-saturation in the pan. This type of pans is used for small scale production. On the contrary, continuous pans are broadly used in large scale and modern processing plants.

Generally, a crystallization pan consists of a vessel which is equipped with heat exchangers and agitator. A jacket or tabular heat exchange element is attached with heat exchange areas. For agitation, mechanical stirrers or a recycling system is also equipped with the system. In recycling crystallization pans, external heat exchangers are attached for evaporation and cooling processes (Fig. 8.6). These types of fans are extensively used for the commercial production of common salt and citric acid. A major limitation with the utilization of these pans is that they cannot be used for the commercial scale production of sugar due to high viscus material.

Agitation process is very critical in order to acquire proper crystals. Vigorous agitation facilitates mixing process and mass transfer, but fractured crystals are obtained by this process. On the other hand, gentle agitation prevents crystal fracture, secondary nucleation and abrasion. Sometimes, vacuum is also applied to lower the boiling point of mixture and to avoid thermal damage that can cause several quality defects like caramelization, browning of sugar and inversion (Martins et al. 2006).

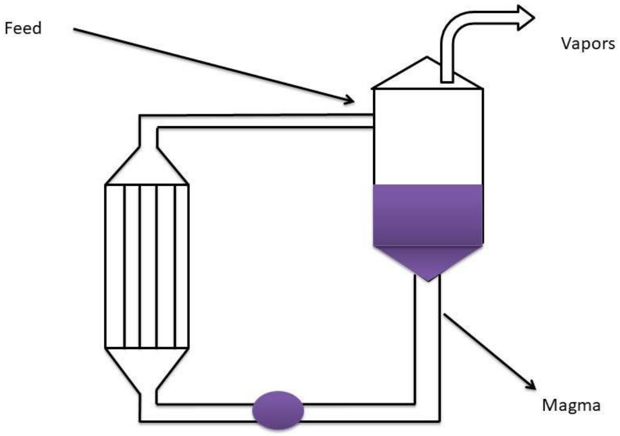

Fig. 8.6 Recycling crystallization pan with external heat exchanger.

Sucrose Crystallization Process

Last step in the production line of sugar from sugar cane or sugar beet is crystallization. This process is also known as sugar boiling. Crystallization is a very complex process which needs defined control, precise skills and experience. In modern plants, this process is completely automatic which requires controlled processing parameters like temperature, brix, pressure, purity of mixture, crystal-liquid ratio, flow rate and shape & size of crystals. Additionally, growth of crystals is also observed by digital image processing techniques in some plants. However, purity of crystals is a very important factor to obtain a good quality end product.

Purity (Q) of crystals can be mathematically depicted by the following expression:

$$Q(\%) = \left(\frac{C_{sucrose}}{C_{total\ solubles}}\right)100 \tag{8.26}$$

Sugar crystallization can be carried out by both, batch or continuous processes. However, in modern processing units, a combination of both processes is used in order to meet the requirements of largescale production. For example, seed preparation is carried out by batch process while other operations are performed by continuous process. Batch process is generally considered having low quality because by batch processing the consistency of the crystal mother liquor mixture is increased whereas purity of the mother liquor is decreased. Both these changes cause detrimental effects on the growth of sugar crystals.

Furthermore, flow pipes are blocked, mixing becomes difficult and crystal fracture is increased due to increase in the crystal content of magma. This problem can be circumvented by multistage crystallization in which first crystals are separated and then the mother liquor is transferred to the next section for concentration and crystallization (Martins et al. 2006).

Crystallization of Other Sugars

Corn starch is mainly used for the commercial production of dextrose by a process of chemical or enzymatic hydrolysis. Firstly, purification of starch hydrolysates is done and then these hydrolysates are concentrated. These are then sold in two forms; either as a thick corn syrup or in powder form. The degree of hydrolysis is expressed in terms of dextrose equivalent (DE) of the product. Complete hydrolysis of starch results in the production of crystalline dextrose. The process of dextrose crystallization is also performed in different stages as sucrose.

Lactose is another sugar which is manufactured by sweet whey. Pure lactose is uncommonly used in food industries but mainly used in pharmaceutical industries. Additionally, some portion of lactose is also found in crystalline form that has vast applications in food processing industries particularly in dairy and bakery products. Crystallization of lactose is very easy because it has very low solubility in water. Moreover, crystallization of lactose is done at low temperature because it contains nitrogenous compounds that are easily subjected to Maillard browning at higher temperature (Berk 2009).

Salt Crystallization Process

Traditionally, solar evaporation of sea water is used for the commercial production of food grade salt (Walter 2005). Solar sea salt is still preferred because solar evaporation is the most economical method of salt production. However, in recent years multiple-effect evaporation is also used for the manufacture of common salt at industrial level. This process involves the use of evaporative crystallization process and cooling step is usually skipped because solubility of salt does not vary significantly with increase in temperature.

Salt is also produced from rocks. In this process, water is forced into the salt bed in the rock. After this step, an impure brine solution is obtained which is purified by a series of purification and filtration procedures. After purification, brine is sent to the multi-effect vacuum evaporators where nuclei are formed by concentration. After nucleation, crystal growth starts from mother liquor. Crystals are then separated from the liquid by filtration or centrifugation process and then dried.

Problems

1. A steam is added into the mixture of benzene and water at total pressure of 130 mm Hg, estimate the temperature of boiling and the composition of the distillate. The two components are immiscible in the liquid. The vapor pressures of chlorobenzene and water are given below:

Pressure, mm Hg	100	50	30	26
Chlorobenzene’s Temperature (ºC)	70.4	53.7	42.7	34.5
Water’s Temperature (ºC)	51.7	38.5	29.9	22.5

2. A feed of 50% hexane and 50% octane is fed into a flash disengaging chamber. The vapor and liquid leaving the chamber are assumed to be in equilibrium. If the fraction of the feed converted to the vapor is 0.5, find the compositions of the top and bottom products. The following table gives the equilibrium data for this system.

Mole fractions of hexane in liquid x	**Mole fractions of hexane in vapor y**
1.00	1.00
0.69	0.932
0.40	0.78
0.192	0.538
0.045	0.1775
0.00	0.00

3. A sodium chloride solution is concentrated at a temperature of 40 °C, has 50% when the solubility of sodium chloride at this temperature is 36.6 g / 100 g water, calculate the quantity of sodium chloride crystals that will form once crystallization has been started.
4. Lactose syrup is concentrated to 5 g lactose per 10 g of water and then run into a crystallizing unit with capacity of 3000 kg. In this unit, containing 3000 kg of syrup, it is cooled from 60 to 10 °C. Lactose crystallizes with one molecule of water of crystallization. The specific heat of the lactose solution is 3470 J/(kg°C). The heat of solution for lactose monohydrate is -15,500 kJ/mol. The molecular weight of lactose monohydrate is 360 and the solubility of lactose at 10 °C is 1.5 g / 10 g water. Assume that 1% of the

water evaporates and that the heat loss through the vat walls is 4 x 104 kJ. Calculate the heat to be removed in the cooling process.

5. Sugar cane juice is contracted in a series of evaporators for crystal formation. The conditions in these evaporators are given below:
    a. 1st evaporator: temperature of liquor at 85 °C, concentration of entering liquor 65%, weight of entering liquor 5000 kg/h, concentration of liquor at seeding, 82%.
    b. 2nd evaporator: temperature of liquor 73 °C, concentration of liquor at seeding 84%.
    c. 3rd evaporator: temperature of liquor 60 °C, concentration of liquor at seeding 86%.
    d. 4th evaporator: temperature of liquor 51 °C, concentration of liquor at seeding 89%.

    Calculate the yield of sugar in each evaporator and the concentration of sucrose in the mother liquor leaving the final evaporator.

6. In a bakery operation, dough was mixed in 100 kg batches and then at a later time to blend in 5 kg of yeast. For product uniformity it is important that the yeast be well distributed and so an experiment was set up to follow the course of the mixing. It was desired to calculate the mixing index after 4 and 8 minutes.

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Chapter 9

Psychrometrics

Muhammad Iqbal, Yus Aniza Yusof, Muhmmad Azam Khan[*]

Abstract

The psychometrics is a scientific study of thermodynamic properties of gas–vapor mixtures. It deals with the air–water vapor system. The knowledge of psychometrics helps in designing and analyzing the food products handling, processing and preservation systems. Air and water being the precious resources of nature has key roles for the survival of both the living and non-living bodies / objects in the universe. Therefore, the properties of air–water vapor mixture must be understood thoroughly prior to designing systems / equipment. In this chapter, air thermodynamic properties, development of psychometrics chart and its practical applications have been explained in detail. Specifically, emphasis has been given on the procedures involved for evaluating air-conditioning processes, refrigeration.

Keywords: Psychometrics; thermodynamics; gas; vapor; processing; dryer; evaporation, refrigeration, enthalpy.

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9.1. Introduction

Psychometrics is the study of atmospheric moist air (mixture of dry air and water vapours). Dry air is the refined state of air that is free from moisture and contaminants. Dry air is a mixture of gasses including Nitrogen (N_2), Oxygen (O_2), Argon (Ar), Carbon Dioxide, (CO_2), Neon (Ne), Methane (CH_4), Helium (He), Krypton (Kr), Hydrogen (H_2), and Xenon (Xe). The geographical location and altitude slightly affect the composition of dry air. The composition of standard dry air with molecular weight of 28.9645 is commonly employed for scientific purposes (Table 9.1). The properties of the standard atmosphere at various elevations have been given in Table 9.2.

Table 9.1 A standard dry air composition at sea level

Air constituents	Symbol	Percent by volume
Nitrogen	N_2	78.084%
Oxygen	O_2	20.9476%
Argon	Ar	0.934%
Carbon Dioxide	CO_2	0.0314%
Neon	Ne	0.001818%
Methane	CH_4	0.0002%
Helium	He	0.000524%
Krypton	Kr	0.000114%
Hydrogen	H_2	0.00005%
Xenon	Xe	0.0000087%
Total		100.000 00%

Boyle's Charles's, Dalton's law, and ideal gas laws apply accurately to atmospheric air for most environmental control applications in all engineering applications including food engineering processing processes. It is safely assumed that the moist air behaves as an ideal gas. Therefore,

$$pv = nR_uT \tag{9.1}$$

Where; v = specific volume of moist air (m^3/kg); T = absolute temperature of moist air (K); p = pressure of moist air (Pa); n = number of moles of moist air (n_a+n_w) R_u = universal gas constant (8314.405 J/kgmolK) and na + nw = number of moles of air + number of moles of water vapor.

