CHAPTER – I

INTRODUCTION AND BASIC EQUATIONS
1.1. FLUID DYNAMICS:

Fluid Dynamics is a branch of mechanics, which deals with the study of fluid in motion and the subsequent effect of the fluid on the boundaries, which may be either solid surface or other fluids. The essence of the subject of fluid flow is that of judicious compromise between theory and experiment. Since fluid dynamics is the branch of mechanics, its fundamental principles are based on Newton’s laws of motion, the indestructibility of matter and conservation of energy. Fluid dynamics has a wide range of applications, including calculating forces and moments on aircraft, determining the mass flow rate of petroleum through pipelines, predicting weather patterns, understanding nebulae in interstellar space and reportedly modeling fission weapon detonation. Some of its principles are even used in traffic engineering, where traffic is treated as a continuous fluid. The following are some of the important areas in fluid dynamics in which flows through such geometries are explored by several authors.

1.2 Newtonian and non-Newtonian fluid dynamics
1.3 Heat Transfer
1.4 Magneto hydrodynamics
1.5 Flows through porous media
1.6 Mass transfer

1.2. NEWTONIAN AND NON-NEWTONIAN FLUID DYNAMICS:

The classical Navier-Stokes equation of motion is derived by assuming a linear relationship between stress tensor and the strain rate tensor in the fluid. Fluids which obey this relationship are known as Newtonian fluids. They possess a single rheological property called viscosity. Water, air, mercury, engine oil are some of the examples of Newtonian fluids.

Many important industrial fluids are non-Newtonian in their flow characteristics. These include paints, various suspensions, glues, printing inks, food
materials, soap and detergent slurries, polymer solutions and many others. Because such fluids have more complicated equations that relate the stress to the velocity gradient than is the case with Newtonian fluids, new branches in the fields of fluid mechanics and heat transfer are developed. Another important characteristic of such fluids, because of their large apparent viscosities, is that they have a tendency towards low Reynolds and Grashoff numbers and high Prandtl numbers. Thus laminar flow situations are encountered more often in practice than with Newtonian fluids. The fundamentals of non-Newtonian laminar flow of heat transfer include an examination of the classification system for such fluids, the development of a method to predict the fully developed pressure drop in ducts both circular and non-circular in cross-sectional shape and a consideration of some aspects of the heat transfer processes.

The subject of thermo physical properties and their measurements is an important one when dealing with non-Newtonian fluids and includes the consideration of both classical methods for making such measurements as well as several approaches which are unique in such fluids. It is unfortunate and time consuming that these property measurements must be made continuously when dealing with non-Newtonian fluids because they are not pure substances and vary in their properties because of different preparation methods. The non-Newtonian fluids can in turn be divided into purely viscous and visco-elastic fluids. The purely viscous time-dependent fluids are defined as those whose shear stress depends only upon some function of the shear rate, and sometimes an initial yield stress. Visco-elastic fluids are those which possess properties of both viscosity and elasticity. We list below various non-Newtonian fluids and some examples.

<table>
<thead>
<tr>
<th>Type</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian</td>
<td>Water, air, mercury, engine oil</td>
</tr>
<tr>
<td>Pseudo plastic</td>
<td>Paints, glues, blood, suspensions</td>
</tr>
<tr>
<td>Dilatants</td>
<td>Wet sand, sugar, and borax solutions</td>
</tr>
<tr>
<td>Bingham Plastic</td>
<td>Certain emulsions land paints</td>
</tr>
<tr>
<td>Thixotropic</td>
<td>Printing inks, food materials, paints</td>
</tr>
<tr>
<td>Rheopectic</td>
<td>Clay suspensions</td>
</tr>
<tr>
<td>Viscoelastic</td>
<td>Polymer solutions (eg. polyox water)</td>
</tr>
</tbody>
</table>
The simplest types of non-Newtonian fluids are the pseudo plastic and dilatants fluids whose relation between shear stress and shear rate can be expressed by an equation of the form $\tau_{yx} = k(\gamma)^n$ where $\gamma$ is strain rate.

Because of this functional relation such fluids are called power law fluids and unlike Newtonian fluids (which have only a single rheological property, i.e. viscosity) two independent properties are required to specify the relation between the shear stress and the shear rate. The term $k$ is called the consistency and $n$ is called flow index. If $n$ is less than one, the fluid is pseudo plastic and if greater than one, it is dilatants. The Couette flow problem helps researchers to investigate the interactions of various forces like viscous force, buoyancy force, electromagnetic force etc., in Newtonian and non-Newtonian fluids.

