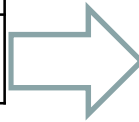


ME265: Thermal Engineering & Heat Transfer

Chapters
1. Energy Scenario
2. Thermodynamics
3. Mechanical Devices & Systems
4. Heat Transfer



4.1 Introduction	
4.2 Conduction	
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

□ Objectives

- Understand drag in external flows
- Evaluate drag coefficient and convection coefficients in external flows—for both laminar and turbulent flows over flat plates.

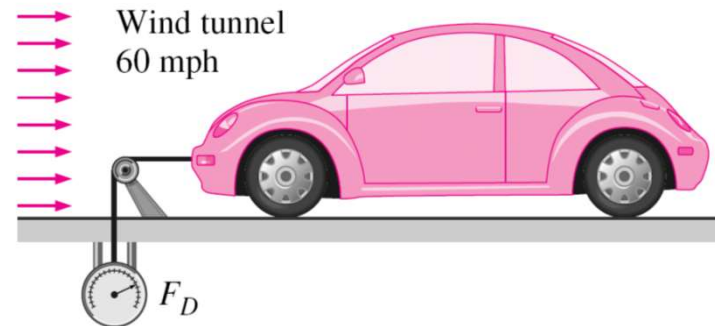
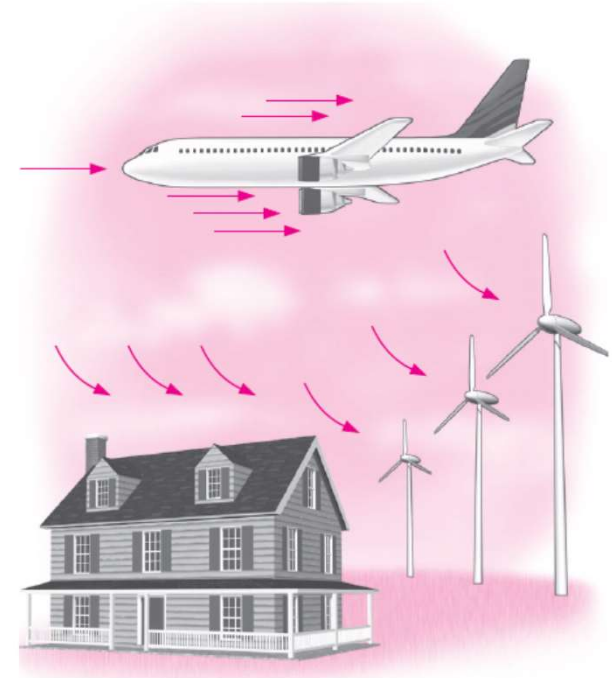
Reference: Cengel, et al. (2011) Heat and Mass Transfer: Fundamentals and Applications, 4th Edition, McGraw-Hill, Chapter-7

4.3.2 External Forced Convection

□ Drag and Heat Transfer in External Flows

Fluid flow over solid bodies is responsible for numerous physical phenomena such as:

- **drag force** in the direction of flow
Example: Automobile, etc.
- **lift force** in the normal direction flow
Example: Aircrafts, kites, birds, etc.
- **Cooling/heating** of the solid bodies.



4.3.2 External Forced Convection

❖ Drag and Heat Transfer in External Flows

- ❑ A stationary fluid exerts only normal pressure forces on the surface of a body immersed in it.
- ❑ A moving fluid, however, also exerts tangential shear forces on the surface due to no-slip condition caused by viscous effects.
- ❑ Both of these forces, have components in the direction of flow, and thus **drag** is composed of:
 - ✓ **Pressure drag**
 - ✓ **Friction drag** (skin friction drag)
- ❑ When the friction and pressure drag coefficients are available, the total drag coefficient is determined by simply adding them:

$$C_D = C_{D, \text{friction}} + C_{D, \text{pressure}}$$

4.3.2 External Forced Convection

❖ Drag and Heat Transfer in External Flows

- ❑ The friction drag is *zero* for a surface normal to flow, and *maximum* for a surface parallel to flow.
- ❑ for parallel flow over a flat plate, the drag coefficient is equal to the *friction drag coefficient*, or simply the *friction coefficient*:

$$C_D = C_{D, \text{friction}} = C_f$$

- ❑ The drag force F_D depends on the
 - density ρ of the fluid,
 - The upstream velocity V , and
 - the size, shape, and orientation of the body.
- ❑ The dimensionless **drag coefficient** C_D is defined as:

$$C_D = \frac{F_D}{1/2 \rho V^2 A}$$

4.3.2 External Forced Convection

❖ Drag and Heat Transfer in External Flows

- The phenomena that affect drag force also affect heat transfer, and this effect appears in the Nusselt number.
- The local and average Nusselt numbers have the functional form

$$\text{Nu}_x = f_1(x, \text{Re}_x, \text{Pr}) \quad \text{Nu} = f_2(\text{Re}_L, \text{Pr})$$

