ME265: Thermal Engineering & Heat Transfer

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2. Thermodynamics
3. Mechanical Devices & Systems
4. Heat Transfer

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4.3 **Convection**	**4.3.1 Convection Fundamentals** **4.3.2 External Forced Convection** **4.3.3 Internal Forced Convection** **4.3.4 Natural Convection**
4.4 Radiation	
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4.3.2 External Forced Convection

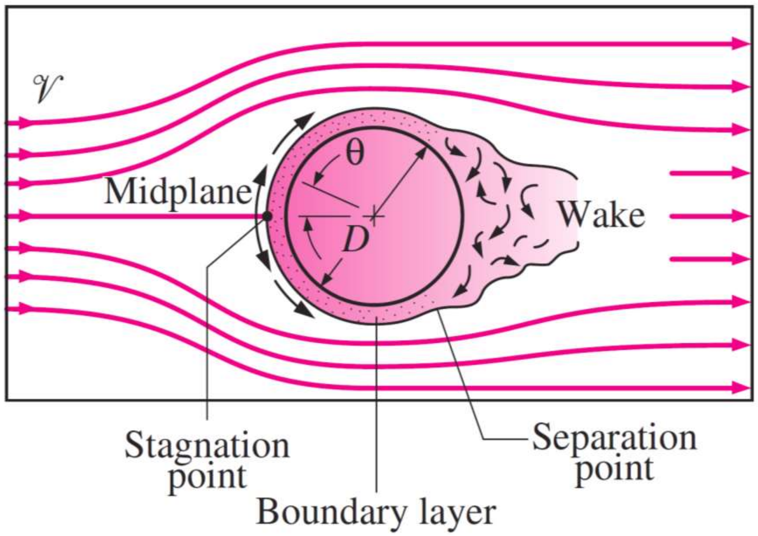
❖ Flow across Cylinders and Spheres

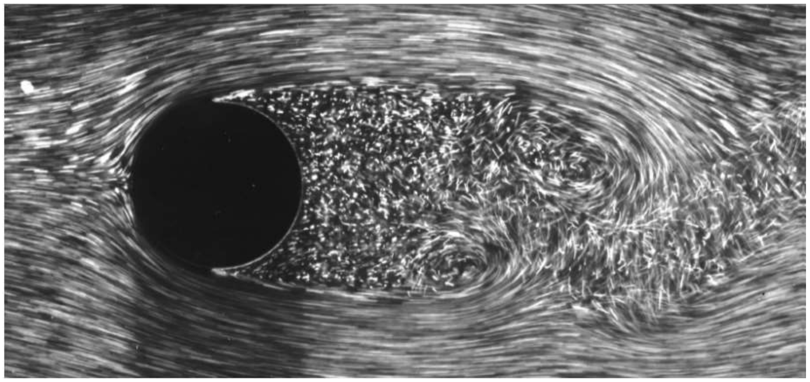
- Flow across cylinders and spheres is frequently encountered in practice.
  - ➢ The tubes in a shell-and-tube heat exchanger, involve both internal flow through the tubes and external flow over the tubes
  - ➢ many sports such as soccer, tennis, base ball, cricket and golf involve flow over spherical balls.
- The characteristic length for a circular cylinder or sphere is taken to be the *external diameter D*. $\boldsymbol{Re = \frac{V\,D}{\nu}}$
- The **critical** Reynolds is about $Re_{cr} = 2\times10^5$.
- The boundary layer remains laminar for about $Re < 2 \times 10^5$ and becomes turbulent for $Re \geq 2 \times 10^5$.

4.3.2 External Forced Convection

❖ Flow across Cylinders and Spheres

- The fluid approaching the cylinder branches out and encircles the cylinder, forming a boundary layer that wraps around the cylinder.
- The fluid particles on the midplane strike the cylinder at the stagnation point, bringing the fluid to a complete stop and thus raising the pressure at that point.



