Ch.6 Forced Convection

ME203 – HEAT TRANSFER

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Introduction

- Previously, we discussed fundamental of convection
  - Type of flow : laminar & turbulent, internal & external, forced & free convection, etc
  - Type of Boundary Layer : Velocity vs Thermal
  - Introducing the dimensionless number (Nu, Re, Pr) and it's significance
- In this chapter, we will discuss the ***forced convection*** in ***external & internal flow.***
- The main objective is to determine :
  - ***heat transfer coefficient (h)***
  - ***rate of heat transfer (q)***

  } For both ***external & internal flow***

Topic of This Chapter

A. Forced Convection in *External Flow*

1) Drag & Heat Transfer in External flow
2) Parallel Flow over Flat Plate
3) Flow across Cylinders & Spheres
4) Flow across Tube Banks

B. Forced Convection in *Internal Flow*

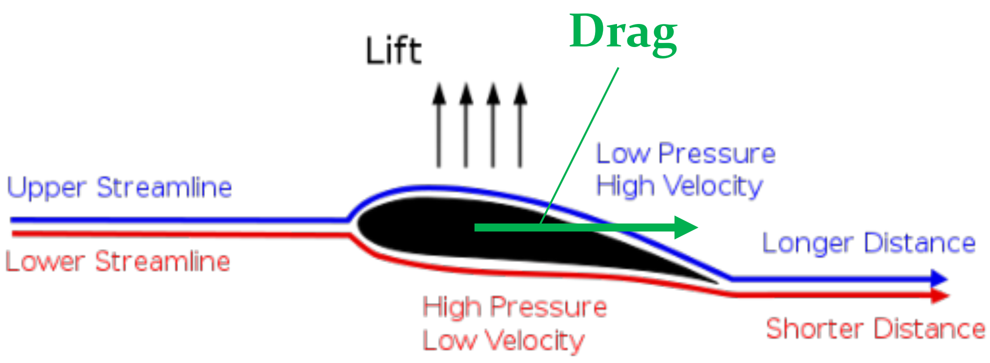
1) Laminar flow in Tubes
2) Turbulent flow in Tubes

Drag Force & Lift Force

Fluid flow over any surfaces creates two type of aerodynamic forces called :

1) **Drag force** → the same direction of the fluid flow

2) **Lift force** → perpendicular to the direction of fluid flow

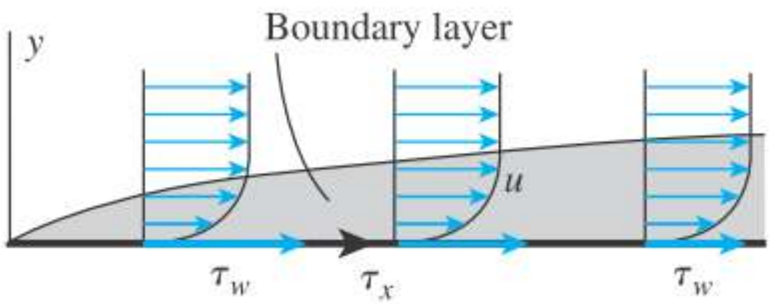


Type of Drag Force

Friction Drag vs Pressure Drag

Let consider the flat plate is placed in different condition:

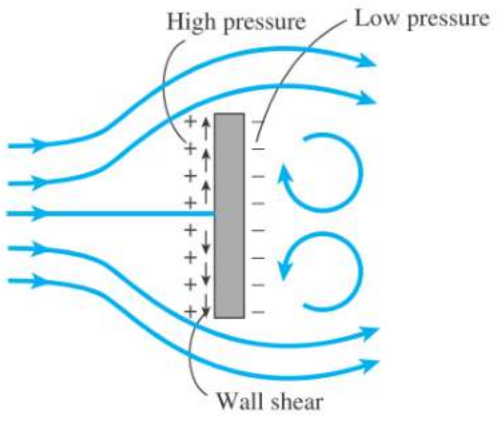
- parallel to the fluid flow
- normal to the fluid flow



Drag force on a flat plate parallel to the flow depends on ***wall shear only*** *→* ***Friction Drag***

