Al-Mustaqbal University
Department of Biomedical Engineering
Third Stage / 1st Course
"Transport Phenomena for BME"
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Lecture 4
"Fluid Flow"

Classifications of Fluid Flows

Some of the general categories of fluid flow are as follows:

1. Viscous and Inviscid flow: The fluid flow in which frictional effects become signification are treated as viscous flow. However, when the friction effect is not important the flow is known as inviscid.

2. Internal and External flow: The flow of an unbounded fluid over a surface is treated as 'external flow', and if the fluid is completely bounded by the surface, then it is called as 'internal flow'.

3. Compressible and Incompressible flow: The flow is said to be 'incompressible' if the density remains nearly constant throughout. When the density variation during flow is more than 5%, then it is treated as 'compressible'. This corresponds to a flow Mach number of 0.3 at room temperature.

4. Laminar and Turbulent flow: The highly ordered fluid motion characterized by smooth layers of fluid is called 'Laminar Flow', e.g., flow of highly viscous fluids at low velocities. The fluid motion that typically occurs at high velocities is characterized by velocity fluctuations are called as 'turbulent.' The flow that alternates between being laminar & turbulent is called 'transitional'. The dimensionless number, i.e., Reynolds number is the key parameter that determines whether the flow is laminar or turbulent.

5. Steady and Unsteady flow: When there is no change in the fluid property at the point with time, then it implies as steady flow. However, the fluid property at a point can also vary with time which means the flow is unsteady/transient. The term 'periodic' refers to the kind of unsteady flows in which the flow oscillates about a steady mean.

6. Natural and Forced flow: In a forced flow, the fluid is forced to flow over a surface by external means such as a pump or a fan. In another case (natural flow), density difference is the driving factor of the fluid flow. Here, the buoyancy plays an important role. For example, a warmer fluid rises in a container due to density difference.

7. One/Two/Three-dimensional flow: A flow field is best characterized by the velocity distribution, and thus can be treated as one/two/three-dimensional flow if velocity varies in the respective directions.

Dimensionless Numbers of Biofluid Mechanics

Dimensionless (pure) numbers represent a property of a physical phenomenon, without any physical units such as distance, time, or mass. These numbers are a useful tool to characterize the mechanical behavior of fluids in dynamic conditions. Dimensionless numbers help us to understand the correlation between some parameters or forces in the phenomenon and also rescaling of a fluidic experience. Mechanical engineering has more than 40 dimensionless numbers. Some of these numbers are very essential in biofluid mechanics, such as: Reynolds number (Re) Womersley number (α) Strouhal number (St) Dean number (De) Stokes number (Stk)

Reynolds number (Re): is defined as the ratio of inertial forces to viscose forces when a fluid flows in a channel. Reynolds number is also an assessment number to evaluate flow regimes within a similar fluid. The Reynolds number for a channel (or pipe) is defined as:

$$Re = \frac{\rho V D_h}{\mu}$$

where Dh is the hydraulic diameter (m), ρ is density (kg/m^3), V is fluid velocity (m/s) and μ is dynamic viscosity (Pa. s).

Womersley number (α): is defined as the ratio of oscillatory inertia to viscose effects for a fluid in pulsatile flow. The Womersley number in the aorta and arteries is large and in arterioles it becomes very small (less than 1). The Womersley number for a channel (or pipe) is defined as:

$$\alpha = \frac{D_h}{2}\sqrt{\frac{\rho(2\pi f)}{\mu}}$$

where Dh is hydraulic diameter (m), ρ is density (kg/m^3), f is fluid frequency (Hz) and μ is dynamic viscosity (Pa.s). In the human body, heart beat rate can be considered as frequency.

Strouhal number (St), is a dimensionless number to explain oscillatory flow mechanisms. This number is the ratio of inertial forces as a result of oscillatory flow conditions to inertial forces because of velocity changing between two points of a flow field. The Strouhal number for a channel (or pipe) is defined as:

Where L is characteristic length (for instance hydraulic diameter Dh) (m), f is fluid frequency (Hz) and V is velocity of the fluid.

There is a relation among Womersley, Reynolds and Strouhal numbers:

$$\alpha = \sqrt{\frac{Re\ St}{2}}$$

Dean number (De), is the ratio of viscous force on a fluid flowing in a curved pipe to the centrifugal force. The Dean number for a channel (or pipe) is defined as:

$$De = Re \cdot \sqrt{\frac{D_h}{2R}}$$

where Re is Reynolds number, Dh is hydraulic diameter (m) and R is the radius of curvature of the channel (m). A schematic of a curved pipe (vessel) is shown in Fig. 1.14.

Stokes number (Stk), is defined as the ratio of the characteristic reaction time of a suspended particle in fluid flow to a characteristic time of the flow. The reaction time is the time that the particle takes to respond to velocity changes in flow. The Stokes number is defined as:

$$Stk = \frac{\rho_p d_p^2 V}{18\mu D}$$

where ρ_p is particle density, d_p is particle diameter, V is fluid velocity, μ is dynamic viscosity of fluid and D is diameter of the obstacle (typically for channels is inner diameter).