1.3. HEAT TRANSFER:

Heat transfer plays a vital role in science and technology. It is the science which predicts temperature distributions, which may be functions of both spatial coordinates and time, within regions of matter. Heat transfer also predicts the rate at which energy is transferred across a surface of interest due to temperature gradients at the surface and temperature differences between different surfaces. There are many engineering applications that are encountered in a variety of disciplines. Mostly all methods of power production involve fluid flow and heat transfer as essential processes. Most power plants produce electricity by converting heat contained within a “working fluid” to work. However, this working fluid may not be the fluid in which heat was generated. Coal may be burnt to produce hot combustion products. Then these hot gases transfer heat to water which serves as the working fluid. Thus, the engineer must provide for transferring heat to where it is wanted.

Heat may be produced as a by-product of a process. If that heat in not removed, it causes damage to the equipment. Heat must be removed from an automobile engine, for example, a liquid coolant will cool the engine in the first step of heat removal. Then, air will cool the liquid coolant. Thus, the engineer plans for removal of the heat from where it is not wanted. Heat must be provided to residential
and commercial buildings to maintain a comfortable environment. For economy, it is desirable to retard the rate at which heat is lost from buildings. Thus, the engineer is concerned with preventing loss of heat from the area where the heat should be kept. Superconducting magnets work properly at very low temperatures. In some cases, these magnets are located very near to high temperature, as in proposed designs for nuclear fusion plants. So, the engineer must prevent heat from entering the superconducting magnet at a faster rate. Hence, it is necessary that heat must be kept away from where it is not wanted.

Major segments of the chemical and metallurgical industries use components such as furnace, heat exchangers, condensers and reactors, where thermo fluid processes are at work. Aircraft and rockets owe their functioning to the fluid flow, heat transfer and chemical reaction. In the design of electrical machinery and electronic circuits, heat transfer is often the limiting factor. In the course of time, temperature, differences in a body are reduced by heat flowing from regions of higher temperature to those of lower temperature. Knowledge of the laws governing this process is of great importance because this knowledge affords means for channeling the flow of heat in a desired manner. For instance, one may be given the task of improving upon the flow of heat by any possible means. In the development of heat engines we are confronted with this task again and again. According to thermodynamic theory, such a heat engine consists in principle of two heat reservoirs at different temperatures, with the engine that performs the work placed between them. The working medium frequently changes in the course of such process. The heat must then be exchanged between the individual media using the smallest possible temperature drop. In steam power plants the heat is contained initially as internal energy in the combustion gases. In the steam boiler the heat is transferred to the steam. In the condenser the steam gives off its heat to the cooling water, and the cooling water while passing through the cooling tower transfers this heat to the air. In internal-combustion engines this type of heat exchange does not exist, since the heat is produced by combustion directly in the working medium. Some of this heat is converted to work, and the waste heat as well as the waste gases is jointly exhausted.

All fields of engineering deal with problems of heat transfer and fluid flow, aerospace engineers are concerned with heat transfer in high-speed flow. Chemical
engineers provide for input or removal of heat, depending on whether processes are endothermic or exothermic. Civil engineers and architects must be concerned with heat transfer in the design and construction of buildings. Electrical engineers are concerned with proper operating temperatures of equipment such as computers and electronic devices. Mechanical engineers are concerned with many heat transfer situations, such as the automobile engines. Nuclear engineers are concerned with dynamic heat removal problems in fission reactors in addition to the fusion reactor. Thus, heat transfer is a basic engineering science of general concern to the engineering profession. The pollution of the natural environment is largely caused by heat and mass transfer and so are storms, floods and fires. In case of changing weather conditions, the human body resorts to heat and mass transfer for its temperature control. This process of heat transfer and fluid flow seems to pervade in all aspects of our life.

There are three basic mechanisms in the processes of heat transfer according to which heat can move from a high-temperature region to a low-temperature region.

i. Heat can move through a static body by interaction with the internal structure of the body. This process is called conduction.

ii. Heat can be carried from one place to another by movement of a fluid. This process is called convection.

iii. Heat can be transported through space even in the absence of any intervening material. This process is called radiation.

