Conduction

It is the mode of heat transfer from a point on a body to another point of the same body, or it is the heat transfer from one body to another body which is in contact with the first body.

Heat transfer by conduction can be from the more energetic particles of the substance to the adjacent less energetic ones-as a result of interaction between the particles.

In solids, particles of a substance vibrate from their mean position. When temperature increases the vibration becomes intense. This result in interactions between molecules, while vibrating about their mean positions.

Conduction is a mode of heat transfer without appreciable movements or dispacement of molecules forming the substances. Heat transfer in soilds occur by molecular interaction and also by free electrons.

Convection

It is the mode of heat transfer between a solid surface and the adjacent liquid or gas which is in motion. That is why convection is explained as involving the combined effect of conduction and fluid motion. The faster the fluids move more is the convection heat transfer.

> In the absecnce of any bulk fluid motion, the heat transfer between a solid surface and the adjacent fluid is by pure conduction.

During convection heat transfer, there is actual movement molecules and they mix or mingle in between. Convection can be in two ways :

1. Free natural convection
2. Forced convection

Convection is said to be free or natural if the motion of the fluid is caused by buoyancy forces that are induced by density difference due to the variation of temperature in the fluid layers.

The denser portion of fluid moves down because of greater force of gravity, as compared to the force of gravity on less dense portion.

Convection is said to be forced if the fluid is forced to flow over the surface by external means such as fans, pumps, blowers etc.

> Heat transfer process that involves change of phase of a fluid is also considered to be convection.

It is because of the fluid motion induced during these processes. Vapour bubble rises during boiling and liquid droplets falls during condensation.

Radiation

Unlike conduction and convection, the transfer of heat by radiation does not require the presence of any intervening medium.

It is the heat energy emitted by matter in the form of electromagnetic waves as a result of the changes in the electronic configuration of atoms or molecules.

In fact, heat transfer by radiation is the fastest and it suffers no attenuation in vacuum.

Thermal radiation differs from other forms of electromagnetic radiations such as X rays, γ rays, microwaves, radio waves etc, as these are not related to temperature.

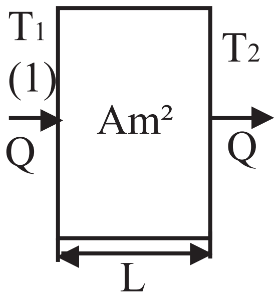
All bodies at a temperature above absolute zero emit thermal radiations.

Radiation is considered to be a surface phenomenon for solids.

Thermal Resistance

In the typical case of a slab having cross sectional area Am^2 perpendicular to the direction of heat flow, 'L' the thickness across which heat flow occurs and K, the coefficient of thermal conductivity, then Q

$$Q(W/m^2) = K\frac{(T_1 - T_2)}{L} \qquad (1)$$



Where T_1 is the higher temperature and T_2 the lower temperature. If Q is in W/m^2

$$Q = \frac{T_1 - T_2}{(L/K)} \qquad (2)$$

Where L/K is known as the thermal resistance of the material (if Q is in W/m^2).

The unit of thermal resistance

$$= \frac{m}{\frac{W}{mK}} = \frac{m^2k}{W}$$

Note

For a slab $Q = \dfrac{T_1 - T_2}{\left(\dfrac{L}{KA}\right)}$

For a Cylinder $Q = \dfrac{T_1 - T_2}{\dfrac{1}{2\pi KL} \log \dfrac{r_2}{r_1}}$

For a Spherical shell $Q = \dfrac{T_1 - T_2}{\dfrac{1}{4\pi r_1 r_2}[r_2 - r_1]}$

Convection Heat Transfer Co-efficient

It is not a property of the fluid or solid undergoing convection heat transfer. Its value depends on all the variables influencing convection such as the surface geometry, nature of fluid motion, fluid properties etc.

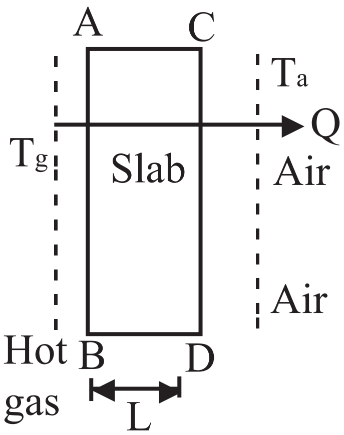
When, $Q = hA(T_1 - T_2)$

$$h = \frac{Q}{A(T_1 - T_2)}$$

Convection can be viewed as combined conduction and fluid motion. Conduction can be viewed as a special case of convection in the absence of fluid motion.

Imagine a hot gas at temperature T_g separated by a slab of thermal conductivity 'K' from atmospheric air at temperature 'T_a' $T_g >>> T_a$

The hot gas is flowing along the face AB and air is flowing along the face CD.



$\dfrac{1}{h_g A} + \dfrac{L}{KA} + \dfrac{1}{h_a A}$. Is the total thermal resistance, where hg and ha are convection heat transfer coefficient at faces AB and CD respectively

$$\therefore Q = \frac{T_g - T_a}{\frac{1}{h_g A} + \frac{L}{KA} + \frac{1}{h_a A}} \text{ or } \frac{A(T_g - T_a)}{\frac{1}{h_g} + \frac{L}{K} + \frac{1}{h_a}}$$

Heat Transfer Through Composite Cylinder

A composite cylinder consists of two or more coaxial cylinder as shown in the figure. The material thermal conductivities of the cylinders are K_1 , K_2 . Let the inner most temperature of composite cylinder is T_1 due to hot fluid flowing inside with temperature T and heat transfer coefficient of h_1 and outermost temperature is T_2 due to cold fluid flowing with temperature T_0 and heat transfer coefficient h_2.

