CHAPTER 1

Introduction to Heat and Mass Transfer
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1. INTRODUCTION TO HEAT AND MASS TRANSFER

1.1 GENERAL INTRODUCTION:

Heat and mass transfer phenomena are found everywhere in nature and are important in all branches of science and technology. The involvement application of heat mass transfer processes go to greater lengths in numerous fields of science, engineering and technology. Heat and mass transfer operations quite often occur in the fields of Electric Engineering, Civil Engineering, Aeronautics, Metallurgy, Environmental Engineering, Refrigeration, Air conditioning, Biological and industrial processes. The study of Geophysics, Astronomy, Meteorology, Agriculture, Oceanography and food processing demand the knowledge of heat and mass transfer. Heat and mass transfer flows are highly significant for their varied practical importance. Many examples of heat and mass transfer applications can be cited from the environment.

A detailed knowledge of the principles of heat transfer and a thorough understanding of its basic mechanisms is necessary to design efficient and economical heat exchange devices such as boilers, condensers, combustion engines, etc. Design problems in nuclear reactors also demand knowledge of temperature distribution in the fluid in which heat is generated immediately after the energy is released. The problems of temperature distribution and heat transfer have become inevitable in Aeronautics for the durability and proper
functioning of space vehicles to avoid structural failures and also for safety considerations. Construction of dams and other large multi strayed buildings need the study of heat transfer. A keen analysis of heat flow is necessary in heating, air-conditioning of buildings to estimate the amount of insulation and to reduce the heat losses or gains. Activities like heating cooling evaporation, sublimation in chemical operations in research laboratories involve heat transfer. Designing of chemical processing equipments, fractional distillation plants for crude petroleum requires a great deal of heat transfer analysis. Many metallurgical and industrial mechanisms are operations like extracting from their purification, casting or metals involve the study of heat transfer. A considerable knowledge of heat transfer is necessary in the control or solving or lessening the environmental problems. To develop a better variety of seeds, breeders have to deal with heat transfer problems. Food processing needs a lot of knowledge of heat transfer.

Mass transfer broadly occurs in biological, physical and engineering fields. It involves in biological functions or process like respiratory mechanisms, oxygenation or purification of blood, kidney functions, osmosis and assimilation of food and drug. Evaporation from a reservoir or a pond, removal of pollutants from atmosphere, formation of clouds and smoke and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damages of crops due to freezing and pollution of environment are some of the mass transfer phenomena found in nature. Mass
transfer finds its place in ablative cooling (sudden decrease of temperature of space vehicles during their re-entry into atmosphere), transpiration and film cooling of rocket and jet engines. Mass transfer application widely found in chemical engineering processes like distillation, absorption of gases, extraction solids and liquids from their mixtures, crystallization and absorption (solids taking up vapour on its surface and chromatography). Processes like air humidification, cooling water, ion exchange involve mass transfer.

Now we define some basic concepts which are used in our discussion.

**1.2 HEAT TRANSFER**

Heat transfer is a science that predicts the transfer of heat energy from one body to another by virtue of temperature difference. Heat transfer occurs as a result of three mechanisms.

I. Conduction

II. Convection

III. Radiation

**I. Conduction**

In conduction heat flows due to molecular interaction, molecules not being displaced or due to the motion free electrons.

Heat conduction may be stated as the transfer of internal energy between the molecules. Heat flows from a region of higher temperature to a region of lower temperature by kinetic motion direct impact of molecules whether the body is at rest or in motion.
II. Convection

Heat transfer due to convection involves the energy exchange between a solid surface and an adjacent fluid.

Convection is a mechanism in which heat flows or transferred between a fluid and a solid surface as a consequence of motion of fluid particles relative to the solid surface when there exist a temperature gradient.

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

**Forced convection**

If heat transfer between a fluid and a solid surface occurs by fluid motion induced by external agencies are forced then the mode of heat transfer is termed as Forced Convection. Heat transfer in all types of exchangers, nuclear reactors, and air conditioning apparatus is by Forced Convection.

**Natural or Free Convection**

If heat transfer between a fluid and a solid surface occurs by the fluid motion due to the density differences caused by the temperature differences between surface and the fluid, then the mode of heat transfer is termed as Free Convection or Natural Convection.

Heat flow from a heated metal plate to the atmosphere, heat flow from hot water to the container is certain examples of free convection.
III. Radiation

The phenomenon or the mode of heat transfer in the form of electromagnetic waves without the presence of any intervening medium is called Radiation. The transfer of heat energy from the sun to the earth is an example of Radiation.

HEAT FLUX

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

\[
Q = \frac{q}{A}
\]

FOURIER LAW OF HEAT CONDUCTION

This fundamental law of heat conduction states that “the heat flux by conduction in a direction is proportional to the temperature gradient in that direction”

\[
Q_x \alpha \frac{dT}{dx}
\]

That is

\[
Q_x = -k \frac{dT}{dx}
\]

Where \( Q_x \) is the heat flux in \( x \)-direction.

\( \frac{dT}{dx} \) is the temperature gradient in \( x \)-direction, opposite to the direction of heat flow.

