ME265: Thermal Engineering & Heat Transfer

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4.3 Convection Heat transfer

❑ Objectives

- Understanding the physical mechanism of convection, and its classification
- Gaining knowledge of the relevant dimensionless numbers: **Nu**, **Re**, **Pr, etc.**
- Reviewing characteristics of fluid flows
- Deriving the governing equations: **Continuity**, **Momentum** and **Energy equations** for forced convection.
- Solving governing equations for laminar flow over a flat plate: **velocity profile, temp profile, boundary layer thicknesses, frictions coefficient, etc.**
- Determining convection coefficient (*h*) from the knowledge of **drag measurement** and also by using **empirical relations**

4.3 Convection Heat transfer

3.1.2 Convection Mechanism

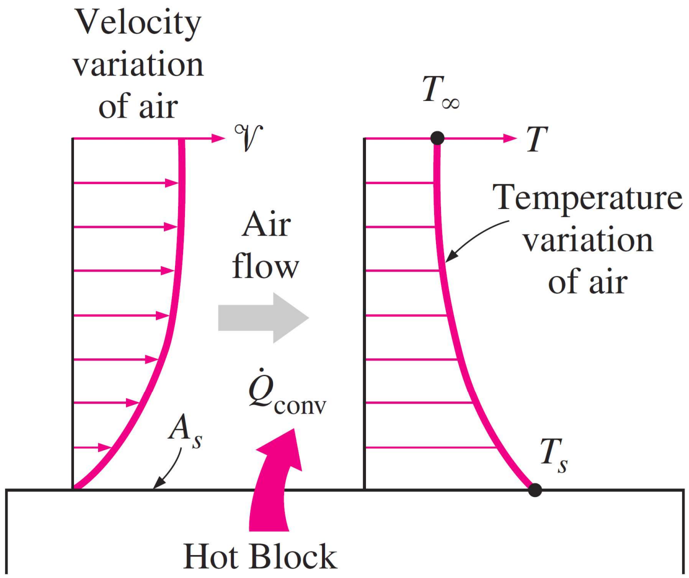

Fig. 3.1: Velocity and temp profile over a hot plate

Convection → diffusion of heat due to bulk motion of particles of a fluid

- It involves the combined effects of conduction and advection (fluid motion).
- The faster the fluid motion, the greater the convection heat transfer.

Newton's Law of Cooling and Fourier's Law of Heat Conduction:

$$\dot{Q}_{cond} = \dot{Q}_{conv}$$

$$\Rightarrow -k_{fluid}\, A\, \frac{\partial T}{\partial y}\bigg|_{y=0} = h\, A\, (T_s - T_\propto) \Rightarrow h = \frac{-k_{fluid}\, (\partial T/\partial y)_{y=0}}{(T_s - T_\propto)} \quad \dots\dots\ (3.1)$$

h is the convection HT coefficient

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Convection HT coefficient, h:

$$\boldsymbol{h} = \frac{-k_{fluid}\,(\partial T/\partial y)_{y=0}}{(T_s - T_\propto)} \quad \text{…… (3.1)}$$

- It is an experimentally determined parameter depending on—
  - surface geometry,
  - nature of fluid motion: Free/Forced,
  - properties of the fluid: k, ρ, c, μ
  - bulk fluid velocity: V

Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

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❑ Dimensionless Numbers

For Forced Convection:

$$Nu = f(Re, Pr) \qquad \dots \dots (3.2)$$

Nu ➔ Nusselt Number
Re ➔ Reynolds Number
Pr ➔ Prandtl Number

For Free/Natural Convection:

$$Nu = f(Gr, Pr) = f(Ra) \qquad \dots \dots (3.3)$$

Gr ➔ Grashof Number ➔ ratio of buoyancy force to viscous force
Ra ➔ Rayleigh Number=Gr.Pr

4.3 Convection Heat transfer

Dimensionless Numbers

❑ Nusselt Number, Nu

It is the dimensionless temperature gradient at the surface. It is a measure of convection heat transfer coefficient.

$$Nu = \frac{Convection\ flux}{Conduction\ flux} = \frac{hL_c}{k} \qquad \ldots\ldots (3.4)$$

where k is the thermal conductivity of the **fluid**, and
L_c is the characteristic length

