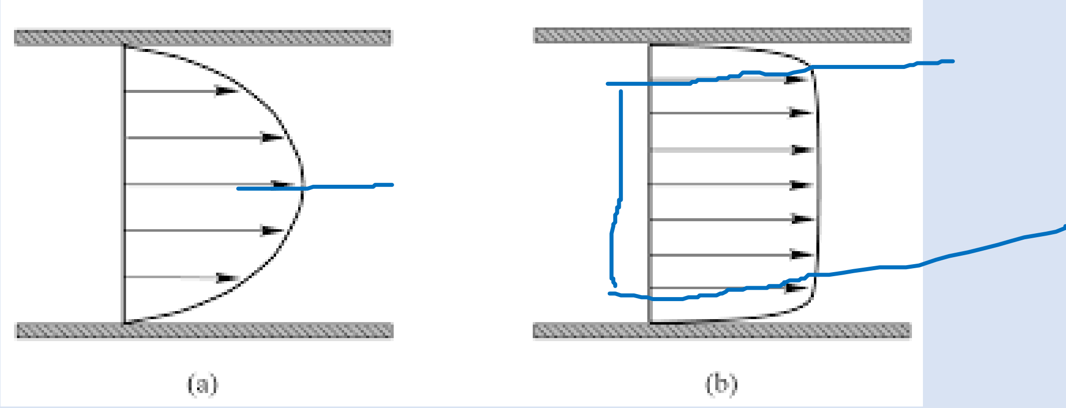
Convection

- Fourier's law used in the case of conductive heat transfer is applicable for both solids and the fluid medium
- For this law to be applicable, the medium must be stagnant
- This, however, rarely occurs in a fluid in which heat is flowing in practical situations
- As a result, heat transfer in a fluid mainly occurs by ***convection***

- *Convection is the transfer of heat in a fluid medium due to fluid motion*
- This is associated with bulk motion in the fluid which may be caused by a pressure gradient or density gradient in a medium

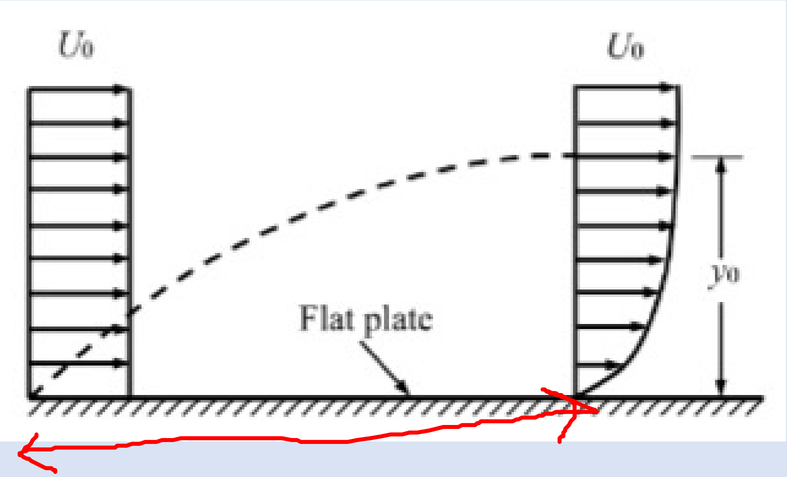
- In case of laminar flow, the fluid elements move in an orderly or streamline flow while for turbulent flow, the fluid elements move in a random manner with a net displacement in the direction of flow
- In either case, the moving fluid element carries with it heat energy as it moves from one point to another when there is a temperature gradient



Velocity profile in laminar flow

Velocity profile in turbulent flow

- When a fluid flows over a solid surface, its *velocity is zero at the surface* (no slip condition) and increases gradually with distance from the surface, eventually attaining free stream velocity
- Transport of heat to the fluid at or very near the surface occurs mainly by conduction because the fluid velocity is practically zero there
- As the velocity of the fluid increases with distance from the surface, the role of convection becomes increasingly important
- Irrespective of the nature of flow of bulk fluid (laminar or turbulent) a fluid layer near the surface always remains laminar



- As the velocity of the bulk fluid increases, the thickness of this layer goes down
- This thin layer at the surface accounts for most of the resistance to heat transfer
- If this resistance can be estimated, the rate of heat transfer to and from the surface can be estimated
- However, as the velocity distribution is not easy to ascertain, estimation of this resistance is not easy
- This is overcome by defining a ***heat transfer coefficient (h)*** for the process
- Rate of heat transfer is proportional to the area of heat transfer and the temperature driving force