If L is the length of the cylinder, the heat transfer rate Q from the hot to cold fluid is the same through each cylinder and are expressed as

$$Q = \frac{T_i - T_o}{\left[\frac{1}{h_i 2\pi r_1 L}\right] + \left[\frac{\ln r/r_1}{2\pi k_1 L}\right] + \left[\frac{\ln r_2 /r}{2\pi k_2 L}\right] + \left[\frac{1}{h_o 2\pi r_2 L}\right]}$$

Energy Equation

$$k \frac{d^2T}{dx^2} + q = 0 \text{ [For steady, 1 - D heat transfer]}$$

$$\text{or } \frac{d^2T}{dx^2} + \frac{q}{k} = 0 \Rightarrow \frac{d}{dx}\left[\frac{dT}{dx}\right] = \frac{-q}{k}$$

Integrating the above equation.

$$\frac{dT}{dx} = \left[\frac{-\dot{q}}{K}\right] x + C_1$$

Again integrating, $T = \left[\frac{-\dot{q}}{2K}\right] x^2 + C_1 x + C_2$

System with Negligible Internal Resistance Lumped Heat Analysis

Let us assume a body which is cooling from initial temperature T_i being exposed to the atmospheric temperature T_∞. If the thermal conductivity of the body is infinity (or very high) then its internal resistance becomes zero and the surface resistance due to the convection is the only factor which is responsible for heat transfer. In these cases, there is no temperature change within the body with change in time. This process is known as Newtonian heating or cooling.

$$\therefore \ln (T - T_\infty) = \left[\frac{-hA_s t}{\rho V C_p}\right] + \ln (T_i - T_\infty)$$

$$\text{or} \quad \ln\left[\frac{T - T_\infty}{T_i - T_\infty}\right] = -\frac{hA_s t}{\rho V C_p}$$

$$\Rightarrow \frac{T - T_\infty}{T_i - T_\infty} = e^{-\left[\frac{hA_s t}{\rho V C_p}\right]}$$

Where : C_p = Specific heat of the body, J/kg-K

h = Heat transfer coefficient, W/m²-K

A_s = Surface area of body, m²

ρ = Density of the material, kg/m³

V = Volume of the body, m³

T_∞ = Ambient temperature, °C

T_i = Initial temperature of body, °C.

T = Temperature of body at any time, °C.

When $R_{condition} <<< R_{convection}$, then body can be treated like a lump.

Temperature-time Response of Thermo Couple

Thermocouple works on the principle of unsteady state heat conduction with infinite thermal conductivity. This is temperature measuring device and should reach the temperature of the source, to which it is exposed as soon as possible. The time taken by the thermocouple to reach the source temperature is known as response time of thermocouple.

- The thermocouple reaches the source temperature as soon as the equation $e^{\left[\frac{hAt}{\rho C_p V}\right]}$ approaches to zero. This can be achieved by increasing the value of h or by decreasing the wire diameter. Therefore, a very thin wire is recommended for thermocouple for rapid response.
- The time required by a thermocouple to reach 63.2% of the value of initial temperature difference indicates the sensitivity of thermocouple and is known as time constant or response time.

$$\frac{T - T_\infty}{T_i - T_\infty} = 1 - 0.632 = 0.368 = e^{-1}$$

or $B_i F_o = 1$

The response or thermal time constant is given by

$$t = \frac{\rho C_p V}{A_s h}$$

Efficiency

The efficiency of a fin is defined as the ratio of the actual heat transferred by the fin to the maximum heat that could be transferred by the fin if the temperature of whole fin area is equal to the base temperature of fin, i.e., 'T_0', everywhere.

$$\eta_{fin} = \frac{Q_{fin}}{Q_{fin\ max\ possible}}$$

• For a very long fin (rectangular)

$$Q_{fin} = \sqrt{hPKA} \cdot \theta_0$$

If the whole surface of the fin were at the same temperature, then heat transfer

$$= h(\text{Area})\,\theta_0$$
$$= hP \times L\,\theta_0$$

$$\eta_{fin} = \frac{\sqrt{hPKA} \cdot \theta_0}{hPL\theta_0} = \frac{\sqrt{hPKA}}{hPL} = \sqrt{\frac{KA}{hPL^2}}$$

But we know that $m = \sqrt{\frac{hp}{KA}}$

Effectiveness

Effectiveness of the fin is defined as the amount of heat transferred with the fin to the amount of heat transferred without the fin in a specified time, and from a specified area.

If this ratio is less than '1' it means, addition of fin has reduced the heat transfer rate. That means the provision of fin for increasing the heat removal rate is not justified.

