BASIC CONCEPTS OF HEAT TRANSFER

- Heat transfer is that science which seeks to predict the energy transfer which may take place between material bodies as a result of a temperature difference. Thermodynamics teaches that this energy transfer is defined as heat. The science of heat transfer seeks not merely to explain how heat energy may be transferred, but also to predict the rate at which the exchange will take place under certain specified conditions.
- Thermodynamics deals with systems in equilibrium; it may be used to predict the amount of energy required to change a system from one equilibrium state to another; it may not be used to predict how fast a change will take place since the system is not in equilibrium during the process.
- Thermodynamics deals with the end states of the process during which an interaction occurs and provides no information concerning the nature of the interaction or the time rate at which it occurs.

What and how?

- **Heat transfer** is the thermal energy in transit due to spatial temperature difference.
- **Conduction** refers to the heat transfer that occurs across the stationary medium, which may be solid or fluid. Due to presence of temperature gradient in the body, conduction heat transfer occurs.
- **Convection** refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperature.

- The third mode of heat transfer is termed **radiation**. All surfaces of finite temperature emit energy in the form of electromagnetic waves. Hence, in the absence of an intervening medium, there is net heat transfer by radiation between two surfaces at different temperatures.

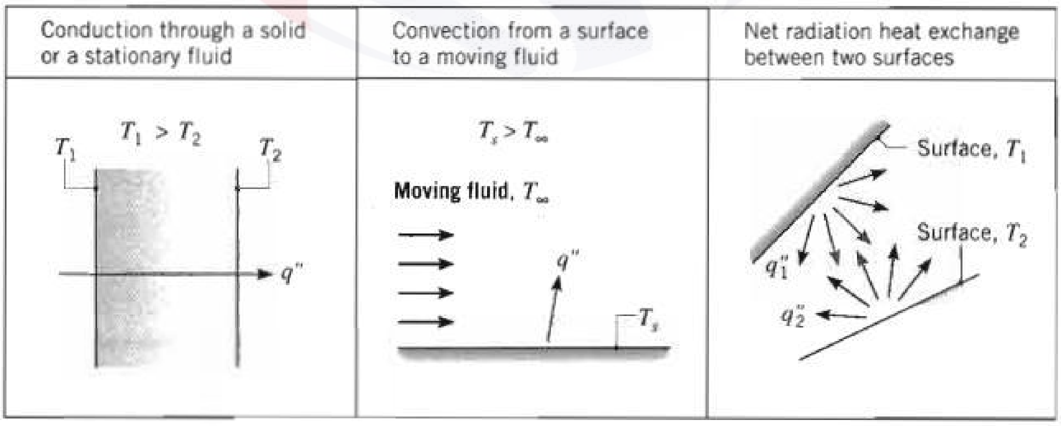
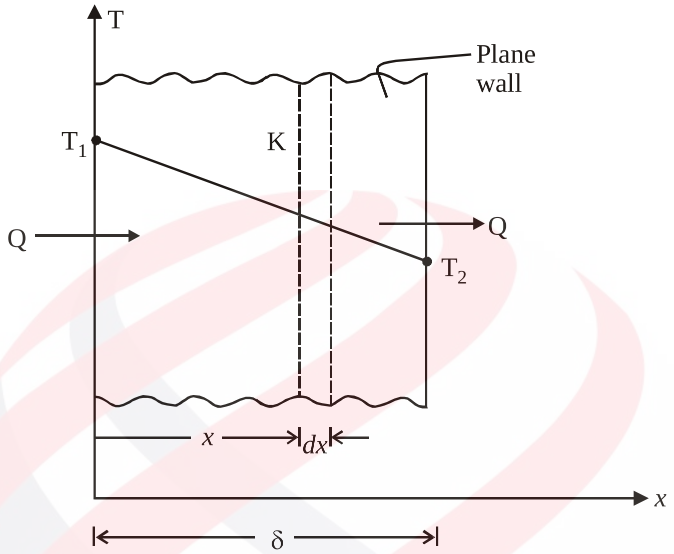


Figure – 1: conduction, convection and radiation heat transfer modes.

Conduction heat transfer:

- Conduction may be viewed as the transfer of energy from the more energetic to the less energetic particles of a substance due to interactions between the particles.

- In a solid, conduction may be attributed to atomic activity in the form of lattice vibrations. The modern view is to ascribe the energy transfer to **lattice waves** induced by atomic motion. In an electrical nonconductor, the energy transfer is exclusively via these lattice waves; in a conductor it is also due to the translational motion of the free electrons.



Temperature profile (PLANE . WALL)

$$T = T_1 + \left(\frac{T_2 - T_1}{\delta}\right) . x$$

Note : No heat conduction in the vertical direction only heat conducted in the *x*-direction of the plane wall.

