Lecture 5 "Surface Phenomena, Solutions, and Properties of Phase Boundaries"

Goal of the lecture: To understand the physical and chemical behavior of molecules at surfaces and interfaces, the formation and properties of solutions, and the thermodynamic principles governing phase boundaries. The lecture aims to explain surface tension, adsorption, types of solutions, and interfacial energy, which are key to understanding catalysis, colloids, detergents, and many industrial and biological processes.

Brief lecture notes:

1. Surface Phenomena and Surface Tension

At the boundary between two phases (for example, liquid–gas or liquid–solid), molecules experience **unbalanced intermolecular forces** because they are not surrounded by identical molecules on all sides. This creates a measurable property known as **surface tension (γ)** — the energy required to increase the surface area of a liquid by one unit.

Mathematically:

$$\boldsymbol{\gamma = \frac{F}{l}}$$

where

- γ = surface tension (N/m),
- F = force acting along the surface (N),
- l = length of the line along which the force acts (m).

Table – 1. Typical values of surface tension at 25°C:

Substance	**Surface Tension (N/m × 10^{-3})**
Water	72.8
Ethanol	22.3
Benzene	28.9
Mercury	485

Surface tension **decreases with temperature** and the presence of surface-active agents (surfactants). This explains how **soap and detergents** reduce the surface tension of water, enabling better cleaning by increasing wetting ability.

2. Adsorption at Interfaces

Adsorption is the accumulation of molecules or ions at the surface of a solid or liquid. It differs from absorption, which occurs throughout the bulk.

There are two main types of adsorption:

- **Physical adsorption (physisorption):** weak van der Waals forces, reversible, low heat of adsorption (~20 kJ/mol).

- **Chemical adsorption (chemisorption):** strong covalent or ionic bonding, often irreversible, high heat of adsorption (~80–400 kJ/mol).

The relationship between the amount adsorbed and gas pressure is described by the **Langmuir adsorption isotherm**:

$$\theta = \frac{bP}{1 + bP}$$

where

- θ = fraction of the surface covered,
- b = adsorption constant,
- P = pressure of the gas.

This equation assumes monolayer adsorption on a homogeneous surface.

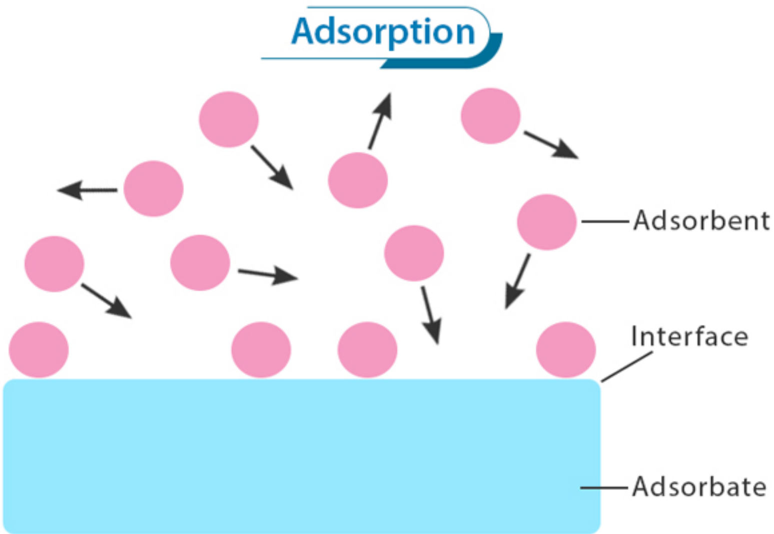

Figure – 1. llustration of Surface Adsorption

Adsorption is fundamental in **heterogeneous catalysis**, such as in the **Haber process** for ammonia synthesis:

$N_2(g)+3H_2(g) \rightleftharpoons 2NH_3(g)$

Catalysts like Fe or Ru adsorb gases on their surface, weakening chemical bonds and lowering activation energy.

3. Solutions and Concentration Units

A **solution** is a homogeneous mixture of two or more substances. The **solute** is the component present in smaller quantity, and the **solvent** is the medium in which it is dissolved.

Table – 2. Common concentration units

Unit	Symbol	Definition
Molarity	M	moles of solute / liter of solution
Molality	m	moles of solute / kg of solvent
Mole fraction	χ	moles of component / total moles of mixture
Mass percent	% w/w	(mass of solute / total mass) × 100

The **vapor pressure lowering** in a solution is given by **Raoult's law**:

$$P_A = X_A P_A°$$

where

- P_A = partial vapor pressure of component A,
- X_A= mole fraction of A in the solution,
- P_A°= vapor pressure of pure component.

This law forms the basis for understanding **colligative properties** like boiling point elevation, freezing point depression, and osmotic pressure.

4. Properties of Phase Boundaries

A **phase boundary** is the interface separating two distinct physical states (e.g., solid–liquid, liquid–gas). At these boundaries, special properties arise due to differences in **density, chemical potential, and energy** between phases.

At equilibrium between two phases α and β:

$$\mu_\alpha = \mu_\beta$$

where μ is the **chemical potential** of the substance.

The **Gibbs phase rule** relates the number of phases (P), components (C), and degrees of freedom (F):

$$F = C - P + 2$$

For example, in a single-component water system:

- At equilibrium between ice, liquid, and vapor (triple point), C=1, P=3, F=0. Hence, the system has **no degrees of freedom** — it exists at a fixed temperature and pressure (T = 273.16 K, P = 611.7 Pa).

Table – 3. Examples of Phase Boundaries and Their Applications

Type of Boundary	Example	Application
Solid–Gas	Charcoal and gas	Adsorption and catalysis
Solid–Liquid	Metal–molten salt	Metallurgical processes
Liquid–Gas	Water surface	Evaporation, surface tension
Liquid–Liquid	Oil–water interface	Emulsions, detergents

Practical Importance: Surface phenomena and phase boundaries have great importance in both nature and technology. In **catalysis**, many industrial reactions, such as the Haber–Bosch process for ammonia production, depend on adsorption of gases on solid catalysts like iron or nickel. This surface interaction lowers activation energy and increases reaction efficiency. In **colloidal systems**, surface forces help keep small particles stable and prevent them from clumping. For example, surfactants in milk or paint form protective layers around particles, maintaining a uniform mixture. **Biological membranes** act as natural phase boundaries that control the transport of molecules in and out of cells. Their function depends on the surface properties of lipid layers. In **nanotechnology**, materials with large surface areas, such as activated carbon or titanium dioxide, are used for adsorption, catalysis, and environmental purification. Similarly, in **environmental chemistry**, adsorption helps remove pollutants from water and air, using materials like zeolites or carbon filters.

Questions for Self-Control:

1. Define surface tension and explain its temperature dependence.
2. What is the difference between adsorption and absorption?
3. State and derive the Langmuir adsorption isotherm.
4. Write Raoult's law and explain its importance in solution chemistry.
5. State the Gibbs phase rule and explain its application at the triple point of water.
6. Give two industrial or biological examples where surface phenomena play a key role.

Literature:

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