∴ Effectiveness 'ε' of the fin is

$$\varepsilon = \frac{\text{Heat lost from a surface, with fin}}{\text{Heat lost from the same surface without fins}}$$

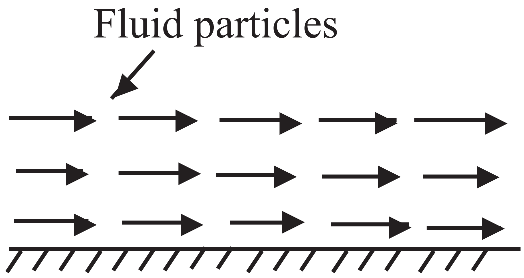
ε should be > 1

$$\varepsilon = \frac{\sqrt{hPKA\theta_0}\ \dfrac{\tanh mL + h/mk}{1 + h/mk \tanh mL}}{hA\theta_0}$$

$$= \sqrt{\frac{PK}{hA}}\left[\frac{\tanh mL + h/mk}{1 + h/mk \tanh mL}\right]$$

Laminar Flow

It is defined as the type of flow in which the fluid particles move along a well defined path or streamline. In laminar flow, fluid layers slide smoothly one over the other as shown in the figure below.



Turbulent Flow

If the fluid particles move in a zigzag way having no fixed direction, then flow is said to be turbulent. In turbulent flows, the eddies formation takes place which are responsible for high energy loss.

Boundary Layer Thickness (δ)

The distance from the solid surface, to the layer measured in Y direction in which the velocity ($v = 0.99\ v_\alpha$) is known as boundary layer thickness same as δ. Special features of a boundary layer are as given below

1. As distance from leading edge increases, δ increases.
2. δ decreases as velocity of fluid increases.
3. As kinetic viscosity 9v) increases δ increases.
4. As shear stress increases δ decreases.

$$\left[\tau = \mu\left(\frac{V}{\delta}\right)\right]$$

5. If Reynolds number > 4000 flow is turbulent (for pipe).
6. If $R_e < 2000$, flow is laminar (for pipe)

Dimensionless Numbers Nusselt Number (N_u)

$$N_u = \frac{hL}{K}$$

$$N_u = \frac{h \cdot A \cdot \Delta T}{K \dfrac{A \cdot \Delta T}{L}}$$, where K is the thermal conductivity of the fluid.

$$= \frac{\text{Rate of heat transfer by convection}}{\text{Rate of heat transfer by conduction}}$$

ΔT is the temperature difference between wall surface and fluid. This N_u is the measure of energy transfer by convection occuring at the surface. larger the value of N_u larger will be the rate of heat transfer by convection.

Reynolds Number (R_e)

Reynolds number signifies the ratio of inertia force to viscous force.

ENTRI

Also, $R_e = \frac{\rho VL}{\mu} = \frac{VL}{\left(\frac{\mu}{\ell}\right)} = \frac{VL}{v}$

In forced convection, Reynolds number characterizes the type of flow. Whether it is laminar or turbulent flow is proportional to velocity and density of fluid thus, for higher values of ρ and V higher will be Reynolds number. It signifies that the inertia forces are higher. The flow is turbulent if Reynolds number is low viscous force is higher and the flow is laminar.

Critical Reynolds number $(R_e)_{er}$. It represents the number where the boundary layer changes from laminar to turbulent flow for flat plate.

$$R_e < 5 \times 10^5 \text{ (laminar) } R_e = \frac{\rho VL}{\mu}$$

$$R_e > 5 \times 10^5 \text{ (turbulent)}$$

For circular plates

$$R_e < 2000 \text{ laminar } R_e = \frac{\rho V}{D\mu}$$

$$R_e > 4000 \text{ (turbulent)}$$

The value of r_e in between laminar and turbulent shows a transition state where laminar boundary changes to turbulent boundary.

Prandtl Number (P_r)

It can be written as

$$(P_r) = \frac{\mu C_p}{k} = \frac{\text{Kinematic viscocity (V)}}{\text{Thermal diffusivity}}$$

$$= \frac{\frac{\mu}{\ell}}{\frac{K}{\ell Q}}$$

$$P_r \ \frac{V}{\alpha} = \frac{\text{Momentum diffusivity through the fluid}}{\text{Thermal diffusivity through the fluid}}$$

Prandtl number signifies the ratio of momentum diffusivity to the thermal diffusivity. It provides a measure of relative effectiveness of momentum and energy transport, by diffusion in hydro-dynamic and the thermal boundary layers, respectively. Higher P_r means higher N_u and it shows higher heat transfer (as $N_u \propto$ to $\bar{h}$)

Prandtl number for various materials

Liquid metals $P_r < 0.01$

For air and gases $P_r = 1$

For water $P_r = 10$

For heavy oils and greases $P_r > 10^5$

Stanton Number (S_t)

It is the ratio of heat transfer coefficient to flow of heat per unit temperature rise due to the velocity of fluid.

$$S_t = \frac{h}{\rho V C_p} = \frac{h}{\rho V C_p} \times \left(\frac{L}{k} \times \frac{k}{L}\right) \times \frac{\mu}{\mu}$$

$$= \frac{h \cdot \frac{L}{k}}{\frac{\rho \cdot v \cdot L}{\mu} \times \frac{\mu C_p}{k}}$$

$$= S_t = \frac{N_u}{R_e \times P_r}$$

The temperature of fluid varies from surface up to the thermal boundary layer thickness. For convective heat transfer analysis the mean temperature of surface and that of fluid is taken, so that mean heat transfer coefficient can be calculated.

$$T_{mean} = \frac{T_s + T_\infty}{2}$$

Grashof Number (G_r)

It represents the product of buoyant and inertia forces to square of viscous forces. It helps in determining the nature of flow (laminar or turbulent) as Reynolds number determines in forced convection.

