Ch.6 Forced Convection

ME203 – HEAT TRANSFER

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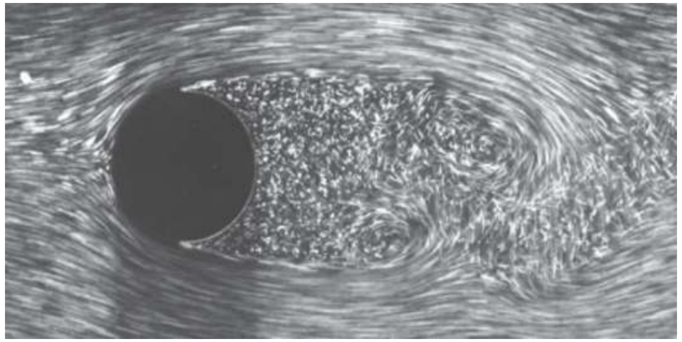
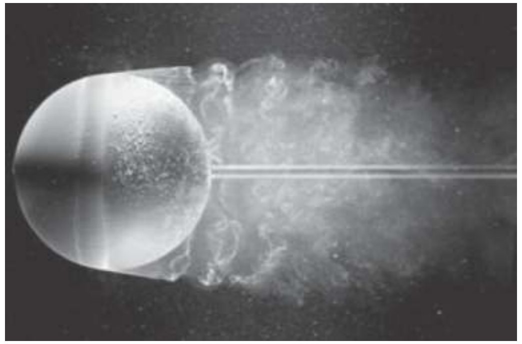
Flow Across Cylinders & Spheres

- Flow across cylinders and spheres can be found in many applications such as
  - external flow over the tubes in heat exchanger
  - The flow of air over the spherical balls (lamp, soccer ball, etc)



Flow over a circular cylinder



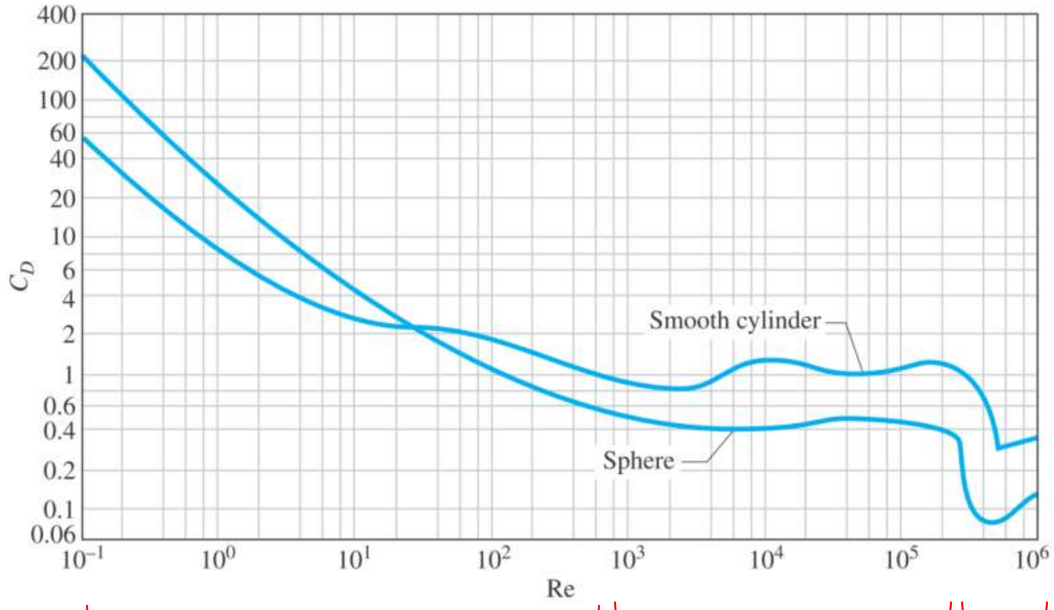
Flow over a sphere

* ***Note that***, The characteristic length (L_c) for a circular cylinder or sphere is taken to be the external diameter D

$$\text{Re} = \frac{VD}{\nu} \quad \& \quad \text{Nu} = \frac{hD}{k}$$

Drag Coefficient vs Reynolds Number

How to determine the Drag Coefficient (C_D) of fluid flow over cylinder or sphere → Calculate (Re) and see the graph below



C_D decreases with increasing Re

C_D relatively constant

Sudden drop in C_D

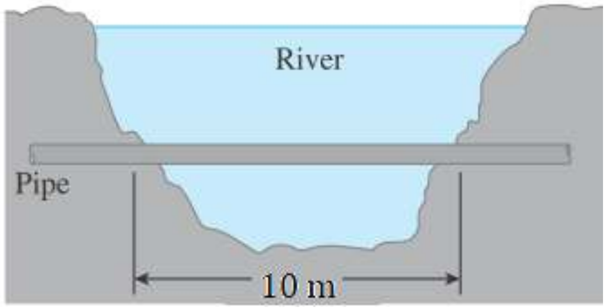
The critical Reynolds number for flow across a circular cylinder or sphere is $\boldsymbol{Re_{cr} = 2\times10^5}$