1.3.1. CONDUCTION:

Heat transfer by conduction arises from temperature gradients within a material. This is considered the only mode of heat transfer within opaque solids. Suppose a solid bar is surrounded by perfect insulation except at the left and right faces with temperatures $T_1$ and $T_2$ ($T_1 > T_2$). Experimentally it is found that if the conduction of the bar is not changing with time and if there are no sources of energy within the bar, there is a net energy transfer rate from the left face to the right face. This is called conduction heat transfer, and the direction of the net energy transfer is in accordance with the second law of thermodynamics. The conduction in a solid is due to the energy transferred during collisions of adjacent molecules and the
migration of free electrons. Conduction in a gas is due to collisions of the molecules which are in continuous random motion. Under steady state conditions, it is found that the heat transfer rate is directly proportional to the cross sectional area and the temperature difference, and it is inversely proportional to the path length in the direction of heat flow. This Fourier’s law of conduction is used to obtain the conduction heat transfer rate. The proportionality constant $K$ is called the thermal conductivity of the material. The thermal conductivity $K$ for homogeneous material is a function of pressure and temperature. Thermal conductivity is only very little dependent upon pressure for solids, and for liquids as well, if they are not near the critical point. Also, the thermal conductivity of most gases is essentially independent of pressure if the gases are at pressures near standard atmospheric. The value of thermal conductivity $K$ increases with temperature for gases and non-metallic solids, and decreases with temperature for most liquids except water.

### 1.3.2. CONVECTION:

The process of convection is heat transfer between solid surface and the bounding fluid. Heat transfer due to convection involves the energy exchange between a solid surface and an adjacent fluid. Convection is mechanism in which heat flows are transferred between a fluid and a solid surface because of motion of fluid particles relative to the solid surface when there exist a temperature gradient.

Convection heat transfer may be classified into Forced convection heat transfer and Free or Natural convection heat transfer.

If the heat transfer between the fluid and the solid surface occurs by fluid motion induced by external agencies or forces then the mode of heat transfer is termed as “Forced convection” in all types of heat. Exchanges, nuclear reactors, air conditioning apparatus are by forced convection.

A free convection flow field is a self-sustained flow driven by the presence of temperature gradient (As opposed to a forced convection flow where external means are used to provide the flow). As the result of the temperature difference, the density field is not uniform. Buoyancy will induce a flow of current due to the gravitational
field and the variation in the density field. In general, a free convection heat transfer is usually much smaller compared to a forced convection heat transfer. It is therefore important only when there is no external flow exists.

Free convection results from the buoyancy forces imposed on the fluid whether it is gas or liquid, when its density in the neighborhood of the heat transfer surface is reduced as a result of heating process. Free convection flow also arises when a heated object is placed in a fluid, otherwise at rest, the density of which varies with temperature. Heat is transferred from the surface of the object to the fluid layers in its neighborhood. The density decreases, when in a normal fluid is convicted to temperature increase, causes these layers to rise and create the free convection flow which now transfer away from the object. Physically such flow is described by stating that it is caused by body force. The example of a practical device which transfers heat by free convection is a radiator used for heating a room.

Free convection flow occurs frequently in Nature. It occurs not only due to temperature difference, but also due to concentration difference or combination of these two. For example, in atmospheric flows there exists differences in the H\textsubscript{2}O concentration and hence the flow is affected by such concentration difference. Flows in bodies of water are driven through the comparable effects upon density of temperature, concentration of dissolved materials and suspended particular matter may transport process exist in nature and in industrial applications in which the simultaneous heat and mass transfer occur as a result of combined buoyancy effects of diffusion of chemical species.

1.3.3. RADIATION:

The process of radiation is a familiar process of heat transfer. When two objects are placed at different temperatures apart from a finite distance in a perfect vacuum, a net energy transfer occurs from the higher temperature object to the lower temperature object, even though there is no medium between the two objects to support heat transfer. This net energy transfer process is called thermal radiation or radiation. This is the mechanism whereby the Sun transmits heat to the earth.
1.4. MAGNETOHYDRODYNAMICS:

Magneto hydrodynamics (MHD) is an important branch of fluid dynamics. It is concerned with the interaction of electrically conducting fluids and electromagnetic fluids. When a conducting fluid moves through a magnetic field, an electric field, consequently current may be induced and, in turn the current interacts with the magnetic field to produce a body force.

According to Faraday, when a conductor carrying an electric current moves in a magnetic field, it experiences a force tending to move it at right angles to the electric field and conversely, when a conductor moves in a magnetic field, a current is induced in the conductor in a direction mutually at right angles to both the field and the direction of motion.

