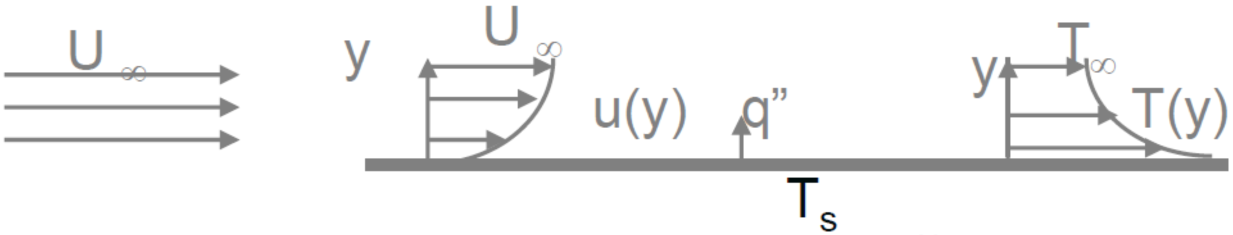
Lecture Eleven

Convection Heat Transfer

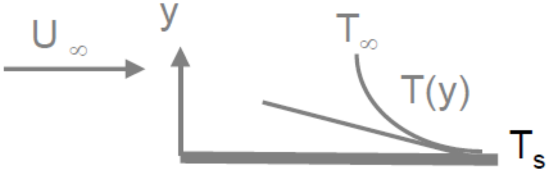
1- Introduction.

- Heat transfer in the presence of a fluid motion on a solid surface
- Various mechanisms at play in the fluid:
  - *advection* → physical transport of the fluid
  - *diffusion* → conduction in the fluid
  - *generation* → due to fluid friction

•But fluid directly in contact with the wall does not move relative to it; hence direct heat transport to the fluid is by conduction in the fluid only.



$$q''_{conv} = -k_f \left.\frac{\partial T}{\partial y}\right)_{y=0} = h\left(T_s - T_\infty\right)$$



But $\left.\frac{\partial T}{\partial y}\right)_{y=0}$ depends on the whole fluid motion, and both fluid flow and heat transfer equations are needed

Convection
- Free or natural convection (induced by buoyancy forces)
- forced convection (driven externally)

May occur with phase change (boiling, condensation)

Heat transfer rate $q = h(T_s - T_\infty)$ W

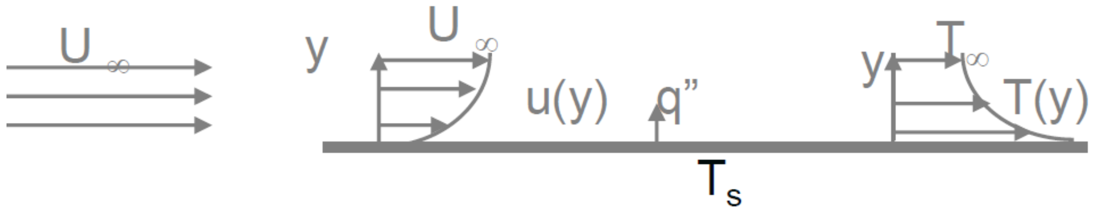
h=heat transfer coefficient (W/m^2K)

(*h* is not a property. It depends on geometry ,nature of flow, thermodynamics properties etc.)

Typical values of h (W/m^2K)

Free convection:	gases:	2 - 25
	liquid:	50 - 100
Forced convection:	gases:	25 - 250
	liquid:	50 - 20,000
Boiling/Condensation:		2500 -100,000

2- Convection Rate Equation.



Main purpose of convective heat transfer analysis is to determine:

- flow field
- temperature field in fluid
- heat transfer coefficient, h

$q'' = \text{heat flux} = h(T_s - T_\infty)$

$q'' = -k(\partial T/\partial y)_{y=0}$

Hence, $h = [-k(\partial T/\partial y)_{y=0}] / (T_s - T_\infty)$

The expression shows that in order to determine h, we must first determine the temperature distribution in the thin fluid layer that coats the wall.

3- Classes of Convective Flows.

- several parameters involved (fluid properties, geometry, nature of flow, phases etc)
- systematic approach required
- classify flows into certain types, based on certain parameters
- identify parameters governing the flow, and group them into meaningful **non-dimensional numbers**
- need to understand the physics behind each phenomenon

Common classifications:

A. *Based on geometry:*
   External flow / Internal flow
B. *Based on driving mechanism*
   Natural convection / forced convection / mixed convection
C. *Based on number of phases*
   Single phase / multiple phase
D. *Based on nature of flow*
   Laminar / turbulent

How to solve a convection problem ?

- Solve governing equations along with boundary conditions
- Governing equations include
    1. conservation of mass
    2. conservation of momentum
    3. conservation of energy
- In **Conduction** problems, only (3) is needed to be solved. Hence, only ***few parameters*** are involved
- In **Convection**, all the governing equations need to be solved.