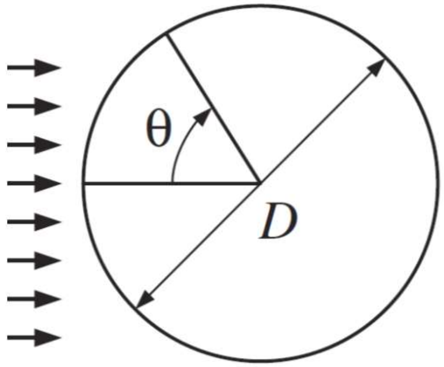


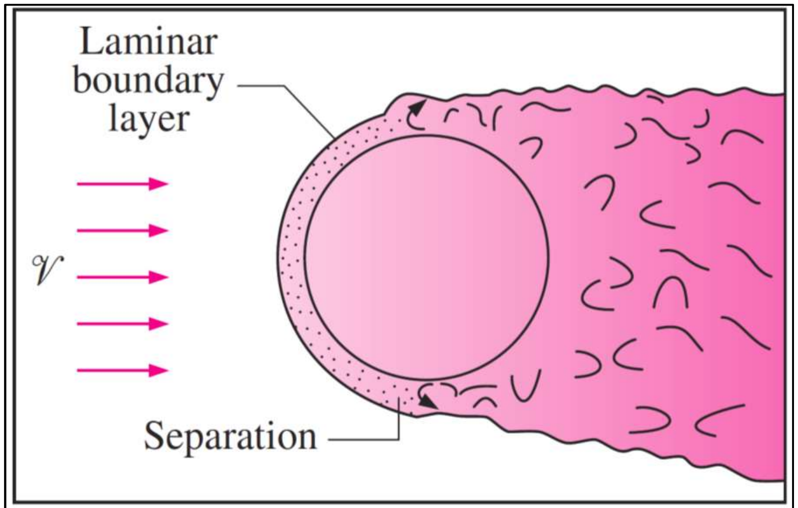
- At low Reynolds numbers (Re<10) ─ friction drag dominates.
- At high Reynolds numbers (Re>5000) ─ pressure drag dominates.

4.3.2 External Forced Convection

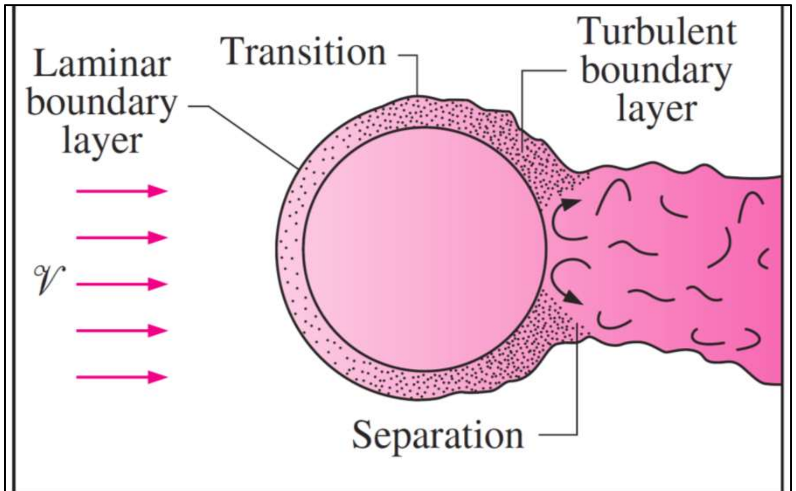
❖ Flow across Cylinders and Spheres

Flow separation occurs at about $\theta \approx 80°$ (measured from the stagnation point) when the boundary layer is *laminar* and at about $\theta \approx 140°$ when it is *turbulent*.





