# HEAT TRANSFER BY CONVECTION

**CONDUCTION**

Mechanism of heat transfer through a solid or fluid in the absence any fluid motion.

**CONVECTION**

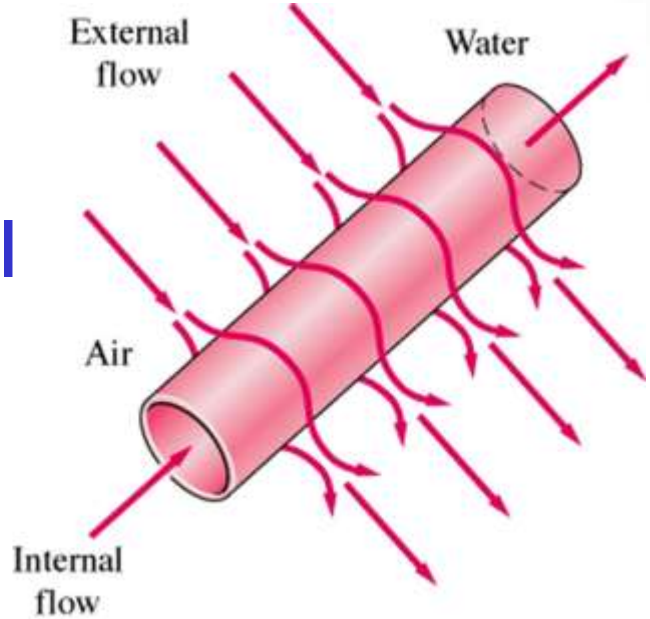
Mechanism of heat transfer through a fluid in the presence of bulk fluid motion

- **Natural (free) Convection**
- **Forced Convection**

(depending on how the fluid motion is initiated)

# CLASSIFICATION OF FLUID FLOWS

- Viscous-inviscid
- Internal flow-External flow
- Open-closed channel
- Compressible-Incompressible
- Laminar-Turbulent
- Natural- Forced
- Steady- Unsteady
- One-,two-,three-dimensional



# VISCOSITY

When two fluid layers move relative to each other, a friction force develops between them and the slower layer tries to slow down the faster layer.

**internal resistance to flow**

- cohesive forces between the molecules in liquid
- molecular collisions in gases.

**Viscous flows**: viscous effects are significant

**Inviscid flow regions**: viscous forces are negligibly small compared to inertial or pressure forces.

→ measure of stickness or resistance to deformation

1. **Kinematic viscosity**
2. **Dynamic viscosity**

# VISCOSITY DEPENDS ON

- **TEMPERATURE**
- **PRESSURE**

For liquids dependence of pressure is negligible

For gases kinematic viscosity depends on pressure since its relation to density

Air at 20°C and 1 atm:

$$\mu = 1.83 \times 10^{-5}\ \mathrm{kg/m \cdot s}$$
$$\upsilon = 1.52 \times 10^{-5}\ \mathrm{m^2/s}$$