Table 9.2 Properties of standard atmosphere with reference to sea level (Own 2017)

Elevations (m)	Temperature (°C)	Pressure (kPa)
-500	18.2	101.478
0	15.0	101.325
500	11.8	95.461
1000	8.5	89.874
2000	2.0	79.495
3000	-4.5	70.108
4000	-11.0	61.640
5000	-17.5	54.020

According to Daltons Law of Partial Pressure; the total pressure exerted by the mixture of dry air and water vapor is equal to the sum of pressures of air and water vapours which each would exert if the whole volume occupied by itself.

$$p = p_a + p_w \tag{9.2}$$

Where, p = total pressure of moist air; p_a = pressure of dry air; and p_w = pressure of water vapours. Also;

$$R_u = M_{a.}R_a \tag{9.3}$$

Or

$$R_a = \frac{R_u}{M_a} = \frac{8314.405}{28.9645} = 287.055\frac{\mathrm{J}}{[\mathrm{kg_a.K}]} \tag{9.4}$$

Where, M_a=28.9645, molecular weight of dry air, and R_a=gas constant of dry air

and

$$R_u = M_{w.}R_w \tag{9.5}$$

$$R_w = \frac{R_u}{M_w} = \frac{8314.405}{18.01534} = 461.52\frac{\mathrm{J}}{[\mathrm{kg_w.K}]} \tag{9.6}$$

Where, M_w=18.01534, molecular weight of water, R_w=gas constant of water vapor.

9.2. Psychrometric properties

The psychrometric properties of air can be classified in various groups like humidity, temperature, and energy air. These are described as below;

9.2.1. Humidity of Air

This is the partial pressure exerted by the water vapors. At fully air saturated condition, this pressure is called saturated vapor pressure (p_{ws}). The p_{ws} is affected by dry bulb temperature that can be described by the following general equation:

$$p_{ws} = f(T_{db}) \tag{9.7}$$

The values of "p_{ws}" can be found from steam tables.

9.2.2. Relative humidity (Φ)

Relative humidity is the ratio of water vapor pressure (p_w) to its potential saturated water vapor pressure (p_{ws}) at constant dry bulb temperature and atmospheric pressure.

$$\Phi = \frac{\mathrm{p_w}}{\mathrm{p_{ws}}} \tag{9.8}$$

Relative humidity of air is the measure of its degree of saturation i.e. Φ=0.00 indicates the air is completely dry and Φ=1.00 indicates the air is completely saturated. Relative humidity equation can also be written as the ratio of mole fraction of water vapor (X_w) of air with the mole fraction of water vapor of fully water saturated air (X_{ws}) at constant dry bulb temperature and atmospheric pressure.

$$\Phi = \frac{\mathrm{X_w}}{\mathrm{X_{ws}}} \tag{9.9}$$

Relative humidity is normally expressed in percentage.

Example 4.1 The atmospheric air has following thermodynamic properties:

- Dry bulb temperature, T_{db}=21 °C
- Wet bulb temperature, T_{wb}=18 °C
- Saturation water vapor pressure, p_{ws}= 0.024871 bar

- Partial pressure of water vapor, $p_w = 0.01862$

Determine the relative humidity of air.

Solution:

Employing equation 9.8, $\Phi = \frac{p_w}{p_{ws}} = \frac{0.01862}{0.020615} = 0.75 = 75\%$

9.2.3. Absolute humidity (W)

It is the ratio of mass of water vapor present per unit mass of dry air.

$$W = \frac{m_w}{m_a} = {}^{kg_w}/_{kg_a} \tag{9.10}$$

Where, W=absolute humidity of air, kg_w/kg_a; m_w= mass of water vapor, kg_w; m_a= mass of dry air, kg_a.

As $p_w.v = m_w.R_w.T$ *and* $p_a.v = m_a.R_{wa}.T$

Therefore, $m_w = \frac{p_w.V}{T.R_w}$ *and* $m_a = \frac{p_a.V}{T.R_a}$

Inserting values of M_w and M_a in equation, absolute humidity is:

$$= \frac{m_w}{m_a} = \frac{\frac{p_w.v}{T.R_w}}{\frac{p_a.v}{T.R_a}} = \frac{p_w.R_a}{P_a.R_w} = \frac{287.0}{461.5}\frac{p_w}{p_a} = 0.622\ \frac{p_w}{p_a} \tag{9.11}$$

Since, $p = p_a + p_w$; therefore,

$$W = 0.622\ \frac{p_w}{p - p_w} \tag{9.12}$$

For water saturated air, saturated absolute humidity (W_s):

$$W_s = 0.622\ \frac{p_{ws}}{p - p_{ws}} \tag{9.13}$$

Degree of saturation,

$$\mu = \frac{air\ absolute\ humidity}{saaturated\ air\ absolute\ humidity} = \frac{W}{W_s} \tag{9.14}$$

Relation between relative humidity (Φ) and absolute humidity can be found through equation 9.8 and 9.12. Therefore, inserting value of $P_w\, from$ equation 9.12 into equation 9.8, relative humidity (Φ):

$$\Phi = \frac{\mathrm{p_w}}{\mathrm{p_{ws}}} = \frac{W.p_a}{0.622p_{ws}} \tag{9.15}$$

Example 9.2

The metrological data indicated that the atmospheric air had dry bulb and wet bulb temperature as, T_{db}=25 °C and T_{wb}=15 °C, respectively. The atmospheric air pressure, partial pressure of water vapor values and saturated vapor pressure values were 1 bar, 0.0133 bar, and 0.03166 bar respectively. Calculate absolute humidity (W) and relative humidity (Φ).

Solution:

Given; T_{db} = 25 °C, T_{wb} = 15 °C, p = 1 bar, p_w = 0.0133, p_{ws} = 0.03166 bar

From equation 9.12, Absolute humidity,

$$\mathrm{W} = 0.622\ \frac{p_w}{p-p_w} = 0.622\ \frac{0.0133}{1-0.0133} = 0.008348 \text{ kgw/kgDA}$$

From equation 9.15, relative humidity,

$$\Phi = \frac{\mathrm{p_w}}{\mathrm{p_{ws}}} = \frac{0.0133}{0.03166} = 0.42 \text{ or } 42\%$$

From equation 9.13

$$\mathrm{W_s} = 0.622\ \frac{\mathrm{P_{ws}}}{\mathrm{P-P_{ws}}} = 0.622\left(\frac{0.03166}{1-0.03166}\right) = 0.020336 \text{ kg/kgDA}$$

From equation 9.14, degree of saturation,

$$\mu = \frac{\mathrm{W}}{\mathrm{W_s}} = \frac{0.008348}{0.020336} = 0.4105$$

9.2.4. Temperature of Air

Dry Bulb Temperature (T_{db})

It is the temperature indicated by an ordinary thermometer at thermal equilibrium with air when placed in a ventilated room.

Wet Bulb (T_{wb}) Temperature

Air is moved at an approximate speed of 3 m/s around a wetted wick covered thermometer. The temperature falls than the surrounding dry air and becomes constant after a few moments known as wet bulb temperature (T_{wb}). This happens because hot dry air passing around the wetted wick covered thermometer at saturation evaporates water and lowers down the temperature of thermometer. This is an adiabatic process of cooling because no external source of energy is employed. Only the air heat contents are used to evaporate water from water saturated environment surrounding the thermometer bulb and the air itself gets cooled lowering the thermometer temperature called as wet bulb temperature (T_{wb}).

Dew Point Temperature (T_{dp})

It is the temperature at which air water vapors begin to condense when the dry bulb temperature is reduced at constant atmospheric pressure (P) and absolute humidity (W).

9.2.5. Energy of Air

Heat contents of moist air called as enthalpy (h) is its heat content with respect to a selected reference point. The reference point for enthalpy of dry air is normally taken as 1-bar atmospheric pressure (101.325 kPa) and 0 ^{o}C temperature for all psychometrics calculations. Mathematical model for calculating enthalpy of moist air has been given in equation in 9.16.

$$h = h_a + h_w \tag{9.16}$$

$$h_a = C_{pa}\left(T - T_{ref}\right) \tag{9.17}$$

here, T_{ref} is 0^{o}C.

Therefore,

$$h_a = C_{pa}T \quad (9.18)$$

$$h_w = \left(h_{fg} + C_{pw}.T\right)W \quad (9.19)$$

Where; h=enthalpy or heat content of moist air, kJ/kga; h_a= enthalpy of dry air, kJ/(kg DA); h_w= enthalpy of water vapor, kJ/(kgDA); T=dry bulb temperature (°C); T_{ref} =0 °C, the reference temperature; C_{pa}=specific heat of dry air =1.006 kJ/(kg DA K) at 0 °C to 1.009 kJ/(kgDAK) at 50 °C; C_{pw}=specific heat of water vapor=1.805 kJ/(kgwK), h_{fg} =heat of vaporization of water =2501 kJ/(kgw) at 0 °C; DA=dry air; w = water vapor; a = air; W = absolute humidity.

Inserting 9.18 & 9.19 into equation 9.16:

$$h = C_{pa}T + \left[\left(h_{fg} + C_{pw}.T\right)W\right] = C_{pa}.T + h_{fg}.W + C_{pw}.T.W$$

$$= (C_{pa} + C_{pw}.W)T + h_{fg}.W = C_{p.mix}.T.W + h_{fg}.W \quad (9.20)$$

Where, $C_{p.mix} = C_{pa} + C_{pw}$.W, kJ/(kgaK); $C_{p.mix}$ is usually estimated very closely with C_{pa}.

Air specific volume (v_a);

Air specific volume **(v_a)** is based on a unit mass of dry air and can be understood as inverse of density of air (m^3/kgDA). The air specific volume of dry air is;

$$v_a = \frac{v}{m_a} = \frac{\mathrm{R_a.T}}{\mathrm{p_a}} = \frac{\mathrm{R_a.T}}{p - \mathrm{p_w}} \quad (9.21)$$

9.2.6. Mass and Energy balance

Let a vessel has standing water as in Fig. 9.1. The atmospheric air enters into the vessel at state condition 1 (state-1) with moist air-dry bulb temperature, T_{db1}, and absolute humidity, W_1. As the air passes over standing water in the vessel, it absorbs water and becomes fully saturated before exiting the vessel. The heat of air evaporates water from vessel and itself gets cooled following adiabatic process. The evaporated water from vessel is refilled from makeup water source to keep the water quantity same in the vessel. The exiting saturated air conditions at state-2 has absolute humidity, W_2, and dry bulb temperature as wet bulb temperature ($T_{db2}=T_{wb}$).

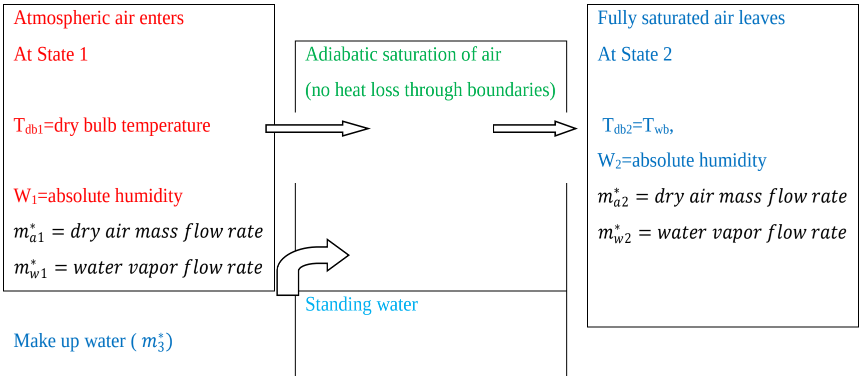


Fig. 9.1. Adiabatic process diagram of air cooling for mass and energy balance

Mass balance

The dry air mass flow rate per unit time [$m_a^* = m_a^* = \frac{V^*}{v}$] remains constant the vessel.

$$m_{a1}^* = m_{a2}^* = m_a^* \tag{9.22}$$

$$since \qquad m_{w1}^* + m_3^* = m_{w2}^* \quad \text{kg/s}$$

$$or \qquad m_3^* = m_{w2}^* - m_{w1}^* \quad \text{kg/s}$$

$$since \quad m_{w1}^* = m_a^*(W_1) \ \ and \quad m_{w2}^* = m_a^*(W_2) \qquad kg/s$$

$$therefore, make\ up\ water\ rate,$$

$$m_3^* = m_a^*(W_2 - W_1) \tag{9.23}$$

Energy balance

It has been assumed that there is no heat loss through the boundary of vessel (adiabatic vessel).

