HEAT TRANSFER :- It is defined as "Transfer of heat from one body to another body (or) transfer of heat from one molecule to another molecule within the body"

(or)

"The transmission of energy from one region to another as a result of temperature gradient."

In heat transfer the driving potential is temperature difference whereas in mass transfer the driving potential is concentration difference. In mass transfer, we concentrate upon mass motion which result in changes in composition

Purpose/Necessity/use of HT :-

To estimate the rate of flow of energy as heat through the boundary of a system under study

To determine the temperature field under steady and transient conditions

In almost every branch of engineering, HT & mass Transfer Problems are encountered which cannot be solved by thermodynamic reasoning alone but require an analysis based on heat transfer principles.

Areas under the discipline of HT are :-

Internal combustion Engines.

R & A C units

Design of cooling systems for → electrical motors, → generators, → Transformers.

Heating and cooling of fluids.
Heat treatment of metals.
Dispersion of atmospheric pollutants

Basic Laws governing Heat Transfer

- First Law of thermodynamics
- Second Law
- Law of conservation of mass
- Newton's law
- Rate equation

1. First Law of TD :-

$$dQ = dE + dw$$

$$dQ = du + dw$$

This Law can be applied to both reversible & irreversible transformations.

2. Second Law :- "Heat will naturally flows from higher reservoir to lower reservoir

3. Law of conservation of mass :- This Law is used to determine the parameter flow

④ Newton's Law :-

Modes of HT

Conduction | Convection | Radiation

① **Conduction** It is the transfer of heat from one part of substances to another part of the same substance, or from one substance to another in physical contact with it.

Example when 2 metallic or non-metallic bodies are in contact with each other. Heat flows from high temperature region to lower temperature

Fourier's Law of heat conduction:- "The rate of flow of heat through a simple homogeneous solid is directly propotional to the area of cross-section & to the change of temperature".

Mathematically, it can be expressed as

$$\boxed{Q \propto A \cdot \frac{dt}{dx}}$$

$$Q = -K \cdot A \frac{dt}{dx}$$; K = Thermal conductivity

where

Quantity	Represents	Units
Q.	Heat flow through a body/unit time	Watts (W)
A.	Surface area of heat flow	(m^2)
dt	Temperature difference	°C (or) K.
dx	Thickness of body	m

Fourier Law is based on following Assumptions

conduction of heat takes place under steady state conditions.

→ The heat flow is unidirectional.

→ The temperature gradient is constant

→ There is no internal heat generation.

→ The material is homogeneous.

Essential features of Fourier Law.

→ It is applicable to any matter (may be liquid, solid or gas)

→ It is based on experimental evidence and cannot be derived from first principle.

Heat transfer by Convection:- It is defined as the transfer of heat in presence of MEDIUM.

Convection
- Free (or) natural convection
- Forced convection.

① **Free or Natural Convection**:- Free or natural convection occurs when the fluid circulates by virtue of natural differences in densities of hot and cold fluids.

Forced Convection when the work is done to blow or pump the fluid, it is said to be forced convection

$$\boxed{Q = hA(t_s - t_f)} \Rightarrow h = \frac{Q}{A(t_s - t_f)} \ W/m^2 {}^\circ C$$

Quantity	Represents	Units
Q	Rate of conductive heat transfer	Watts (W)
A	Area exposed to HT	m^2
t_s	Surface temperature	$^\circ C$ (or) K.
t_f	Fluid temperature final "	$^\circ C$ (or) K.
	Ambient "	
h.	Coefficient of convective heat transfer (film HT)	$W/m^2 {}^\circ C$ (or) $W/m^2 K$

Radiation:- In this mode, heat is transfered in the form of radiant energy (or) wave motion from higher temperature region to lower temperature region. It means, heat is transfered even in the absence of medium.

Examples:-

Heat is transfered from sun to earth.

Transfer of heat from thermo flask.

$$\boxed{Q = F\sigma A(T_1^4 - T_2^4)}$$

Quantity	Represents	Units
F	Factor depending on geometry and surface properties	
σ	Stefan-Boltzman constant	W/m^2K^4.
A	Area	m^2
T_1, T_2	Temperatures	$^\circ C$ (or) kelvin

* $$\boxed{Q = \frac{T_1 - T_2}{\dfrac{1}{[F\sigma A(T_1+T_2)(T_1^2+T_2^2)]}}}$$ [the above equation can also be written in this form)

Radiation:- In this mode, heat is transferred in the form of radiant energy (or) wave motion from higher temperature region to lower temperature region. It means, heat is transfered even in absence of medium.

Examples:-
Heat is transfered from sun to earth
Transfer of heat from thermo flask.

List some good conductors of heat and some poor conductors.

from Fourier law of heat transfer, the rate at which heat is conducted will be propotional to the area measured normal to the direction of heat flow and to the temperature gradient in that direction.

$$\boxed{Q = -KA \cdot \frac{\partial T}{\partial x}}$$

(or)

$$q = \frac{-K \partial T}{\partial x} \left[\because \frac{Q}{A} = q \right]$$

The propotionality constant (K) is called coefficient of Thermal conductivity.

Thermal conductivity (K) is a physical property defined as the ability of a substance to conduct heat.

Its units are W/m°C

W/m K.

→ Thermal conductivity for most materials can be determined experimentally by measuring the rate of heat flow and temperature gradient in the given substance

→ The ability of conducting heat will more in substances having higher values of thermal conductivity

Pure metals have the highest values of thermal conductivities whose "K" value decreases with increasing temperature

Gases and vapours have the lowest thermal conductivity (K) and for them the value of K increases with increase in temperature

Substances	K (W/mK)
Pure Silver	407.0
Pure Copper	386.0
Pure Aluminium	175.6
Mild Steel	37.2
Lead	29.8
Wood	0.15
Asbestos (fibre)	0.095
water	0.51
Air	0.022

from table, pure metals express high value of thermal conductivity and hence are good conductors of heat.

Define the following terms.

a) Thermal conductivity (b). Convection HT coefficient (c) Thermal diffusivity (d) Thermal resistance (e) thermal conductance. (f) thermal contact resistance.

a) Thermal conductivity:- It is defined as the quantity of heat that passes through unit area of a plate of unit thickness in unit time. when temperature difference b/w the 2. faces is maintained in degrees. It is defined by the fourier Law

$$K = \frac{Q}{A}\frac{dx}{dt}$$

$$\boxed{Q \propto KA\frac{dT}{dx}}$$

$$= Q = -AK.\frac{dT}{dx}$$

b) Convection HT Coefficient: It is defined as the quantity of heat that passes through a unit area of surface in unit time for unit temperature difference b/w the fluids

2) write the general conduction equation for 1D heat flow with uniform heat generation unsteady state for rectangular and spherical co-ordinate systems.

(or)

Derive the general conduction equation for

a) cylindrical coordinates

b) spherical co-ordinates

Heat conduction equation in rectangular co-ordinate is given by,

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t}$$

a) <u>Heat Conduction Equation in cylindrical co-ordinates</u>

Consider a small element of a cylinder whose volume is $r\,dr\,d\phi\,dz$ as shown below & Let it be subjected to conduction process.

<u>Applying energy balance Equation.</u>

$$\begin{bmatrix}\text{Energy conducted} \\ \text{into element/unit time}\end{bmatrix} + \begin{bmatrix}\text{Internal} \\ \text{energy/unit time}\end{bmatrix} = \begin{bmatrix}\text{Increase} \\ \text{in internal} \\ \text{energy/unit time}\end{bmatrix} + \begin{bmatrix}\text{workdone by} \\ \text{the element/} \\ \text{unit time}\end{bmatrix}$$

Units W/m^2K.

It mainly depends on viscosity, density, nature of flow.

Thermal diffusivity:- It is defined as the ratio of thermal conductivity to the thermal capacity. It is represented by α

$$\boxed{\alpha = \frac{K}{\rho C_p}}$$

Materials having higher value of α will have faster heat diffusion rate.

Thermal Resistance:- It is defined as the reciprocal of thermal conductance. It is denoted by r and mathematically represented as

$$\boxed{r = \frac{dx}{K/A} = \frac{L}{KA}}$$

It helps in making calculations on heat flow

Thermal conductance The ratio KA/L is called thermal conductance and it is the reciprocal of thermal resistance It is represented as,

$$K_{th} = \frac{KA}{L}$$

Thermal Contact Resistance. At the contact surfaces of 2 bodies the surface roughness and voids causes the contact surfaces to touch at discrete Locations. This reduces the area of contact at the interface and results in resistance to flow of heat. This resistance is called as thermal conductance resistance

$$= \frac{(t_2 - t_3)}{Q/A}$$

Let Q_r be heat entering into element in radial direction, then according to Fourier's law of heat conduction

$$Q_r = -k \cdot A \frac{\partial T}{\partial r}$$
$$= -k \frac{\partial T}{\partial r} r \, d\phi \, dz.$$

Let Q_{r+dr} be the heat leaving the element in radial direction at $r+dr$, then,

$$Q_{r+dr} = Q_r + \frac{\partial}{\partial r}(Q_r) \cdot dr$$
$$= -k \cdot \frac{\partial T}{\partial r} r \, d\phi \, dz + \frac{\partial}{\partial r} dr \left(-k \frac{\partial T}{\partial r} r \cdot d\phi \, dz\right) dr$$

Net heat energy conducted in radial direction is

$$Q_r - Q_{r+dr} = \left[-k \frac{\partial T}{\partial r} r \cdot d\phi \, dz\right] - \left[-k \frac{\partial T}{\partial r} r \, d\phi \, dz + \frac{\partial}{\partial r}\left[-k r \frac{\partial T}{\partial r} d\phi \, dz \, dr\right]\right]$$
$$= -k \frac{\partial}{\partial T}\left[\left[r \cdot \frac{\partial T}{\partial r} d\phi \, dz \, dr\right]\right] = -k\left[\frac{\partial}{\partial r}\left[r \frac{\partial T}{\partial r}\right] \cdot dr \, d\phi \, dz\right]$$

$$Q_\phi = -k \cdot \frac{\partial T}{\partial \phi} dr \, dz \longrightarrow 1$$

$$Q_{\phi+d\phi} = \frac{\partial}{r \partial \phi}(Q_\phi) \cdot r \, d\phi \longrightarrow 2$$

1 − 2

$$Q_\phi - Q_{\phi+d\phi} = \frac{\partial}{r \, d\phi}(Q_\phi) d\phi = \frac{\partial}{r \partial \phi}\left[k \frac{\partial T}{\partial \phi} * dr \, dz\right] r \, d\phi$$
$$= \frac{k}{r^2} \frac{\partial^2 T}{\partial \phi^2} \cancel{r} \cdot dr \cdot d\phi \, dz. \quad \frac{k}{r}$$

$$Q_z = -k \cdot \frac{\partial T}{\partial z}(r \, d\phi \cdot dr) \longrightarrow 3$$

$$Q_{z+dz} = \frac{\partial}{\partial z}(Q_z) dz = \frac{\partial}{\partial z}\left[k \cdot \frac{\partial T}{\partial z} r \, d\phi \, dz\right] = \frac{k \partial^2 T}{\partial z^2} r \, dr \cdot d\phi \, dz \longrightarrow 4$$

1, 3, 7, 15, 18, 23, 37, 38, 39

③ – ④ 40, 54

$$Q_z - Q_{z+dz} = K\frac{\partial^2 T}{\partial z^2} \times r \times dr \times d\phi \times dz.$$

<u>Net heat</u>

$$Q_r - Q_{r+dr} + Q_\phi - Q_{\phi+d\phi} + Q_z - Q_{z+dz}$$

$$\Rightarrow K\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right] r\,dr.d\phi\,dz + \frac{K}{r^2}\frac{\partial^2 T}{\partial \phi^2} r\,dr\,d\phi\,dz + K\frac{\partial^2 T}{\partial z^2} \times r\,d\ldots$$

As there is heat conducted in element and energy generated, there will be change in Internal energy.

change in energy, dE = mass of element × Specific heat × change in tem...

$$= \rho C_p r\,dr.d\phi.dz.dT.$$

Change in IE / unit time

$$= \rho C_p . r . dr . d\phi . dz . \frac{dT}{dt}$$

Substituting the values of net energy conducted in the element, element generated / unit time & change in internal energy in the energy balance equation, we get

$$K\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right] r\,dr.d\phi.dz + \frac{K}{r^2}\frac{\partial^2 T}{\partial \phi^2} r.dr.d\phi.dz + K\frac{\partial^2 T}{\partial z^2} r\,dr\ldots$$

$$+ q\,r.dr.d\phi\,dz.$$

$$= \rho C_p\, r.dr.d\phi\,dz.\frac{dT}{dt}.$$

dividing by $Kr.dr.d\phi.dz$ we get

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{k} = \frac{\rho c_p}{k}\cdot\frac{\partial T}{\partial t}$$

$$'' \quad '' \quad '' \quad '' \quad '' = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Above equation in cylindrical coordinates