In the case when the conductor is either a liquid or gas, electromagnetic forces will be generated and may be of the same order of magnitude as the hydro dynamical and inertial forces. Thus the equations of motion will have taken these electromagnetic forces into account in addition to the other forces. The science which treats these phenomena is called Magneto hydrodynamics (MHD).

MHD interactions occur both in nature and in new man-made devices. MHD flow occurs in the sun, the earth interior, the ionosphere, and the stars and their atmosphere, to mention a few. In the laboratory many new devices have been made which utilize the MHD interaction directly, such as propulsion units and power generators or which involve fluid-electromagnetic field interactions, such as electron beam dynamics, travelling wave tubes, electrical discharges and many others.

The growth of civilization over the world is the history of the growth of energy. An energy-deficient society is weak and cannot make economic advancement and it is primarily the electrical energy that keeps the wheels of progress moving at a very accelerating pace. The main source of electrical energy has been fossil fuels, hydel and nuclear, even though solar energy geothermal energy, wind power, tidal power and fusion power offer hopeful and technological alternatives. However, for
most of the nations, the main burden of rapid growth rate of electrical power production for the next few decades is to be borne by power stations using fossil fuel-fired steam turbine-units. In this context the advent of direct conversion of thermal energy to electrical energy by means of a Magneto hydrodynamic (MHD) converter has gained considerable attention. MHD has many applications in science and industry. To name a few, Astrophysical, Geophysical and Cosmic physics are some. It is still very important, in the problem of fusion power. It has applications in the creation and containment of hot plasmas by electromagnetic forces, since material walls would be destroyed. Astrophysical includes solar structure especially in the outer layers, the solar wind bathing the earth and other planets, and interstellar magnetic fields. The primary geophysical is plenary magnetism, produced by currents deep in the planet. Thermonuclear fusion and direct energy conversion are some of the areas volume MHD plays an important role even with present level of knowledge and engineering technology, which is the result of the first generation open circle.

Suppose the fluid is electrically conducting, and a uniform transverse magnetic field of strength $B_0$ is applied, then the interaction between the motion and the magnetic field can be described by Maxwell’s equations. As in most problems involving conductors Maxwell’s displacement currents are ignored, so that electric currents are regarded as flowing in closed circuits. Assuming that the velocity of flow is too small compared to the velocity of light i.e. the relativistic effects are ignored. The system of Maxwell’s equations can be written in the form:

\[
\begin{align*}

\text{Curl} \ H &= 0 \quad \text{(1.4.1)} \\
\text{Div} \ \vec{B} &= 0 \quad \text{(1.4.2)} \\
\text{Div} \ \vec{E} &= 0 \quad \text{(1.4.3)} \\
\text{Curl} \ \vec{E} &= \mu_0 \frac{\partial H}{\partial t} \quad \text{(1.4.4)} \\
\text{Div} \ \vec{J} &= 0 \quad \text{(1.4.5)}
\end{align*}
\]
The ohm’s law (current density and electric field relation):

\[ \vec{J} = \sigma \left[ \vec{E}_0 + \vec{q} \times \vec{B} \right] \]  \hspace{1cm} (1.4.6)

Where \( \vec{q} \) is the velocity vector, \( \vec{B} = \mu_0 \vec{H} \), \( \vec{E} \) the electromagnetic induction, \( \vec{B} \) the applied magnetic field, \( \vec{J} \) the electric field, \( \vec{q} \times \vec{B} \) is the Lorentz force per unit volume, \( \vec{E}_0 \) the electric field, \( \vec{J} \) the electric current density.

### 1.5. FLOWS THROUGH POROUS MEDIA:

A porous medium is a continuous solid phase with many pores in it. Examples are sponges, clothes wicks, paper sand gravel, filters, concrete, bricks, plaster walls, many naturally occurring rocks, packed beds used for distillation, absorption etc. Most of the studies of flow in porous media assume the Darcy’s law is valid. However this law is known to be valid only for relatively slow flows through porous media. In general we must consider the effect of fluid inertia as well as of viscous diffusion at boundaries which may become significant for material with high porosities such as fibrous and foams.

