Al-Mustaqbal University
Department of Biomedical Engineering
Third Stage / 1st Course
"Transport Phenomena for BME"
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Lecture 1
"Principles and Definitions"

Introduction:

- The transport of energy, mass, and momentum is essential to the function of living systems. Changes in these processes often underlie pathological conditions.
- Transport phenomena are also central to the operation of instrumentation used to analyze living systems and to many of the technological interventions used to repair or improve tissues or organs.
- The objective study of biological transport phenomena began historically in the field of physiology and, indeed, helped define that field. Today, the engineering application of biological transport phenomena contributes to research advances in physiology, immunology, and cell and molecular biology. Thus, transport processes are important considerations in basic research related to molecule, organelle, cell, and organ function; the design and operation of devices, such as filtration units for kidney dialysis, high-density cell culture, and biosensors; and applications including drug and gene delivery, biological signal transduction, and tissue engineering.

The roles of transport phenomena in biological systems:

1. Control of biological functions:

In order for cells, organs, and tissues to function properly, nutrients and regulators of growth and function must be able to move rapidly to and through them. Organisms control the concentrations of molecules in their tissues and organs. Consequently, specialized mechanisms have evolved to regulate the movement of molecules across and within cells.

2. Disease treatments:

Many organs, such as the lungs, liver, and kidneys, are organized to enable the rapid exchange of molecules between the blood and tissues. In addition, various levels of biological organization, for example, the density of capillaries in various tissues and the size and structure of cells can be explained, in part, by the rates of transport of molecules from their sources to their sites of delivery. Alterations in transport processes are important factors in a number of diseases, such as atherosclerosis, cancer, and kidney diseases.

3. Design and operation of biomedical devices

Transport phenomena involve the integrated study of momentum, mass, and energy transfer, as well as the thermodynamics and kinetics of chemical reactions. For the biomedical engineer, a mechanistic understanding of transport processes is important for the characterization of physiological and cellular processes, the design and operation of a number of devices, and the development of new therapies. Examples of biomedical devices influenced by transport processes include kidney dialysis machines, heart-lung bypass machines, and membrane oxygenators.