The, the energy entering rate in vessel (state-1):

$$m_a^*.h_1 \tag{9.24}$$

[air mass flow rate x enthalpy, h_1 = kga/s x kJ/kga=kJ/s]

Energy leaving the vessel (state-2):

$$m_2^*. h_2 \tag{9.25}$$

[air mass flow rate x enthalpy, h_2 = kga/s x kJ/kga=kJ/s]

Energy content of makeup water to maintain the water level inside the vessel:

$$m_3^*. h_3 \tag{9.25a}$$

[water mass flow rate x enthalpy, h_3 = kga/s x kJ/kga=kJ/s]

Where,

$$m_3^* = m_a^*(W_2 - W_1) \tag{9.26}$$

Now the energy balance equation:

[energy at state-2 = energy at state-1 + energy of makeup water entered from inside the vessel]

$$m_a^*. h_2 = m_a^*. h_1 + m_3^*. h_3 \tag{9.27}$$

Inserting the equation 9.26 into equation 9.27.

$$m_a^*. h_2 = m_a^*. h_1 + m_a^*(W_2 - W_1). h_3 \tag{9.28}$$

$simplifying\ the\ equation$

$$h_2 = h_1 + (W_2 - W_1). h_3 \tag{9.29}$$

[Enthalpy at state-2=enthalpy at state-1 + enthalpy associated with makeup water in vessel]

$$h_3 = h_l = C_{pl}. T_{wb} \tag{9.30}$$

[$h_3 = enthalpy\ of\ liquid = specific\ heat\ of\ liquid\ x\ Abs\ temp$] and $C_{pl} = 4.186\ \frac{kJ}{kgl.K}$, therefore,

$$h_3 = 4.186\ . T_{wb} \tag{9.31}$$

Now the equation 9.29 could be written as:

$$h_2 = h_1 + 4.186T_{wb}(W_2 - W_1) \tag{9.32}$$

This equation describes the adiabatic saturation.

9.3. Psychrometric Chart

The psychrometric chart represents graphically seven thermodynamics properties of moist air. These seven psychrometric properties of moist air are dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), dew point temperature (T_{dp}), absolute humidity (w), relative humidity (Φ), specific volume (v), and heat content (H, enthalpy). The knowledge of any two air properties helps in determining the other five properties. Moreover, processes like sensible heating/cooling, cooling with dehumidification, adiabatic mixing, evaporative cooling etc can easily be traced on a psychrometric chart.

9.3.1. Dry bulb temperature lines

Dry bulb temperature is represented by the vertical lines on a psychrometric chart (Fig. 9.2). Going from left to right on the x-axis shows increasing dry bulb temperature (T_{db}) indicating increase in sensible heat and vice versa.

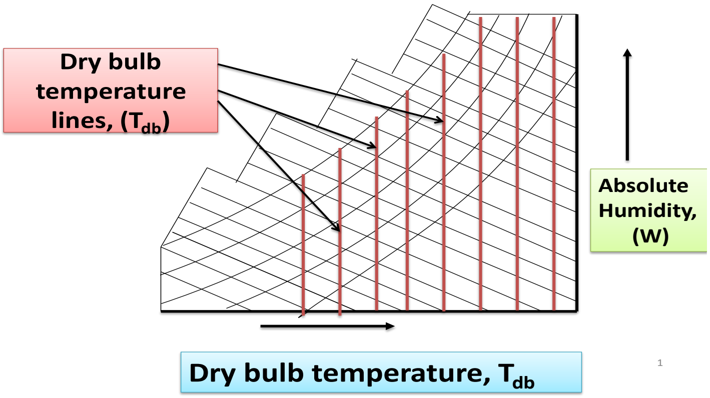


Fig. 9.2 Dry bulb temperature lines on psychrometric chart

9.3.2. Absolute Humidity lines

Absolute humidity (W) is the amount of moisture the air contains and is measured as kg of water per kg of dry air (kgw/kgDA). The horizontal lines on the psychrometric chart represent the absolute humidity lines (Fig. 9.3). Going upward along y-axis shows the increase in absolute humidity and vice versa.

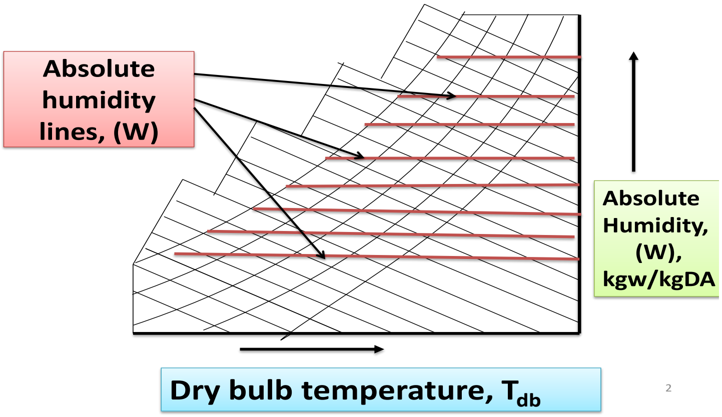


Fig. 9.3 Absolute humidity lines on psychrometric chart

9.3.3. Saturation curve

The curve on the extreme left upward represents the saturation curve (Fig.9.4). This curve indicates the maximum amount of humidity that the saturated air can have at the constant atmospheric pressure at various dry bulb temperature values. On this saturation curve the dry bulb, wet bulb and dew point temperatures become equal to each other.

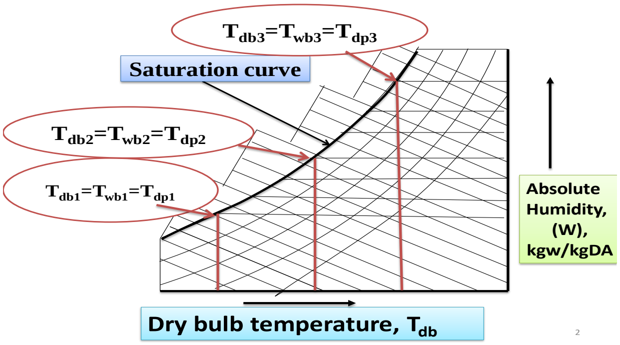


Fig. 9.4 Saturation curve on psychrometric chart

9.3.4. Relative humidity curves

The percentage of absolute humidity relative to the saturation humidity of air at the given temperature is called relative humidity. Curves of constant relative humidity below the saturation curve have been drawn on the psychrometric chart (Fig.4.5). At the same absolute humidity as the air-dry bulb temperature rises in the day time, the air expands hence the relative humidity decreases which are an indication of increase in its water holding capacity. The curves on psychrometric chart from left and top to right and bottom show the decreasing relative humidity curves.

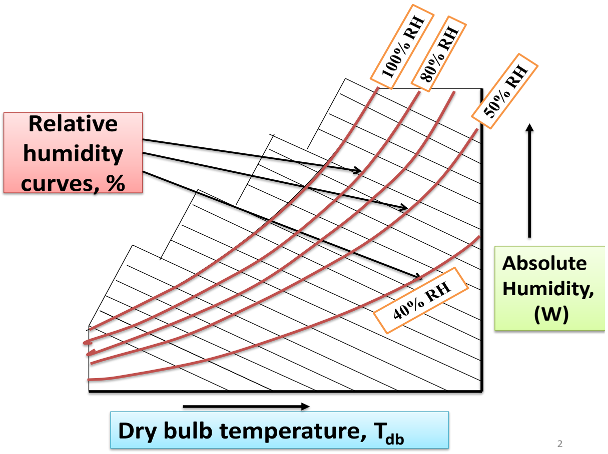


Fig. 9.5 Relative humidity curves on Psychrometrics chart

9.3.5. Wet-bulb Temperature lines

Wet-bulb temperature is measured with a wetted wick covered thermometer. Dry air passing around the wetted wick covered thermometer at saturation evaporates water and lowers down the temperature of thermometer. It shows adiabatic changes on the Psychrometric Chart because the dry air provides heat to evaporate water from wet wick and gets itself cooled lowering the temperature of thermometer. The lines of constant wet bulb temperatures run diagonally up and to the left on the chart (Fig.9.6). Since evaporation causes cooling effect, therefore, the wet bulb temperature is always lower than the respective dry bulb temperature.

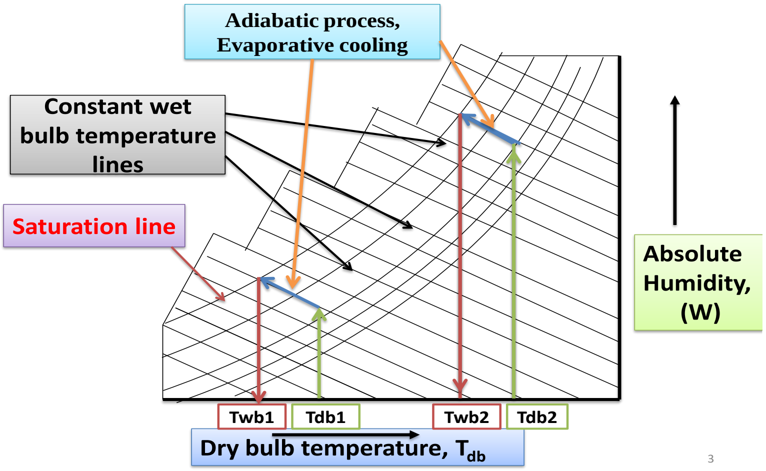


Fig. 9.6 Wet bulb temperature lines on Psychrometrics chart

9.3.6. Dew point temperature

The temperature at which the air becomes completely saturated at constant absolute humidity is called dew point temperature. At this temperature the water starts to drip out of the fully saturated air at the saturation curve. As the day time temperature falls in the night, the volume of air reduces at the same absolute humidity and becomes fully saturated. The dew point temperature (T_{dp}) is read vertically down from the saturation curve on the x-axis (dry bulb temperature line) (Fig.9.7).

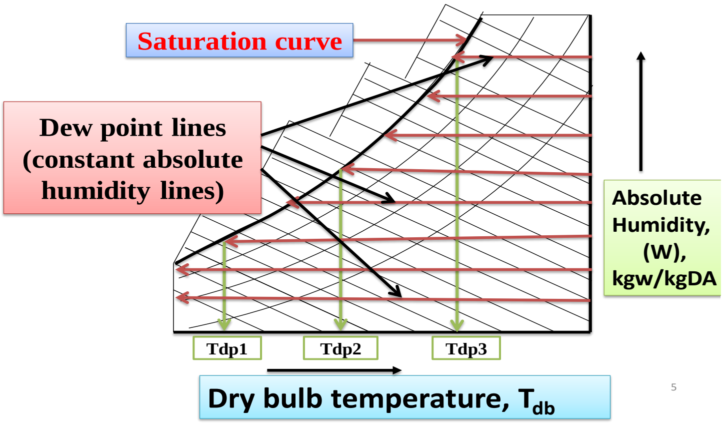


Fig. 9.7 Dew point temperature lines on Psychrometrics chart

9.3.7. Air specific volume lines

With the increase in day time temperature the air expands and its specific volume (v, m^3/kgDA) increases. The constant specific volume lines have been plotted on a psychrometric chart as shown in Fig. 9.8. From left to right are the increased volume lines ($v_4 > v_3 > v_2 > v_1$).

