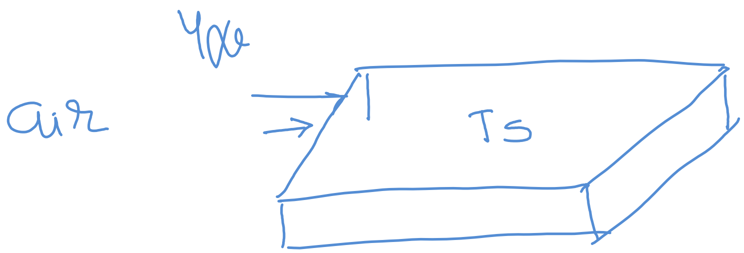
Chapter-3
Convective Heat Transfer

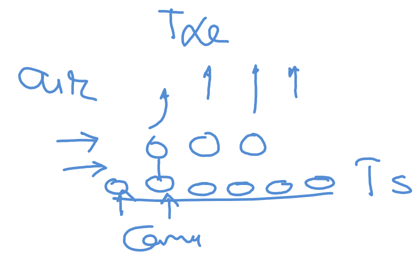
Learning objective

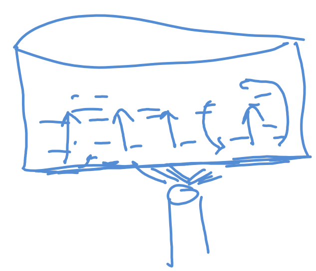
- Student will be able to define convection heat transfer
- To understand & apply dimensional analysis
- Understand various dimensionless number and their significant

Convection

- Thermal convection occurs when a temperature difference exists between a solid surface and a fluid flowing on it.







Newton's law of cooling

- The appropriate convection rate equation for the convective heat transfer between a surface and an adjacent fluid is given by Newton's law of cooling:

$$\phi_{con} = h A_s (T_s - T_\infty) \quad \text{— (I)}$$

ϕ_{con} = Rate of heat Transfer by Convection

A_s = Surface area

T_s = Surface Temp

T_∞ = bulk fluid Temp.

$\phi \rightarrow W$

$A \rightarrow m^2$

$T_s, T_\infty \rightarrow K, °C$

$$h = \frac{\phi_{con}}{A_s (T_s - T_\infty)} = \frac{W}{m^2 \, °C} = \frac{W}{m^2 K}$$

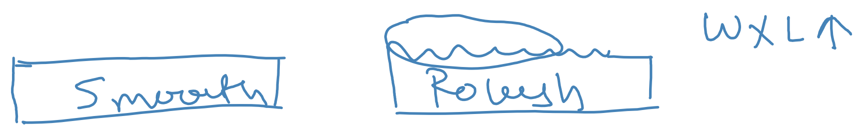
$T_s - T_\infty$ — ✓

$A_s \rightarrow$ ✓

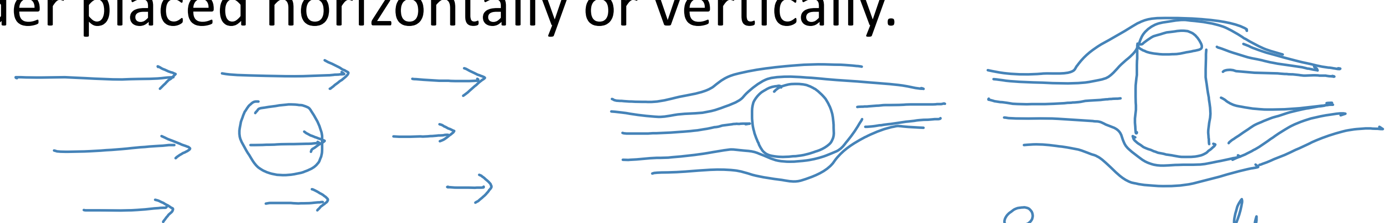
$$\phi_{con} = f(h)$$

Convective Heat Transfer coefficient

- The value of film co-efficient is dependent upon:
- 1. Surface conditions: Roughness & Cleanliness



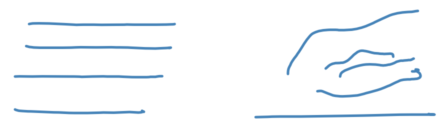
- 2. Geometry and orientation of surface: Plate, Tube and Cylinder placed horizontally or vertically.