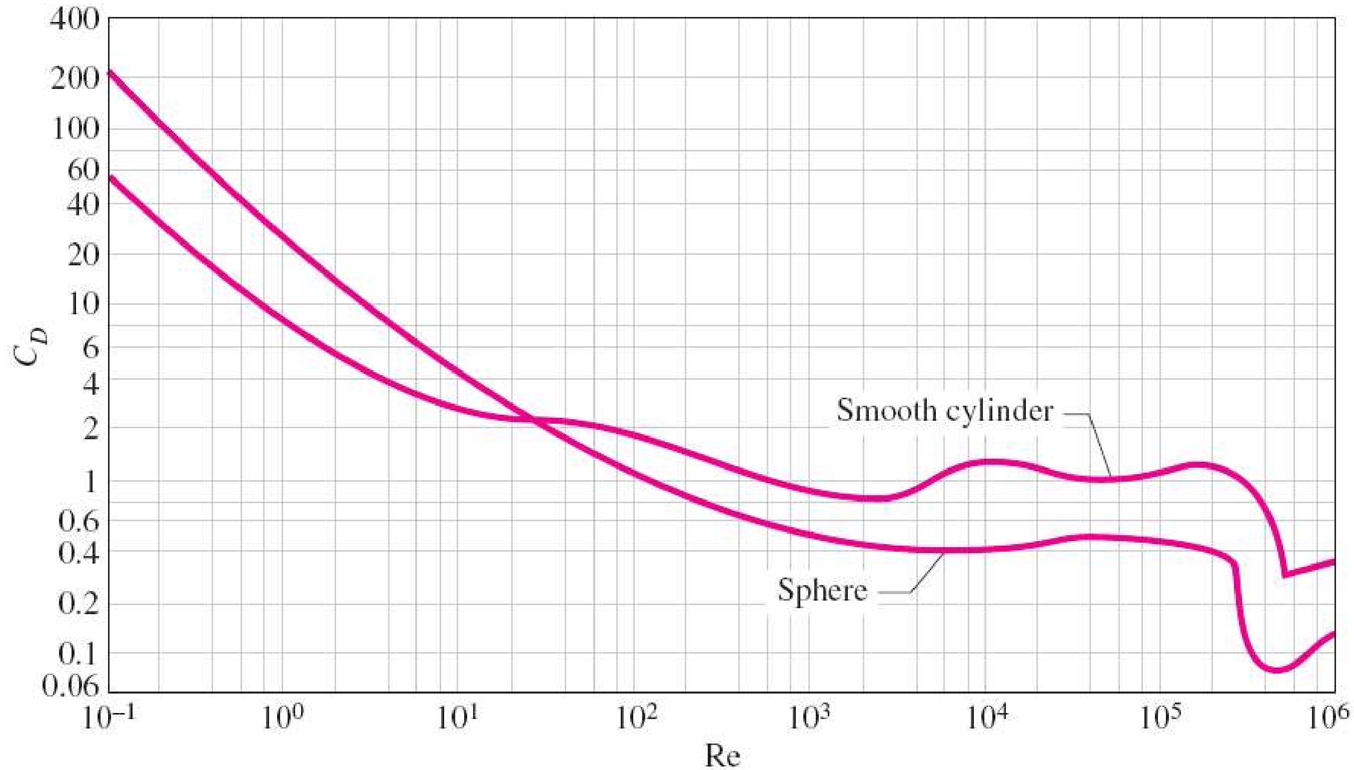
(a) Laminar flow ($\mathrm{Re} < 2 \times 10^5$)



(b) Turbulence occurs ($\mathrm{Re} > 2 \times 10^5$)

4.3.2 External Forced Convection

❖ Flow across Cylinders and Spheres



10^3<Re<10^5

-Laminar flow in the boundary layer

-Turbulent flow in the separated region

10^5<Re<10^6 — large reduction in C_D due to *turbulent flow* in the boundary layer.