[we can obtain this equation, from heat conduction in rectangle co-ordinates by substituting $x = r\cos\phi$, $y = r\sin\phi$ & $\phi = \tan^{-1}\left[\frac{y}{x}\right]$ & $z = z$.

we have,

$$\frac{\partial T}{\partial r} = \frac{\partial T}{\partial x}\cdot\frac{\partial x}{\partial r} + \frac{\partial T}{\partial y}\cdot\frac{\partial y}{\partial r}$$

$$\frac{\partial x}{\partial r} = \cos\phi \;\&$$

$$\frac{\partial y}{\partial r} = \sin\phi$$

So, $\frac{\partial T}{\partial r} = \cos\phi\frac{\partial T}{\partial x} + \sin\phi\frac{\partial T}{\partial y} \longrightarrow (1)$

Similarly $\frac{\partial T}{\partial \phi} = -r\sin\phi\frac{\partial T}{\partial x} + r\cos\phi\frac{\partial T}{\partial y} \longrightarrow (2)$

equation (1) $\times \cos\phi = \cos\phi\frac{\partial T}{\partial r} = \cos^2\phi\frac{\partial T}{\partial x} + \sin\phi\cdot\cos\phi\frac{\partial T}{\partial y} \rightarrow (3)$

equation (2) $\times \frac{\sin\phi}{r} = -\sin^2\phi\frac{\partial T}{\partial x} + \sin\phi\cdot\cos\phi\frac{\partial T}{\partial y} \;-(4)$

By simplifying (3) & (4)

$$\frac{\partial T}{\partial x} = \cos\phi\frac{\partial T}{\partial r} - \frac{\sin\phi}{r}\frac{\partial T}{\partial \phi} \;\&$$

$$\frac{\partial T}{\partial y} = \sin\phi \frac{\partial T}{\partial r} + \frac{\cos\phi}{r} \frac{\partial T}{\partial \phi}$$

Now, put $T = \frac{\partial T}{\partial x}$ in above equation, we get

$$\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) = \frac{\partial^2 T}{\partial x^2} = \cos\phi \frac{\partial}{\partial r}\left(\frac{\partial T}{\partial x}\right) - \frac{\sin\phi}{r} \frac{\partial}{\partial \phi}\left(\frac{\partial T}{\partial x}\right)$$

$$= \cos\phi \frac{\partial}{\partial r}\left[\cos\phi \frac{\partial T}{\partial r} - \frac{\sin\phi}{r} \cdot \frac{\partial T}{\partial \phi}\right] - \frac{\sin\phi}{r} \frac{\partial}{\partial \phi}\left[\cos\phi \frac{\partial T}{\partial r} - \frac{\sin\phi}{r}\right.$$

$\therefore$

$$\frac{\partial^2 T}{\partial x^2} = \left[\sin^2\phi \frac{\partial^2 T}{\partial r^2} + \frac{\cos^2\phi}{r} \frac{\partial T}{\partial r} - \frac{\cos\phi \cdot \sin\phi}{r^2} \frac{\partial T}{\partial \phi} + \frac{\cos\phi}{r^2} \frac{\partial^2 T}{\partial \phi^2} + \left[-\frac{\cos\phi \sin\phi}{r^2}\right.\right.$$

Substitute the values of $\frac{\partial^2 T}{\partial x^2}$ & $\frac{\partial^2 T}{\partial y^2}$ in heat conduction equat

heat conduction equation in rectangular co-ordinates is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{K} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t}$$

on substituting the values of $\frac{\partial^2 T}{\partial x^2}$ & $\frac{\partial^2 T}{\partial y^2}$ we get

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\left(\frac{\partial T}{\partial r}\right) + \frac{1}{r^2} \cdot \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{K} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t}$$

39
23
75
38

What is transient heat conduction? How does this differ from steady conduction?

A body in which there is no change in its temperature w.r.t. time, such a body is said to be in a steady state.

If there is no change in the surface temperature of the body, it attains an equilibrium temp, after some period called the steady state.

If the temp. of the body varies with sometime period then the body is said to be in unsteady state. This unsteady state is also called as transient state.

The transient condition take place in the following system.

① Cooling of IC engines
② Cooling & freezing of food
③ Vulcanization of rubber
④ For burning bricks.

Lumped capacity & Assumptions:-

It is a type of analysis which reduces a thermal system to number of discrete lumps and assume that the difference in temp. inside each lump is negligible.

It is applicable to transient heat flow conduction problems.

Assumptions:-

1. Internal conductive resistance of the system is very small.
2. The temp. within the system at any instant is uniform
3. It assumes temp. inside a solid is constant
4. It deals with heat transfer b/w solid & ~~c~~ ambient fluids.

①. A chrome-nickle wire of 2mm diameter initially at 25°c, is suddenly exposed to hot gases at 725°c. If the convection HT coefficient is 10 W/m²-K. Calculate the time constant of the wire as lumped capacity system. Take $k = 20\ W/m\text{-}K$, $\rho = 7800\ kg/m^3$, $C_p = 0.46\ kJ/kg\text{-}k$.

Sol Given data.

$D = 2mm = 2\times10^{-3} m$.

$t_\alpha = 25°c$

$t_i = 725°c$.

$h = 10\ W/m^2\text{-}k$

$k = 20\ W/m\text{-}k$.

$\rho = 7800\ kg/m^3$

Lumped capacity system is applicable to the cases with Biot No < 0.1

$\therefore \boxed{B_i = \frac{hL_c}{K}}$

here L_c is unknown. finding L_c.

$L_c = \frac{D}{4}$ (for cylindrical shapes)

$$L_c = \frac{2\times10^{-3}}{4}$$

$$Bi = \frac{hL_c}{K} \Rightarrow \frac{10\times 2\times10^{-3}}{20\times 4}$$

$Bi = 2.5\times10^{-4} < 0.1$

$\therefore$ Time constant $= \frac{\rho\, C_p V}{h A_s} = \frac{KV}{\alpha h A_S}$

where,

ρ = density = 7800 kg/m3

C_p = Specific heat = 0.46 KJ/kg-K.

V = Volume for cylinder $= \frac{\pi}{4} D^2 L$

A_s = Surface area of cylinder $= \pi DL$

α = Thermal diffusivity in m^2/sec

$$= \frac{7800\times0.46\times10^3}{10} \times \frac{\frac{\pi}{4}D^2L}{\pi DL}$$

$$= \frac{7800\times0.46\times10^3}{10} \times \frac{2\times10^{-3}}{4}$$

$\boxed{= 179.4 \text{ seconds}}$

2) A cylinder nickel steel billet of 0.1m diameter & 0.5m length, initially at 800°c is suddenly dropped in a large vessel containing oil at 30°c. The convective heat transfer co-efficient b/w the billet and the oil is 20 W/m²k. Calculate the time required for the billet to reach a temperature of 250°c. Take for nickel, steel, $K = 20$ W/m-K, $\rho = 8000$ kg/m³, $C_p = 0.45$ KJ/kg·k, .

Sol Given data

$L = 0.5m$

$D = 0.1m$

$T_0 = 800°c$

$T_\infty = 30°c$

$h = 20$ W/m²k.

$K = 20$ W/m-K.

$\rho = 8000$ kg/m³

$C_p = 0.45$ KJ/kg·k

$= 450$ J/kg·k.

$$\text{Biot No} = \frac{hL_c}{k}.$$

$$L_c = \frac{V}{A} = \frac{D}{4}$$

$$\left[\because V = \frac{\pi}{4} D^2 L = \frac{\pi}{4}(0.1)^2 \times 0.5 = 3.927 \times 1\right.$$

$$\left. A = \pi D L = \pi \times 0.1 \times 0.5 = 0.157\,m^2\right]$$

$$L_c = \frac{0.1}{4} = 0.025$$

$$Bi = \frac{hL_c}{k}.$$

$$= \frac{20 \times 0.025}{20} = 0.025 << 0.1$$

$\because$ Bi << 0.1, Lumped capacity analysis is applicable

$$\frac{T - T_\infty}{T_0 - T_\infty} = e^{\left[-\left[\frac{hA}{\rho C \cdot V}\right] \times t\right]}$$

$$\Rightarrow \frac{250 - 30}{800 - 30} = e^{-\left[\frac{20 \times 0.157}{8000 \times 450 \times 3.927 \times 10^{-3}}\right]}$$

$$\Rightarrow 0.2857 = e^{-222.1 \times 10^{-6} t}$$

$$-1.2528 = -222.1 \times 10^{-6}\, t$$

$$t = \frac{1.2528}{222.1 \times 10^{-6}} = 5640.7 \text{ seconds}$$

$$\Rightarrow t = \frac{5640.7}{60 \times 60} = 1.567 \text{ hours}$$

③. A solid copper cylinder of 5cm diameter was dropped into ice water after recording the temp as 20°c. After 3 minutes, the temp. of cylinder is again measured & recorded as 1°c. calculate the convective HT coefficient by taking ρ & C_p of copper 8600 kg/m³ & 334.94 J/kg-K. neglect the thermal resistance of the cylinder.

Sol given data.

Time, τ = 3 minutes = 180 sec.

$d = 5cm = 0.05 m$

$T_i = 20°c$

$T = 1°c$

$T_\infty = 0°c$ ($\because$ fluid is ice water)

$\rho = 8600 kg/m^3$

$C = 334.94 J/kg-k$.

formula $\rightarrow \frac{T - T_\infty}{T_i - T_\infty} = e^{\left[\frac{-hA_s}{CV\rho} \times \tau\right]}$

$V = \frac{\pi}{4} d^2 L$

$A_s = \pi d L$

$$\left[\frac{1-0}{20-0}\right] = e^{\left[\frac{-h\cdot 80(180)}{334.94 \times 8600}\right]}$$

$$0.05 = e^{[-4.999 \times 10^{-3} h]}$$

$$\ln(0.05) = -4.999 \times 10^{-3} h$$

$$\Rightarrow -2.9957 = -4.999 \times 10^{-3} h$$

$$h = -\frac{2.9957}{4.999 \times 10^{-3}}$$

$$\boxed{h = 599.26 \ W/m^2 K.}$$

(4). An aluminium sphere of 0.1m diameter and at a uniform temperature of 500°c, with h 30Wl

Calculate the temp of sphere.

a) 100 s

b) 300s

c) 500s after it is exposed to the environment

Justify any method you use for the analysis.

Take, for aluminium

$k = 200 \ W/mK$, $\rho = 2700 \ kg/m^3$, $C_p = 0.9 \ kJ/kg$-

Sol Given data.

$D = 0.1 m$.

$R = 0.05 m$.

$T_1 = 500°c$

$T_\infty = 20°c$

$h = 30 w/m^2-k$.

$k = 200 w/m-k$.

$\rho = 2700 kg/m^3$

$c_p = 0.19 kJ/kg-k$, $c_p = 900 J/kg-k$.

$$Bi = \frac{hL_c}{k} = \frac{30 \times 0.0166}{200}$$

$$= 2.5 \times 10^{-3} = 0.0025$$

$Bi << 0.1$

hence lumped heat analysis is applied

a) $$\frac{T_2 - T_\infty}{T_i - T_\infty} = exp^{\left[\frac{hA\tau}{\rho c V}\right]}$$

$$\frac{T_2 - 20}{500 - 20} = exp^{-\left[\left[\frac{h}{\rho c_p}\right] \times \left(\frac{A}{V}\right) \times \tau\right]}$$

Let $\left[\frac{h}{\rho \times c_p}\right] \times \left[\frac{A}{V}\right] = x$.

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$$x = \left[\frac{30}{2700 \times 900}\right]\left[\frac{1}{0.0166}\right]$$

$$\left[\because \frac{V}{A} = 0.0166\right]$$

$x = 7.4059 \times 10^{-4}$.

Substituting x in formula.

$$\frac{T_2 - 20}{480} = \exp^{-(7.4059 \times 10^{-4}) \times 100}$$

$$T_2 - 20 = 480 \times 0.9283$$

$$T_2 = 20 + 445.584.$$

$$\boxed{T_2 = 465.584°c}$$

b) $$\frac{T_3 - 20}{480} = e^{-(xt)}$$

$$\frac{T_3 - 20}{480} = e^{-(7.4059 \times 10^{-4}) \times 300}$$

$$T_3 - 20 = 480 \times 0.80077.$$

$$T_3 = 20 + 384.37$$

$$\boxed{T_3 = 404.37°c}$$

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c) $\frac{T_4 - 20}{480} = e^{-(xt)}$

$T_4 - 20 = 480 \times e^{-(7.4059 \times 10^{-4}) \times 500}$

$T_4 - 20 = 331.45$

$T_4 = 331.45 + 20$

$\boxed{T_4 = 351.45°c}$

⑤. A Large slab of aluminium has a thickness of 10 cm is initially uniform at temp of 400°c. Suddenly exposed to a convection environment at 90°c with h = 1400 W/m²-k. How long does it take the center line temp to drop to 180°c?