The value of G_r depend upon the shape position of body defined by characteristic length L.

$$G_r = \text{Inertia force} \times \frac{\text{Buoyancy force}}{(\text{Viscous force})^2}$$

$$= \frac{(\rho V^2 L^2)(\rho \beta g \Delta T L^3)}{(\mu V L)^2}$$

$$= \frac{\rho^2 \beta g \Delta T L^3}{\mu^2}$$

$$= \frac{\beta g \Delta \theta L^3}{v^2}, \left(v = \frac{\mu}{\rho}\right)$$

The role played by Grashoff's number in natural (free) convection is identical to the role played by Reynolds No. in forced convection. Just as Reynolds No. decides whether the fluid flow is laminar or turbulent, Grashoff number decides in the case of natural convection, whether the flow is laminar or turbulent.

Rayleigh number (R_a)

It is the product of Grashof number and Prandtl number

$R_a = G_r P_r$

$$= \frac{\rho^2 \beta g \Delta T L^3}{\mu^2} \times \frac{\mu C_p}{K} = \frac{g\beta L^3 \Delta T}{\nu \cdot \alpha}$$

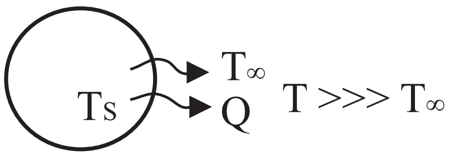
If free or natural convection then

$10^4 < R_a < 10^9$ laminar flow

$R_a > 10^9$ - turbulent flow

Radiative Heat Transfer

Let us take a body with very high temperature kept in ambient condition.



Let A be the surface area of the body, ε is the emissivity of the surface and σ be the Stephan Boltzman constant then the radiative heat transfer will be given as

$$Q = \varepsilon \sigma A[\, T_s^4 - T_\infty^4 \,]$$

Where,

T_s = Surface temperature of body

T_∞ = Ambient temperature

$\sigma = 5.67 \times 10^{-8}$ Q/m²-K⁴

Black Body

It is defined as a perfect emitter and perfect absorber of radiations. A black body absorbs all radiations falling on it. The radiation energy emitter by a black body per unit time per unit area is given by

$$E = \sigma T^4 \text{ W/m}^2$$

Where $\sigma = 5.67 \times 10^{-8}$ W/m² K⁴

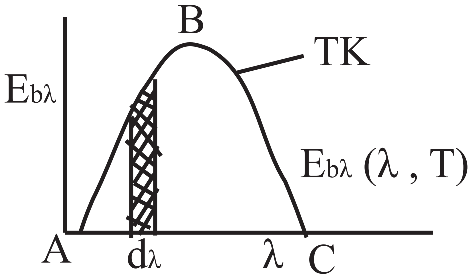
(Stefan Boltzmann constant)

Emissive Power

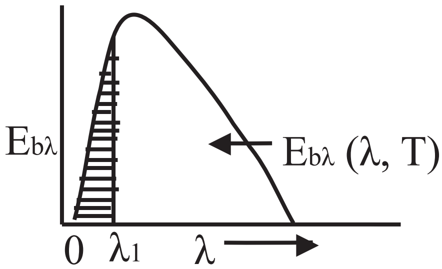
Emissive power of a black body is defined as the energy emitted by the surface per unit time per unit area (E_b).

It depends on the surface roughness and material of surface.

At a given temperature the ampunt of radiations emitted per unit wavelength varies at different wavelength. Hence comes the term Mono Chromatic emissive power.



Area under the curve ABC gives the total radiation energy of a black body at temperature T.



Area of the curve left of $\lambda = \lambda_1$ gives the total radiation energy emitted by the black body in the wavelength range $0 - \lambda_1$.

Mono Chromatic emissive power is the amount of radiant energy emitted by a black body at temperature TK per unit time per unit wavelength about wavelength λ is (i.e., λ to λ + dλ)

$$E_b(\lambda, T) = \frac{C_1}{\lambda^5 [e^{C2/\lambda T} - 1]}$$

$$\text{Where } C_1 = 2\pi h c_0^2 = 3.74177 \times 10^{8} \times w\mu \frac{m^4}{m^2}$$

$$C_2 = \frac{hc_0}{K} = 1.43878 \times 10^4 \, \mu mK$$

$$K = 1.38065 \times 10^{-23} \frac{J}{K}$$

Transmissibility, Absorptivity, Reflectivity

The radiation flux incident on a surface is known as Irradiation. It is denoted by G.

When radiation strikes a surface part of it is transmitted, part of it is reflected and part of it is absorbed.

The amount of radiation absorbed out of the total radiation falling on a surface is known as absorptivity.

$$\text{Absorptivity } \alpha = \frac{\text{Radiation absorbed}}{G}$$

Reflectivity $\rho = \dfrac{\text{Radiation reflected}}{G}$

Transmissibility $\tau = \dfrac{\text{Radiation transmitted}}{G}$

$$\alpha + \ell + \tau = \frac{G}{G} = 1$$

All Radiations	Value of α, τ, ρ	Nature of Bodies
Absorbed	$\alpha = 1$ $\rho = 0$ $\tau = 0$	Black body
Reflected	$\rho = 1$ $\alpha = 0$ $\tau = 0$	White body
Transmitted	$\tau = 1$ $\alpha = 0$ $\rho = 0$	Transparent body
Partly reflected	$\alpha + \rho = 1$ $\tau = 0$	Opaque body and absorbed

Gray Body

The emissive power of any body is less than the emissive power of the black body.