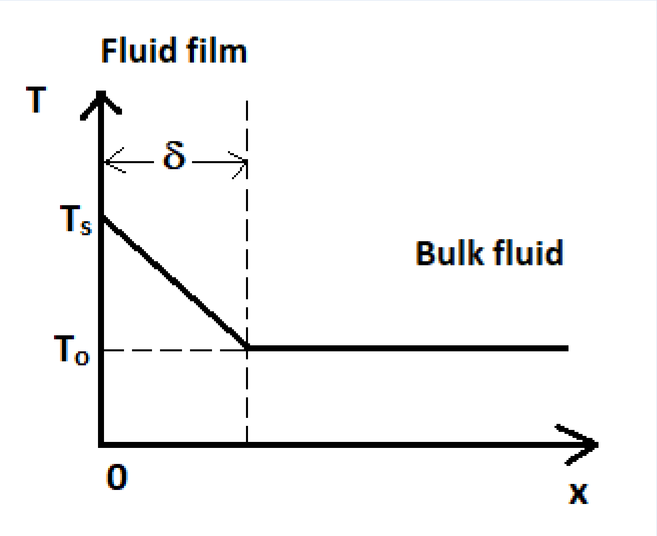
$$Q \propto A(T_s - T_o) \quad \text{or} \quad Q = hA(T_s - T_o)$$

$$\boxed{h = \frac{Q}{A(T_s - T_o)} = \frac{q}{\Delta T}}$$

Q= rate of heat transfer
q = heat flux
A = area of heat transfer
T_s = surface temperature
T_o = bulk fluid temperature

Heat transfer coefficient is equal to the heat flux per unit temperature driving force

- ***Heat transfer coefficient (h) depends on***
  - (a) geometry of the system
  - (b) characteristics of fluid flow
  - (c) properties of fluid such as viscosity, density, thermal conductivity



- Heat transfer coefficient is also known as ***film coefficient***
- The heat transfer at the phase boundary is sometimes visualized as occurring through a thin, stagnant film attached to the boundary or the interface between the phases
- Beyond the film the fluid is well-mixed
- The change in temperature of the fluid from the value at the surface (T_s) to that in the bulk (T_o) occurs across the film only and there is no further temperature change
- The fluid in the film is ‘stagnant’ and heat transfer occurs only by conduction
- The rate of heat transfer in the film can be written as,

$$Q = -kA\left(\frac{T_o - T_s}{\delta}\right) \qquad \text{or,} \qquad Q = \frac{k}{\delta}A(T_s - T_o)$$

- Comparing this equation with the previous one [$Q = hA(T_s - T_o)$] gives

$$\boxed{h = \frac{k}{\delta}}$$

- Heat transfer coefficient can be calculated if k and δ are known
- However, estimation of δ is not possible and hence, the above equation cannot be used to estimate h
- The above is known as ***film theory of heat transfer***
- ***The film thickness, δ, is the thickness of the stagnant fluid that offers the same heat transfer resistance as that which actually exists in the fluid under the given hydrodynamic conditions***
- The determination of the heat transfer coefficient, h, is carried out using a large number of empirical correlations developed by researchers applicable to various physical situations and geometries

- Convective heat transfer occurs due to the motion of the fluid
- If the motion or velocity in the medium is created by application of an external force such as an agitator or a pump, it is known as ***forced convection***
- However, if the temperature of a layer of fluid is higher than the upper layer, buoyancy induced motion is generated and the heat transfer due to such a motion is called ***free or natural convection***

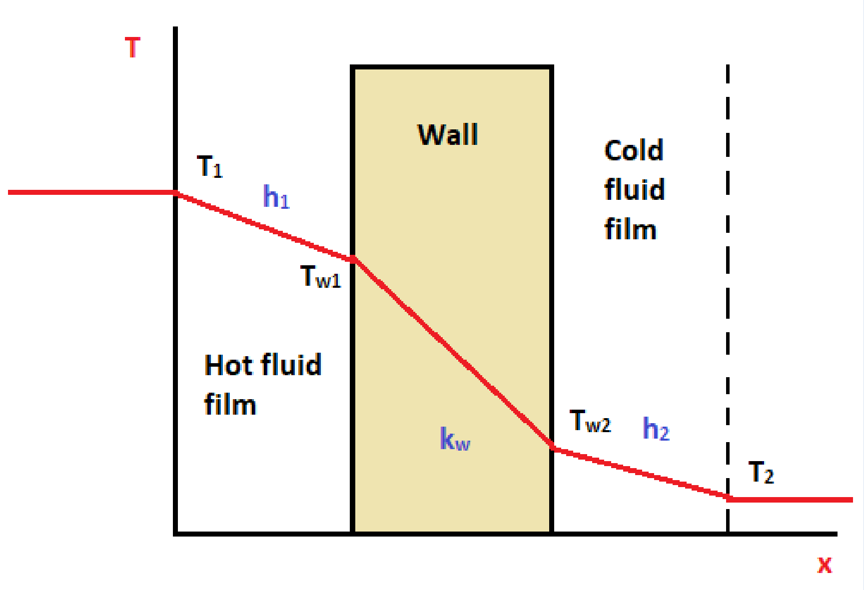
- ***Forced convection takes place at a rate faster than free convection***
- ***The heat transfer coefficient corresponding to forced convection is generally much higher than that in free convection***

