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General Introduction

Biophysics is an interdisciplinary science that applies approaches and methods traditionally used in physics to study biological phenomena. Biophysics covers all scales of biological organization, from molecular to organismic and populations. Biophysical research shares significant overlap with biochemistry, molecular biology, physical chemistry, physiology, nanotechnology, bioengineering, computational biology, biomechanics, developmental biology and systems biology.

The term biophysics was originally introduced by Karl Pearson in 1892. Ambiguously, the term biophysics is also regularly used in academia to indicate the study of the physical quantities (e.g. electric current, temperature, stress, entropy) in biological systems, which is, by definition, performed by physiology. Nevertheless, other biological sciences also perform research on the biophysical properties of living organisms including molecular biology, cell biology, biophysics, and biochemistry.

Much effort in biophysics is directed to determining the structure and dynamics of specific biological molecules and of the larger architecture into which they assemble. Some of this effort involves inventing new methods and building new instruments for viewing these dynamic structures in action. In addition, biophysicists are increasingly concerned with the mechanical properties of biological systems, on length scales from nanometers to meters.

These lectures are divided into six chapters:

- **The first chapter** gives a reminder of the different state of matter, it focuses on clarifying the following topics: (1) Solids: different structures and classification, (2) Liquids: water structure, dissolution, (3) Gases: elements of kinetic theory, equation of state of ideal or real gases, changes of state, (4) Plasma and (5) Phase transitions.

- **The second chapter** is devoted to Generality on Aqueous Solution, where it focuses on clarifying the following topics: (1) Study of solutions: classification of solutions, (2) The concentrations and fractions: molarity, molality, weight concentration, osmolarity, equivalent concentration, mass and molar fractions, (3) Solubility and (4) Electrolyte solutions: electrical

conductivity, physical and chemical properties of electrolytes.

- **The third chapter** presents Phenomenon of interfaces, where it dealt with the following topics: (1) Surface tension: definition, measurements and biological applications, (2) Phenomenon of capillarity: definition, measurements and biological applications and (3) Adsorption.

- **The fourth chapter** provides Diffusion phenomenon, where the following items are detailed: (1) Diffusion, (2) Osmosis phenomenon and osmotic pressure: definition, measurements and biological applications and (3) Permeability: definition, measurements and biological applications.

- **The fifth chapter** is devoted to the Study of viscosity, it focuses on clarifying the following topics: (1) Laminar and turbulent flow, (2) Viscous resistance and viscosity measurements and (3) Sedimentation.

- **The sixth chapter** presents an overview about the Sound waves and Ultrasound, where it dealt with the following topics: (1) The sound waves and its properties: production, nature and classification, (2) Doppler effect: definition, measurements and biological applications and (3) Ultrasound: definition, measurements and biological applications.

Chapter 01

States of Matter (Reminder)

Chapter 01: States of Matter (reminder)

Plan

1. Introduction to Matter
2. Physical States of Matter
3. Changes of State
4. Gas Laws
5. Liquids and Solids
   - Viscosity, surface tension, and diffusion in liquids
   - Crystal structure and types of solids (molecular, ionic, metallic, covalent)
6. Plasma and Bose–Einstein Condensate

objective

1. Define matter and distinguish between its different physical states.
2. Describe the arrangement and motion of particles in solids, liquids, and gases.
3. Explain the role of intermolecular forces in determining the properties of substances.
4. Identify and explain the different changes of state and the energy involved.
5. Apply gas laws to solve simple numerical and conceptual problems.
6. Compare the properties of solids, liquids, and gases using the kinetic molecular theory.

Chapter 01: States of Matter (reminder)

1. Introduction

Matter is anything that has mass and occupies space. Depending on conditions of temperature and pressure, matter can exist in different states: solid, liquid, gas, and plasma (Petrucci et al., 2017).

2. Solid

2.1. Introduction

A solid is characterized by particles packed in fixed positions, vibrating around equilibrium. This explains why solids have definite shape and volume (Silberberg, 2015).

2.2. Classification of solids

- Crystalline solids: ordered, repeating structure (e.g., NaCl, diamond).
- Amorphous solids: random arrangement, no long-range order (e.g., glass) (Callister & Rethwisch, 2018).

2.3. Physical properties

- Definite shape and volume
- High density and incompressibility
- Rigidity
- Sharp melting point in crystalline solids, broad in amorphous solids .

3. Liquid

3.1. Introduction

In liquids, particles are close but not fixed, allowing them to flow. Liquids have definite

volume but no fixed shape (Chang & Goldsby, 2016).

3.2. Mechanical properties

- Fluidity: ability to flow
- Viscosity: resistance to flow
- Surface tension: cohesive forces at the surface
- Diffusion: gradual mixing due to particle motion (Silberberg, 2015).

4. Gas

4.1. Introduction

Gas particles are far apart, moving freely with high kinetic energy. Gases have neither fixed shape nor fixed volume (Halliday et al., 2014).

4.2. Elemental gases

Examples include O_2, N_2, H_2, He, and Ne. These are essential for life and technology.

4.3. Kinetic theory

- Constant random motion of particles
- Elastic collisions
- Average kinetic energy $\propto$ temperature (Young et al., 2019).

4.4. Ideal and perfect gas models

Ideal gas law: $$PV = nRT \dots\dots\dots\dots\dots\dots\dots (I.1)$$

Real gases deviate from this law under high pressure and low temperature.

5. Plasma

5.1. Definition

Plasma is an ionized gas with free electrons and ions, often called the “fourth state of matter” (Halliday et al., 2014).

5.2. Temperature

Exists at very high temperatures, such as in stars.

5.3. Plasma potential

Because of its charged particles, plasma interacts strongly with electric and magnetic fields

5.4. Comparison with gas

- Gas: neutral particles, weak interactions.
- Plasma: charged particles, strong electromagnetic interactions.

Examples: lightning, auroras, fluorescent lamps, stars.

6. Phase transitions

6.1. Definition

A phase transition is a transformation of matter from one physical state (phase) to another when temperature, pressure, or another external condition changes.

Example:

- Ice → Water (melting)
- Water → Vapor (vaporization)

During a phase transition, the chemical composition remains the same, but the physical structure and energy of the system change.

6.2. Types of Phase Transitions

(a) First-Order Transitions

- Involve a discontinuous change in density or volume.
- Accompanied by latent heat (energy absorbed or released).

- **Examples:**
    - Melting (solid → liquid)
    - Boiling (liquid → gas)
    - Sublimation (solid → gas)

Characteristics:

- Heat absorbed = latent heat (L)
- Temperature remains constant during the transition
- Entropy changes abruptly

$$Q = mL \ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{I}.2)$$

(b) Second-Order (Continuous) Transitions

- No latent heat is involved.
- Physical properties (like magnetization, heat capacity) change continuously, but their derivatives show discontinuities.
- **Examples:**
    - Ferromagnetic to paramagnetic transition (Curie point)
    - Superconducting transition
    - Superfluid transition in liquid helium

Examples of Phase Transitions

Transition Type	Example	Description
Solid → Liquid	Melting of ice	Endothermic, absorbs heat
Liquid → Gas	Boiling of water	Constant temperature
Solid → Gas	Sublimation of iodine	Direct transition
Gas → Liquid	Condensation of steam	Exothermic
Liquid → Solid	Freezing	Energy released
Solid → Solid	Graphite ↔ Diamond	Change in crystal structure

Chapter

02

Generalities on Aqueous Solutions

C H A P T E R II : Generalities on Aqueous Solutions

plan

II.1. Study of solutions: classification of solutions

II.2. The concentrations and fractions: molarity, molality, osmolarity, equivalent concentration, mass and molar fractions.

II.3. Solubility

II.4. Electrolyte solutions: electrical conductivity, physical and chemical properties of electrolytes

Objective

1. Recognize basic notions about aqueous solutions
2. Learn how to calculate:
3. Concentrations
4. Fractions
5. Conductivity

II.1. STUDY OF SOLUTIONS

1.1. Introduction

An electrolytic solution is a homogeneous mixture (consisting of a single phase) resulting from the dissolution of one or more solute (s) (dissolved chemical species) in a solvent. The molecules (or ions) of solute are then solvated and dispersed in the solvent.

- Solvent: the material that exists in greater quantity.
- Solute: the material (materials) that exists in small quantities. If the solvent is water, the solution obtained is called an aqueous solution.

It is noted that all the properties and the physicochemical characteristics of the aqueous solutions

are dependent on the nature of these substances.

1.2. Classification of solutions

Solutions can be classified in several ways depending on the physical state, concentration, solvent type and electrical behavior.

1. Based on Physical State of Solvent

- Gaseous solutions: Solute and solvent are gases. Example: Air (O_2, CO_2, etc. dissolved in N_2).
- Liquid solutions: Solvent is liquid. Example: Salt in water, alcohol in water.
- Solid solutions: Solvent is solid. Example: Alloys (brass = Cu + Zn).

2. Based on Concentration of Solute

- Dilute solution: Contains small amount of solute relative to solvent.
- Saturated solution: Contains maximum solute at a given temperature.
- Unsaturated solution: Contains less solute than its solubility limit.
- Supersaturated solution: Contains more solute than theoretically possible; unstable.

3. Based on Solvent Type

- Aqueous solutions: Water is the solvent (e.g., NaCl in water).
- Non-aqueous solutions: Solvent is not water (e.g., iodine in alcohol).

4. Based on Electrical Conductivity

- Electrolytic solutions: Conduct electricity.
- Strong electrolytes: Fully ionize (e.g., NaCl in water).
- Weak electrolytes: Partially ionize (e.g., CH_3COOH in water).

- Non-electrolytic solutions: Do not conduct electricity (e.g., sugar in water).

II. 2. Quantitative characteristics of solutions (concentration and fraction)

A solution is obtained by dissolving one or more chemical species, called solutes, in a solvent (usually water). The solute can be solid, liquid or gaseous, molecular or ionic.

2.1. Mass Concentration (C_{mass})

The mass concentration of a solute in a solution is defined as the mass of solute per unit volume of solution. It expresses how many grams of solute are present in a certain volume of solution.

$$C_{mass} = \frac{m_{solute}}{V_T} \dots\dots\dots\dots\dots\dots\dots (II.1)$$

(m_{solute} in g and V_T in l)

2.2. Molar Concentration – molarity (C_{mol})

The molar concentration (also called molarity) of a solution is defined as the amount of substance (in moles) of solute per unit volume of solution.

$$C_{mol} = \frac{n_{solute}}{V_T} \dots\dots\dots\dots\dots\dots\dots (II.2)$$

C_{mol} : molar concentration (mol/l)

n_{solute} : number of moles of solute (mol)

V_T : volume of solution (l)

Since the number of moles is related to the solute's mass and molar mass:

$$n_{solue} = \frac{m_{solute}}{M_{solue}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (II.3)$$

we can also write: $$C_{mass} = C_{mol}\ X\ M_{solue} \dots\dots\dots (II.4)$$

(C_{mass} in $g.l^{-1}$, C_{mol} in $mol.l^{-1}$ et M_{solue} in $g.mol^{-1}$)

2.3. Molal Concentration – molality (C_{molal})

It represents the amount of material of the dissolved chemical species per unit mass of solvent. It is expressed in mol. Kg-1.

$$C_{molal} = \frac{n_{solute}}{m_{solvant}} \dots\dots\dots\dots\dots\dots\dots (II.5)$$

Example: (The solution during the lecture)

A solution contains 15 g of KOH (molar mass M=56 g/mol) dissolved in 500 ml of water.

Calculate:

1. The molar concentration C_{mol}.
2. The mass concentration C_{mass}.
3. The molality C_{molal} (assuming the mass of water is 500 g).

2.4. Particulate molar concentration - Osmolarity (W)

The osmolarity of a solution is a measure of the total concentration of dissolved particles (ions or molecules) in a solution. It is given by the number of particulate moles (non-dissociable molecules or ions) per liter of solution:

$$W = \frac{n_{par}}{V_T} \ (Osmol.l^{-1}) \dots\dots\dots\dots\dots\dots\dots (II.6)$$

If the solute dissociates into several ions, osmolarity is calculated as:

$$w = i\ C_{mol} \dots\dots\dots\dots\dots\dots\dots (II.7)$$

W: osmolarity (osmol/l)

C_{mol}: molar concentration of solute (mol/l)

i: van't Hoff factor (number of particles produced per formula unit of solute after dissociation).

Thevan't Hoff factor, i, can be connected with the degree of dissociation, α, in the following way.

$$i = 1 + \alpha(\beta - 1)\text{……..}(II.8)$$

where

β: number of ions formed if dissociation were complete.

α: Degree of Dissociation

The degree of dissociation α is the fraction of solute molecules that actually dissociate into ions in solution.

$$\alpha = \frac{number\ of\ dissociated\ molecules}{initial\ number\ of\ molecules} \text{……..}(II.9)$$

So:

- If α=0: no dissociation (non-electrolyte).
- If α=1: complete dissociation (strong electrolyte).
- If 0<α<1: partial dissociation (weak electrolyte).

Example 1: NaCl (strong electrolyte)

$NaCl \rightarrow Na^+ + Cl^- \rightarrow \beta=2$.

For complete dissociation (α=1):

i=1+1(2−1) =2

Example 2: CH_3COOH (weak acid)

$CH_3COOH \rightleftharpoons CH_3COO^- + H^+ \rightarrow \beta=2$.

If only 30% dissociation (α=0.3):

i=1+0.3(2−1)=1.3

2.5. Equivalent concentration (Ceq)

The equivalent concentration (also called normality) is defined as the number of equivalents of solute per unit volume of solution.

$$C_{eq} = \frac{n_{eq}}{V_T} \ (Eq.l^{-1}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.10)$$

$$n_{eq} = n_{mol} \times Z \ldots\ldots\ldots\ldots\ldots\ldots (II.11)$$

Z: depends on the reaction:

- For acid–base: number of H^+ (or OH^-) exchanged per mole.
- For redox: number of electrons transferred per mole in the reaction considered.
- For ions forming charge: can be the ionic charge when counting charge balancing.

$$C_{eq}(i) = C_{mol}(i).|Z_i| \ (eq.l^{-1}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.12)$$

C_{mol} (i) is the molar concentration of the ion i in mol.l^{-1} and Z_i is the valence of the ion i. For a solution containing N ions, its equivalent concentration is:

$$C_{eq} = \sum C_{mol}(i).|Z_i| \ (eq.l^{-1}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.13)$$

Example: (The solution during the lecture)

Dissolve 4.90 g of NaOH (M = 40 g·mol^{-1}) in water to make 250 mL solution. Find the normality (C_{eq}).