A gray body is one that absorbs a definite percentage of radiations falling on it irrespective of their wavelength.

If the ratio of the monochromatic emission power of a body to the monochromatic emissive power of the black body over the entire wavelength spectrum is less than one then the body is said to be a gray body.

Emissivity of a Gray Surface

The emissivity of a surface is defined as the ratio of the radiation emitted by the surface at a temperature to the radiation emitted by the black body at that temperature.

Coloured Body

When the absorbitivity of a body varies with wavelength of radiation, then the body is known as a coloured body.

Kirchoff's law

Kirchoff's law states that the ratio of the total emissive power to the absorptivity is a constant for all substances which are in thermal equilibrium with the surroundings i.e., consider bodies 1, 2, 3, ... which are in thermal equillibrium

$$\frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \frac{E_3}{\alpha_3} \ldots$$

Where E_1 , E_2 , E_3 . . . are the emissive power and α_1 , α_2 , α_3 . . . are the absorptive.

$$\frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \frac{E_3}{\alpha_3} = \ldots \frac{E_b}{\alpha_b}$$

But for a black body $\alpha_b = 1$

$$\therefore \frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \frac{E_3}{\alpha_3} = \ldots = E_b$$

$$\therefore \frac{E_1}{E_b} = \alpha_1 , \frac{E_2}{E_b} = \alpha_2 , \frac{E_3}{E_b} = \alpha_3 \ldots$$

But $$\frac{E_1}{E_b} = \varepsilon_1 , \frac{E_2}{E_b} = \varepsilon_2 , \frac{E_3}{E_b} = \varepsilon_3 \ldots$$

$$\therefore \alpha_1 = \varepsilon_1 , \alpha_2 = \varepsilon_2 , \alpha_3 = \varepsilon_3 \ldots$$

$\therefore$ Absorptivity of a body is equal to emissivity when he body remains in thermal equilibrium with the surroundings.

Shape Factor

It is the function of geometry of a surface radiating heat energy.

When two bodies are radiating enery with each other the shape factor relation will be $A_1F_{12} = A_2F_{21}$

Where A_1 and A_2 are the surface areas.

In a convex surface is enclosed in another surface all the radiations from the convex surface will be intercepted by the enclosing surface.

If '1' is the convex surface and '2' the enclosing surface the $F_{11} + F_{12} = 1$

F_{11} is the fraction of radiations from the convex surface intercepted by itself and F_{12} is the fraction of radiations emitted by the convex surface intercepted by the enclosing surface.

Since it is a convex surface no radiation from it can be intercepted by itself.

$\therefore$ $F_{11} = 0$

$F_{11} + F_{12} = 1$

Such that $F_{11} = 0$, $F_{12} = 1$

But for a concave surface then is a shape factor by itself, i.e., $F_{11} \neq 0$.

Let 1 is a concave surface enclosed within another surface 2.

Surface 1 radiates heat. All radiations from 1 will not fall on 2. A portion of the radiations will fall on 1 itself. In this case $F_{11} \neq 0$.

But $F_{11} + F_{12} = 1$

If there are 'n' surfaces taking part in the radiation exchange, then

$F_{11} + F_{12} + F_{13} + F_{14} + \ldots + F_{1n} = 1$

$F_{21} + F_{22} + F_{23} + F_{24} + \ldots + F_{2n} = 1$

. . .

Quantum Theory or Planck's Theory

thermal radiation propagates in the form of quanta or photon and each photon has an energy = hv.

Where the value of h is $h = 6.625 \times 10^{-34}$ J - s

This constant is known as Planck's crest

Surface Emission Properties

Emission of radiation by a body depends upon the following factors.

1. The temperature of the surface
2. The nature of the surface
3. The wave length or frequency of radiation

The parameters which deals with the surface emission properties.

Total Emission Power (E)

It is defined as the total amount of radiation emitted by a body per unit area and time. It is expressed in W/m². The emission power of a black body, according to Stefan-Boltzmann is proportional to absolute temperature the 4th power of

$$E_b = \sigma T^4 \text{ W/m}^2$$

$$E_b = \sigma A T^4 \text{ Watt}$$

Where s = Stefan-Boltzmann constant

$= 5.67 \times 10^{-8}$ W/m² K^4

Monochromatic (spectral)
Emission Power (Eλ)

It is often required to determine the spectral distribution of the energy radiated by a surface. At any temperature the amount of radiation emitted per unit wave length varies at different wave lengths. The mono-chromatic emissive power of a radiating surface is the energy emitted by the surface at a given wavelength. It is measured as W/m². The expression for mono-chromatic emissive power (Spectral emissive power is)

$$E_\lambda \int_{\lambda}^{\lambda + d\lambda} E_\lambda \, d\lambda$$

Emission from Real Surface Emissivity

The emissive power from a real surface is given by $E = \varepsilon\sigma AT^4$ Watt

Where (ε) = emissivity of the surface

Emissivity 9ε) it is known as ability of the surface of a body to radiate heat. It is also defined as the ratio of the emissive power of anybody to the emissive power of a black body of same temperature (i.e.) $\varepsilon = \frac{E}{E_b}$. Its value varies for different substances ranging from 0 to 1. For a black body $\varepsilon = 1$, for a white body surface $\varepsilon = 0$ and for gray bodies. It lies between 0 and 1. It may vary with temperature or wavelength also.