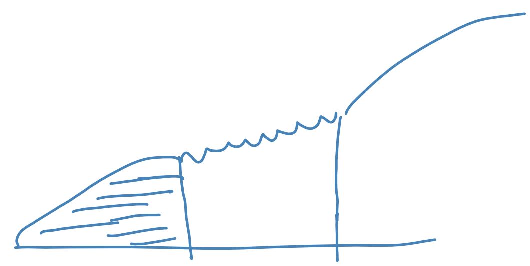
- 3. Thermo-physical properties of the fluid: Density, Viscosity, Specific heat, Coefficient of expansion and thermal conductivity.

Convective Heat Transfer coefficient

- 4. Nature of fluid flow: Laminar or Turbulent
- 5. Boundary layer configuration

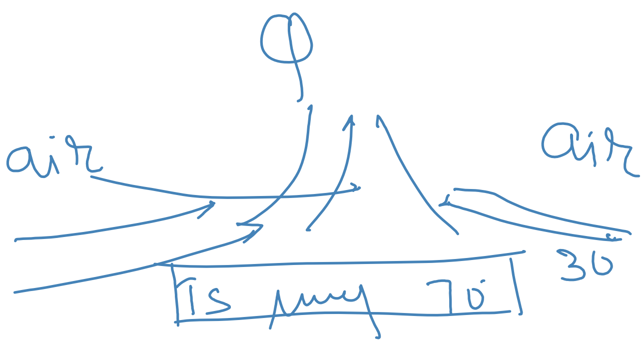


- 6. Existing thermal conditions

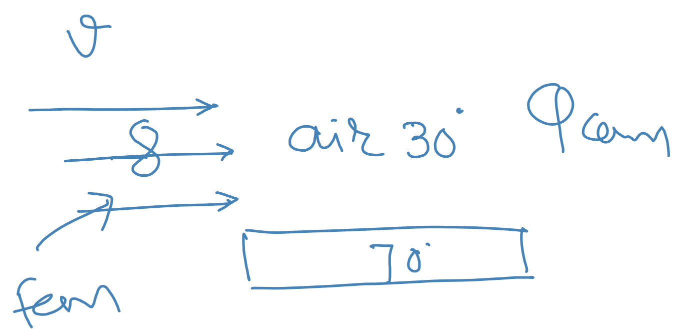


Free and Forced Convection

- With respect to the cause of fluid flow, two types of convection are distinguished
- 1. Free Convection or Natural Convection
- 2. Forced Convection

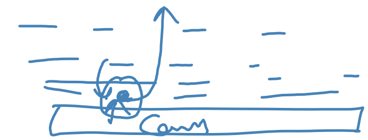


Case-I



Case-II

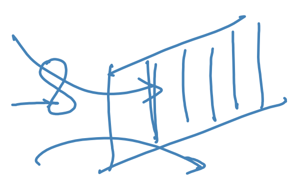
1. Free Convection or Natural Convection

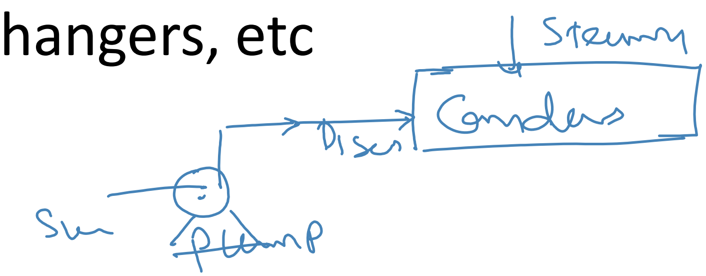


- When a surface is maintained in still fluid at a temperature higher or lower than that of the fluid, a layer of fluid adjacent to the hot or cold surface gets heated or cooled by conduction.
- A density difference is created between this adjacent layer and the still fluid surrounding it. "Convection currents"
- The density difference introduces a buoyant force causing flow of fluid near the surface.
- Heat transfer under such conditions is known as Free or Natural Convection. Thus, “Free or Natural convection is the process of heat transfer which occurs due to movement of the fluid particles by density changes associated with temperature differential in a fluid.”