Re≤1 — creeping flow, no separation

Re≈10 — separation starts rear of the body

Re≈10^3 — about 95 percent of drag is pressure drag

❖ Flow across Cylinders and Spheres

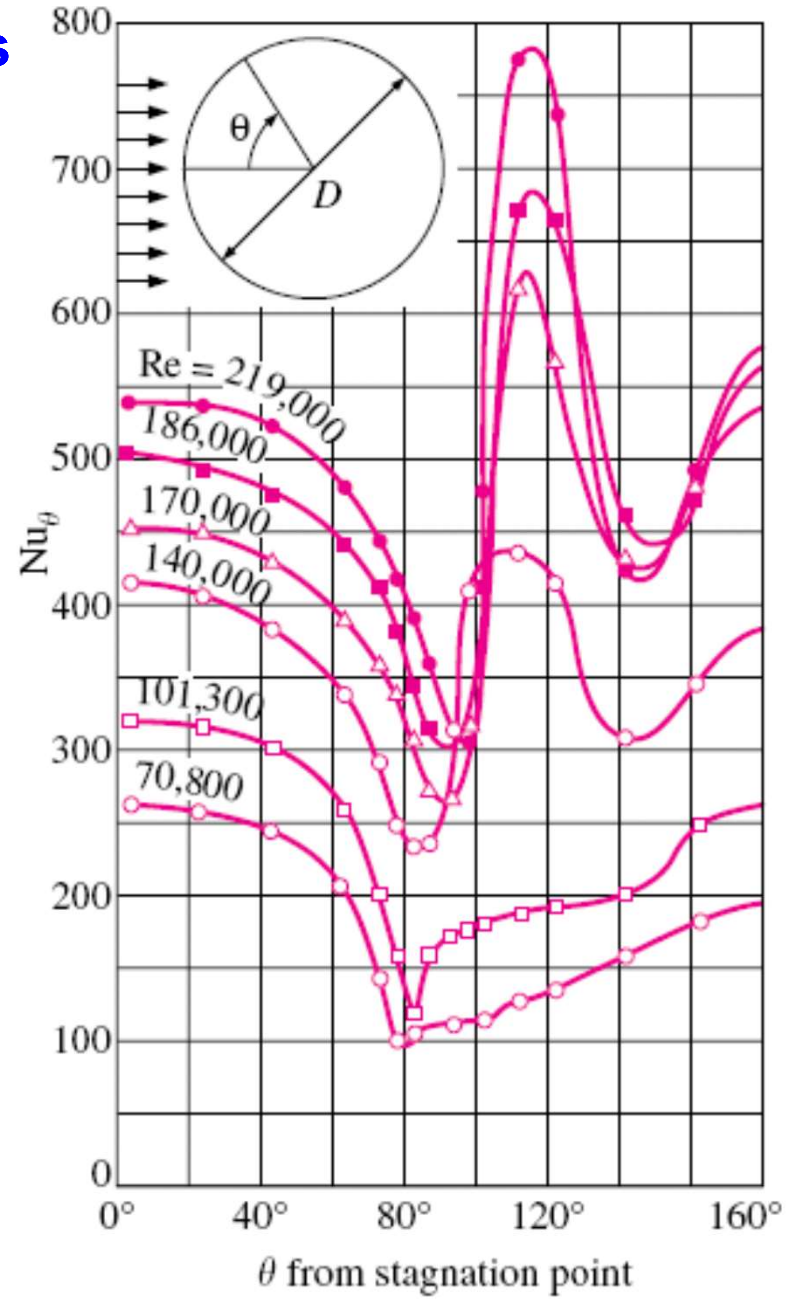
Small θ : Nu_θ decreases as a result of the thickening of the laminar boundary layer.

80º<θ <90º: u_θ reaches a minimum
- low Reynolds numbers ─ due to separation in laminar flow
- high Reynolds numbers ─ transition to turbulent flow.

θ **>90º laminar flow** ─ Nu_θ increases due to intense mixing in the separation zone.

90º<θ <140º turbulent flow ─ Nu_θ decreases due to the thickening of the boundary layer.

θ **≈140º turbulent flow** ─ Nu_θ reaches a second minimum due to flow separation point in turbulent flow.



4.3.2 External Forced Convection

❖ Flow across Cylinders and Spheres

❑ For flow over a cylinder (**Churchill and Bernstein**):

$$Nu_{cyl} = \frac{hD}{k} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right]^{4/5}$$

While, Re Pr > 0.2

The fluid properties are evaluated at the *film temperature*

Uncertainly: ±30%

❑ Flow over a *sphere* (**Whitaker**):

$$Nu_{sph} = \frac{hD}{k} = 2 + \left[0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3}\right]\mathrm{Pr}^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

$3.5 \le \mathrm{Re} \le 80{,}000$ and $0.7 \le \mathrm{Pr} \le 380$

The fluid properties in this case are evaluated at the free-stream temperature T_∞, except for μ_s, which is evaluated at the surface temperature T_s.

Uncertainly: ±30%

4.3.2 External Forced Convection

EP# 3.5

A long 10-cm-diameter steam pipe whose external surface temperature is 110°C passes through some open area that is not protected against the winds. Determine the rate of heat loss from the pipe per unit of its length when the air is at 1 atm pressure and 10°C and the wind is blowing across the pipe at a velocity of 8 m/s.

EP# 3.5 Solution

Assumptions

1. The flow is steady and incompressible.
2. Radiation effects are negligible.
3. Air is an ideal gas.

Properties at T_f=(110+10)/2=60^{o}C:

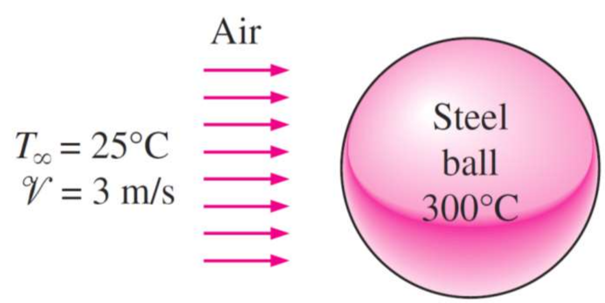
k = 0.02808 W/m.K
Pr =0.7202
ν = 1.896 x 10^{-5} m^2/s