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

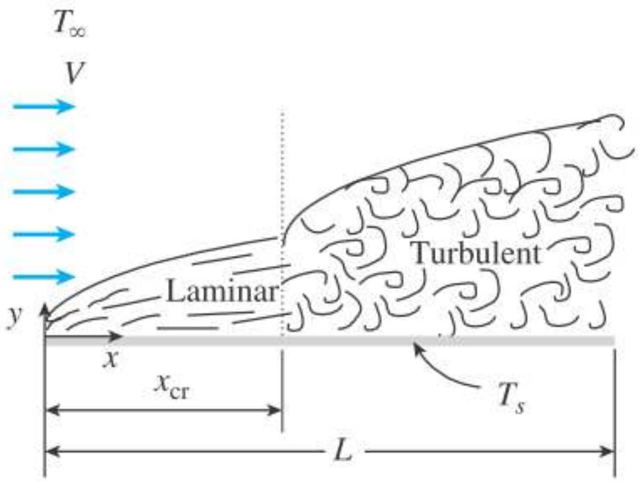
→ ***Friction Drag Force***



Drag force on a flat plate normal to the flow depends on the ***pressure only*** *and is independent of the wall shear →* ***Pressure Drag***

Local Friction Coefficients ($C_{f,x}$)

Consider the parallel flow of a fluid over a flat plate L in the flow direction



The Reynolds number at a distance x from the leading edge of a flat plate

$$Re_x = \frac{\rho V x}{\mu} = \frac{Vx}{\nu}$$

Where:

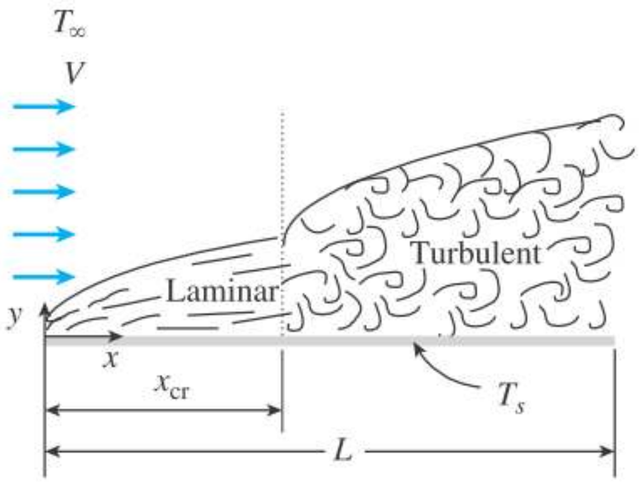
$$Re_{cr} = 5 \times 10^5$$

The velocity boundary layer thickness (δ) and the local friction coefficient at location x ($C_{f,x}$)

Laminar Region	*Turbulent Region*
$\delta = \frac{4.91x}{Re_x^{1/2}}$	$\delta = \frac{0.38x}{Re_x^{1/5}}$
$C_{f,x} = \frac{0.664}{Re_x^{1/2}}$	$C_{f,x} = \frac{0.059}{Re_x^{1/5}}$

Average Friction Coefficients (C_f)

Consider the parallel flow of a fluid over a flat plate L in the flow direction



The **average friction coefficients (C_f)** *for the entire surface* can be determined by integration from :

$$C_f = \frac{1}{L}\int_0^L C_{f,x}\,dx \qquad ;\text{where} \quad C_{f,x} = \frac{0.664}{\mathrm{Re}_x^{1/2}}$$

Laminar Region	***Turbulent Region***
$C_f = \dfrac{1.33}{\mathrm{Re}_L^{1/2}}$	$C_f = \dfrac{0.074}{\mathrm{Re}_L^{1/5}}$

* Note that, the friction coefficient for ***turbulent*** is taken from the experiments

Heat Transfer Coefficient (h)