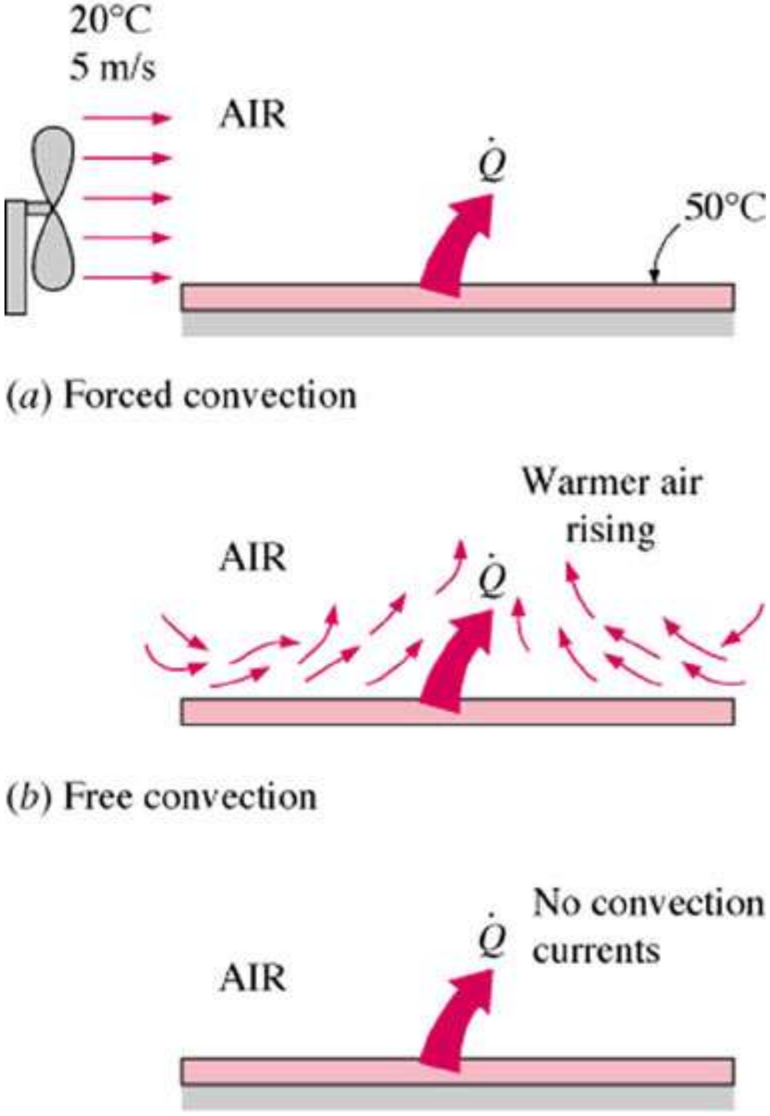
Air at 20°C and 4 atm:

$$\mu = 1.83 \times 10^{-5}\ \mathrm{kg/m \cdot s}$$
$$\upsilon = 0.380 \times 10^{-5}\ \mathrm{m^2/s}$$

$\mu$ Dynamic viscosity (kg/m.s or poise)

$$\nu = \frac{\mu}{\rho}$$

$\nu$ Kinematic viscosity, $m^2/s$ or stroke




(*a*) Forced convection

(*b*) Free convection

(*c*) Conduction

Convection heat transfer

- Dynamic viscosity
- Thermal conductivity
- Density
- Specific heat
- Fluid velocity
- Geometry
- Roughness
- Type of fluid flow

