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قسم الجذع المشترك
COMMON CORE DEPARTMENT

Biophysics course handout

Intended for second-year students (Common Core) in Natural and Life Sciences (L2)

By

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Rank : MCA

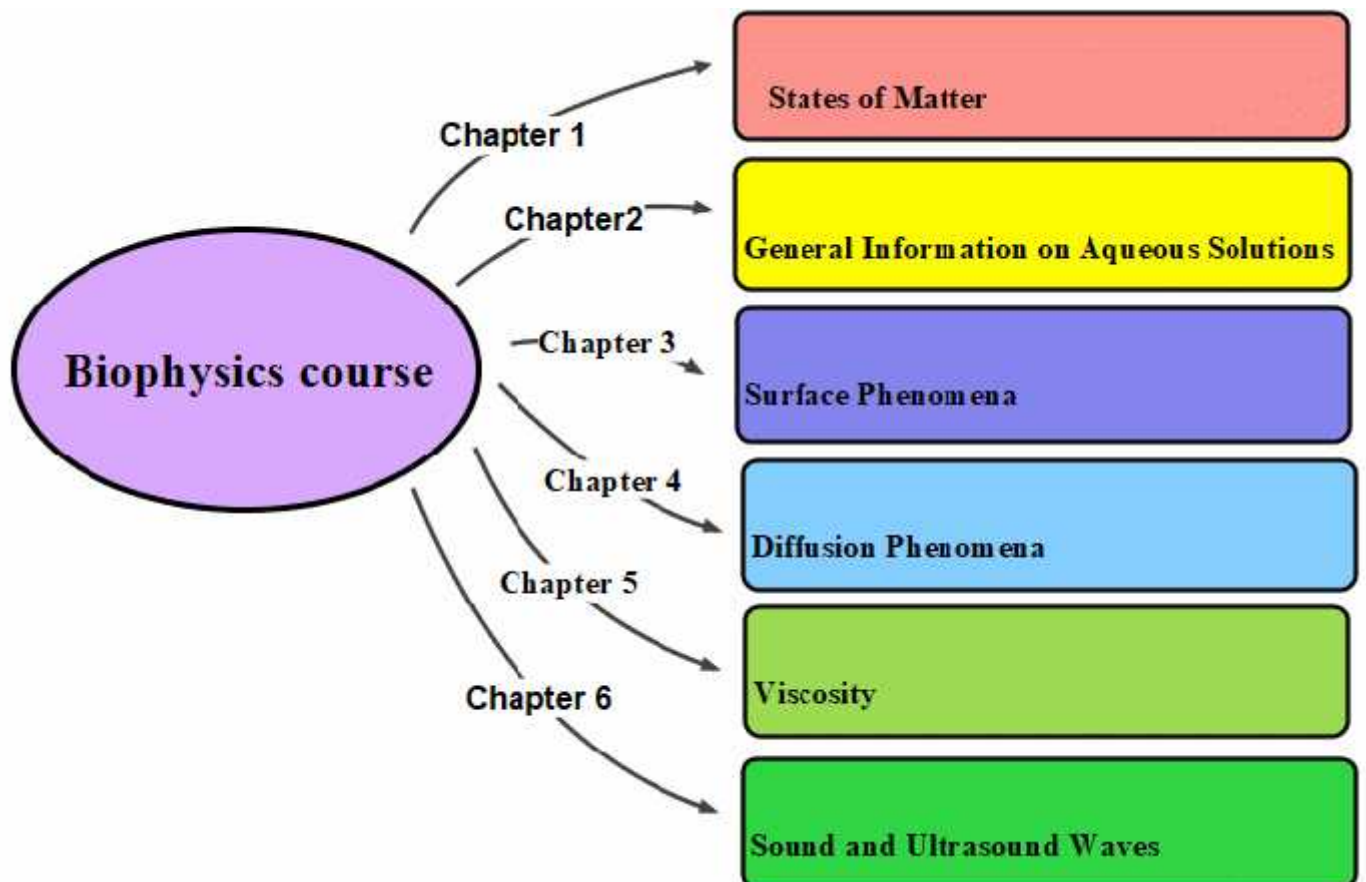
Academic year : 2025/2026

Prerequisites:

What you should know before starting this course:

- 1/ Mathematical Tools.
- 2/ Fundamentals of aqueous solutions.
- 3/ Conductance and conductivity.
- 4/ Notions of fluid mechanics.
- 5/ Pressure Concept.
- 6/ Definition of matter.

Biophysics course concept map:



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General introduction

This Biophysics course handout is intended for second-year Common Core students. The Biophysics course is taught in the third semester for the level mentioned above. It is part of the Methodology Unit, identified by the code UEM 2.1.2 with 5 credits and a coefficient of 3.

The general objective of the biophysics course is to enable students in Life and Nature Sciences (SNV) to acquire the fundamentals of physics.

This document was created after several years of teaching the course. It prioritizes simplification wherever possible without compromising the scientific content, and thus covers the entire prescribed syllabus. Each chapter includes the core content, supplemented by a simple application in the field of biology, and concludes with solved exercises to deepen understanding. The document was written using the English language. This choice reflects the Algerian University's directive to integrate English into instruction, and also acknowledges the language's necessity in the field of scientific research.

This document is divided into six chapters (See Figure:0.1) according to the approved syllabus, which include the following:

- 1- States of matter.
- 2- General information on aqueous solutions.
- 3- Surface phenomena.
- 4- Diffusion phenomena.
- 5- Viscosity.
- 6- Sound and ultrasound waves.

Ultimately, I hope this handout helps students grasp the module and teachers provide their course. Thanks to anyone who gives suggestions to improve it.

Chapter 1

States of matter

1.1 Introduction

In this chapter, we will explore the fundamental concept of matter [31] and its various states, along with the properties that characterize each state. We will also touch upon some basic laws governing certain states. The primary focus of this chapter will be the descriptive aspect of matter's states and their phase transitions. This approach is specifically tailored to align with disciplines outside of core physics and chemistry, such as Life and Natural Sciences (Biology) (See Figure :1.1).

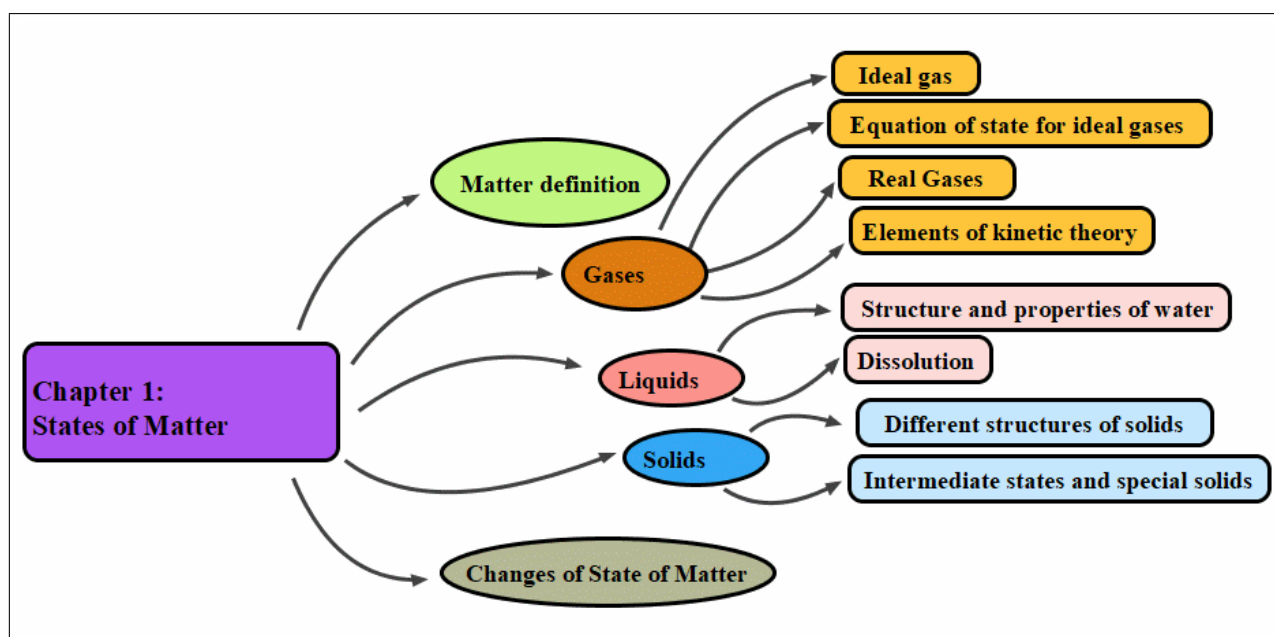


Figure 1.1: Chapter 1 Concept Map.

1.2 Matter definition

Matter is any substance that has mass and takes up space by having volume.

1.3 Gases

The gaseous state of matter has the following properties (Figure 1.2):

- * Dispersed state: The particles are far apart.
- * Disordered state: The particles move randomly.
- * Compressible: A gas can be easily squeezed into a smaller volume
- * Indefinite shape: It will take the shape of its container.
- * Low density.

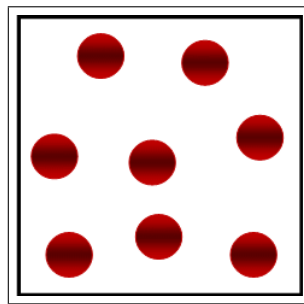


Figure 1.2: Gas.

We have two types of gases: **ideal** and **real**.

1.3.1 Ideal gas

An ideal gas is defined by the following two theoretical assumptions:

- Molecules are assimilated to points (without volume).
- There are no intermolecular attractive forces.

1.3.2 Equation of state for ideal gases

Equation of state for ideal gases is given by:

$$PV = nRT, \tag{1.1}$$

where;

P : Pressure exerted by the gas in *Pascal* (Pa).

V : Volume occupied by the gas in m^3 .

n : Quantity of matter (number of moles) in *Mole* (mol).

R : Universal gas constant ; $R = 8.314 J.K^{-1}.mol^{-1}$.

T : Absolute temperature in *Kelvin* (K).

1.3.3 Real gases

Real gases is characterized by:

* The non-negligible intermolecular forces : Consume energy and decrease the pressure (P) of the ideal gas (p) by the internal pressure (π).

* The total volume (V) of a real gas is composed of the volume of the ideal gas (v) as well as the volume (b).

1.3.4 Elements of kinetic theory

The kinetic theory of ideal gases considered that the gas particles are in continuous, random, and rapid motion with negligible intermolecular forces and perfectly elastic Collisions.

According to the kinetic theory of ideal gases, The absolute temperature (T) of an ideal gas is directly proportional to the average kinetic energy ($\bar{E}$) of its molecules. Mathematically, this relationship is expressed as;

$$\bar{E} = \frac{3}{2} k_B T, \quad (1.2)$$

where

k_B : Boltzmann constant; $k_B = 1.3810^{-23} J/K$.

T : Absolute temperature in kelvin (K).

$\bar{E}$: The average kinetic energy in *Joule* (J).

1.4 Liquids

The liquid state of matter is characterized by (Figure 1.3):

- * Condensed state
- * Disordered state: Move randomly.
- * Dense: The particles are close together

- * High density
- * Practically incompressible : The particles are tightly packed
- * Indefinite shape: It will take the shape of its container.

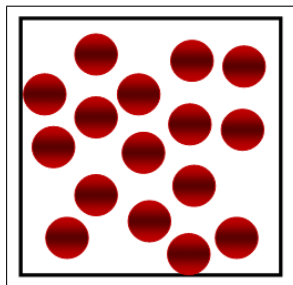


Figure 1.3: Liquid.

1.4.1 Structure and properties of water

The composition of the water molecule and its most important characteristics are summarized as follows (Figure 1.4) : **Composition:** **One Oxygen** (O) atom covalently bonded to **two Hydrogen** (H) atoms (H_2O).

Bond Lengths: **Two O-H** bonds, each $0.96\text{\AA}$ long.

Bond Angle: The bonds form an angle of 104.28° , giving the molecule a bent, asymmetric shape.

Polarity: The asymmetric structure leads to a strong permanent **dipole moment** (1.84debye). The **oxygen** side is partially **negative**, and the **hydrogen** sides are partially **positive**.

Hydrogen Bonds: The **positive** hydrogen charges **attract** the electronegative atoms of neighboring molecules, forming powerful **hydrogen bonds**. These are electrostatic bonds of a particular type.

In the liquid state: Water has a pseudocrystalline structure; each water molecule is linked to four neighboring molecules.

In the solid state: Ice exhibits an even better-organized hexagonal structure.

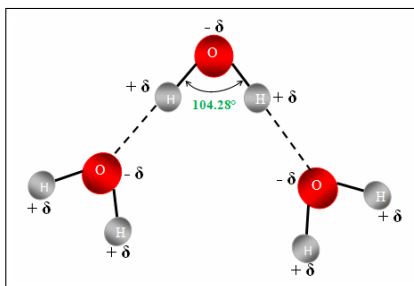


Figure 1.4: Water molecules.

1.4.2 Dissolution

Dissolution is the process by which a solute is dispersed completely into a solvent to form a homogeneous mixture called a solution.

Example:

- * The salt is soluble in water.
- * The mixture obtained during a dissolution is called an **aqueous solution**.
- * The **water** that dissolves the solid acts as the **solvent**.
- * The **solid (salt)** that is dissolved acts as the **solute**.

1.5 Solids

The solid state of matter is characterized by molecule (Figure 1.5):

- * Intermediate state: The particles are held tightly together.
- * Ordered state.
- * Strong cohesion between molecules.
- * Dense.
- * High density.
- * Incompressible.
- * Definite shape: Fixed positions of the particles.

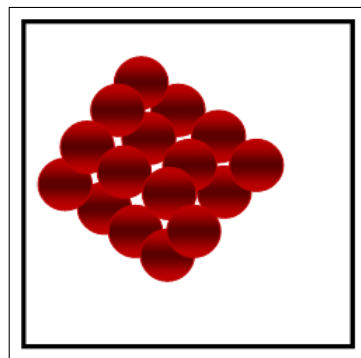


Figure 1.5: Solid.

1.5.1 Different structures of solids

Solids are primarily classified based on the long-range order of their constituent particles (atoms, ions, or molecules):

*** Crystalline Solids (Crystals):**

These solids have a highly ordered, three-dimensional arrangement of particles called a crystal lattice. This arrangement repeats over the entire solid.

Examples: Salt ($NaCl$), Quartz (SiO_2), Diamond (C).

*** Amorphous Solids (Glasses):**

These solids lack long-range order. Their particles are randomly arranged, similar to the structure of a liquid, but they are frozen in place.

Examples: Glass, Rubber, Plastics.

1.5.2 Intermediate states and special solids

Some materials exhibit structures or behaviors that are considered intermediate states or variations:

*** Polycrystalline solids:**

These solids are composed of many small, randomly oriented crystalline.

Examples: Most common metals and ceramics.

*** Liquid Crystals:**

This is an intermediate phase (mesophase) between the true liquid and crystalline solid phases.

Examples: Used in LCD (Liquid Crystal Display) screens.

*** Semicrystalline Solids:**

These are typically polymers that contain both amorphous regions (disordered) and crystalline regions (ordered lamellae).

Examples: Polyethylene and polypropylene plastics..

1.6 Changes of state of matter

A change of state is a physical process where matter moves from one state (solid, liquid, gas, or plasma) to another. These changes are typically caused by **heating** (adding thermal energy) or **cooling** (removing thermal energy) at specific temperatures and pressures. Here are the six common changes of state (Figure 1.6).

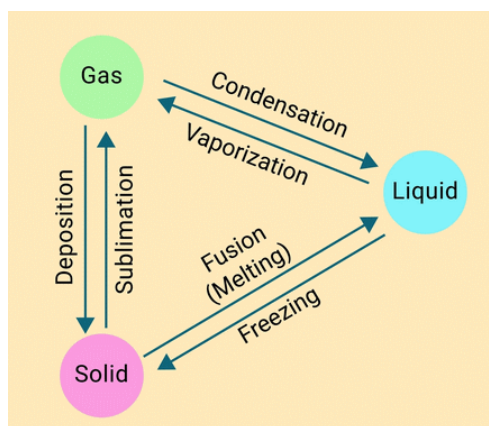


Figure 1.6: Change of state.

1.7 Exercises

Exercise 1

The following graph (Figure 1.7) represents the change in temperature as a function of time during the solidification of cyclohexane.

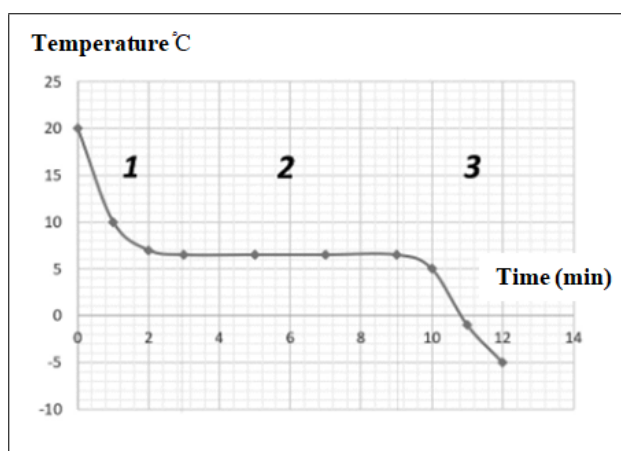


Figure 1.7: The change in temperature as a function of time during the solidification of cyclohexane.

- 1/ During solidification, what are the initial and final states of the change of state?
- 2/ In the graph, in which state is the cyclohexane found in phase 1?
- 3/ In the graph from question 2, what happens to the temperature during phase 2?
- 4/ What is this phase called?
- 5/ What is present in the medium at that time?
- 6/ In the graph, in which state is the cyclohexane found in phase 3?

Exercise 2

A car tire is inflated to a temperature of $20^{\circ}C$ under a pressure of $2.10bar$. Its internal volume, assumed constant, is $30L$.

1/ What quantity of air does it contain?

2/ After driving for some time, a pressure check shows the pressure to be $2.30bar$. What is the temperature of the air inside the tire at this pressure? Express the result in the usual temperature scale.

3/ Are the recommended pressure values for inflating the tire with air different from those for nitrogen inflation?

Given: Perfect gas constant, $R = 8,314SI$,

Molar mass of air $M = 29g/mol$.

1.8 Solutions**Exercise 1**

1/ During solidification, we start from a **liquid** compound which becomes **solid** over time

2/ In **phase 1**, the cyclohexane is in the **liquid** state.

3/ The temperature remains constant.

4/ Solidification.

5/ Mixture of solid and liquid.

6/ Solid.

Exercise 2

We must first convert the given values to SI units:

$$2.10bar = 2.10 \times 10^5 Pa \quad (1.3)$$

$$30L = 30 \times 10^{-3} m^3 \quad (1.4)$$

$$20^{\circ}C = 20 + 273.15 = 293.15K \quad (1.5)$$

$$R = 8.314 J.mol^{-1}.K^{-1}$$

1/ The quantity of air in the tire

Using the ideal gas law:

$$n = \frac{P_1 V}{RT} = \frac{2.10 \times 10^5 (Pa) \times 30 \times 10^{-3} (m^3)}{8.314 (J.mol^{-1}.K^{-1}) \times 293.15 (K)} = 2.58 mol, \quad (1.6)$$

2/ Temperature (T_2) :

$$T_2 = T_1 \frac{P_2}{P_1} = T_2 = 293.15 \text{ (K)} \times \frac{2.30 \text{ (bar)}}{2.10 \text{ (bar)}} = 320.94 \text{ K}, \quad (1.7)$$

$$T_2 = \approx 320.94 - 273 \approx 47.94^\circ \text{C}. \quad (1.8)$$

3/ No, the recommended pressure values for inflating the tire with air are not different from those for nitrogen inflation.

Chapter 2

General information on aqueous solutions

2.1 Introduction

In this chapter, we will cover the concept of the chemical solution [22, 27], as well as the classification of various solutions, focusing on how to calculate the different concentrations of solutions, especially since we will need them in later chapters (See Figure: 2.1).