2.6. Fractions

1. Molar fraction

The molar fraction (fi) of a component (i) is expressed by the ratio of the number of molecular moles (ni) of this component to the total number of moles (ntot) of the solution.

$$f_i = \frac{n_i}{\sum n_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.14)$$

where $\sum \boldsymbol{f_i} = \mathbf{1}$ *(without dimension)*

2. Mass fraction

If (m_i) the mass of a constituent (i) of the solution. The mass fraction (w_i) of this constituent is given by the ratio of its mass to the total mass (m_{tot}) of the solution.

$$w_i = \frac{m_i}{\sum m_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.15)$$

where $\sum w_i = \mathbf{1}$ (*without dimension*)

Example: (The solution during the lecture)

A solution is prepared by dissolving 20 g of NaOH (M = 40 g/mol) in 180 g of water.

1. Find the mole fractions of solute and solvent.
2. Find the mass fractions of solute and solvent.

II.3. SOLUBILITY

3.1. Definition

Solubility is the property of a solid, liquid or gaseous chemical substance called solute to dissolve in a solid, liquid or gaseous solvent. The solubility of a substance fundamentally depends on the physical and chemical properties of the solute and solvent as well as on temperature, pressure and presence of other chemicals (including changes to the pH) of the solution.

The extent of the solubility of a substance in a specific solvent is measured as the saturation concentration, where adding more solute does not increase the concentration of the solution and begins to precipitate the excess amount of solute. Insolubility is the inability to dissolve in a solid, liquid or gaseous solvent.

3.2. Ways of expressing solubility

- **Mass solubility (S_{mass})**

$$S_{mass} = \frac{m_{soute}}{m_{solvent}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.16)$$

Expressed as g of solute per 100 g of solvent or g/L of solution.

- **Molar solubility (S)**

$$S = \frac{n_{soute}}{V_{solutin}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.17)$$

Expressed as mol/L.

Examples

✓NaCl in water: highly soluble → about 360 g/l at 25 °C.

✓$CaCO_3$ in water: very low solubility → about 0.013 g/l at 25 °C.

✓Oxygen in water (gas): ~ 8.3 mg/l at 25 °C and 1 atm.

- **Relation with Molar Solubility**

Molar solubility (S) = number of moles of solute that dissolve per liter of solution.

Mass solubility (S_{mass}) = molar solubility × molar mass

$$S_{mass} = S \times M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.18)$$

3.3. Factors Affecting Solubility

The solubility of a substance (solid, liquid, or gas) in a solvent depends on several factors:

1. Nature of the Solute and Solvent

- "Like dissolves like": Polar solutes tend to dissolve in polar solvents (e.g., NaCl in water), while non-polar solutes dissolve in non-polar solvents (e.g., iodine in benzene).

2. Temperature

- For most solids in liquids, solubility increases with temperature (endothermic dissolution).
- For some salts, solubility decreases with temperature (exothermic dissolution, e.g., $Ce_2(SO_4)_3$).

- For gases in liquids, solubility decreases with increasing temperature (because gases escape more easily).

3. Pressure

- Pressure has little effect on solids and liquids.
- For gases in liquids, solubility increases with pressure, as described by Henry's Law:

$S = K.P$…… (II.19)

where S is the solubility, K the Henry's constant, and P the partial pressure of the gas.

4. Common Ion Effect

- In ionic compounds, solubility decreases when a solution already contains a common ion.
- Example: Solubility of AgCl decreases in a NaCl solution because both provide Cl^- ions.

5. pH of the Solution

Solubility of salts of weak acids (e.g., carbonates, phosphates) increases in acidic solutions because H^+ ions react with the anions (CO_3^{2-}, PO_4^{3-}), reducing their concentration and shifting equilibrium.

6. Presence of Complexing Agents

Solubility of certain salts increases in the presence of ligands that form soluble complexes.

Example: AgCl dissolves in NH_3 solution due to the formation of $[Ag(NH_3)_2]^+$.

II.4. ELECTROLYTE SOLUTIONS

An electrolyte solution is a solution that generally contains ions, atoms or molecules that have lost or gained electrons, and is electrically conductive. For this reason, they are often called ionic solutions, however there are some cases where the electrolytes are not ions. For this discussion we will only consider solutions of ions.

Examples of electrolytic substances: acids, bases, and salts.

A non-electrolyte substance is one that, when in solution, does not allow an electric current to pass through it.

Examples of non-electrolyte substances include sugar and alcohol.

There are two types of electrolytes: strong and weak:

- Strong electrolytes: Substances that dissociate completely in water, producing ions with good electrical conductivity.
- Weak electrolytes: Substances that partially dissociate in water, producing ions with poor electrical conductivity. Examples include weak acids and weak bases.

- ***Properties of Solutions of Electrolytes***

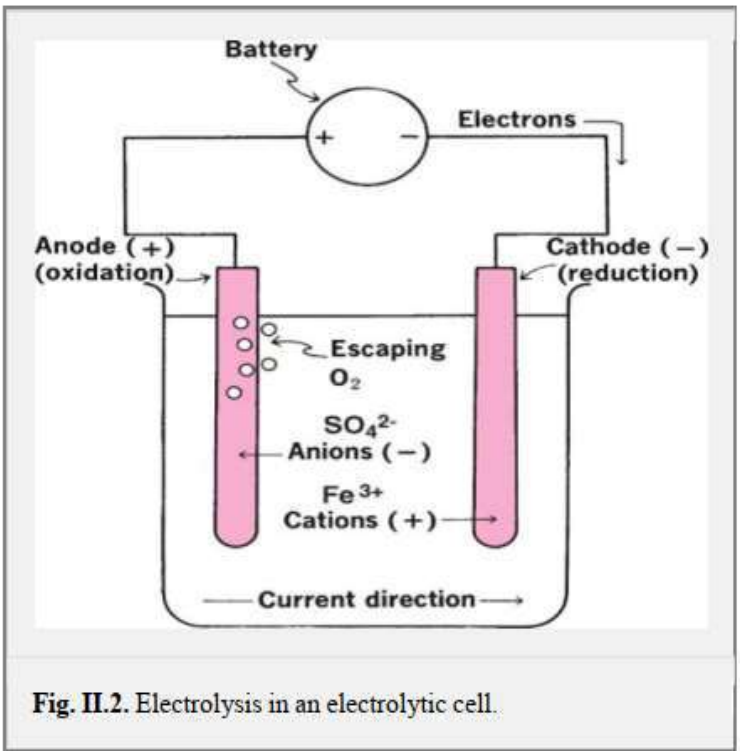

Fig. II.2. Electrolysis in an electrolytic cell.

Electrolysis: When a direct electric current flows through an electrolytic cell, a chemical reaction occurs. This process is known as electrolysis.

Electrons enter the cell from the battery or generator at the cathode, they combine with

positive ions or cations, in the solution, and the cations are accordingly reduced.

The negative ions, or anions, carry electrons through the solution and discharge them at the anode, and the anions are accordingly oxidized.

Reduction is the addition of electrons to a chemical species

oxidation is removal of electrons from a species.

The current in a solution consists of a flow of positive and negative ions toward the electrodes,

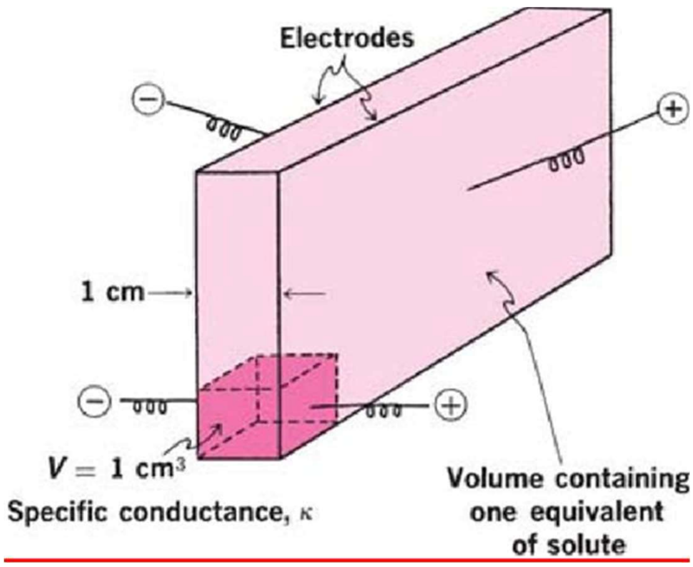

Fig. II.3. Relationship between specific conductance and equivalent conductance.

The resistance, R, in ohms of any uniform metallic or electrolytic conductor is directly proportional to its length, l, in cm and inversely proportional to its cross-sectional area, A, in cm^2,

$$R = \rho \frac{l}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (II.20)$$

where ρ is the resistance between opposite faces of a unit cube of the conductor and is known as the specific resistance.

The conductance, G, is the reciprocal of resistance,

$$G = \frac{1}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (II.21)$$

and hence can be considered as a measure of the ease with which current can pass through the

conductor. It is expressed in reciprocal ohms or mhos. From equation (II.20):

$$G = \frac{1}{R} = \frac{1}{\rho} \times \frac{A}{l} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (II.22)$$

The specific conductance (also called conductivity, symbol σ) is defined as the reciprocal of the specific resistance (resistivity, ρ).

$$\sigma = \frac{1}{\rho} \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.23)$$

The relationship between specific conductance and conductance or resistance is obtained by combining equations (II.22) and (II.23):

$$\sigma = G\frac{l}{A} = \frac{1}{R} \times \frac{l}{A} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (II.24)$$

For a solution containing the anion A^{x-} at the concentration C^{-} and the cation B^{y+} at the concentration C^{+} and if A represents the surface of the electrodes, it is shown that the intensity of the current which passes through such an electrolyte is given by:

$$I = \frac{dQ}{dt} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (II.25)$$

If we denote by $\vec{J}$ the current density vector and by ρ the electrical conductivity of the solution, we show that:

$$\vec{J} = \sum_i \rho_i \times \vec{v}_i \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.26)$$

ρ: the volume density of charge

$\vec{v}$: the moving speed of charge

In the case of several ions, if we denote Z_i the valence of the species A_i, C_i its concentration and μ_i its mobility, then:

$$\vec{J} = \sum_i \rho_i \times \vec{v}_i \dots\dots\dots\dots\dots\dots\dots\dots\dots (II.27)$$

$$\vec{J} = \sum_i (Z_i \times C_i \times \mu_i) \times \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.28)$$

We can also write that the total conductivity is equal to the contributions sum of all the ions:

$$\sigma = \sum_i \sigma_i = \sum_i |Z_i| \times C_i \times \lambda_i \ldots\ldots\ldots\ldots\ldots\ldots . (II.29)$$

where (λ_i) represents the molar conductivity of the ion "i"

In the system S.I.: σ is expressed in $S.m^{-1}$, C_i in $mol.m^{-3}$ and λ_i in $S.m^2.mol^{-1}$.

Molar conductivity (λ) is the conductivity of a solution containing one mole of electrolyte, placed between two electrodes of unit area and unit distance.

$$\lambda = \frac{\sigma \times 1000}{C} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.30)$$

where:

- σ: specific conductivity ($S \cdot cm^{-1}$),
- C: molar concentration of the electrolyte ($mol \cdot l^{-1}$),
- λ: molar conductivity ($S \cdot cm^2 \cdot mol^{-1}$).

Example: (The solution during the lecture)

Consider the sodium chloride solution NaCl obtained after dissolving a mass m = 10 g of NaCl salt in 100 ml of water.

1) What is the molar concentration of the solution?

2) What is the molar concentration of the solution in sodium (Na^+) and chlorine (Cl^-) ions?

3) Find the conductivity of the NaCl sodium chloride solution.

Ionic molar conductivities are given:

λ_{Na^+} =5 $mS.m^2.mol^{-1}$ and λ_{Cl^-}= 7.6 $mS.m^2.mol^{-1}$.

Exercises Serie number 1

Exercise 1

A solution of copper (II) sulfate ($CuSO_4$) has a concentration of C = 0.100 mol/l.

1. Calculate the number of moles of $CuSO_4$ present in 500 ml of solution.
2. Determine the corresponding mass of $CuSO_4$.
3. Find the mass concentration of $CuSO_4$ in this solution.

- The molar mass of atomic elements in (g/mol) is given as: Cu=63.5, S=32 and O=16.

Exercise 2

An aqueous solution of volume 500 ml contains 9 g of urea, whose molar mass is 60 $g \cdot mol^{-1}$.

1. Calculate the mass concentration of the solution, expressed in $g \cdot l^{-1}$. Deduce the molarity and the molality of the solution in SI units.

2. What is the osmolarity of the solution, expressed in $mOsmol \cdot l^{-1}$?

3. Compare the osmolarity of this solution with that of a NaCl solution having the same mass concentration.

Data: density ρ = 1 kg. l^{-1}.

Exercise 3

We consider a solution of ammonium sulfate $(NH_4)_2SO_4(s)$ of mass fraction w=0.4 and a density ρ = 1,2277 kg. l^{-1}.

1) Find the initial molarity of the solution (molar concentration in solute).
2) Calculate the molality of the solution (molal concentration).
3) Determine the molar fraction of the solute and then that of the solvent.

We give the atomic molar mass in (g / mol): N=14, S=32, H=1 and O=16.

Exercise 4

Consider a solution of Na_2SO_4 obtained after dissolving a mass m=14.2 g of Na_2SO_4 crystals in 500 ml of water.

1) Calculate the molar concentration of the solution in sodium (Na^+) and sulfate (SO_4^{-2}) ions?
2) Calculate the equivalent concentration of the solution?

- We give the atomic molar mass in (g/mol): Na=23, S=32, H=1and O=16.

Exercise 5

From the initial molar concentration, calculate the particulate molar concentration (osmolarity) of each solution in the following table:

Solution	Initial molar concentration (C_{mol})	Osmolarity (W)
Glucose	0.1 $mol.l^{-1}$	.....
NaCl	0.1 $mol.l^{-1}$	.....
$CaCl_2$ (α=0.65)	0.1 $mol.l^{-1}$	.....

Exercise 6

Consider a sodium chloride solution NaCl obtained after dissolving a mass m = 14.2 g of NaCl salt in 500 ml of water.

1) What is the molar concentration of the solution?
2) What is the molar concentration of the solution in sodium (Na^+) and chlorine (Cl^-) ions?
3) Find the conductivity of the NaCl sodium chloride solution.

- Ionic molar conductivities are given: λ_{Na+} =5 $mS.m^2.mol^{-1}$ and λ_{Cl-}= 7.6 $mS.m^2.mol^{-1}$.

Exercise 7

1. A conductivity cell (cell constant 0.75 cm^{-1}) gives a conductance G = 4.00×10^{-3} S for a solution of concentration 0.025 M. Find σ and λ

2. In a conductivity titration experiment of an acetic acid solution:

- An initial solution of concentration C_0=0.020 mol/l is prepared.
- The measured specific conductivity is σ =4.70×10^{-3} S/m
- The total volume of the solution is V=100 ml

1. Calculate the molar conductivity.
2. If the molar conductivity at infinite dilution is

$$\lambda_m^{\infty} = 390\ S.cm^2.mol^{-1}$$

- calculate the degree of dissociation α

Chapter 03
Phenomenon of interfaces

CHAPTER III : Phenomenon of interfaces

PLAN

III.1. Introduction

III.2. Surface tension: definition, measurements and biological applications

III.3. Phenomenon of capillarity: definition, measurements and biological applications

III.4. Adsorption

OBJECTIVE

1. Understand liquid-gas and liquid-solid surface phenomena,
2. Know the connection angle, Young's relationship and Jurin's law,
3. Know how to calculate: surface tension and their force, the capillary height ....