In Transient Conduction, the dimensionless number, Biot Number, is used as defined as :

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

Here, k is the thermal conductivity of the **solid**

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Dimensionless Numbers

❑ Reynolds Number, Re

- ➢ It is the dimensionless number defined as:

$$Re = \frac{Inertia\ force}{Viscous\ force} = \frac{\rho V L_c}{\mu} = \frac{V L_c}{\nu} \qquad \text{…… (3.5)}$$

where V is the fluid velocity
ρ is the density of fluid
μ is the dynamic viscosity of fluid
L_c is the characteristic length, and
$\nu = \mu/\rho$ is the kinematic viscosity

- ➢ It characterizes forced convection flows and determines a flow to be laminar and turbulent

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Dimensionless Numbers

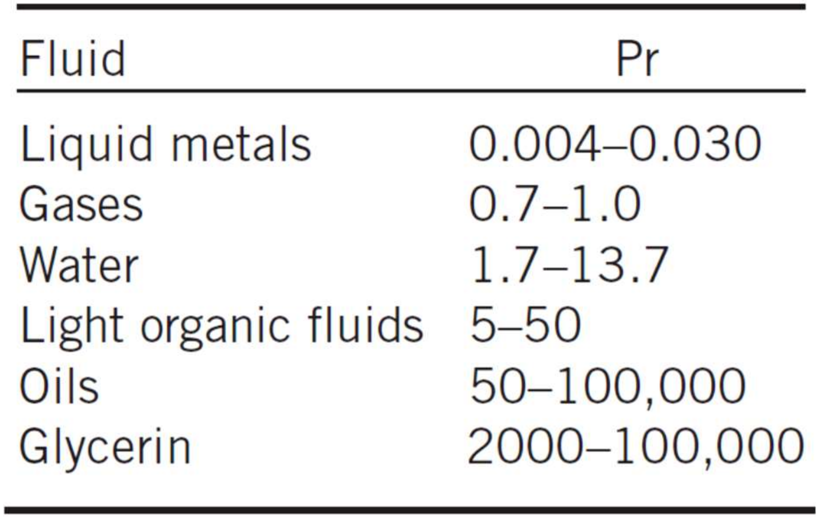
☐ Prandtl Number, Pr

- It is the dimensionless number that depends on fluid properties only:

$$Pr = \frac{Diffusivity\ of\ momentum}{Diffusivity\ of\ heat} = \frac{\nu}{\alpha} = \frac{\mu/\rho}{k/\rho c_p}$$

$$Pr = \frac{\mu c_p}{k} \qquad \text{… … (3.6)}$$

where k is the conductivity of fluid
ρ is the density of fluid, and
μ is the viscosity of fluid