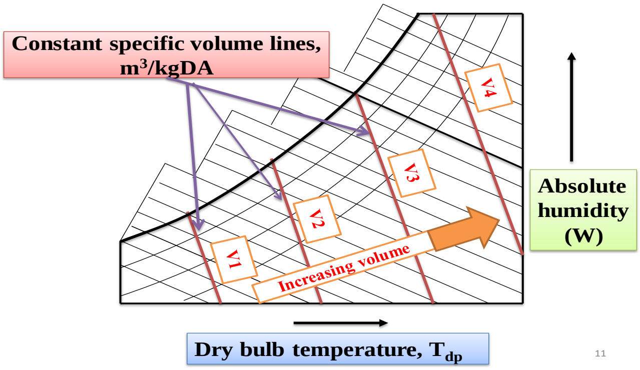


Fig. 9.8 Specific volume lines on Psychrometrics chart

9.3.8. Enthalpy lines

During adiabatic process of evaporative cooling, heat energy of air is consumed for evaporating water and air itself gets cold. Following the law of conservation of energy, the total energy of the system remains same but is transformed in another form. The adiabatic process constant enthalpy lines have been plotted on a psychrometric chart as shown in Fig.4.9. Since the adiabatic process of cooling results also in producing wet bulb temperature, therefore, the enthalpy lines and wet bulb temperature lines nearly superimpose each other. A psychrometric chart with all the air thermodynamic properties have been plotted as shown in Fig. 9.10.

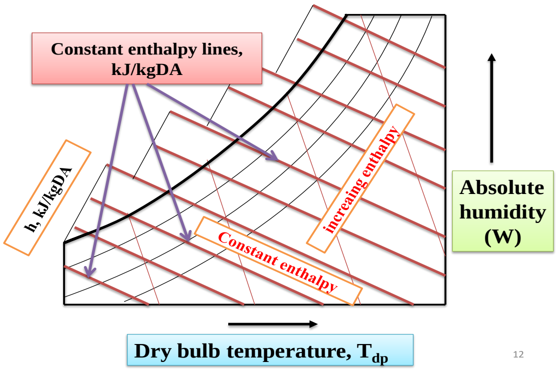


Fig. 9.9 Enthalpy lines on Psychrometrics chart

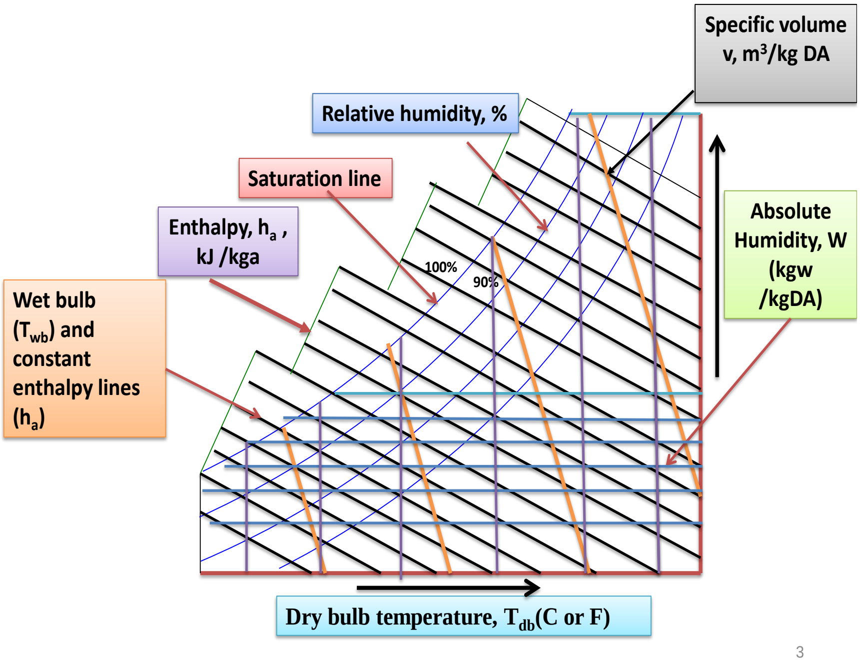


Fig. 9.10 Psychrometric chart for determining the thermodynamic properties of air

Example 9.3

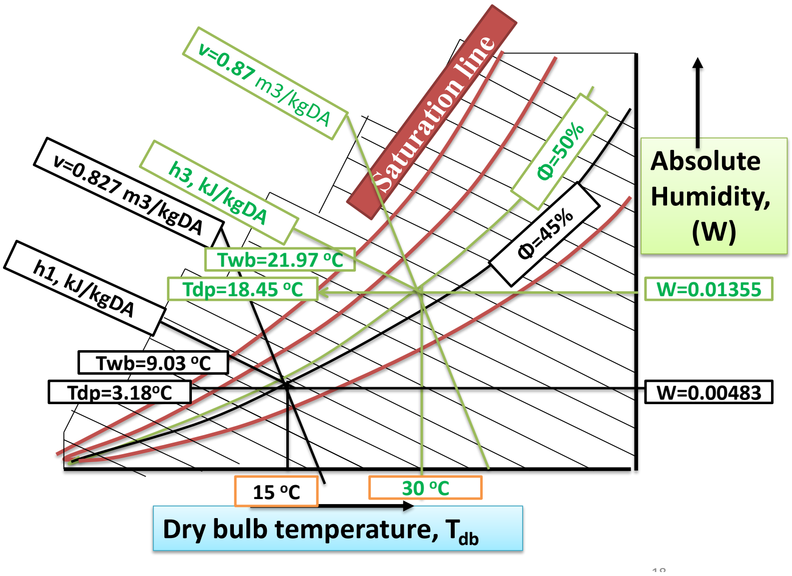
Fill in the blanks using with the use of psychrometric chart

T_{db} °C	T_{wb} °C	T_{dp} °C	W kgw/kgDA	Φ,%	v m^3/kgDA
15	?	?	0.00483	?	?
20	?	6.06	?	?	?
30	21.97	?	?	?	?

Solution

State Point	T_{db} °C	T_{wb} °C	T_{dp} °C	W kgw/kgDA	Φ,%	v m^3/kgDA
1	15	9.03	3.175	0.00483	45	0.821
2	20	12.7	6.06	0.00588	40	0.84
3	30	21.97	18.45	0.01355	50	0.87

State points 1 and 3 have been plotted on psychrometric chart below.



Example 9.3 State points 1 and 3 plotted on psychrometric chart

9.4. Psychrometric Processes

9.4.1. Sensible heating and cooling process

Let air flowing through a duct has been heated (q*, kJ/s) with an electric heater (Fig. 9.11). The state conditions of air both before and after heating have been shown in Fig. 9.11. Because the air has been heated only, therefore, the absolute humidity (W_2=W_1, kgw/kgDA) remained same. The sensible heating process line has been plotted on the psychrometric chart as a horizontal line from state-1 to state-2. Due to heating, the air has expanded in volume, resulting in reduced relative humidity and increased water holding capacity.

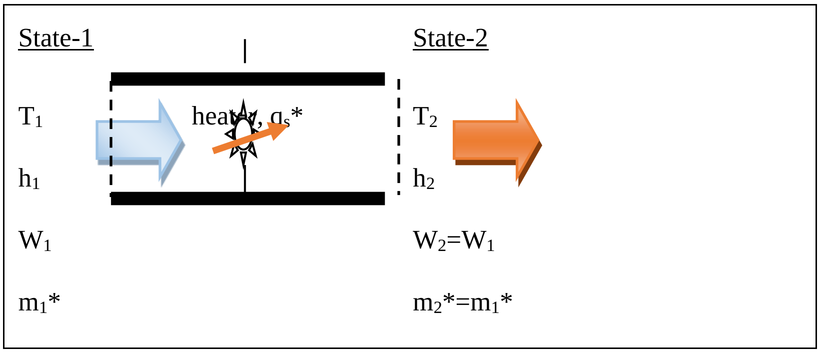


Fig. 9.11 Sensible heating of air

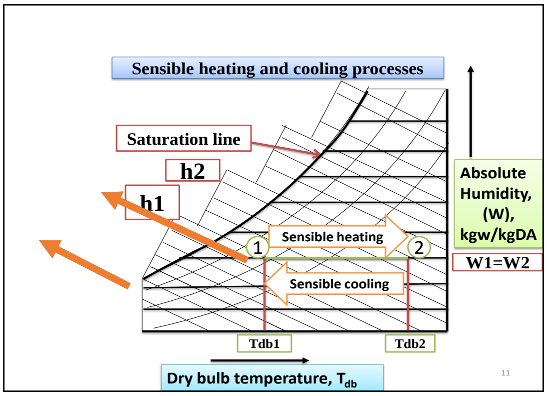


Fig. 9.12 Sensible heating and cooling processes lines plotted on a psychrometric chart

The mass balance and energy balance can be described as following:

$$m_1^* = m_2^* = m^* \tag{9.33}$$

Energy balance

$$m_a^* h_1 + q_s^* = m_a^* h_2$$

$$q_s^* = m_a^*(h_2 - h_1) \tag{9.34}$$

Where, h=Enthalpy, kJ/kgDA; W=absolute humidity, kgw/kgDA; q_s*=sensible heating rate, kJ/s; m_a*=air mass flow rate, kga/s.

9.4.2. Cooling with dehumidification process (Refrigeration principle)

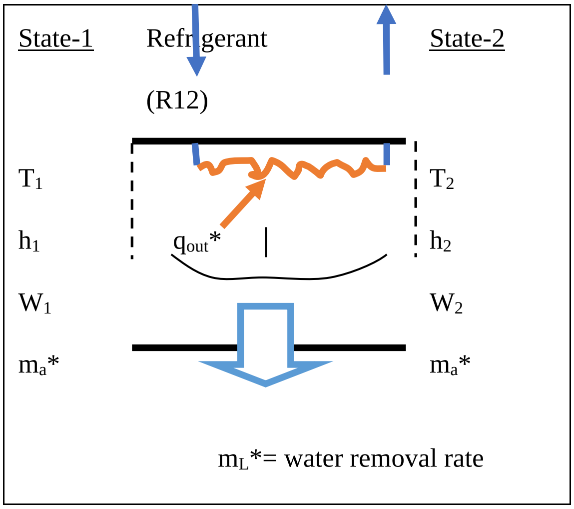


Fig. 9.13 Cooling with de-humidification

Process line 1-4: With the start of refrigeration system (state point-1), the air starts cooling keeping the absolute humidity unchanged (W1) until the air is cooled to point-4 (dew point, T_{dp1}) at saturation line. The enthalpy at state-1 is equal h1 (kJ/kgDA).