III.1. INTRODUCTION

Unlike gases, a body in the liquid state does not occupy all the available volume, because of cohesion phenomena. Liquid cohesion is due to interatomic or intermolecular attraction forces. These cohesion phenomena tend to minimize the free surface of a liquid, this surface seems to behave like a stretched elastic membrane, where there is a phenomenon of surface tension. In this respect, several examples or observations make it possible to illustrate the influence of surface tension such as:

1. A needle or razor blade floating on water — even though it's denser than water, the surface tension supports it as long as the surface is not broken.
2. Formation of spherical water droplets — surface tension pulls the molecules

into the smallest possible surface area, which is a sphere.

3. Water striders (insects) walking on water — they are supported by the strong surface tension of water.

4. Drops of dew on leaves — the spherical shape of the dew drops shows the effect of surface tension.

5. Soap bubbles and liquid films — surface tension allows the formation of stable thin films that can stretch into bubbles.

6. Capillary rise of liquids in thin tubes or porous materials — due to surface tension and adhesion between the liquid and the solid surface.

III.2. SURFACE TENSION

At the microscopic level, each molecule is subject to attractive forces from all around it. The resultant of its forces acting on the molecule situated inside liquid or gas is null. Then there is a statistical balance of forces $\vec{F} = \vec{0}$.

On the contrary, for molecules located at the interface of the liquid (i.g at a distance from the surface below the molecular radius), they are subjected to attractive forces whose resultant is not zero $\vec{F} \neq \vec{0}$ because the distribution around is not iso-tropic.

Thus, the liquid exerts on these surface molecules a restoring force towards the inside of the liquid (see the figure below). To minimize the area of the interface to decrease potential energy.

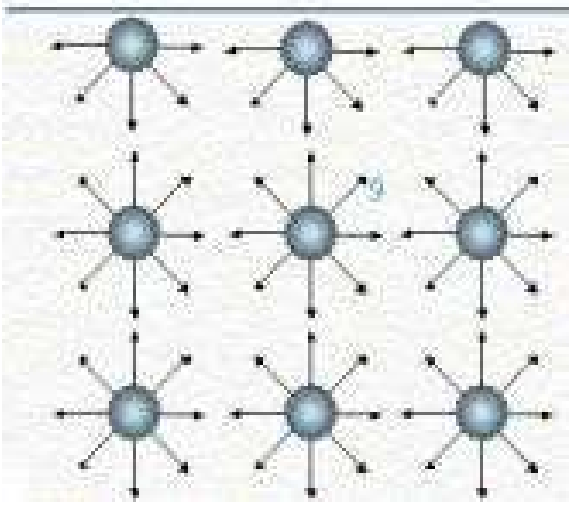

Figure III.1: The distribution of molecules at the interface and inside of liquid.

2.1. Superficial tension force

In order to obtain the expression of the surface tension force, we assume a rectangular soapy blade, of length l and width x, formed in a thin metal frame ABCD of which one of the sides CD is movable.

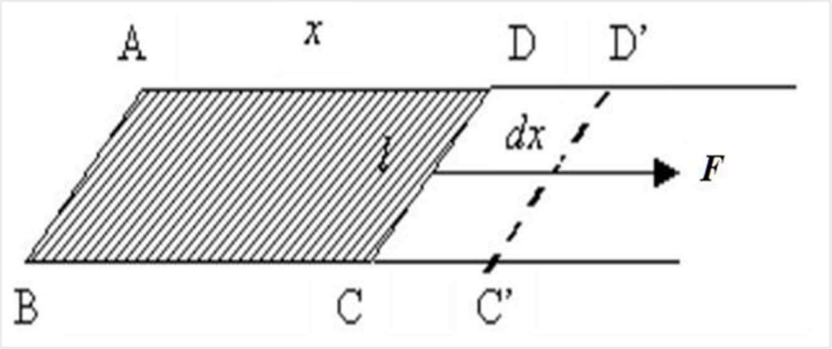

Figure III.2 : Cadre métallique pour former une lame savonneuse ABCD.

It is noted here that the total area of the blade, given its two faces is 2×x×l. The blade has a tendency to retract; in order to maintain its constant surface, it is necessary to exert on CD a force F which is obviously proportional to its length. This force is called: Superficial tension force.

$$F = \sigma \times 2 \times l \quad [N] \qquad \text{III.1}$$

where σ [N / m] is a constant characterizes each liquid called "Superficial tension".

On Experimental results of the surface tension are given in Table III.1.

Table III.1: Some experimental values of the surface tension in [mN/m] at different temperatures.

Liquide	0°	20°	40°
Eau	75,64	72,75	69,56
Méthanol	24,50	22,65	20,90
Ethanol	24,05	22,27	20,60
Acétone	26,21	23,70	21,16

1- The constant σ depends on the temperature T and it decreases when T increases.

2- From the energetic point of view: to move the CD side of a length dx in the previous example it is necessary to supply the work:

$$dW = F \times dx \qquad \text{III.2}$$

This displacement, at constant temperature and volume, corresponds to an increase in the liquid surface of:

$$dS = 2l \times dx \quad \text{So: } \sigma = dW / dS \ [J/ m^2] \qquad \text{III.3}$$

3- The surface tension energy is given by:

$$E_S = \sigma \times S \qquad \text{III.3}$$

4- Cohesion energy

In a pure liquid, intermolecular attraction forces are called cohesion forces. If we want to separate these columns (set of molecules), we must provide an energy. This energy is called "cohesion energy" which is equal to:

$$W = ES_f - ES_i = \sigma (S_f - S_i) \qquad \text{III.4}$$

2.2. Laplace pressure and its applications

In this part, we will see Laplace's law and what are its applications and its usefulness in the description of some biophysical phenomena.

2.2.1. Bulle Bubble of air in a liquid

To form an air bubble of radius R within a surface tension liquid σ, it is necessary that the pressure ΔP exerted on the spherical membrane of the air bubble is positive. That is, the internal pressure P_{int} in the bubble is greater than that of the external medium P_{ext}. The law of Laplace, allows us to give the expression of this overpressure:

$$\Delta P = P_{int} - P_{ext} \qquad \text{III.5}$$

According to R and σ. Indeed, on the one hand, to increase the volume V of the drop of dV (we increase the radius R of the bubble of dR, see Figure III.3), we must provide a work of the pressure forces dW during the variation volume such as:

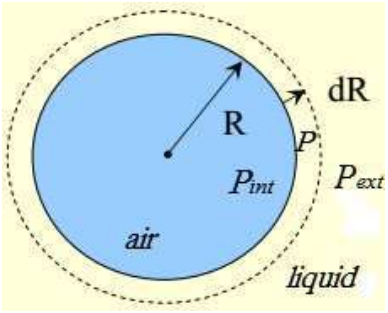

Figure III.3: Bubble of air in the water

- $dV = S \times dR = 4\pi.R^2.Dr$ (III.6)
- $dW = \Delta P \times dV = \Delta P.4\pi.R^2.dR$ (III.7)

On the other hand, we note that this expression of work is totally similar (equal) to that of 'work of superficial tension forces.

- $dS = 2 \times 4\pi.R.dR = 8\pi.R.d$ (III.8)
- $W = \sigma \times dS = \sigma.8\ \pi.R.dR$ (III.9)

Finally, after comparison, it is found that the expression of the pressure inside an air bubble in a liquid is given by:

$$\Delta p = \frac{2\sigma}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III.10)$$

2.2.2. Soap bubble in the air

Consider a soapy bubble of surface tension σ and of radius R on the inner layer and radius R + dR on the outer layer (see Figure III.4).

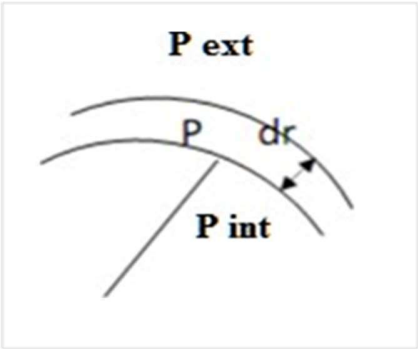

Figure III.4: Soap bubble

With the same reasoning as the previous case, we can write the overpressure due to the external (outer) layer as:

$$P - P_{ext} = \frac{2\sigma}{R + dR} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III.11)$$

and the overpressure due to the internal (inner) layer by:

$$P_{int} - P = \frac{2\sigma}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III.12)$$

which give us the final overpressure of the soap bubble in the air by the following relation (where we have supposed that dR << R):

$$\Delta p = \frac{2\sigma}{R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III.13)$$

III.3. PHENOMENON OF CAPILLARITY

The interaction of a liquid with a solid is characterized by the word 'Wetting'. Solid bodies like liquids have superficial energy. This energy is defined by the average work that must be provided to create reversibly and isothermally 1 cm^2 of apparent surface.

$$\Delta W = \sigma \times \Delta S \qquad (III.14)$$

3.1. Angle of connection solid to a liquid

The contact angle of a solid to a liquid (θ) is defined by the angle between the plane of the solid and the tangent to the free surface of the liquid and is always measured inside the liquid.

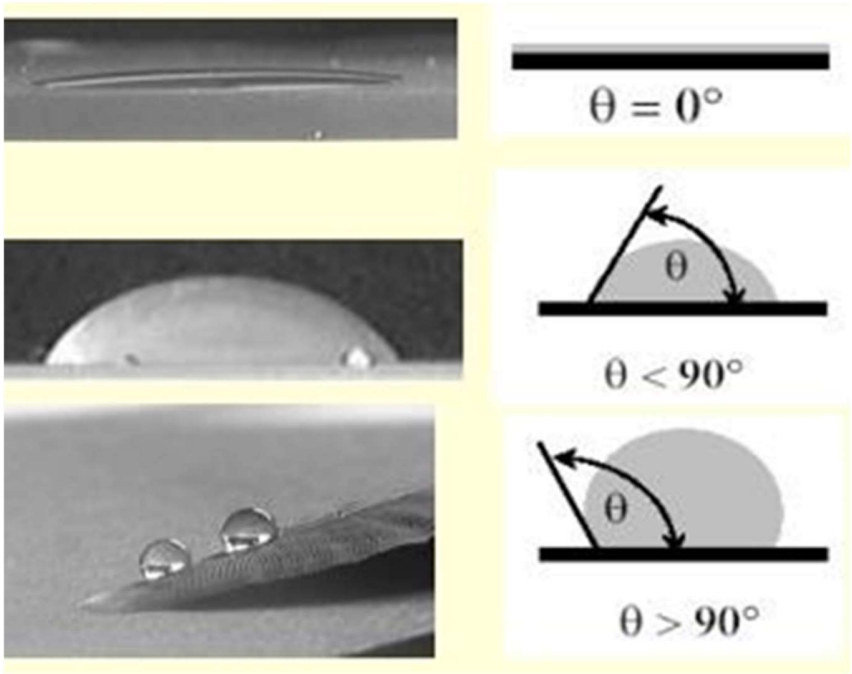

Figure III.5 : Solid-liquid connection angle

- If the connection angle θ = 0 °, the liquid wets the solid perfectly (eg water on clean glass)
- If θ <90 °, the liquid imperfectly wets the solid (for example water on dirty glass) If θ>

90 °, the liquid does not wet the solid (for example mercury on glass).

3.2. Young's relationship

It is very convenient to understand the role of the contact angle or liquid-solid connection. In this respect, it is well known that when a drop of liquid is deposited on a flat or horizontal solid plate, there are three surface tension forces acting on the separation surfaces which meet at the periphery of the surface. drop (see Figure III.6):

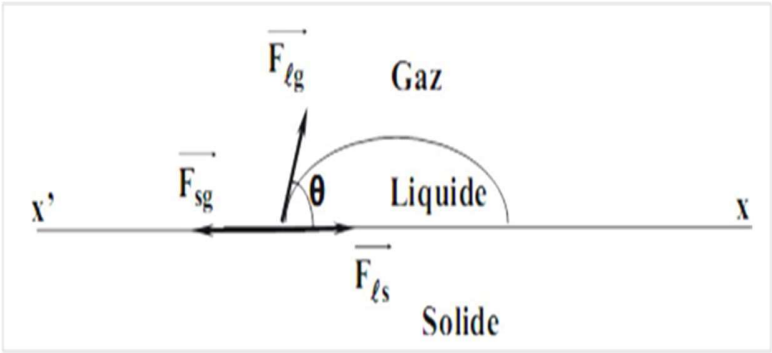

Figure III.6: Presentation of surface tension forces acting on surfaces

$\overrightarrow{F_{lg}}$: is the force exerted on the liquid molecules located around the drop by the other molecules of gas located on the liquid-gas separation surface.

$\overrightarrow{F_{sg}}$: is the force exerted on the liquid molecules located around the drop by the other solid molecules located on the solid-gas separation surface.

$\overrightarrow{F_{ls}}$ is the force exerted on the liquid molecules located around the drop by the other molecules of gas located on the liquid-solid separation surface.

At the point of equilibrium, the resultant of these forces is written:

$$\overrightarrow{F_{lg}} + \overrightarrow{F_{sg}} + \overrightarrow{F_{ls}} = \vec{0} \dots\dots\dots\dots\dots\dots\dots (III.16)$$

After a simple projection on the axis XX ', we obtain the following equilibrium condition:

$$F_{sg} = F_{lg} \times cos\theta + F_{ls} \dots\dots\dots\dots\dots\dots (III.17)$$

$$\Longrightarrow \sigma_{sg} \times dl = \sigma_{ls} \times dl + \sigma_{lg} \times dl \times cos\theta$$

$$\Longrightarrow \sigma_{sg} = \sigma_{ls} + \sigma_{lg} \times cos\theta$$

$$\Longrightarrow cos\theta = \frac{\sigma_{sg} - \sigma_{ls}}{\sigma_{lg}} \dots\dots\dots\dots\dots\dots\dots (III.18)$$

This equation expresses a balance of horizontal forces acting on the contact line between the three phases.

- σ_{sg}: pulls along the solid surface (outward)
- σ_{sl}: pulls along the solid surface (under the liquid)
- $\sigma_{lg}\cos\ \theta$: horizontal component of the liquid–gas tension

3.3. Jurin's law

The appearance of the limit angle results in the formation of the liquid surface curvature near the solid plane. In the case of capillary tubes this curvature encompasses the entire

surface of the liquid. When the liquid is wetting, the shape of the curvature is concave and when the liquid is non-wetting the shape of the curvature is convex (see Figure III.7).

It is also noted that this phenomenon of wetting also occurs in the case of a vertical solid wall, where we observe an ascent (with a concave meniscus outwards) or a descent (with a convex meniscus towards the inside).