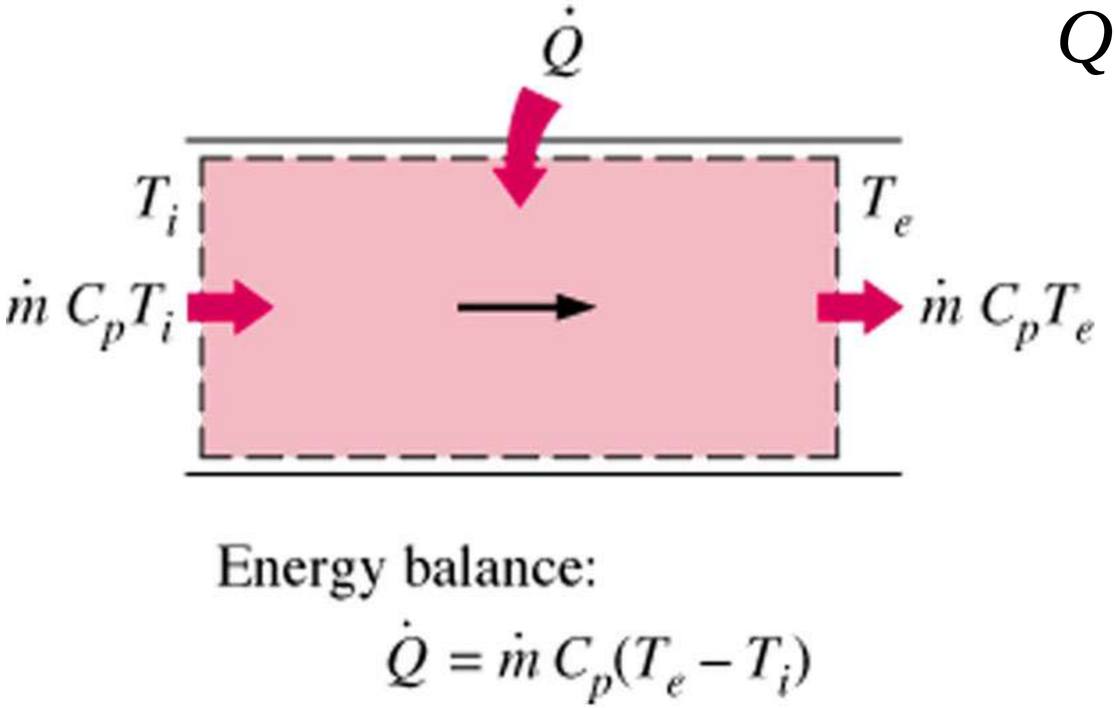
# NEWTON'S LAW OF COOLING

$$\dot{Q}_{conv} = hA_S(T_S - T_\infty) \quad \text{(W)}$$

$h$ Convection heat transfer coefficient (W/m$^2$.$^0$C)

The rate of heat transfer between a solid surface and a fluid per unit surface area per unit temperature difference

# GENERAL THERMAL ANALYSIS




$$\dot{Q}_{conv} = hA_S(T_S - T_\infty)$$

$$\dot{Q} = \dot{m}\, C_p(T_e - T_i)$$

# FORCED CONVECTION

- **LAMINAR FLOW**

Smooth streamlines

Highly- ordered motion

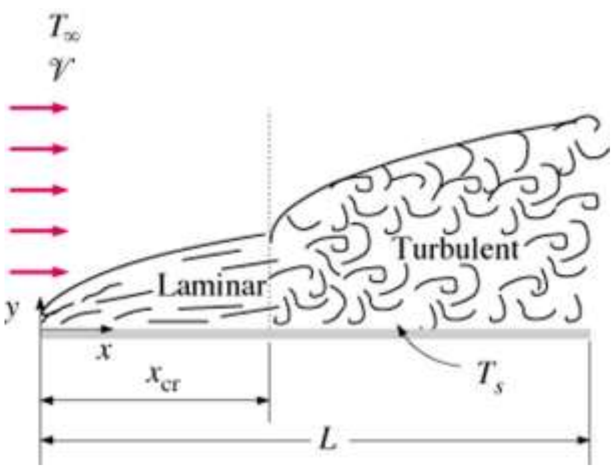
(highly viscous fluids in small pipes)

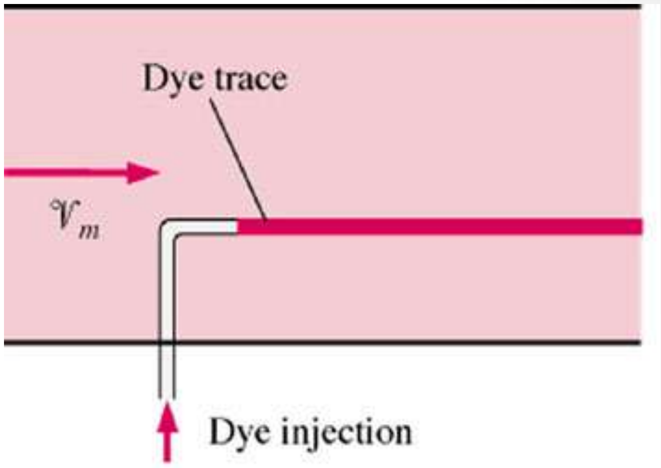
- **TURBULENT FLOW**

Velocity fluctuations

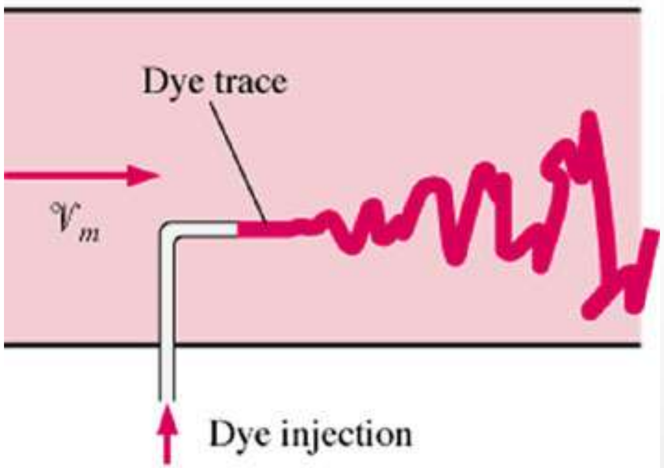
Highly-disordered motion

- **TRANSITIONAL FLOW**




(*a*) Laminar flow




(*b*) Turbulent flow

# REYNOLDS NUMBER

Flow Regime:

Geometry

Surface roughness

Flow velocity

Surface temperature

type of fluid

Ratio of the inertial forces to viscous forces in the fluid

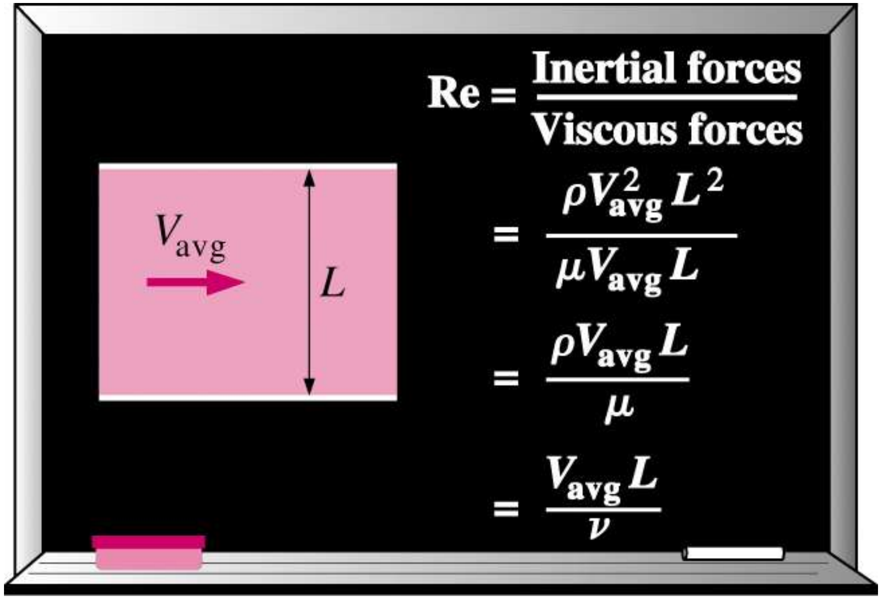
$$\mathrm{Re} = \frac{\upsilon_m D}{v} = \frac{\rho \upsilon_m D}{\mu}$$

$\upsilon_m$ Mean flow velocity

$D$ Characteristic length of the geometry

$v = \mu / \rho$ Kinematic viscosity

Definition of Reynolds number




- Critical Reynolds number ($Re_{cr}$) for flow in a round pipe

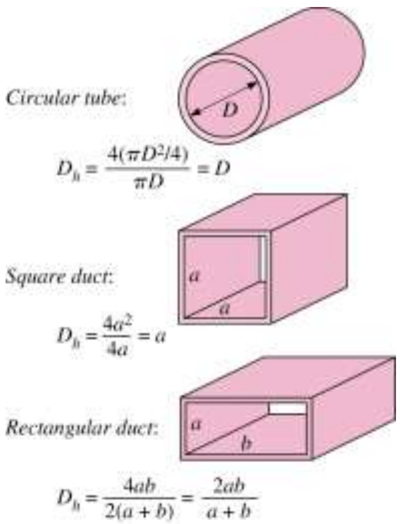
  $Re < 2300 \Rightarrow$ laminar

  $2300 \le Re \le 4000 \Rightarrow$ transitional

  $Re > 4000 \Rightarrow$ turbulent

- Note that these values are approximate.
- For a given application, $Re_{cr}$ depends upon
  - Pipe roughness
  - Vibrations
  - Upstream fluctuations, disturbances (valves, elbows, etc. that may disturb the flow)