Sol Thickness, L = 10cm.

$T_i = 400°c.$

$T_\infty = 90°c$

$h = 1400\ W/m^2k.$

$T = 180°c$

$k = 206\ W/m\text{-}k$ (assuming)

$\alpha = 84.18 \times 10^{-6}\ m^2/s$ (")

$$Bi = \frac{hL_c}{k}$$

$$L_c = \frac{L}{2} = \frac{10}{2} = 5\ cm = 0.05\ m$$

$$Bi = \frac{1400 \times 0.05}{206} = 0.3398$$

$\therefore$ $Bi > 0.1$ & less than 100

$\left.\begin{array}{l} Bi > 0.1 \\ Bi < 100 \end{array}\right\}$ $\therefore$ we can use Heisler charts.

$$\frac{T - T_\infty}{T_i - T_\infty} = \frac{180 - 90}{400 - 90} = 0.2903$$

From Heisler charts, corresponding to $Bi = 0.3398$

Fourier No, $F_o = 4.2$.

$$F_o = \frac{\alpha \tau}{L_c^2}$$

$\Rightarrow$ finding τ

$$4.2 = \frac{84.18 \times 10^{-6} \times \tau}{(0.05)^2}$$

$$\tau = \frac{4.2 \times (0.05)^2}{84.18 \times 10^{-6}}$$

$$= 124.73 \text{ seconds.}$$

[illegible]

= [illegible]

(5) On a hot summer's day concrete highway reach to temperature of 55°C. Suppose that a stream of H_2O is directed on the highway so that the surface temp is suddenly lowered to 35°C. How long it will take to cool the concrete to 45°C at a depth of 5cm from the surface?

Sol: Given Data:

$T_i = 55°C$

$T_\infty = 35°C$

$t = ?$

$T_0 = 45°C$

$x = 5cm = 0.05m$

$$\frac{T - T_\infty}{T_i - T_\infty} = erf\left[\frac{x}{2\sqrt{\alpha t}}\right]$$

$$\frac{45-35}{55-35} = erf\left[\frac{0.05}{2\sqrt{\alpha t}}\right]$$

$$0.5 = erf\left[\frac{0.05}{2\sqrt{\alpha t}}\right]$$

Different Types of flows in convective HT:-

I. Causation of flow.

a) mixed & unmixed flow.

b). Natural & forced flow.

II. Condition of flow

a) Steady & unsteady flow.

b). compressed. & incompressed flow.

c) Laminar & Turbulent flow.

III configuration of flow.

a) I, II & III D flows.

b) Internal & external flows.

IV Medium of flow.

a) viscous flow.

Eg:- oil, water

b) Inviscid flow.

Eg:- Gases.

LAMINAR FLOW	TURBULENT FLOW
1. Flow follows a smooth continous path	1. Flow follows a random (or) irregular path.
2. No transverse movement of fluid particles	2. Transverse displacement of fluid particles
3. Re < 2000 describes a Laminar flow	3. Re No > 4000 describes a turbulent flow.
4. Head loss $\propto$ Velocity $\therefore h_f \propto V$	4. Head loss $\propto$ n^{th} power of velocity $h_f \propto V^n$.
5. Flow of high viscosity fluid at low velocity has Laminar flow Example:- oil	5. Flow of low viscosity fluids at high velocity has turbulent flow Example:- Air

1. Air at 27°C flows over a flat plate at a velocity of 2 m/s. The plate is heated over its entire Length to a temp of 60°C. calculate the H T for the first 20cm of the plate.

Sol Given data.

$T_\alpha = 27°C$.

$U = 2$ m/s

$T_s = 60°C$.

$x = 20$ cm $= 0.2$ m.

$$T_f = \frac{27+60}{2} = \frac{87}{2} = 43.5°C.$$

physical properties of air at 43.5°C.

$\nu = 17.3 \times 10^{-6}$ m²/s

$K = 0.0278$

$Pr = 0.679$

$$Re = \frac{u x}{\nu}$$

$$= \frac{2 \times 0.2}{17.3 \times 10^{-6}} = 2.31 \times 10^4.$$

$$Nu = 0.332 \times Re^{1/2} \times Pr^{1/3}$$

$$= 0.332 \times (2.31 \times 10^4)^{1/2} \times (0.679)^{1/3}$$

$Nu = 44.35$

$Nu = \frac{hL}{k}$

$44.35 = \frac{h \times 0.2}{0.0278}$

$h = \frac{44.35 \times 0.0278}{0.2}$

$h = 6.16 \ W/m^2K$

Avg. HT coefficient, $\bar{h} = 2 \times 6.16$
$= 12.32 \ W/m^2K$

$Q = \bar{h} A (T_s - T_\infty)$

$\frac{Q}{A} = q = 12.32 (60 - 27)$
$= 406.56 \ W/m^2$

② . Air at 20°c & 1 atmosphere flows over a flat plate at 35 m/s. The plate is 75cm long & is maintained at 60°c. calculate the HT from the plate/unit width of plate. Also calculate the turbulent boundary Layer thickness at the end of the plate assuming it to develop from the leading edge of plate.

Sol given data.

$T_a = 20°c$

$T_s = 60°c$

$u = 35\ m/s$

$l = 75cm = 0.75m$.

$$T_f = \frac{20+60}{2} = \frac{80}{2} = 40°c$$

The properties of air at 40°c,

$\nu = 16.96 \times 10^{-6}\ m^2/s$

$k = 0.02756\ W/mk$.

$P_r = 0.669$

$$Re = \frac{uL}{\nu} = \frac{35 \times 0.75}{16.96 \times 10^{-6}} = 1547759.43$$

From tables, mean value of Nu is

$$Nu = \frac{hL}{k} = P_r^{1/3}(0.037 \times Re^{0.8} - 871)$$

$$= (0.0669)^{1/3}[0.037 \times (1547759.43)^{0.8} - 871]$$

$$= 2134.056$$

$h_L = \frac{Nu \times k}{L}$

$= \frac{2134.056 \times 0.02756}{0.75}$

$= 78.419 \ W/m^2k.$

$Q = hA\Delta t$

$= 2 \times 78.419 \times 0.75 (60-20)$

$= 4705.140 \ W$

$\delta_{hx} = 0.37 \times L \times Re^{-0.2}$

$= 0.37 \times 0.75 (1547759.43)^{-0.2}$

$= 0.016 \ m$

$= 16 mm$

③ Water at 20°c was flowing over a plate of uniform heat flux of 9000 w/m2. The flow velocity was 200 mm/s. The length of the plate was 1.3 m. Determine the temp of the plate.

Sol Given data.

$T_\alpha = 20°c.$

$q = 9000 \ W/m^2$

$u = 200 mm/s$

$= 0.2 m/s$

$L = 1.3 m$

Properties of water at 20°c are,

$\nu = 1.006 \times 10^{-6} m^2/s$

$Pr = 7.020$

$k = 0.5978 W/mk.$

$$Re = \frac{uL}{\nu}$$

$$= \frac{0.2 \times 1.3}{1.006 \times 10^{-6}}$$

$= 0.258 \times 10^{6}$

$= 2.58 \times 10^{5} < 5 \times 10^{5}.$

$Nu = 0.662 \cdot Re^{1/2} \; Pr^{1/3}$

$= 0.662 \; (2.58 \times 10^{5})^{1/2} \; (7.020)^{1/3}$

$= 643.84$

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

$$643.84 = \frac{hL}{K.}$$

$$h = \frac{643.84 \times 0.5978}{1.3}$$

$h = 295.88 \; W/m^2 k$

$Q = hA\Delta t \Rightarrow \frac{Q}{A} = h\Delta t \Rightarrow q = h\Delta t$

$q_v = h(T_s - T_\infty)$

$9000 = 295.88(T_s - 20)$

$T_s = 50.41°c$

(4). Air at 35°c flows across a cylinder of 50mm diam at a velocity of 50 m/s. The cylinder surface is maintained at 145°c. Calculate the heat loss/length of the cylinder.

Sol Given Data.

$T_s = 145°c$

$T_\infty = 35°c$

$V = 50\ m/s$

$d = 50mm = 0.05m$.

$T_f = \dfrac{145+35}{2} = 90°c$.

At $T_f = 90°c$, properties of air are,

$\mu = 21.48 \times 10^{-6}\ Ns/m^2$

$K = 0.03128\ W/mK$.

$C_p = 1009\ J/kgK$.

$\rho = 0.972\ kg/m^3$

$$Re = \frac{\rho v d}{\mu}$$

$$= \frac{0.972 \times 50 \times 0.05}{21.48 \times 10^{-6}}$$

$$= 0.113 \times 10^{6} = 1.13 \times 10^{5}$$

$$Pr = \frac{\mu C_p}{K}$$

$$= \frac{21.48 \times 10^{-6} \times 1009}{0.03128}$$

$$= 0.692$$

$$Nu = 0.027\, Re^{0.805} (Pr)^{1/3}$$

$$= 0.027 (1.13 \times 10^{5})^{0.805} (0.692)^{1/3}$$

$$= 279.1211$$

$$h = \frac{Nu \times k}{d} \left[\because Nu = \frac{hL}{k} \right]$$

$$= \frac{279.121 \times 0.03128}{0.05}$$

$$= 174.618 \text{ W/m}^2 {}^\circ C$$

$$Q = hA\Delta t = h \times (\pi d L)(T_s - T_\infty)$$

$$= 174.618 \times \pi \times 0.05 (145 - 35)$$

$$= 3017.18 \text{ W}$$

⑤. Air at 1 atm & 35°c flow across a 5-cm diameter cylinder at a velocity of 50 m/s. The cylinder surface is maintained at a temp of 150°c. Calculate the heat loss per unit length of cylinder.

Sol Given data

$T_i = 35°c$

$T_o = 150°c$

$D = 5 cm = 0.05 m$

$U = 50 m/s$.

$T_f = \frac{T_i + T_o}{2} = \frac{35+150}{2} = 92.5°c$.

The properties of air at 92.5°c

$\rho = 0.966 Kg/m^3$

$Pr = 0.695$.

$K = 0.03 W/mk$.

$\mu = 2.14 \times 10^{-5} kg/ms$.

$Re = \frac{\rho U D}{\mu}$

$= \frac{0.966 \times 50 \times 0.05}{2.14 \times 10^{-5}}$

$= 1.129 \times 10^5$

$$Nu = \frac{hD}{k} = C_p \, (Re)^n \, (P_r)^{1/3}$$

$Re = 1.129 \times 10^5$

$C_p = 0.0266$

$n = 0.805.$

$$Nu = \frac{hD}{k} = C_p \, (Re)^{0.805} \times (P_r)^{1/3}$$

$$h = \frac{k}{D} \times 0.0266 \times (1.1299 \times 10^5)^{0.805} (0.697)^{1/3}$$

$h = 165.271 \text{ W/m}^2\text{K}.$

$Q = hA(T_o - T_i)$

$Q = h\pi \times D(T_o - T_i)$

$Q = (165.271) \times \pi \times (0.05)(150-35)$

$Q = 2985.47 \text{ W}$

⑥ In an ice plant, Liquid ammonia flows through a rectangular pipe of section 50 mm × 25 mm, at a velocity of 1 m/min & inlet temp of −30°c & leaves at 0°c. estimate HT coefficient & HT rate.

Sol $A = 50 \times 25$

$u = 1\ m/min$

$= 0.0166\ m/s$

$T_i = -30°C$

$T_o = 0°c$

Properties of NH_3 at mean temp of $-15°c$.

$\rho = 660\ kg/m^3$

$\nu = 0.3795 \times 10^{-6}\ m^2/s$

$C_p = 4536.5\ J/kg.K$.

$k = 0.54485\ W/mK$.

$$L_c = \frac{4A_c}{P}$$

$$= \frac{4 \times 0.05 \times 0.025}{2(0.05 + 0.025)} = 0.033\ m$$

$$Re = \frac{L_c u}{\nu}$$

$$= \frac{0.033 \times 0.0166}{0.3795 \times 10^{-6}} = 1443.478$$

$$P_r = \frac{\rho V C_p}{k}.$$

$$= \frac{660 \times 0.3795 \times 10^{-6} \times 4536.5}{0.54485}$$

$$= 2085$$

$$Nu = \frac{h L_c}{k}$$

$$h = \frac{3.391 \times 0.54485}{0.033}$$

$$= 55.98 \ W/m^2 K.$$

$$Q = m C_p \Delta t$$

$$= \rho \times A \times L \times C_p (T_o - T_i)$$

$$\frac{Q}{L} = \rho A C_p (T_o - T_i)$$

$$= 660 \times 0.05 \times 0.025 \times 4536.5 (0 - (-30))$$

$$= 112278.37 \ W$$

(7) Water at 50°c enters a 1.5cm diameter & 3m Long tube with a velocity of 1m/s. The tube wall is maintained at a constant temp of 90°C. calculate the HT coefficient & total amount of HT if the exit water temp is 64°c.