(a) (b)

Figure III.7 : Illustration of wetting phenomenon (a) wetting liquid and (b) non wetting liquid.

In 1717 the English physician James Jurin showed that when a capillary tube of radius R, open at both ends, is immersed in a liquid of surface tension σ, this one goes up or down in the tube of a height h. where he found that the pressure in the liquid just below the meniscus (curvature of liquid) obeys simultaneously two laws:

The hydrostatic law in the liquid, , the relation of the pressure difference under the meniscus by:

$$\Delta P = P_{atm} - P_{ext} = \rho \times g \times h \qquad \text{(III.19)}$$

The Laplace law through the interface constituting the meniscus, which allows us to give the expression of the overpressure:

$$\Delta P = P_{int} - P_{ext} = P_{atm} - P_{ext} = 2 \times \sigma / r \qquad \text{(III.20)}$$

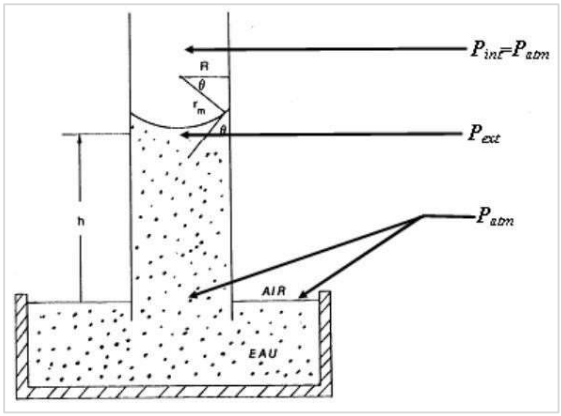

Figure III.8 : Description of the wetting phenomenon

where :

R: Inner radius of the tube.

ρ: Density of the liquid.

g: Intensity of gravity.

σ: Surface tension of the liquid.

θ: liquid / solid connection angle.

With these expressions, Jurin stated the relation of the height h with the tube radius R:

$$h = \frac{2.\sigma.cos\theta}{\rho.R.g} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (III.21)$$

With the use of the following relation: $cos\theta = \frac{R}{r}$ –

where:

- σ : surface tension of the liquid
- θ : contact angle between liquid and tube wall
- R : radius of the capillary tube
- ρ : density of the liquid
- g : acceleration due to gravity

III.4. ADSORPTION

Adsorption is the phenomenon in which molecules (atoms or ions) from a gas or liquid accumulate on the surface of a solid or a liquid, forming a thin layer.

- Adsorbate: the substance that is being adsorbed (the molecules that stick to the surface).
- Adsorbent: the material on whose surface the adsorption occurs.

Example:

When a gas like ammonia (NH_3) is adsorbed on the surface of activated charcoal:

- NH_3 → *adsorbate*
- Activated charcoal → *adsorbent*

4.1. Types of Adsorptions:

1. Physical Adsorption (Physisorption):

- Caused by weak van der Waals forces.
- Reversible.
- Occurs at low temperature.
- Not specific (any gas can be adsorbed).
- Example: Adsorption of N_2 gas on charcoal.

2. Chemical Adsorption (Chemisorption):

- Caused by chemical bond formation between adsorbate and adsorbent.
- Irreversible.
- Occurs at high temperature.
- Highly specific.
- Example: Adsorption of O_2 on metals forming oxides.

4.2. Absorption vs. Adsorption

Absorption is the process in which a fluid is dissolved by a liquid or a solid (absorbent). Adsorption is the process in which atoms, ions or molecules from a substance (it could be gas, liquid or dissolved solid) adhere to a surface of the adsorbent. Adsorption is a surface-based process where a film of adsorbate is created on the surface while absorption involves the entire volume of the absorbing substance.

Adsorption and absorption are both sorption processes. Absorption occurs when atoms pass through or enter a bulky material. During absorption, the molecules are entirely dissolved or diffused in the absorbent to form a solution. Once dissolved, the molecules cannot be separated easily from the absorbent.

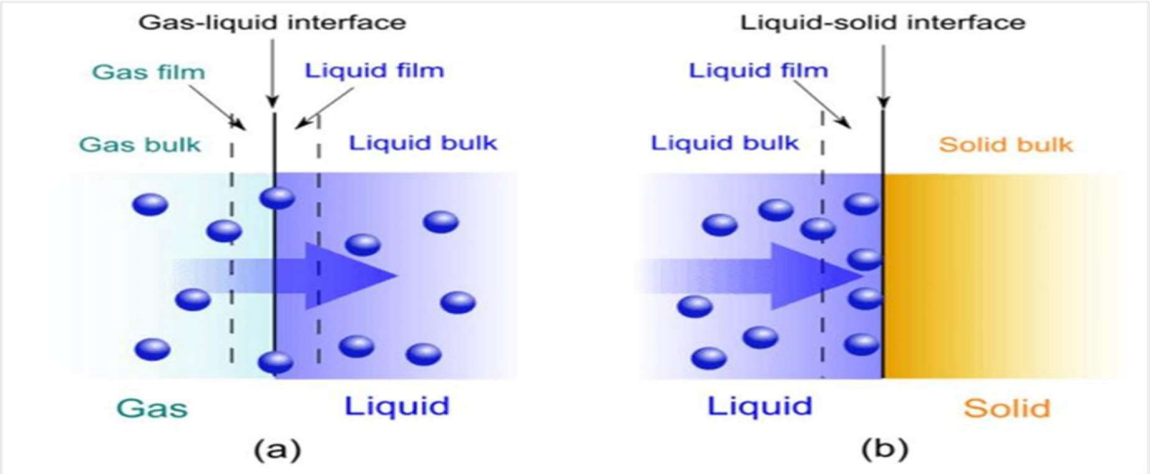

Figure III.11: Gas-liquid absorption (a) and liquid-solid adsorption (b) mechanism. Blue spheres are solute molecules.

Adsorption is generally classified into physisorption (weak van der Waals forces) and chemisorption (covalent bonding). It can also be caused by electrostatic attraction. The molecules are held loosely on the surface of the adsorbent and can be easily removed.

III.5. Phenomenon of Interfaces (Biological Applications)

An interface is the boundary separating two phases — for example, liquid–air, liquid–solid, or liquid–liquid.

At these boundaries, interfacial (surface) phenomena occur due to the unbalanced molecular forces acting on the surface molecules.

2. Main Interfacial Phenomena

- Surface tension
- Adsorption
- Capillarity
- Wetting

These play vital roles in biological and physiological systems.

3. Biological Applications

(a) Surface Tension in Lungs

- The alveoli (air sacs) in the lungs are lined with a thin film of fluid.
- Surface tension tends to make the alveoli collapse.
- The body produces a surfactant (a phospholipid called *dipalmitoyl lecithin*) that reduces surface tension and prevents alveolar collapse — essential for normal breathing.

(b) Cell Membranes

- The plasma membrane acts as an interface between the cell cytoplasm and its environment.
- Its structure (lipid bilayer) is stabilized by interfacial forces — hydrophilic heads face water, hydrophobic tails face inward.
- This arrangement depends on surface and interfacial tension between lipids and water.

(c) Blood and Capillary Action

- In narrow capillaries, surface tension and adhesion help the movement of blood and interstitial fluids.
- Similar principles explain how plants transport water through xylem vessels.

(d) Adsorption of Drugs and Toxins

- Many drugs and toxins are adsorbed on biological membranes or colloidal surfaces (like activated charcoal).
- This property is used in detoxification treatments — for example, adsorption of poisons in the gut.

(g) Adsorption in Biological Systems

- Proteins and other biomolecules can adsorb at interfaces, affecting stability, transport, and biochemical reactions.

Exercises Serie number 2

Exercise 01:

1. A rectangular frame has a movable wire of length l.

If the surface tension of water at 20 °C is σ=0.072 N/m, and the length of the wire is l=5.0 cm,

- **calculate the force due to surface tension acting on the wire.**

2. The surface area of a liquid increase by ΔA=10.0 cm2.

The surface tension is γ=0.072 N/m

- **Calculate the work done.**

3. A spherical liquid drop has radius r=1 mm and surface tension γ=0.072 N/m.

- **Find the pressure difference between the inside and outside of the drop.**

4. A drop of water rests on a smooth, clean solid surface in equilibrium with its vapor. The following surface tensions are measured at 25 °C:

- Surface tension of solid–vapor interface: σ_{sg} = 0.080N/m
- Surface tension of solid–liquid interface: σ_{sl} =0.030N/m
- Surface tension of liquid–vapor interface (water surface tension): σ_{lg} =0.072N/m

- **Calculate the contact angle θ between the liquid drop and the solid surface.**

Exercise 02:

During expiration, the total surface area of all pulmonary alveoli is 70 m², and their number is estimated to be 5 × 10^8 alveoli.

Assume each alveolus is spherical.

1. Calculate the radius of one alveolus during expiration.

2. During inspiration, the total alveolar volume becomes 5.0 L.

   Calculate the total alveolar surface area at inspiration.

3. The alveolar surface is covered with a surfactant film having a surface tension $\sigma_1=1.8\times10^{-2}$ N/m.

   Determine the energy required to increase the alveolar surface area during inspiration.

4. In the case of a disease (lack of surfactant), the surface tension increases to $\sigma_2=4.8\times10^{-2}$ N/m.

   Calculate the new energy required and comment on the physiological consequence

Exercise 03:

A glass capillary tube of radius R=0.30mm is placed vertically into two different liquids at $20°C$:

- Case A (Water):

  $\sigma_{\text{water}} = 7.2 \times 10^{-2}\ \text{N/m}$,
  contact angle $\theta_{\text{water}} = 0°$,

  density $\rho_{\text{water}} = 1000\ \text{kg/m}^3$.

- Case B (Mercury):

  $\sigma_{\text{Hg}} = 4.85 \times 10^{-1}\ \text{N/m}$,
  contact angle $\theta_{\text{Hg}} = 140°$,

  density $\rho_{\text{Hg}} = 13600\ \text{kg/m}^3$.

Take $g = 9.81\ \text{m/s}^2$.

1. Derive Jurin's Law and calculate the rise height $h$of water in the tube (show all numerical steps).

2. Compute the height (or depression) of mercury in the tube and interpret the sign.

3. Calculate the pressure difference across the curved meniscus for both liquids:

Chapter

04

Diffusion Phenomenon

CHAPTER04: Diffusion Phenomenon

PLAN

IV.1. Introduction

IV.2. Diffusion

IV.3. Osmosis phenomenon and osmotic pressure: definition, measurements and biological applications

IV.4. Permeability: definition, measurements and biological applications

OBJECTIVE

1. Understand the phenomena of diffusion and osmosis,
2. The 1st and 2nd laws of Fick and their applications
3. Knowing how to calculate: molar and mass flow rates, diffusion coefficient, osmotic pressure ....

IV.1. INTRODUCTION

In 1827, botanist Robert Brown observed the erratic movement of small particles inside pollen grains. It is not a phenomenon of diffusion, since what moves is a macroscopic particle, but this "random walk", otherwise called by the name of its observer "Brownian motion", will serve as a model for diffusion.

In 1855, Adolph Fick proposed phenomenological, empirical laws, inspired by the Fourier

law for heat (established in 1822). It is Albert Einstein who will demonstrate Fick's laws in 1905 with his work on the stochastic law.

In 1896 Roberts-Austen, who was responsible for the currency in Britain, put a gold plate on a lead plate, heated it up, and measured the depth of penetration of one metal into the other. This is the first measure of a solid-state inter-diffusion coefficient.

In 1908, Jean Perrin, founder of CNRS and Nobel Prize in Physics, was the first to measure the trajectory of particles subjected to Brownian motion and thus confirmed the theoretical analysis of Einstein.

IV.1. DIFFUSION PHENOMENON

2.1. Definition

This transport occurs in a system initially out of equilibrium, with more regions concentrating in particulate matter to regions less concentrated in particles; it therefore tends to standardize the distribution of particles that diffuse.

2.2. Types of Diffusion

Diffusion is the movement of particles from a region of high concentration to a region of low concentration until equilibrium is reached. It can be classified according to the presence of a membrane and the nature of the process.

1. Free Diffusion

The movement of particles in a medium (gas or liquid) without a membrane, i.e., in an open space.

◈ Characteristics:

- Occurs spontaneously without energy.
- Results from the random motion of particles.
- Continues until the concentration is uniform throughout the medium.

◈ Examples:

- The spread of perfume scent in a room.
- The diffusion of carbon dioxide gas in the air.

2. Simple Diffusion

The movement of particles across a semipermeable membrane from a region of high concentration to a region of low concentration, without using energy.

◈ Characteristics:

- Does not require carrier proteins or energy.
- Allows passage of small, nonpolar molecules (O_2, CO_2, N_2).

◈ Examples:

- Oxygen entering the cell and carbon dioxide leaving it.

3. Facilitated Diffusion

The movement of molecules across the cell membrane with the help of carrier or channel proteins, without energy consumption.

◈ Characteristics:

- Used for large or polar molecules (such as glucose and ions).
- Depends on specific carrier or channel proteins.
- Always moves from high to low concentration.

◈ Examples:

- Glucose entering the cell via a carrier protein (GLUT).
- Movement of sodium and potassium ions through ion channels.

4. Active Transport

The process of moving molecules against the concentration gradient (from low to high concentration) using energy (ATP).

4.1. Characteristics:

- Requires energy.
- Involves special carrier proteins (pumps).
- Maintains specific concentration differences across membranes.
  - **Examples:**
- Sodium–potassium pump (Na^+/K^+ pump).

5. Solid-State Diffusion

The movement of atoms or ions within a solid material, especially in metals or alloys at high temperatures.

- **Examples:**
- The diffusion of carbon into iron to form steel.

3. Factors Affecting Diffusion

1. Concentration gradient: The greater the difference in concentration, the faster the diffusion.
2. Temperature: Higher temperature increases particle movement, accelerating diffusion.
3. Molecular size: Smaller particles diffuse faster than larger ones.
4. Medium: Diffusion is faster in gases, slower in liquids, and slowest in solids.

IV.4. Membrane diffusion

Membrane diffusion is the process by which molecules move across a biological membrane from an area of higher concentration to an area of lower concentration, driven by the

concentration gradient. It does not require energy (ATP) (it is a passive transport mechanism).

4.2. Types of Membrane Diffusion

4.2.1. Simple Diffusion :

- Molecules move directly through the lipid bilayer without the help of proteins.
- Only small, nonpolar molecules (e.g., O_2, CO_2, N_2) and some lipid-soluble substances can pass this way.

4.2.2. Facilitated Diffusion:

- Molecules move through the membrane via specific transport proteins.
- These proteins help larger or polar molecules (e.g., glucose, ions) cross the membrane.
- Two main types:
  - Channel proteins: create hydrophilic pores (e.g., ion channels).
  - Carrier proteins: bind to molecules and change shape to move them across.

4.3. Characteristics

- Passive: no energy required.
- Direction: from high to low concentration.
- Selectivity: depends on molecule size, charge, and lipid solubility.