# HYDRAULIC DIAMETER



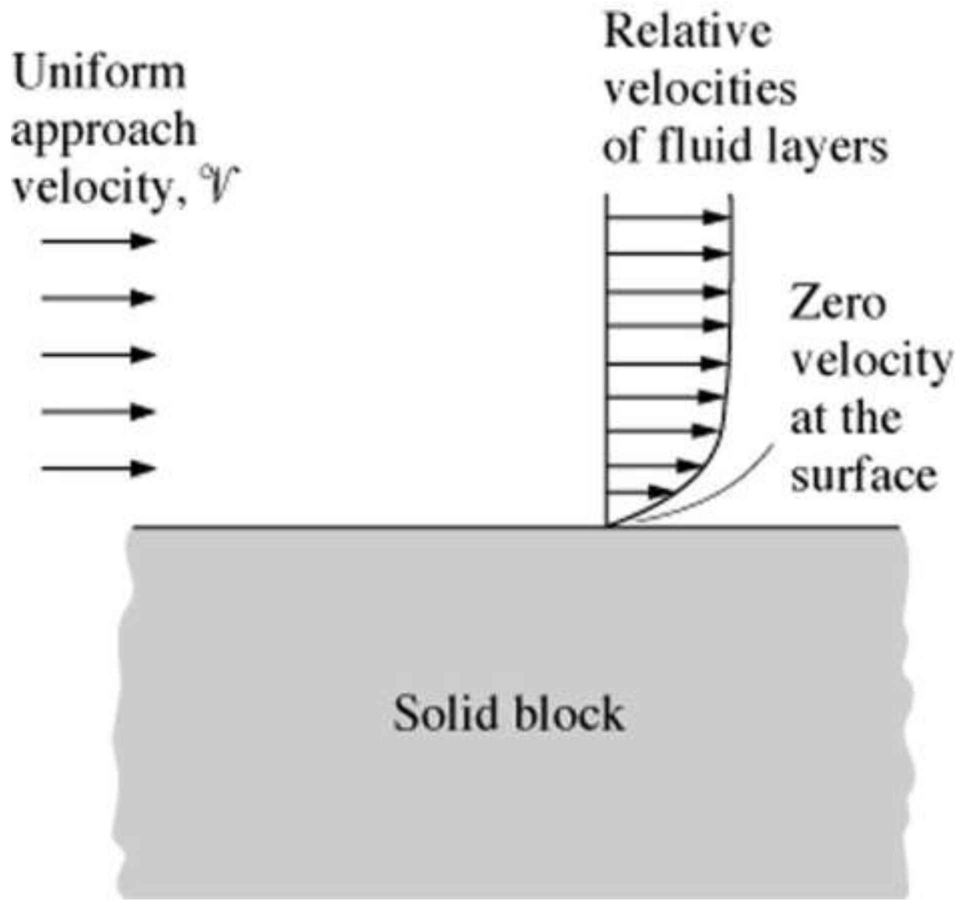

- For non-round pipes,
- the hydraulic diameter $D_h = 4A_c/P$

  $A_c$ = cross-section area

  $P$ = wetted perimeter

Velocity

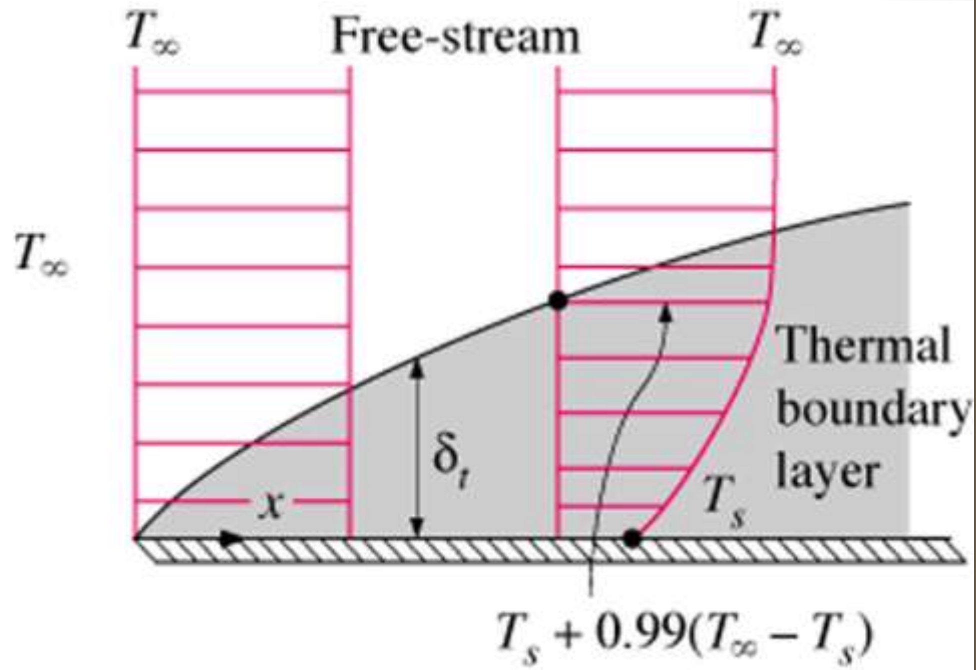
**No-slip condition**



# THERMAL BOUNDARY LAYER

Flow region over the surface in which the temperature variation in the direction normal to the surface