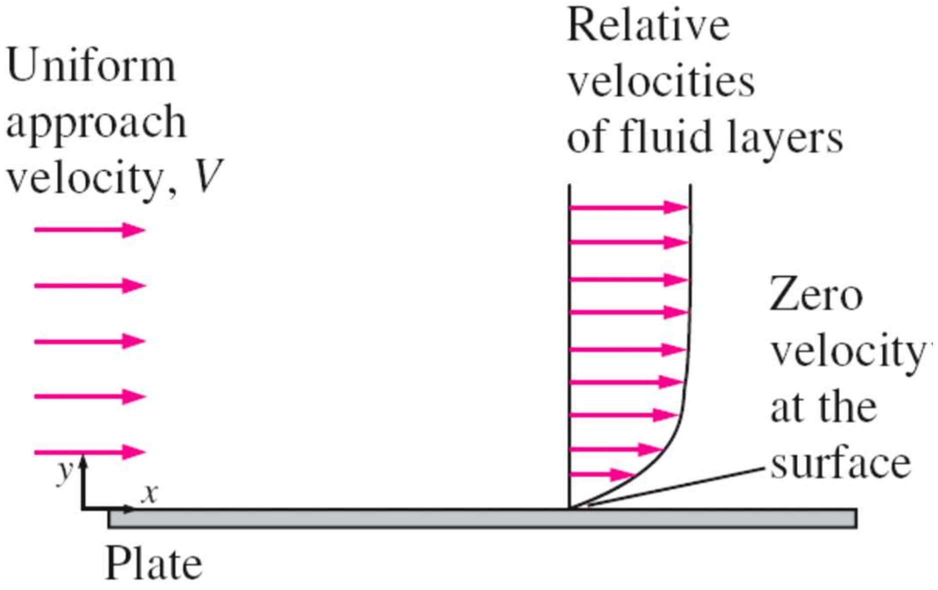


Fluid	Pr
Liquid metals	0.004–0.030
Gases	0.7–1.0
Water	1.7–13.7
Light organic fluids	5–50
Oils	50–100,000
Glycerin	2000–100,000

4.3 Convection Heat transfer

☐ Characteristics of fluid flows

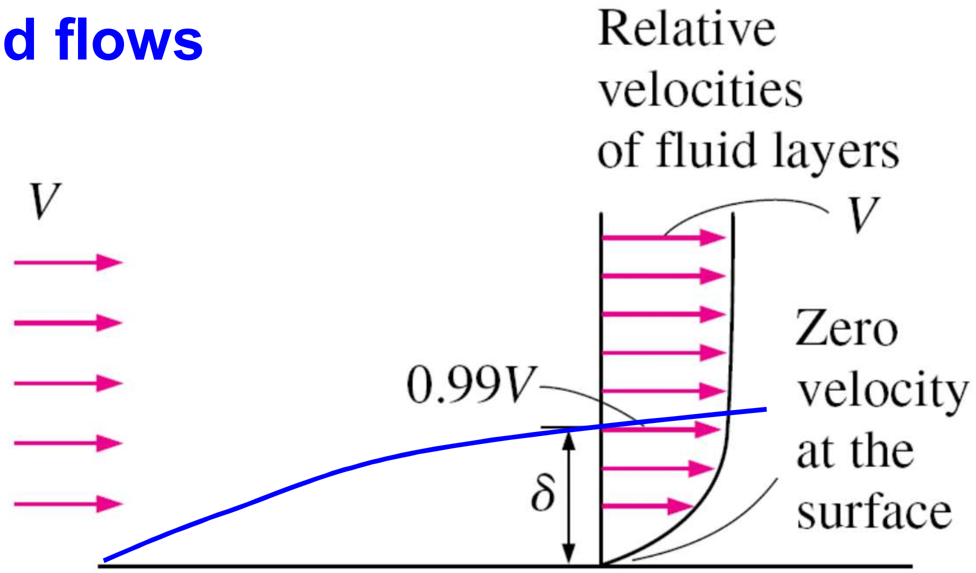
- **Experimental observations**:
  - – Fluid in motion comes to a complete stop at the surface
  - – It has a zero velocity relative to the surface (**no-slip condition**).



- The motionless layer adjacent to the surface slows down the neighboring fluid layer as a result of friction and causes the development of the velocity profile.

4.3 Convection Heat transfer

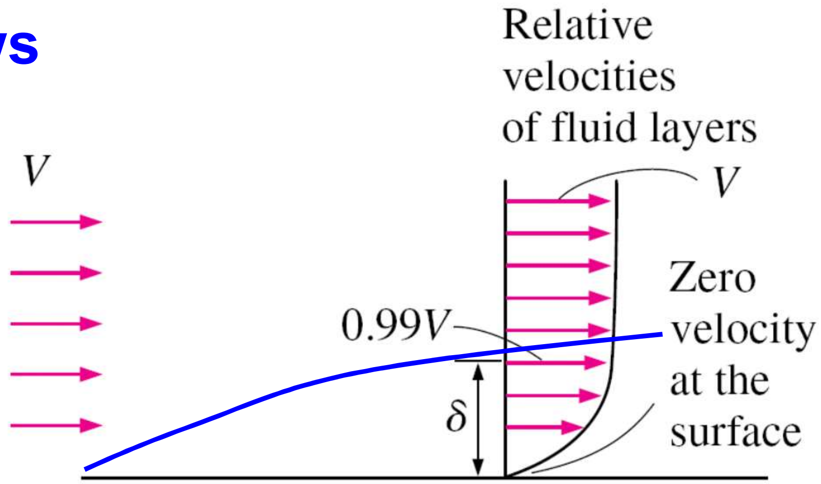
❑ Characteristics of fluid flows



- The flow region adjacent to the wall in which the viscous effects (and thus the velocity gradients) are significant is called the **velocity boundary layer.**
- The fluid velocity, *u,* varies from 0 at *y*=0 to nearly *V* at *y*=δ.
- δ is typically defined as the distance *y* from the surface at which *u*=0.99*V*.
- **This δ is called boundary layer thickness**