4.4. Examples:

- O_2 and CO_2 exchange in lungs (simple diffusion).
- Glucose transport via GLUT proteins (facilitated diffusion).

IV. 2. Free Diffusion in the Absence of a Membrane

Free diffusion is the spontaneous movement of molecules or ions within a homogeneous

medium (gas or liquid) without the presence of a separating membrane.

It occurs as a result of the random thermal motion of particles, moving from a region of high concentration to a region of low concentration until the medium becomes uniform.

2.2. Diffusion coefficient "D"

A diffusion coefficient is a characteristic quantity of the diffusion phenomenon of matter. The diffusion coefficient measures the ratio between the molar flux due to molecular diffusion, and the concentration gradient of the chemical species considered, as formulated by Fick's law.

2.2.1. Einstein's relationship

Einstein found that diffusion (and consequently D) increases with increasing temperature (driving force due to thermal agitation) or when the solute friction with the solvent decreases (friction resistance force).

Since the diffusion coefficient D plays a primordial role in the diffusion phenomenon, it is convenient to study explicitly the expression of this coefficient which is given by:

$$D = R.T.b = kB.T.\mu^{-1}$$

Where R = 8,31[J.°K^{-1}.mol^{-1}], T [°K] et b [s.kg $^{-1}$] respectively represent the perfect gas coefficient, the temperature and the molar mechanical mobility.

2.2.2. Stocks law

When considering a spherical particle of radius r [m] in a medium of viscosity η [pa.s], the equation of mechanical mobility becomes as:

$$f = b - 1 = NA.6.\pi.\eta.r$$

Where f is the coefficient of friction depends on the viscosity of the medium η and the radius of the particle r and N_A=6.023×10^{23} is the number of Avogadro. Which can lead us to a new expression (of Einstein's relation) of diffusion coefficient like:

$$K_B = \frac{R}{N_A}$$

$$D = \frac{K_B.T}{6\pi\eta r}$$

Where $K_B = 1.38\times10^{-23}$ [J.K-1] represents the Boltzmann constant.

2.3. 1st law of FICK

Fick's law describes the diffusion of matter in a binary medium. It was established by Adolf Fick in 1855. In aqueous phase, the diffusion is highlighted by the following experiment:

In the absence of a temperature gradient and mechanical agitation, it is observed that a dye carefully poured over a liquid (water) is distributed evenly throughout the liquid (Figure 2.5).

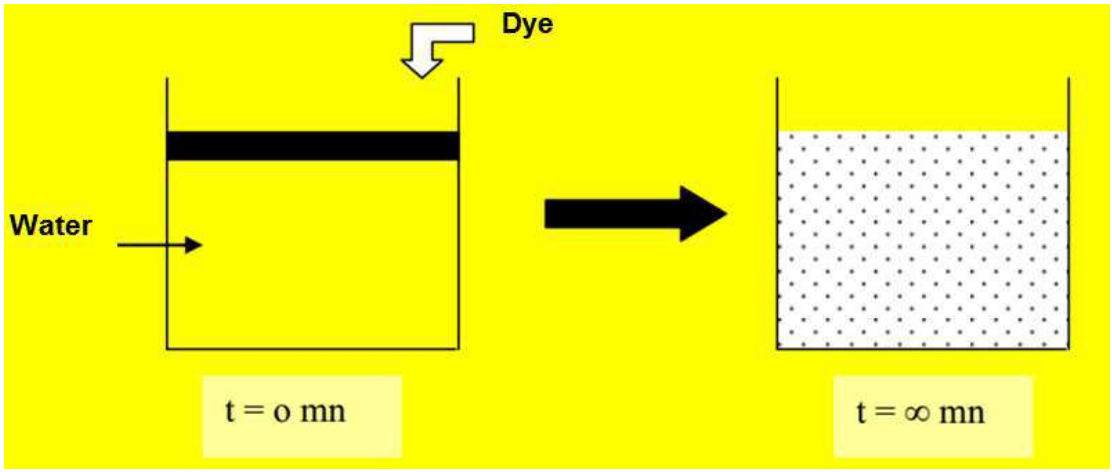

Figure IV.5. Phenomenon of diffusion in aqueous phase

Quantitatively: either "dn", the quantity of material crossing the interface, water-dye, of section "S" during a time "dt", and "dx" the distance of two points between which the difference of molar concentration "dCmol " the expression of the phenomenon of diffusion with only one direction (Ox) is given by the 1st law of FICK:

$$J_{D.mol} = \frac{dn}{dt} = -D.S.\frac{\partial C_{mol}(x,t)}{\partial t}$$

Or

$$dn = -D.S.\frac{\partial C_{mol}(x,t)}{\partial t}.dt$$

Where $\boldsymbol{m} = \boldsymbol{n} \times \boldsymbol{M}$

$$J_{D.mass} = \frac{dm}{dt} = -D.S.\frac{\partial C_{mass}(x,t)}{\partial t}$$

Or

$$dm = -D.S.\frac{\partial C_{mass}(x,t)}{\partial t}.dt$$

The coefficient D is the diffusion coefficient. The negative sign (-) that appears, means that the diffusion takes place in the direction of decreasing concentrations.

2.4. 2nd law of Fick (or diffusion equation)

During the molecular migration through the pores of the membrane, the unidimensional concentration C (x, t) at any point in the system depends on the position x and also on the time t and is a solution of the equation of the second order relative to the position, which is given by Fick's 2nd law (or the diffusion equation).

To obtain the diffusion equation, simply postpone Fick's first law in the continuity equation:

$$\frac{\partial J(x,t)}{\partial x} + \frac{\partial C_{mol}(x,t)}{\partial t} = 0$$

$$\frac{\partial C_{mol}(x,t)}{\partial t} = -\frac{\partial J(x,t)}{\partial x} = \frac{\partial^2 C_{mol}(x,t)}{\partial x^2}$$

In the stationary regime, the concentration is independent of time (case of the concentration variation inside the pore).

$$\frac{\partial C_{mol}(x,t)}{\partial t} = 0$$

$$C(x,t) = f(x)$$

This implies that the concentration becomes a linear function of the first order in x.

Example 1:

Demonstrate that the diffusion coefficient of a spherical molecule is inversely proportional to the cube root of its molecular mass.

II.8. Diffusion through artificial membranes

Artificial membranes, such as cellophane and some types of plastic, are not completely permeable; they contain pores whose size depends on the manufacturing method. Therefore, molecules larger than the pores can pass through these membranes. The membrane's permeability coefficient is then determined, which is directly proportional to the ratio of the pore diameter to the molecule diameter [7,8].

At equilibrium, the solute concentrations in the two compartments are equal. The flow rate is therefore zero.

IV.2. OSMOSIS PHENOMENON AND OSMOTIC PRESSURE

Osmosis is a passive physical phenomenon that occurs only if the solutions are separated by a permselective (semi-permeable) membrane.

- Only the water molecules pass through the membrane of the hypotonic solution (the most diluted) to the hypertonic solution (the most concentrated solution) until the solutions are isotonic (with the same concentrations)

- Osmosis is found both for the living cell and for the dead cell.

- If the two media are of the same concentration, no movement of water is observed: the cell is in osmotic equilibrium.

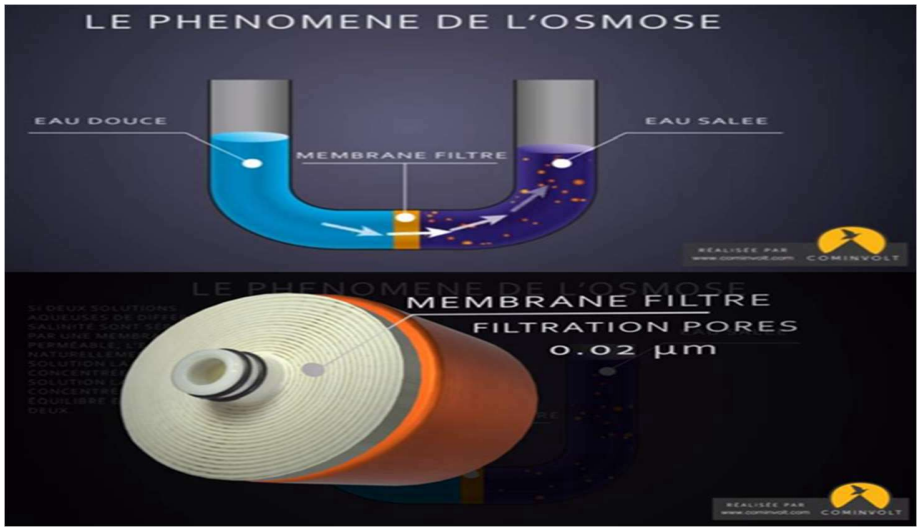

Figure IV.8. Illustration of the osmosis phenomenon

The membrane is permeable to water but impermeable to solutes.

The movement of water is from the least concentrated compartment in solutes to the most concentrated compartment. The water molecules follow their concentration gradient.

2. Osmotic pressure

The osmotic pressure of a solution is the hydrostatic pressure that should be exerted on the solution to prevent the pure solvent from crossing the membrane.

It is empirically established from numerous experimental studies and finally expressed in theoretical form by Vant 'Hoff as:

$$\pi = i.Cmol.R.T$$

Where:

i is the ionization coefficient that can be given by i = 1+α×(β-1), for a weak electrolyte and i =β for a strong electrolyte.

Cmol: molar concentration,

R: perfect gas constant and T: the temperature.

In this expression, one can also reason in Osmolarity (particulate molar concentration):

$$\pi = W.R.T$$

α: degree of dissociation (≤ 1) and

β: number of particles provided by the dissociation.

Experience:

The pressure (π = W × R × T) can be measured in the osmometer (Figure 2.8). The solution is placed in "A", the pure solvent (water) in "B"; between the two a semi-permeable membrane. The osmotic pressure is measured by the drop "h" of the liquid rising in the capillary tube.

Initially, the incoming solvent flow is much higher than the outgoing flow, then the equilibrium is reached. At this moment the hydrostatic pressure $\pi = h \times \rho \times g$ is equal to the osmotic pressure.

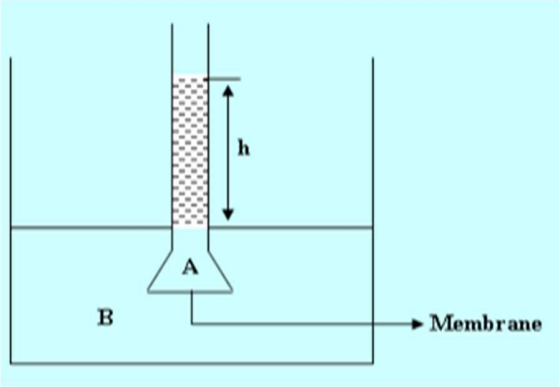

Figure IV.9. Schematic representation of an Osmometer

IV.5. Reverse Osmosis

Definition:

Reverse osmosis (RO) is the process in which solvent molecules (usually water) are forced to move from a concentrated solution to a dilute solution through a semipermeable membrane, by applying a pressure greater than the osmotic pressure.

Principle:

- Normally, in osmosis, water moves from low solute concentration → high solute concentration.
- In reverse osmosis, an external pressure greater than the osmotic pressure (π) is applied on the concentrated side.
- This reverses the natural flow, causing the solvent to pass in the opposite direction (from concentrated to dilute), while impurities and solutes are left behind.

Key Equation:

$$\boldsymbol{P > \pi}$$

where

- P= applied pressure and π= osmotic pressure

Applications:

- Water desalination: Converting seawater into fresh drinking water.
- Purification of drinking water: Removes salts, bacteria, and other contaminants.
- Food industry: Concentration of fruit juices or dairy products.
- Pharmaceutical industry: Production of ultra-pure water.

Advantages:

- Produces high-purity water.
- No heating required (energy-efficient compared to distillation).
- Environmentally friendly, since it doesn't require chemical additives.

Limitations:

- Requires high pressure and specialized membranes.
- Membrane fouling (blockage) can occur over time.
- The process produces brine (wastewater) that needs proper disposal.

IV.3. Application of Diffusion and Osmosis

1. In Biological Systems

a) Gas Exchange (Diffusion)

- Oxygen (O_2) diffuses from the lungs (high concentration) into the blood (low concentration).
- Carbon dioxide (CO_2) diffuses in the opposite direction — from blood to the lungs — to be exhaled. This is how respiration occurs in living organisms.

b) Nutrient and Waste Transport

- In cells: Nutrients like glucose and amino acids diffuse from extracellular fluid into the

cytoplasm.

- Waste products (like urea) diffuse from cells into the bloodstream to be eliminated.

c) Water Balance in Cells (Osmosis)

- Osmosis controls the movement of water through cell membranes.
- **Example:**
    - Plant cells absorb water from the soil by osmosis.
    - Red blood cells shrink in hypertonic solutions and swell in hypotonic ones.

2. In Industrial and Technological Applications

a) Dialysis (Medical Application of Osmosis and Diffusion)

- Used in artificial kidneys to remove waste products (like urea) from the blood through a semi-permeable membrane.
- Diffusion removes solutes, and osmosis maintains fluid balance.

b) Water Purification (Reverse Osmosis)

- Involves forcing water through a semi-permeable membrane that retains salts and impurities.
- Used in desalination plants to produce fresh water from seawater.

c) Food Preservation

- Salting and sugaring create hypertonic conditions around food (fish, jam, etc.), causing water to leave microbial cells by osmosis, thus preventing their growth.

d) Industrial Gas Separation (Diffusion)

- Diffusion is used to separate gases with different molecular sizes (e.g., in uranium enrichment or air purification).

3. In Plants

- **Diffusion:** Exchange of gases (O_2, CO_2) through the **stomata** during photosynthesis and respiration.
- **Osmosis:** Uptake of water from the soil by **root hair cells**, maintaining **turgor pressure** that supports the plant structure.

4. In Daily Life

- Smelling perfume or cooking odors (diffusion in air).
- Soaking vegetables in water to make them crisp (osmosis).
- Rehydration of dried fruits in water (osmosis).

Exercises Serie number 3

Exercise 1:

1. Define diffusion in your own words.
2. Explain the difference between free diffusion and membrane diffusion.
3. Why does diffusion not require energy?

Exercise 2:

For each of the following situations, indicate the direction of diffusion (from which side to which side):

a. O_2 between alveoli and blood in the lungs.

b. CO_2 between blood and alveoli.

c. Glucose between intestinal lumen and blood.

d. Water molecules across a semi-permeable membrane.

Exercise 3:

A) We consider a porous membrane that separates two compartments containing sucrose with concentrations of 0.5 and 0.2 $mol.l^{-1}$. These concentrations are held constant during the diffusion of sucrose molecules across the membrane. Assume steady (stationary) state.

1. Find the diffusion coefficient of sucrose?
2. What is the value of the sucrose Flux ?

Data: The molar flow rate of sucrose $J_D = 1.2 \times 10^{-2}$ $mol.s^{-1}$ is given.

Total number of pores in the membrane $N = 2.\ 10^4$, each pore of radius r = 0.9 mm. Thickness of the membrane h = 10 μm.