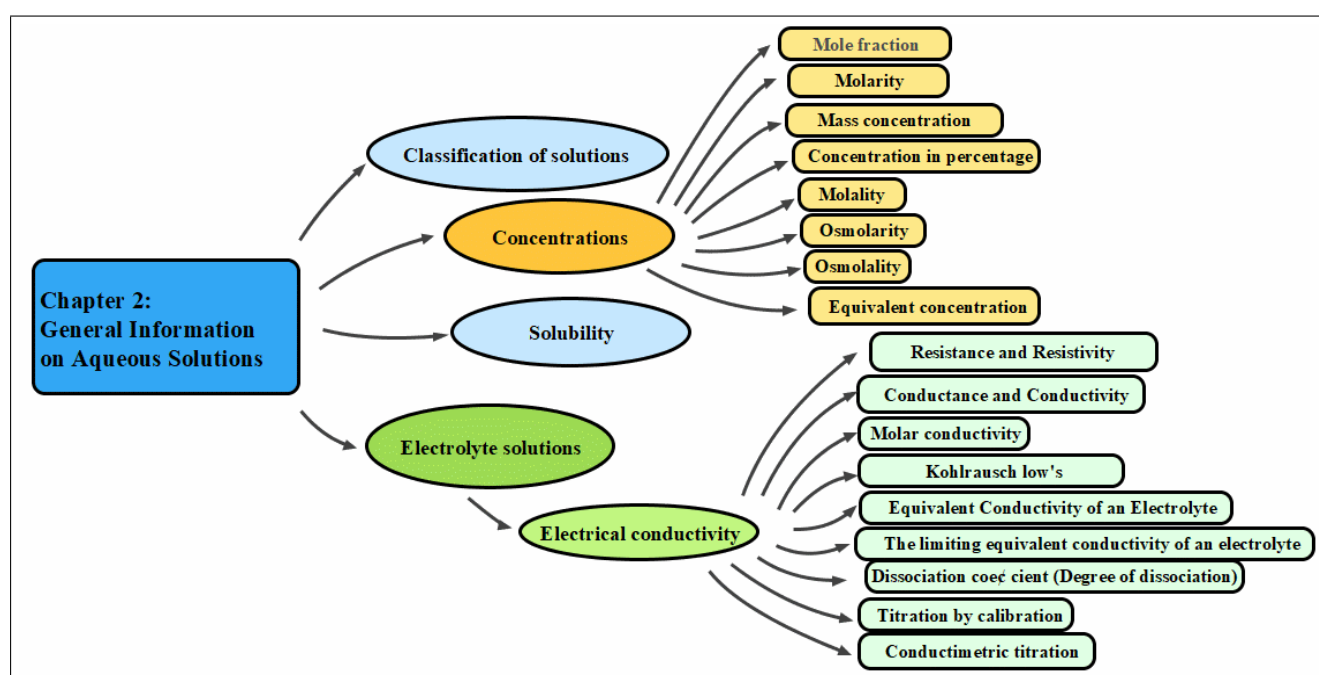


Figure 2.1: Chapter 2 concept map.

2.2 Definition

A **solution** is a **homogeneous mixture** formed of a **solute** and a **solvent** (Figure 2.2);

$$\text{Solution} = \text{Solute} + \text{Solvent}. \quad (2.1)$$

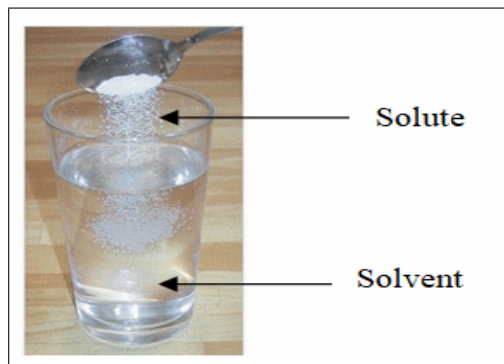


Figure 2.2: Solution

* A **homogeneous mixture** is a mixture where the components cannot be distinguished with the naked eye.

* A **solute** is a substance (solid, liquid, or gas) that can be dissolved in a solvent to form a solution.

* A **solvent** is the substance, typically a **liquid**, that a solute dissolves into.

* An **aqueous solution** is a solution where the **solvent** is **water**;

$$\text{Aqueous solution} = \text{Solute} + \text{water}. \quad (2.2)$$

2.3 Classification of solutions

* According to the *charge*:

- Neutral solutions (molecules). Example; Sucrose .
- Electrolytic solutions (ions). Example; Sodium Chloride, NaCl ;
- * **Strong electrolytes**: Substances that dissociate completely in water.

Example: NaCl .

* **Weak electrolytes**: Substances that partially dissociate in water.

Example: CH_3COOH .

* According to the *size*:

- Micromolecular solutions or **Crystalloids**. Examples include sugar and salt solutions.
- Macromolecular or **Colloidal** solutions. like milk and gelatin.

2.4 Concentrations

2.4.1 Mole fraction

The mole fraction (F_i) of a component (i) is equal to the ratio of the number of moles (n_i) of this component to the total number of moles (n_t) of the solution.

$$F_i = \frac{n_i}{n_t}. \quad (2.3)$$

Note

- Mole fraction of **solute**

$$F_{solute} = \frac{n_{solute}}{n_{solution}} = \frac{n_{solute}}{n_{solute} + n_{solvent}}, \quad (2.4)$$

where

$$n_{solution} = n_{solute} + n_{solvent}. \quad (2.5)$$

- Mole fraction of **solvent**

$$F_{solvent} = \frac{n_{solvent}}{n_{solution}} = \frac{n_{solvent}}{n_{solute} + n_{solvent}}. \quad (2.6)$$

- The sum of the mole fractions of all components in a solution is equal to one;

$$F_{solute} + F_{solvent} = 1. \quad (2.7)$$

2.4.2 Molarity

The molar concentration (m_r) (or molarity) for a given solute is the number of moles of the solute per liter of solution.

$$m_r = \frac{n_{solute}}{V}. \quad (2.8)$$

n_{solute} : Represents the number of moles of the solute, expressed in moles (mol).

V : Represents the volume of the solution in liters (L).

Units: mol/L , $mmol/L$.

Note :

A solution is said to be **molar** when it has a concentration of exactly $1mol$ per liter ($1mol/L$).

2.4.3 Mass concentration

Mass concentration (C_p) is the mass of the solute in 1 liter of solution.

$$C_p = \frac{m_{solute}}{V}. \quad (2.9)$$

m_{solute} : The mass of the solute in grams (g).

V : The volume of the solution in liters (L).

Unit: g/L

Note

The relationship between mass concentration (C_p) and molar concentration (m_r) :

$$C_p = M \cdot m_r. \quad (2.10)$$

Where M is the molar mass of the solute.

2.4.4 Concentration in percentage

Concentration in percentage is the ratio of the mass (m_{solute}) of solute (s) to the mass ($m_{solution}$) of the solution (S).

$$p = \frac{m_{solute}}{m_{solution}} \times 100\%. \quad (2.11)$$

Unit: without unit.

2.4.5 Molality

Molal concentration (m_l) or molality is the number of moles of the solute per unit mass of the solvent.

$$m_l = \frac{n_{solute}}{m_{solvent}}, \quad (2.12)$$

where

n_{solute} : The number of moles of the **solute**, expressed in moles (mol).

$m_{solvent}$; The mass of the **solvent** in kilograms (kg).

Unit: mol/kg .

2.4.6 Osmolarity

Osmolarity ω_r is the number of osmoles of solute per liter of solution (*osm/L*).

$$\omega_r = [1 + \alpha(\beta - 1)] \times m_r. \quad (2.13)$$

Unit: *osmol/l*.

where α is the dissociation coefficient

$$\alpha = \frac{N_d}{N_0}, \quad (2.14)$$

with

N_d : Number of dissociated molecules.

N_0 : Total initial number of molecules introduced into the solvent.

Unit: α without unit.

Examples: (*NaCl*, $\alpha = 1$), (*HCOOH*, $\alpha =$)

Note 1

★ For neutral solute (No dissociation);

$$\alpha = 0. \quad (2.15)$$

★ For weak electrolyte (Partial dissociation);

$$0 < \alpha < 1. \quad (2.16)$$

★ For strong electrolyte (Total dissociation);

$$\alpha = 1. \quad (2.17)$$

Note 2

• For neutral solute

$$\omega_r = m_r. \quad (2.18)$$

• For strong electrolyte

$$\omega_r = \beta m_r. \quad (2.19)$$

• For several solutes

$$\omega_r = \sum_{i=1}^n \omega_{r_i}. \quad (2.20)$$

and β is the number of osmoles represent the number of particles after dissociation.

2.4.7 Osmolality

Osmolality (ω_l) is the number of osmoles of solute per kilogram of solvent (*osm/kg*).

$$\omega_l = [1 + \alpha(\beta - 1)] \times m_l. \quad (2.21)$$

where

α : The dissociation coefficient.

β : The number of osmoles .

m_l : Osmolality.

Unit: Osmol/Kg .

2.4.8 Equivalent concentration

Equivalent concentration is the number of **gram equivalents** per liter of solution.

$$C_{eq} = 2n\alpha |Z| m_r, \quad (2.22)$$

where

α : The dissociation coefficient.

n : The number of positive or negative ions.

m_r : Osmolarity.

$|Z|$: The absolute value of the charge of positive or negative ions.

Unit: Eq/l .

★ **A gram equivalent** is the quantity of a substance that carries an electric charge equal to one Faraday ($1F = 96,500$ *coulombs*).

Note

To apply the previous rule (2.22), you only need to choose to work with either the positive or negative ions (Figure 2.3);

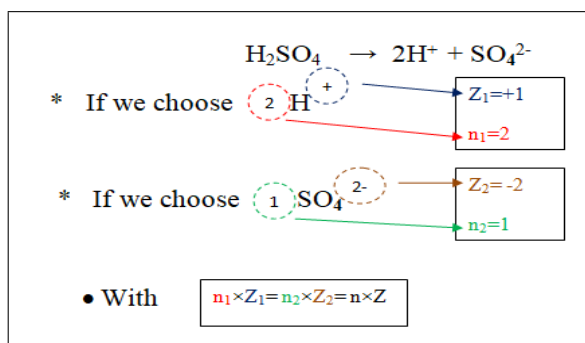


Figure 2.3: Fixing n and z .

2.5 Solubility

The solubility of a solid, liquid, or gas is the maximum amount of that substance that can be dissolved in $1L$ of a solution at a given temperature and pressure.

Solubility is related to several factors, including the nature of both the solvent and the solute, as well as temperature.

A **saturated solution** contains the maximum amount of solute, while an unsaturated solution does not.

This solubility can be expressed in mol/L or as a mass concentration in g/L .

2.6 Electrolyte solutions

Substances that dissolve in water to form **ions** are called **electrolytes** (Figure 2.4) .

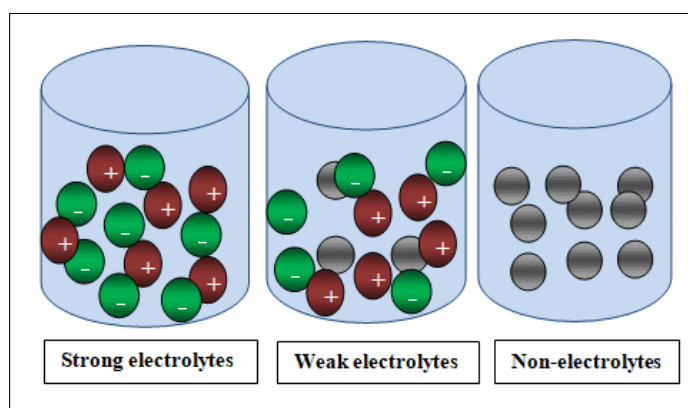


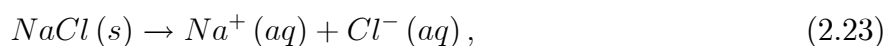
Figure 2.4: Electrolyte and non-electrolyte solutions.

Electrolytes are classified as:

Strong electrolytes:

A **strong electrolyte** is one that dissociates **completely** in water. At the end of dissociation, it contains only ions.

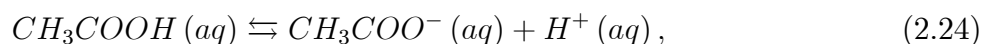
Example: $NaCl$



Weak electrolytes:

A **weak electrolyte** is one that dissociates **partially** in water. At the end of dissociation, it contains ions as well as some of the undissociated solute.

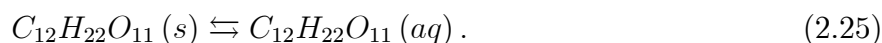
Example: $CH_3COOH, \dots$



Non-electrolytes:

Non-electrolytes do not form ions.

Examples: $C_{12}H_{22}O_{11}, \dots$



Notes

- * For the **strong electrolyte** : $\alpha = 1$ (Dissociation coefficient).
- * For the **strong electrolyte** $0 < \alpha < 1$.
- * **Non-electrolytes** do not form ions $\alpha = 0$.
- * Solutions containing **ions (electrolytes)** are **conductors of electricity** and those that contain **molecules (Non-electrolytes)** are nonconductors.

2.7 Electrical conductivity

- * An electrolytic solution is a solution that conducts electric current.
 - * The charge carriers are ion.
 - * Cations move in the conventional direction of the current and anions move in the opposite direction.
 - * Non-ionic (molecular) solutions do not conduct electric current.

2.7.1 Resistance and resistivity

The resistance of a conductor is defined by Ohm's Law

$$R = \frac{U}{I}, \quad (2.26)$$

where

U : Effective voltage in *Volt* (V)

I : Effective current intensity in *Ampere* (A)

R ; Resistance in *Ohm* (Ω) verifying Ohm's law;

For an electrical conductor, the resistance is also defined by

$$R = \rho \frac{L}{S}, \quad (2.27)$$

where

ρ : Resistivity in $\Omega.m$.

L ; Distance (or width) between the plates in m .

S ; Surface area of the cell in m^2 .

2.7.2 Conductance and conductivity

The transport of charges by cations and anions is measured using a Conductivity meter composed of a sensor called a conductimetric cell, powered by an alternating current (Figure 2.5).

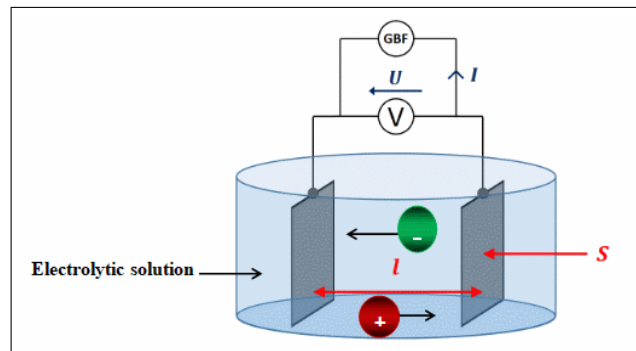


Figure 2.5: Conductimetric cell.

Conductance (G) is the inverse of the resistance (R) of the conductimetric cell is defined by the relation;

$$G = \frac{1}{R}, \quad (2.28)$$

where

G : Conductance in *Siemens* (S)

U : Effective voltage in *Volt* (V)

I : Effective current intensity in *Ampere* (A)

R ; Resistance in *Ohm* (Ω)

The conductance (G) is also defined by

$$G = \chi \frac{L}{S}, \quad (2.29)$$

where

L : Distance (or width) between the plates in m .

S : Surface area of the cell in m^2 .

$\frac{L}{S}$: Cell constant of the conductimetric cell in m^{-1} .

χ : Conductivity in $S \cdot m^{-1}$ (Siemens per meter) which is the inverse of the resistivity (ρ);

$$\chi = \frac{1}{\rho}. \quad (2.30)$$

Note

The conductivity χ of an electrolytic solution depends on:

- * The nature of the ions.
- * The temperature of the solution.
- * Their concentrations:

The conductivity χ varies proportionally with the number of ions. This number is significant at low concentrations but decreases rapidly if the concentration increases (Figure 2.6).

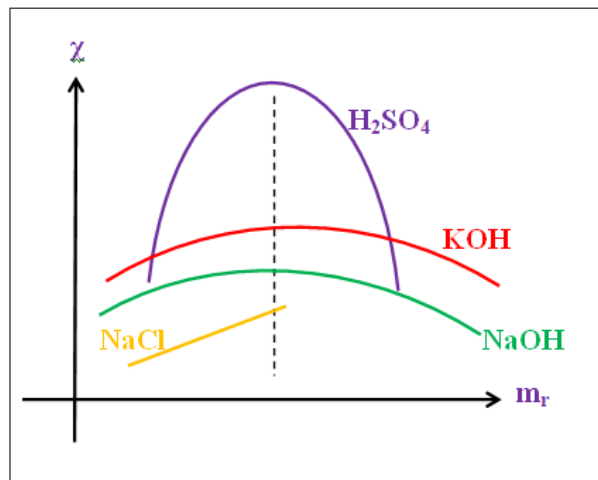


Figure 2.6: Variation of the conductivity with concentration

2.7.3 Molar conductivity

The molar conductivity (λ_m) of an electrolyte is defined by:

$$\lambda_m = \frac{\chi}{m_r}, \quad (2.31)$$

λ_m : Molar conductivity in mol/m^3 (moles per cubic meter).

χ : Conductivity in $S \cdot m^{-1}$ (Siemens per meter).

m_r : Molar concentration in mol/m^3 .

2.7.4 Kohlrausch low's

The conductivity (χ) of a solution depends on the concentrations ($[X_i]$) and the molar ionic conductivities (λ_i) of the ions X_i present, according to the relation below:

$$\chi = \sum_i \lambda_i [X_i], \quad (2.32)$$

where:

χ : Conductivity in or Siemens per meter ($S.m^{-1}$).

λ_i : Molar ionic conductivity of the ion X_i in $S.m^2.mol^{-1}$.

$[X_i]$: Molar concentration of the ion X_i in $mol.L^{-1}$.

Note

The **Kohlrausch** low's is only valid for concentrations below $1.0 \times 10^{-2} mol.L^{-1}$.

2.7.5 Equivalent conductivity of an electrolyte

The equivalent conductivity (λ) of an electrolyte is defined by:

$$\lambda = \frac{\chi}{C_{eq}}, \quad (2.33)$$

where

λ : Equivalent conductivity expressed in ($s.m^2.eqg^{-1}$).

χ : Conductivity) is expressed in siemens per meter ($S.m^{-1}$)

C_{eq} : Equivalent concentration is in equivalents-gram per cubic meter ($eqg.m^{-3}$)

Notes

If m_r tends toward zero (infinite dilution), (λ) tends toward a finite, non-zero limit called the limiting equivalent conductivity (λ_0) (Figure 2.7).

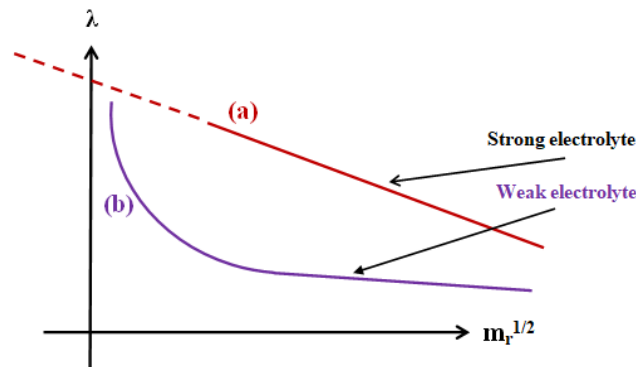


Figure 2.7: Variation of the equivalent conductivity with the square root of the concentration .

2.7.6 The limiting equivalent conductivity of an electrolyte

The limiting equivalent conductivity of an electrolyte λ_0 is the sum of the limiting ionic equivalent conductivities characteristic of each constitutive ion of the electrolyte:

$$\lambda_0 = \lambda^+ + \lambda^-,$$

where

λ_0 : Limiting equivalent conductivity

λ^+ : Limiting ionic equivalent conductivity of the anions.

λ^- : Limiting ionic equivalent conductivity of the cations.