2. Forced Convection

- Flow of fluid is caused by a pump, a fan or by the atmospheric winds.
- These mechanical devices speeds up the heat transfer rate.
- In free convection flow velocities encountered are lower compared to flow velocities in forced convection, consequently the value of convection co-efficient is lower, and for a given rate of heat transfer larger area could be required.
- Examples of forced convection are: cooling of I.C. Engines, Air conditioner, Heat exchangers, etc





Dimensional Analysis

- "Dimensional analysis is a mathematical technique which makes use of the study of the dimensions for solving several engineering problems."

- Dimensional analysis has become an important tool for analyzing fluid flow

- problems. It is especially useful in presenting experimental results in a concise form.

- There are two methods are used in dimensional analysis: 1) Rayleigh's Method and 2) Buckingham's -Theorem

② → Dimension System MLTθ → MLθH ×

Sr. No.	Quantity	Symbol	Units (SI)	Dimensions (MLTθ System)
A	**Fundamental**			
1	Mass	M	Kg	$M^1 L^0 T^0 \theta^0$
2	Length	L	m	$M^0 L^1 T^0 \theta^0$
3	Time	T	Sec	$M^0 L^0 T^1 \theta^0$
4	Temperature	θ	K	$M^0 L^0 T^0 \theta^1$
5	Heat	Q, H	Joule	$M^1 L^2 T^{-2} \theta^0$
B	**Geometric**			
1	Area	A	m_2	L^2
2	Volume	V	m_3	L^3

Sr. No.	Quantity	Symbol	Units (SI)	Dimensions (MLTθ System)
C	**Kinematic**			
1	Linear Velocity	u, v	m/s	$L^1 T^{-1}$
2	Angular Velocity	ω	rad/s	T^{-1}
3	Acceleration	a	m/s_2	$L^1 T^{-2}$
4	Angular Acceleration	α	rad/s_2	T^{-2}
5	Discharge	Q	m_3/sec	$L^3 T^{-1}$
6	Kinematic Viscosity	ν	m_2/sec	$L^2 T^{-1}$
D	**Dynamic**			
1	Force / Resistance	F/R	N ($kg\text{-}m/s_2$)	$M^1 L^1 T^{-2} \theta^0$
2	Density	ρ	Kg/ m_3	$M^1 L^{-3}$
3	Specific Weight	w	N/ m_3	$M^1 L^{-2} T^{-2} \theta^0$
4	Dynamic Viscosity	µ	Kg/m-sec	$M^1 L^{-1} T^{-1}$
5	Work, Energy	W, E	N-m (Joule)	$M^1 L^2 T^{-2} \theta^0$
6	Power	P	Watt (J/sec)	$M^1 L^2 T^{-3}$

Sr. No.	Quantity	Symbol	Units (SI)	Dimensions (MLTθ System)
E	**Thermodynamic**			
1	Thermal Conductivity	K	W/m-K	$M^1 L^1 T^{-3} \theta^{-1}$
2	Specific Heat	C_p, C_v	kJ/kg-K	$M^0 L^2 T^{-2} \theta^{-1}$
3	Heat Transfer Co-efficient	h	W/m_2-K	$M^1 T^{-3} \theta^{-1}$
4	Gas Constant	R	J/kg-K	$L^2 T^{-2} \theta^{-1}$
5	Thermal Diffusivity	α	m_2/sec	$L^2 T^{-1}$

Dimensionless Numbers & Their Physical Significance

1. Reynolds Number (Re)

It is defined as a ratio of inertia force to viscous force.

$$\tau = \mu \frac{du}{dy}$$

$$\tau \times A = F$$

$$Re = \frac{\text{inertia force}}{\text{viscous force}}$$

$$\text{Viscous} = \tau \times A = \mu \frac{du}{dy} \cdot L^2 = \mu \frac{V}{L} \cdot L^2 = \mu V L$$

$$F = ma = \rho V \left(\frac{L}{T^2}\right) = \frac{\rho L^3 L}{T^2} = \rho \left(\frac{L}{T}\right)^2 L^2 = \rho V^2 L^2$$

- It indicates the relative importance of the inertial and viscous effects in a fluid motion

$$Re = \frac{\rho V^2 L^2}{\mu V L} = \frac{\rho V l}{\mu} = \frac{\rho V d}{\mu}$$

- At low Reynolds number, the viscous effect dominates and the fluid motion is laminar.
- At high Reynolds number, the inertial effects lead to turbulent flow.
- Reynolds number constitutes an important criterion of kinematic and dynamic similarity in forced convection heat transfer.