\( k \) is the thermal conductivity of the material.

HEAT DISSIPATION

The heat generated by internal friction within the volume element of the fluid per unit time is called Heat Dissipation.
1.3 MASS TRANSFER

Mass transfer is defined as the transfer of matter by virtue of species concentration differences in a system. The difference in concentration provides in 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

I. Diffusion mass transfer

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

II. 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.

Natural or Free Convection mass transfer

In a natural convection mass transfer is 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.

**Forced Convection Mass Transfer**

In forced convection mass transfer, mass is transferred due to forced circulation of species by some external agency.

**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 \( G = \frac{m}{A} \)

**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.

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

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 among the fluids and the solid surface of the heat exchange 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 or convective heat and mass transfer problem. The aerodynamic heating of high speed aircraft is a convective heat transfer process, but it also becomes a mass transfer process when temperatures are so high that the gas dissociates forming mass concentration gradient (Kays [55]). 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, movement and energy. The fluid flow obeys certain principles of mass, momentum and energy.

**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.
CONTROL SURFACE

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

PRINCIPLE OF CONSERVATION OF MASS

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

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 = gF

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 force)

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 in viscid. 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 (Kays and Crawford [44]).

**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 Hydrodynamic boundary layer or Velocity boundary layer.

**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.

**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 surface.
BOUSSINESQ APPROXIMATION

The fluid is incompressible except in so far as the thermal expansion produces buoyancy (gαT). Where, g - acceleration due to gravity, α - coefficient of thermal expansion and T - temperature.

VISCOSITY (μ)

The viscosity of the fluid is an extremely significant property in the investigation of liquid behaviour and fluid motion close to a solid boundary. It is the result of inter molecular forces exerted as layers of non-turbulent fluid moving is straight, parallel lines can be defined as

\[ \tau_{yx} \alpha \frac{\partial u}{\partial y} \]

where, \( \tau_{yx} \) is the shearing on the surface with thermal in the y-direction and velocity in the x-direction.

The relation among the shearing stress and the transverse velocity gradient is given by

\[ \tau_{yx} = \mu \frac{\partial u}{\partial y} \]

The constant of proportionality \( \mu \) is called the coefficient of viscosity.

The flow of water and air is much easier than syrup and heavy oil. This shows the existence of a viscosity property in the fluid which controls in the rate of flow.
SKIN FRICTION (τ)

A type of friction force which exists at the surface of a solid body immersed in a much large volume of fluid which is in motion relative to the body.

Skin friction is defined as drag per unit area and is given by

\[ \tau_{yy} = \mu \frac{\partial u}{\partial y} \]

HEAT TRANSFER COEFFICIENT (q)

The quantity of heat which passes during a unit area of a standard of system in a unit time when the temperature difference between the boundaries of the system is 1 degree.

The main part of the resistance of heat transfer is generally determined in a thin layer right away adjacent to wall surface. Heat transfer is essentially a problem of the interplay of heat conduction and energy transfer by the moving fluid inside this layer. As soon as the heat has penetrated this layer, it is carried away readily by the care of the fluid. Hence the heat transfer coefficient is determined essentially by the thickness and the characteristics of this boundary layer which in turn depend on all the parameters determining the flow along the surface.

Now we shall discuss the various numbers which we encounter in the study of convective heat and mass transfer.

PRANDTL NUMBER (Pr)

It is an important dimensionless parameter dealing with the properties of a fluid. It refers to or relates the relative thickness of
velocity boundary layer and thermal boundary layer. It is defined as the ratio of kinematic viscosity (\(\nu\)) to thermal diffusivity (\(\alpha\)) of a fluid. Prandtl number physically means or signifies the relative speed with which the momentum and heat energy are transmitted through a fluid. It thus associates the velocity and temperature fields of a fluid. For gases Prandtl number is of unit order and varies over a wide range in case of liquids (Sukhatme [76]).

**GRASHOF NUMBER (Gr)**

It plays a significant role in free convection heat and mass transfer. The ratio of the product of the inertial force and the buoyancy force to the square of viscous force in the convection flow system is interpreted as Grashof number. Grashof number in free convection is analogous to Reynolds number in forced convection.

**SCHMIDT NUMBER (Sc)**

The ratio of molecular diffusivity of momentum to the mass molecular diffusivity is given by Schmidt number.

**NUSELT NUMBER (Nu)**

Nusselt number gives a compute of the ratio of the heat transfer to convective heat transfer and is equal to the heat transfer coefficient times a character length divided by the thermal conductivity.

**SHERWOOD NUMBER (Sh)**

Sherwood number is equal to the mass transfer coefficient times the thickness of a layer through which mass transfer is satisfying place divided by the molecular diffusivity.
1.4 GOVERNING EQUATIONS:

The basic equation used to understand and analyze natural convection is the partial differential equations which result from the conservation of mass, Navier-Stokes equation, energy equation and diffusion equation.

In free convection, the fluid motion arises solely from the buoyancy forces. The buoyancy effect arises due to the interaction between the density differences in a body of fluid and a body force, generally gravitational force. The density differences of the diffusing species or the combination of both. So, both thermal and mass diffusing processes must be considered simultaneously for all aspects of the flow.