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Sol $A = \frac{\pi}{4} \times \left(\frac{1.5}{100}\right)^2$

$= 1.767 \times 10^{-4} m^2$

$V = 1 m/s$

$T_i = 50°c$

$T_o = 64°c.$

$T_{wall} = 90°c$

Properties of H_2O at 50°c

$\rho = 990 kg/m^3$

$\nu = 0.567 \times 10^{-6} m^2/s$

$\alpha = 0.1532 \times 10^{-6} m^2/s$

$P_r = 2.18$

$C_p = 4180.5 J/kg.k.$

$k = 1.2793 W/mk.$

$\mu = \nu \times \rho = 5.67 \times 10^{-6} \times 990$

$= 5.6133 \times 10^{-4} Ns/m^2$

$Re = \frac{\rho v d}{\mu}$

$= \frac{990 \times 1 \times \frac{1.5}{100}}{5.6133 \times 10^{-4}} = 2.6455 \times 10^4$

$$Nu = 0.332\, Re^{0.5} \cdot P_r^{0.333}$$

$$= 0.332 \times (2.6455 \times 104)^{0.5} \times (2.18)^{0.33}$$

$$= 70$$

The only driving force in free convection is buoyancy force out of which a flow field exists, without the presence of any external field.

The ratio of buoyancy force to the viscous force in the fluid is termed as the Grashoff No.

This number plays a significant role in free convection in a similar way as Reynolds no in forced convection.

When both free & forced convections occurs simultaneously.

$$Nu = f(Re_L, Pr, Gr_L)$$

where

$Nu \rightarrow$ Nusselt no.

$Re \rightarrow$ Reynolds no.

$Pr \rightarrow$ prandtl no.

$Gr \rightarrow$ Grashoff no.

What is the criterian for transition from laminar to turbulent flow in free convective HT?

Ans The transition from laminar to turbulent flow in free convection boundary layer occurs when the value of $Gr \cdot Pr$ (Ra_L) approaches 10^9.

$$Ra_L = Gr \cdot Pr = \frac{g \beta L^3 (T_s - T_\infty)}{\nu^2} \times Pr = 10^9.$$

where

β coefficient of thermal expansion.

L length of the plate, m.

T_s Surface temp, °C.

T_∞ = Ambient temp, °C.

ν = Kinematic viscosity, m^2/s

Pr = prandtl number

Gr = Grashoff's no.

Ra_L = Rayleigh number

Grashoff no significance in natural convective HT:-

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1. A vertical cylinder 1.8m high and 7.5cm in diameter is maintained at a temperature of 93°c in an atmospheric air of 30°c. Calculate the heat loss by free convection from this cylinder.

Sol Given Data.

$L = 1.8m$

$D = 7.5m = 0.075m$

$T_s = 93°c$

$T_\infty = 30°c$

$$T_f = \frac{T_s + T_\infty}{2} = \frac{93+30}{2} = 61.5°c$$

Physical properties at 61.5°c.

$\rho = 1.055 kg/m^3$

$\nu = 19.1275 \times 10^{-6} m^2/s$

$\mu = 20.17 \times 10^{-6} Ns/m^2$

$P_r = 0.6957$

$C_p = 1005.6 J/kg-k$

$K = 0.02911 W/mk$

$$\beta = \frac{1}{T_f}$$

$$\beta = \frac{1}{T_f + 273} \Rightarrow \frac{1}{61.5+273} = 2.989 \times 10^{-3}$$

$$Gr = \frac{L^3 g \beta \Delta T}{v^2}$$

$$Gr = \frac{(1.8)^3 \times 9.81 \times 2.989 \times 10^{-3} \times (93-30)}{(19.1275 \times 10^{-6})^2}$$

$$Gr = 2.94 \times 10^{10}$$

$$Pr = 0.6957.$$

$$Gr \cdot Pr = 2.94 \times 10^{10} \times 0.6957$$

$$= 2.045 \times 10^{10}$$

$$Nu = \frac{hL}{K} = 0.1\,(Gr\,Pr)^{1/3} \left[10^9 < Gr\,Pr < 10^{12}\right]$$

$$h = \frac{k}{L} \times 0.1\,(Gr \cdot Pr)^{1/3}$$

$$= \frac{0.02911}{1.8} \times 0.1\,(2.045 \times 10^{10})^{1/3}$$

$$= 4.422 \text{ kJ/h m}^2\,^\circ C$$

$Q = hA\Delta t$

$\Rightarrow 4.422 \times (\pi \times 0.075 \times 4.8)(93-30)$

$= 118.15$ kJ/h.

② The surface of human body may be approximated by a vertical cylinder 0.3m in diameter 2 2m in length. Assuming the surface temperature to be 30°c. Determine the heat loss from a human body in a quiescent atmosphere of air at 20°c. use the appropriate correlation

Sol Given Data.

$d = 0.3$ m

$h = 2$ m

$T_s = 30°c$

$T_\infty = 20°c$

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

$= \frac{30+20}{2}$

$= \frac{50}{2}$

$\boxed{T_f = 25°c}$

Properties of air at 25°C.

$\rho = 1.184\ kg/m^3$

$k = 0.02551\ W/m \cdot k$

$\nu = 1.562 \times 10^{-5}\ m^2/s$

$P_r = 0.7296$

$$\beta = \frac{1}{T_f}$$

$$= \frac{1}{25+273}$$

$$= \frac{1}{298} = 0.003$$

$\beta = 3 \times 10^{-3}\ k^{-1}$

$$G_{r_L} = \frac{g\beta(T_s - T_\infty) \times L^3}{\nu^2}$$

$$= \frac{(9.81) \times 3\times10^{-3} \times (30-20)(2)^3}{(1.562\times10^{-5})^2}$$

$G_{rL} = 9.649 \times 10^9$

$$Nu = \frac{hL}{k} = 0.12 \times (G_{rL} \cdot P_r)^{1/3}$$

$$= 0.12 \times (9.649\times10^9 \times 0.7246)^{1/3}$$

$Nu = 229.46$

$$Nu = \frac{hL}{K}.$$

$$h = \frac{K \times Nu}{L}$$

$$= \frac{0.02551 \times 229.46}{2}$$

$h = 2.926 \simeq 3 \ W/m^2 k.$

$h = 3 \ W/m^2 k.$

$Q = hA \Delta t$

$= hA(T_s - T_\infty)$

$Q = 3 \times (\pi \times 0.3 \times 2)(30 - 20)$

$Q = 56.549 W$

③ A hot square plate of 75cm x 75cm at 120°C is exposed to atmospheric air at 40°C. find the heat loss from both surface of the plate if it is kept in
(i) vertical position
(ii) Horizontal "

Sol Given Data.

$A = 0.75 \times 0.75 = 0.5625 \ m^2$

$T_s = 120°C$

$T_\infty = 40°C$

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

$$= \frac{120+40}{2}$$

$$= \frac{160}{2} = 80^\circ c$$

Properties of air at $80^\circ c$,

$\nu = 21.09 \times 10^{-6}\ m^2/sec$

$k = 0.03047\ w/m\text{-}k$.

$\rho = 1\ kg/m$

$Pr = 0.0692$.

$g = 9.81\ m/sec^2$

$$\beta = \frac{1}{T_f}$$

$$T_f = \frac{1}{T_s + T_\infty} = \frac{1}{80+273} = 2.8328 \times 10^{-3}\ K^{-1}$$

(i) If plate is kept vertical

$$Gr = \frac{g \beta L^3 \Delta t}{\nu^2}$$

$$Gr = \frac{9.81 \times 2.8328 \times 10^{-3} \times (0.75)^3 \times 80}{(21.09 \times 10^{-6})^2}$$

$Gr = 2.108 \times 109$

$Ra = (Gr \cdot Pr)$

$= 2.108 \times 109 \times 0.692 \Rightarrow \boxed{Ra = 1.459 \times 109}$

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$Ra = 1.459 \times 10^9 \geq 10^9$.

$\therefore$ flow is turbulent.

$Nu = 0.125 (Ra)^{0.33}$

$Nu = 0.125 (1.459 \times 10^9)^{0.33}$

$\boxed{Nu = 132.15}$

$Nu = \frac{hL}{k} \Rightarrow h = Nu \cdot \frac{k}{L} = \frac{132.15 \times 0.03047}{0.75}$

$\bar{h} = 5.368 \, W/m^2\text{-}k$

$Q = hA\Delta t$

$= 5.368 \times (0.75)^2 \times 80$

$Q = 241.56 \, W$

$\boxed{Q = 0.24 \, kW}$

(ii) If plate is kept at horizontal

for $Ra \geq 7 \times 10^8$ (turbulent)

$Nu = 0.107 (Ra)^{0.33}$

$Nu = 113.12$

$$\bar{h} = \frac{Nu \cdot k}{(A/P)}$$

$$\bar{h} = \frac{113.12 \times 0.03047}{\left(\frac{0.75}{2}\right)} = 9.19 \ W/m^2\text{-}K.$$

④ A vertical plate 5m high & 1.5m wide has one of its surface insulated. The other surface is maintained at a uniform temp of 400k is exposed to quiescent atmospheric air at 300k. Calculate the total rate of heat loss from the plate. properties of air at 350K are $v = 20.75 \times 10^{-6} \ m^2/s$, $P_r = 0.697$ & $k = 0.03 \ W/mk$

Sol Given Data.

$h = 5m$

$b = 1.5 \ m$

$T_s = 400 \ k$

$T_\infty = 300 \ k$

$$T_f = \frac{400 + 300}{2}$$

$= 350 \ K$

Properties of air at 350K.

$\nu = 20.75 \times 10^{-6}\ m^2/s$

$P_r = 0.697$.

$k = 0.03\ W/mK$.

$$\beta = \frac{1}{T_f}$$

$$\beta = \frac{1}{350} = 2.8 \times 10^{-3}$$

$$Ra = \frac{g \beta \Delta t L^3}{\nu^2} \times P_r$$

$$= \frac{9.81 \times 2.8 \times 10^{-3} \times (400-300) \times 5^3}{(20.75 \times 10^{-6})^2} \times 0.697$$

$= 5.5 \times 10^{11}$

$Ra > 10^9$, $\therefore$ flow is turbulent.

$Nu = 0.125\ Ra^{0.33}$

$= 0.125 \times (5.5 \times 10^{11})^{0.33}$

$= 935.9$

$$Nu = \frac{hL}{k}$$

$$h_c = \frac{935.9 \times 0.03}{5}$$

$= 5.615\ W/m^2k$.

$Q = hA\Delta t$

$Q = hA(T_s - T_\infty)$

$= 5.615 \times 5 \times 1.5\,(400-300)$

$= 4.2 \times 10^3\ W$

⑤. A vertical plate 20cm x 60 cm size is at 110°c in an atmosphere at 30°c. Determine the rate of heat transfer by free convection from the plate when 20cm side is kept vertical.

Sol $A = 20cm \times 60cm$

$T_f = \cancel{110} \cdot \dfrac{110+30}{2} = 70°c$

Physical properties at 70°c.

$K = 0.02966\ W/mK.$

$\nu = 20.02 \times 10^{-6}\ m^2/s$

$P_r = 0.694$

$\beta = \dfrac{1}{t_f} = \dfrac{1}{70+273} = 2.9 \times 10^{-3}$

$$Gr_L = \frac{L^3 g \beta \Delta T}{\nu^2}$$

$L = 20cm$
$= 0.2\,m$

$$Gr_L = \frac{(0.2)^3 \times 9.8 \times 2.9 \times 10^{-3} \times (110-30)}{(20.02 \times 10^{-6})^2}$$

$= 4.54 \times 10^7$

$Gr < 10^9$ hence flow is Laminar

$$Nu = 0.677 (P_r)^{1/2} (0.952 + P_r)^{-1/4} (Gr)^{1/4}$$

$$= 0.677 (0.694)^{1/2} (0.952 + 0.694)^{-1/4} (4.54 \times 10^7)^{1/4}$$

$= 5.65 \times 10^6$

$$Nu = \frac{hL}{k}$$

$$h = \frac{Nu \times k}{L}$$

$$\Rightarrow \frac{5.65 \times 10^6 \times 0.02966}{0.2}$$

$\Rightarrow 8.38 \times 10^5\ W/m^2 °c$

$Q = hA\Delta t$

$= 8.38 \times 10^5 \times (0.2 \times 0.6) \times (110-30)$

$= 8.04 \times 10^6$ Watts

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⑥. A metal plate 0.71 m in length & 1.02 m in width forms the vertical wall of an oven. The temp of the plate is maintained at 230°c, where as the air outside the oven is at 23°c. Assuming the oven to be uninsulated compute the convection heat loss from the wall to the outside air.

Sol Given data.

$H = 0.71 \text{ m}$

$W = 1.02 \text{ m}$

$T_\infty = 23°c$

$T_s = 230°c$

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

$$= \frac{230+23}{2}$$

$T_f = 126.5°c$

Properties of air at 126.5°c.