2.7.7 Dissociation coefficient (Degree of dissociation)

The dissociation coefficient (α) of an electrolyte is defined by;

$$\alpha = \frac{\lambda}{\lambda_0}, \quad (2.34)$$

where

$$*\alpha = 1 \quad (\text{Strong electrolyte}), \quad (2.35)$$

$$*0 < \alpha < 1 \quad (\text{Weak electrolyte}), \quad (2.36)$$

$$*\alpha = 0 \quad (\text{Non-electrolyte}). \quad (2.37)$$

To determine the concentration of a solute in a solution, one can perform:

Assay by calibration (non-destructive), which relies on physical measurements.

2.7.8 Titration by calibration

In order to find the molar concentration m_r of a solution of unknown concentration, we follow these steps:

* Measure the conductivity (χ_i) of a group of solutions with known molar concentrations (m_{r_i}).

* Plot the graph: Conductivity as a function of concentration ($\chi = f(m_r)$) (Figure 2.8).

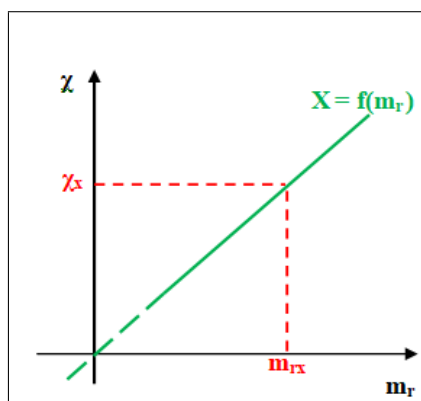


Figure 2.8: Conductivity as a function of molarity.

- * The graph (calibration curve) is a straight line passing through the origin.
- * Measure the conductivity (χ_x) of the solution whose concentration is required, locate it on the graph (y -axis), and by projecting onto the x -axis (abscissa), determine the unknown molar concentration (m_{rx}).

2.7.9 Conductimetric titration

To find the molar concentration of a solution (A) of unknown concentration m_{rA} using titration via conductivity measurement (Figure 2.10), rely on the setup illustrated below and follow the following steps:

- * Place a known volume (A) of the solution to be titrated (unknown molar concentration m_{rA}) in a beaker.
- * Using a burette, add varying volumes of the titrant solution (B) (known molar concentration m_{rB}), recording the conductivity (χ) for each volume(V) added.
- * Plot the graph: Conductivity (χ) as a function of the added volume (V): $\chi = f(V)$ (Figure 2.9).

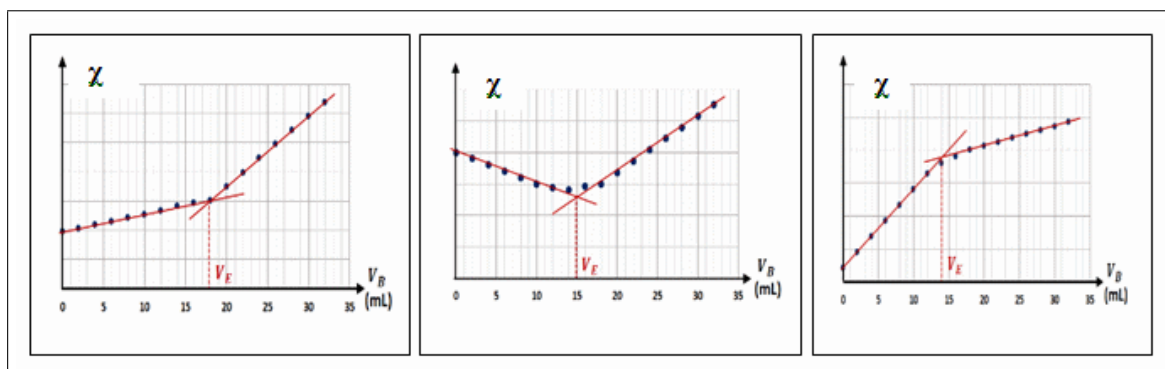


Figure 2.9: Examples (Conductivity as a function of volumes of the titrant solution).

* The resulting graph consists of two half-lines (linear segments) that meet at a single point called the equivalence point (E).

* At the equivalence point, we find the equivalent volume (V_{Beq}), from which the concentration of the unknown solution can be determined:

$$n_A = n_B, \quad (2.38)$$

$$m_{rA} \times V_A = m_{rB} \times V_{Beq}. \quad (2.39)$$

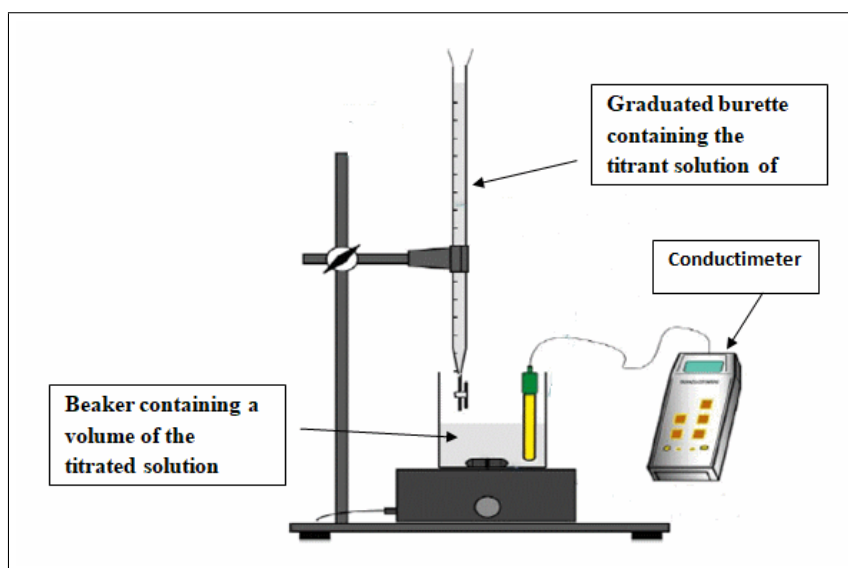


Figure 2.10: Apparatus for a conductimetric titration

2.8 Exercises

Exercise 1

2 liters of an aqueous solution containing a mass $m = 17.55g$ of $NaCl$ with a molar mass of $M = 58.5g/mol$.

- 1/ Calculate the molarity of the solution.
- 2/ Deduce the mass concentration.
- 3/ What is the quantity of water added to obtain a solution with a molar concentration of $0.015mole/L$?

Exercise 2

A one-liter solution contains:

- $18g$ of glucose ($180g/mol$)
- $2mole$ of $CaCl_2$

· 1mole of $NaCl$

Assuming the electrolytes are completely dissociated.

Calculate the osmolarity and the equivalent concentration of the solution.

Exercise 3

The conductivity χ of an aqueous solution of an AB_2 type electrolyte with a concentration of $7mmol/L$ is $12mS.m^{-1}$. Its equivalent conductivity at infinite dilution is $200 S.cm^2.eqg^{-1}$.

Calculate its degree of dissociation and its equilibrium constant.

Exercise 4

The conductivity χ at $18^\circ C$ of a saturated solution of calcium fluoride CaF_2 is $3.71mS.m^{-1}$.

Given at $18^\circ C$: $\lambda_{Ca^{2+}} = 10.50mS.m^2.mol^{-1}$, $\lambda_{F^{-}} = 4.04mS.m^2.mol^{-1}$.

Deduce the molar concentration of the ions in the solution.

2.9 Solutions

Exercise1

1/ Molarity of the solution (m_r) :

$$m_r = \frac{m}{M} = \frac{\frac{17.55g}{58.5g/mol}}{2L} = 0.15mol/l. \quad (2.40)$$

2/ Mass concentration (C_p);

$$C_p = M \times m_r = 58.5 (g/mol) \times 0.15 (mol/l) = 8.775g/l. \quad (2.41)$$

3/Volume of the water added;

$$V_f = \frac{m_{r_i} \times V_i}{m_{r_f}} = \frac{0.15 \times 2}{0.1} = 3L \quad (2.42)$$

$$V_{water} = V_f - V_i = 3 - 2 = 1L. \quad (2.43)$$

Exercise2

1/ Solution osmolarity:

$$\omega_{r_{solution}} = \omega_{r_{glucose}} + \omega_{NaCl} + \omega_{CaCl_2}, \quad (2.44)$$

$$= (0.1 + 2 + 6) 8.1osmol/l = 8.1osmol/l. \quad (2.45)$$

where;

* Glucose ($C_6H_{12}O_6$):

* Molarity

$$m_{r_{glucose}} = \frac{n_{glucose}}{V_{Solution}} = \frac{\frac{m_{glucose}}{M_{glucose}}}{V_{Solution}} = \frac{\frac{18g}{180g/mol}}{1l} = 0.1mol/l, \quad (2.46)$$

with

$$1glucose \rightarrow 1glucose, \quad (2.47)$$

then $\beta = 1$.

* $\alpha = 0$ (Non-electrolytes).

* Osmolarity:

$$\omega_{r_{glucose}} = [1 + \alpha(\beta - 1)] m_{r_{glucose}}, \quad (2.48)$$

$$\omega_{r_{glucose}} = [1 + 0(1 - 1)] 0.1mol/l = 0.1osmol/l. \quad (2.49)$$

* $NaCl$:

* Molarity:

$$m_{r_{NaCl}} = \frac{n_{NaCl}}{V_{Solution}} = \frac{1mol}{1l} = 1mol/l. \quad (2.50)$$

with



then $\beta = 2$.

* $\alpha = 1$.(Total dissociation)

* Osmolarity

$$\omega_{r_{NaCl}} = [1 + \alpha(\beta - 1)] m_{r_{NaCl}}, \quad (2.52)$$

$$\omega_{r_{NaCl}} = [1 + 1(2 - 1)] 1mol/l = 2osmol/l. \quad (2.53)$$

* $CaCl_2$;

* Molarity

$$m_{r_{CaCl_2}} = \frac{n_{CaCl_2}}{V_{Solution}} = \frac{2mol}{1l} = 2mol/l, \quad (2.54)$$

with



then $\beta = 3$.

* $\alpha = 1$.(Total dissociation)

* Osmolarity

$$\omega_{r_{CaCl_2}} = [1 + \alpha(\beta - 1)] m_{r_{CaCl_2}}, \quad (2.56)$$

$$\omega_{r_{NaCl}} = [1 + 1(3 - 1)] 2mol/l = 6osmol/l. \quad (2.57)$$

2/ Equivalent concentration (C_{eq}):

$$C_{eq}(solution) = C_{eq}(glucose) + C_{eq}(Nacl) + C_{eq}(CaCl_2). \quad (2.58)$$

$$= (0 + 2 + 8) eqg/l = 10eqg/l. \quad (2.59)$$

where:

* Glucose ($C_6H_{12}O_6$):

$$C_{eq}(glucose) = 2n |z| \alpha m_r = 0eqg/l \quad (2.60)$$

where $z = 0, \alpha = 0$ (non-electrolytes).

* $Nacl$:

we have:



For $Na^+; n = 1, z = +1$, then

$$C_{eq}(NaCl) = 2n |z| \alpha m_r. \quad (2.62)$$

$$= 2 \times 1 \times 1 \times 1 \times 1 = 2eqg/l. \quad (2.63)$$

* $CaCl_2$:

We have



For $Ca^{2+}; n = 1, z = +2$, then

$$C_{eq}(CaCl_2) = 2n |z| \alpha m_r. \quad (2.65)$$

$$= 2 \times 1 \times 2 \times 1 \times 2 = 8eqg/l. \quad (2.66)$$

Exercise 3

Degree of dissociation (α);

$$\alpha = \frac{\lambda}{\lambda_0} = \frac{\chi}{\lambda_0 C_{eq}} = \frac{\chi}{\lambda_0 \times 2n |z| \alpha m_r}, \quad (2.67)$$

then

$$\alpha = \sqrt{\frac{\chi}{2n|z|m_r}} = \sqrt{\frac{12 \times 10^{-3} (S.m^{-1})}{200 \times 10^{-4} (S.m^2.Eqg^{-1}) \times 2 \times 1 \times 2 \times 7 (mol/m^3)}}, \quad (2.68)$$

$$= 0.0429. \quad (2.69)$$

where



For A^{+2} , $n = 1$ and $z = +2$.

$$\lambda = \frac{\chi}{C_{eq}}, \quad (2.71)$$

and

$$C_{eq} = 2n|z|\alpha m_r, \quad (2.72)$$

Equilibrium constant (K)

$$K = \frac{[A^{+2}] + [B^{-}]^2}{[AB_2]} = \frac{4\alpha^3 m_r^2}{1 - \alpha} \quad (2.73)$$

$$= \frac{4(0.0429)^3 \times (7mol/m^3)^2}{(1 - 0.0429)} \quad (2.74)$$

$$\approx 0.0161. \quad (2.75)$$

where

$$[A^{+2}] = \alpha m_r, \quad (2.76)$$

$$[B^{-}] = 2\alpha m_r, \quad (2.77)$$

$$[AB_2] = (1 - \alpha) m_r. \quad (2.78)$$

Exercise 4

Kohlrausch low's

$$\chi = \lambda_{Ca^{2+}} [Ca^{+2}] + \lambda_{F^{-}} [F^{-}], \quad (2.79)$$

$$= (\lambda_{Ca^{2+}} + 2\lambda_{F^{-}}) m_r, \quad (2.80)$$

then

$$m_r = \frac{\chi}{\lambda_{Ca^{2+}} + 2\lambda_{F^{-}}}, \quad (2.81)$$

$$= \frac{3.71mS.m^{-1}}{(10.50 + 2 \times 4.04) mS.m^2.mol^{-1}}, \quad (2.82)$$

$$= 2 \times 10^{-4} mol.L^{-1}. \quad (2.83)$$

where the dissociates of calcium fluoride write



then

$$[Ca^{+2}] = m_r, \quad (2.85)$$

$$[F^{-}] = 2m_r. \quad (2.86)$$

Chapter 3

Surface phenomena

3.1 Introduction

The objective of this chapter is to study surface phenomena [16, 18, 19, 20, 28, 29, 30], as they provide explanations for several occurrences observed in our daily lives, such as the movement of certain insects on water, the shape of liquids in capillary tubes, the formation of liquid droplets in various shapes, and the creation of perfectly spherical soap bubbles, among others (See Figure: 3.1 and Figure: 3.2).

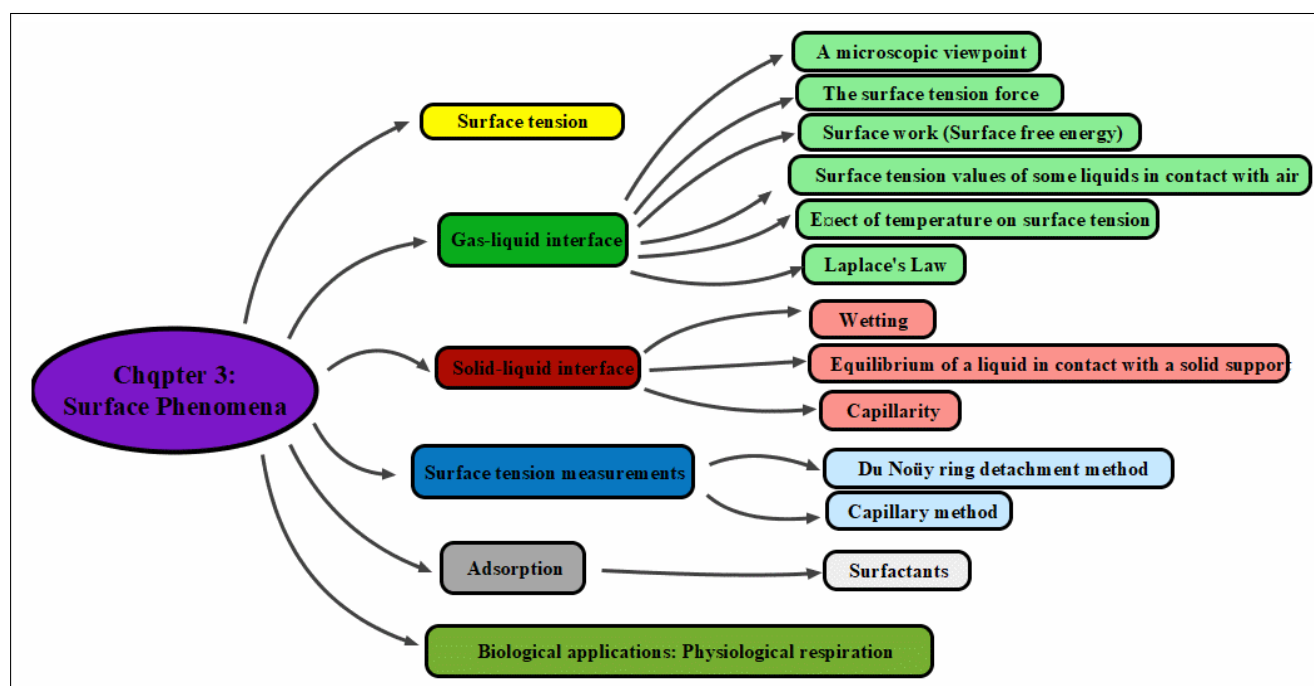


Figure 3.1: Chapter 3 concept map.



Figure 3.2: Surface Phenomena.

3.2 Surface tension

3.2.1 Definition

* **The interface** is a contact surface between two different media.

* **Surface tension** is a property of liquids that allows their free surface to maintain equilibrium.

3.3 Gas-liquid interface

3.3.1 A microscopic viewpoint

* In the bulk of the liquid, the molecules attract one another with cohesive forces (Van der Waals forces), but the resultant force on any given molecule is zero due to symmetry ($\sum \vec{F} = 0$).

* Molecules located at the liquid surface (as there are no other liquid molecules above them) interact with the surrounding molecules and the underlying molecules via attractive forces. This

results in a non-zero net attractive force that is directed **downwards**, **perpendicular** to the liquid surface. This force is known as the **surface tension force** (Figure 3.3).

- * The gas-liquid interface is analogous to a **membrane**.
- * Surface tension acts to **minimize** the liquid's surface area.

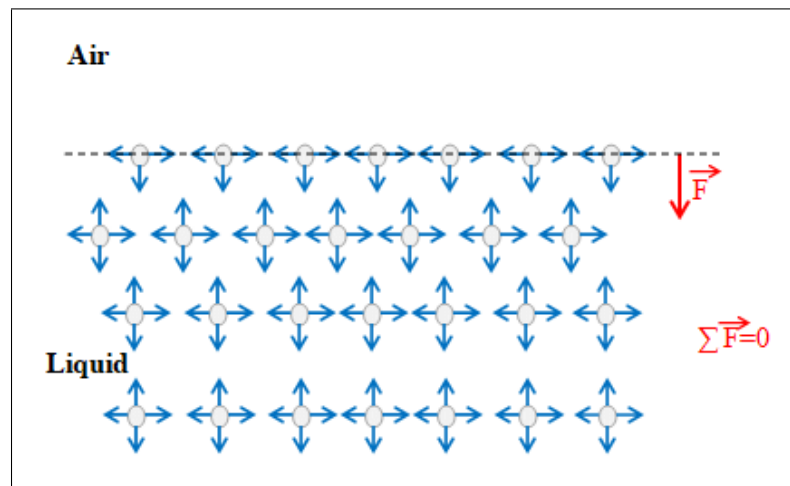


Figure 3.3: A microscopic viewpoint of surface tension.

3.3.2 The surface tension force

Suppose a rectangular soap film $ABCD$ of length l and width x , one of whose sides, CD , is movable (Figure 3.4).

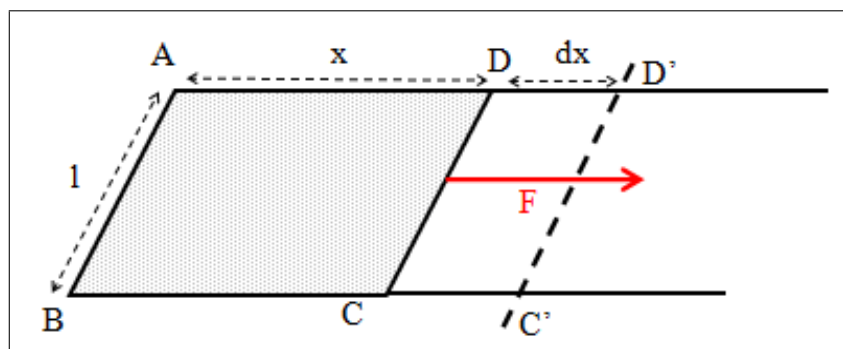


Figure 3.4: Surface tension force.