2. Prandtl Number (Pr)

m^2/s m^2/s

- "It is the ratio of kinematic viscosity to thermal diffusivity of the fluid".

Kinematic Viscosity $\nu = \frac{\mu}{\rho} = \frac{\text{Dynamic Viscosity}}{\text{Density}}$

Thermal Diffusivity $\alpha = \frac{K}{\rho C_p}$

$$Pr = \frac{\nu}{\alpha} = \frac{\mu/\rho}{K/\rho C_p} = \frac{\mu C_p}{K}$$

$Pr = 1 \rightarrow$ gas

3. Nusselt Number (Nu)

- Nu established the relation between convective film co-efficient (h), thermal conductivity of the fluid ( ) and a significant length parameter ( ) of the physical system. $L_c \rightarrow$

$$Nu = \frac{hl}{K_{fluid}} \qquad Bi = \frac{hl}{K_{solid}} \qquad Nu \rightarrow h \rightarrow \phi$$

$$\phi = -kA\left(\frac{\partial T}{\partial y}\right)_0 = hA(T_s - T_\infty)$$

$$h = \frac{-k(\partial T/\partial y)_{y=0}}{(T_s - T_\infty)} \Rightarrow \frac{hl}{k} = \frac{(-\partial T/\partial y)_{y=0}}{(T_s - T_\infty)\, l}$$

- Heat transfer through the fluid layer is by ***convection*** when the fluid involves some motion and by ***conduction*** when the fluid layer is motionless.

4. Grashoff Number (Gr) → Free Convection

- It indicates the relative dominance of inertia and buoyant forces over viscous force

$$Gr = \frac{\text{inertia force} \times \text{buoyant}}{(\text{viscous})^2}$$

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

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

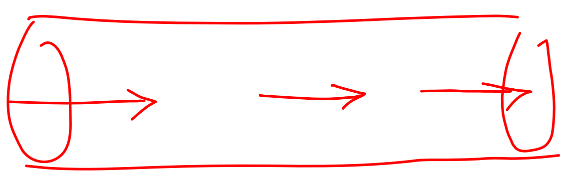
5. Stanton Number (St)

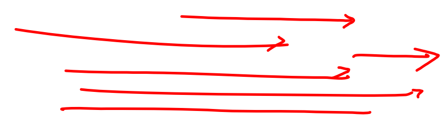
- "It is the ratio of heat transfer co-efficient to the flow of heat per unit temperature rise due to the velocity of fluid".

$$St = \frac{h \Delta T}{\rho v c \Delta T} = \frac{(hl/k)}{\left(\frac{\rho v l}{\mu}\right) \times \left(\frac{\mu c_p}{k}\right)}$$

$$St = \frac{Nu}{Re \times Pr}$$

internal flow





flate plate

- **6. Peclet Number (Pe)**
- “It is the ratio of mass heat flow rate by convection to the flow rate by conduction under an unit temperature gradient and through a thickness ”.

$$Pe = \frac{q_{conv}}{q_{cond}} = \frac{(\rho A V) C_p}{KA/l} = \frac{\rho V l}{\mu} \times \frac{\mu C_p}{K}$$

$$Pe = Re \times Pr$$

- **7. Graetz Number (G)**
- "It is the ratio of heat capacity of fluid flowing through the pipe per unit length to the conductivity of pipe material."

$$G = \frac{(\dot{m} C_p / l)}{k}$$

$$G = \pi/4 \cdot Re \cdot Pr \cdot D/L$$

$$G = Pe\left(\frac{\pi D}{4L}\right)$$