- In a solid, vibrational mode of energy transfer is not as large as the electron transport. Due to this reason, good electrical conductors are almost always good heat conductors. A notable exception is diamond, which is an electrical insulator, but which can have a thermal conductivity five times as high as silver or copper.
- In a gas and liquid, conduction occurs due to the collision and diffusion of the molecules during their random motion.
- In a gas or liquid, the molecules are in continuous random motion, colliding with one another and exchanging energy and momentum. The molecules have this random motion whether or not a temperature gradient exists in the fluid. If a molecule moves from a high-temperature region to a region of lower temperature, it transports kinetic energy to the lower-temperature part of the system and gives up this energy through collisions with lower-energy molecules.
- Thermal conductivity of a gas varies with the square root of the absolute temperature.
- Fourier’s law of heat conduction:

- **Assumptions**

The following are the assumptions on which Fourier law is based

1. Heat flow is in unidirectional.

2. Conduction of heat takes place under steady state conditions.

3. There is no internal heat generation.

4. Temperature gradient is constant and the temperature profile is linear

5. The material is homogeneous and isotropic (*i.e.*, the value of thermal conductivity is constant in all directions).

$$q = -kA\frac{\partial T}{\partial x}$$

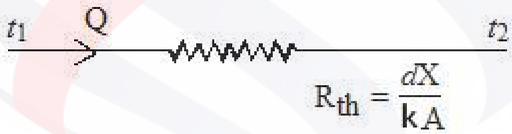
- Where q is the heat transfer rate and $\frac{\partial T}{\partial x}$ is the temperature gradient in the direction of heat flow. The positive constant k is called the thermal conductivity of the material and the minus sign is inserted so that the second principle of thermodynamics is satisfied.
- The heat transfer surface area '*A*' is always normal to the direction of heat transfer.

- **Essential Features of Fourier Law:**

1. It is applicable to all matter (Solid, Gas, and Liquid)

2. It is indicating that heat flow rate is in the direction of decreasing temperatures and is normal to an isotherm.

3. It is help to define thermal conductivity (k) of the medium through which heat is conducted.



$$\text{Heat flow } q = \frac{\text{Ttemperature difference } (dt)}{\frac{dX}{kA}}$$

$$(R_{th})_{cond} = \frac{dX}{kA}$$

4. The reciprocal of the thermal resistance is known as thermal conductance.

Convection:

- The convection heat transfer mode is comprised of two mechanisms. In addition to energy transfer due to random molecular motion {diffusion), energy is also transferred by the bulk, or macroscopic, motion of the fluid.
- Energy transfer due to bulk motion of the fluid is termed as **advection**.

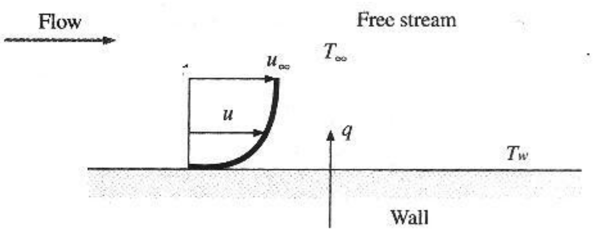


Figure-2:convection heat transfer from a plate.

- The convection heat transfer mode is sustained both by random molecular motion and by the bulk motion of the fluid within the boundary layer. The contribution due to random molecular motion (diffusion) dominates near the surface where the fluid velocity is low. In fact, at the interface between the surface and the fluid ($y = 0$), the fluid velocity is zero and heat is transferred by this mechanism only.

- In forced convection, flow of fluid is caused by external means, such as by a fan, a pump. In contrast, for free (or natural) convection the flow is induced by buoyancy forces, which are due to density differences caused by temperature variations in the fluid.

- Boiling and condensation phenomena are also grouped under the general subject of convection heat transfer.

- Newton's law of cooling
  $Q_{conv} = hA(T_S - T_\infty)$
  Where h is the convection heat transfer co-efficient (W/m^2 °C) and A is the surface area.

- Convection heat transfer co-efficient h depends on the thermal properties of the fluid and viscosity of the fluid. This is expected because viscosity influences the velocity profile and, correspondingly, the energy-transfer rate in the region near the wall.

- Convection heat transfer co-efficient is sometimes called the film conductance because of its relation to the conduction process in the thin stationary layer of fluid at the wall surface.

Radiation:

- Electromagnetic radiation which is propagated as a result of a temperature difference is called thermal radiation

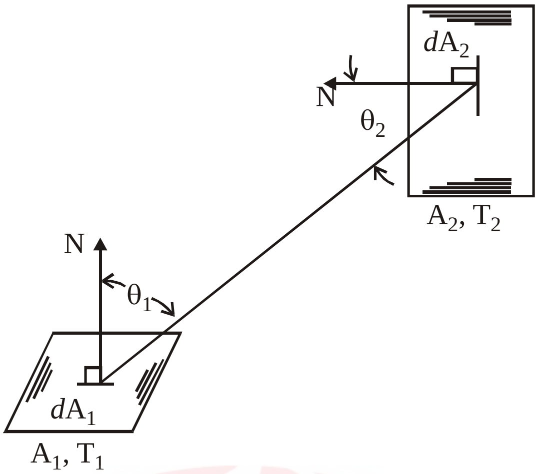


Figure: Radient Heat exchange

- Apart from solid surfaces, emission may also occur from liquids and gases. Regardless of the form of matter, the emission may be attributed to changes in the electron configurations of the constituent atoms or molecules.
- While the transfer of energy by conduction or convection requires the presence of a material medium, radiation does not. In fact, radiation transfer occurs most efficiently in a vacuum.
- Radiation that is emitted by the surface originates from the thermal energy of matter bounded by the surface, and the rate at which energy is released per unit area (W/m^2) is termed the surface emissive power *E*.
- There is an upper limit to the emissive power, which is prescribed by the **Stefan-Boltzmann law:**