The surface (S) of soap film is

$$S = 2xl, \quad (3.1)$$

In order to increase the area (S) of this soap film ($S + dS$), it suffices to move the movable side with a force (F), called the **surface tension force**, which is proportional to the length (l) and

is written in the form:

$$F = \sigma l, \quad (3.2)$$

where the constant of proportionality (σ) is known as the surface tension coefficient.

Units;

F in Newtons (N)

σ in $N.m^{-1}$, Jm^{-2} or $dyne.cm^{-1}$.

3.3.3 Surface work (Surface free energy)

The experiment mentioned above requires energy (dW) that is directly proportional to (dS). The proportionality coefficient in this case is also the surface tension coefficient (σ). Therefore, energy(dw) is written in the form

$$dW = Fdx = 2\sigma ldx = \sigma (2ldx) = \sigma dS, \quad (3.3)$$

where the surface area S represents the hatched part in the figure:3.4 and the presence of the factor 2 in equation (3.3) is explained by the fact that the soap film has **two** rectangular surfaces in contact with the air.

3.3.4 Surface tension values of some liquids in contact with air

Liquid	$\sigma(Nm^{-1})$ at $20C^{\circ}$
Water	73×10^{-3}
Vegetable oil	32×10^{-3}
Ethanol	22×10^{-3}
Mercury	480×10^{-3}

3.3.5 Effect of temperature on surface tension

An **increase** in the liquid's temperature leads to a **decrease** in its surface tension. The table below illustrates this.

Temperature (C°)	0	10	20	30	80	100
$\sigma (mNm^{-2})$	75	74.2	72.7	71.2	62	58

Note

Surface tension depends on;

- The liquid itself.
- The medium above its free surface.
- The temperature.

3.3.6 Laplace's law

Let's consider an air sphere inside a liquid as shown in the (Figure 3.5)

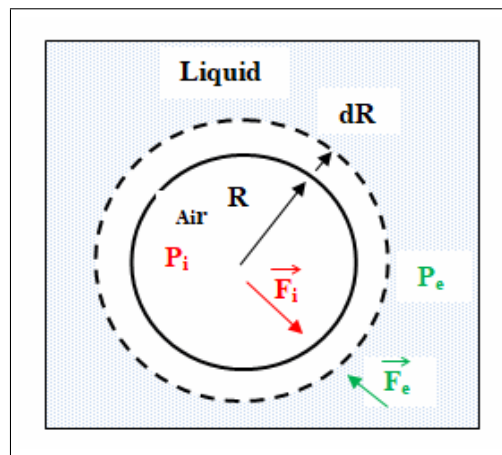


Figure 3.5: A sphere inside a liquid.

where

P_i : Internal pressure of the air bubble.

P_e : External pressure of the air bubble (pressure in the surrounding liquid).

with

$$P_i > P_e. \quad (3.4)$$

Work done by the internal and external pressure forces of the bubble given by

$$dW_i = F_i dR = P_i S dR = P_i (4\pi R^2) dR, \quad (3.5)$$

$$dW_e = -F_e dR = -P_e S dR = -P_e (4\pi R^2) dR, \quad (3.6)$$

where

$$F_i = P_i S, \quad (3.7)$$

$$F_e = P_e S, \quad (3.8)$$

$$S = 4\pi R^2. \quad (3.9)$$

We assume that the positive direction for calculating the work of the force F_i is towards the direction of the air bubble's volume increase (from the inside out). Consequently, the work of the force F_e directed opposite to the volume increase (from the outside in) is negative.

Total work

$$dW = dW_i + dW_e = (P_i - P_e) (4\pi R^2) dR. \quad (3.10)$$

This work is equal to that of the surface tension forces:

$$dW = \sigma dS = \sigma 8\pi R dR, \quad (3.11)$$

where

$$dS = 8\pi R dR, \quad (3.12)$$

comparing the two equations, the Laplace's law reads

$$\Delta P = \frac{2\sigma}{R}. \quad (3.13)$$

For a **soap** bubble, we have two interfaces (Figure 3.6)

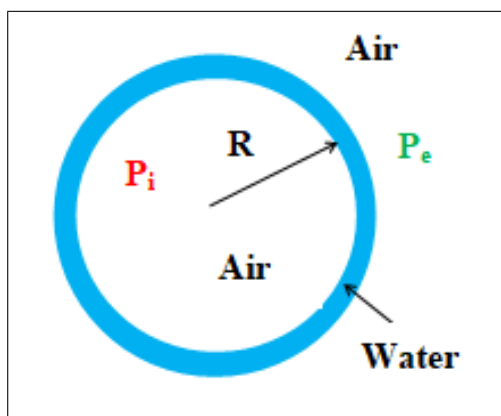


Figure 3.6: Soap bubble

therefore Laplace's law is written in the form

$$\Delta P = \frac{4\sigma}{R}. \quad (3.14)$$

3.4 Solid-liquid interface

3.4.1 Wetting

* Wetting represents the extent to which a liquid droplet spreads on a solid surface.

* To determine the degree of wetting, it is sufficient to know the angle formed between the liquid droplet and the solid surface.

* This angle, which is measured between the solid surface and the tangent to the liquid droplet, is known as the wetting angle or contact angle(θ).

* The value of the contact angle allows us to define the following cases for the degree of wetting:

- $\theta = 0$; Perfect wetting (Figure 3.7).

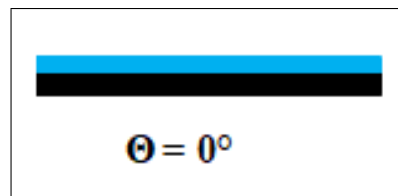


Figure 3.7: Perfect wetting.

- $\theta < \frac{\pi}{2}$; Partial wetting (Figure 3.8).

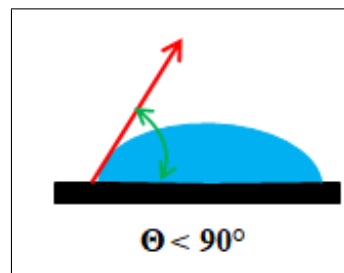


Figure 3.8: Partial wetting.

- $\theta > \frac{\pi}{2}$; Non-wetting (Figure 3.9).

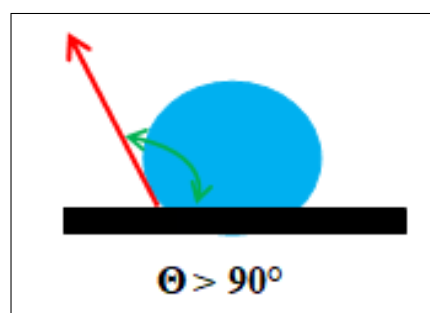


Figure 3.9: Not-wetting.

3.4.2 Equilibrium of a liquid in contact with a solid support (Young's equation)

The equilibrium of wetting is formally described by Young's equation, which balances the interfacial tensions at the three-phase boundary (solid, liquid, and gas/vapor) (Figure 3.10):

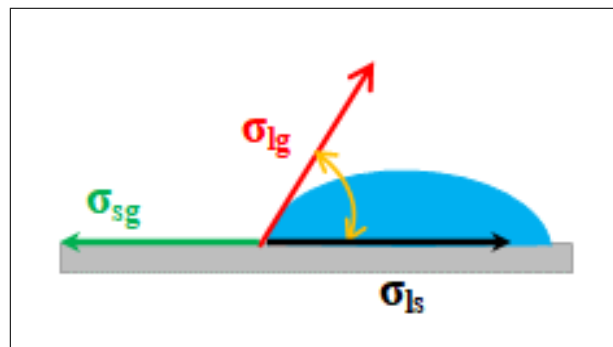


Figure 3.10: Equilibrium of a liquid in contact with a solid support.

Young's equation writes

$$\sigma_{sg} = \sigma_{sl} + \sigma_{lg} \cos \theta, \quad (3.15)$$

Where σ represents the interfacial tension between the solid (s), liquid (l), and gas/vapor (g) phases.

3.4.3 Capillarity

Definition

Capillarity is the property by which liquids rise or fall in a tube of very small diameter due to surface tension.

Capillary rise and depression

* The rise or depression of a liquid inside a capillary tube is related to the nature of the liquid and the radius of the capillary tube (Figure 3.11).

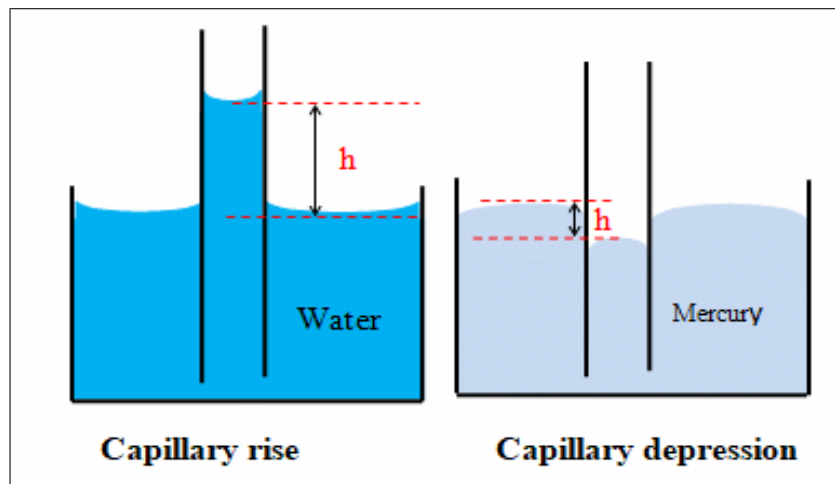


Figure 3.11: Capillary rise and depression.

* The height of the liquid's rise (or depression) is inversely proportional to the radius of the capillary tube (Figure 3.12) .

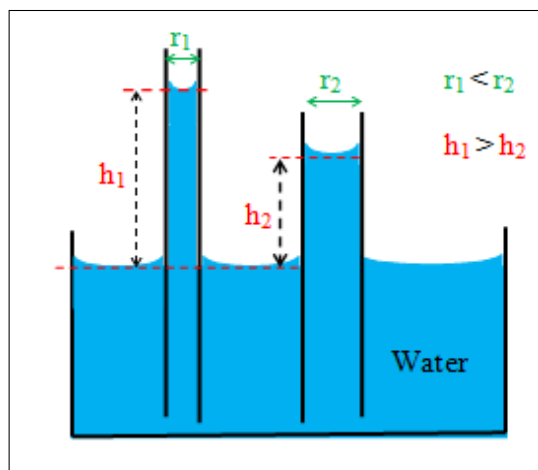


Figure 3.12 :Capillary rise and radius of the tube.

* The interpretation of such phenomena related to **capillarity** is done according to **Jurin's Law**.

Jurin low's

For the rise of a liquid inside a capillary tube (Figure 3.13);

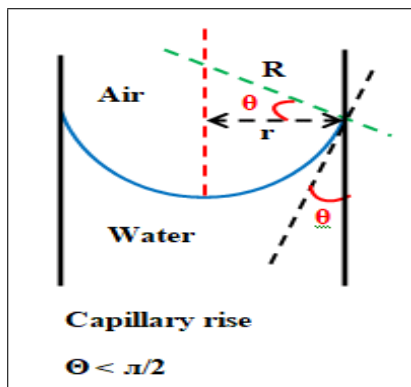


Figure 3.13: Relation between R and r.

We can write;

Hydrostatic law;

$$P_{int} = P_{ext} + \rho gh, \quad (3.16)$$

and **Laplace's** Law;

$$P_{int} - P_{ext} = \frac{2\sigma}{R}, \quad (3.17)$$

from the two equation, we have

$$h = \frac{2\sigma}{\rho g R}. \quad (3.18)$$

where

$$R = \frac{r}{\cos \theta}, \quad (3.19)$$

then the **Jurin** law's takes the form

$$h = \frac{2\sigma \cos \theta}{\rho g r}. \quad (3.20)$$

3.5 Surface tension measurements

There are several methods for measuring the surface tension (σ), among which we mention:

3.5.1 Du Noüy ring detachment method

A platinum ring is pulled out of the liquid while measuring the force exerted by a dynamometer. The value of the force is noted just before the meniscus detaches (Figure 3.14).

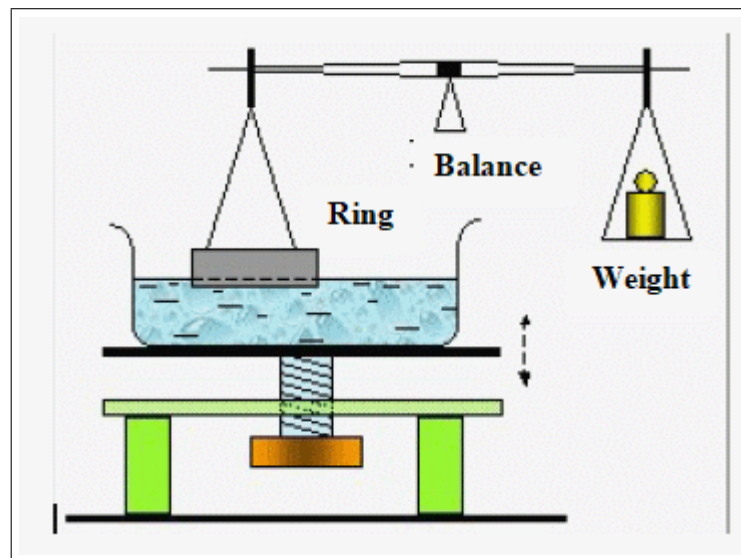


Figure 3.14: Du Noüy ring detachment method.

The ring is subjected to a downward force from the liquid equal to

$$F = 2\sigma L = 4\pi R\sigma. \quad (3.21)$$

where σ is the surface tension and L is the ring circumference ;

$$L = 2\pi R. \quad (3.22)$$

At equilibrium

$$P = F, \quad (3.23)$$

$$mg = 4\pi R\sigma, \quad (3.24)$$

then surface tension reads

$$\sigma = \frac{mg}{4\pi R}. \quad (3.25)$$

3.5.2 Capillary method

When a capillary tube of radius (r) is immersed in a liquid with a surface tension (σ) , the liquid rises or falls in the tube by a height (h) .

In order to measure the surface tension (σ), it is sufficient to measure the height (h) and the contact angle (θ) and substitute them into Jurin's Law;

$$\sigma = \frac{\rho g r h}{2 \cos \theta}. \quad (3.26)$$

3.6 Adsorption

3.6.1 Definition

Adsorption is a surface phenomenon by which atoms or molecules of gas or liquid (**adsorbates**) attach to a solid surface (**adsorbent**) (Figure 3.15).



Figure 3.15: Adsorption.

We distinguish two types of **adsorption**:

Physical adsorption (Physisorption) ;

- Involves very weak interactions between molecular entities, such as Van der Waals attractive forces and forces due to electrostatic polarization interactions.

- It is reversible and not very specific.
- Fast and generally limited by diffusion phenomena.

Chemical adsorption (Chemisorption) ;

- Irreversible phenomenon
- Strong chemical bond, typically a covalent type, between the surface atoms of the solid and the adsorbed molecules.

- Involves high attractive energies, which lead to high heats of adsorption.

Do not confuse adsorption with absorption:

In **adsorption**, the molecules **remain** on the surface of the solid, while in the case of **absorption**, the molecules **penetrate** the interior of the liquid or solid phase.

3.6.2 Surfactants

Surfactants (surface-active agents) are amphiphilic organic molecules composed of two distinct parts (Figure 3.16):

- * A hydrophilic head, which has a strong affinity for water molecules.
- * A non-polar hydrophobic tail, which water molecules tend to avoid.

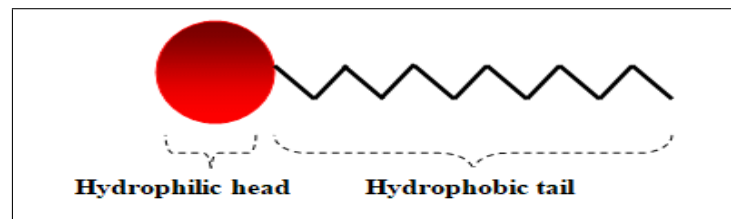


Figure 3.16: Surfactants

A **surfactant** or **surface-active agent** is a compound that **modifies the surface tension** between two surfaces.

- * Surfactant agents lower the value of σ of the liquids to which they are added and make them **wetting, foaming, deterging, emulsifying** ...

- * Surfactants allow for the stabilization of bubbles

- * Surfactants are substances soluble in water and have the property of concentrating and aggregating at the interfaces between water and other substances that are poorly soluble in water, notably fatty substances

Surfactants can be used as:

- * Detergents.
- * Solubilizing agents.
- * Foaming agents.
- * Wetting agents.
- * Dispersing agents.
- * Emulsifying agents.
- * Antiseptics.

3.7 Biological applications: Physiological respiration

The Figure below illustrates the role of surface tension within the pulmonary alveolus in the process of respiration (Figure 3.17)

- * The lung contains pulmonary alveolus.
- * The alveoli are considered as air bubbles inside a liquid.
- * The alveoli produce a pulmonary surfactant.
- * The compound that modified the surface tension is the pulmonary surfactant.
- * When an alveolus is small, the surface tension is strong and the surfactant is concentrated.
- * The surface tension (σ) must be modified to maintain equilibrium.

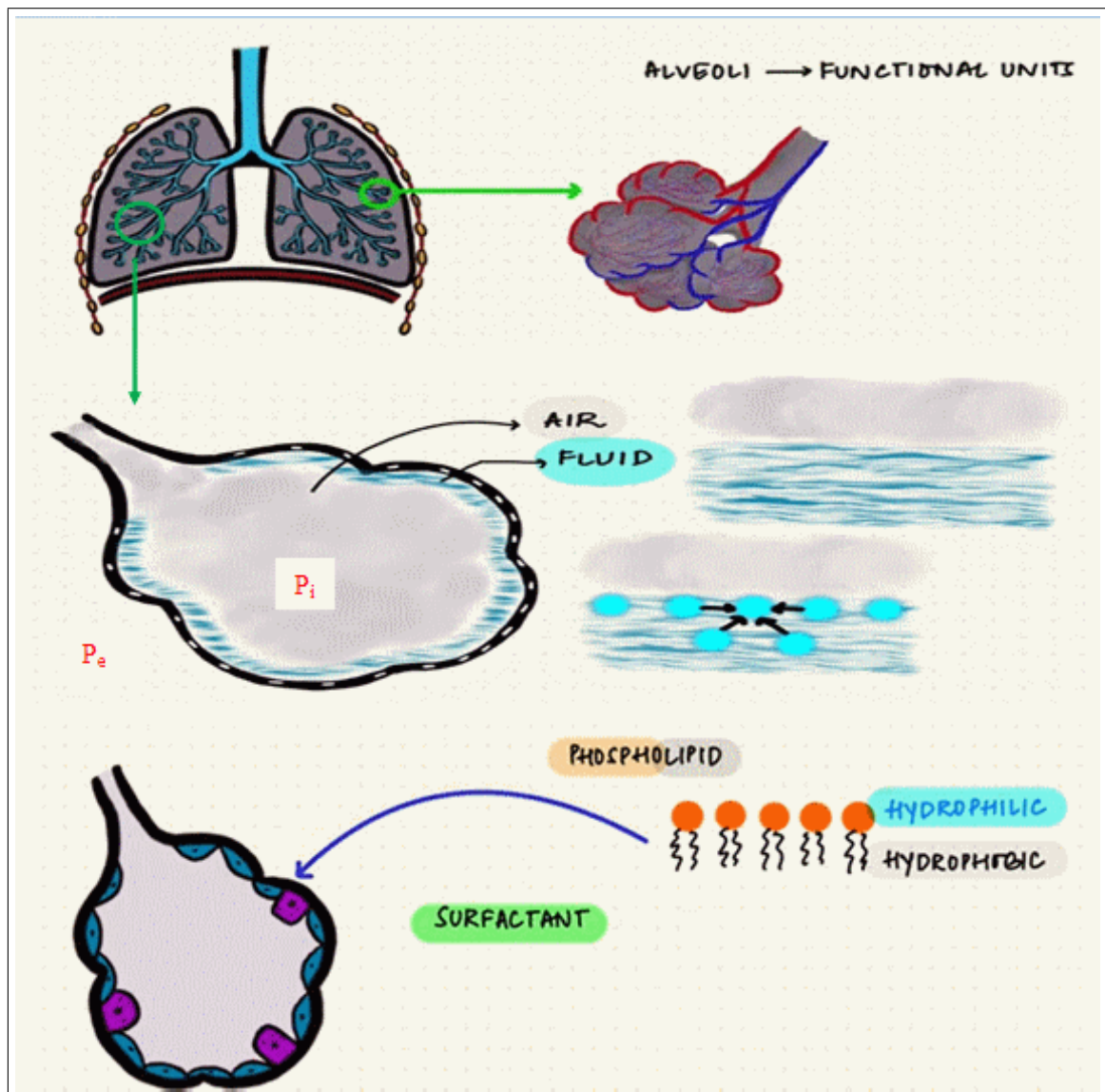


Figure 3.17: Physiological respiration.