Flows through porous media are of principal interest because these are quite prevalent in nature. Such flows have attracted the attention of a number of scholars due to their applications in many branches of science and technology viz., in the field of agricultural engineering to study the under-ground water resource, seepage of water in river beds, in petroleum technology to study the movement of natural gas, oil and water through oil reservoirs, in chemical engineering for filtration and purification processes. These problems are also of much interest in geophysics and in the study of the interaction of the geomagnetic field with the fluid in the geothermal region.

The study on flows through porous media is of great interest in many scientific and engineering applications. A study on such type of flows is applied to the problems of movement of underground water resources and for filtration and water purification process. The petroleum industry has been showing a lot of interest in these problems
in connection with the crude oil production from the underground reservoirs. These reservoirs contain many process materials like limestone and dolomite where oil is preserved. Oil can be obtained by drilling wells down into the reservoir and it can be allowed to flow through the porous regions of the well. Since the percentage of oil recovery is an important factor in the oil economy, it is necessary to apply to know how concerning the mechanics of oil production in increasing the recovery percentage. The textile technologist is interested in fluid flow through fibers, whereas biologists are interested in water movement through plant roots of the cells of living systems.

1.5.1. **DARCY LAW:**

Darcy was the first to initiate pioneering work on the flow through porous medium that postulated the famous Darcy law in the year 1856. Generally this law is accepted as the macroscopic equation of motion for Newtonian fluids in porous media at small Reynolds number. Darcy has empirically established this law. Since then, numerous investigators have verified it experimentally. According to this law, the flow is linearly dependent on the pressure gradient and the gravitational force. In other words, the mean filter velocity, which is known as Darcy velocity \( q \), is proportional to the sum of the gradient of the pressure and the gravitational force. That is

\[
q = \frac{\text{cons} \tan t}{\mu} (-\nabla p) \tag{1.5.1}
\]

Later, Muskat gave a new formulation of the above relation as

\[
q = -\frac{k}{\mu} \nabla p \tag{1.5.2}
\]

Where the constant \( k \) is the permeability of the porous medium and has been determined experimentally. The permeability constant \( k \) has the dimension of square of length.

Darcy law takes place into account only the frictional force offered by the solid particles to the fluid rather than the boundary layer and internal effects. In other words
the flow governed by this law, in case of homogeneous isotropic porous medium, is of potential type rather than boundary layer.

1.5.2. BRINKMAN MODEL:

In order to deal with the dynamics of flow through porous media one has to solve the boundary layer of equation postulated by Brinkman. Brinkman obtained the governing equation for the flow through porous media as

$$\rho \left( \frac{\partial \vec{q}}{\partial t} + (\vec{q} \cdot \nabla) \vec{q} \right) = -\nabla p - \frac{\mu}{K} \vec{q} + \nu \nabla^2 \vec{q}$$

(1.5.3)

This equation takes care of viscous shear force in addition to the frictional force offered by the solid particle to the fluid movement rather than the potential type of flow generated by usual Darcy’s law.

1.5.3. BRINKMAN-FORCHHIERMER MODEL:

Brinkman-Forchhiermer considered a model of boundary layer and inertial effects for flow through porous medium. This model equation consists of viscous term $\nu \nabla^2 q$, Darcy resistance, in addition to the Forchhiermer term $\frac{F}{\sqrt{k}} q^2$, in the momentum equation. This model generalizes the fact that when the permeability $k \to \infty$, we obtain the equation for pure Newtonian flows.

Under the following two approximations, the basic equations of the motion for this media are valid.

(i) The saturated porous medium is homogeneous and isotropic so that the porosity and permeability are constant.

(ii) The porous medium is assumed to consist of sparsely distributed particles so that viscous shear and internal effects play an important role in addition to the Darcy resistance.
1.6. MASS TRANSFER:

Mass transfer is defined as the transfer of matter by virtue of species concentration difference in a system. The difference in concentration provides a driving force for the transfer of mass. Mass transfer always occurs in the direction of reducing concentration gradient.

Mass transfer occurs by two mechanisms:
(i) Diffusion mass transfer
(ii) Convective mass transfer

1.6.1. DIFFUSION MASS TRANSFER:

In diffusion mass transfer the transfer of matter occurs by the movement of molecules or species or particles of one component into another. Diffusion mass transfer may occur either due to concentration gradient (Molecular Diffusion) or temperature gradient (Thermal Diffusion) or pressure gradient (Pressure Diffusion).

1.6.2. CONVECTIVE MASS TRANSFER:

Convective mass transfer is a mechanism in which mass is transferred between the fluid and the solid surface as a result of movement of matter from the fluid to the solid surface or fluid. Convective mass transfer is again classified as "Natural or Free Convection mass transfer" and" Forced Convection mass transfer".