4.3 Convection Heat transfer

❑ Characteristics of fluid flows



- The fluid layer in contact with the surface tries to drag the plate exerting a ***friction force*** on it.

- Friction force per unit area is the **shear stress (τ).** Experiments indicate that the shear stress for most fluids is proportional to the velocity gradient.
- **Newton's Law of viscosity**: $\tau_s = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0}$ **… … (3.7)**

- The fluids that follow this linear relationship are called **Newtonian fluids.**

4.3 Convection Heat transfer

❑ Characteristics of fluid flows

- In many cases the flow velocity profile is unknown and the surface shear stress τ_s can not be obtained.
- A more practical approach in external flow is to relate τ_s to the upstream velocity *V* as

$$\boxed{\tau_s = C_f \frac{\rho V^2}{2}} \qquad \text{…… (3.8)}$$

Where, C_f is the dimensionless **friction coefficient** (most cases it is determined experimentally)

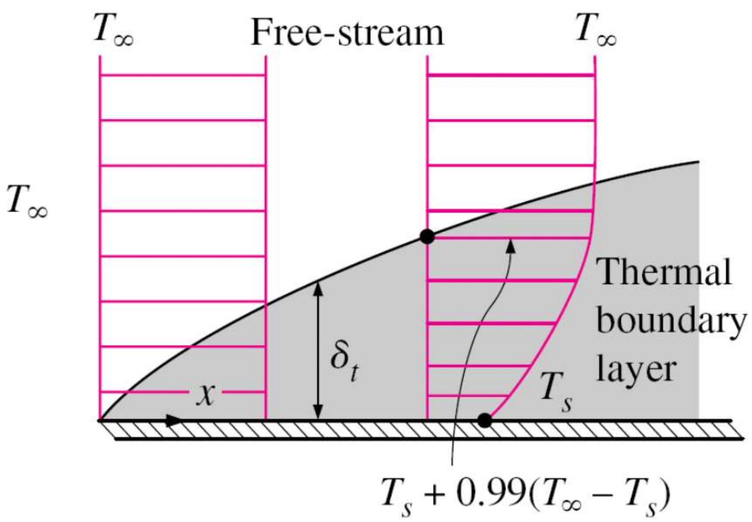
- The friction force over the entire surface is determined from

$$F_f = C_f A_s \frac{\rho V^2}{2} \qquad \text{…… (3.9)}$$

4.3 Convection Heat transfer

❑ Characteristics of fluid flows

- In flow over a heated (or cooled) surface, both **velocity and thermal boundary layers** develop simultaneously.



- δ_t is the **thermal boundary layer thickness,** where fluid temperature reaches 99% of the difference between free stream and surface temperatures.
- **Prandtl number, Pr** determines the relative thicknesses of velocity and thermal boundary layers.

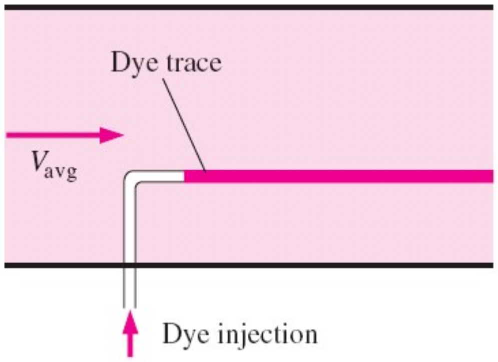
➢ Heat diffuses very quickly in liquid metals (Pr<<1) and very slowly in oils (Pr>>1) relative to momentum.

➢ Consequently, the thermal boundary layer is much thicker for liquid metals and much thinner for oils relative to the velocity boundary layer.