* This describes how the radius of an alveolus changes during the breathing cycle and the resulting implications for surface tension, particularly in the context of Laplace Law's;

$$r\Delta P = r(P_i - P_0) = 2\sigma \quad (3.27)$$

where

P_0 : Pressure outside the alveolus (atmospheric pressure or surrounding tissue pressure)

ΔP : Transmittal pressure difference ($\Delta P = P_{in} - P_{out}$)

r : Radius of the alveolus (assumed to be spherical)

σ : Surface tension

Expiration (Exhalation):

P_0 increases, ΔP and r decrease.

Inspiration (Inhalation):

P_0 decreases, ΔP and r increase

3.8 Exercises

Exercise 1

A square metallic frame with a side length of (l) is placed in a bath of fuel oil. To separate the frame from the liquid, a force of $7.32 \times 10^{-3} N$ must be exerted. The surface tension of the fuel oil is given by $\sigma = 1.83 \times 10^{-2} N/m$ (recall that two surfaces are created when separating the frame from the liquid).

* Calculate the side length of (l) of the square metallic frame.

Exercise 2

A glass tube with a diameter of $3mm$, open at both ends, is immersed in a tank of liquid mercury at $20^\circ C$.

Given: $\sigma = 0.485 N/m$, $\rho = 13,546 kg/m^3$ and the contact angle between mercury and glass is $\theta = 130^\circ$.

* What will be the difference in height (h) between the mercury in the tube and the mercury in the tank?

Exercise 3

A liquid has a surface tension constant $\sigma = 25 \times 10^{-3} N \cdot m^{-1}$. With this liquid, a soap bubble of radius $R = 3 cm$ is blown.

1/ Calculate the overpressure inside this bubble. The external pressure being equal to $105 Pa$.

2/ Calculate the total work expended to blow the bubble.

3.9 Solutions

Exercise 1

The surface tension force is given by:

$$F = n \times \sigma \times L = 2 \times \sigma \times 4l, \quad (3.28)$$

then the side length of (l) reads;

$$L = \frac{F}{8\sigma} = \frac{7.32 \times 10^{-3} (N)}{8 \times 1.83 \times 10^{-2} (N/m)} = 0.05m = 5Cm. \quad (3.29)$$

Exercise 2

Using Jurin's law

$$h = \frac{2\sigma \cos(\theta)}{\rho g R} = \frac{2 \times 0.485 (N/m) \times \cos(130^\circ)}{13,546 (kg/m^3) \times 9.81 (N/Kg) \times 1.5 \times 10^{-3} (m)}, \quad (3.30)$$

$$= -0.003128m = -3.13mm. \quad (3.31)$$

The negative sign indicates the descent (lowering) of the liquid.

Exercise 3

Laplace's law

$$\Delta P = \frac{4\sigma}{R}, \quad (3.32)$$

$$= \frac{4 \times (25 \times 10^{-3} N/m)}{0.03m} = 3.33Pa. \quad (3.33)$$

1/ The overpressure inside this bubble

$$\Delta P = P_i - P_e, \quad (3.34)$$

then

$$P_i = \Delta P + P_e = (3.33 + 105) Pa = 108.33Pa. \quad (3.35)$$

2/ The total work expended to blow the bubble

$$W = n \times \sigma \times S = 2\sigma (4\pi R^2) = 8 \times 3.14 \times 25 \times 10^{-3} (N \cdot m^{-1}) (3 \times 10^{-2})^2 (m^2) \quad (3.36)$$

$$= 5.66 \times 10^{-4} J. \quad (3.37)$$

Chapter 4

Diffusion phenomena

4.1 Introduction

Some physical and chemical phenomena that occur, such as the diffusion of a colored substance in a cup of water (Figure 4.2), as well as the passage of some particles across porous membranes, have been studied in what is known as the phenomena of diffusion and osmosis [31, 32]. In this chapter, we will address both phenomena and the laws that govern them, as well as some of their applications in the biological field (See Figure: 4.1).

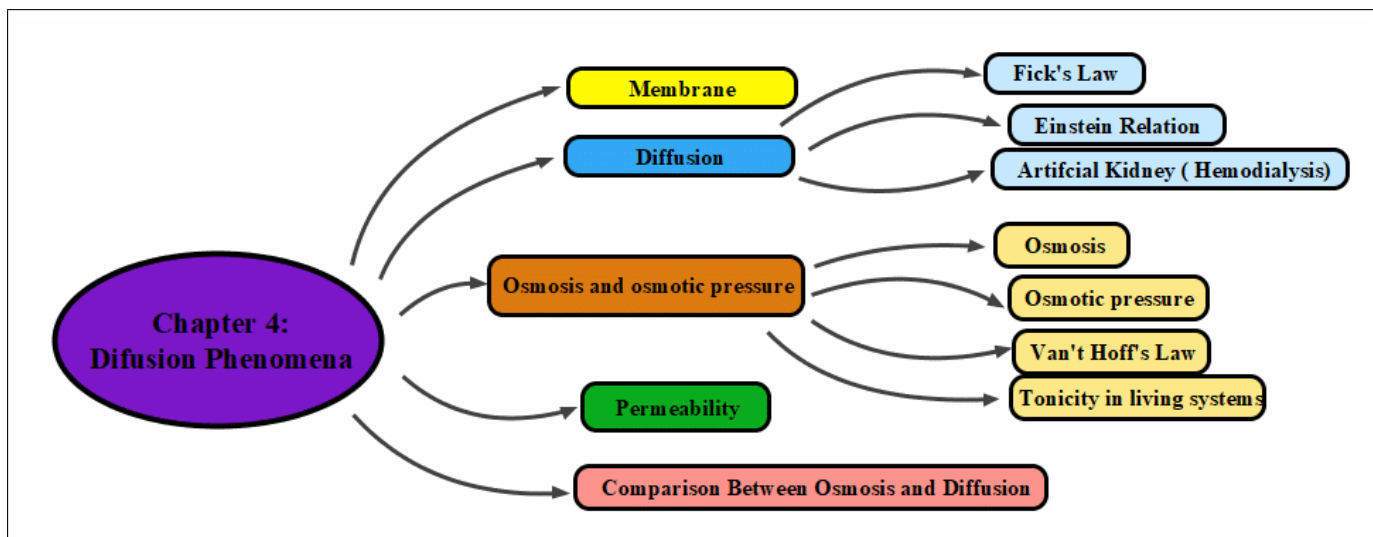


Figure 4.1: Chapter 4 concept map.

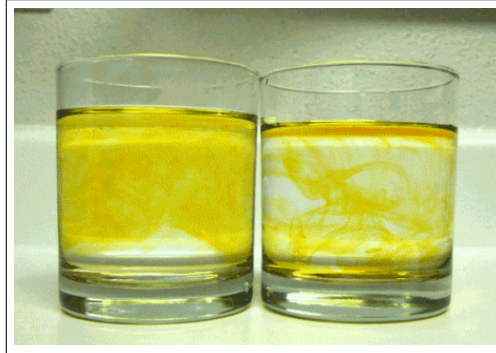


Figure 4.2: Diffusion of a colored substance in water.

4.2 Membrane

A membrane is a thin film that enables the selective separation of ions, molecules, or biological organisms.

4.2.1 Types of membranes

There are two types of membranes:

Semi-permeable membrane:

- * Allows water molecules to pass through.
- * Completely stops all solute particles.

Dialyzing membrane:

- * Allows water and the small molecules dissolved in it to pass freely.
- * Stops macromolecules (molecules with molar masses greater than 10kg/mol).

4.3 Diffusion

Diffusion is the movement of solutes through a **permeable membrane** from a region of higher concentration (C_2) to a region of lower concentration (C_1) so that it is distributed uniformly (Equilibrium ($C_1' = C_2'$)) (Figure 4.3).

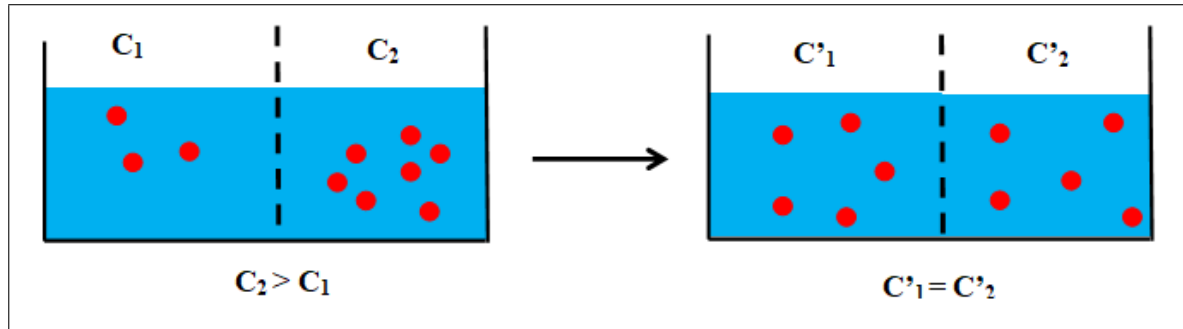


Figure 4.3: Diffusion.

4.3.1 Fick's law

Fick's law defines the molar diffusion flux (J_n) in a **steady state regime**.

It represents the rate at which a substance passes through a unit area of the membrane.

Fick's law is defined as;

$$J_n = -D.S.\frac{dC}{dx}, \quad (4.1)$$

where

J_n : Molar diffusion flux in $mol.m^{-2}.s^{-1}$, with

$$J_n = \frac{dn}{dt}. \quad (4.2)$$

D : Diffusion coefficient in $m^2.s^{-1}$

S : The surface area of the membrane in m^2 .

$\frac{dC}{dx}$: Concentration gradient.

Fick's law can be expressed in terms of mass flow rate as follows

$$J_m = -D.S.\frac{dC_m}{dx}, \quad (4.3)$$

where

J_m : Mass diffusion flux in $mol.m^{-2}.s^{-1}$;

$$J_m = \frac{dm}{dt}, \quad (4.4)$$

C_m : Mass concentration.

4.3.2 Einstein relation

Einstein relation of diffusion coefficient (D) takes the form

$$D = \frac{K_B T}{f}, \quad (4.5)$$

where

T : Absolute temperature (K).

k_B : Boltzmann constant.

$$k_B = 1.38 \times 10^{-23} J/K, \quad (4.6)$$

f : Viscous friction coefficient.

$$f = 6\pi\eta r, \quad (4.7)$$

with

η :Viscosity coefficient in $Pa.s$.

r : is the radius of the molecule in m .

Notes

Let us consider two solutes with radii r_1 and r_2 diffusing in two media with viscosities η_1 and η_2 at temperatures T_1 and T_2 , respectively. We have

$$\frac{D_1}{D_2} = \frac{T_1 \cdot \eta_2 \cdot r_2}{T_2 \cdot \eta_1 \cdot r_1}, \quad (4.8)$$

For two solutes with radii r_1 and r_2 in the same media ($\eta_1 = \eta_2$) and temperature ($T_1 = T_2$), the equation becomes;

$$\frac{D_1}{D_2} = \frac{r_2}{r_1}, \quad (4.9)$$

The radius of the molecule reads

$$r = \sqrt[3]{\frac{M}{\frac{4}{3}\pi N \rho}}, \quad (4.10)$$

with

$$\rho = \frac{M}{V} \quad (4.11)$$

$$V = \frac{4}{3}\pi r^3 \quad (4.12)$$

$$M = N \cdot m. \quad (4.13)$$

For ($\rho_1 = \rho_2$), the equation becomes;

$$D_1 = \sqrt[3]{\frac{M_2}{M_1}} D_2, \quad (4.14)$$

4.3.3 Artificial kidney (Hemodialysis)

* The patient is connected to a large machine called a dialyzer (artificial kidney) (Figure 4.4).

* Two tubes; one for the outgoing blood and one for the incoming blood connect the patient's arm to the machine.

* Inside the machine, the blood is cleared of its waste products and, once purified, it is reintroduced into the circulatory system.

* The membrane allows small molecules like urea to diffuse through, while retaining larger proteins.

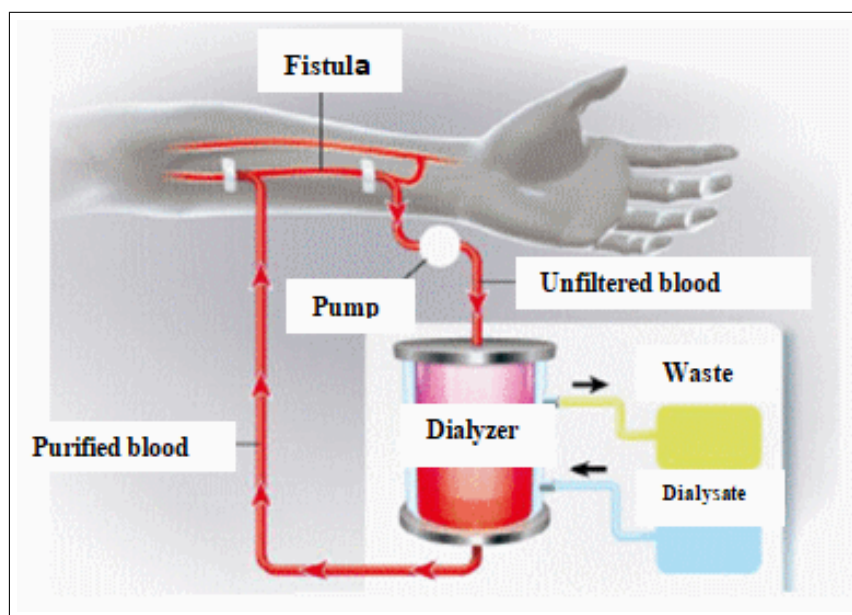


Figure 4.4: Hemodialysis

4.4 Osmosis and osmotic pressure

4.4.1 Osmosis

Dutrochet experiment (Dutrochet osmometer)

A funnel equipped with a long tube, and whose opening is wrapped with a semi-permeable membrane, containing a colored glucose solution, is inverted into a crystallizing dish filled with pure water (Figure 4.5).

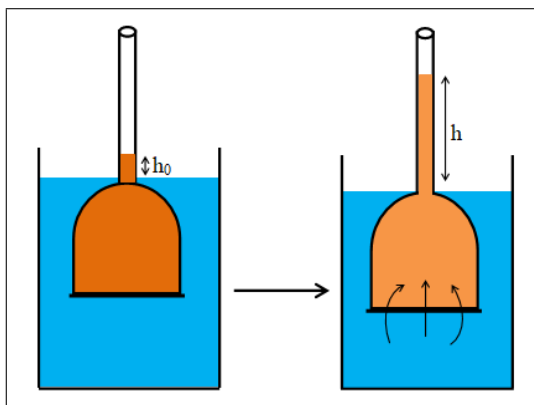


Figure 4.5: Dutochet osmometer.

After some time, a rise in the glucose solution level is observed in the thin tube of the funnel up to a certain height (h).

The colored glucose solution is diluted. This indicates an entry of water from the crystallizing dish into the funnel through the semi-permeable membrane. This phenomenon is called osmosis.

Osmosis:

Osmosis is defined as the process by which solvent (water) molecules move from a **dilute** solution to a **concentrated** solution across a selectively permeable membrane.

4.4.2 Osmotic pressure

Consider two compartments separated by a **selective** and **semi-permeable membrane** (Figure 4.6):

Compartment 1: contains **pure water**.

Compartment 2: contains an aqueous solution of a substance (**solute**).

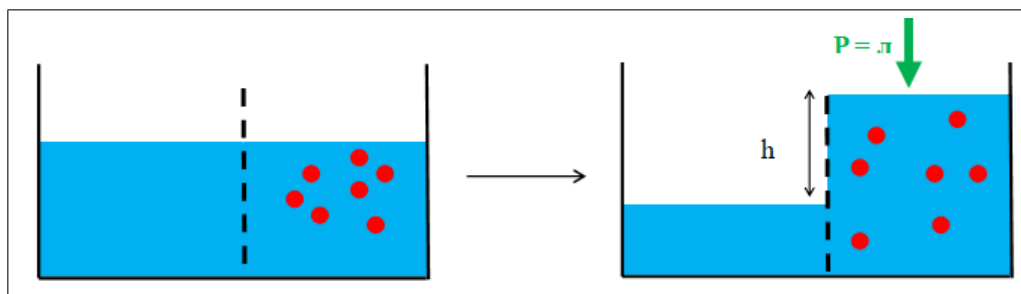


Figure 4.6: Osmosis and osmotic pressure.

* After some time, a rise in the water level is observed in the compartment 2 up to a certain height (h).

* The rise of the liquid in Compartment 2 (containing the solution) creates a hydrostatic overpressure (P) that opposes the pressure driving the water diffusion.

* The reason for the movement of water is due to osmotic pressure (π) because of the difference in concentrations.

* At equilibrium, the hydrostatic pressure (P) exactly equals the osmotic pressure(π).

$$P = \pi. \quad (4.15)$$

This passage of pure solvent through a semi-permeable membrane is called osmosis.

Osmotic pressure

The osmotic pressure of a solution is the pressure that must be exerted on the solution to **prevent** the flow of solvent.

4.4.3 Van't Hoff's Law

When two solutions of different osmolarities, w_{r_1} and w_{r_2} (where $w_{r_2} > w_{r_1}$), are separated by a **semi-permeable** membrane, the osmotic pressure of this system obeys the following relationship:

$$\Delta\pi = \pi_2 - \pi_1 = R.T (w_{r_2} - w_{r_1}), \quad (4.16)$$

where

$\Delta\pi$:Difference in osmotic pressure in

R :Ideal gas constant: $R = 0.08206 \text{ L.atm.mol}^{-1}.K^{-1}$.

T : Absolute temperature in Kelvin (K).

4.4.4 Tonicity in living systems

The tonicity of a living system describes how an extracellular solution affects the volume of a cell.

Tonicity dictates the net movement of water across the cell membrane via osmosis, which can cause a cell to shrink, swell, or remain stable.

There are three main types of tonicity (Figure 4.7):

Isotonic Solution: The extracellular fluid has the same concentration of non-penetrating solutes as the cell's cytoplasm. There is no net movement of water. Water moves into and out of the cell at the same rate, and the cell maintains its normal volume and shape.

Hypotonic solution: The extracellular fluid has a lower concentration of non-penetrating solutes than the cell's cytoplasm. Water moves into the cell by osmosis.

- * Animal cells: The cell swells (**lysis**).
- * Plant cells: The cell becomes turgid (**firm**).

Hypertonic solution: The extracellular fluid has a higher concentration of non-penetrating solutes than the cell's cytoplasm. Water moves out of the cell by osmosis.

- * Animal cells (**crenation**).
- * Plant cells (**plasmolysis**).