Process line 4-2: Further cooling of air after reaching the dew point (T_{dp1}) on saturation line, the process follows downward left on the saturation line and removing water from air by condensation till the desired state point-2 is reached. The final dry bulb temperature, T_2 is achieved at state-2.

Alternatively, the state point-2 could also be achieved from state-1following process line 1-3 (latent heat process line) followed by process line 3-2 (sensible cooling process line).

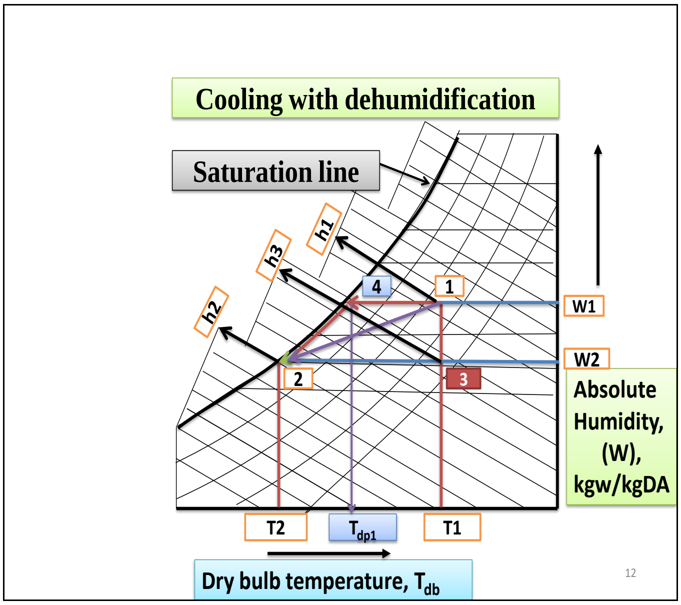


Fig. 9.14 Cooling with de-humidification process on psychrometric chart

Mass balance

$$m_a^* W_1 = m_L^* + m_a^* W_2 \tag{9.35}$$

Therefore, water removal rate through condensation:

$$m_L^* = m_a^* (W_1 - W_2) \tag{9.36}$$

Energy balance

State-1: Entering energy $= m_a^* . h_1$

State-2: Energy leaving $= m_a^* . h_2 + q_{out}^* + m_L^* . h_L$

At steady state conditions: Entering energy $=$ Energy leaving

$$m_a^* . h_1 = m_a^* . h_2 + q_{out}^* + m_L^* . h_L \tag{9.37}$$

Insert equation 9.26 $\quad m_3^* = m_a^* (W_2 - W_1) = \boldsymbol{m_L^*}$

Then, the above energy equation simplifies to:

$$m_a^*.h_1 = m_a^*.h_2 + q_{out}^* + m_a^*(W_2 - W_1).h_L$$

$$q_{out}^* = m_a^*(h_1 - h_2) + m_a^*(W_1 - W_2).h_L \tag{9.38}$$

From psychrometric chart in Fig. 9.14:

Sensible heat component, $q_s = h_3 - h_2$ [no change in absolute humidity ΔW=0]

Latent heat component, $q_L = h_1 - h_3$ constant dry bulb temperature

T1=T3, ΔT=0

Sensible heating factor,

$$SHF = \frac{q_s}{q_s + q_L} \tag{9.39}$$

Example 9.4

For the given two psychrometric properties of air, T_{db1} = 30.1 °C and Φ_1 = 45.1%, condition the air to T_{db2}=17.1 °C and T_{wb2} = 15.05 °C. Determine the total amount of heat taken out of the air. Moreover, find the sensible heat factor of the air conditioning process.

Solution;

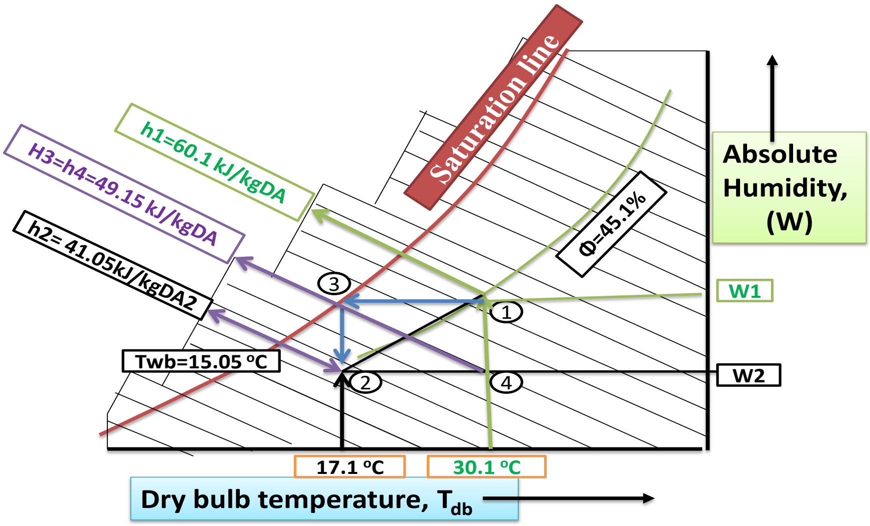
Locate state-1: go vertically up from T_{db1} = 30.1°C and intersect Φ_1 = 45.1% curve of psychrometric chart of example 9.4

Locate state-2: go vertically up from T_{db1} = 17.1°C and move from T_{wb2} = 15.05 °C to right downward parallel to wet bulb temperature lines to intersect T_{db1} line and determine location of state-2.

There are two paths to reach from state-1 to state-2:

Pathe-1: process 1-3 [cooling] followed by process 3-2 [dehumidifying]

Path-2: process 1-4 [dehumidifying] followed by process 4-2 [cooling]



Example 9.4 Sensible heat factor determination through psychrometric chart

From psychrometric chart:

h_1=60.1 kJ/kgDA; h_2=41.051 kJ/kgDA; h_3=h_4=49.151 kJ/kgDA

process 1-3 [cooling] – sensible heat out:

$$\Delta h_1 = q_s = h_1 - h_3 = 60.1 - 49.15 = 10.95\ kJ/kgDA$$

Process 3-2 [dehumidifying] – latent heat removed due to removal of water:

$$\Delta h_2 = q_L = h_3 - h_2 = 49.15 - 41.05 = 8.1\ kJ/kgDA$$

Total heat removed:

$\Delta h_1 + \Delta h_2 = q_s + q_L$=$10.95 + 8.1 = 19.05\ kJ/kgDA$

For sensible heat factor, employ equation-

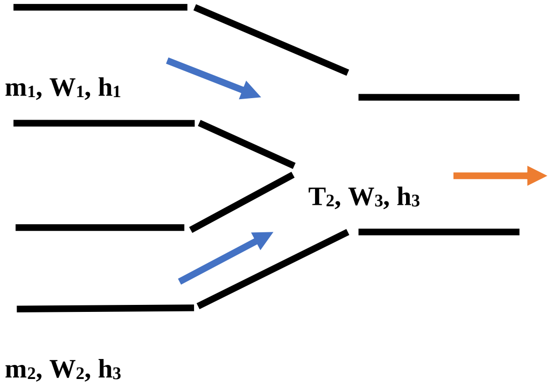
$SHF = \frac{q_s}{q_s+q_L} = \frac{10.95}{19.05}$=0.575

9.4.3. Adiabatic mixing process

Let two air streams of different thermodynamic properties were mixed adiabatically (Fig. 9.15). The properties of final of mixed air are dependent upon the masses, absolute humidity's and enthalpies of air streams involved.

Table 9.1 an overview of various air streams and their properties

Air stream	Mass flow rate (kg/s)	Absolute humidity (kg/kgDA)	Enthalpy (kJ/kgDA)
1	m_1^*	W_1	h_1
2	m_2^*	W_2	h_2
3 (mixed)	m_3^*	W_3	h_3



where

T=temperature, W=absolute humidity, H=enthalpy

Fig. 9.15 Adiabatic mixing two air streams

Mass balance

Mass balance of dry air component (kgDA/s)

$$m_{a3}^* = m_{a1}^* + m_{a2}^* \tag{9.40}$$

Mass balance of water vapor component (kgw/s)

$$m^*_{a3}W_3 = m^*_{a1}W_1 + m^*_{a2}W_2 \tag{9.41}$$

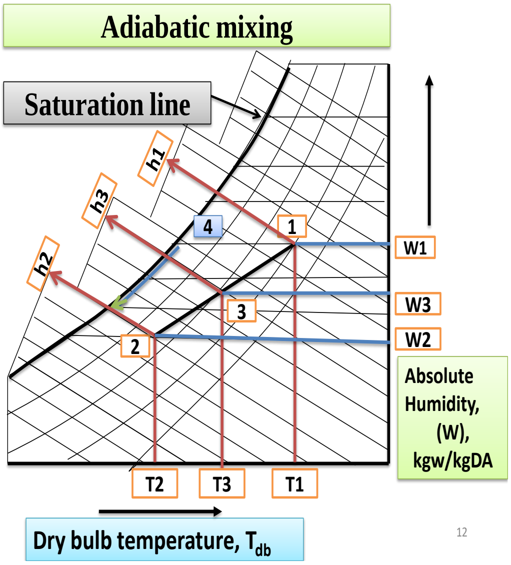


Fig. 9.16 Adiabatic mixing two streams process lines on a psychrometric chart

Energy balance

$$m^*_{a3}h_3 = m^*_{a1}h_1 + m^*_{a2}h_2 \tag{9.42}$$

Insert value of m^*_{a3} from equation 9.40 into equation 9.42

$$(m^*_{a1} + m^*_{a2})h_3 = m^*_{a1}h_1 + m^*_{a2}h_2$$

Or

$$m^*_{a1}h_3 + m^*_{a2}h_3 = m^*_{a1}h_1 + m^*_{a2}h_2$$

Re-arranging

$$m^*_{a1}h_1 - m^*_{a1}h_3 = m^*_{a2}h_3 - m^*_{a2}h_2$$

Or

$$m^*_{a1}(h_1 - h_3) = m^*_{a2}(h_3 - h_2)$$

Or

$$\frac{m_{a1}^{*}}{m_{a2}^{*}} = \frac{h_3 - h_2}{h_1 - h_3} \tag{9.43}$$

Now insert value of m_{a3}^{*} from equation 9.40 into equation 9.41

$$(m_{a1}^{*} + m_{a2}^{*})W_3 = m_{a1}^{*}W_1 + m_{a2}^{*}W_2$$

Or, $m_{a1}^{*}W_3 + m_{a2}^{*}W_3 = m_{a1}^{*}W_1 + m_{a2}^{*}W_2$

Re-arranging, $m_{a1}^{*}W_1 - m_{a1}^{*}W_3 = m_{a2}^{*}W_3 - m_{a2}^{*}W_2$

Or, $m_{a1}^{*}(W_1 - W_3) = m_{a2}^{*}(W_3 - W_2)$

Or

$$\frac{m_{a1}^{*}}{m_{a2}^{*}} = \frac{W_3 - W_2}{W_1 - W_3} \tag{9.44}$$

From equations 9.43 and 9.44

$$\frac{m_{a1}^{*}}{m_{a2}^{*}} = \frac{W_3 - W_2}{W_1 - W_3} = \frac{h_3 - h_2}{h_1 - h_3} \tag{9.45}$$

After mixing the initial two air streams, the properties of mixed air stream-3 have been plotted on the psychrometric chart in Fig. 9.16. This implies a straight-line relationship.