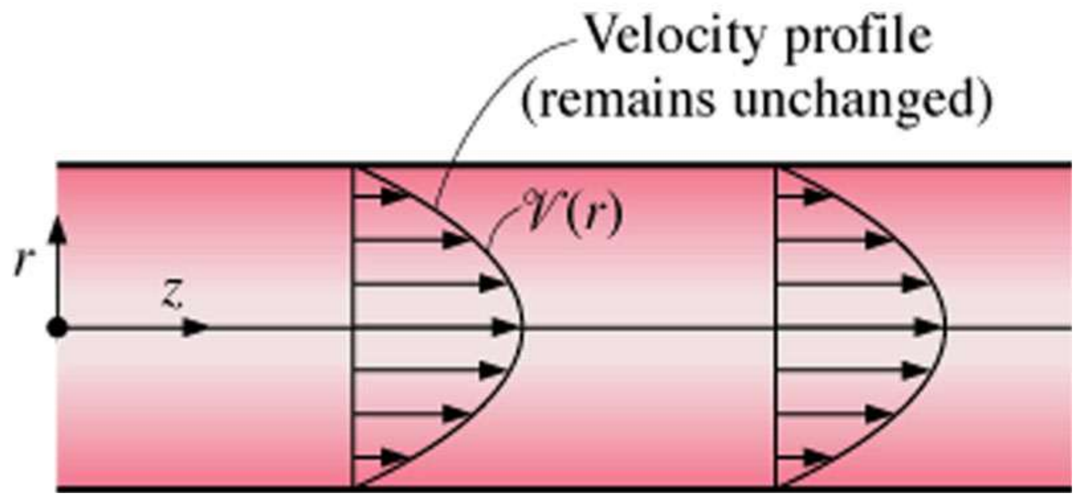
Velocity profile influences temperature profile



# VELOCITY

A flow field is best characterized by the velocity distribution, and velocity may vary in three dimension

$\vec{\upsilon}(x, y, z)$ in rectangular $\vec{\upsilon}(r, \theta, z)$ in cylinderical coordinates



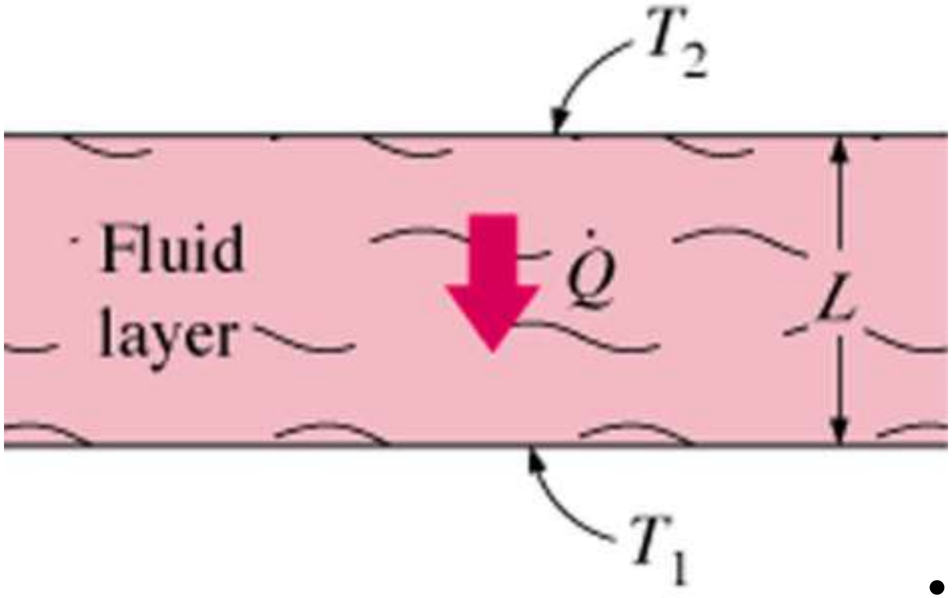

One dimensional flow in a circular pipe

In which direction does the velocity change in this figure???