A two dimensional, laminar, free convection flow of a fluid past an infinite vertical plate is considered. The x-axis is taken along the plate in the upward direction and the y-axis is taken normal to it. The two-dimensional boundary layer governing equations of a laminar free convective flow of an incompressible viscous fluid past an infinite vertical plate (Schlichting [70]; Eckert and Drake [25]) are:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1.1}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = - \frac{\partial P}{\partial x} - \rho g + \mu \frac{\partial^2 u}{\partial y^2} \tag{1.2}
\]

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} \tag{1.3}
\]

\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \alpha \frac{\partial^2 C}{\partial y^2} \tag{1.4}
\]
Where \( u, v \) are the velocity components in \( x, y \)-directions respectively, \( t \) – time, \( \rho \) – density of the fluid, \( P \) – pressure, \( g \) – acceleration due to gravity, \( \mu \) – coefficient of viscosity, \( T \) – temperature of the fluid in the boundary layer, \( \alpha \) – fluid thermal diffusivity, \( C \) – species concentration in the boundary layer and \( D \) – mass diffusivity.

Here the fluid properties are understood to be constant except for the body force term. It is also assumed that the heat due to viscous dissipation in the energy equation is very small and is neglected. In the species equation it is assumed that concentration of the diffusing species is very small compared to that of the other chemical species present. Considering the flow to be without chemical reaction, the term representing the chemical reaction is neglected in the species equations.

Outside the boundary layer (i.e., \( y \to \infty \)), the viscous effects are negligibly small and the momentum equation (1.2) reduces along a stream line to

\[
0 = -\frac{\partial P}{\partial x} - \rho \alpha g
\]  

(1.5)

Substituting equation (1.5) in equation (1.2), we obtain

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - (\rho - \rho_\alpha) g + \mu \frac{\partial^2 u}{\partial y^2}
\]

(1.6)

Where \( \rho_\alpha \) is the reference pressure
For small temperature and concentration differences the density $\rho$ in equation (1.6) can be considered constant except for the term $(\rho - \rho_\infty)$. Boussinesq first introduced this approximation.

Since the flow is determined by the buoyancy forces arising from the density differences due to both temperature and concentration difference expressing the effect of buoyancy force through volumetric coefficients, the density differences can be expressed as

$$
\rho - \rho_\infty = -\rho \left[ \beta (T - T_\infty) + \beta^* (C - C_\infty) \right] 
$$

(1.7)

In view of the equation (1.7), the equation (1.6) can be written as

$$
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right) = g \beta (T - T_\infty) + g \beta^* (C - C_\infty) + v \frac{\partial^2 u}{\partial y^2} 
$$

(1.8)

Where $g$ - acceleration due to gravity

Thus the governing equations of free convection are equations (1.1), (1.8), (1.3), and (1.4)

**MAGNETO HYDRODYNAMIC CASE**

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 equations. As in most problems connecting conductors Maxwell’s displacements 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 equation can be written in the following form

\[
\nabla \times \mathbf{B} = \mu_0 \mathbf{J}, \nabla \cdot \mathbf{J} = 0 \\
\n\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \nabla \cdot \mathbf{B} = 0
\]

(1.9)

Ohm's law can be written in the form

\[
\mathbf{J} = \sigma (\mathbf{E} + \mathbf{q} \times \mathbf{B})
\]

(1.10)

If we add the body force \( \mathbf{J} \times \mathbf{B} \) per unit volume, the equation of the motion, then the body force represents the coupling between the magnetic field and the fluid motion which is called Lorentz force.

The induced magnetic field can be neglected under the assumption that the magnetic Reynolds number is small. This is rather significant case for some practical engineering problems where the conductivity is not large in the absence of an externally applied field and with negligible effects of divergence of the ionized gas. Taking \( \mathbf{E} = 0 \) i.e., in the absence of convection outside the boundary layer, \( \mathbf{B} = B_0 \) and \( \nabla \times \mathbf{B} = \mu_0 \mathbf{J} = 0 \)

Then the equation (1.10) leads to \( \mathbf{J} = \sigma (\mathbf{q} \times \mathbf{B}) \). Thus the Lorenze force becomes \( \mathbf{J} \times \mathbf{B} = \sigma (\mathbf{q} \times \mathbf{B}) \times \mathbf{B} \). In the absence of the induced magnetic field, to get a better degree of approximation, the Lorentz force can be replaced by

\[
\sigma (\mathbf{q} \times B_0) \times B_0 = -\sigma \mathbf{B}_0^2 \mathbf{q}
\]

Now equation (1.8) takes the form
\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right) = g \beta (T - T_x) + g \beta^* (C - C_x) + v \frac{\partial^2 u}{\partial y^2} - \frac{\sigma}{\rho} B_0^2 u \tag{1.11}
\]

Thus the equations, (1.1), (1.11), (1.3) and (1.4) represent the governing equations for the hydro magnetic case. The boundary conditions are prescribed approximately by the particular problems.