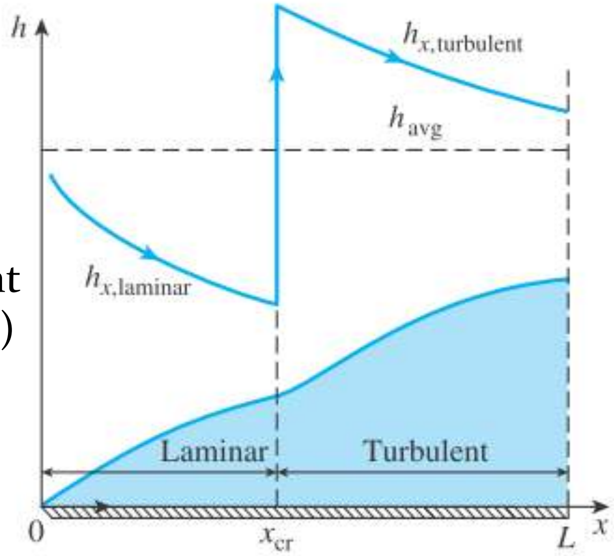
Local vs Average *heat transfer coefficient*

The local heat transfer coefficient a location x can be found using local Nu (Nu_x) :

Laminar: $$Nu_x = \frac{h_x x}{k} = 0.332\, Re_x^{0.5}\, Pr^{1/3}$$

Turbulent: $$Nu_x = \frac{h_x x}{k} = 0.0296\, Re_x^{0.8}\, Pr^{1/3}$$

**Note that*: T_s = constant (isothermal)



The average heat transfer coefficient (h) over the entire plate can be found by integrate the local Nu (Nu_x) :

Laminar: $$Nu = \frac{hL}{k} = 0.664\, Re_L^{0.5}\, Pr^{1/3}$$

Turbulent: $$Nu = \frac{hL}{k} = 0.037\, Re_L^{0.8}\, Pr^{1/3}$$

How To Evaluate The Fluid Properties?

Recall the heat transfer coefficient (h) equation

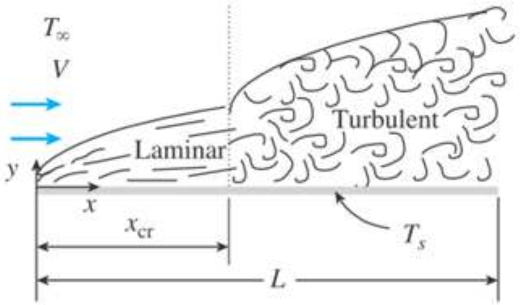
$$\text{Laminar:} \quad \text{Nu} = \frac{hL}{k} = 0.664\ \text{Re}_L^{0.5}\ \text{Pr}^{1/3}$$

$$\textit{Turbulent:} \quad \text{Nu} = \frac{hL}{k} = 0.037\ \text{Re}_L^{0.8}\ \text{Pr}^{1/3}$$

To calculate h, it is necessary to know the fluid properties, such as

- Thermal conductivity, k
- Kinematic viscosity, ν
- Prandtl Number, Pr
- Density, ρ

All above properties can be found from the properties table, by evaluating the fluid at the so-called *film temperature* (T_f)



$$T_f = \frac{T_s + T_\infty}{2}$$

Average temperature between surface and ambient

How To Evaluate The Fluid Properties?

Once the film temperature is calculated → refer to the table

Properties of liquids

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr	Volume Expansion Coeff. β, 1/K
				Methane [CH_4]				
−160	420.2	3492	0.1863	1.270×10^{-7}	1.133×10^{-4}	2.699×10^{-7}	2.126	0.00352
−150	405.0	3580	0.1703	1.174×10^{-7}	9.169×10^{-5}	2.264×10^{-7}	1.927	0.00391
−140	388.8	3700	0.1550	1.077×10^{-7}	7.551×10^{-5}	1.942×10^{-7}	1.803	0.00444
−130	371.1	3875	0.1402	9.749×10^{-8}	6.288×10^{-5}	1.694×10^{-7}	1.738	0.00520
−120	351.4	4146	0.1258	8.634×10^{-8}	5.257×10^{-5}	1.496×10^{-7}	1.732	0.00637
−110	328.8	4611	0.1115	7.356×10^{-8}	4.377×10^{-5}	1.331×10^{-7}	1.810	0.00841
−100	301.0	5578	0.0967	5.761×10^{-8}	3.577×10^{-5}	1.188×10^{-7}	2.063	0.01282
−90	261.7	8902	0.0797	3.423×10^{-8}	2.761×10^{-5}	1.055×10^{-7}	3.082	0.02922
				Methanol [$CH_3(OH)$]				
20	788.4	2515	0.1987	1.002×10^{-7}	5.857×10^{-4}	7.429×10^{-7}	7.414	0.00118
30	779.1	2577	0.1980	9.862×10^{-8}	5.088×10^{-4}	6.531×10^{-7}	6.622	0.00120
40	769.5	2644	0.1972	9.690×10^{-8}	4.460×10^{-4}	5.795×10^{-7}	5.980	0.00123
50	760.1	2718	0.1965	9.509×10^{-8}	3.942×10^{-4}	5.185×10^{-7}	5.453	0.00127
60	750.4	2798	0.1957	9.320×10^{-8}	3.510×10^{-4}	4.677×10^{-7}	5.018	0.00132
70	740.4	2885	0.1950	9.128×10^{-8}	3.146×10^{-4}	4.250×10^{-7}	4.655	0.00137