9.4.4. Evaporative cooling

Evaporative cooling is most effective in dry hot conditions. This method of cooling is achieved by passing outdoor hot air through a water wetted medium to permit an adiabatic process. As the dry hot air passes through the wetted medium, it evaporates its water and gets cool itself. Since no any external source of heat energy is employed, therefore, it is an adiabatic process. This process follows the wet bulb line on a psychrometric chart. The enthalpy of air remains constant.

Total reduction in temperature through evaporative cooling is called wet bulb depression, WBD.

$$WBD = T_{db1} - T_{WB} \tag{9.46}$$

Wet Bulb Depression (WBD) is the maximum temperature difference that a food engineer can obtain with an evaporative cooling system. However, a properly designed evaporative cooler is expected to achieve up to 80% of the WBD.

The efficiency (η) of evaporative cooler-It is the ratio of the difference of T_{db1} *and* T_{db2} with WBD.

$$\eta = \frac{T_{db1} - T_{db2}}{T_{db1} - T_{WB}} = \frac{T_{db1} - T_{db2}}{WBD} \tag{9.47}$$

therefore,

$$T_{db2} = T_{db1} - \eta(\mathrm{WBD}) = T_{db1} - \eta(T_{db1} - T_{WB}) \tag{9.48}$$

9.5. Problems

1. Fill in the blanks with the help of psychrometric chart.

T_{db} °C	**T_{wb} °C**	**RH (%)**	**T_{dp} °C**	**W kgw/kgDA**	**h kJ/kgDA**	**V (m^3/kgDA)**
15	11	61.64	?	?	?	?
22		34.39	5.62	?	?	?
25	15	?	7.74	?	?	?
25	23	?	?	?	68.16	?
28	?	?	?	0.00757	47.48	?
29	15	?	?	?	?	0.8612
30	22	?	?	0.0133	?	?
35	20	?	?	?	?	0.8839
35	30	?	?	?	?	0.9070
39	?	?	?	?	63.82	0.8970
44	?	?	?	?	?	?
45	30	34.12	?	?	?	?

2. Atmospheric air has W_{db} =12 °C from T_{db}=36 °C and Φ=50%, during an evaporative cooling process. Determine:
    - Humidity ratio
    - Dew-point temperature.
3. Atmospheric has T_{db}= 22ºC and T_{wb} = 20ºC. Using the psychrometric chart, determine:
    - Relative humidity Φ
    - Dew-point temperature T_{dp}
    - Air specific volume
    - Absolute humidity W
    - Enthalpy of air h
4. Two streams of air were adiabatically mixed with following characteristics:

Air stream	**Flow rate (kg/s)**	**Dry bulb temperature (T_{db}ºC)**	**Wet bulb temperature (T_{wb}ºC)**	**Φ (%)**
1	3	45	20	
2	4	35	-	65

Employing psychrometric chart and equations, determine the followings

- Absolute humidity, W
- Wet bulb temperature T_{wb} of the two streams mixed together
- Dry bulb temperature T_{db}
- Enthalpy of air h

5. Atmospheric air at a dry bulb temperature T_{db} = 15ºC and relative humidity Φ = 80% has been heated and humidified to 41ºC and 41% relative humidity. Determine the amount of water added and the amount of heat added to the air.
6. Atmospheric air at 36ºC and 60% relative humidity has been heated to 56ºC without the change in absolute humidity. Using psychrometric chart, determine how much sensible heat has been added per kg of air.
7. Relative humidity of atmospheric air at 36ºC and 60% has been increased to 80%. Draw the process line on psychrometric chart and find all the other air properties as well. Also find enthalpy change during the process.

8. Atmospheric air at a dry bulb temperature T_{db1}= 40ºC and relative humidity Φ_1 = 10% was humidified to a relative humidity Φ_2 = 40%. Find the amount of moisture added per kg of dry air.
9. Atmospheric air conditions are found to have dry bulb temperature T_{db1} = 45ºC and relative humidity Φ_2 = 35%. Find the room air conditions after the ambient air has passed through an evaporative cooler with 80% efficiency. Also find the moisture added per cubic meter air passed through the cooler.

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Chapter 10

Storage Engineering

Muhammad Kashif Iqbal Khan*, Muhammad Mudassir Arif

Abstract

Storage determines the quality of food product. It may reduce or increase shelf life depending upon the storage conditions. Food are stored in cold storage, restaurants and hotel for further processing and after processing. In cold storage, refrigeration principle is used at larger scale. Similarly, oxygen depletion principle is used at smaller scale or portable type of storage (trucks, or smaller packages). An outlook has been presented in this chapter about these technologies.

Keywords: Centrifugation, Mixing, Sedimentation, Distillation, Extraction, Crystallization,

10.1. Introduction

Food quality is the most valuable things for producer and consumer. Various strategies have been developed to increase / maintain the quality. It may include drying, evaporation and nonthermal processing. However, processed food need to be stored for its availability throughout the year. In this regard, food should be protected from rodents, insects and microbial contamination. Thus, various storage houses have been developed based on engineering principles. Among these, refrigeration is the most commonly used for food industry and restaurants. Besides,

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oxygen depleted environment is used to enhance the shelf life of food products. These principles have been discussed in the following sections.

10.2. Refrigeration

Refrigeration is a process in which product temperature is reduced to a level that inhibit the activities of enzyme and microbes. Low temperature reduces the rate of chemical reactions, enzymatic activity and microbial growth which increases the shelf life of food products. It is generally believed that lowering 10ºC reduced the one half of reaction rates. In ancient times, ice was commonly used material to reduce the temperature which is quiet older technique. Nowadays, mechanical refrigerators are used to lower the temperature. In refrigeration system, food material is cooled with a coolant which takes off the heat and lower temperature of foods. Various type of coolants is available; however, general properties of a good coolant/ refrigerant are as follow;

- It should have high latent heat of vaporization that will reduce the amount of refrigerant required for circulation per unit time
- The condensing pressure of refrigerant should be high. However, its freezing temperature should be lower than evaporator temperature
- It should be non-toxic, non-flammable and chemically stable
- It should not have corrosive effect for the material of a refrigeration system
- Cost effective refrigerant is always preferred for industrial use
- It should be environment friendly and its leak should not damage the surrounding. Moreover, leakage should be easily detectable

10.2.1. Component of Refrigeration System

Simple mechanical refrigeration system consists of following components as shown in Fig. 10.1;

- Compressor
- Condenser
- Expansion valve
- Evaporator

Compressor

Function of a compressor is to compress the superheated vapours of refrigerant to higher pressure which is lower than critical pressure of refrigerant. It facilitates the condensation at temperature slightly higher than ambient one. However, compression of refrigerant occurs at constant entropy inside the compressor. Increase in pressure also increases the temperature of refrigerant. This compressed and superheated refrigerant is passed toward the condenser (Fig. 10.1).

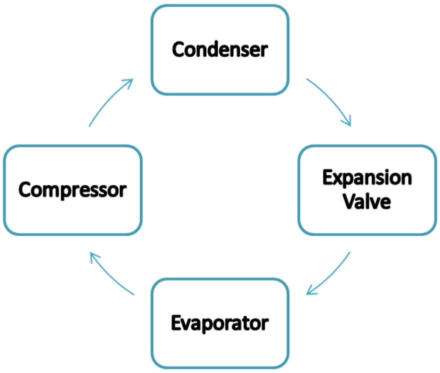

Fig. 10.1 A graphical representation of refrigeration cycle

Condenser

In condenser, refrigerant is cool down by exchanging heat with surrounding. This done using cooled air or water and gaseous refrigerant is condensed into liquid form. Temperature of refrigerant falls below its condensation temperature. Then, refrigerant is condensed into liquid and known as sub cooled state which is due to extra removal of heat. Now, sub cooled refrigerant moves toward the expansion valve.

Expansion valve

Function of expansion valve is to separate the high and low-pressure regions/areas. Before entering in expansion valve, refrigerant is in higher pressure region. Afterwards, it moves to low pressure region which results in further reduction of coolant temperature. This change in pressure results in the conversion of some liquid into gaseous state. At this point, coolant consists of two phases; liquid and gas and this mixture is known as “flash gas”. Flash gas leaves the valve to enter in evaporator.

Evaporator

Flash gas enters the evaporator; here it is completely vaporized into gas. This happens due to heat exchange between the flash gas and surroundings through the evaporator coils. Evaporator coils reduced the temperature of food product placed in the refrigerator. Hence, food is cooled down at this stage and its heat is transfer to the coolant. This heat exchange results in increase of refrigerant temperature which is converted into saturated vapours. This stage in termed as a superheated period owing to addition of heat from the environs. This superheated refrigerant enters compressor and cycle continues (Fig.10.1).

10.2.2. Applications in Food preservation

Refrigeration system is widely used as food preservation and major applications are cold storage, preparation of freezing agent for freezing mechanism, household refrigerators. All these application work on above mentioned principle. However, it can be used in direct (common fridge, trucks, cold storage, and freezers) and indirect (cooled air, chilled solutions) way to preserve food. Both are commonly known as food freezing.

Food freezing

It reduces the availability of water to enzyme and microbes thus increasing the shelf life of product. Moreover, very low temperature stops the growth of microbes and prevent enzyme’s activity to occur. Thereby, significantly extends shelf life of food products. It is successfully applied for long term preservation of many foods. Freezing is one of the most widely used approaches of food preservation. In freezing, physical state of a substance changes with the change of water into ice. It is attributed to the energy removal in the form of cooling below freezing temperature. Generally, temperature is reduced to -18 °C which is mostly commonly adopted storage temperature which influences the quality of stored products.

In freezing process, freezing starts from outside to inward. While, freezing rate determine the shelf life and quality of frozen products. Rapid freezing produces smaller ice crystals which are good to maintain quality. Slow freezing produces larger ice crystals which may damage the food tissues. Thereby, reduce the quality and shelf life of a food product. Besides, fluctuation in temperature of frozen product may alter the quality and shelf life. Various techniques are being used to freeze a food products e.g. cryogenic freezing, plate freezing, immersion freezing, and freezing with cooled air / gas. Selection of an appropriate methods is dependent on the cooling rate, physical attributes, coolant attributes, toxicity of the coolant and size of products.

10.3. Oxygen Depletion Technology

With the advancement in engineering, the food industry has developed a smaller and portable storage house known as novel packaging. It has become inevitable for the manufacturers to provide safe packaging ensuring the consumer demands of fresh consumption, controlled quality and extended shelf life for which the packaging industry is revolutionizing itself by endeavouring to introduce various concepts of technology packaging and developing effective and efficient barriers for ultraviolet radiation, light, gases and other environmental conditions.

Innovations in packaging have given birth to a set of new terms attributed to the role that packaging plays in the shelf life enhancement, safety improvement and food product convenience (Fig. 10.2). Three broad categories of food packaging are passive packaging, active packaging and intelligent packaging, the latter two being of utmost importance for meeting the modern customer demands.