$\rho = 0.876 \text{ kg/m}^3$

$\mu = 23.29 \times 10^{-6} \text{ Ns/m}^2$

$\nu = 26.625 \times 10^{-6} \text{ m}^2/s$

$\alpha = 38.583 \times 10^{-6} \text{ m}^2/s$

$Pr = 0.685$

$k = 0.03413$ W/mK

$\beta = \frac{1}{T_f}$

$= \frac{1}{126.5+273}$

$= 2.5031 \times 10^{-3}\ K^{-1}$

$Gr = \frac{g \beta H^3 (T_s - T_\infty)}{\nu^2}$

$\Rightarrow \frac{9.81 \times 2.5031 \times 10^{-3} \times (0.71)^3 \times 207}{(26.625 \times 10^{-6})^2}$

$Gr = 2.566 \times 10^9$

$Ra = Gr \cdot Pr \Rightarrow 2.566 \times 10^9 \times 0.685$

$Ra = 1.757 \times 10^9$ ($\because Ra > 10^9$)

$\therefore$ flow is turbulent

$Nu = 0.10 (Gr \cdot Pr)^{0.333}$

$= 0.10 (1.757 \times 10^9)^{0.333}$

$= 119.81$

$Nu = \frac{hH}{k}$

$h = \frac{Nu \times k}{H} = \frac{119.81 \times 0.03413}{0.71} \Rightarrow h = 5.759\ W/m^2\ {}^\circ C$

$Q = hA\Delta t \; [\because A = WH]$

$= 5.759 \times 0.71 \times 1.02 \times (230 - 23)$

$Q = 863.328$ Watts

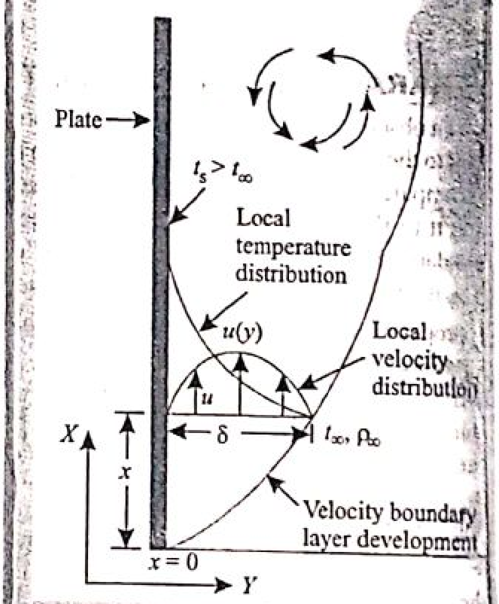

Fig. 8.1. Free-convection boundary layer over vertical plate.

Boiling:- Boiling is a phase change from liquid to vapour state.

The boiling HT phenomenon may occur in the following forms.

- Pool boiling
- forced convection boiling
- Sub cooled boiling
- Saturated boiling.

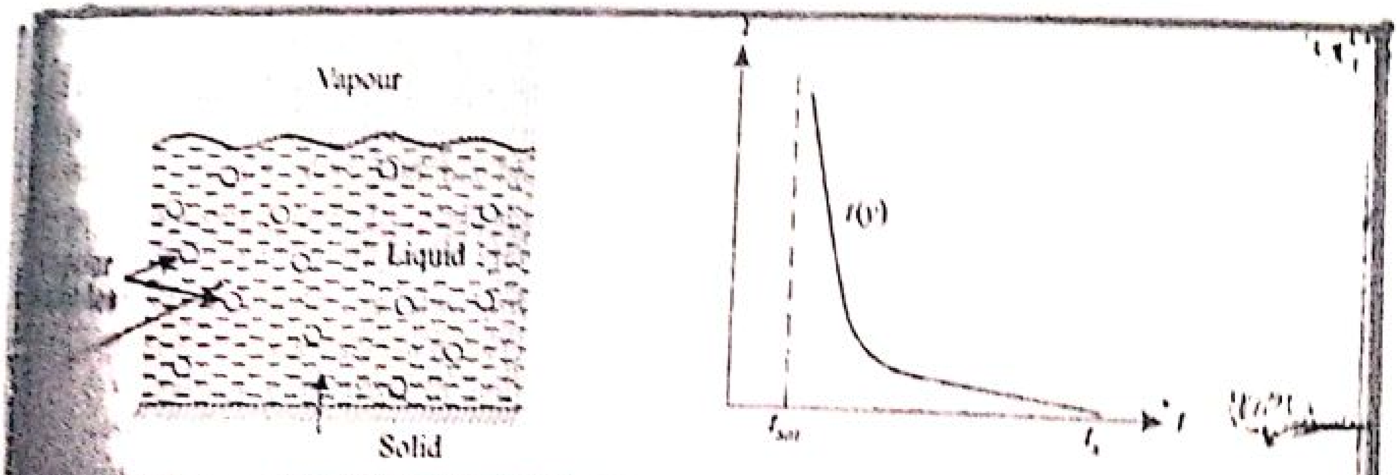

Fig. 9.1. Pool boiling with liquid-vapour interface.

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Boiling Regimes :- There are 3 regimes of Boiling

- interface evaporation
- nucleate boiling
- film boiling.

540

Condensation Process:- The condensation process is the reverse of boiling.

Liquid $\longrightarrow$ Solid.

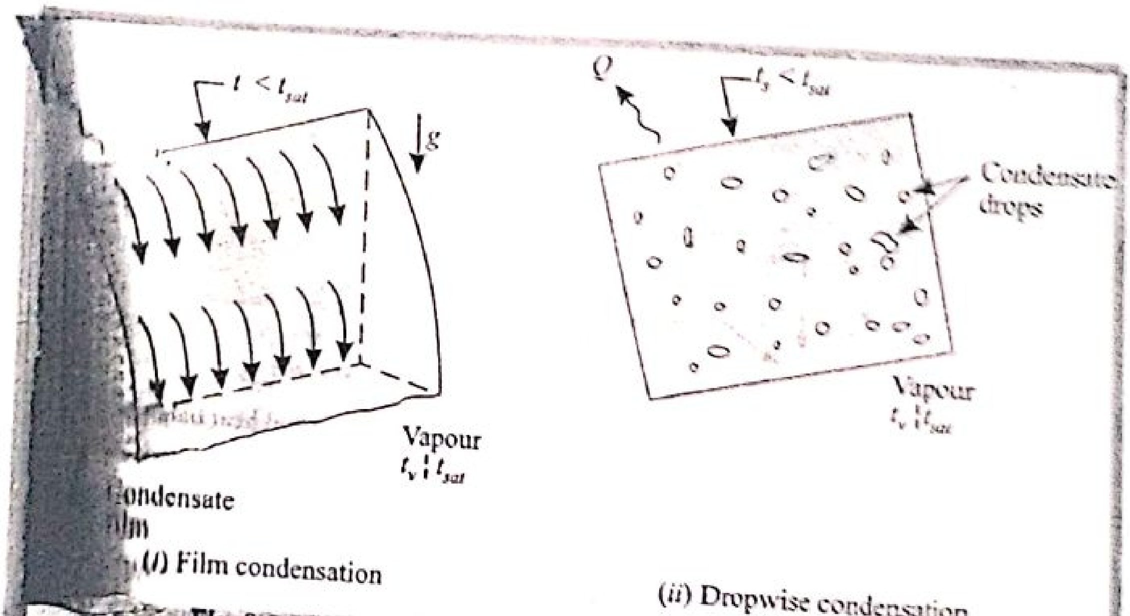
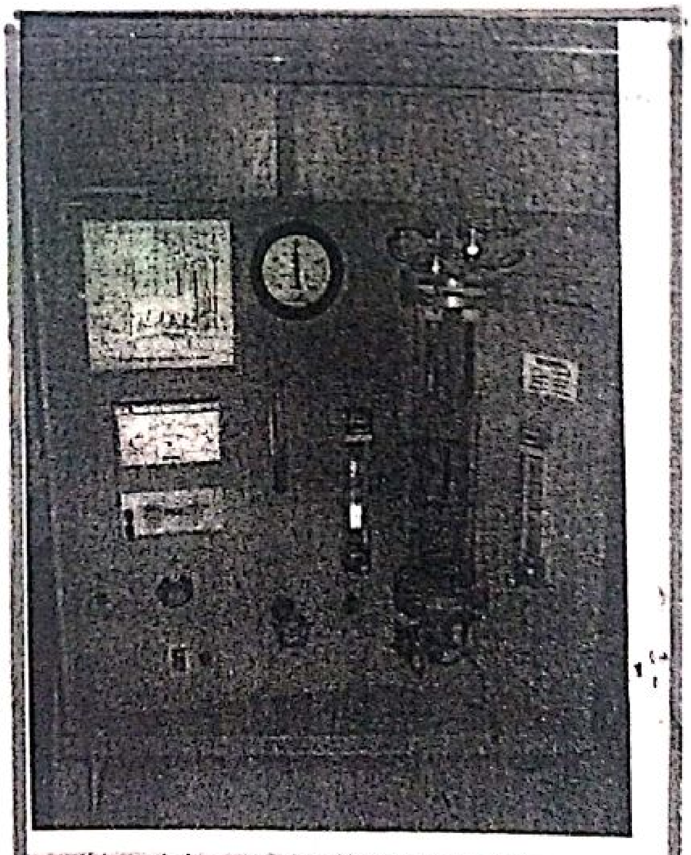


Fig. 9.6. Film and dropwise condensations on a vertical surface.


Film and dropwise condensation unit.

1. Steam at atmospheric pressure & the tube surface temp is maintained at 98°C. what is the rate at which steam is condensed/unit length of the tubes.

Sol

$T_s = 98°c$

$T_{sat} = 100°c.$

$D = 1.27 mm$

$= 1.27 \times 10^{-3} m$

$T_f = \frac{T_s + T_{sat}}{2} = \frac{100+98}{2} = 99°c$

properties of condensate at this temp

$\rho_l = 961 \ kg/m^3$

$V = 0.293 \times 10^{-6} \ m^2/s$

$\alpha = 0.168 \times 10^{-6} \ m^2/s$

$P_r = 1.740$

$C_p = 4216 \ J/kg k$

$K = 0.6804 \ W/m k$

$\mu = \rho \times \nu = 2.8157 \times 10^{-8} \ kg/ms$

$\lambda = 2074.7$ kJ/kg

$h_{fg} = \overset{2258}{\cancel{2074.7}}$ kJ/kg.

$N = \sqrt{100} = 10$

The HT coefficient for tubes is given by

$$\bar{h} = 0.725\left[\frac{\lambda \cdot \rho^2 L g k^3 h_{fg}}{\mu D(\theta_{sat} - \theta_s) N}\right]^{1/4}$$

$$= 0.725\left[\frac{2074.7 \times (961)^2 \times 1.27 \times 9.81 \times (0.6804)^3 \times 2258}{2.8157 \times 1.27 (100 - 98)}\right]$$

$h =$

② A heated polished copper plate is immersed in a pool of water boiling at atmospheric pressure. If the surface of the copper plate is maintained at a temp. of 123°C. Find the surface heat flux and the evaporation rate/unit area of the plate

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Sol Given data.

$T_{sat} = 100°c$

$T_w = 125°c$

The properties of water at 100°c are

$\rho_l = 961\ kg/m^3$

$c_p = 4216\ J/kg.k.$

$\lambda = 2256.6\ kJ/kg.$

$v_l = 0.293 \times 10^{-6}\ m^2/s$

$\mu = \rho \times v = 961 \times 0.293 \times 10^{-6}$

$\Rightarrow 2.815 \times 10^{-4}\ Ns/m^2$

$P_r = 1.740;$

$n = 1.7;\ k = 0.0013,\ \rho_v = 0.598\ kg/m^3$

$\sigma = 58.9 \times 10^{-3}\ N/m.$

$$q_v = \mu\lambda \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} \times \left[\frac{C_p\,(T_w - T_{sat})}{k \cdot \lambda \cdot P_r^{\,n}}\right]^3$$

$$\Rightarrow \left[2.815 \times 10^{-4} \times 2256.6 \times 10^3 \times \sqrt{\frac{9.81\,(961 - 0.598)}{58.9 \times 10^{-3}}} \times \left(\frac{4216\,(125 - 100)}{0.0013 \times 2256.6 \times 10^3 \times (1.740)^{1.7}}\right)^3\right]$$

$\Rightarrow 698.960 \times 10^6\ kW/m^2$

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Heat flux

$q = 698.960 \times 10^6$ kW/m2

Evaporation rate per unit area is

$$m = \frac{q}{\lambda}$$

$$\Rightarrow \frac{698.960 \times 10^6}{2256.6 \times 10^3}$$

$$= 309.74$$

③ Water at 5 bar flows inside a 25mm diameter tube under local boiling conditions where the tube wal temp is 15°c above the saturation temp. Estimate the HT in a 0.6m length of tube.