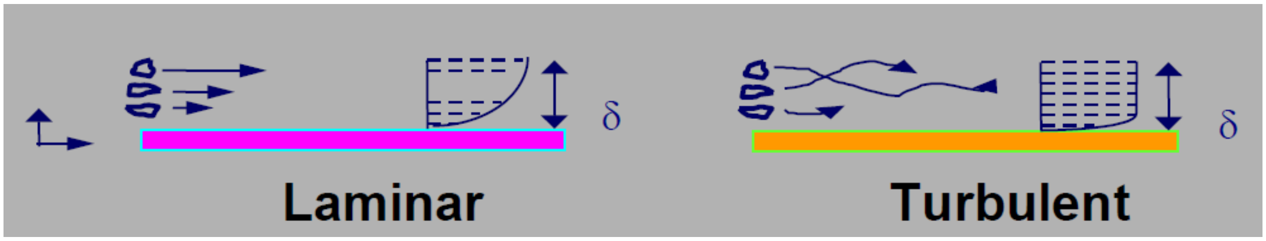
$\Rightarrow$ **large number of parameters** can be involved

Forced convection: **Non-dimensional groupings**

- **Nusselt No**. $Nu = hx / k$ = (convection heat transfer strength)/ (conduction heat transfer strength)
- **Prandtl No.** $Pr = \nu/\alpha$ = (momentum diffusivity)/ (thermal diffusivity)
- **Reynolds No**. $Re = U\,x / \nu$ = (inertia force)/(viscous force)

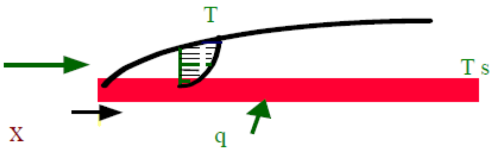
Viscous force provides the dampening effect for disturbances in the fluid. If dampening is strong enough ⇒ **laminar flow**

Otherwise, instability ⇒ **turbulent flow** ⇒ **critical Reynolds number**



4- <u>Forced Convection. External Flow (over Flat Plate)</u>

An internal flow is surrounded by solid boundaries that can restrict the development of its boundary layer, for example, a pipe flow. An external flow, on the other hand, are flows over bodies immersed in an unbounded fluid so that the flow boundary layer can grow freely in one direction. Examples include the flows over airfoils, ship hulls, turbine blades, etc.



•Fluid particle adjacent to the solid surface is at rest

•These particles act to retard the motion of adjoining layers

•⇒ **boundary layer effect**

Momentum balance: inertia forces, pressure gradient, viscous forces, body forces

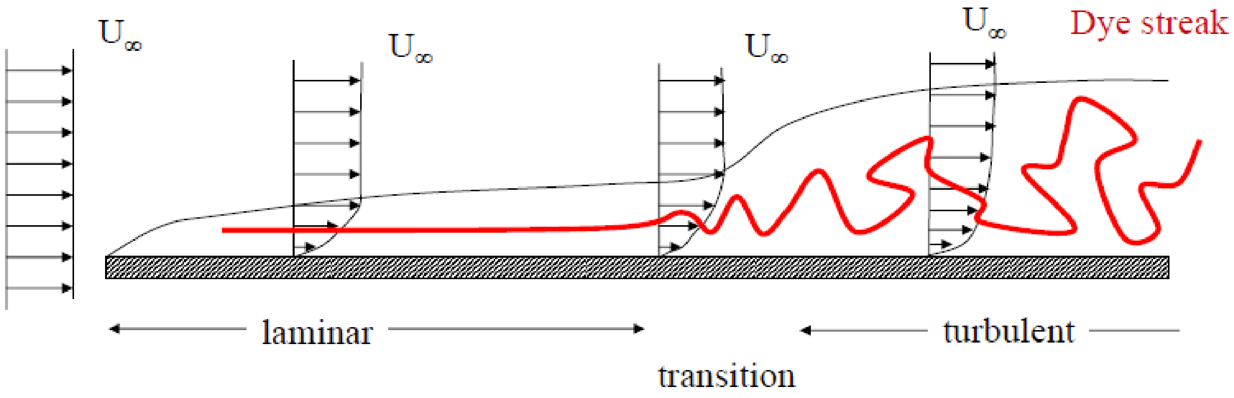
Energy balance: convective flux, diffusive flux, heat generation, energy storage

h=f(Fluid, Vel ,Distance,Temp)

5-

Hydrodynamic boundary layer

One of the most important concepts in understanding the external flows is the boundary layer development. For simplicity, we are going to analyze a boundary layer flow over a flat plate with no curvature and no external pressure variation.



Boundary layer definition

- Boundary layer thickness (δ): defined as the distance away from the surface where the local velocity reaches to 99% of the free-stream velocity, that is $u(y=\delta)=0.99U_\infty$. Somewhat an easy to understand but arbitrary definition.
- Boundary layer is usually very thin: δ/x usually $\ll 1$.

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Hydrodynamic and Thermal boundary layers

As we have seen earlier,the hydrodynamic boundary layer is a region of a fluid flow, near a solid surface, where the flow patterns are directly influenced by viscous drag from the surface wall.

$$0<u<U, \quad 0<y<\delta$$

The Thermal Boundary Layer is a region of a fluid flow, near a solid surface, where the fluid temperatures are directly influenced by heating or cooling from the surface wall.

$$0<t<T, \quad 0<y<\delta_t$$

The two boundary layers may be expected to have similar characteristics but do not normally coincide. Liquid metals tend to conduct heat from the wall easily and temperature changes are observed well outside the dynamic boundary layer. Other materials tend to show velocity changes well outside the thermal layer.

7-

Effects of Prandtl number, Pr

Pr >>1

ν >> α

e.g., oils

Pr = 1

ν = α

e.g., air and gases have Pr ~ 1

(0.7 - 0.9)

$$\frac{u}{U_\infty} \text{ similar to } \frac{T - T_W}{T_\infty - T_W}$$

(Reynold's analogy)

Pr <<1

ν << α

e.g., liquid metals