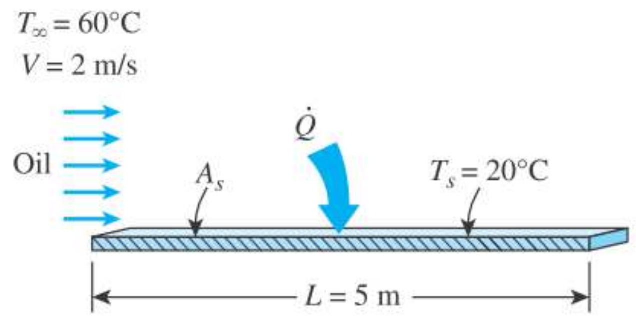
SAMPLE of Property Table of A Substance

Example

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 area of the entire plate.

Known:

Find:



Properties of liquids

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
Engine Oil (unused)							
0	899.0	1797	0.1469	9.097×10^{-8}	3.814	4.242×10^{-3}	46,636
20	888.1	1881	0.1450	8.680×10^{-8}	0.8374	9.429×10^{-4}	10,863
40	876.0	1964	0.1444	8.391×10^{-8}	0.2177	2.485×10^{-4}	2,962
60	863.9	2048	0.1404	7.934×10^{-8}	0.07399	8.565×10^{-5}	1,080
80	852.0	2132	0.1380	7.599×10^{-8}	0.03232	3.794×10^{-5}	499.3

Example

Assumptions:

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

Properties:

The film temperature $T_f = \frac{T_S+T_\infty}{2} = \frac{20+60}{2} = 40°C$, thus the properties of oil engine at T_f are (Table A-13)

$\rho = 876\, kg/m^3 \qquad Pr = 2962$

$k = 0.1444\, W/m.K \qquad v = 2.485{\times}10^{-4}\, m^2/s$

Analysis:

$$Re_L = \frac{VL}{v} = \frac{(2\, m/s){\times}(5\, m)}{2.485{\times}10^{-4}\, m^2/s} = 4.024{\times}10^4 < Re_{cr} \implies$$

$we\ have\ laminar\ flow\ over\ the\ entire\ plate.$

$Thus\ the\ average\ friction\ cofficient$ is:

$$C_f = 1.33 Re_L^{-0.5} = 1.33{\times}(4.024{\times}10^4)^{-0.5} = 0.00663$$

Example

Noting that the pressure drag is zero and thus $C_D = C_f$ for parallel flow over a flat plate, the drag force acting on the plate per unit width becomes

$$F_D = C_f A \frac{\rho V^2}{2} = 0.00663 \times (5 \times 1\ m^2) \frac{(876\ kg/m^3)(2\ m/s)^2}{2} = 58.1\ N$$

Similarly, the Nusselt number is determined using the laminar flow relations for a flat plate:

$$Nu = \frac{hL}{k} = 0.664 Re_L^{0.5} Pr^{1/3} = 0.644 \times (4.024 \times 10^4)^{0.5} \times 2962^{1/3} = 1913$$

Then,

$$h = \frac{k}{L} Nu = \frac{0.1444\ W/m.K}{5\ m}(1913) = 55.25\ \ W/m^2.K$$

And

$$\dot{q} = hA_s(T_\infty - T_s) = (55.25\ \ W/m^2.K)(5 \times 1\ m^2)(60 - 20)°\text{C} = 11050\ W$$

END OF THE SLIDES