Sol $\Delta T_e = T_s - T_{sat}$

$= 15^\circ C$

$D = 25$ mm

$= 0.025$ m

$l = 0.6$ m

$P = 5$ bar

$= 5 \times (1.0132 \times 10^5)$

$= 5.066 \times 10^5$ N/m2

$= 0.5066 \times$ MN/m2

$h = 2.54(\Delta T_e)^3 \cdot e^{P/1.551}$

$\Rightarrow 2.54(15)^3 \times e^{\frac{0.5066}{1.551}}$

$= 11883.9 \ W/m^2K$

HT in 0.6 m length of tube

$Q = hA\Delta t$

$Q = h(\pi DL) \times \Delta t$

$= (11883.9)(\pi \times 0.025 \times 0.6) \times 15$

$= 8400.23 \ W.$

(5) A heated 30 x 30 cm square copper plate serves as the bottom for a pan of water at 1 atm pressure. The temp. of the plate is maintained at 119°C. Estimate the heat transferred / hour by the plate.

Sol Given Data.

$T_s = 119°C$

$T_{sat} = 100°C$

$L = 30 \ cm$

$= 0.3 \ m.$

$$T_f = \frac{T_s + T_{sat}}{2}$$

$$= \frac{119 + 100}{2}$$

$$= 109.5^\circ C$$

Amount of condensate

$$M = \frac{Q}{h_{fg}}$$

where, $Q = h \cdot A (T_{sat} - T_s)$

At $109.5^\circ C$,

Properties of water,

$\rho_l = 953\ kg/m^3$

$\nu = 0.27 \times 10^{-6}\ m^2/s$

$\alpha = 0.1694\ m^2/s$

$P_r = 1.393$

$c = 4.233\ J/kg \cdot k$

$K = 0.6827\ W/mk$

$h_{fg} = 2257\ kJ/kg$

$\mu_l = \rho \times \nu$

$\Rightarrow 2.573 \times 10^{-6}\ Ns/m^2$

$$h = 0.953\left[\frac{\rho_l^2\, h_{fg} \times g \times k^3}{L\, \mu_l\, (T_{sat} - T_s)}\right]^{1/4}$$

$$h = 0.953\left[\frac{(0.953)^2 \times 2257 \times 9.81 \times (0.06827)^3}{0.3 \times 2.57 \times 10^{-8}\,(100-119)}\right]^{1/4}$$

$h = -527.284\ W/m^2K.$

$\dot{Q} = hA\Delta t$

$$Re = \frac{4hL(T_{sat} - T_s)}{h_{fg} \times \mu}$$

$$\Rightarrow \frac{4 \times (-16499.233) \times 0.3 \times (100-119)}{2257 \times 2.573 \times 10^{-8} \times 10^3}$$

$= 2.07 \times 10^5$

$\dot{Q} = hA\Delta t$

$= hA(T_{sat} - T_s)$

$\Rightarrow 527.284 \times 0.3^2\,(100-119)$

$= 901.655\ W$

Rate of condensation/hr

$$M = \frac{Q}{h_{fg}} = \frac{901.655 \times 10^3}{2257} = 0.4\ kg/hr.$$

⑤ Saturated steam at ~~one~~ 1 atm. pressure condenses on a 3m high & 4m wide vertical plate that is maintained at 90°c by circulating cooling water through the other side. Determine

a) The total rate of HT by condensation to the plate
b) The avg. HT coefficient over the entire plate.

Sol

$L = 3m$

$W = 4m$

$A = 4 \times 3 = 12 m^2$

At 1 atm pressure

$t_{sat} = 100°c$

$h_{fg} = 2257 \times 10^3 \; J/kgk.$

$t_\infty = 90°c$

$t_f = \frac{t_{sat} + t_\infty}{2} = 95°c.$

At 95°c, properties of water are

$\rho = 964.5 \; kg/m^3$

$k = 0.6775 \; W/mk.$

$\mu = 299.7 \times 10^{-6} \; kg/m\text{-}sec$

4)

$$h_v = 0.943\left[\frac{k_f^3 \rho_f^2 g h_{fg}}{\mu_f L (T_{sat} - T_\infty)}\right]^{1/4} \quad \because \rho_g <<<< \rho_f$$

$$h_v = 0.943\left[\frac{(0.6775)^3 \times (964.5)^2 \times 9.81 \times 2257 \times 10^3}{299.7 \times 10^{-6} \times 3 \times (100-90)}\right]^{1/4}$$

$= 4871.83 \ W/m^2K$

b) $Q = hA\Delta t$

$= 4.871 \times 12 \times (100-90)$

$= 584.62 \ kW$

⑥. Dry saturated steam at a pressure of 2.5 bar condenses on the surface of vertical tube of height 1.5m. The tube surface temp is 120°C. Estimate the thickness of condensate film & the local HT coefficient at a distance of 0.3 m from the upper end of the tube.

Sol

Dry saturated steam at a pressure of 2.5 bar

$T_g = 127.4°c$

$h = 1.5m$

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$T_w = 120°C$

Thickness $(\delta) = ?$

$h = ?$

$x = 0.3$

$T_f = \frac{127.4 + 120}{2}$

$= 123.7°C$

$\rho = 941.855 \, kg/m^3$

$k = 0.6847 \, W/mK$

$C = 4256.105 \, J/kg\text{-}K$

$\mu = \rho_l \times \nu$

$= 941.85 \times 0.24 \times 10^{-6}$

$= 2.26 \times 10^{-4} \, kg/ms$

h_{fg} at $127.4°C = 2781 \, kJ/kg$

$\rho_v = \frac{1}{0.781}$

$= 1.39 \, kg/m^3$

$$\delta = \left[\frac{4 \mu k x (T_g - T_w)}{g h_{fg} (\rho_l - \rho_v) \rho_l}\right]^{1/4}$$

$$\Rightarrow \left[\frac{4 \times 2.26 \times 10^{-4} \times 0.6847 \times 0.3 \times (127.4 - 120)}{9.81 \times 218 \times 10^3 \times 941.85 (941.85 - 1.39)}\right]^{0.25}$$

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$= 9.227 \times 10^{-5}$

But, $G = \dfrac{\rho_1(\rho_1 - \rho_v) \times g \times \delta^3}{3\mu}$

$= \left[\dfrac{941.85(941.85 - 1.39) \times 9.81}{3 \times 2.26 \times 10^{-4}}\right] \times (9.227 \times 10^{-5})^3$

$= 0.01$ kg/m width

$Re = \dfrac{4G}{\mu_1}$

$= \dfrac{4 \times 0.01}{2.26 \times 10^{-4}} = 176.99$

$h = \left[\dfrac{\rho_1(\rho_1 - \rho_v) g \times h_{fg} \times k^3}{4\mu \times (T_g - T_w)}\right]^{1/4}$

$\Rightarrow \left[\dfrac{941.85(941.85 - 1.39) \times 9.81 \times 2181 \times 10^3 \times (0.6847)^3}{4 \times 2.26 \times 10^{-4} \times 0.3(127.4 - 120)}\right]^{0.25}$

$\boxed{h = 7420.045 \text{ W/m}^2\text{K}}$

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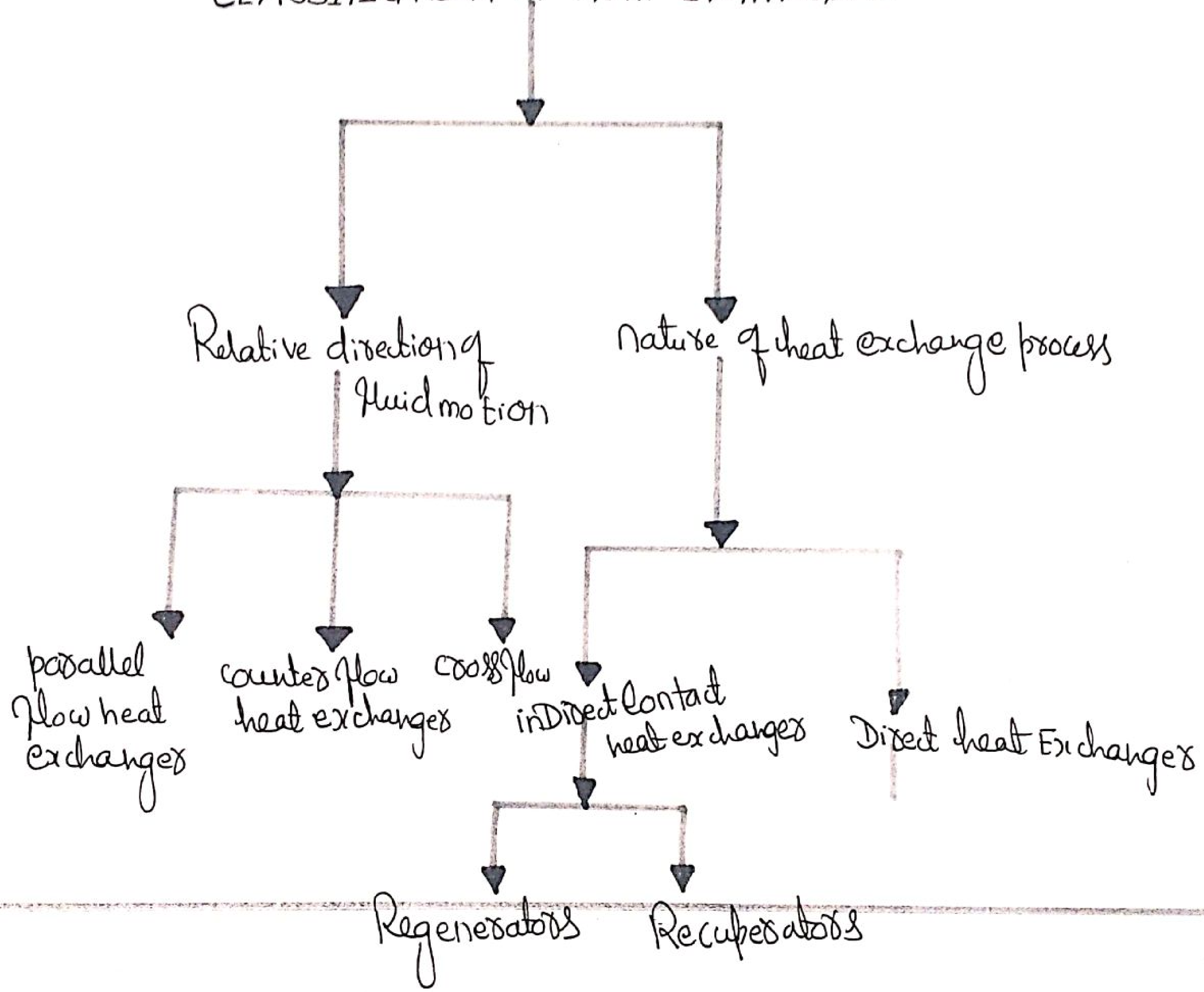
CLASSIFICATION OF HEAT EXCHANGERS



Classification of heat exchangers:-

1- Relative direction of fluid motion.

a) Parallel flow heat exchanger.

b) Counter flow heat exchanger.

- Nature of heat exchange process.

a) Direct contact heat exchanger

b) Indirect contact heat exchanger

→ Regenerators

→ Recuperators.

Difference b/w parallel & counter flows.

Parallel flow heat exchanger	Counter flow heat exchanger
The 2 fluid streams (hot & cold) travel in same direction	The 2 fluids travel in opposite direction
LMTD is smaller	② LMTD is greater
Requires more area for heat transfer	③ Requires less area for heat transfer.
The 2 fluids enter at one end and leave at the other end.	④. The hot and cold fluids enter at opposite directions
The temp difference b/w the hot & cold fluids goes on decreasing from inlet to outlet	⑤ The temp. difference b/w 2 fluids remains more or less nearly constant.

FOULING:- The phenomenon of rust formation and deposition of fluid impurities is called fouling. It results in a lower overall heat transfer coefficient in operation than that calculated for clean surfaces.

Due to fouling effect, the effectiveness of heat exchanger may be greatly reduced.

An allowance is often made for scaling and fouling in design of heat exchangers by assigning "fouling factors" to surfaces which will become coated in use.

The fouling factor for any given scaling or fouling is equal to the thermal resistance of scale. The magnitude of fouling factors depends on the nature of the scale. If the scale is in uniform in composition and structure, the resistance may be calculated by ~~calculated~~ dividing the thickness of the scale to ~~thermal~~ conductivity of the scale material.

However, the scale is usually of unknown or complicated composition and structure.

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Fouling factors are determined experimentally by testing the heat exchanger in both clean and dirty conditions.

$$\boxed{R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}}}$$

where, U_{dirty} → overall heat transfer coefficient of dirty surface.

U_{clean} → overall heat transfer coefficient of clean surface.