Churchill-Bernstein Correlation:

$$Nu_{cyl} = \frac{hD}{k} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282,000}\right)^{5/8}\right]^{4/5}$$

EP# 3.6

A 25-cm-diameter stainless steel ball (ρ=8055 kg/m^3, c_p=480 J/kg°C) is removed from the oven at a uniform temperature of 300°C. The ball is then subjected to the flow of air at 1 atm pressure and 25°C with a velocity of 3 m/s. The surface temperature of the ball eventually drops to 200°C. Determine the average convection heat transfer coefficient during this cooling process and estimate how long the process will take.



EP# 3.6 Solution

Assumptions

1. The flow is steady and incompressible.
2. Radiation effects are negligible.
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Whitaker Correlation:

$$Nu_{sph} = \frac{hD}{k} = 2 + \left[0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3}\right]\mathrm{Pr}^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

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4.3.3 Internal Forced Convection

❑ Objectives:

(i) Review of Internal flows:

- **Average velocity** and **average temperature** from the knowledge of velocity and temperature profiles in internal flows
- Laminar and turbulent flows in tubes
- **Hydrodynamic and thermal boundary layers**
- Visual understanding of different **flow regions in internal flow**, such as the entry and fully developed flow regions

(ii) General Thermal Analysis:

- Analyze heating/cooling of a fluid flowing in a tube under **constant surface temperature** and **constant surface heat flux** conditions
- Work with the logarithmic mean temperature difference **(LMTD)**

(iii) Forced Convection in Tubes:

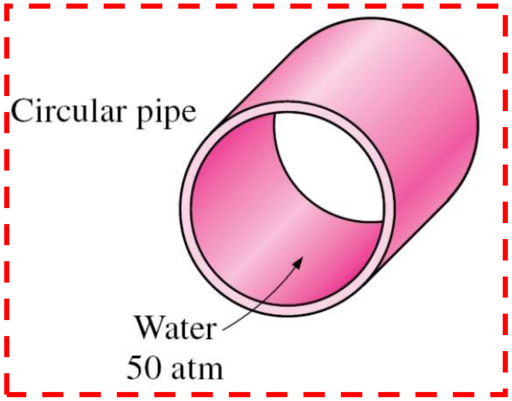
- Obtain analytic relations for **Nusselt number/heat transfer rate** in **fully developed laminar flow.**
- Use **empirical relations** to determine **Nusselt number/heat transfer rate** in the fully developed turbulent flow

4.3.3 Internal Forced Convection

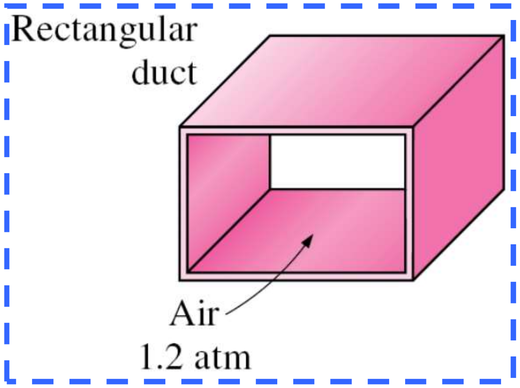
Internal flow fundamentals

❑ **Classification of flow channels:**

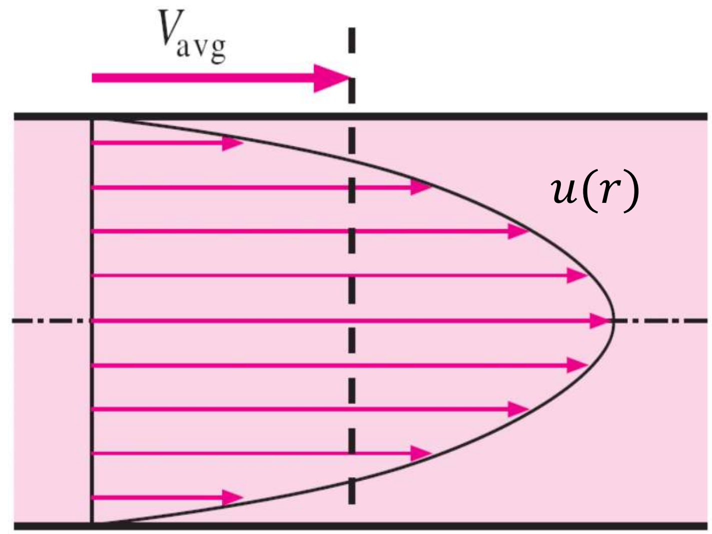
- **Pipe** — circular cross section.
- **Tubes** — small-diameter pipes.