# NUSSELT NUMBER

(Dimensionless number)

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




$$\dot{q}_{cond} = k\frac{\Delta T}{L}$$

$$\dot{q}_{conv} = h\Delta T$$

$$\Delta T = T_2 - T_1$$

$$\frac{\dot{q}_{conv}}{\dot{q}_{cond}} = \frac{h\Delta T}{k\Delta T / L} = \frac{hL}{k} = Nu$$

# PRANDTL NUMBER

- Boundary layer theory

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

$$\Pr = \frac{molecular \quad diffusivity \quad of \quad momentum}{molecular \quad diffusivity \quad of \quad heat} = \frac{\nu}{\alpha} = \frac{\mu C_p}{k}$$

Pr<<1 heat diffuses very quickly in liquid metals, *tbl* thicker

Pr>>1 heat diffuses very slowly in oils relative to momentum, *tbl* thinner than *vbl*

# PARALLEL FLOW OVER FLAT PLATES

$$\text{Re}_{cr} = \frac{\rho \upsilon\, x_{cr}}{\mu} = 5 \times 10^5$$

$$Nu = \frac{hL}{k} = 0.664 \;\; \text{Re}_L^{0.5} \, \text{Pr}^{1/3}$$ $\text{Re}_L < 5 \times 10^5$ laminar

$$Nu = \frac{hL}{k} = 0.037 \;\; \text{Re}_L^{0.8} \, \text{Pr}^{1/3}$$ $0.6 \le \text{Pr} \le 60$ turbulent

$5 \times 10^5 \le \text{Re}_L \le 10^7$

# NATURAL CONVECTION

# CONVECTIVE HEAT TRANSFER COEFFICIENT

Coefficient of volume expansion

Grashof number

$$Gr_L = \frac{g\beta(T_s - T_\infty)L_C^3}{\upsilon^2}$$

viscosity

Rayleigh number

$$Ra_L = Gr_L \Pr$$

Prandtl number

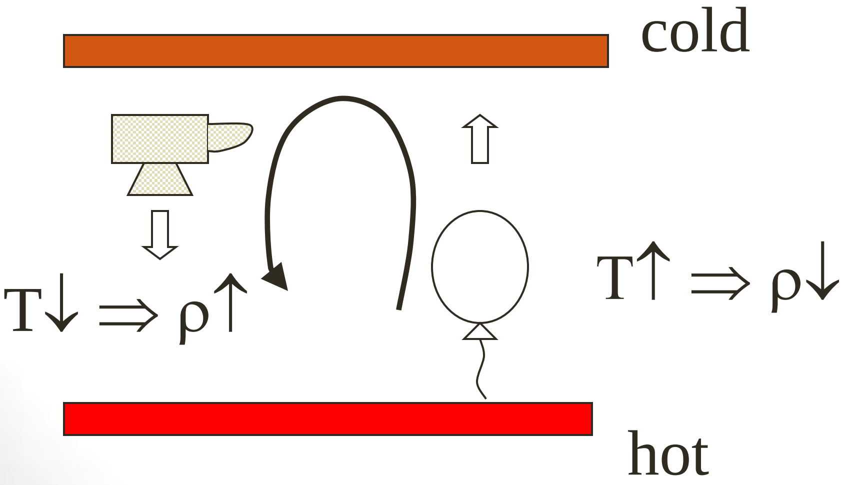
Nusselt number

$$Nu = \frac{hL_C}{k} = CRa_L^n$$

Table 20-1

# Free Convection

A free convection flow field is a self-sustained flow driven by the presence of a temperature gradient. (As opposed to a forced convection flow where external means are used to provide the flow.) As a result of the temperature difference, the density field is not uniform also. Buoyancy will induce a flow current due to the gravitational field and the variation in the density field. In general, a free convection heat transfer is usually much smaller compared to a forced convection heat transfer. It is therefore important only when there is no external flow exists.