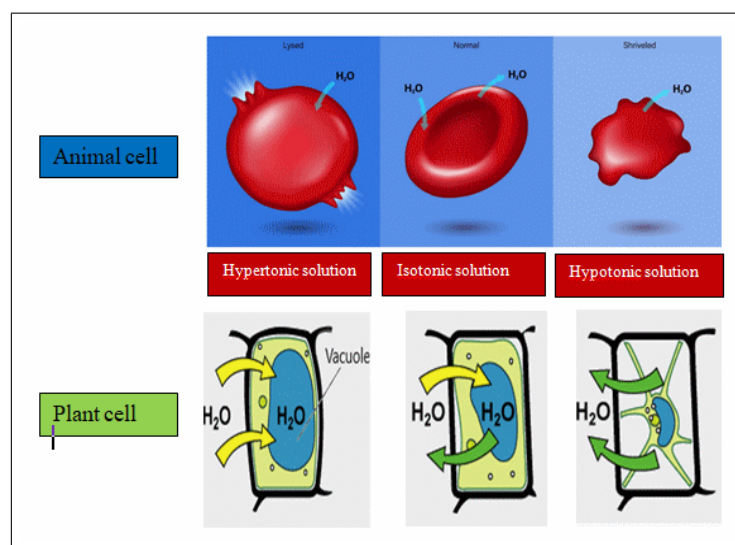


Figure 4.7: Action of isotonic, hypotonic and hypertonic solution on animal and plant cells.

4.5 Permeability

4.5.1 Definition

Selective permeability refers to the ability of the membrane (plasma) to allow certain substances to pass through while blocking other substances.

4.5.2 Permeability coefficient

The permeability coefficient (P) is an intrinsic property of the membrane-solute system and can be mathematically expressed as:

$$P = \frac{D}{e} \frac{S_p}{S}, \quad (4.17)$$

where

P : Permeability coefficient in $m.s^{-1}$.

D : Diffusion coefficient in $m^2.s^{-1}$

S_p : Useful surface area for transport in m^2

e : Membrane thickness in m .

S : Total membrane surface area in m^2 .

For

$$S = S_p, \quad (4.18)$$

then the permeability coefficient (P) writes

$$P = \frac{D}{e}. \quad (4.19)$$

4.6 Comparison between osmosis and diffusion

Phenomena	Diffusion	Osmosis
Type de membrane	Permeable membrane	Semi-permeable
Nature of migrating molecules	Solute	Solvent (water)
Direction of movement	Passage of solute from a higher concentrated solution to a lower concentrated solution	Passage of solvent from a solution of lower solute concentration to a solution of higher solute concentration
Governing physical law	Fick's law $\frac{dn}{dt} = -D.S.\frac{dC}{dx}$	Van't Hoff's law $\Delta\pi = R.T(w_{r_2} - w_{r_1})$
Cause of phenomenon	Difference in concentration	Difference in osmolarity
Final State	Equilibrium in concentrations	Equilibrium between osmotic and hydrostatic pressure

4.7 Exercises

Exercise 1

A porous membrane separates two compartments containing sucrose at concentrations of 0.5mol.L^{-1} and 0.2mol.L^{-1} . These concentrations are maintained constant during the diffusion of sucrose molecules across the membrane. A steady (stationary) state is assumed.

- 1/ Why does the phenomenon of diffusion occur?
- 2/ Which molecules diffuse and in which direction? Justify.
- 1/ Find the diffusion coefficient of sucrose D .
- 2/ What is the value of the sucrose flux?
- 3/ Calculate the diffusion coefficient of sucrose D .

Given:

Molar flow rate (debit) of sucrose: $J_n = 1.2 \times 10^{-2}\text{mol.s}^{-1}$.

Total surface area of the membrane: $S = 0.05\text{m}^2$.

Membrane thickness: $e = 10\text{mm}$.

Exercise 2

two compartments separated by a perfect semipermeable membrane contain:

Compartment 1: An aqueous solution of 2.9 g/L of NaCl .

Compartment 2: An aqueous solution of 9g/L of glucose.

Calculate the osmotic pressure Π at 27°C .

Given: $R = 8.32\text{J.osmol}^{-1}.\text{K}^{-1}$, $M_{\text{glucose}} = 180\text{g/mol}$, $M_{\text{NaCl}} = 58.5\text{g/mol}$.

- 1/Why does the phenomenon of osmosis occur?
- 2/ Which molecules transfer during this phenomenon and in which direction do they transfer? Justify.
- 3/Calculate the osmotic pressure π at 27°C .

4.8 Solutions

Exercise 1

- 1/ The phenomenon of diffusion occur because the membrane porous (permeable).
- 2/ Diffusing molecules ;Sucrose (Solute), direction: compartments containing glucose with concentration 0.5mol/L to compartments containing glucose with concentration 0.2mol/L (com-

partments containing solute at **higher** concentrations to compartments containing **lower** concentrations).

3/ Diffusion coefficient of sucrose D

Using Fick's law, we find

$$D = -\frac{e \cdot j_n}{S \cdot \Delta c} = -\frac{10 \times 10^{-3} (m) \times 1.2 \times 10^{-2} (mol \cdot s^{-1})}{0.05 (m^2) (0.2 - 0.5) 10^3 (mol \cdot m^{-3})} = 8 \times 10^{-6} m^2 \cdot s^{-1}. \quad (4.20)$$

Exercise 2

1/ The phenomenon of osmosis occur because the membrane is semipermeable.

2/ Diffusing molecules ;Water (Solvent), direction: Compartments containing **glucose** to compartments containing $NaCl$ (Compartments containing solute at **lower** concentrations to compartments containing **higher** concentrations). ($w_{rNaCl} > w_{rglucose}$)

Calculating the osmolarity :

* Solution of $NaCl$ (2.9g/L):

$$w_{rNaCl} = [1 + \alpha (\beta - 1)] m_r = [1 + \alpha (\beta - 1)] \frac{C_p}{M}, \quad (4.21)$$

$$= [1 + 1 (2 - 1)] \frac{2.9}{58.5g/mol} = 0.0992 osmol/L. \quad (4.22)$$

* Solution of glucose (9g/L):

$$w_{rglucose} = [1 + \alpha (\beta - 1)] m_r = [1 + \alpha (\beta - 1)] \frac{C_p}{M},$$

$$= [1 + 0 (1 - 1)] \frac{9}{180g/mol} = 0.05 osmol/L.$$

3/ Calculate the osmotic pressure π at $27^\circ C$.

$$\pi = RT (w_{rNaCl} - w_{rglucose}), \quad (4.23)$$

$$= 8.32 (J \cdot osmol^{-1}) \times (27 + 273) (K) [0.0992 - 0.05] \times 10^3 osmol/m^3, \quad (4.24)$$

$$= 122.9 kPa. \quad (4.25)$$

Chapter 5

Viscosity

5.1 Introduction

Upon macroscopic observation when comparing the flow of certain liquids, we find a distinct difference in their flow [23, 24, 25, 33]. For example, water flows quickly and turbulently, whereas honey flows slowly but smoothly (laminary). What is the reason for this difference, and how can it be explained ? This question was answered by some physicists in what is known as viscosity. So, what is the coefficient of viscosity and how can it be measured ? We will answer this in this chapter, in addition to other questions related to this type of study, especially in branches of biology (See Figure: 5.1).

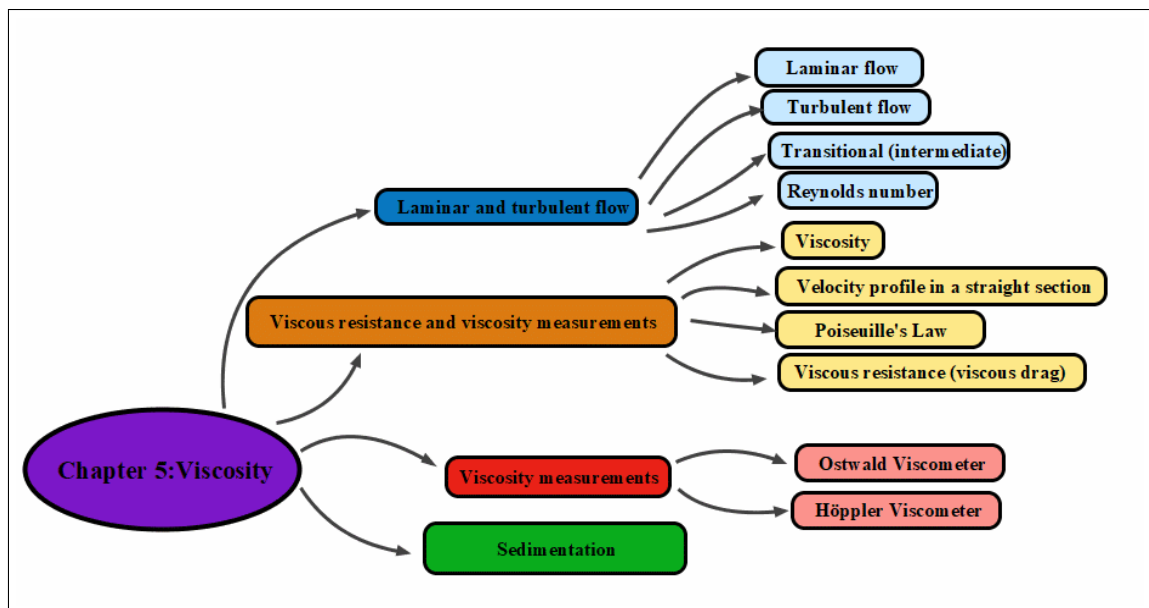


Figure: 5.1: Chapter 5 concept map.

5.2 Laminar and turbulent flow

In 1883, Osborne **Reynolds** studied the flow of fluids through a cylindrical pipe, concluding that there are three main types of fluid flow: **laminar**, **transitional**, and **turbulent**.

5.2.1 Laminar flow (Figure 5.2)

- * Characterized by its order and regularity.
 - * Particles follow uniform and predictable paths.
 - * Does not generate turbulence or mixing of fluids.
 - * Occurs at low speed.

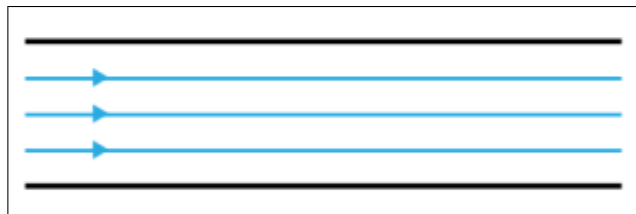


Figure 5.2: Laminar flow.

5.2.2 Turbulent flow (Figure 5.3)

- * Chaotic and irregular.
 - * Particles move in a random and unpredictable manner.
 - * Does generate turbulence or mixing of fluids.
 - * Occurs at high speed.

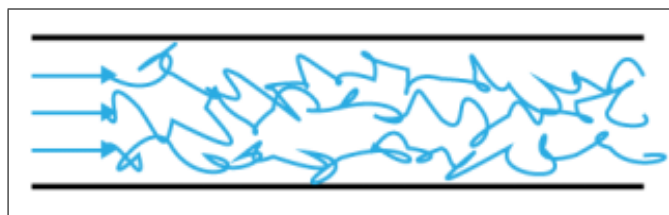


Figure 5.3: Turbulent flow.

5.2.3 Transitional (intermediate) (Figure 5.4)

It is a transition between the laminar and turbulent regimes.

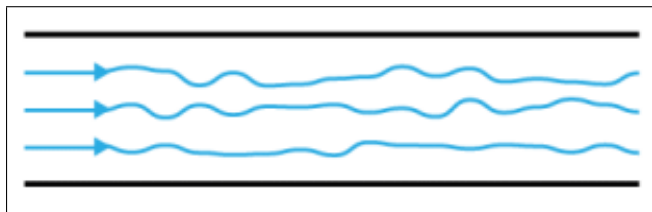


Figure 5.4: Transitional flow.

5.2.4 Reynolds number

These flow types are significantly influenced by several factors, primarily:

- The properties of the fluid (e.g., **density** and **viscosity**).
- The fluid's **velocity**.

This led him to establish a criterion known as the **Reynolds** number (R_e), which is defined by the following formula:

$$R_e = \frac{\rho v D}{\eta}, \quad (5.1)$$

where

ρ : Mass density of fluid.

v : Average velocity.

D : Pipe diameter.

η : Dynamic viscosity.

with

$$R_e < 2000, \quad \rightarrow \quad \textit{Laminar flow}, \quad (5.2)$$

$$2000 < R_e < 3000, \quad \rightarrow \quad \textit{Turbulent flow}, \quad (5.3)$$

$$R_e > 3000. \quad \rightarrow \quad \textit{Transitional flow}. \quad (5.4)$$

Unit: R_e without unit (number).

5.3 Viscous resistance and viscosity measurements

5.3.1 Viscosity

Dynamic viscosity, viscous friction force

We consider two adjacent fluid layers separated by a distance of Δz (Figure 5.5)

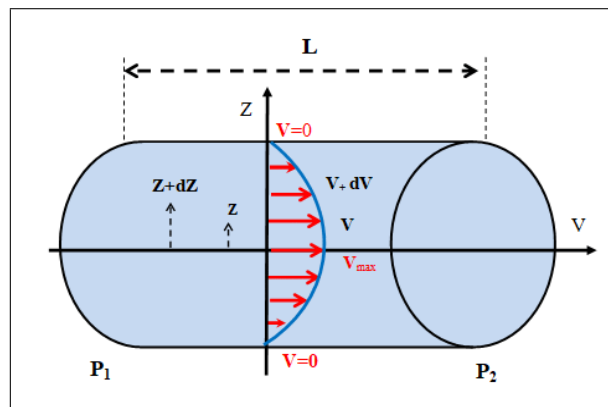


Figure 5.5: Velocity variation during flow.

* The **friction force** F exerted at the surface separating these two layers opposes the **sliding** of one layer over the other.

* The **friction force** F is **proportional** to the difference in *velocity* of the layers (Δv) to their *surface area* S and **inversely proportional** to Δz , then

$$F = \eta S \frac{dv}{dz}, \quad (5.5)$$

where

η ; Dynamic viscosity of the fluid.

Unit of the dynamic viscosity of the fluid;

- In the *International System (SI)*: **Pascal-second** ($Pa.s$) or **Poiseuille** (Pl):

$$1pa.s = 1Pl = 1Kg m^{-1} s^{-1}. \quad (5.6)$$

- In the *CGS System* (*centimeter-gram-second*): **Poise** (Po):

$$1Pl = 10Po. \quad (5.7)$$

Kinematic viscosity

Kinematic viscosity (ν) is the ratio of dynamic viscosity (η) and mass density(ρ) appears

$$\nu = \frac{\eta}{\rho}. \quad (5.8)$$

Unit of the kinematic viscosity (ν)

- In the *International System (SI)*: m^2/s .
- In the *CGS System* : Stokes (St);

$$1m^2/s = 10^4 St. \quad (5.9)$$

5.3.2 Velocity profile in a straight section

We consider the cylindrical fluid **portion**, with radius r and length that of the pipe L , centered on the axis (Figure 5.6).

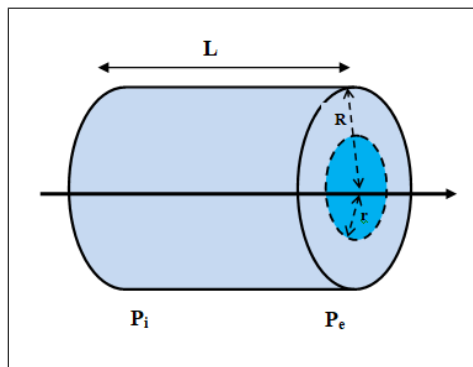


Figure 5.6: Cylindrical fluid portion.

The **velocity profile** $v(r)$ is given by

$$v(r) = \frac{P_e - P_s}{4\eta L} (R^2 - r^2), \quad (5.10)$$

Notes:

For

1/ $r = R$ (The fluid adheres to the wall);

$$v(R) = 0 \quad (5.11)$$

2/ $r = 0$ (The velocity is maximal at the center of the pipe)

$$v(r) = \frac{P_e - P_s}{4\eta L} R^2, \quad (5.12)$$

5.3.3 Poiseuille's law

A fluid with dynamic viscosity η and density ρ flows steadily and incompressibly through a cylindrical pipe with axis Oz , length L , and radius R . Gravity is neglected throughout the volume of the tube.

The pressure difference $\Delta P = P_e - P_s$ between the pressures at the ends of the pipe are P_e upstream ($z = 0$) and P_s downstream ($z = L$) is proportional to the volumetric flow rate Q :

$$Q = \frac{\Delta V}{\Delta t} = \frac{\pi \Delta p R^4}{8\eta L}. \quad (5.13)$$

Which is the **Poiseuille's** law.

5.3.4 Viscous resistance (viscous drag)

By **analogy** with the flow of **electric current** in a conductor, which exhibits a **resistance** according to **Ohm's law**

$$U = R_e I, \quad (5.14)$$

where

U : voltage in V .

I : current in A .

R_e : resistance in Ω .

The flow of a fluid in a pipe also exhibits a resistance. In this analogy, the fluid flow rate (or volume flux) corresponds to the electric current intensity.

To find the fluid resistance, we use the Poiseuille's Law to write

$$\Delta p = \frac{8\eta L}{\pi R^4} Q. \quad (5.15)$$

By comparing the two equations, we find the resistance

$$R_f = \frac{8\eta L}{\pi R^4}. \quad (5.16)$$

5.4 Viscosity measurements

The viscosity coefficient is measured by several methods, including:

- * **Ostwald** Viscometer (Capillary Method): Using **Poiseuille's** law.
- * **Höpler** Viscometer (Falling-Ball Method): Using **Stokes'** law.

5.4.1 Ostwald Viscometer

To measure the viscosity coefficient, we use the setup shown in (Figure 5.7), which consists of:

- A capillary tube,
- A bulb A bearing two marks M_1 and M_2 ,
- A U-shaped reservoir containing the liquid being studied.

The standard procedure for determining the coefficient of viscosity (η) using a **capillary viscometer** (based on **Poiseuille's** Law) involves the following steps:

- * The liquid is introduced into the capillary viscometer and drawn (aspirated) above the upper mark (M_1).

- * The sample is then allowed to flow by gravity through the capillary tube.
- * The flow time (Δt) required for the liquid's meniscus to pass from the upper mark (M_1) to the lower mark (M_2) is measured.
- * This measured flow time (Δt) is directly **proportional** to the liquid's **viscosity** coefficient (η) and inversely proportional to the pressure driving the flow.

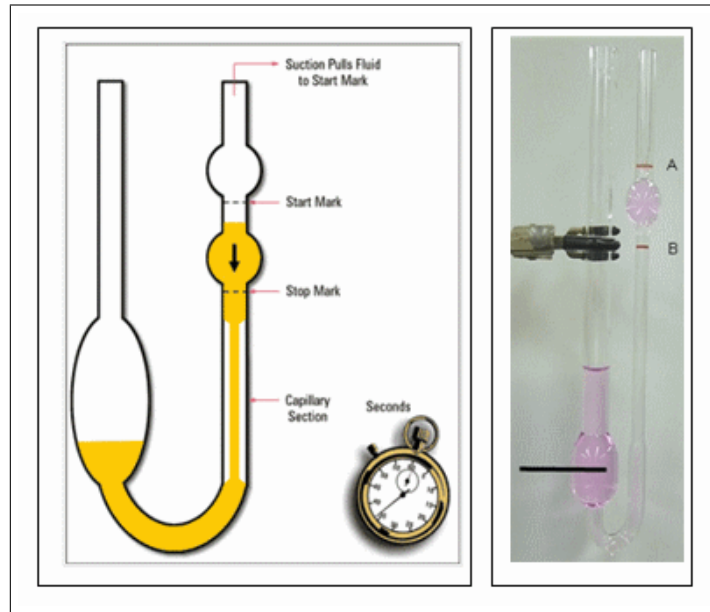


Figure 5.7: Ostwald viscometer.

The relationship is governed by **Poiseuille's** law for laminar flow in a tube

$$Q = \frac{\Delta V}{\Delta t} = \frac{\pi \Delta p R^4}{8 \eta L}, \quad (5.17)$$

where

Q : Flow rate,

R : Tube's radius,

L : Tube's length,

Δp : Pressure difference:

$$\Delta p = \rho g h, \quad (5.18)$$

ΔV : Volume difference.