Exercise 04 :

We consider a membrane with thick 0.1mm separating two compartments A and B, compartment A contains a glucose solution at 0.2 mol / l, the concentration of glucose in compartment B is 0.1mol/ l.

1. Calculate the initial molar flux of glucose diffusion at 25 ° C knowing that the radius of these molecules supposed spherical is r = 3 Å.

2. What would be the initial molar flux of glucose diffusion at 0 ° C? Data: $k_B = 1.38.10^{-23}$ JK^{-1} and the viscosity of glucose; $\eta_g = 10^{-3}$ Pa.s.

Exercise 05 :

- Calculate the osmotic pressure at 27 ° C of an aqueous solution containing 9 g glucose and 2.92 g NaCl per liter.

With: R = 8.31 μmol^{-1}, $M_{NaCl} = 58.5\ g.mol^{-1}$, $M_{glucose} = 180\ g.mol^{-1}$.

Exercise 06 :

The blood serum contains about 75 g / l of protein including albumin (75000 g mol) and globulins (150000 g mol^{-1}). The ratio of mass albumin / globulin concentrations being equal to 1.5.

1. Calculate the molar concentration of serum proteins (these proteins are assumed non- dissociated).

2. Find the osmotic pressure that will be developed by these proteins through a perfect semipermeable membrane.

Chapter 05

Study of Viscosity

CHAPTER V: Study of Viscosity

Plan

V.1. Introduction
V.2 Laminar and turbulent flow
V.3. Viscous resistance and viscocity measurements
V.4. Sedimentation

Objective

Knowledge of the basic physics and properties of:

1. Viscosity
2. Laminar and turbulent flow
3. Resistance and measurements of viscosity
4. Sedimentatation

V.1. INTRODUCTION

Viscosity is the property of a fluid that resists flow. It measures the internal friction between adjacent layers of the fluid that move at different velocities. In simple terms, viscosity determines how “thick” or “sticky” a liquid or gas is.

When a fluid flows, its particles move past each other. The internal friction that opposes this relative motion is what we call viscosity.

A fluid with high viscosity (like honey or oil) flows slowly.

A fluid with low viscosity (like water or air) flows easily.

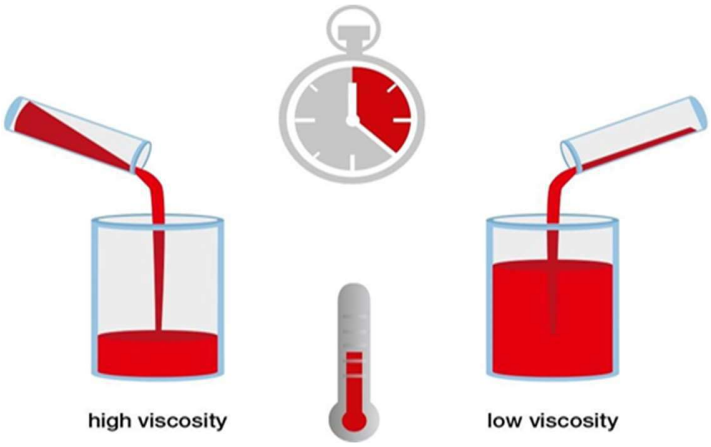

Figure V.1: Viscosity measurement in the personal care industry

In such a case, experiments show that some stress (such as a pressure difference between the two ends of the tube) is needed to sustain the flow through the tube. This is because a force is required to overcome the friction between the layers of the fluid which are in relative motion: the strength of this force is proportional to the viscosity.

A fluid that has no resistance to shear stress is known as an ideal or inviscid fluid. Zero viscosity is observed only at very low temperatures in superfluids. Otherwise, the second law of thermodynamics requires all fluids to have positive viscosity;[2][3] such fluids are technically said to be viscous or viscid. A fluid with a high viscosity, such as pitch, may appear to be a solid.

V.2. LAMINAR AND TURBULENT FLOW

From a practical engineering point of view, the flow regime can be categorized according to several criteria.

All fluid flow is classified into one of two broad categories or regimes. These two flow regimes are:

- Single-phase Fluid Flow
- Multi-phase Fluid Flow (or Two-phase Fluid Flow)

This is a basic classification. All of the fluid flow equations (e.g. Bernoulli's Equation) and relationships that were discussed in this section (Fluid Dynamics) were derived for the flow of a single phase of fluid whether liquid or vapor. Solution of multi-phase fluid flow is very complex and difficult and therefore it is usually in advanced courses of fluid dynamics.

Another usually more common classification of flow regimes is according to the shape and type of streamlines. All fluid flow is classified into one of two broad categories. The fluid flow can be either laminar or turbulent and therefore these two categories are:

- Laminar Flow
- Turbulent Flow

Laminar flow is characterized by smooth or in regular paths of particles of the fluid. Therefore, the laminar flow is also referred to as streamline or viscous flow. In contrast to laminar flow, turbulent flow is characterized by the irregular movement of particles of the fluid. The turbulent fluid does not flow in parallel layers, the lateral mixing is very high, and there is a disruption between the layers. Most industrial flows, especially those in nuclear engineering are turbulent.

The flow regime can be also classified according to the geometry of a conduit or flow area. From this point of view, we distinguish:

- Internal Flow
- External Flow

Internal flow is a flow for which the fluid is confined by a surface. Detailed knowledge of behavior of internal flow regimes is of importance in engineering, because circular pipes can withstand high pressures and hence are used to convey liquids. On the other hand, external flow is such a flow in which boundary layers develop freely, without constraints imposed by adjacent surfaces. Detailed knowledge of behavior of external flow regimes is of importance especially in aeronautics and aerodynamics.

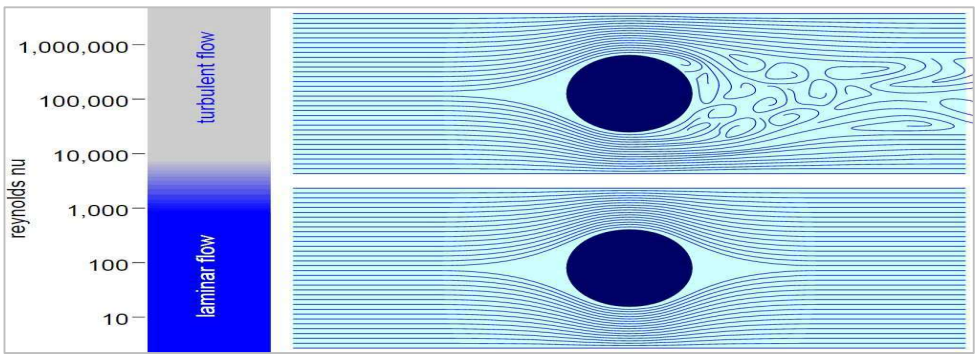

Figure V.2: Laminar vs Turbulent flow

2.1. Laminar flow

In fluid dynamics, laminar flow is characterized by smooth or in regular paths of particles of the fluid, in contrast to turbulent flow, that is characterized by the irregular movement of particles of the fluid. The fluid flows in parallel layers (with minimal lateral mixing), with no disruption between the layers. Therefore, the laminar flow is also referred to as streamline or viscous flow. The term streamline flow is descriptive of the flow because, in laminar flow, layers of water flowing over one another at different speeds with virtually no mixing between layers, fluid particles move in definite and observable paths or streamlines.

2.2. Turbulent flow

In fluid dynamics, turbulent flow is characterized by the irregular movement of particles (one can say chaotic) of the fluid. In contrast to laminar flow the fluid does not flow in parallel layers, the lateral mixing is very high, and there is a disruption between the layers. Turbulence is also characterized by recirculation, eddies, and apparent randomness. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.

Detailed knowledge of behavior of turbulent flow regime is of importance in engineering, because most industrial flows, especially those in nuclear engineering are turbulent. Unfortunately, the highly intermittent and irregular character of turbulence complicates all analyses. In fact, turbulence is often said to be the "last unsolved problem in classical mathematical physics." The main tool available for their analysis is CFD analysis. CFD is a branch of fluid mechanics that uses numerical analysis and algorithms to solve and analyze problems that involve turbulent fluid flows. It is widely accepted that the Navier–Stokes equations (or simplified Reynolds-averaged Navier–Stokes equations) are capable of exhibiting turbulent solutions, and these equations are the basis for essentially all CFD codes.

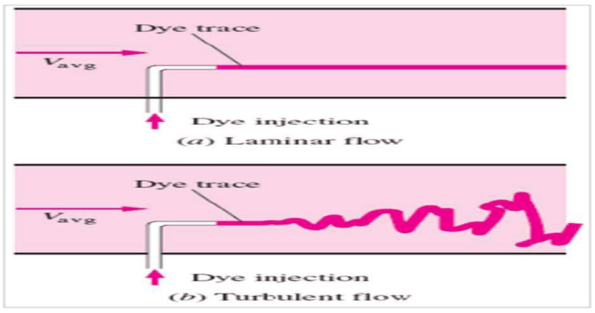

Figure V.3: The behavior of the injected dye in laminar and turbulence flow.

V.3. VISCOUS RESISTANCE AND VISCOCITY MEASUREMENTS

1. Viscous resistance

A moving body in a viscous fluid carries with it a thin film of fluid, called the boundary layer. This phenomenon induces an expenditure of energy which results in a force opposing the movement of the body called "Viscous resistance" the viscous resistance (RV), whose coefficient of viscous resistance (Cv) is related to the number of Reynolds (Re) and to the roughness (K) relative to the length of the shell (L):

$$R_V = C_V \times (Re \times K / L) \qquad V.1$$

If the object moves near the surface, the viscous resistance or drag will be accompanied by resistance due to surface wave formation.

3.1. Viscosity measurements

Viscosity is measured with various types of viscometers and rheometers. A rheometer is used for fluids that cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than is the case for a viscometer. Close temperature control of the fluid is essential to obtain accurate measurements, particularly in materials like lubricants, whose viscosity can double with a change of only 5 °C.

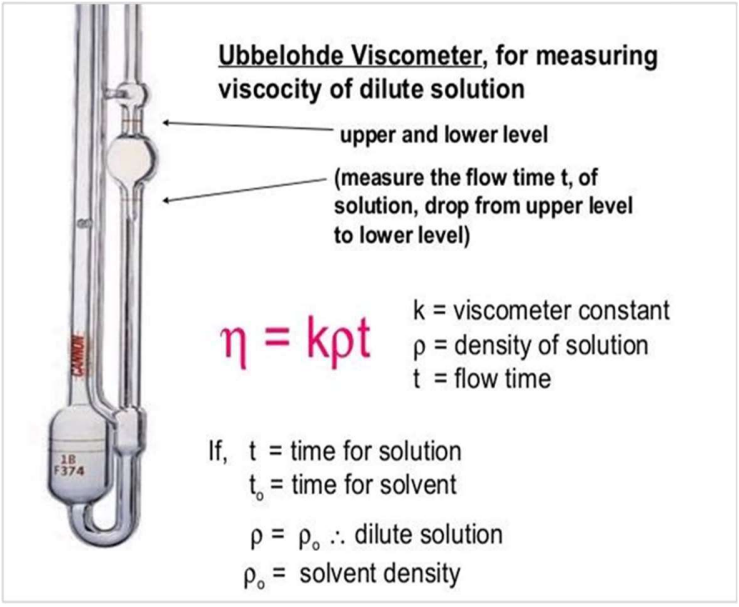

Figure V.3: Viscosity measurement.

For some fluids, the viscosity is constant over a wide range of shear rates (Newtonian fluids). The fluids without a constant viscosity (non-Newtonian fluids) cannot be described by a single number. Non-Newtonian fluids exhibit a variety of different correlations between shear stress and shear rate.

One of the most common instruments for measuring kinematic viscosity is the glass capillary viscometer.

In coating industries, viscosity may be measured with a cup in which the efflux time is measured. There are several sorts of cup – such as the Zahn cup and the Ford viscosity cup – with the usage of each type varying mainly according to the industry. The efflux time can also be converted to kinematic viscosities (centistokes, cSt) through the conversion equations.

Also used in coatings, a Stormer viscometer uses load-based rotation in order to determine viscosity. The viscosity is reported in Krebs units (KU), which are unique to Stormer viscometers.

Vibrating viscometers can also be used to measure viscosity. Resonant, or vibrational viscometers work by creating shear waves within the liquid. In this method, the sensor is submerged in the fluid and is made to resonate at a specific frequency. As the surface of the sensor shears through the liquid, energy is lost due to its viscosity. This dissipated energy is then measured and converted into a viscosity reading. A higher viscosity causes a greater loss of energy.

Extensional viscosity can be measured with various rheometers that apply extensional stress. Volume viscosity can be measured with an acoustic rheometer.

Apparent viscosity is a calculation derived from tests performed on drilling fluid used in oil or gas well development. These calculations and tests help engineers develop and maintain the properties of the drilling fluid to the specifications required.

V.4. SEDIMENTATION

Sedimentation is the physical process by which particles suspended in a liquid settle under the effect of gravity or centrifugal force. It separates solid particles from a fluid (usually water) when the particles are heavier than the liquid.

4.1. Principle:

When a suspension is left undisturbed, the solid particles, due to their higher density, move downward and accumulate at the bottom, forming a sediment layer. The clearer liquid that remains above is called the supernatant.

4.2. Types of Sedimentation:

1. Simple (Gravity) Sedimentation:

Occurs naturally under the action of gravity (e.g., mud settling in water).

2. Accelerated Sedimentation (Centrifugation):

Achieved using a centrifuge, which increases the rate of sedimentation by applying a centrifugal force.

3. Flocculent Sedimentation:

Involves the use of coagulants or flocculants to form larger aggregates (flocs) that settle faster.

4.3. Applications:

- Water and wastewater treatment: to remove suspended solids.
- Biology: separation of cells or organelles (by centrifugation).
- Industrial processes: clarification of liquids, purification, and recovery of solids.

Example:

When muddy water is left in a beaker, the soil particles gradually settle at the bottom forming a layer of sediment, while clear water remains above.

4.4. Measurement

A particle or droplet will settle in a fluid if its density is greater than that of the fluid in which it is suspended. The (laminar) settling velocity of particles whose concentration is very

low, that is when the flow of fluid around a particle does not affect the flow around neighboring particles, can be calculated from Stokes Law:

$$u = \frac{D^2 \times g}{18\eta}\Delta\rho$$

where D is the diameter of the particle and η is the absolute viscosity of the surrounding fluid. Δρ is the density difference between that of the particle and its surrounding fluid: if Δρ is positive the particle will settle (see Thickeners), or if it is negative the particle will float (see Flotation).