Irradiation (G)

It is defined as the total radiation incident upon a surface per unit time per unit area. Its unit is W/m^2.

Radiosity (J)

Total radiation leaving a surface per unit time per unit area.

Reflectivity

It is defined as the fraction of total incident radiation that are reflected by material.

$$\text{Reflectivity } (\rho) = \frac{\text{Energy reflected } (Q_r)}{\text{Total incident radiation}}$$

Absorptivity

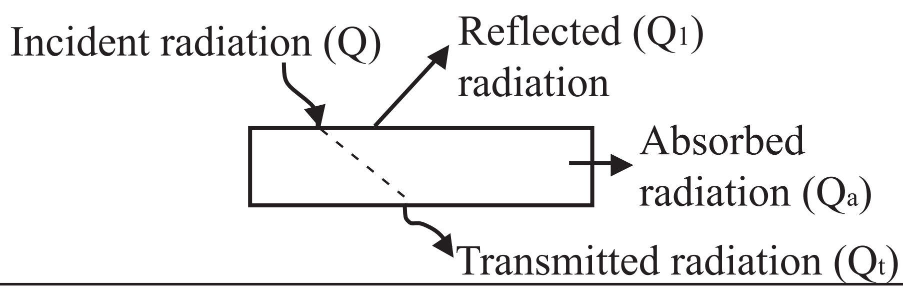
It is defined as the fraction of total incident radiation that are absorbed by material.

$$\text{Absorptivity } (\alpha) = \frac{\text{Energy absorbed}}{\text{Total incident radiation}}$$

Transmissivity (τ)

It is defined as the fraction of total incident radiation that is transmitted through the material.

$$\text{Transmissivity } (\tau) = \frac{\text{Energy transmitted}}{\text{Total incident radiation}}$$



By applying the law of conservation energy

$Q = Q_r + Q_\tau + Q_\alpha$

$$\frac{Q}{Q} = \frac{Q_r}{Q} + \frac{Q_\tau}{Q} + \frac{Q_\alpha}{Q}$$

$1 = \rho + \tau + \alpha$

The Stefan - Boltzmann Law

This law states that the emission power of a black body directly proportional to the fourth power of the absolute temperature.

i.e. $Eb = \sigma T^4$

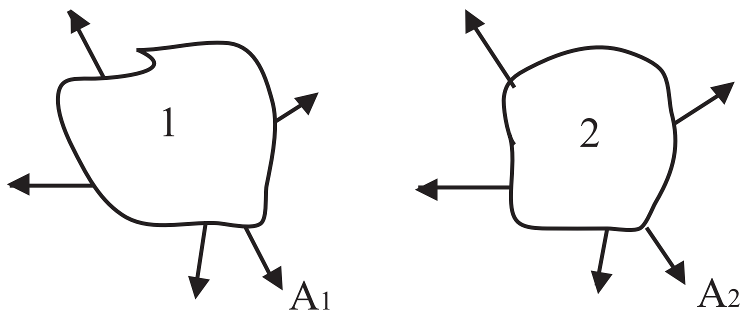
Where Eb = Emissive power of a black body

σ = Stefan constant - Boltzmann constant

Constant = $5.67 \times 10^{-8} W/m^2K$

Heat Exchange Between Two Black Bodies

Radiation emitted by body 1 = $\sigma A_1 T_1^4$



Stefan-Boltzmann law part of this radiation on

2 = $F_{1-2} \sigma A_1 T_1^4$

Radiation emitted by body 2 = $\sigma . A_2 T_2^4$

Part of this radiation falling on 1 = $F_{2-1} \sigma A_2 T_2^4$

Heat exchange between two bodies

$= F_{1-2} \sigma A_1 T_1^4 - F_{2-1} \sigma A_2 T_2^4$

By reciprocity theorem

$A_1 F_{1-2} = A_2 F_{2-1}$

$= A_1 F_{1-2} \sigma (T_1^4 - T_2^4)$

Regenerators

Regenerators are type of heat exchanges, where hot and cold fluids pass alternatively through a space containing solid particles (matrix). These particles provide alternatively a sink and a source or heat flow. e.g. IC engines and gas turbines. A regenerator generally operates periodically (the solid matrix alternatively stores heat extracted from the hot fluid and then delivers it to cold fluid. However in some regenerators, the matrix is rotated through the fluid passages arranged side by side which makes the heat exchange process continuous.

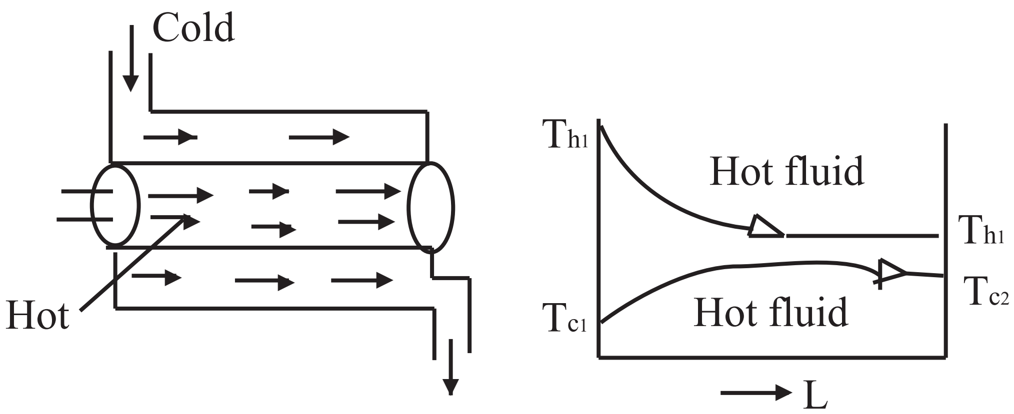
Recuperators

A recuperator is a special purpose counter flow energy recovering heat exchanger positioned within the supply and exhaust gases of an industrial process in order to recover the waste heat.