1.6.3. NATURAL OR FREE CONVECTION MASS TRANSFER:

In a natural convection mass transfer, the transfer of mass occurs by the motion of species due to the density resulting from temperature or concentration differences of the mixture of varying composition.

1.6.4. FORCED CONVECTION MASS TRANSFER:

In forced convection mass transfer, mass is transferred due to forced circulation of species by some external agency.
1.6.5. **MASS FLUX** :

The amount of mass transfer per unit area of the flow is called Mass Flux. If \( m \) is the amount of mass flow and \( A \) is the area normal to the direction of mass flow, then the mass flux is

\[
G = \frac{m}{A}
\]

1.6.6. **FICK'S LAW OF DIFFUSION**:

Fick's law relates the diffusion rate or mass flux of the species to its driving potential or the concentration gradient responsible for the flow.

It states that the mass flux of a component of a system in any direction is proportional to its concentration gradient in that direction.

\[
G_A \propto \frac{dC_A}{dx}
\]

\[
G_A = -D_{AB} \frac{dC_A}{dx}
\]

where \( G_A \) is the mass flux of a component A, \( C_A \) is the mass concentration of component A, \( \frac{dC_A}{dx} \) is the concentration gradient in the \( x \)-direction opposite to the direction of mass flow, \( D_{AB} \) is the coefficient of mass diffusivity for a system of components A and B.

Engineering application of convective heat and mass transfer are extremely varied. In a multi-fluid heat exchange we are solely concerned with heat transfer rates between the fluids and the solid surfaces of the heat exchanger separating the fluids. Calculation of temperature of a closed turbine blade or the throat of a rocket nozzle involves convective heat transfer alone but if a fluid is injected through the surface (transpiration cooling) the problem is a mass transfer one. If the surface material is allowed to vaporize and / or burns to protect it from a higher temperature gas (ablation) we have another combination of convective heat and mass transfer problem. The aerodynamic heating of high speed aircraft is a connective heat transfer process, but it also becomes a mass transfer process when temperatures are so high that the gas...
dissociates forming mass concentration gradient. Thus the problems of convective heat and mass transfer are highly significant for their wide application in various fields.

The study of convective heat and mass transfer is based on terms or concepts of mass, momentum and energy. The fluid flow obeys certain principles of mass, momentum and energy.

**1.6.7. CONTROL VOLUME:**

An arbitrary and fixed region in space across the boundaries of which the matter, momentum and energy flow within which, changes of matter momentum and energy take place and on which the external forces act is termed as “Control Volume”.

**1.6.8. CONTROL SURFACE:**

The closed surface around the control volume is termed as "Control Surface".

**1.6.9. PRINCIPLE OF CONSERVATION OF MASS:**

This principle states that "in any control volume the rate of creation of mass or matter is zero ", that is, Mass flowing from the control volume - Mass flowing into the control volume + Mass change inside the control volume = 0.

**1.6.10. PRINCIPLE OF CONSERVATION OF MOMENTUM:**

This law states that "in any control volume the rate of change of momentum is proportional to the external forces acting on the control volume".

Rate of change of momentum = g F

Where, g is the acceleration due to gravity
F is the external force acting on the control volume
According to this law, Rate of momentum flow from the control volume - Rate of momentum flow into the control volume + Rate of change of momentum inside the control volume = (Acceleration due to Gravity x External forces).

1.6.11. PRINCIPLE OF CONSERVATION OF ENERGY:

This law states that energy in a control volume is neither created nor destroyed ". That is, Energy flow from the control volume - Energy flow outside the control volume + change of Energy inside the control volume = 0.

For the most of convective heat and mass transfer applications the influence of viscosity is confined to an extremely thin region very close to the body and the remainder of the flow field is treated to be inviscid. The thin region near the body surface is known as boundary layer. It is assumed that the fluid immediately adjacent to the body surface is at rest relative to the body.

1.6.12. HYDRO-DYNAMIC (OR) VELOCITY BOUNDARY LAYER:

The region in which the velocity of the fluid particles changes from its free stream value to zero at the body surface is termed as "Hydro-dynamic Boundary Layer" or “Velocity Boundary Layer".

1.6.13. THERMAL BOUNDARY LAYER:

A thin region in which the temperature of the fluid particles changes from its free stream value to body surface value is called "Thermal Boundary Layer".