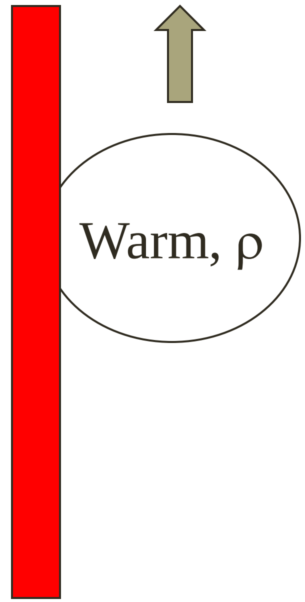



Flow is unstable and a circulatory pattern will be induced.

# Basic Definitions

Buoyancy effect:

Hot plate




Surrounding fluid, cold, $\rho_\infty$

Net force=$(\rho_\infty - \rho)gV$

The density difference is due to the temperature difference and it can be characterized by ther volumetric thermal expansion coefficient, β:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \approx -\frac{1}{\rho}\frac{\rho_\infty - \rho}{T_\infty - T} = -\frac{1}{\rho}\frac{\Delta\rho}{\Delta T}$$

$$\Delta\rho \approx \beta\Delta T$$

# Grashof Number and Rayleigh Number

Define Grashof number, Gr, as the ratio between the buoyancy force and the viscous force:

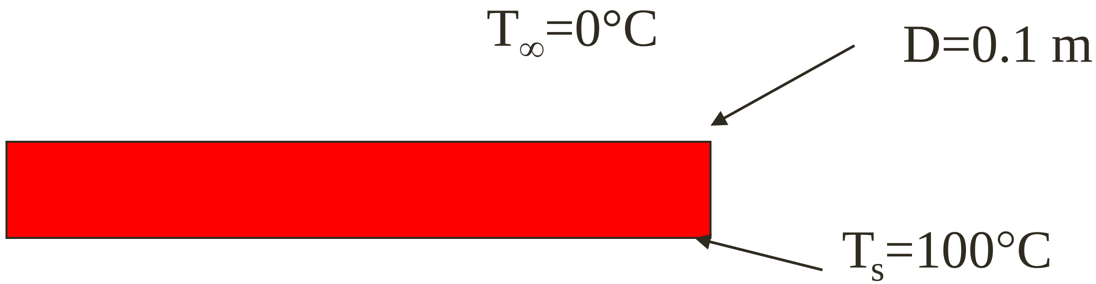
$$Gr = \frac{g\beta\Delta T L^3}{\nu^2} = \frac{g\beta(T_S - T_\infty)L^3}{\nu^2}$$

- Grashof number replaces the Reynolds number in the convection correlation equation. In free convection, buoyancy driven flow sometimes dominates the flow inertia, therefore, the Nusselt number is a function of the Grashof number and the Prandtle number alone. Nu=f(Gr, Pr). Reynolds number will be important if there is an external flow. (see chapter 11.5, combined forced and free convection.

- In many instances, it is better to combine the Grashof number and the Prandtle number to define a new parameter, the Rayleigh number, Ra=GrPr. The most important use of the Rayleigh number is to characterize the laminar to turbulence transition of a free convection boundary layer flow. For example, when $Ra>10^9$, the vertical free convection boundary layer flow over a flat plate becomes turbulent.

# Example

Determine the rate of heat loss from a heated pipe as a result of natural (free) convection.




Film temperature( $T_f$): averaged boundary layer temperature $T_f=1/2(T_s+T_\infty)=50$ °C.

$k_f=0.03$ W/m.K, Pr=0.7, $\nu=2\times10^{-5}$ m$^2$/s, $\beta=1/T_f=1/(273+50)=0.0031$(1/K)

$$Ra=\frac{g\beta(T_S-T_\infty)L^3}{\nu^2}\Pr=\frac{(9.8)(0.0031)(100-0)(0.1)^3}{(2\times10^{-5})^2}(0.7)=7.6\times10^6.$$

$$Nu_D=\{0.6+\frac{0.387Ra^{1/6}}{[1+(0.559/\Pr)^{9/16}]^{8/27}}\}^2=26.0$$ (equation 11.15 in Table 11.1)

$$h=\frac{k_f}{D}Nu_D=\frac{0.03}{0.1}(26)=7.8(W/m^2K)$$

$$q=hA(T_S-T_\infty)=(7.8)(\pi)(0.1)(1)(100-0)=244.9(W)$$

Can be significant if the pipe are long.