4.3 Convection Heat transfer

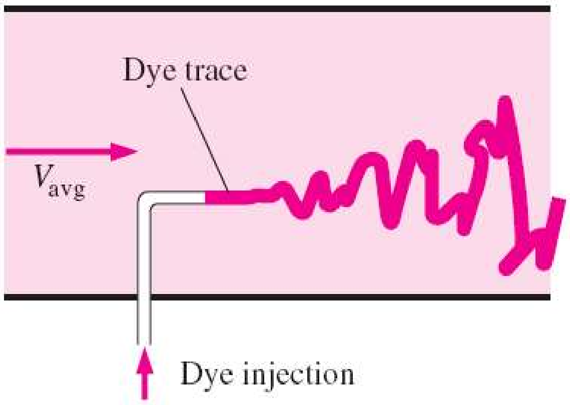
❑ Characteristics of fluid flows

- **Laminar flow and Turbulent flow**



(*a*) Laminar flow

Laminar flow— the flow is characterized by *smooth streamlines* and *highly-ordered motion.*



(*b*) Turbulent flow

Turbulent flow — the flow is characterized by *velocity fluctuations* and *highly-disordered motion*

The *intense mixing* in turbulent flow enhances heat and momentum transfer, which increases the friction force on the surface and the convection heat transfer rate.

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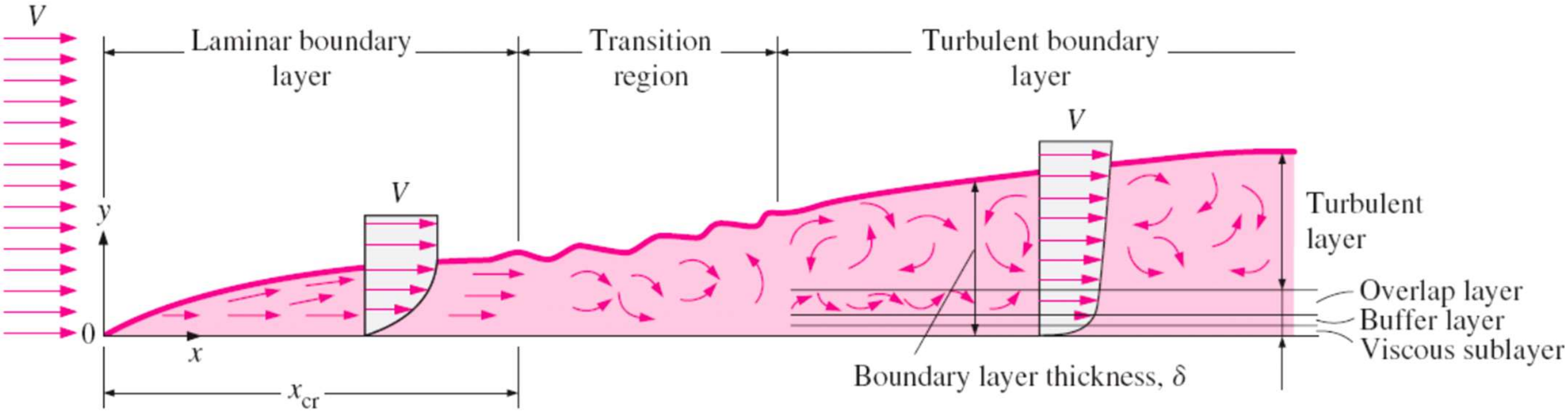
❑ Characteristics of fluid flows

- **Boundary layer over a flat plate**



The turbulent wall shear stress and turbulent heat transfer

$$\tau_{turb} = -\rho\overline{u'v'} = \mu_t \frac{\partial \bar{u}}{\partial y} \quad ; \quad \dot{q}_{turb} = \rho c_p \overline{vT} = -k_t \frac{\partial T}{\partial y} \qquad \dots\dots (3.10)$$

where, μ_t ─ turbulent (or eddy) viscosity

k_t ─ turbulent (or eddy) thermal conductivity

4.3 Convection Heat transfer

❑ Governing Equations for forced convection

- ❑ Continuity Equation:
  Conservation of Mass
- ❑ Momentum Equation:
  Conservation of Momentum
- ❑ Energy Equation:
  Conservation of Energy