- **Duct** — noncircular cross section.
- **Conduit**—circular / noncircular cross-section to convey hot gases



❑ Average velocity, V_{avg}



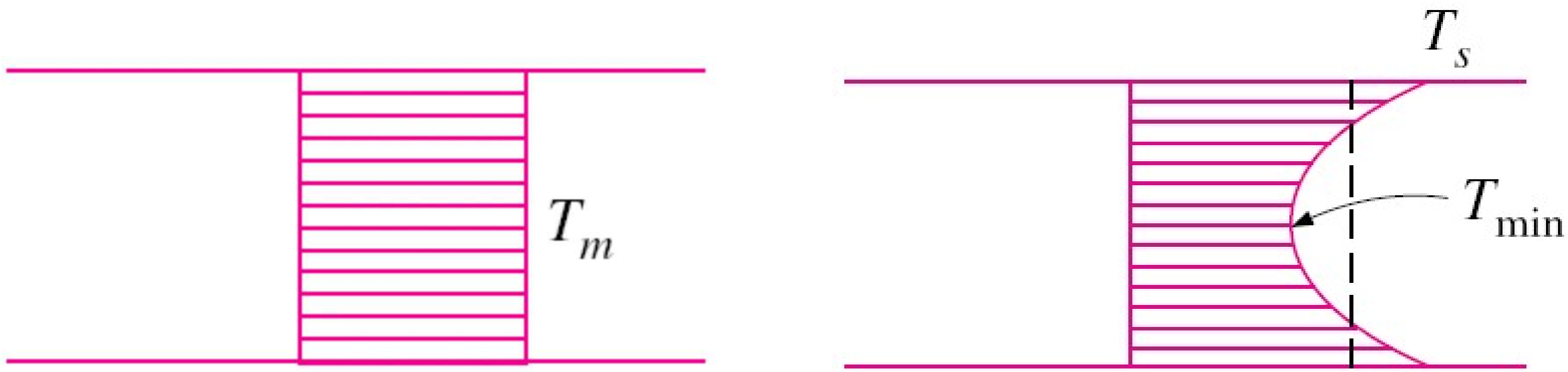
- The fluid velocity changes from zero at the surface (no-slip) to a maximum at the pipe center.
- It is convenient to work with an average velocity, V_{avg}, which remains constant in incompressible flow in a constant cross-sectional pipe.

$$\dot{m} = \rho V_{avg} A_C = \int_{A_c} \rho u(r)\, dA_C$$

For incompressible flow in a circular pipe of radius *R*

$$V_{avg} = \frac{\int_{A_c} \rho u(r)\, dA_C}{\rho A_C} = \frac{\int_0^R \rho u(r) 2\pi r dr}{\rho \pi R^2} = \frac{2}{R^2}\int_0^R u(r) r dr \quad \text{…… (3.3.1)}$$

❑ Average / mean Temperature, T_m



$$\dot{E}_{fluid} = \dot{m} c_p T_m = \int_{\dot{m}} c_p T(r) \delta \dot{m} = \int_{A_c} \rho c_p T(r) u(r) V dA_c$$

For incompressible flow in a circular pipe of radius *R*

$$T_m = \frac{\int_{\dot{m}} c_p T(r) \delta \dot{m}}{\dot{m} c_p} = \frac{\int_{A_c} c_p T(r) \rho u(r) 2\pi r dr}{\rho V_{avg} \left(\pi R^2\right) c_p}$$

$$= \frac{2}{V_{avg} R^2} \int_0^R T(r) u(r) r dr \qquad \text{…… (3.3.2)}$$

EP# 3.7

The velocity and temperature profile for a fluid flowing in a circular tube of radius, R= 4 cm are given by: $u(r) = 0.2[1-(r/R)^2]$ in m/s and $\mathrm{T}(r) = 250 + 200(r/R)^3$ in K
Determine the mean fluid temperature.

EP# 3.7 Soln