Based on the relative direction of fluid flow, heat exchangers are categorized in to the following groups :

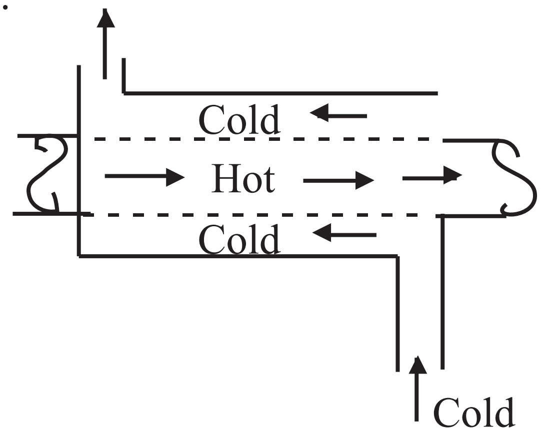
Parallel Flow Heat Exchanger

When two streams of fluids enters at one end and leaves at other end, the flow is known as parallel flow. The temperature difference goes on decreasing as we move along the length as shown in figure.



Counter Flow Heat Exchanger

In counter flow heat exchanger two fluids flow in opposite directions. The flow arrangement and temperature distribution for such a heat exchanger are shown in figure. The temperature differences between two fluids remain nearly constant. This type of heat exchanger, due to counter flow gives maximum rate of heat transfer for a given surface area. hence such heat exchangers are mostly favoured.



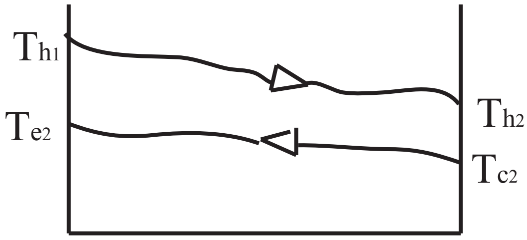
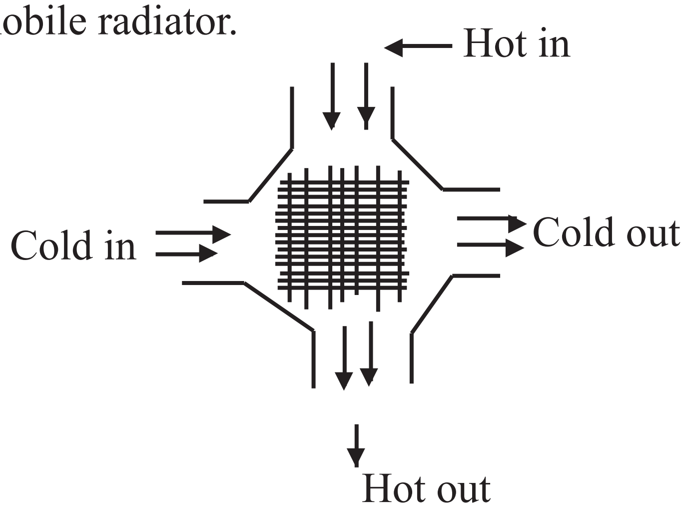


Figure : Counter flow heat exchanger

Cross Flow Heat Exchanger

When the two fluids cross one another usually at right angles, then the heat exchanger is called a cross flow heat-exchanger. The common example is auto mobile radiator.



On the basis of design and construction heat exchangers are classified as

Concentric Tubes

In this type, two concentric tubes are used, each carrying one of the fluids. The direction of flow may be parallel or counter as applicable. The effectiveness of heat exchanger is increased by using swirling flow.