Fig. 10.2 Advanced packaging systems related to packaging functions

10.3.1. Passive Packaging

The only physical barrier that exists between the ambient environment and the product in the package is passive packaging system. Most conventional packaging that we see is included in passive packaging systems. Examples are metal cans, plastic bottles, glass bottles and many other packages which act as a physical barrier between the environmental conditions and the product. They prevent the properties and agents in the environment to contact the product they contain. However, these packaging systems are not responsive to any changes that might occur in the container.

10.3.2. Active Packaging

Active packaging system has the capability to detect the changes within package's environment, followed by the modification of package properties in response to detected change. In other words, an active packaging system is based on the interaction of among product, package and the environment; ensuring an enhanced shelf life, improved microbial safety and preserved product quality.

According to the European commission active packaging is defined as "materials and articles that are intended to extend the shelf life / to maintain or improve the condition of packaged food. They are designed to deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding food". Some of the important quality indicators are shown in Fig. 10.3.

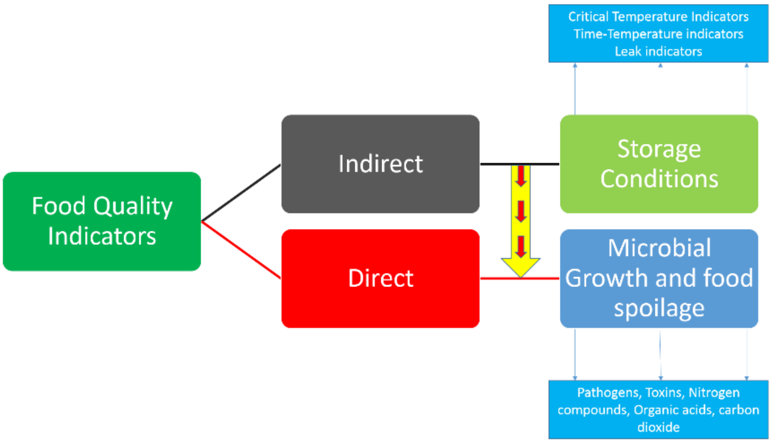

Fig. 10.3 An overview of food quality indicators

The principles of active packaging rely on the polymer intrinsic properties itself or on the inclusion of the desired substances in the polymer. The polymer intrinsic properties are responsible for the active function by introduction of an active monomer in the polymer chain. In practice the active agents are also incorporated in the packaging or on the packaging material surfaces in multilayer structures or sometimes in the components that are themselves the part of packaging such as labels, bottle caps and sachets. There is a vast diversity in the nature of the active agents that can be used the most prominent being enzymes, fungicides, bacteriocins, organic acids, ions, natural extracts and ethanol which can be applied in compliance to the nature of the materials in which they can be included.

Active packaging can be classified into two classes namely, nonmigratory active packaging and active release packaging. In case of the former a desired response is elicited from the food system without the migration of the active component into the food from the packaging such as moisture absorbers, oxygen scavengers, ethylene scavengers and antimicrobial packaging. In case of the latter, a controlled migration of the non-volatile agents is permitted or also there is allowance of the emission of volatile compounds in the atmosphere around the food. Ethanol releasers, Sulphur dioxide releasers and water vapor sachets are good examples of active release packaging. Another worth mentioning example is a commercially available plastic film in Japan which includes a strong antimicrobial substance called allyl isothiocyanate (AITC) extracted from mustard.

In the present decade, the approximate market for the active packaging films is $50 million. The major aim of the active packaging is the shelf life extension of the foods which is achieved by impacting the physiological processes such as respiration in vegetables and fruits, chemical processes like oxidation, microbiological variations and physical processes. In case of the food industry the most significant concepts of active packaging include oxygen scavengers, carbon dioxide emitters and scavengers, antioxidant release, moisture regulators, ethylene scavengers and antimicrobial packaging concepts. The problems curbed by active packaging are shown in Fig. 10.2 elaborating its need whereas Fig. 10.4 depicts a basic idea of the components involved in active packaging.

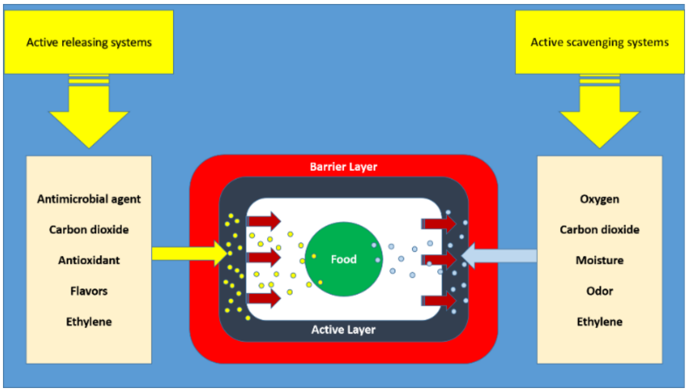

Fig. 10.4 An overview of components of active packaging system

As an example, release on command packaging systems are being used for the maintenance of high quality by providing the right preservatives at the right time following a concept of bio-switch (Fig. 10.5). Bio switch detects the changes in the environment around it and responds to these changes automatically. This system was designed to only release the preservatives when the bacteria started to grow hence inhibiting the bacterial growth. In this way, the antimicrobial meets the food only when required. One of the major advantages of this technique are reduces quantity of the chemicals needed with an increased stability and specificity of the product.

Another important domain in modern packaging is intelligent packaging which conceptually is communicative or indicative of the product quality. Intelligent packaging can be defined as “packaging that monitors the internal and/or external conditions of a product throughout its life cycle”. Intelligent packaging operates in two modes, external measurement of the package condition and direct measurement of the food product quality inside the package. The most commonly used indicators are time temperature indicators (TTI), gas leakage indicators, toxin indicators and spoilage/freshness indicators.

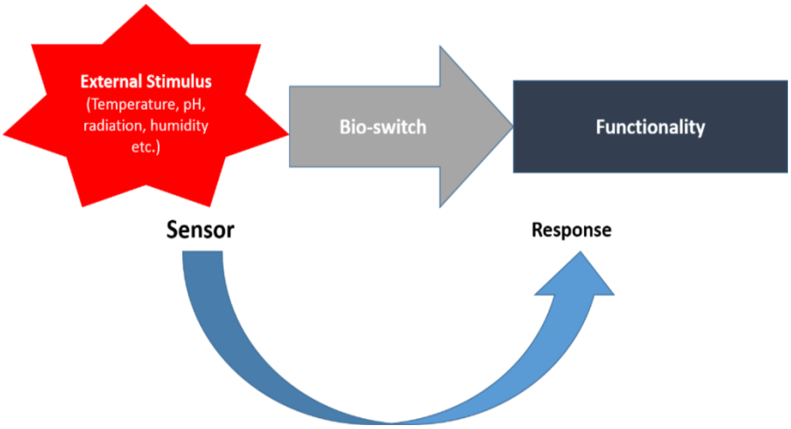

Fig. 10.5 A graphical representation of bio-switch concept

It is well known that the food quality deteriorates at high temperatures therefore, the TTIs are a reliable source to judge if the food inside the package has been exposed to undesired temperature conditions. TTIs are small measuring devices that are prone to irreversible colour change once prone to high temperatures and they are usually outside each single package or inside a container to determine the temperatures the products in the container have been prone to; also giving an estimate of the time span of the undesired change to the consumers. Various studies have been conducted investigating the role of temperature time indicators in meat, vegetables, dairy products and sea foods.

10.4. Types of Packaging

10.4.1. Controlled Atmosphere Packaging

When the food is enclosed in a package in which the gases cannot permeate and the environment w.r.t nitrogen, water vapours, oxygen and carbon dioxide in altered desirably then this technique of packaging is called Controlled atmosphere packaging (CAP). In this technique, the concentration of the gases inside the package is continuously monitored and controlled for product shelf life enhancement. The components of the storage system in this technology are:

1) Storage chambers which are airtight
2) unit for O_2 regulation
3) equipment to absorb, monitor and control CO_2 gas
4) Generator for Liquid N_2 flush it for maintaining optimum level of O_2.
5) The air present in the chamber passes through the CO_2 scrubber recurrently to maintain desired CO_2 level inside the chambers. Hydrated lime, calcium hydroxide and potassium hydroxide are commonly used scrubbers.
6) For the maintenance of storage temperature, a refrigeration unit is used.

By using Controlled Atmosphere storage technology, the shelf life of different vegetables and fruits can be enhanced by two to four times their normal life span. But in case of exposure to normal atmospheres during marketing the CA stored produce deteriorates rapidly. Hence leading to a shortened post storage life, which implicates adverse effects on the marketing.

The use of CA technology is limited during transport due to the involvement of sophisticated and bulky equipment. The technology is considered cost intensive because of the air tight storages are required along with the systems ensuring continuous monitoring and time to time controlling of the composition of the stored air.

10.4.2. Modified Atmosphere Packaging

To maintain the standard quality of food and for shelf life enhancement Modified Atmosphere Packaging (MAP) is the phenomenon of enclosing the edible stuff into atmospherically (actively or passively) modified packages. In active modification, the air is displaced by gas flushing, a process in which a controlled, desired mixture of gases replaces the air.

Passive modification occurs when the food items respire or may be due to the metabolic activity of the microorganisms attributed to the food; the structure of the package includes a polymeric film, and the developed atmosphere inside the package is affected by the permeability of the film. The permeation of the film depends upon the type or the material of which the film is made film and the temperature at which it is stored.

Advantages of MAP

- 50 to 400% enhancement in shelf life of the product
- Economic losses are lessened because of enhanced storage period
- Provides better quality of the product
- Portion control and centralized packaging
- Better presentation–the product can be clearly viewed and elaborated
- Requirement for chemical preservatives eliminated / reduced
- Product is not re-contaminated, or it cannot drip out of the package
- Ultimate convenience is provided by the package and it is odourless

Disadvantages of MAP

- The machinery needed for the purpose, the material of packaging and the gases required for the atmospheric alteration in the package add to the cost
- It is inevitable to control the temperature
- For every product to be packed a different gas formulation is required
- Without proper trained staff and equipment, the job cannot be efficiently done
- If the volume of the package is increased, it adds to the transportation cost and space requirement on the market shelf
- The entire benefit of the technology is vanished as the package is opened or leaked
- Increased drip and pack collapse occur as result of CO_2 dissolving into the food

The gases which are used in MAP are; carbon dioxide, oxygen and nitrogen. The characteristics of these gases are defined below;

Carbon dioxide

1) Significant due to its fungi static and bacteriostatic properties
2) The growth of many bacteria that cause spoilage is inhibited, the inhibition level increases with increase in concentration
3) This technique is very operative against species named Pseudomonas which cause aerobic spoilage
4) Its solubility and temperature are inversely proportional, due to this reason at lower temperatures the CO_2 antimicrobial activity is very high.
5) The headspace volume can be reduced because of high solubility of CO_2 in high moisture/high fat foods
6) Increased levels of CO_2 can be a cause of drip increasing or flesh food exudation, so to compensate this effect the absorbent pads are used in the base package

Oxygen

1) It promotes different forms of deterioration in food e.g. oxidation of fat, pigment oxidation and browning reactions
2) Help many common spoilage bacteria and fungi to grow
3) O_2 is either excluded from food products or its level is set as low as possible
4) O_2 is needed for respiration of fruits and vegetables and for retaining colour in red meat.