* Note that, A decrease in the drag coefficient does not necessarily indicate a decrease in drag force.

$$F_f = C_f A \frac{\rho V^2}{2}$$

Example

A 2.2-cm-outer-diameter pipe is to span across a river at a 10-m-wide while being completely immersed in water. The average flow velocity of water is 4 m/s and the water temperature is 15°C. Determine the drag force exerted on the pipe by the flow of water in the river



Example

Given: A pipe is submerged in a river. The drag force that acts on the pipe is to be determined.
Assumptions:
1 The outer surface of the pipe is smooth so that Fig. 7–17 can be used to determine the drag coefficient.
2 Water flow in the river is steady.
3 The direction of water flow is normal to the pipe.
4 Turbulence in river flow is not considered.
Properties: The density and dynamic viscosity of water at 15°C are $\rho = 999.1$ kg/m^3 and $\mu = 1.138 \times 10^{-3}$ kg/m.s (Table A–9).
Analysis: Noting that D = 0.022 m, the Reynolds number is

$$Re = \frac{VD}{v} = \frac{\rho VD}{\mu} = \frac{(999.1\ kg/m^3)(4\ m/s)(0.022\ m)}{1.138\times10^{-3}\ kg/m.s} = 7.73\times10^4$$

Example

The drag coefficient corresponding to this value is, from Fig. 7–17, C_D = 1.0.
Also, the frontal area for flow past a cylinder is A = LD. Then the drag force acting on the pipe becomes

$$F_D = C_D A \frac{\rho V^2}{2} = 1.0(30\times 0.022\ m^2)\frac{(999.1\ \ kg/m^3)(4\ \ m/s)^2}{2}\left(\frac{1\ N}{1\ kg.m/s^2}\right) = 5275\ N \approx 5.30\ kN$$

Discussion: Note that this force is equivalent to the weight of a mass over 500 kg. Therefore, the drag force the river exerts on the pipe is equivalent to hanging a total of over 500 kg in mass on the pipe supported at its ends 30 m apart. The necessary precautions should be taken if the pipe cannot support this force. If the river were to flow at a faster speed or if turbulent fluctuations in the river were more significant, the drag force would be even larger. Unsteady forces on the pipe might then be significant.

Heat Transfer Coefficient (h)

- Flows across cylinders & spheres is difficult to handle analytically.
- Therefore heat transfer coefficient (h) is calculated based on empirical studies done by numerous researchers.

For flow over a *cylinder*

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

$$\mathrm{RePr} > 0.2$$

The fluid properties are evaluated at the *film temperature* $T_f = \frac{1}{2}(T_\infty + T_s)$

Heat Transfer Coefficient (*h*)

For flow over a *sphere*

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

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

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

Heat Transfer Coefficient (h)

$$\text{Nu}_{\text{cyl}} = \frac{hD}{k} = C\,\text{Re}^m\,\text{Pr}^n \qquad n = \frac{1}{3}$$

Constants C and m are given in the table.

The relations for cylinders above are for *single* cylinders or cylinders oriented such that the flow over them is not affected by the presence of others. They are applicable to *smooth* surfaces.

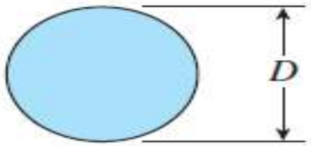
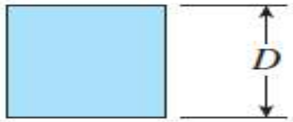
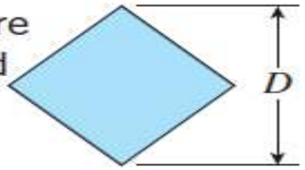
* ***Remember***:
Nusselt number (Nu) is used to calculate heat transfer coefficient (h)

$$\text{Nu} = \frac{hD}{k} \;\Rightarrow\; h = \frac{k}{D}\text{Nu}$$

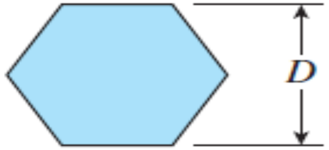
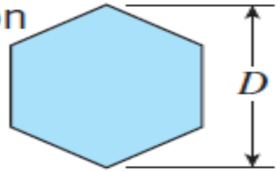
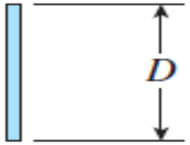
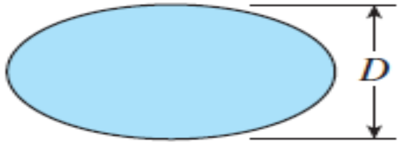
Heat Transfer Coefficient (h)