1.6.14. CONCENTRATION BOUNDARY LAYER:

A thin region in which the concentration of a component in a fluid mixture changes from its free stream concentration to that at body surface is termed as "Concentration Boundary Layer". The heat and mass transfer problems deal with the transfer of heat and mass by moving fluids within these thermal and concentration boundary layers. The flow pattern of the fluid within these boundary layers depends on the characteristics of the boundary layers. The characteristics of the boundary
layers in turn depend on the non-dimensional parameters determining the flow of the fluid along the solid surfaces.

1.7. **SORET EFFECT:**

When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of more intricate nature. Mass fluxes can be created by temperature gradients and this is the Soret effect or the thermo-diffusion effect. The Soret effect dramatically lowers the thermal convection threshold, since concentration gradients release much more slowly than temperature gradients due to the disparate values of the mass diffusion coefficient and of the thermal diffusivity.

The name ‘Soret effect’ is usually attributed to mass separation induced by temperature gradients. The effect was discovered in 1879 by the Swiss scientist Charles Soret who noticed that a salt solution contained in a tube with two ends at different temperatures did not remain uniform in composition. The salt was more concentrated near the cold end than near the hot end of the tube. Charles Soret concluded that a flux of salt was generated by a temperature gradient resulting, in steady state conditions, in a concentration gradient. Although the German C. Ludwig described the same phenomenon several years before in 1856 in a short communication, the phenomenon bears his name because Soret studied the effect rather in detail and formulated the fundamental equations describing the phenomenon.

The Soret effect plays an important role in the operation of solar ponds, biological systems and the microstructure of the world oceans. In biological systems, mass transport across biological membranes induced by small thermal gradients in living matter is an important factor. One of the challenges in optimizing exploitation of oil reservoirs is a good knowledge of the fluid physics in crude oil reservoirs. Today, the modeling methods are based on pressure – temperature equilibrium diagrams and on gravity segregation of the different components of crude oil. However, improved models which more accurately predict the concentration of the
different components are necessary. The concentration distribution of the different components in hydrocarbon mixtures is mainly driven by phase separation and diffusion and the Soret effect plays an important role.

### 1.8. BASIC EQUATIONS IN VECTOR FORM:

The investigation of any liquid motion involves solving a set of non-linear partial differential equations called the fundamental equations of fluid dynamics. The fundamental equations governing any flow phenomena are stated below:

**CONSERVATION OF MASS:** Mass can neither be created nor be destroyed.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{q}) = 0
\]  

(1.8.1)

Here, \( \rho \) is density and \( \vec{q} \) is the velocity vector of the fluid.

**CONSERVATION OF MOMENTUM:** The total force acting on a fluid mass enclosed in an arbitrary volume fixed in space is equal to the time rate of change of linear momentum.

\[
\rho \left[ \frac{\partial \vec{q}}{\partial t} + \vec{q} \cdot \nabla \vec{q} \right] = \rho \vec{X} - \nabla p + \mu \nabla^2 \vec{q} + \vec{J} \times \vec{B}
\]  

(1.8.2)

Here, \( \mu \) is the coefficient of viscosity, \( p \) pressure of the liquid and \( \vec{J} \times \vec{B} \) is the Lorentz force per unit volume. The momentum equation (1.8.2) is called as the **Navier-Stokes equation**.

**CONSERVATION OF ENERGY:** The energy added to a closed system increases the internal energy per unit mass of the fluid.
\[ \rho \frac{Du}{Dt} = -\nabla \cdot \mathbf{Q} - p \nabla \cdot \mathbf{q} + \phi \] (1.8.3)

Where \( u \) is called internal energy, \( \mathbf{Q} = -k \nabla T \) (Fourier’s law of heat conduction) is heat flux vector, \( \phi = \nabla \cdot (\tau \mathbf{q}) - \mathbf{q} \cdot \nabla \tau \) is the dissipation function. \( \sigma \ [\Omega^{-1} \text{m}^{-1}] \) the electric conductivity, \( \rho \ [\text{kg/m}^3] \) density of the fluid, \( \nu = \frac{\mu}{\rho}, \frac{\partial q}{\partial t} \) is unsteady acceleration, \( \nabla p \) is pressure gradient and \( \rho \ [\text{kg/m}^3] \) fluid density in the boundary layer.

The above three equations are the fundamental equations of fluid dynamics.