- The flow fields and geometries for most external flow problems are too complicated to be solved analytically, and thus we have to rely on correlations based on **experimental data**.
- The **experimental data for heat transfer** can be represented conveniently by a simple power-law relation of the form:

$$\text{Nu} = C \text{Re}_L^m \text{Pr}^n$$

where, m and n are constant exponents, and the value of the constant C depends on geometry and flow.

4.3.2 External Forced Convection

□ For Parallel flow over flat plates

Critical Reynolds number

$$Re_{cr} = \frac{\rho V x_{cr}}{\mu} = 5 \times 10^5$$

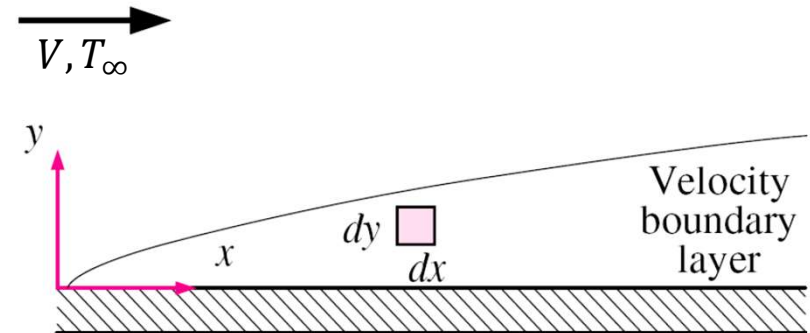


Fig. 3.2: Flow over an isothermal flat plate

Parameter	Laminar flow $Re_x < 5 \times 10^5$	Turbulent Flow $5 \times 10^5 \leq Re_x \leq 10^7$
BL Thickness, δ	$\delta = \frac{4.91 x}{Re_x^{1/2}}$	$\delta = \frac{0.38 x}{Re_x^{1/5}}$
Local Friction Coefficient, $C_{f,x}$	$C_{f,x} = \frac{0.664}{Re_x^{1/2}}$	$C_{f,x} = \frac{0.059}{Re_x^{1/5}}$
Local Convection Coefficient, Nu_x	$Nu_x = 0.332 Re_x^{1/2} Pr^{1/3}$ For $Pr > 0.6$	$Nu_x = 0.0296 Re_x^{0.8} Pr^{1/3}$ For $0.6 \geq Pr \geq 60$

Fluid properties are taken at film temperature: $T_f = (T_s + T_\infty)/2$

4.3.2 External Forced Convection

□ For Parallel flow over flat plates

Average friction and convection coefficient:

$$C_f = \frac{1}{L} \int_0^L C_{f,x} dx$$

$$Nu = \frac{1}{L} \int_0^L Nu_x dx$$

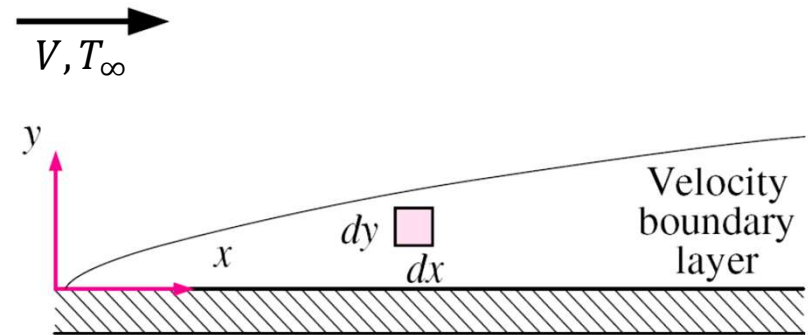


Fig. 3.2: Flow over an isothermal flat plate

Parameter	Laminar flow $Re_x < 5 \times 10^5$	Turbulent Flow $5 \times 10^5 \leq Re_x \leq 10^7$
Average Friction Coefficient, C_f	$C_f = \frac{1.33}{Re_L^{1/2}}$	$C_f = \frac{0.074}{Re_L^{1/5}}$
Avg. Convection Coefficient, Nu	$Nu = 0.664 Re_L^{1/2} Pr^{1/3}$ For $Pr > 0.6$	$Nu = 0.037 Re_L^{0.8} Pr^{1/3}$ For $0.6 \geq Pr \geq 60$