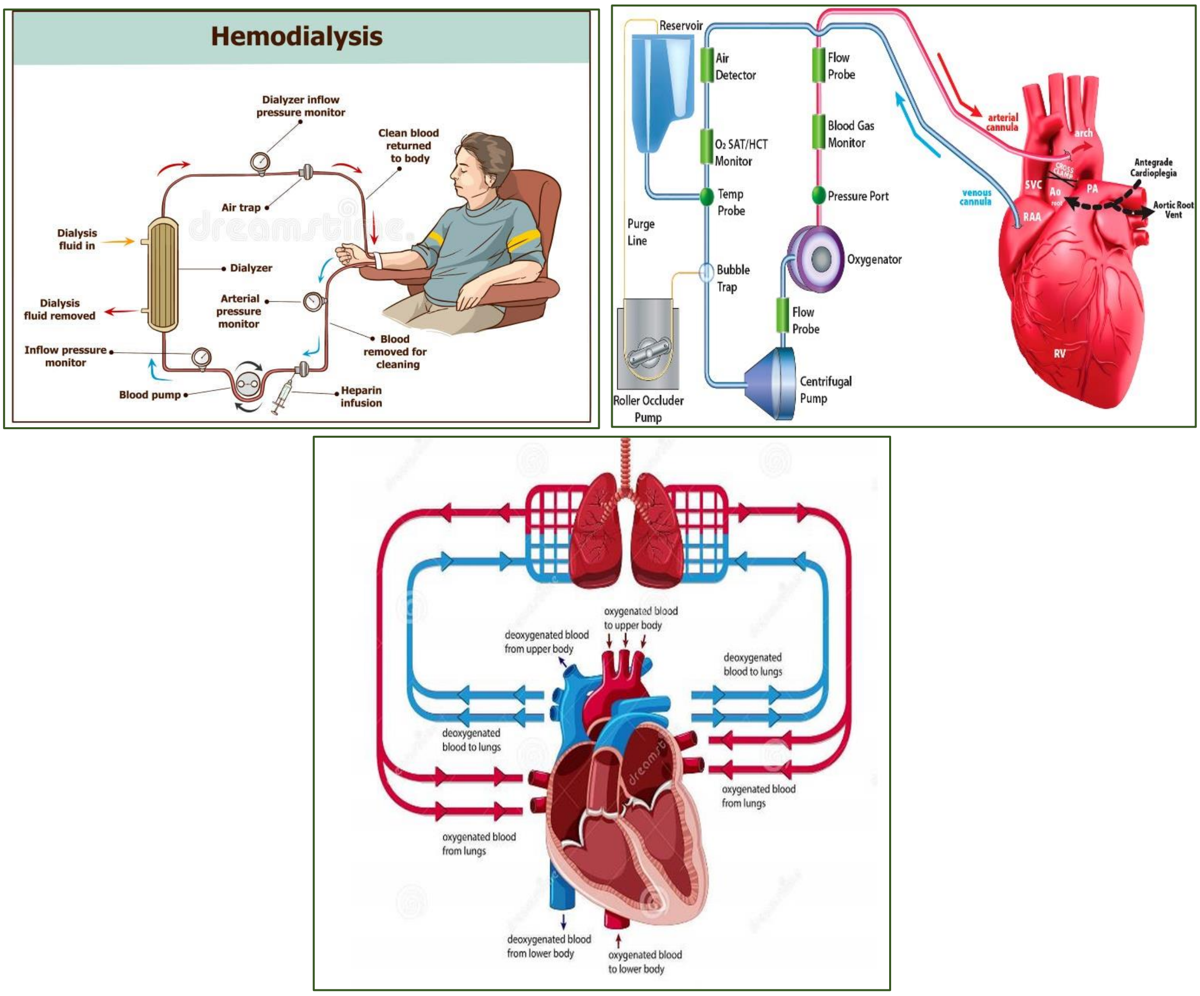


Figure (1): kidney dialysis machines and heart-lung bypass machines.

4. Genetic and molecular medicine and therapies:

Transport processes are critical in the removal of toxins from blood, the design of replacement tissues, and the delivery of drugs. Understanding and exploiting transport processes will be necessary in the application of molecular medicine. For example, the methods for delivering gene therapies must exploit biological transport pathways in order to successfully deliver the gene, in a functional form, to sites of action in the body.

The field of transport phenomena is sufficiently advanced that the basic processes can be characterized mathematically. The predictive capabilities of models are quite good, even for complex biological systems. Analytical and numerical solutions are already available for many commonly encountered problems pertaining to a number of natural phenomena, as well as to the design of many technologies.

Term Definitions:

Transport phenomenon, in physics, is any of the phenomena involving the movement of various entities, such as Mass Transport (Mass Transfer), Momentum Transport (Fluid Mechanics), or energy (Heat Transport) (Heat Transfer), through a medium, fluid, or solid, by virtue of non-equilibrium conditions existing within the medium.

Two physical phenomena are involved in the transport of molecules: *diffusion and convection.*

Diffusion is the random motion of molecules that arises from thermal energy transferred by molecular collisions.
Convection is a mechanism of transport resulting from the bulk motion of fluids.

The movement of energy and momentum in biological systems is influenced also by these two mechanisms.

Fluid

A fluid (in the liquid or gas phase) is defined as a substance that deforms continuously under the application of a shearing stress, regardless of how small the stress is. The distinction between a solid and a fluid is made by a substance's ability to resist an applied shear (tangential) stress that tends to change its shape. A solid can resist an applied shear by deforming its shape. In solids, stress is proportional to strain, but in fluids, stress is proportional to 'strain rate".

Two major groups are defined for the fluids: liquids and gases (in a generic state, plasma is a third group of fluids). The liquid formed from relatively compressed molecules with powerful, cohesive forces. A liquid tends to retain its volume and will shape a free surface under a gravitational field, but gases are the opposite of liquids. Gas elements are generally separated from one another and gases have no defined volume or free surface.

To study the behavior of materials that act as fluids, it is useful to define a number of important fluid properties, which include *density, specific weight, specific gravity, and viscosity.*

Density: is defined as the mass per unit volume of a substance and is denoted by the Greek character ρ (rho). The SI units for ρ are kg/m^3.

Specific weight: is defined as the weight per unit volume of a substance. The SI units for specific weight are N/m^3.

Specific gravity: (S) is the ratio of the weight of a liquid at a standard reference temperature to the weight of water. For example, the specific gravity of mercury $S_{Hg} = 13.6$ at 20°C. Specific gravity is a unitless parameter.
Density and specific weight are measures of the "heaviness" of a fluid.

Example: What is the specific gravity of human blood, if the density of blood is 1060 kg/m^3?
Solution: $\rho_{(blood)} / \rho_{(water)} = 1060/1000 = 1.06$