  $$E_b = \sigma T_S^4$$

  where T_s is the absolute temperature (K) of the surface and σ is the Stefan-Boltzmann constant (σ = 5.67 × 10^{-8} W/m^2 K^4). Such a surface is called an ideal radiator or blackbody.
- The heat flux emitted by a real surface is less than that of a blackbody at the same temperature and is given by:

  $$E = \sigma T_S^4$$

  where ε is a radiative property of the surface termed the **emissivity**. With values in the range $0 < \varepsilon < 1$, this property provides a measure of how efficiently a surface emits energy relative to a blackbody. It depends strongly on the surface material and finish.
- The rate at which radiant energy is absorbed per unit surface area may be evaluated from knowledge of a surface radiative property termed the **absorptivity** α.

  $$G_{abs} = \alpha G$$

  where $0 < \alpha < 1$. If $\alpha < 1$ and the surface are opaque, portions of the irradiation are reflected.

- Note that the value of α depends on the nature of the irradiation, as well as on the surface itself. For example, the absorptivity of a surface to solar radiation may differ from its absorptivity to radiation emitted by the walls of a furnace.
- The net radiant exchange between two surfaces will be proportional to the difference in absolute temperature to the fourth power.

$$\frac{q_{net\ exchange}}{A} \propto \sigma\left(T_1^4 - T_2^4\right)$$

- Net radiant exchange between two surface is:

$$q_{net\ exchange} = h_r A\left(T_S - T_{surr}\right)$$

- Radiation heat transfer co-efficient is:

$$h_r = \varepsilon\ \sigma\left(T_s + T_{surr}\right)\left(T_s^2 + T_{surr}^2\right)$$

Summary:

Table : Summary of heat transfer processes

Mode	Mechanism	Rate Equation	Transport property or Co-efficient
Conduction	Diffusion of energy due to Random Molecular Motion	$Q\left(W/m^2\right) = -k\frac{dT}{dx}$	$k\left(W/m-K\right)$
Convection	Diffusion of energy due to Random Molecular Motion plus energy transfer due to bulk motion (Advection)	$Q\left(W/m^2\right) = h(T_s - T_\infty)$	$h\left(W/m^2-K\right)$
Radiation	Energy transfer by electromagnetic waves	$Q\left(W/m^2\right) = \varepsilon\sigma(T_s^4 - T_o^4)$	ε(emissivity)

Dimensionless Numbers:

Group	Definition	Interpretation
Biot number (Bi)	$\frac{hL}{k}$	Ratio of the internal thermal resistance of a solid to the boundary layer thermal resistance
Coefficient of friction (C_J)	$\frac{2_s}{{}^\circ V^2/2}$	Dimensionless surface shear stress.
Eckert number (Ec)	$\frac{V^2}{c_p(T_s - T_\infty)}$	Kinetic energy of the flow relative to the boundary layer enthalpy difference.
Fourier number (Fo)	$\frac{\sim t}{L^2}$	Ratio of the heat conduction rate to the rate of thermal energy storage in a solid. Dimensionless time.
Friction factor (f)	$\frac{\Delta p}{(L/D)({}^\circ u_m^2/2)}$	Dimensionless pressure drop for internal flow.
Grashof number (Gr)	$\frac{g\ \ (T_s - T_\infty)L^3}{v^2}$	Measure of the ratio of buoyancy forces to viscous forces.
Lewis number (Le)	$\frac{\sim}{D_{AB}}$	Ratio of the thermal and mass diffusivities.
Nusselt number(Nu)	$\frac{hL}{k_f}$	Ratio of convection to pure conduction heat transfer.
Peclet number (Pe)	$\frac{VL}{\sim} = RePr$	Ratio of advection to conduction heat transfer rates.
Prandtl number (Pr)	$\frac{c_p «}{k} = \frac{v}{\sim}$	Ratio of the momentum and thermal diffusivities.
Reynolds number (Re)	$\frac{VL}{v}$	Ratio of the inertia and viscous forces.
Schmidt number (Sc)	$\frac{v}{D_{AB}}$	Ratio of the momentum and mass diffusivities.
Sherwood number (Sh)	$\frac{h_m L}{D_{AB}}$	Dimensionless concentration gradient at the surface.
Stanton number (St)	$\frac{h}{{}^\circ V c_p} = \frac{Nu_L}{Re_L Pr}$	Modified Nusselt number.
Weber number (W_b)	$\frac{{}^\circ V^2 L}{\pm}$	Ratio of inertia to surface tension forces.