4.3.2 External Forced Convection

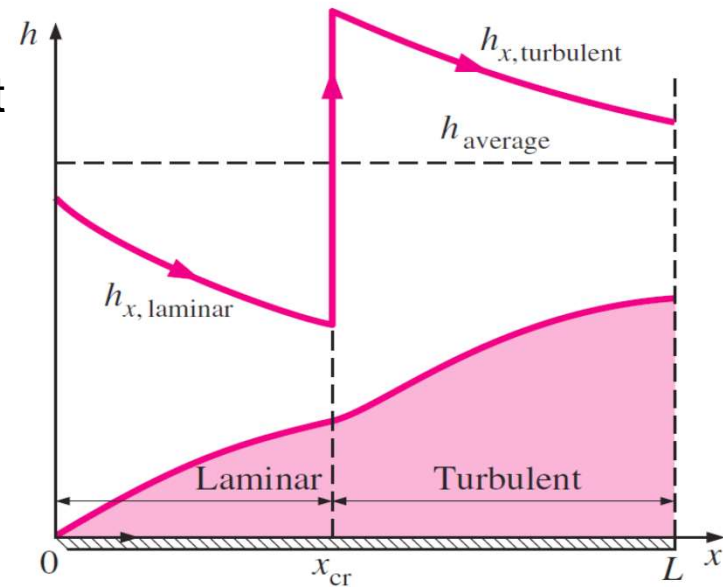
□ For Parallel flow over flat plates

When laminar and turbulent flows are significant

$$C_f = \frac{1}{L} \left(\int_0^{x_{cr}} C_{f,x \text{ laminar}} dx + \int_{x_{cr}}^L C_{f,x \text{ turbulent}} dx \right)$$

$$h = \frac{1}{L} \left(\int_0^{x_{cr}} h_{x, \text{ laminar}} dx + \int_{x_{cr}}^L h_{x, \text{ turbulent}} dx \right)$$

$$Re_{cr} = 5 \times 10^5$$

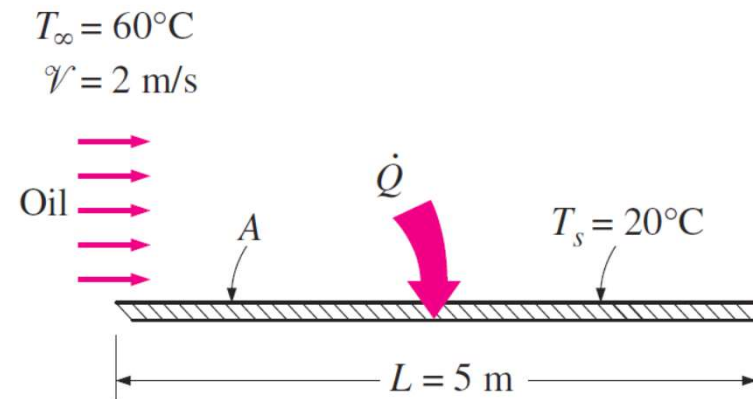


Parameter	Relationship
	$5 \times 10^5 \leq Re_x \leq 10^7$
Average Friction Coefficient, C_f	$C_f = \frac{0.074}{Re_L^{1/5}} - \frac{1742}{Re_L}$
Avg. Convection Coefficient, Nu	$Nu = 0.037 (Re_L^{0.8} - 871) Pr^{1/3}$ For $0.6 \geq Pr \geq 60$

4.3.2 External Forced Convection

EP# 3.3 Cengel et al. Example: 7-1

Engine oil at 60°C flows over the upper surface of a 5-m-long flat plate whose temperature is 20°C with a velocity of 2 m/s. Determine the total drag force and the rate of heat transfer per unit width of the entire plate.



EP# 3.3 Solution

Assumptions

1. The flow is steady and incompressible.
2. The critical Reynolds number is $Re_{cr} = 5 \times 10^5$.

Properties

The properties of engine oil at the film temperature of $T_f = (T_s + T_\infty)/2 = (20 + 60)/2 = 40^\circ\text{C}$ are (Table A-13):

$$\rho = 876 \text{ kg/m}^3$$

$$Pr = 2962$$

$$k = 0.1444 \text{ W/m } ^\circ\text{C}$$

$$\nu = 2.485 \times 10^{-4} \text{ m}^2/\text{s}$$