Using a reference solution with a known viscosity coefficient η_0 , after replacing (5.18) in the Poiseuille's law (5.17), flow rate Q_0 write

$$Q_0 = \frac{V}{t_0} = \frac{\pi \rho_0 g h R^4}{8 \eta_0 L}, \quad (5.19)$$

For another solution (x), the flow rate Q_x of the same volume V reads;

$$Q_x = \frac{V}{t_x} = \frac{\pi \rho_x g h R^4}{8 \eta_x L}. \quad (5.20)$$

Dividing (5.19) by (5.20), then we have:

$$\frac{t_x}{t_0} = \frac{\eta_x \rho_0}{\eta_0 \rho_x}. \quad (5.21)$$

5.4.2 H  ppler viscometer

* An object (a sphere of radius r and known density ρ_s) is dropped into a stationary fluid of density ρ_f (Figure 5.8).

* The sphere undergoes an initial acceleration phase before achieving a **terminal velocity** (v_t) when the **gravitational**, buoyant, and **viscous drag forces** are in **equilibrium**.

* The viscosity (η) is then calculated using the terminal velocity value, often precisely measured by advanced methods

* We measure the time (t) it takes for the ball (sphere) to travel a certain distance. The

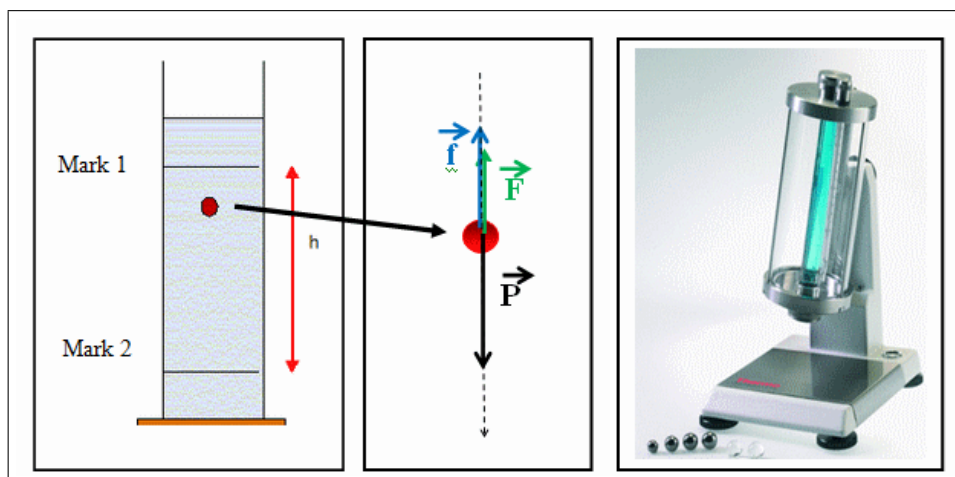


Figure 5.1: Figure 5.8: H  ppler viscometer.

forces applied to the ball are:

P : weigh;

$$P = mg = \rho_s V_s g = \frac{4}{3} \pi r^3 \rho_s g, \quad (5.22)$$

with

$$V_s = \frac{4}{3} \pi r^3, \quad (5.23)$$

and

$$m = \rho_s V_s. \quad (5.24)$$

F : **Archimedes'** thrust;

$$F = \rho_l V_s g = \frac{4}{3} \pi r^3 \rho_l g, \quad (5.25)$$

f : **Stokes'** force;

$$f = k \times v = 6\pi\eta r v. \quad (5.26)$$

where

ρ_s : Density of the ball.

ρ_l : Density of the liquid.

η : Dynamic viscosity.

We apply **Newton's Second Law** at equilibrium to the center of mass of the sphere, we obtain

$$\sum \vec{F} = \vec{P} + \vec{F} + \vec{f} = \vec{0}, \quad (5.27)$$

By projecting onto the vertical axis directed downwards (in the direction of motion):

$$P - F - f = 0, \quad (5.28)$$

By substituting the expressions for the forces:

$$\frac{4}{3} \pi r^3 \rho_s g - \frac{4}{3} \pi r^3 \rho_l g - 6\pi\eta r v = 0, \quad (5.29)$$

then, the dynamic viscosity write

$$\eta = \frac{2}{9} g r^2 \frac{(\rho_s - \rho_l)}{v} = \frac{2}{9} g r^2 \frac{(\rho_s - \rho_l) t}{d}, \quad (5.30)$$

where

$$v = \frac{d}{t} = cte. \quad (5.31)$$

5.5 Sedimentation

To measure the sedimentation rate, we consider the following:

* Blood can be considered as a suspension of **red blood cells** (hematite) in plasma which is subject to the gravitational force g .

* The red blood cells will be considered spherical.

* For simplicity, we neglect the centrifugal acceleration.

Taking:

$r = 2.7\mu m$: Average radius of the red blood cells.

$\eta = 1.46 \times 10^{-3} Pa.s$: Viscosity of blood.

$\rho_0 = 1100 kg/m^3$: The density of the red blood cells.

$\rho_1 = 1020 kg/m^3$: The density of the plasma.

$g = 9.8 m/s^2$.

Using **Stokes' Law**, the velocity (v) of the red blood cells can be found based on the formula

$$v = \frac{2gr^2(\rho_0 - \rho_1)}{9\eta} = \frac{210 \times (2.7 \times 10^{-6})^2 (1100 - 1020)}{9 \times 1.46 \times 10^{-3}} = 0.87 m/s. \quad (5.32)$$

5.6 Exercises

Exercise 1

A pipe, $0.5m$ long and $0.01m$ in diameter, is carrying water with a dynamic viscosity η equal to $10^{-3} Pl$. The average velocity of the water in this pipe is $v_m = 0.2m/s$.

1/ What is the flow regime in this pipe?

2/ Calculate the pressure gradient required to sustain this flow.

3/ A cuff surrounding the pipe reduces its diameter by $3/4$ over a length of $2cm$. Assuming that the flow rate is conserved.

a/ What is the average velocity in this constriction?

b/ What is the flow regime in the constricted section?

Exercise 2

Metallic sphere with a density of $7.8g.cm^{-3}$ and a diameter of $4mm$ falls from a height of $1m$ through an oil with a density of 1.12 under the effect of gravity over a duration of $55s$.

1/ Calculate the dynamic viscosity of the oil.

2/ Deduce the value of the kinematic viscosity.

Exercise 3

A mercury (density; $d = 13.6$, viscosity; $\eta = 0.0015 Pa.s$) flows from left to right in a horizontal pipe without turbulence (see the Figure 5.9) with a flow rate of $3cm^3s^{-1}$. At $50cm$ intervals along the horizontal pipe are four vertical tubes (A, B, C and D) open at the top. In tube A, the mercury rises to $60cm$; in tube D, located $1.5m$ further, the mercury rises to $40cm$.

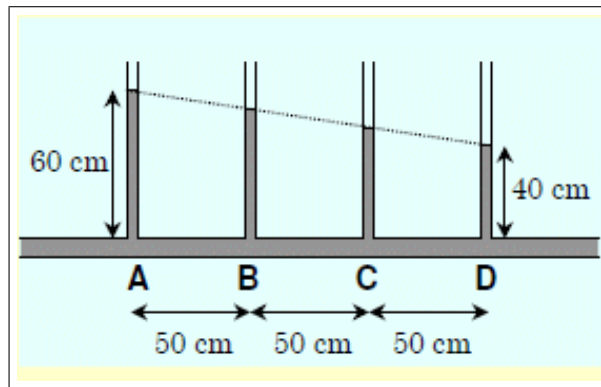


Figure 5.9: Flow of liquids.

- 1/ Determine the hydraulic resistance of the pipe section located between tube *A* and tube *D*.
- 2/ Determine the radius of the horizontal pipe.
- 3/ Determine the magnitude of the velocity of the mercury in the pip.

5.7 Solutions

Exercise 1

- 1/ Determine the flow regime (Initial);

The flow regime is determined by the **Reynolds** number (R_{e1})

$$R_{e1} = \frac{\rho v_1 d_1}{\eta}, \quad (5.33)$$

$$= \frac{1000 (kg/m^3) \times 0.2 (m/s) \times 0.01 (m)}{10^{-3} (Pa \cdot s)}, \quad (5.34)$$

$$= 2000, \quad (5.35)$$

here

$$R_{e1} \leq 2000. \quad (5.36)$$

then, the flow in the initial pipe is considered to be laminar flow.

- 2/ The pressure gradient required to sustain this flow

$$D_1 = \frac{\pi (\Delta P) R_1^4}{8\eta l} = S v_1, \quad (5.37)$$

then

$$\frac{\Delta P}{l} = \frac{8\eta S_1 v_1}{\pi R^4} = \frac{8\eta v_1}{R_1^2}, \quad (5.38)$$

$$= \frac{8 \times 10^{-3} (Pa \cdot s) \times 0.2 (m/s)}{(0.005)^2 (m^2)}, \quad (5.39)$$

$$= 64 Pa \cdot m^{-1}, \quad (5.40)$$

where

$$S_1 = \pi R_1^2. \quad (5.41)$$

3/

a/ Calculate the average velocity in the constriction (v_2);

* Continuity equation

$$S_1 v_1 = S_2 v_2, \quad (5.42)$$

then

$$v_2 = \frac{S_1 v_1}{S_2} = \left(\frac{R_1}{R_2} \right)^2 v_1, \quad (5.43)$$

$$= \left(\frac{0.005}{\frac{0.005}{4}} \right)^2 0.2 (m/s), \quad (5.44)$$

$$= 3.2 m/s. \quad (5.45)$$

where the diameter is reduced by 3/4, which means the new diameter d_2 is 1/4 of the original diameter d_1 or

$$R_2 = \frac{R_1}{4}. \quad (5.46)$$

b/ the flow regime in the constricted section;

The flow regime is determined by the **Reynolds** number (R_{e2});

$$R_{e2} = \frac{\rho v_2 d_2}{\eta}, \quad (5.47)$$

$$= \frac{1000 (kg/m^3) \times 3.2 (m/s) \times 0.0025 (m)}{10^{-3} (Pa \cdot s)}, \quad (5.48)$$

$$= 8000, \quad (5.49)$$

here

$$R_{e1} \geq 3000. \quad (5.50)$$

then, the flow in the constricted section is turbulent flow.

Exercise 2

The dynamic viscosity of the oil(η):

Using the formula derived from Stokes Law for terminal velocity

$$v = \frac{2R^2g(\rho_s - \rho_f)}{9\eta} = \frac{h}{t}, \quad (5.51)$$

then

$$\eta = \frac{2R^2g(\rho_s - \rho_f)}{9\frac{h}{t}}, \quad (5.52)$$

$$= \frac{2 \times (4 \times 10^{-6}m^2) \times (9.81m/s^2) \times (6680kg/m^3)}{9 \times 0.018(m/s)}, \quad (5.53)$$

$$= 3.2076Pa.s \quad (5.54)$$

2/ Kinematic viscosity(ν)

$$\nu = \frac{\eta}{\rho_f}, \quad (5.55)$$

$$= \frac{3.2076(kg/m.s)}{1120(kg/m^3)}, \quad (5.56)$$

$$\approx 0.002864m^2/s. \quad (5.57)$$

Exercise 3

The hydraulic resistance (R) is defined by the relationship between the pressure drop (ΔP) across the section and the volumetric flow rate (D):

$$\Delta P = R \times D, \quad (5.58)$$

where

$$\Delta P = P_A - P_D = \rho g (h_A - h_B), \quad (5.59)$$

then

$$R = \frac{\rho g (h_A - h_B)}{D}, \quad (5.60)$$

$$= \frac{13.6 \times 10^3 (Kgm^{-3}) \times 9.8 (ms^{-2}) (60 - 40) \times 10^{-2} (m)}{3 \times 10^{-6} m^3 s^{-1}}, \quad (5.61)$$

$$\approx 8.90 \times 10^9 Pa.s/m^3, \quad (5.62)$$

where

$$\rho = d \times \rho_{water} = 13.6 \times 10^3 Kgm^{-3}, \quad (5.63)$$

$$D = 3cm^3s^{-1} = 3 \times 10^{-6}m^3s^{-1}. \quad (5.64)$$

2/ The radius of the horizontal pipe.

From Poiseuille's law, the radius write

$$R = \left(\frac{8\eta LD}{\pi \Delta P} \right)^{\frac{1}{4}}, \quad (5.65)$$

$$= \left[\frac{8 \times 0.0015 (Pa.s) \times 1.5(m) \times 3 \times 10^{-6} (m^3s^{-1})}{3.1416 \times 2.666 \times 10^{-6}(m)} \right]^{\frac{1}{4}}, \quad (5.66)$$

$$= 0.008961m = 8.96mm. \quad (5.67)$$

where

$$\Delta P = P_A - P_D = \rho g (h_A - h_B), \quad (5.68)$$

$$= 13.6 \times 10^3 (Kgm^{-3}) \times 9.8 (ms^{-2}) (60 - 40) \times 10^{-2} (m), \quad (5.69)$$

$$= 2.666 \times 10^{-6} Pa. \quad (5.70)$$

3/ The magnitude of the velocity of the mercury in the pip

$$v = \frac{D}{S} = \frac{3 \times 10^{-6} (m^3s^{-1})}{2.523 \times 10^{-4} (m^2)} = 0.01186m/s = 1.19cm/s. \quad (5.71)$$

where

$$S = \pi R^2 = 3.1416 \times (0.008961m)^2 = 2.523 \times 10^{-4}m^2. \quad (5.72)$$

Chapter 6

Sound and ultrasound waves

6.1 Introduction

A healthy human has inherently used sound for communication (speech) and reception (hearing) since birth. Yet, humanity's engagement with sound extends further, encompassing the creation of music and, significantly, the discovery and application of ultrasound outside the audible range. This advanced application has revolutionized fields like Medicine, primarily through diagnostic techniques such as Echography. Given this crucial importance, this chapter will delve into the fundamental concepts of sound, covering its nature, its propagation as a mechanical wave (which may be simple, complex, periodic, or aperiodic), and the physical laws governing this phenomenon. Our approach, specifically tailored for Life and Natural Sciences students, prioritizes clarity and simplification without sacrificing scientific accuracy (See Figure: 6.1) .

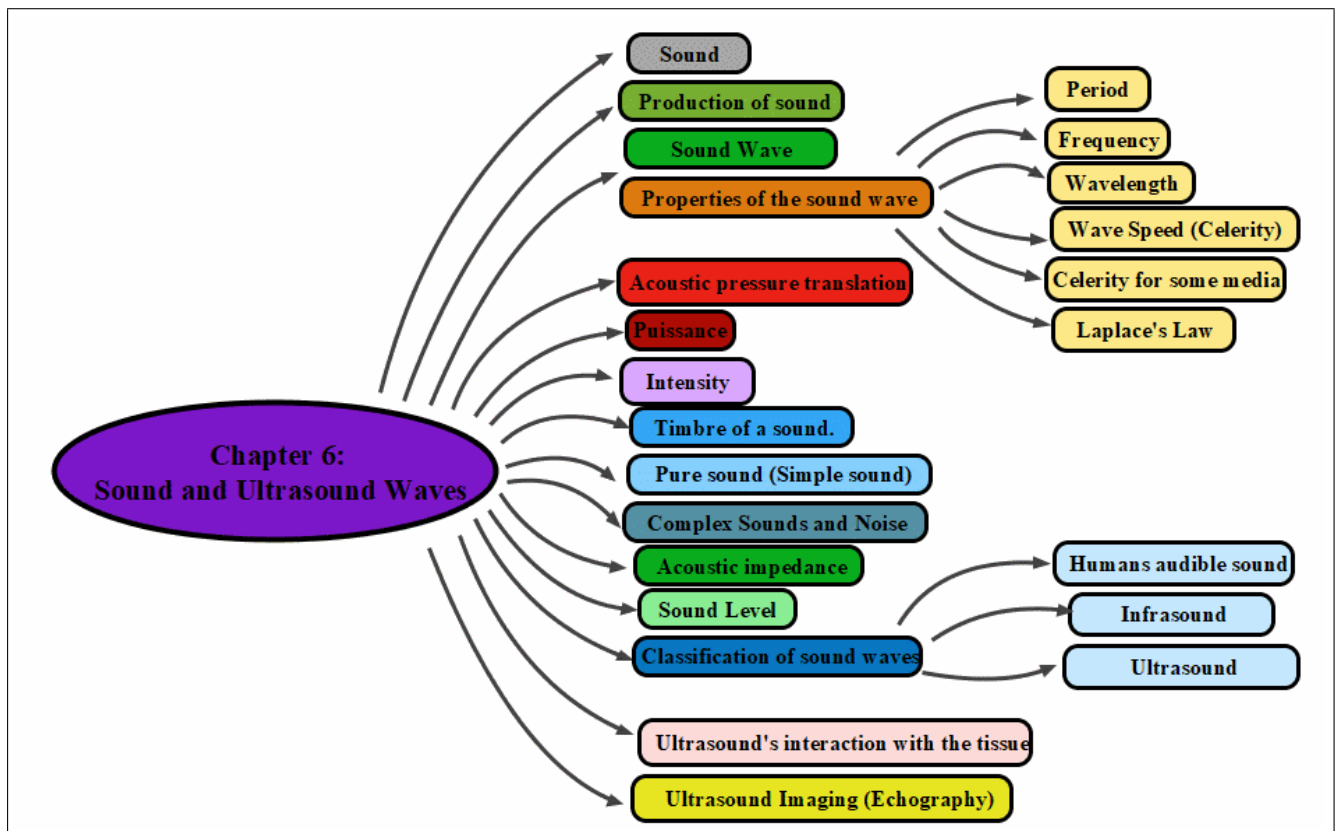


Figure: 6.1: Chapter 6 concept map.

6.2 Sound

Sound is a mechanical wave produced by any solid, liquid, or gaseous body that vibrates. It propagates through an elastic medium.

6.3 Production of sound

Sound is produced by vibrating bodies. The vibrations then cause a disturbance in the pressure of the medium (Figure 6.2).

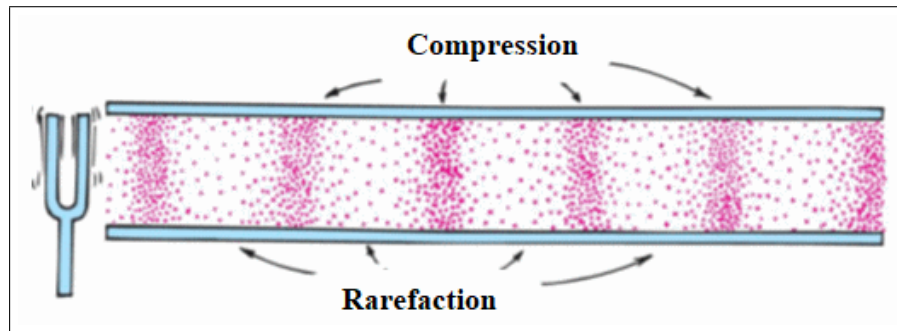


Figure 6.2: Sound propagation (Compression and Rarefaction).

6.4 Sound wave

A sound wave or acoustic wave is a **longitudinal wave** that propagates sequentially through a material medium by the compression and decompression of its molecules (Figure 6.3).

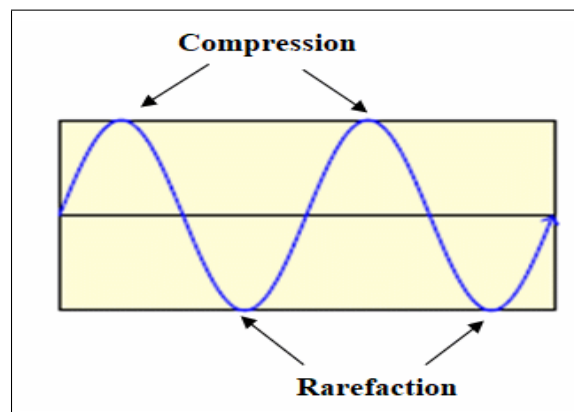


Figure 6.3: Sound wave (acoustic wave).