ANALOGY B/W HEAT, MASS & MOMENTUM TRANSFER:-

The mathematical laws governing momentum heat & mass transfers are similar. ∴ heat, mass and momentum transfer equations for the boundary layer can be written as.

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$$

heat transfer.

$$u \cdot \frac{\partial T}{\partial x} + v \cdot \frac{\partial T}{\partial y} = \alpha \cdot \frac{\partial^2 T}{\partial y^2}$$

mass transfer,

$$u \cdot \frac{\partial C_a}{\partial x} + v \cdot \frac{\partial C_a}{\partial y} = D \cdot \frac{\partial^2 C_a}{\partial y^2}.$$

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Momentum Transfer,

$$u \cdot \frac{\partial u}{\partial x} + v \cdot \frac{\partial u}{\partial y} = \nu \cdot \frac{\partial^2 u}{\partial y^2}$$

$$Pr = \frac{\nu}{\alpha} = 1$$

$$Sc = \frac{\nu}{D} = 1$$

$$Le = \frac{\alpha}{D} = 1$$

$$Pr = Sc = Le = 1.$$

A double pipe heat exchanger is constructed of a stainless steel ($k = 151$ W/mK) innertube of $D_i = 15$ mm and $D_o = 19$ mm & the outer tube of dia 32 mm. The convective HT coefficient is given to be $h_i = 800$ W/m²K & $h_o = 1200$ W/m²K. For a fouling factor $R_{fi} = 0.0004$ m²K/W on the tube side & $R_{fo} = 0.0001$ m²K/W on shell tube, determine

(i) Total thermal resistance

(ii) U_i

(iii) U_o

$D_i = 15\,mm$

$r_i = 7.5\,mm$

$D_o = 19\,mm$

$r_o = 9.5\,mm$

$h_i = 800\ W/m^2 k$

$h_o = 1200\ W/m^2 k$

$R_{fi} = 0.0004\ m^2 k/w$

$R_{fo} = 0.0001\ m^2 k/w$

k of stainless $= 15.1\ W/mk$.

(I) $R_s = \dfrac{\ln(r_o/r_i)}{2\pi k}$

$= \dfrac{\ln\left(\frac{9.5}{7.5}\right)}{2\pi(15.1)}$

$= 2.49 \times 10^{-3}$

$= 0.00249$

Resistance on inside

$R_i = \dfrac{1}{h_i A_i} = \dfrac{1}{h_i 2\pi r_i}$

$= \dfrac{1}{1200 \times 2\pi \times 9.5 \times 10^{-3}} = 0.01396.$

Total Resistance $= R_s + R_i + R_o$

$= 0.04297$.

(ii) U_i

$$U_i = \frac{1}{\frac{1}{h_i} + R_{fi} \left[\frac{r_i}{k}\right] \ln\left[\frac{r_o}{r_i}\right] + \left[\frac{r_i}{r_o}\right] R_{fo} + \left[\frac{r_i}{r_o}\right]\left[\frac{1}{h_o}\right]}$$

$$\Rightarrow \frac{1}{\frac{1}{800} + (0.0004)\left[\frac{7.5}{15.1}\right] \ln\left[\frac{9.5}{7.5}\right] + \left[\frac{7.5}{9.5}\right] 0.0001 + \left[\frac{7.5}{9.5}\right]\left[\frac{1}{1200}\right]}$$

$$U_i = \frac{1 \times 10^4}{20.3375}$$

$= 0.049170252 \times 10^4$

$= 491.702 \ W/m^2k$.

(iii)

$$U_o = \frac{1}{\frac{1}{h_o} + R_{fo} \left(\frac{r_o}{k}\right) \ln\left(\frac{r_o}{r_i}\right) + \left(\frac{r_o}{r_i}\right) R_{fi} + \left(\frac{r_o}{r_i}\right) \frac{1}{h_i}}$$

$$\Rightarrow \frac{1}{\left[\frac{1}{1200}\right] + \left[(0.0001)\left[\ln\left(\frac{9.5}{7.5}\right)\right] \times \frac{9.5}{15.1}\right] + \left[\left[\frac{9.5}{7.5}\right] \times (0.0004)\right] + \left[\left[\frac{9.5}{7.5}\right] \times \frac{1}{800}\right]}$$

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$= 0.034039 \times 10^4$

$= 340.3942 \ W/m^2 K.$

② Determine the overall HT coefficient based on the outer area of a 3.81 cm O.D & 3.175 cm ID brass (K = 103.8 W/mK) if the HT coefficient for flow inside & outside the tube are 2270 & 2840 W/m²K & the unit fouling resistances at inside & outside are $R_{fi} = R_{fo} = 0.0088 \ m^2 K/W$.

Sol

$d_i = 3.175 cm = 0.0317 m.$

$d_o = 3.81 cm = 0.0381 m$

$K = 103.8 \ W/mK.$

$h_i = 2270 \ W/m^2 K.$

$h_o = 2840 \ W/m^2 K.$

$R_{fi} = 0.0088 \ m^2 K/W.$

Overall HT Coefficient is

$$\frac{1}{U_o} = \left[\frac{r_o}{r_i} \times \frac{1}{h_i}\right] + \left[\frac{r_o}{r_i} \times R_{fi}\right] + \left[\frac{r_o}{K} \times \ln\left(\frac{r_o}{r_i}\right)\right] + R_{fo} + \frac{1}{h_o}$$

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$$\frac{1}{U_o} = 5.294\times10^{-4} + 0.0105 \text{ [illegible]}$$

$$+ 3.5211\times10^{-4} + 0.00 \text{ [illegible]}$$

$$\frac{1}{U_o} = 202.918\times10^{-4}$$

$$U_o = 49.2808 \text{ W/m}^2\text{K}$$

(13) A heat exchanger is required to cool 55000 kg/h of alcohol from 66°C to 40°C using [illegible] kg of water entering at 5°C. Calculate the surface area required for

(i) parallel flow

(ii) counter flow

Take $U = 580$ W/m²K, Cp for water = 4180 J/kg K,

$C_p = 3760$ J/kg.K

Sol

$$C_{p_c} = 4180 \text{ J/kg.K}$$

$$C_{p_h} = 3760 \text{ J/kg.K}$$

$$U = 580 \text{ W/m}^2\text{K}$$

$$m_h = \frac{55000}{3600} = 15.2 \text{ kg/s}$$

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$$m_c = \frac{40000}{3600}$$

$$= 11.11 \ kg/s$$

$t_{h1} = 66°c$

$t_{h2} = 40°c$

$t_{c1} = 5°c$

$$Q = m_h \, Cp_h (t_{h1} - t_{h2})$$

$$= 15.277 \times 3760 (66-40)$$

$$= 11.111$$

$$t_{c2} = \left[\frac{15.277 \times 3760 \times 26}{11.11 \times 4180}\right] + 5$$

$$t_{c2} = 37.156°c$$

(i) $$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)} = \frac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln\left[\frac{(t_{h1} - t_{c1})}{(t_{h2} - t_{c2})}\right]}$$

$$\theta_m = \frac{(66-5) - (40 - 37.156)}{\ln\left(\frac{66-5}{40-37.156}\right)} = 18.97°c.$$

$$Q = UA\theta_m$$

$$A = \frac{Q}{U\theta_m}$$

$$= \frac{m_c C p_c (t_{c_2} - t_{c_1})}{U\theta_m}$$

$$= \frac{11.111 \times 4180 \times (37.156 - 5)}{580 \times 18.9}$$

$$= 135.72\ m^2$$

(ii) counter flow mode

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)}$$

$$= \frac{(t_{h_1} - t_{c_2}) - (t_{h_2} - t_{c_1})}{\ln(t_{h_1} - t_{c_2} / t_{h_2} - t_{c_1})}$$

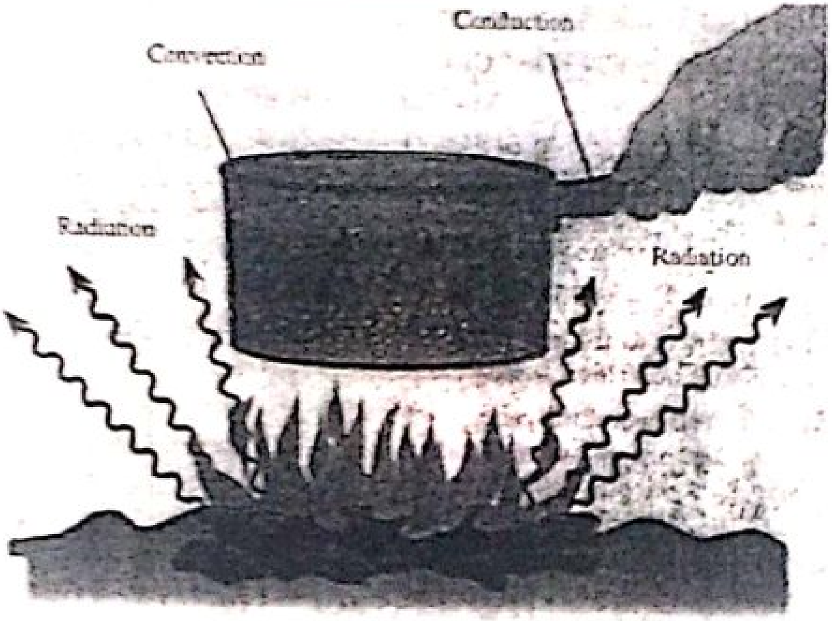
$$\Rightarrow \frac{(66 - 37.156) - (40 - 5)}{\ln\left(\frac{66 - 37.1}{40 - 5}\right)}$$

$$= \cancel{37} = \frac{-6.156}{-0.1934}$$

$$= 31.8304$$

Radiation:- The transfer of energy across a system by means of an electromagnetic waves.

Chapter : 12 : Radiation Exchange Between Surfaces



Heat transfer by conduction, convection and radiation.

The rate of emission of radiation by a body depends on the following.

(i) Temperature of the surface.

(ii) nature " " "

(iii) wavelength

- Total emissive power
- monochromatic emissive power
- emissivity
- intensity of radiation
- Radiation density
- Radiosity
- relation b/w surface emission & irradiation properties

FACTORS WHICH DEALS WITH THE SURFACE EMISSION PROPERTIES ARE GIVEN BELOW

Black body :- Black body is one which neither reflects nor transmits any part of incident radiation.

$$\boxed{\alpha = 1, \rho = 0, \tau = 0} \longrightarrow \text{for black body}$$

Opaque body :- when no incident radiation is transmitted through the body is called an opaque body

$$\boxed{\tau = 0, \alpha + \rho = 1} \longrightarrow \text{for opaque body.}$$

White body :- If all the incident radiation falling on the body are reflected called white body.

$$\boxed{\rho = 1, \alpha = 0 \text{ \& } \tau = 0} \longrightarrow \text{for white body.}$$

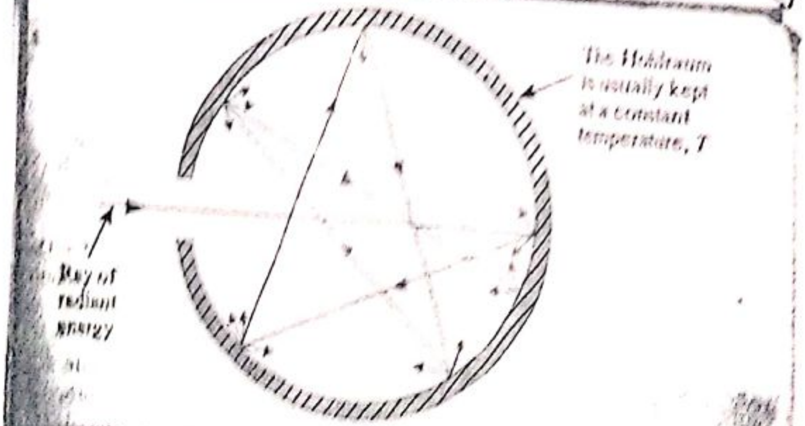


Fig. 11.4. Concept of a black body

Absorptivity:- The amount of heat absorbed by the body is called absorptivity.

Reflectivity:- The amount of heat reflected by the body is called Reflectivity.

Transmissivity:- The amount of heat transmitted by body is called transmissivity.

Stefan-Boltzman law:- This law states that emissive power of a black body is directly proportional to the fourth power of its absolute temp.