In practice, the concentration of particles in industrial suspensions is usually high enough for there to be significant interactions between particles as they settle (making Stokes Law invalid): these interactions can greatly increase the frictional force at the surfaces of the settling particles. When the effects of mutual interference are negligible, free settling conditions are said to prevail; at higher concentrations hindered settling occurs. The reasons for modification of the settling rate of particles in a concentrated suspension include:

a. when a wide range of particle sizes are present in the feed, differential settling rates between large and small particles lead to modification of the effective density of the suspension (this is more significant in small scale batch sedimentation),

b. the upward velocity of the fluid is greater at higher concentrations (causing a decrease in the apparent settling velocity),

c. the velocity gradients in the fluid surrounding the particles are greater due to the closer proximity of the particles,

d. the ability of particles to aggregate is enhanced at higher concentrations.

In addition to particle size, density and concentration, and fluid viscosity, other less obvious factors affect the sedimentation rate. These include particle shape and orientation, convection currents in the surrounding fluid, and chemical pretreatment of the feed suspension. Particle with diameters of the order of a few microns settle too slowly for most practical operations; wherever possible these are coagulated or flocculated to increase their effective size, and hence increase their rate of settling.

Sedimentation of a suspension is generally assessed by a jar test, during which a suspension

is allowed to settle and the height of the clear liquid (supernatant)-suspension interface is measured as a function of the settling time. In a jar test particle can be observed to settle in any of several quite different ways, dependent on their concentration and their tendency to cohere. The different modes of sedimentation make different demands on the size and shape of a settling tank, and different test procedures are used for evaluating them [details of these are given by Fitch and Stevenson (1986)].

When the particles are, on average, far apart and free to settle individually, clarification sedimentation occurs. This behavior is recognized in a jar test as slower settling particles "string out" behind faster ones, and the supernatant gradually clarifies; solids collect at the bottom of the jar to form a sediment, and the supernatant-suspension interface is generally indistinct.

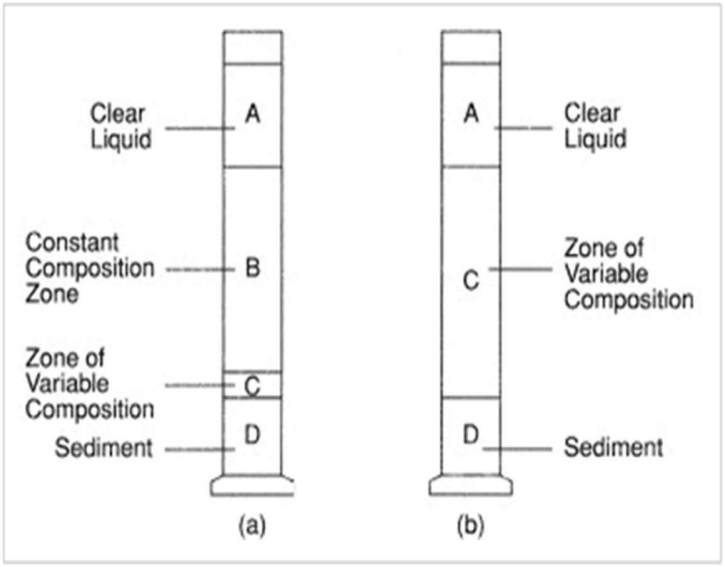

Figure V.4. Line settling (a), and clarification (b), behavior during sedimentation.

In more concentrated suspensions, the particles are closer together; in the extreme they can cohere to form a plastic structure which constrains the sedimentation of individual particles. The solids settle with a sharp interface between the pulp and supernatant, and the slurry enters a consolidated or zone settling regime and exhibits zone settling or line settling behavior. These two extremes of behavior are shown in Figure V.4.

In a jar test exhibiting line settling behavior the interface height can be plotted against time as in Figure V.5. After an initial transient the suspension settles at a constant rate in the section from A to B, followed by the first falling rate period from B to C and a second falling rate

period from C. The constant rate period corresponds to pulp settling at its initial concentration. During the final falling rate section the pulp is in compression. Point C is known as the compression point or the critical sedimentation point, and identifies the point at which the pulp-supernatant interface goes from zone settling into compression.

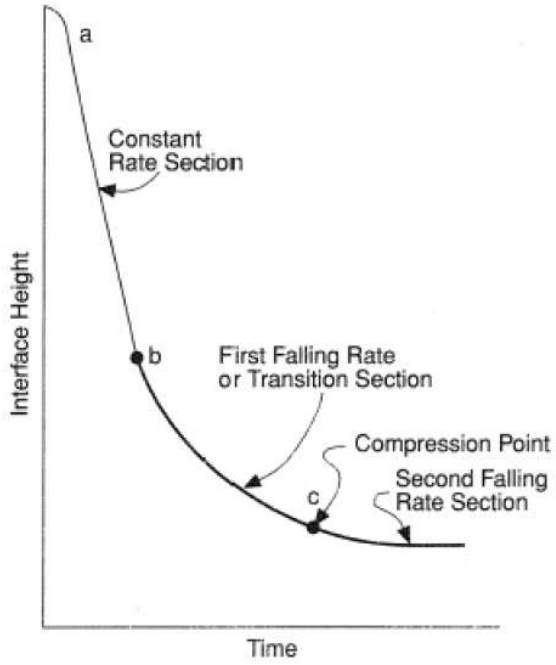

Figure V.5. Sedimentation curve arising from line settling behavior.

Chapter 06

Sound waves and Ultrasound

CHAPTER VI : Sound waves and Ultrasound

Plan

VI.1. The sound waves and its properties: production, nature and classification.

VI.2. Doppler effect: definition, measurements and biological applications.

VI.3. Ultrasound: definition, measurements and biological applications.

Objective

Knowledge of the basic physics and properties of:

1. Sound waves
2. Doppler effect
3. ultrasound

VI.1. INTRODUCTION

Sound is one of the most familiar and important phenomena in our daily lives. It is a form of mechanical energy that travels through matter by means of vibrations or oscillations of the particles in a medium such as air, water, or solid materials. These vibrations produce longitudinal waves, characterized by successive compressions and rarefactions that transfer energy from the source to the receiver without any net movement of the medium itself.

The study of sound, known as acoustics, explores how sound waves are generated, transmitted, and detected. Several physical parameters define sound waves, including frequency, wavelength, amplitude, velocity, and intensity. The frequency determines the pitch of the sound, while the amplitude relates to its loudness. The speed of sound depends on the medium's density and elasticity, being faster in solids, slower in liquids, and slowest in gases.

According to their frequency, sound waves are classified into three main categories:

- Infrasound: frequencies lower than 20 Hz, below the threshold of human hearing.
- Audible sound: frequencies between 20 Hz and 20,000 Hz, detectable by the human ear.
- Ultrasound: frequencies above 20,000 Hz, beyond the range of human hearing.

Ultrasound has unique characteristics due to its high frequency and short wavelength, allowing it to be reflected, refracted, and absorbed by different materials in precise ways. These properties make it extremely valuable in various scientific, industrial, and medical applications. In medicine, ultrasound is used for non-invasive imaging techniques such as echography and Doppler ultrasound, which provide real-time visualization of internal organs, tissues, and blood flow. In industry, ultrasonic waves are applied in non-destructive testing, cleaning, and even welding processes. Moreover, in research, ultrasound assists in studying physical properties of materials and biological tissues.

VI.2. SOUND WAVES

The sound is produced when an object's vibrations move through a medium until they enter the human eardrum. In physics, the sound is produced in the form of a pressure wave. When an object vibrates, it causes the surrounding air molecules to vibrate, initiating a chain reaction of sound wave vibrations throughout the medium. While the physiological definition includes a subject's reception of sound, the physics definition recognizes that sound exists independently of an individual's reception.

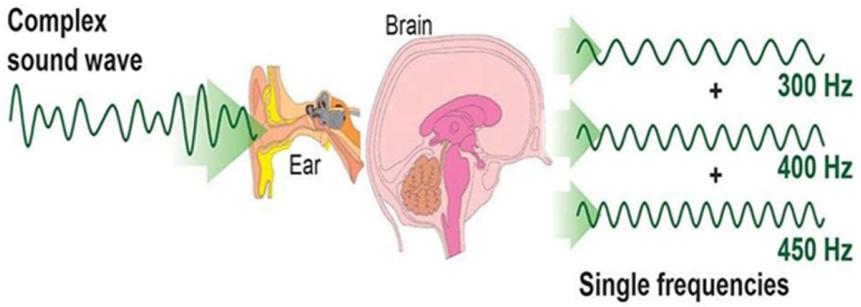

Figure VI.1: Treatment and regulation of sound waves by the human eardrum.

There are many different types of sound including, audible, inaudible, unpleasant, pleasant, soft, loud, noise and music. You're likely to find the sounds produced by a piano player soft,

audible, and musical. And while the sound of road construction early on Saturday morning is also audible, it certainly isn't pleasant or soft. Other sounds, such as a dog whistle, are inaudible to the human ear. This is because dog whistles produce sound waves that are below the human hearing range of 20 Hz to 20,000 Hz. Waves below 20 Hz are called infrasonic waves (infrasound), while higher frequencies above 20,000 Hz are known as ultrasonic waves (ultrasound).

2.1.1. Infrasonic waves (infrasound)

Infrasonic waves have frequencies below 20 Hz, which makes them inaudible to the human ear. Scientists use infrasound to detect earthquakes and volcanic eruptions, to map rock and petroleum formations underground, and to study activity in the human heart. Despite our inability to hear infrasound, many animals use infrasonic waves to communicate in nature. Whales, hippos, rhinos, giraffes, elephants, and alligators all use infrasound to communicate across impressive distances – sometimes hundreds of miles!

2.1.2. Ultrasonic waves (ultrasound)

Sound waves that have frequencies higher than 20,00 Hz produce ultrasound. Because ultrasound occurs at frequencies outside the human hearing range, it is inaudible to the human ear. Ultrasound is most often used by medical specialists who use sonograms to examine their patients' internal organs. Some lesser-known applications of ultrasound include navigation, imaging, sample mixing, communication, and testing. In nature, bats emit ultrasonic waves to locate prey and avoid obstacles.

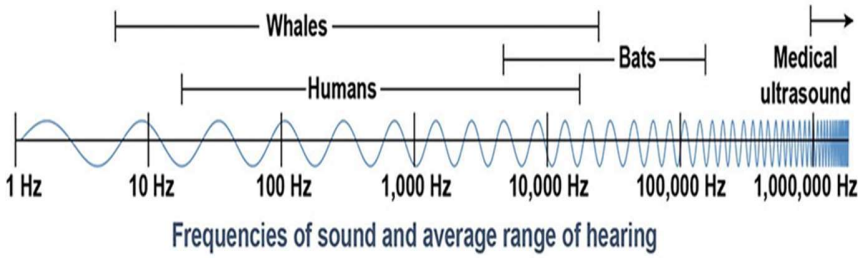

Figure VI.2: Frequencies of sound and average range of hearing

2.2. Production of sound

Sound is produced when an object vibrates, creating a pressure wave. This pressure wave

causes particles in the surrounding medium (air, water, or solid) to have vibrational motion. As the particles vibrate, they move nearby particles, transmitting the sound further through the medium. The human ear detects sound waves when vibrating air particles vibrate small parts within the ear.

In many ways, sound waves are similar to light waves. They both originate from a definite source and can be distributed or scattered using various means. Unlike light, sound waves can only travel through a medium, such as air, glass, or metal. This means there's no sound in space.

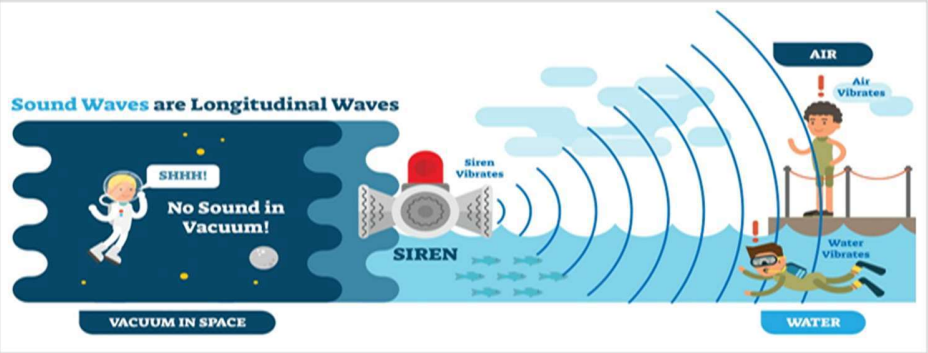

Figure VI.3: Sound waves

2.3. Type of waves

Sound waves fall into three categories: longitudinal waves, mechanical waves, and pressure waves.

2.3.1. Longitudinal waves

A longitudinal wave is a wave in which the motion of the medium's particles is parallel to the direction of the energy transport. Sound waves in air and fluids are longitudinal waves, because the particles that transport the sound vibrate parallel to the direction of the sound wave's travel. If you push a slinky back and forth, the coils move in a parallel fashion (back and forth). Similarly, when a tuning fork is struck, the direction of the sound wave is parallel to the motion of the air particles.

2.3.2. Mechanical waves

A mechanical wave is a wave that depends on the oscillation of matter, meaning that it

transfers energy through a medium to propagate. These waves require an initial energy input that then travels through the medium until the initial energy is effectively transferred. Examples of mechanical waves in nature include water waves, sound waves, seismic waves and internal water waves, which occur due to density differences in a body of water. There are three types of mechanical waves: transverse waves, longitudinal waves, and surface waves.

Sound waves move through air by displacing air particles in a chain reaction. As one particle is displaced from its equilibrium position, it pushes or pulls on neighboring molecules, causing them to be displaced from their equilibrium. As particles continue to displace one another with mechanical vibrations, the disturbance is transported throughout the medium. These particle-to- particle, mechanical vibrations of sound conductance qualify sound waves as mechanical waves. Sound energy, or energy associated with the vibrations created by a vibrating source, requires a medium to travel, which makes sound energy a mechanical wave.

2.3.3. Pressure waves

A pressure wave, or compression wave, has a regular pattern of high- and low-pressure regions. Because sound waves consist of compressions and rarefactions, their regions fluctuate between low and high-pressure patterns. For this reason, sound waves are considered to be pressure waves. For example, as the human ear receives sound waves from the surrounding environment, it detects rarefactions as low-pressure periods and compressions as high-pressure periods.

2.3.4. Transverse waves

Transverse waves move with oscillations that are perpendicular to the direction of the wave. Sound waves are not transverse waves because their oscillations are parallel to the direction of the energy transport; however sound waves can become transverse waves under very specific circumstances. Transverse waves, or shear waves, travel at slower speeds than longitudinal waves, and transverse sound waves can only be created in solids. Ocean waves are the most common example of transverse waves in nature.

2.4. Characteristics of sound waves:

There are five main characteristics of sound waves: wavelength, amplitude, frequency, time

period, and velocity.

- The wavelength of a sound wave indicates the distance that wave travels before it repeats itself. The wavelength itself is a longitudinal wave that shows the compressions and rarefactions of the sound wave.

- The amplitude of a wave defines the maximum displacement of the particles disturbed by the sound wave as it passes through a medium. A large amplitude indicates a large sound wave.

- The frequency of a sound wave indicates the number of sound waves produced each second. Low-frequency sounds produce sound waves less often than high-frequency sounds.