Nitrogen

1) Nitrogen is an odourless and tasteless inert gas
2) It density is less than that of air. Nitrogen is not well dissolved in water or in other food items
3) As previously mentioned that CO_2 gas causes the package collapse when it gets mixed with food, so nitrogen is filled in the package to prevent this effect in MAP technology
4) It retards the growth of aerobic microbes causing spoilage
5) The anaerobic bacterial growth is not prevented

10.5. Mass Transfer

Barrier properties of packaging materials hold cardinal significance in the selection of packaging systems for foods. For the maintenance of crispiness and freshness of the food the package must provide barrier to moisture. Similarly, the package must act like a barrier of O_2 to prevent oxidation of the food. In the same way, for the preservation of aroma the package must provide barrier to aroma.

Permeability can be used to define the barrier properties of materials. In quantitative terms, permeability can be defined as the mass of vapor/gas transmitted per unit area, time and a driving force. For example, differences in partial pressures act as a driving force during diffusional mass transfer.

10.5.1. Mass Transfer through Polymeric Materials

Mass transfer through polymeric materials can be summarized in three steps. The dissolution of gas, vapor or liquid molecules in the polymeric material on the layer of the film exposed to higher concentration. Diffusion of gas or vapor molecules takes place through the material and their movement is directed towards that side of film which is exposed to lower concentration. The final step involves desorption of vapor or gas molecules and their evaporation from the surface of the film.

The molecular movement is dependent over the availability of hole in the polymeric materials. Holes are formed when large chain segments of polymer slide over each other as a result of thermal agitation. Thermal agitation resulting from the sliding of large chain sections of polymers creates holes in the polymers.

Fick's law: It states that, the flux of a mass per unit area is directly proportional to its concentration gradient. Thus, for a component B,

$$\frac{m_B}{A} = -D\frac{\partial c}{\partial x} \tag{10.1}$$

Where, m_B= mass flux of component B(kg/s), c= concentration of component B, mass per unit volume (kg/m^3), D = mass diffusivity (m^2/s), A = area(m^2).

An expression can be developed to express the transportation process of gas through polymeric material by using the Fick's law of diffusion.

$$\frac{m_B}{A} = \frac{D_B(c_{B1} - c_{B2})}{x_2 - x_1} \tag{10.2}$$

This equation may suffice to determine the rate of flux, but it is more difficult to measure the concentrations of gas at the film surfaces than that of partial pressures. Henry's law is used to convert the concentrations to partial pressures.

$$c = Sp \tag{10.3}$$

Where, S= solubility (moles/cm^3 atm) p= partial pressure of gas (atm) Therefore, we can write,

$$m_B = \frac{D_B SA(c_{B1} - c_{B2})}{x_2 - x_1} \tag{10.4}$$

The quantity D_BS is known as the permeability coefficient, P_B.

$$P_B = T_f V_g / tA\Delta P \tag{10.5}$$

T_f is the film thickness, and V_g is the amount of gas vapours pass in time t through an area A with the P pressure difference across the film.

The word permeance is also used by some authors but it is not correct word for a unit thickness. Sometimes water vapor permeability is stated in such units which are not applicable to both pressure and unit thickness, but specified thickness, temperature, humidity and water vapor permeability must be stated with this value. For example, the permeability of water vapor is defined as grams of water per day per 100 cm^2 of package surface for a specified thickness and temperature or a relative humidity on one side of approximately 0% and on the other side of 95%. Fixed gases have very low boiling points such as Gases such as hydrogen, nitrogen, oxygen and carbon dioxide. These gases behave similarly with respect to permeability through packaging materials.

There are many materials with wide differences in permeability e.g. Saran possesses 100000 times less permeability to oxygen than silicone rubber. Different gases permeate at different rates through the same material e.g. CO_2 permeates four to six times faster than O_2, and O_2 four to six times faster than N_2. Among the three molecules, CO_2 is the largest and has a low coefficient of diffusion. As compared to other gases the solubility of CO_2 is very high in polymers because of its high permeability coefficient. Ideal behaviour which is shown by fixed gases is as follow:

Permeability can be considered independent of concentration.

The permeability changes as the temperature is changed and follows the below mentioned relation:

$$P = P_o e^{-E_p/RT} \tag{10.6}$$

Where, E_p is the activation energy for permeability (kcal/mol). The permeability curve is not followed by all the materials, there is a break in the permeability temperature curve of these materials; they become more permeable above the critical temperature. Polyvinyl acetate has a critical temperature of 300ºC, while polystyrene has the critical temperature of 800ºC. Breaks in the curve are due to a glass transition temperature Tg, if the material is at lower temperature from this break then it will be glassy, and above this break point the material will be rubbery.

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Glossary

Abrasion Resistance: It is type of resistance which may be defined as ability of materials to withstand against abrasion. It is a method of wearing down or rubbing away due to friction during transport in processing line of supply chain.

Active packaging: It is a mode of packaging in which the package, product and environment interact to increase shelf life, safety or sensory characteristics of food products.

Antioxidants: A substance that inhibits oxidation or reactions promoted by oxygen, peroxides, or free radicals.

Bingham: Bingham plastic is a material that behaves as rigid body at low stresses; but flows like viscous fluid at high stress. This behaviour is exhibited by slurries, suspensions of solids in liquids, paints, emulsions, foams, etc.

Blanching: To parboil in water or steam in order to stop enzymatic action in food.

Bulk density: The dry weight of food materials per unit volume. In bulk density measurement, both solids and pore space are taken into account.

Canning: A process of food preservation through storing in that are hermetically sealed and sterilized containers. The process was invented after prolonged research by Nicolas Appert of France in 1809.

Centrifugation: Centrifugation is a separation process which uses the action of centrifugal force to promote accelerated settling of particles in a solid-liquid mixture.

Cleaning: The act of removing dirt or something undesirable from food.

Colloidal: It refers to solution of a floating particles in a medium.

Compressor: A device for reducing the volume of something (as air) by pressure.

Concentration Polarization: It is the polarization of an ions or electrolytes due to the passage of current through the electrode/solution interface.

Concentration polarization also refers to the concentration gradient of salts on the high-pressure side of the reverse-osmosis membrane surface.

Conduction*:* It is the transfer of heat through matter by communication of kinetic energy from particle to particle with no net displacement of the particles.

Convection*:* the movement caused within a fluid due to temperature differences. In which hotter (lighter) particles material to rise, and colder (denser) material to sink due to gravity; ultimately cause the heat transfer to occur.

Crystallization*:* Crystallization is the solidification of atoms or molecules into a highly structured form (crystals) known as purist form of a material.

Deformation: Change in the shape of a body caused by the application of a force (stress).

Dehydration*:* The process of losing or removing water or moisture up to a certain limit i.e. Jam, jellies etc.

Denaturation: Denaturation is the alteration of a protein shape through some form of external stress (for example, by applying heat, acid or alkali), in such a way that it will no longer be able to carry out its cellular function.

Diffusion*:* The movement of atoms or molecules from an area of higher concentration to an area of lower concentration.

Distillation*:* A process in which the components of a substance or liquid mixture are separated by heating at certain temperature followed by condensing the vapours.

Drying: Drying may be defined as the vaporization and removal of water or other liquids from a substance. Simply, removing the free water from food.

Emulsifiers*:* An emulsifier is a substance used to stable two immiscible liquids like water and oil.

Emulsions: A fine dispersion of droplets of a liquid in another in which it is not soluble or miscible.

Energy flow: It is the amount of energy that moves through a food chain. The energy input, or energy that enters the ecosystem, is measured in Joules or calories.

Enthalpy: It is the sum of the internal energy and the product of pressure & volume.

Enzyme: Complex proteins that are produced by living cells and catalyze specific biochemical reactions at body temperatures.

Evaporation: Evaporation is the process by which water changes from a liquid to a gas or vapor.

Extraction: Extraction is a process to separate a desired substance from the mixture when it is mixed with others. The mixture is brought into contact with a solvent in which the substance of interest is soluble, but the other substances present are insoluble.

Foams*:* A light frothy mass of fine bubbles formed in or on the surface of a liquid or from a liquid

Freeze drying: In a subject (food, vaccines, etc.) water is quickly freezed and ing followed by sublimation process that cause the removeal of water.

Heat capacity: The heat capacity of a defined system is the amount of heat needed to raise the system's temperature by one degree.

Heat exchanger: A device used to transfer heat from one fluid to another without direct contact of the fluids.

Higher pressure processing: High pressure processing is a cold pasteurization technique in which food is subjected to a high level of hydrostatic pressure (pressure transmitted by water) up to 600 MPa / 87,000 psi for a few seconds to a few minutes.

Low-density polyethylene (LDPE): Low-density polyethylene is a thermoplastic made from the monomer ethylene. It was the first grade of polyethylene, produced in 1933 by Imperial Chemical Industries (ICI) using a high-pressure process via free radical polymerization.

Modified atmosphere packaging (MAP*):* Modified Atmosphere Packaging is the phenomenon of placing the edibles into atmospherically modified packages to increase shelf life.

Membrane separation: A process in which constituents are separated through the membrane in the absence of heating.

Molecular weight cut off (MWCO): It is defined as the lowest molecular weight of solute (in Daltons) in which more than 90% of the solute is reserved by a membrane.

Newtonian fluids*:* Viscous fluids are the fluids which on applying stress will deform continuously and follow the law of newton.

Ohm*:* It is an electrical resistance between two points of a substance that have a constant potential difference of one volt.

Ohmic heating: It is a process where the energy of an electric current is converted into heat as it flows through a resistance.

Oleo-Chemistry: The branch of chemistry that deals with oleo chemicals. A chemical compound derived industrially from animal or vegetable oils or fats.

Osmosis*:* The movement of a solvent through a membrane separating two solutions of different concentrations.

Peeling: To remove the skin or rind from something.

Mole*:* Mole is unit of amount of substance and denoted as mol. It is the amount that contains the elementary entities equal to the atoms in 0.012 kg of carbon 12.

Permeate*:* Permeate is the part which pass through the pores of membrane.

Retentate*:* Retentate is the part which cannot pass through the pores of membrane.

Reverse osmosis: A process by which a solvent pass through a porous membrane in the direction opposite to that for natural osmosis when subjected to a hydrostatic pressure greater than the osmotic pressure.

Sedimentation: The process of settling or being deposited as a sediment.

Shape: A geometric figure such as a square, triangle, or rectangle.

Shelf life: The length of time for which an item remains usable, fit for consumption.

Sorting: Sorting is systematically arranging according to some criteria.

Specific heat: The specific heat is the amount of heat per unit mass required to raise the temperature by one-degree Celsius.

Suspensions: A mixture in which small particles of a substance are dispersed throughout a gas or liquid. If a suspension is left undisturbed, the particles are likely to settle to the bottom. The particles in a suspension are larger than those in either a colloid or a solution.

Ultrafiltration: It is the process of passing a liquid through something which has very small holes in it, in order to remove solids.

Vapours: Gas or extremely small drops of liquid that result from the heating of a liquid or solid.

Viscosity: The extent to which a fluid resists a tendency to flow.

Watt: Amount of power to produce energy at the rate of one joule per second.

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