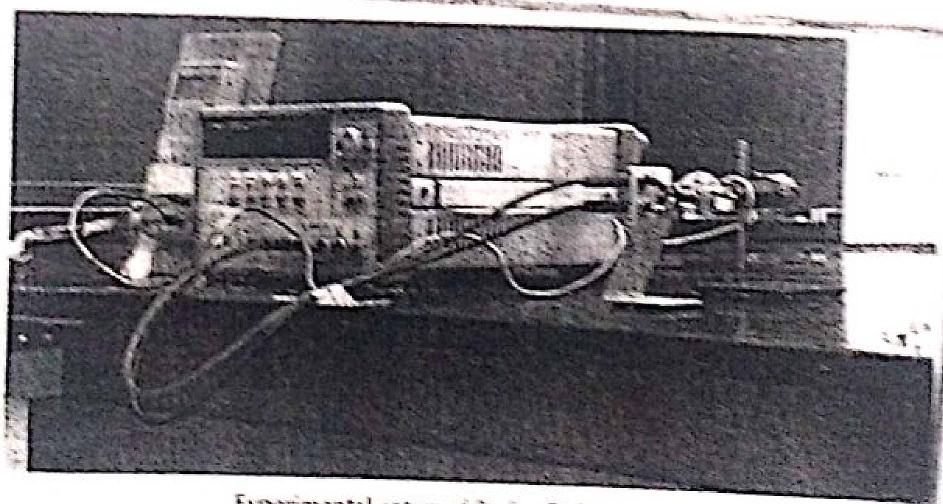
$$\boxed{E_b = \sigma T^4}$$

where,

E_b = emissive power of a black body.

σ = Stefan-boltzman constant

$= 5.67 \times 10^{-8}\ W/m^2 K^4$.



Experimental setup of Stefan-Boltzmann law

KIRCHOFF'S LAW :- The Law States that any at any temp, the ratio of total emissive power E to the total absorptivity α is a constant for all substances which are in thermal equilibrium with their environment.

Gustav Kirchhoff (1824-1887)

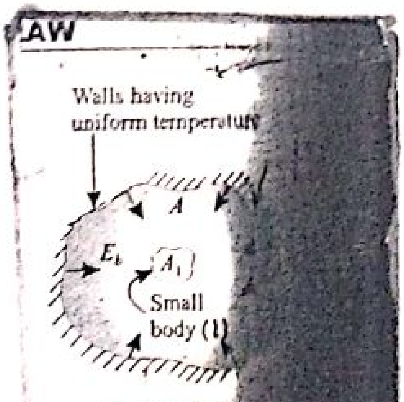
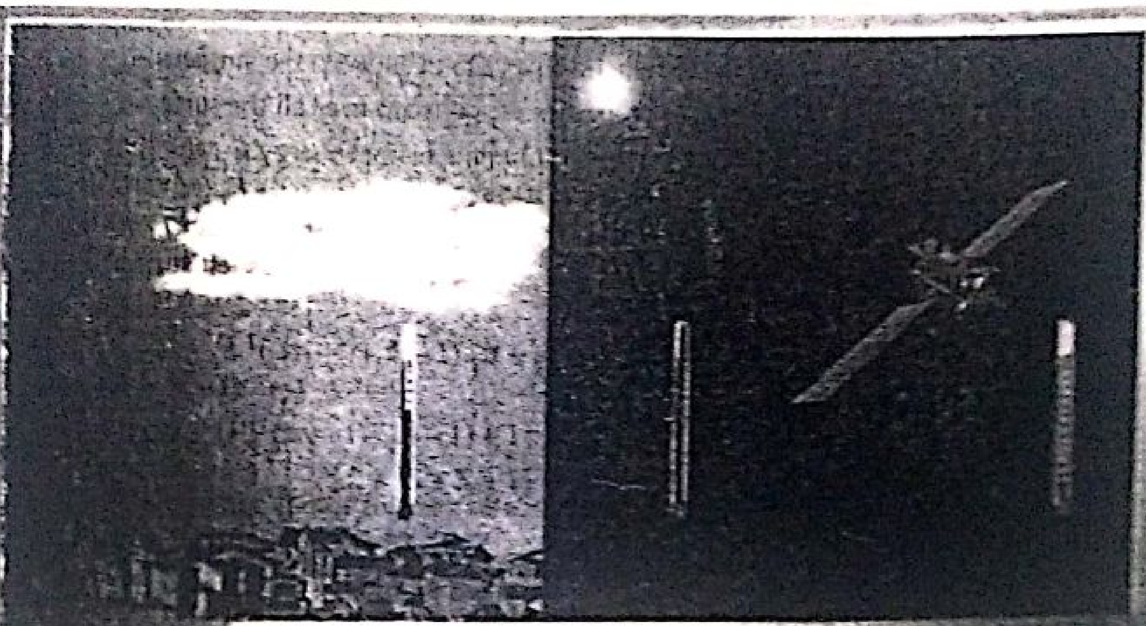


Fig. 11.5. Der
Kirchhoff's



radiation, convection In space, heat travels
conduction.

Thermal radiation system.

Table 12.1. Geometric (F_{1-2}) and interchange (f_{1-2}) factors

S.No.	Configuration	Geometric factor (F_{1-2})	Interchange factor (f_{1-2})
1.	Infinite parallel planes	1	$\dfrac{1}{\dfrac{1}{\varepsilon_1}+\dfrac{1}{\varepsilon_2}-1}$
[illegible]	Infinitely long concentric cylinders or concentric spheres	1	$\dfrac{1}{\dfrac{1}{\varepsilon_1}+\dfrac{A_1}{A_2}\left(\dfrac{1}{\varepsilon_2}-1\right)}$
[illegible]	Body 1 (small) enclosed by body 2	1	ε_1
[illegible]	Body 1(large) enclosed by body 2	1	$\dfrac{1}{\dfrac{1}{\varepsilon_1}+\dfrac{A_1}{A_2}\left(\dfrac{1}{\varepsilon_2}-1\right)}$
[illegible]	Two rectangles with common side at right angles to each other	1	$\varepsilon_1\varepsilon_2$

① Calculate the following for an industrial furnace in the form of a black body & emitting radiation at 2500°c

(i) monochromatic emissive power at 1·2 μm
(ii) wavelength at which the emission is maximum.
(iii) max. emissive power.
(iv) total emissive power

Sol Given Data.

$T = 2500 + 273$
$= 2773\ k.$
$\lambda = 1 \cdot 2\ \mu m$
$\varepsilon = 0 \cdot 9$

(i) According to placks Law

$$(E_\lambda)_b = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

$C_1 = 3 \cdot 742 \times 10^8\ W \mu m^4/m^2$
$= 0 \cdot 3742 \times 10^{-15}\ W \cdot m^4/m^2$
$C_2 = 1 \cdot 4388 \times 10^{-2}\ m \cdot k.$

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$(E_\lambda)_b$

$$= \frac{0.3742\times10^{-15}\times(1.2\times10^{-6})^5}{\exp\left[\frac{1.4388\times10^{-2}}{1.2\times10^{-6}\times2773}\right]-1}$$

$= 2.014\times10^{12}$ W/m2

(ii) According to Weins Displacement law

$$\lambda_{max} = \frac{2898}{T}$$

$$= \frac{2898}{2773} = 1.045\ \mu m.$$

(iii) $(E_\lambda b)_{max}$

$= 1.285\times10^{-5}T^5$ W/m2 per metre length

$= 1.285\times10^{-5}\times(2773)^5$

$= 2.1\times10^{12}$ W/m2 per meter length.

(iv) Total emissive power

$E_b = \sigma T^4$

$= 5.67\times10^{-8}(2773)^4$

$= 3.352\times10^6$ W/m2.

(12) The effective temp of a body having an area of 0.12 m^2 is 527°C. Calculate the following.

(i) total rate of energy emission.

(ii) intensity of normal radiation.

Sol Given Data

$A = 0.12\ m^2$

$T = 527 + 273$

$= 800\ K$

(i) $E_b = \sigma A T^4\ W$

$= 5.67 \times 10^{-8} \times 0.12 \times (800)^4$

$= 2786.9\ W$

(ii) $I_{bn} = \frac{E_b}{\pi}$

$= \frac{\sigma T^4}{\pi} \Rightarrow \frac{5.67 \times \left(\frac{800}{100}\right)^4}{\pi}$

$= 7392.5\ W/m^2.sr.$

③ figure shows a cavity having surface temp as 900°C & emissivity as 0.6. find the rate of emission from the cavity to surrounding

707

Sol $Q = A_1 \varepsilon_1 \sigma T_1^4 \left[\dfrac{1-F_{1-1}}{1-(1-\varepsilon_1)F_{1-1}}\right]$

A_1 = area of cavity.

A_2 = " " opening of cavity

$= \frac{\pi}{4} d_2^2$

$= \frac{\pi}{4} \times \left(\frac{5}{100}\right)^2$

$= 0.001963 \ m^2$

$A_1 = A_f + A_{hs}$

A_f = Area of frustrum

A_{hs} = Area of half sphere.

$A_f = \pi(r_1 + r_2)\sqrt{(r_2 - r_1)^2 + h^2}$

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$r_1 = 2.5\,cm$

$r_2 = 5\,cm$

$h = 4\,cm$

$$A_f = \pi(2.5+5)\sqrt{(5-2.5)^2+4^2}$$

$$= 0.01111\,m^2$$

$$A_{hs} = \frac{1}{2} \times 4\pi r^2$$

$$= 2\pi r^2$$

$$= 0.0157\,m^2$$

$$A_1 = 0.01111 + 0.0157$$

$$= 0.0268\,m^2$$

$$F_{1-1} = 1 - \frac{A_2}{A_1} = 1 - \frac{0.001963}{0.0268}$$

$$= 0.926$$

$$Q = 0.0268 \times 0.6 \times 5.67 \left[\frac{900+273}{100}\right]^4 \left(\frac{1-0.926}{1-(1-0.6)0.926}\right)$$

$$= 202.87\,W$$

(4) The filament of a 75 W light bulb may be considered a black body radiating into a black enclosure at 70°C. The filament dia 0.10 mm & L is 5 cm.

Sol $Q = 75 W$

$= 75 J/s$

$T_2 = 70 + 273$

$= 343 K$

$d = 0.01 mm$

$l = 5 cm$

$Q = \sigma \varepsilon A (T_1^4 - T_2^4)$

$75 = 5.67 \times 10^{-8} \times 1 \times (\pi d l) \times (T_1^4 - T_2^4)$

$75 = 5.67 \times 10^{-8} \times (\pi \times 0.1 \times 10^{-3} \times 5 \times 10^{-2}) (T_1^4 - 343^4)$

$T_1^4 = \frac{75}{8.906 \times 10^{-13}} + (343)^4$

$T_1^4 = 8.42 \times 10^{13} + (343)^4$

$T_1 = \sqrt[4]{8.42 \times 10^{13} + 343}$

$t_1 = 2756°C$

⑤. Two parallel rectangular surfaces 1m × 2m are opposite to each other at a distance of 4m. The surfaces are black & at 100°c & 200°c. Calculate the heat exchange by radiation b/w 2 surfaces.

Sol $Q_{12} = A_1 F_{1-2} \sigma (T_1^4 - T_2^4)$

$\varepsilon_1 = \varepsilon_2 = 1$

$\frac{X}{L} = \frac{2}{4} = 0.5$ (from tables)

$\frac{Y}{L} = \frac{1}{4} = 0.25$

$F_{1-2} = 0.043$

$Q_{12} = (2 \times 1) \times 0.043 \times 5.67$

$= 149.5$ Watts.

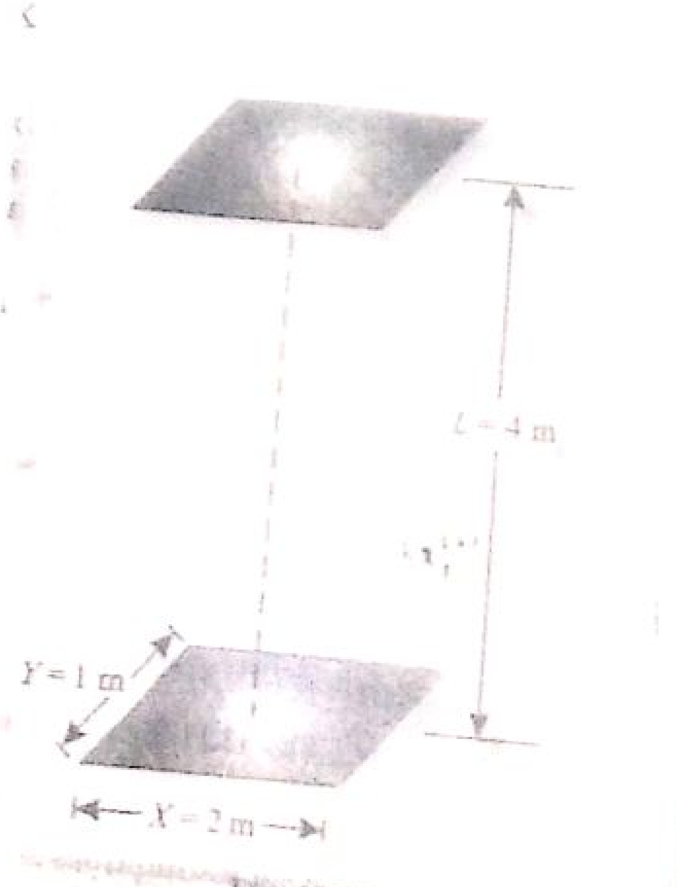

FIG. 12.20.