Notes:

- 1/ Longitudinal waves are waves in which the direction of vibration is the same as their direction of propagation .
- 2/ Accompanied by variation in medium pressure.
- 3/ No transport of matter .
- 4/ Transport of energy.
- 5/ Three elements are necessary for sound to exist:
 - a/ A **Source**: Producing a mechanical vibration.
 - b/ A **Carrying medium**: Transmitting this vibration.
 - c/ A **Receiver**: The ear, which receives this vibration.

6/ Elastic medium: which deforms as a mechanical wave passes through it and returns to its initial shape when the wave disappears.

6.5 Properties of the sound wave

The sound waves have several characteristics and features which we summarize as follows:

6.5.1 Period

The Period (T) is the time interval that elapses between two consecutive, identical states of vibration (Figure 6.4).

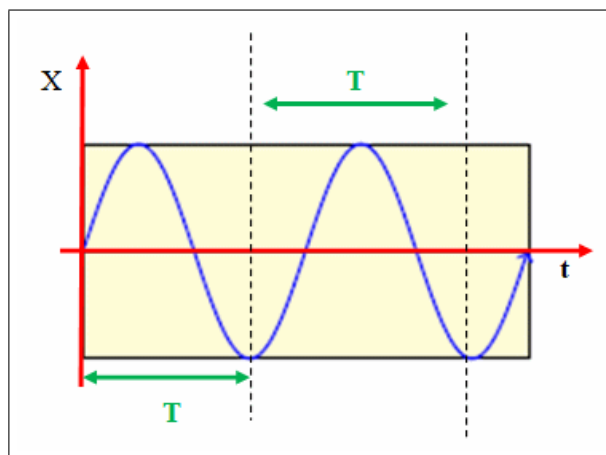


Figure 6.4: Period (T).

6.5.2 Frequency

Frequency (f) is the number of repetitions of the same state of vibration (the number of periods T) that occur per unit of time.

$$f = \frac{1}{T}, \quad (6.1)$$

Its unit is the Hertz (Hz), which is equivalent to one cycle per second (s^{-1}).

Note

The **pitch** (tonal height) of a sound is the quality that makes it perceived as **low** or **high**. It is equal to its fundamental *frequency*.

- **Low pitch:** Corresponds to low frequencies.
- **High pitch:** Corresponds to high frequencies.

6.5.3 Wavelength

The wavelength (λ) is the smallest distance separating two points that are in the same state of vibration. Alternatively, it is the distance traveled by the wave during one period (T) (Figure 6.5).

Its unit is the meter (m).

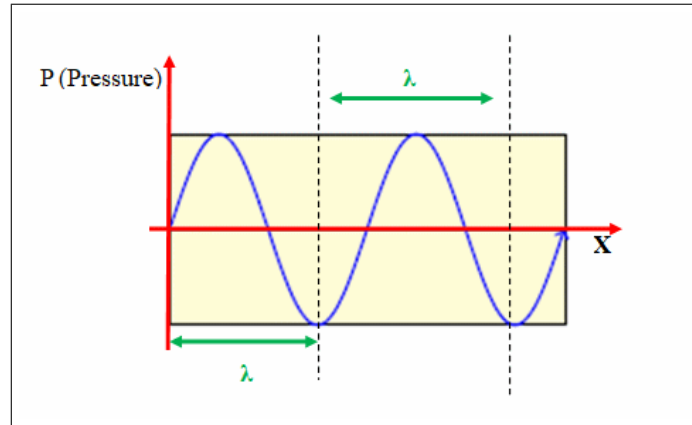


Figure 6.5: Wavelength (λ).

6.5.4 Wave speed (Celerity)

The celerity (c) of a wave is its speed of propagation. It depends on the medium through which the wave travels.

$$c = \frac{\lambda}{T}, \quad (6.2)$$

where

c : in m/s .

λ : in m .

T : in s .

The speed of sound (c) is expressed according to the medium in which it propagates:

In solids

$$c = \sqrt{\frac{E}{\rho}}, \quad (6.3)$$

where

E : Young's modulus of the solid in N/m^2 or Pa .

ρ : Mass density of the medium in Kg/m^3 .

In liquids

$$c = \sqrt{\frac{k}{\rho}}, \quad (6.4)$$

where

k : Isothermal bulk modulus of the liquid in N/m^2 or Pa .

ρ : Mass density of the medium in Kg/m^3 .

In gases

$$c = \sqrt{\frac{YP}{\rho}}, \quad (6.5)$$

where

Y : Adiabatic compression coefficient (Dimensionless).

P : absolute pressure of the gas in Pa .

ρ : Mass density of the medium in Kg/m^3 .

6.5.5 Celerity for some media

Medium	Celerity m/s
Air	330
Water	1530
Fat	1450
Muscle	1600
Liver	1570
Blood	1580
Bone	3000-4000

6.6 Acoustic pressure translation

The acoustic pressure corresponds to the variation in air pressure during the passage of a sound wave, which creates compressions and rarefactions (dilations) of the medium.

$$P_{acou}(t) = \Delta P = P(t) - P_{atm}, \quad (6.6)$$

where

$$P_{atm} = 1.013 \times 10^5 Pa \text{ (Pascal)}.$$

$P_{acou}(t)$: Acoustic pressures in Pascals (Pa) range between $20\mu Pa$ and $20Pa$.

Two notable values are distinguished:

P_c : Peak Pressure is the maximum acoustic pressure over the duration of the sample being studied.

P_{eff} : Effective Pressure (RMS Pressure) is the effective pressure, and it is calculated by the following formula;

$$P_{eff} = \frac{P_c}{\sqrt{2}}. \quad (6.7)$$

6.7 Power

Power (p) is a quantity of energy (E) emitted during a certain time (Δt). It is given by the relation

$$p = \frac{E}{\Delta t}. \quad (6.8)$$

6.8 Intensity

Sound Intensity(I)is the power (W) carried by sound waves per unit area (S) perpendicular to the direction of propagation. It is defined as

$$I = \frac{W}{S} = \frac{E}{S \cdot \Delta t}. \quad (6.9)$$

Note

* The **amplitude** is the peak pressure (Figure 6.6).

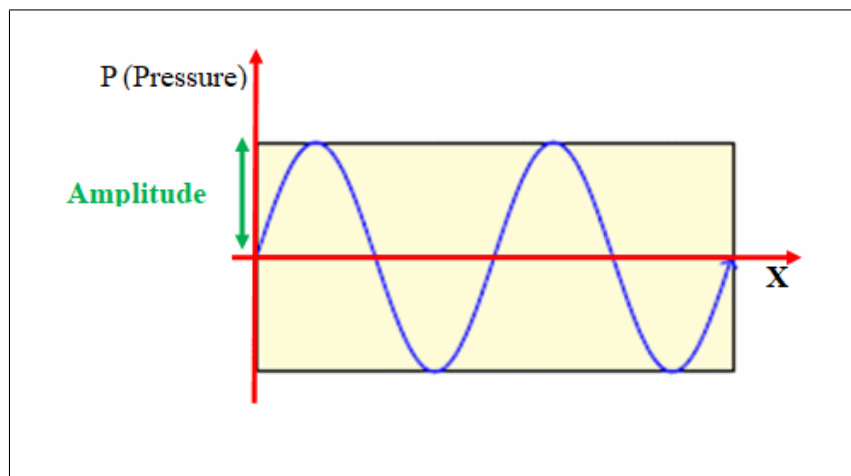


Figure 6.6: Amplitude.

* **Sound intensity** (or loudness) is the quality that distinguishes a **loud** sound from a **soft** sound. This quality is directly related to the amplitude (acoustic pressure) of the sound vibrations.

When the wave's **amplitude** is **large**, the **intensity** is **large**, and therefore, the sound is perceived as **louder** (**Figure: 6.7**).

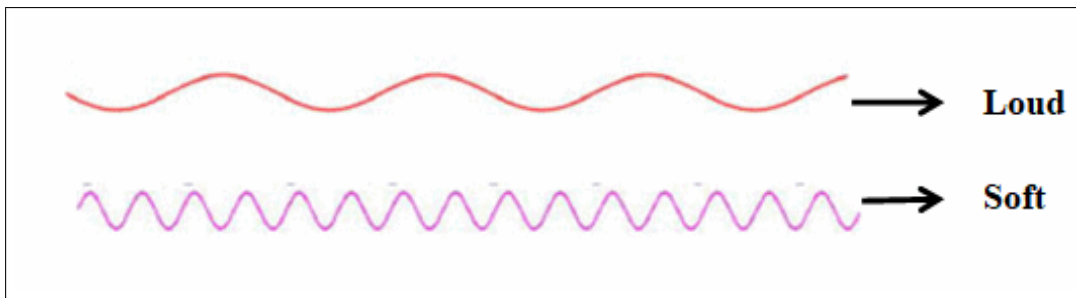


Figure 6.7: loud and soft sound.

6.9 Timbre of a sound.

Timbre, one of the qualities of sound, makes it possible to distinguish between sounds emitted by different instruments

6.10 Pure sound (Simple sound)

A pure tone or simple sound corresponds to a sinusoidal wave whose frequency and maximum amplitude are constant over time (Figure 6.8).

It is represented by a sinusoidal function

$$X(t) = A \sin \omega t, \quad (6.10)$$

where

A : Amplitude.

ω : Angular frequency in rad/s with

$$\omega = 2\pi f, \quad (6.11)$$

where

f : Frequency in Hertz (Hz).

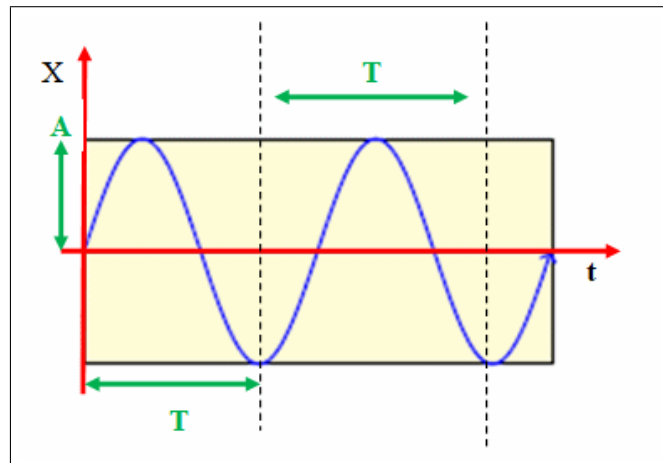


Figure 6.8: Pure sound wave (Sinusoidal wave).

6.11 Complex Sounds and Noise

Most sounds we perceive are not pure tones but are complex sounds. It is classified into two types:

*** Periodic Complex Sound:**

- Represented by a periodic, non-sinusoidal, and complicated waveform.
- A periodic complex sound is composed of several pure tones with different frequencies and amplitudes.

*** Non-Periodic complex sound (Noise)**

- A non-periodic complex sound or noise is a complex and random mixture of sounds of arbitrary frequencies.
- Noise is represented by a non-periodic, non-sinusoidal waveform (Figure 6.9).

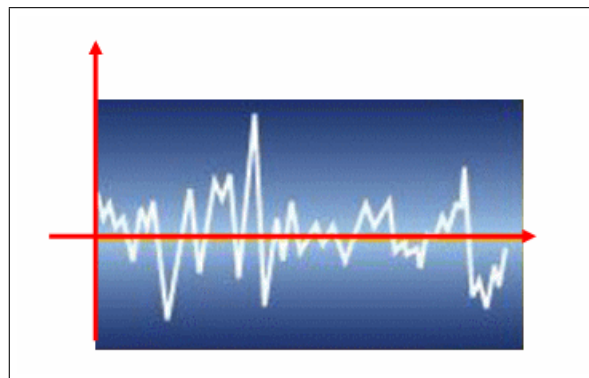


Figure 6.9: Noise (Complex sound).

6.12 Acoustic impedance

Acoustic Impedance (Z) characterizing the medium of propagation. It represents the resistance to wave propagation and is given by

$$Z = \rho.c = \frac{P}{v}, \quad (6.12)$$

where

Z : Acoustic impedance in $kg.m^{-2}.s^{-1}$ or *Rayl* ($Pa.sm^{-1}$)

c : Speed of sound in m/s .

ρ : Mass density in kg/m^3 .

P : Acoustic pressures in Pa .

v : Particle velocity.

6.12.1 Acoustic impedance for some media

Medium	Acoustic impedance Z ($10^6 Kg/m^2.s$)
Air	0.0004
Water	1,48
Fat	1,65
Brain	1,55
Muscle	1,65-1,74
Liver	1.65
Blood	1.66
Bone	4.11-8

6.13 Sound Level

The sound level, denoted (L), depends on the sound intensity, denoted (I), given by the following relation:

$$L = 10 \log \left(\frac{I}{I_0} \right), \quad (6.13)$$

where

L : The sound level is measured in acoustic **decibels** (dB) using a device called a sound level meter.

I : Sound intensity.

I_0 : Reference intensity corresponding to the threshold of human hearing, conventionally set at $I_0 = 10^{-12} \text{ W.m}^{-2}$.

6.14 Classification of sound waves

there are three classification of sound waves (Figure 6.10) :

6.14.1 Humans audible sound

* The frequency between 20Hz and 20kHz .

* It heard by **human** ear

6.14.2 Infrasound

* The frequency is **less** than 20Hz .

* It cannot be heard by human ear.

6.14.3 Ultrasound

* The frequency is higher than 20Khz .

* It cannot be heard by **human** ear.

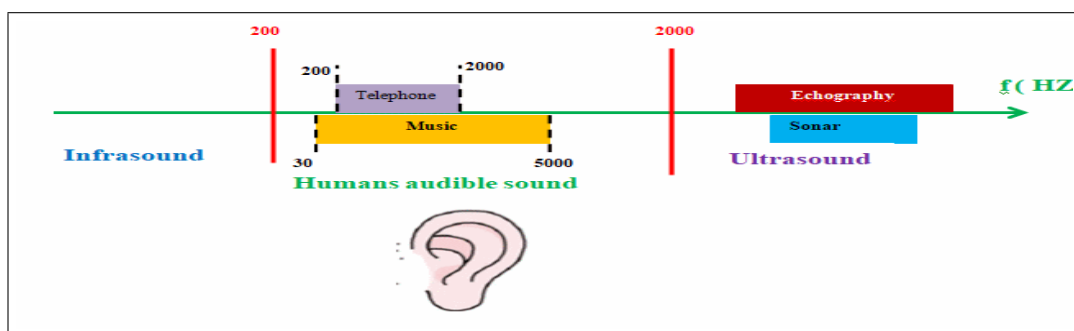


Figure 6.10: Classification of sound waves.

6.15 Ultrasound's interaction with the tissue

The main interaction of ultrasound waves in tissue

- 1/ Reflection:
- 2/ Refraction.
- 3/ Scattering.
- 4/ Absorption.

6.16 Ultrasound imaging (Echography)

* **Echography** (Figure 6.11) utilizes the fact that **ultrasounds** are reflected to a greater or lesser degree depending on the **nature** of the **media** encountered.

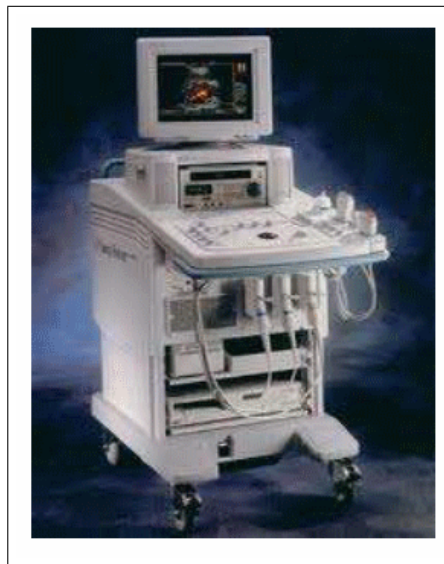


Figure 6.11: Echography.

* The ultrasound emitter-receiver is placed directly on the skin, and each time the **ultrasonic waves** encounter a different tissue texture, they are partially **reflected**.

* The echoes are then **converted** into electrical **energy** and displayed on a screen (Figure 6.12).

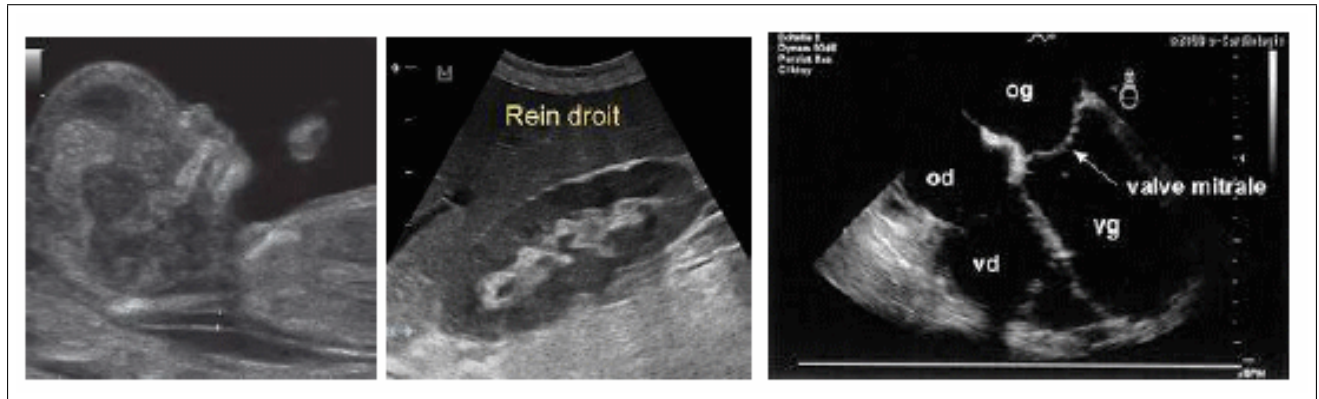


Figure 6.12: Echography Image's.

6.17 Exercises

Exercise 1

Answer with True or False, correcting the mistake if found;

- a/ The speed of sound in air is 300000km/s .
- b/ An acoustic wave with a frequency of 40kHz is an audible sound.
- c/ Sound carries energy.
- d/ Sound can propagate in a vacuum.
- e/ The human ear is capable of hearing sound with a frequency between 20Hz and 20000Hz .

Exercise 2

Consider three sound waves propagating in air at a speed $v_{\text{air}} = 340\text{m/s}$:

- a/ $f_1 = 15\text{Hz}$, b/ $f_2 = 1500\text{Hz}$. c/ $f_3 = 150\text{kHz}$.

- 1 / Calculate the associated wavelengths for each.
- 2/ During an echography (ultrasound), the wave with frequency $f_3 = 150\text{kHz}$ propagates in bone with a speed $v = 3000\text{m/s}$. Calculate the new associated wavelength for this wave.

Exercise 3

An ultrasound exam performed with a probe that emits ultrasonic pulses with a frequency f of 4MHz . The speed v of the waves in the tissues is $v_{\text{tissues}} = 1540\text{m/s}$.

- 1/ Calculate the associated period for this wave.
- 2/ Calculate the wavelength.

6.18 Solutions

Exercise 1

a/ **False:** Speed of sound in air ; $v_{air} = 340m/s$ at $20^\circ C$.

b/ **False:** This frequency ($40kHz$) is known as **ultrasound**.

c/ **True.**

d/ **False:** Sound is a mechanical wave requires a material medium (solid, liquid, or gas) .

e/ **True.**

Exercise 2

1/ Wavelength (λ) :

$$\lambda = \frac{v}{f}, \quad (6.14)$$

we find: a/ $\lambda_1 = 22.67m$, b/ $\lambda_2 = 0.2267m$. c/ $\lambda_3 = 0.002267m$.

2/ $\lambda_3 = 0.02m$

Exercise 3

1/ Period for the wave (T):

$$T = \frac{1}{f} = \frac{1}{4 \times 10^6 (Hz)} = 0.25 \times 10^{-6}s = 0.25\mu s. \quad (6.15)$$

2/ Wavelength (λ):

$$\lambda = \frac{v}{f} = \frac{1540 (m/s)}{4 \times 10^6 (Hz)} = 385 \times 10^{-6}m = 0.385mm, \quad (6.16)$$

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