TABLE 7–1

Empirical correlations for the average Nusselt number for forced convection over circular and noncircular cylinders in cross flow (from Zukauskas, 1972, Jakob 1949, and Sparrow et al., 2004)

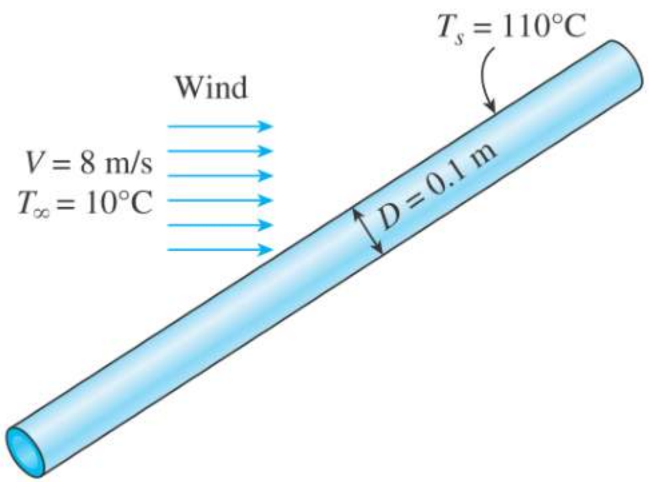
Cross-section of the cylinder	Fluid	Range of Re	Nusselt number
Circle 	Gas or liquid	0.4–4 4–40 40–4000 4000–40,000 40,000–400,000	$Nu = 0.989Re^{0.330}\ Pr^{1/3}$ $Nu = 0.911Re^{0.385}\ Pr^{1/3}$ $Nu = 0.683Re^{0.466}\ Pr^{1/3}$ $Nu = 0.193Re^{0.618}\ Pr^{1/3}$ $Nu = 0.027Re^{0.805}\ Pr^{1/3}$
Square 	Gas	3900–79,000	$Nu = 0.094Re^{0.675}\ Pr^{1/3}$
Square (tilted 45°) 	Gas	5600–111,000	$Nu = 0.258Re^{0.588}\ Pr^{1/3}$

Heat Transfer Coefficient (h)

Hexagon 	Gas	4500–90,700	$Nu = 0.148 Re^{0.638} Pr^{1/3}$
Hexagon (tilted 45°) 	Gas	5200–20,400 20,400–105,000	$Nu = 0.162 Re^{0.638} Pr^{1/3}$ $Nu = 0.039 Re^{0.782} Pr^{1/3}$
Vertical plate 	Gas	6300–23,600	$Nu = 0.257 Re^{0.731} Pr^{1/3}$
Ellipse 	Gas	1400–8200	$Nu = 0.197 Re^{0.612} Pr^{1/3}$

Example

A steam pipe passes through some open area that is not protected against the winds. If the wind is blowing across the pipe, determine the rate of heat loss from the pipe per unit of its length (see figure)



Example

SOLUTION

A steam pipe is exposed to windy air. The rate of heat loss from the steam is to be determined.

Assumptions:

1 Steady operating conditions exist.

2 Radiation effects are negligible.

3 Air is an ideal gas.

Properties:

The properties of air at the average film temperature of $T_f = (T_s + T_\infty)/2 = (110 + 10)/2 = 60°C$ and 1 atm pressure are (Table A–15)

k = 0.02808 W/m.K   Pr = 0.7202 $\nu = 1.896 \times 10^{-5}\ m^2/s$

Analysis:

The Reynolds number is

$$Re = \frac{VD}{\nu} = \frac{(8\ m/s)(0.1\ m)}{1.896\times10^{-5}\ m^2/s} = 4.219\times10^4$$

Example

The Nusselt number can be determined from

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

$$= 0.3 + \frac{0.62(4.219\times10^4)^{1/2}(0.7202)^{1/3}}{[1 + (0.4/0.7202)^{2/3}]^{1/4}} [1 + \left(\frac{4.219\times10^4}{282{,}000}\right)^{5/8}]^{4/5} = 124$$

$$h = \frac{k}{D} Nu = \frac{0.02808}{0.1}(124) = 34.8\ W/m^2.K$$

Then, the rate of heat transfer from the pipe per unit of its length becomes

$$A_s = pL = \pi DL = \pi(0.1\ m)(1\ m) = 0.314\ m^2$$

Example

$$\dot{Q} = hA_s(T_s - T_\infty) = (34.8\ W/m^2.K)(0.314\ m^2)(110 - 10)°C = 1093\ W$$

The rate of heat loss from the entire pipe can be obtained by multiplying the value above by the length of the pipe in m.

Discussion: The simpler Nusselt number relation in Table 7–1 in this case would give Nu = 128, which is 3 percent higher than the value obtained above using Eq. 7–35.

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