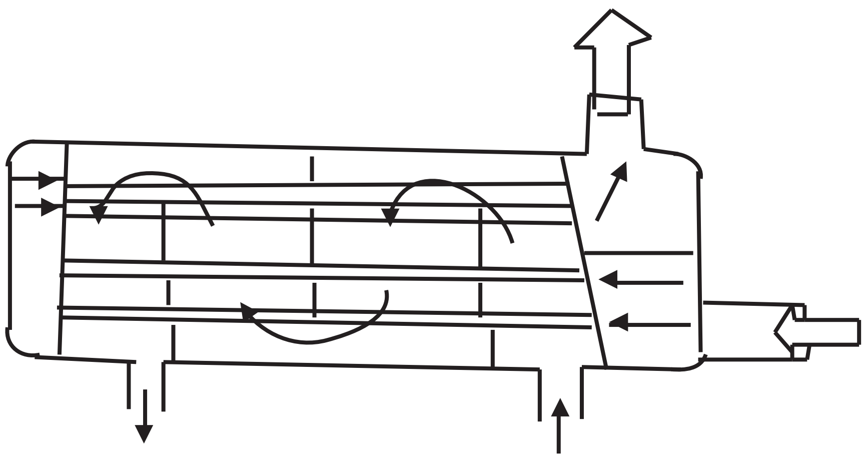


Figure : One shell pass and two tube pass heat exchanger

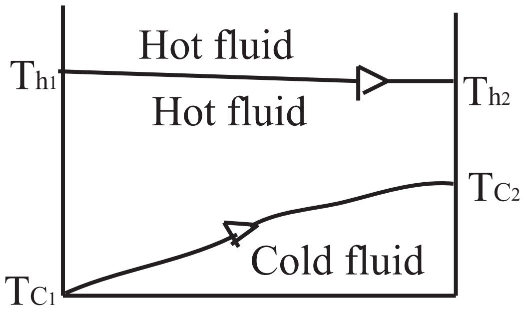
Multiple Shell and Tube Passes

Multiple shell and tube passes are used for increasing the overall heat transfer baffles are used to force the fluid back and forth across the tubes carrying the other fluid.

Based on the physical state of the fluids heat exchangers are classified as :

Condensers

In condensers the condensing fluid remains at constant temperature throughout the exchanger while temperature of the colder fluid gradually increases from inlet to outlet.



Evaporator

In this case, the boiling liquid (cold fluid) remains at constant temperature while temperature of hot fluid gradually decreases from inlet to outlet.

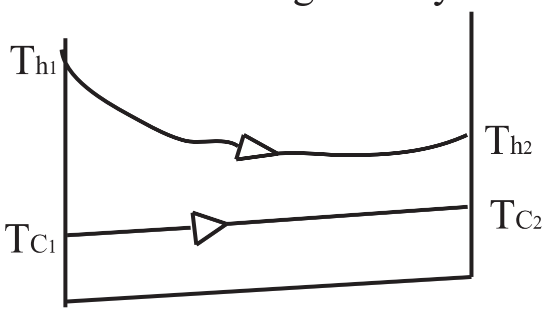


Figure : Evaporator

Boiling

Boiling is a 'liquid to vapour phase transformation' like evaporation. But there is significant difference between these two. Evaporation occurs when the vapour pressure is less than the saturation pressure at that temperature. Drying of clothes, evaporation of sweat from hyman body etc are examples.

Condensation heat Transfer

A vapour condenses when its temperature is brought below the saturation temperature when the vapour comes in contact with a surface which is at a temperature below the saturation temperature, then condensation of the vapour begins. It can occur, on the free surface of a liquid or on a body of gas mass, if they are at temperature below the saturation temperature and the vapour is exposed to them. In the case of the gas the condensed liquid droplets suspended in the gas form a fog.

There are two forms of condensation. They are

1. Film wise condensation
2. Drop wise condensation

NTU Method of Effectiveness of heat Exchangers

NTU means number of transfer units. Effectiveness of the heat exchanger is the ratio of actual heat transferred to the maximum possible heat that can be transferred

$$\varepsilon = \frac{\text{Actual heat transferred}}{\text{Maximum heat that can be transferred}}$$

Effectiveness depends on the dimensionless factor $\frac{UA}{C_{min}}$

Thix quantity is known as No. of Transfer Units (NTU) $\varepsilon \propto$ NTU

$$\varepsilon \propto \frac{UA}{C_{min}}$$

For a given value of U and C_{min} , ε is proportional to 'A' , the heat transfer Area.

Therefore higher value for NTU means large size heat exchanger. Actually effectiveness is a function of NTU and capacity ratio. Capacity ratio is nothing but $\frac{C_{min}}{C_{max}} = C$

$$\therefore \varepsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right) \quad \varepsilon = f(NTU, C)$$

For parallel flow heat transfer $\varepsilon = \frac{1 - e^{-NTU(1+c)}}{1+c}$

Effectiveness is maximum when NTU = ∞

$$\varepsilon_{max} = \frac{1}{1+c}$$

For boilers and Condensers

$$\frac{C_{min}}{C_{max}} = 0$$

$$\therefore e = 1 - e^{-NTU}$$

For gas turbines $\frac{C_{min}}{C_{max}} = 1$

$$\therefore \varepsilon = \frac{1}{2}[1 - 2^{-2NTU}]$$

For counter flow heat exchangers

$$\varepsilon = \frac{1 - e^{-NTU(1-c)}}{1 - e^{-NTU(1-c)}}$$

When NTU = ∞ , $\varepsilon_{max} = 1$

For boilers and condensers $\frac{C_{min}}{C_{max}} = 0$

$$\varepsilon = \frac{1 - e^{-NTU}}{1 - o \times e^{-NTU}} = 1 - e^{-NTU}$$

For gas turbines $\frac{C_{min}}{C_{max}} = 1$

$$\varepsilon = \frac{1 - e^{o}}{1 - le^{o}} = \text{Limited to } \frac{NTU}{NTU + 1}$$

Effectiveness of Heat Exchanger

$$\epsilon = \frac{q}{q_{max}}$$

It is the ratio of actual heat transfer to the maximum transfer.

Now $q = C_h [T_{hi} - T_{ho}] = C_h [T_{co} - T_{ci}]$

$$\epsilon = \frac{C_h [T_{hi} - T_{ho}]}{C_{min} [T_{hi} - T_{Ci}]} = \frac{C_c [T_{Co} - T_{Ci}]}{C_{min} [T_{hi} - T_{ci}]}$$