Overall heat transfer coefficient

- In the chemical industry, the heat exchanger is a common heat transfer equipment
- In a heat exchanger, heat is transferred from one fluid to another separated by an intervening solid wall
- In such a case, the resistances involved include resistance in the two fluid films on either side of the wall and due to the material of the wall itself
- These resistances are summed up and the heat transfer in such a case is estimated using an ***overall heat transfer coefficient***

Heat transfer between two fluids separated by a plane wall

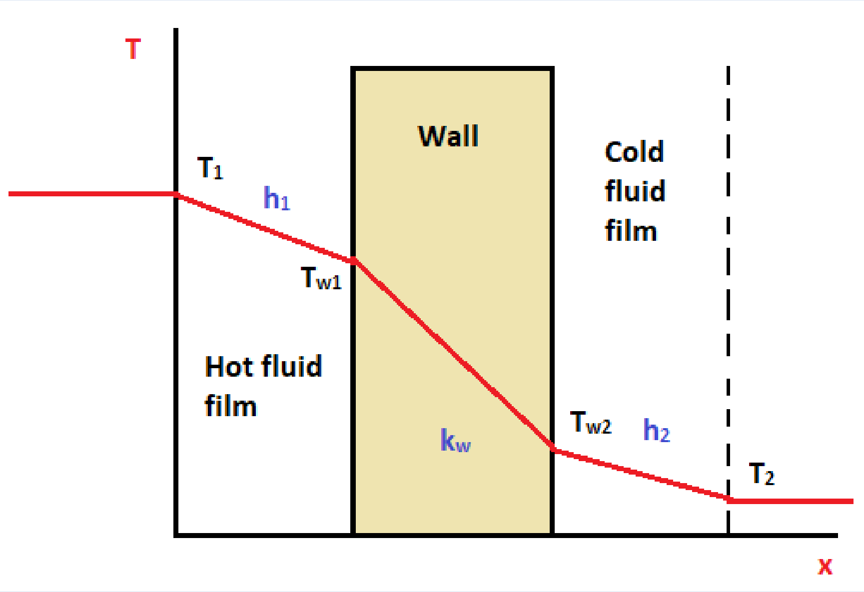
- Consider the transfer of heat from a hot fluid (T_1) to the cold fluid (T_2) separated by a solid wall of thickness 'l'
- Temperature at the interface between the hot fluid and wall is T_{w1} and that between the cold fluid and wall is T_{w2}
- Heat transfer coefficient between the hot fluid and wall is h_1 and that between the cold fluid and wall is h_2
- Thermal conductivity of the material of the wall is k_w



- Rate of heat transfer from hot fluid to wall = $Q_1 = h_1 A(T_1 - T_{w1})$
- Rate of heat transfer through the wall = $Q_2 = k_w A \frac{(T_{w1}-T_{w2})}{l}$
- Rate of heat transfer from hot fluid to wall = $Q_1 = h_2 A(T_{w2} - T_2)$

- In this case, heat transfer takes place at steady state through a constant area and $Q_1 = Q_2 = Q_3 = Q$

$$(T_1 - T_{w1}) = \frac{Q}{h_1 A} \qquad (T_{w1} - T_{w2}) = \frac{Q}{k_w A/_l} \qquad (T_{w2} - T_2) = \frac{Q}{h_2 A}$$



Adding then we get,

$$(T_1 - T_2) = \frac{Q}{A}\left(\frac{1}{h_1} + \frac{1}{k_w/_l} + \frac{1}{h_2}\right) = \frac{Q}{UA}$$

The temperature distributions in the hot fluid film, wall and cold fluid film are all linear but have different slopes

or,

$$\boxed{\frac{1}{U} = \frac{1}{h_1} + \frac{1}{k_w/_l} + \frac{1}{h_2}}$$

and

$$\boxed{Q = UA(T_1 - T_2)}$$

***U* is the overall heat transfer coefficient**

In the overall heat transfer coefficient, if the value of one of the thermal resistance terms is much larger than the sum of the other two, it is called the ***controlling resistance***