- The time period of a sound wave is the amount of time required to create a complete wave cycle. Each vibration from the sound source produces a wave's worth of sound. Each complete wave cycle begins with a trough and ends at the start of the next trough.

- Lastly, the velocity of a sound wave tells us how fast the wave is moving and is expressed as meters per second.

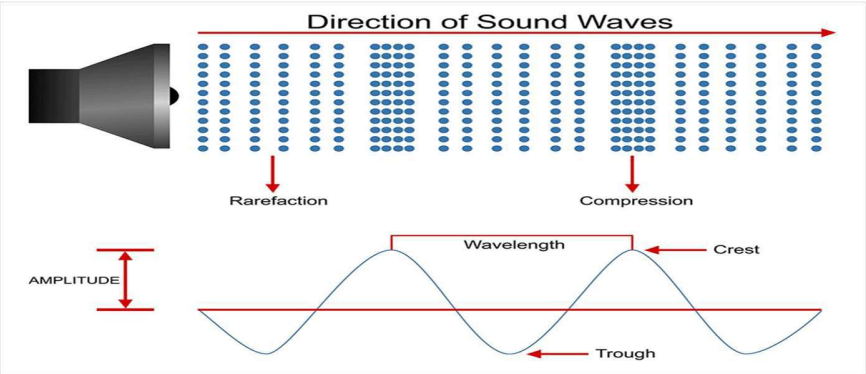

Figure VI.5: Sound wave diagram. A wave cycle occurs between two troughs.

2.4.1. Units of sound

When we measure sound, there are four different measurement units available to us. The first unit is called the decibel (dB). The decibel is a logarithmic ratio of the sound pressure compared to a reference pressure. The next most frequently used unit is the hertz (Hz). The hertz is a measure of sound frequency. Hertz and decibels are widely used to describe and measure sounds, but Phon and sone are also used. A sone is the perceived loudness of a sound and a

Phon is the unit of loudness for pure tones. Additionally, the Phon refers to subjective loudness, while the sone is the perceived loudness.

2.4.2. Sound waves graphs explained

Sound waves can be described by graphing either displacement or density. Displacement-time graphs represent how far the particles are from their original places and indicates which direction they've moved. Particles that show up on the zero line in a particle displacement graph didn't move at all from their normal position. These seemingly motionless particles experience more compressions and rarefactions than other particles. Since pressure and density are related, a pressure versus time graph will display the same information as a density versus time graph. These graphs indicate where the particles are compressed and where they are very expanded. Unlike displacement graphs, particles along the zero line in a density graph are never squished or pulled apart. Instead, they are the particles that move back and forth the most.

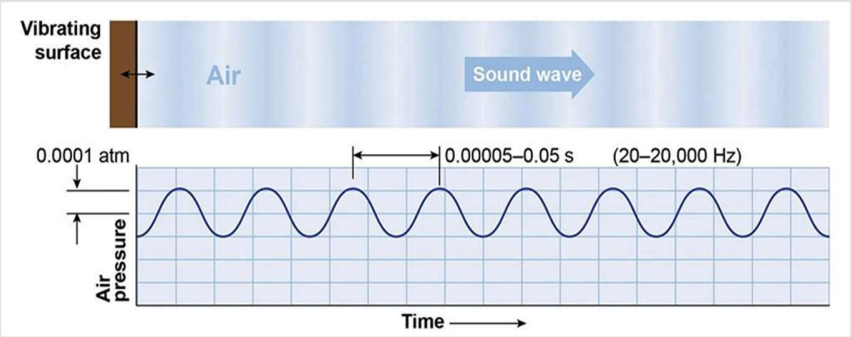

Figure VI.6: Description of sound waves by graphing

2.4.3. Sound Pressure

Sound pressure describes the local pressure deviation from the ambient atmospheric pressure as a sound wave travels. It's important to recognize that sound pressure and air pressure are not the same concept.

Overall, the speed of sound is not influenced by air pressure. As sound waves pass from the sound source through the air, they alter the pressure experienced by air nearby particles.

2.4.4. Sound level

Sound level is a comparison of the sound wave's pressure relative to the reference point.

Sound level is measured in decibels, with higher decibels correlating to higher sound levels. Some sound instruments measure sound level in dBc, which is the power ratio (decibels) of a signal to its carrier signal.

Other sound instruments measure the relative loudness of sounds as perceived by the human ear using a-weighted decibels, known as dBa. When dBa is used, sounds at low frequencies have their decibel values reduced and compared to unweighted decibels.

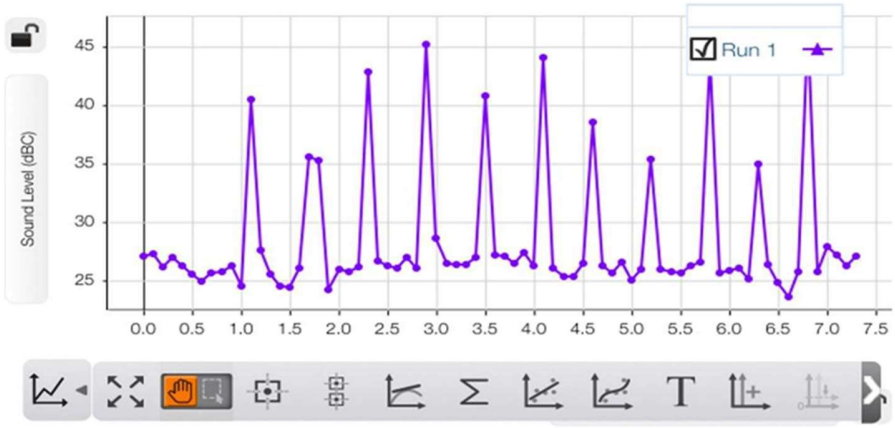

Figure VI.7: Demonstration of sound level

2.4.5. Sound intensity

Sound intensity is the power per unit area carried by a sound wave. The more intense the sound is, the larger the amplitude oscillations will be. As sound intensity increases, the pressure exerted by the sound waves on nearby objects also increases.

Decibels are used to measure the ratio of a given intensity (I) to the threshold of hearing intensity, which typically has a value of 1000 Hz for the human ear.

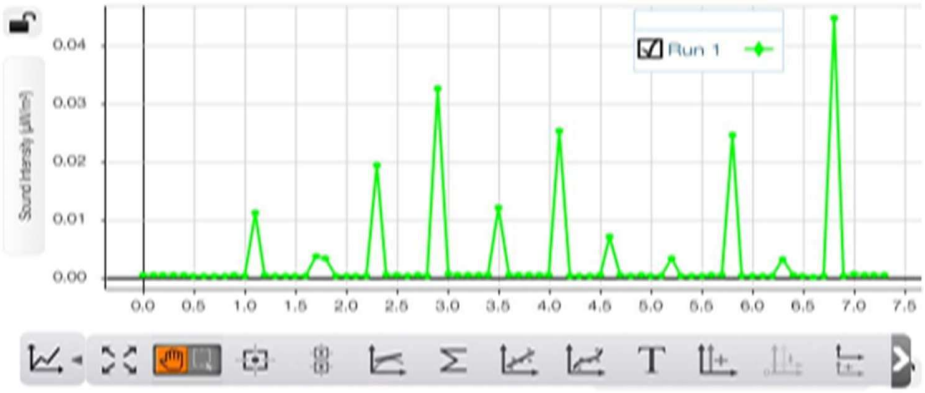

Figure VI.8: Demonstration of sound intensity

2.5. Speed of sound

The speed of sound is the distance traveled by a sound wave per unit of time as it propagates through a medium (solid, liquid, or gas). It depends on the elastic properties and density of the medium.

$$v = \sqrt{\frac{E}{\rho}}$$

where:

- v: speed of sound (m/s)
- E: elastic modulus of the medium (e.g., bulk modulus for fluids, Young's modulus for solids)
- ρ: density of the medium (kg/m³)

2.5.1. Factors Affecting the Speed of Sound:

1. **Medium Type:**

   Sound travels faster in solids than in liquids, and faster in liquids than in gases.

2. **Temperature (for gases):**

   The higher the temperature, the faster the sound travels.

$$v = 331 + 0.6T$$

where T= temperature in °C.

3. **Density:**

   Higher density usually slows down the wave (if elasticity doesn't increase accordingly).

4. **Elasticity:**

   The more elastic the medium, the faster the sound travels.

2.5.2. Biological Importance:

- In medical ultrasound, knowing the speed of sound in tissues (~1540 m/s) allows accurate calculation of distance and image formation.
- Differences in sound speed between tissues help to distinguish organs and detect abnormalities.

VI.3. DOPPLER EFFECT

The Doppler effect (or the Doppler shift) is the change in frequency of a wave in relation to an observer who is moving relative to the wave source. It is named after the Austrian physicist Christian Doppler, who described the phenomenon in 1842. A common example of Doppler shift is the change of pitch heard when a vehicle sounding a horn approaches and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by, and lower during the recession.

The reason for the Doppler effect is that when the source of the waves is moving towards the observer, each successive wave crest is emitted from a position closer to the observer than the crest of the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave. Hence, the time between the arrivals of successive wave crests at the observer is reduced, causing an increase in the frequency. While they are traveling, the distance between successive wave fronts is reduced, so the waves "bunch together". Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wave fronts is then increased, so the waves "spread out".

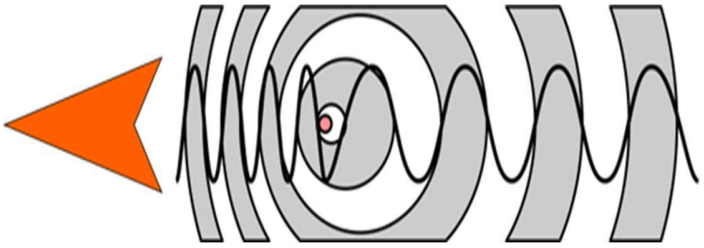

Figure VI.9: Change of wavelength caused by motion of the source.

For waves that propagate in a medium, such as sound waves, the velocity of the observer and of the source are relative to the medium in which the waves are transmitted.[1] The total Doppler effect may therefore result from motion of the source, motion of the observer, or motion of the medium. Each of these effects is analyzed separately. For waves which do not require a medium, such as electromagnetic waves or gravitational waves, only the relative difference in velocity between the observer and the source needs to be considered, giving rise to the relativistic Doppler effect.

3.1. Mathematical Expression:

For sound waves:

$$f' = f\left(\frac{v + v_o}{v + v_s}\right)$$

where:

- f': observed frequency
- f: emitted frequency
- v: velocity of sound in the medium
- v_o: velocity of the observer (positive if moving toward the source)
- v_s: velocity of the source (positive if moving away from the observer)

3.2. Measurements:

- In ultrasound diagnostics, the Doppler effect is used to measure the velocity of moving objects, such as blood cells.
- The frequency shift ($\Delta f = f' - f$) allows calculation of the speed of movement:

$$v = \frac{c\,\Delta f}{2 f_0 \cos\,\theta}$$

where:

- c: speed of sound in the medium

- f_0: transmitted frequency
- θ: angle between the ultrasound beam and the direction of blood flow

3.3. Biological Applications:

1. **Medical Ultrasound (Doppler Ultrasound):**
   - Measures blood flow velocity in arteries and veins.
   - Detects blockages or narrowing of blood vessels.
   - Monitors heart valve function and fetal blood circulation during pregnancy.
2. **Cardiology:**
   Used to analyze the movement of the heart walls and measure cardiac output.
3. **Obstetrics:**
   Monitors blood circulation between the mother and fetus.

- **Example:**

In a Doppler echocardiogram, the change in frequency of reflected ultrasound waves from red blood cells is used to calculate the velocity and direction of blood flow in the heart.

VI.4. ULTRASOUND

Ultrasound is defined by the American National Standards Institute as "sound at frequencies greater than 20 kHz". In air at atmospheric pressure, ultrasonic waves have wavelengths of 1.9 cm or less. Ultrasound is sound waves with frequencies higher than the upper audible limit of human hearing. Ultrasound is not different from "normal" (audible) sound in its physical properties, except that humans cannot hear it. This limit varies from person to person and is approximately 20 kilohertz (20,000 hertz) in healthy young adults. Ultrasound devices operate with frequencies from 20 kHz up to several gigahertz.

Ultrasound is used in many different fields. Ultrasonic devices are used to detect objects and measure distances. Ultrasound imaging or sonography is often used in medicine.

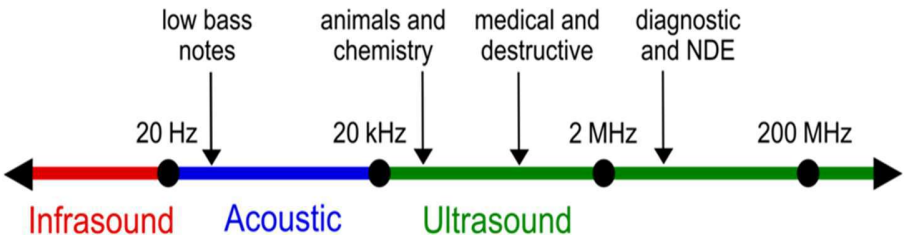

Figure VI.13: Approximate frequency ranges corresponding to ultrasound, with rough guide of some applications.

In the nondestructive testing of products and structures, ultrasound is used to detect invisible flaws. Industrially, ultrasound is used for cleaning, mixing, and accelerating chemical processes. Animals such as bats and porpoises use ultrasound for locating prey and obstacles.

4.1. Principle:

Ultrasound waves are generated by piezoelectric crystals that vibrate when an electric current passes through them.

When these waves travel through the body, they are reflected at boundaries between tissues of different densities.

The reflected waves (echoes) are detected and converted into images or measurements.

4.2. Measurements:

1. **Velocity of Ultrasound in Tissues:**
    - Varies depending on tissue type:
        - Air: ~330 m/s
        - Water: ~1500 m/s
        - Soft tissues: ~1540 m/s
        - Bone: ~3500 m/s
2. **Wavelength (λ):**

$$\lambda = \frac{c}{f}$$

3. **Intensity:**
    - Expressed in watts per square meter (W/m^2).

- Important for determining safe exposure levels during medical use.

4. **Resolution:**

   - Higher frequencies → better image resolution, but lower penetration depth.
   - Lower frequencies → deeper penetration, but lower resolution.

VI.6. Biological Applications:

1. Medical Imaging (Ultrasonography):

- Visualizes organs, fetuses, muscles, and tendons.
- Detects tumors, cysts, or inflammation.

2. Doppler Ultrasound:

- Measures blood flow and cardiac activity using the Doppler effect.

3. Therapeutic Applications:

- Used in physiotherapy to accelerate tissue healing.
- In surgery, focused ultrasound can destroy targeted tissues (e.g., kidney stones, tumors).

4. Biological Research:

- Studies cell structures and tissue properties.

Example:

During pregnancy, an ultrasound scan allows visualization of the fetus and monitoring of its development without any invasive procedure.

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