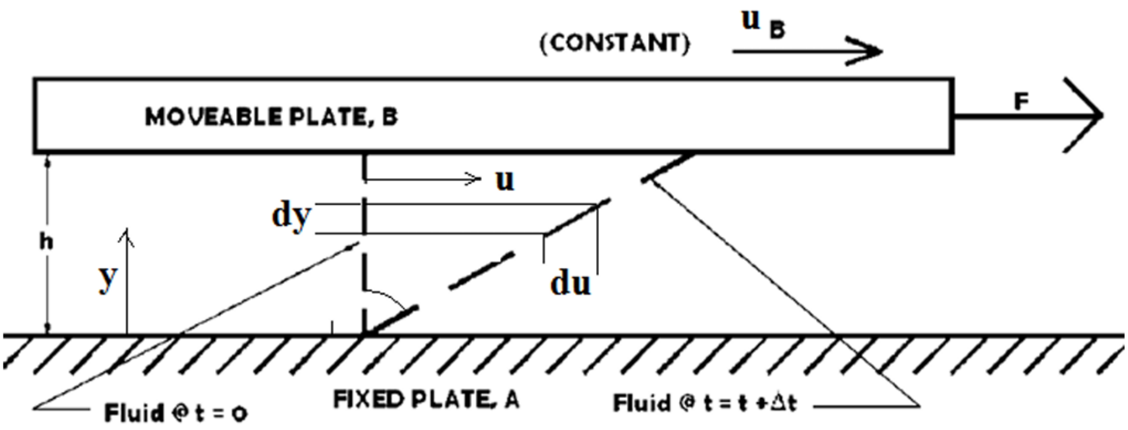
Density and specific weight are measures of the "heaviness" of a fluid, but two fluids with identical densities and specific weights can flow quite differently when subjected to the same forces. You might ask, "What is the additional property that determines the difference in behavior?" *That property is **viscosity.***

Viscosity is a measure of a fluid's resistance to flow. It describes the internal friction of a moving fluid. A fluid with large viscosity resists motion because its molecular makeup gives it a lot of internal friction. A fluid with low viscosity flows easily because its molecular makeup results in very little friction when it is in motion. Gases also have viscosity, although it is a little harder to notice it in ordinary circumstances.

To understand viscosity, let fluid between two parallel infinites in width and length plates. See Fig. 1.1. The bottom plate A is fixed and the upper plate B is moveable. The vertical distance between the two plates is represented by h. A constant force F is applied to the moveable plate B causing it to move along at a constant velocity uB with respect to the fixed plate. This behavior is consistent with the definition of a fluid: a material that deforms continuously under the application of a shearing stress, regardless of how small the stress is.

After some infinitesimal time dt, a line of fluid that was vertical at time t= 0 will move to a new position, as shown by the dashed line in Fig. 1.1. The tan of angle between the line of fluid at t = 0 and t = t + dt is defined as the shearing strain du/dy.

The fluid that touches plate A has zero velocity u=0. The fluid that touches plate B moves with the same velocity as that of plate B, uB. That is, the molecules of the fluid adhere to the plate and do not slide along its surface. This is known as the no-slip condition. The no-slip condition is important in fluid mechanics. All fluids, including both gasses and liquids, satisfy this condition.



2- Normal and Shear Stress: Given a surface of a body on which a force is acting, there are two types of stresses acting on that surface: normal stress and shear (or tangential) stress.

a- Normal stress: Normal stress o is the force per unit area exerted perpendicularly to the surface over which it acts.

b- Shear stress: Shear (or tangential) stress T is the force per unit area exerted tangentially to the surface over which it acts.

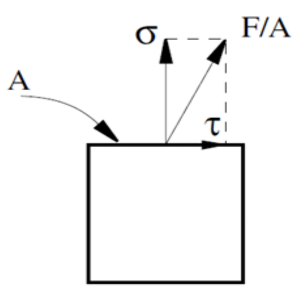
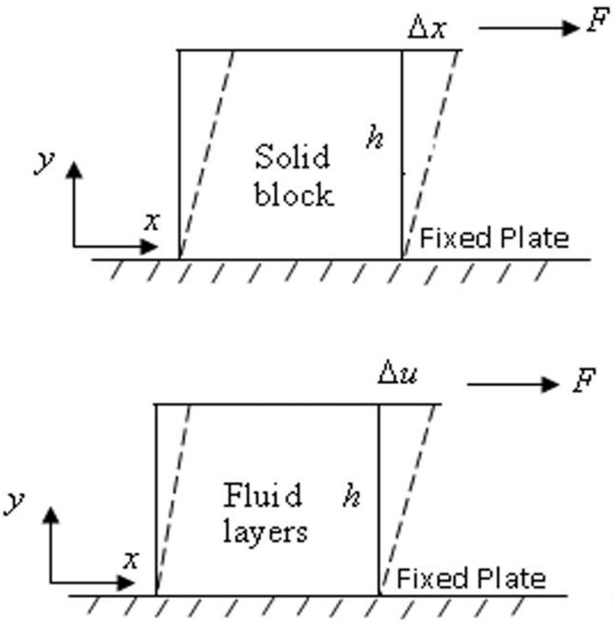


Figure (3): Normal stress (σ) and shear stress (τ) due to the force acting on the surface A.



$$S = \frac{\text{Shear stress}}{\text{Shear strain}} = \frac{(F/A)}{(\Delta x/h)}$$

$$\mu = \frac{\text{Shear stress}}{\text{Shear strain rate}} = \frac{(F/A)}{(\Delta u/h)}$$

Figure (4): Solid and Liquid deformation.