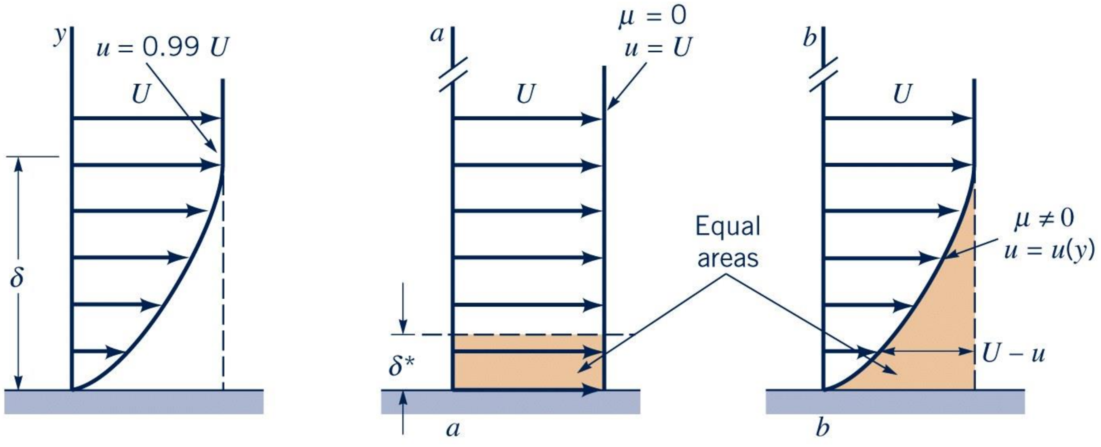
Lecture 23

Turbulent Boundary-Layer Flows (1)



Lecture 23 Turbulent Boundary-Layer Flows (1)

Contents

Objectives

- Study wall turbulence
- Derive equations of velocity distribution and friction coefficient for both smooth and rough walls

23.1 Introduction

• Turbulence occurs most commonly in shear flows.

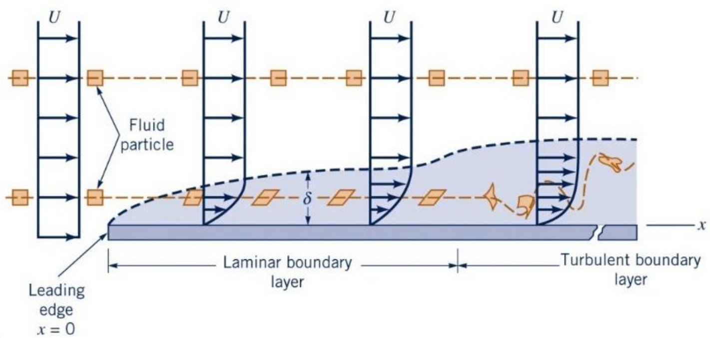
1) Wall turbulence: along solid surface → no-slip condition at surface

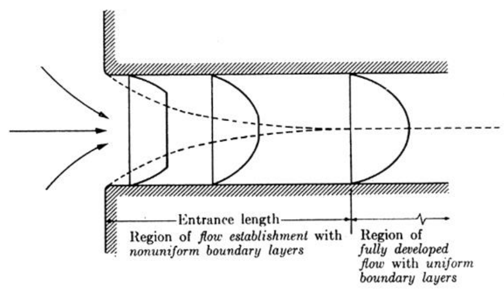
2) Free turbulence: at the interface between fluid zones having different velocities, and at boundaries of a jet → jet, wakes

• Wall turbulence:

1) Non-uniform boundary layers on immersed bodies

2) Uniform boundary layers of fully developed flow in uniform conduits





23.2 Structure of a Turbulent Boundary Layer

23.2.1 Boundary layer flows

(1) Smooth boundary

Consider a fluid stream flowing past a smooth boundary.

→ A boundary-layer zone of viscous influence is developed near the boundary.

1) $\mathrm{Re}_x \left(= \frac{V_0 x}{\nu} \right) < \mathrm{Re}_{crit}$

→ The boundary-layer is initially laminar.

$$u = u(y) \qquad (23.1)$$

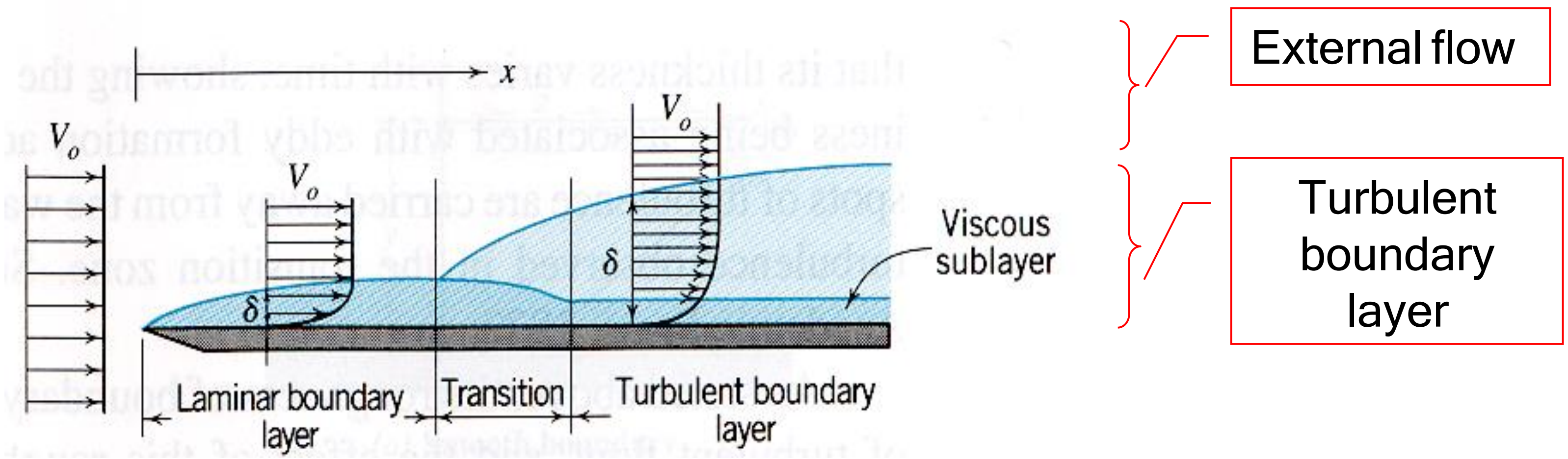
2) $\mathrm{Re} > \mathrm{Re}_{crit}$

→ The boundary-layer is turbulent.

$$\bar{u} = \bar{u}(y) \qquad (23.2)$$

→ Turbulence reaches out into the free stream to entrain and mix more fluid.

23.2 Structure of a Turbulent Boundary Layer



$$\mathrm{Re}_c = 500{,}000 \qquad (23.3)$$

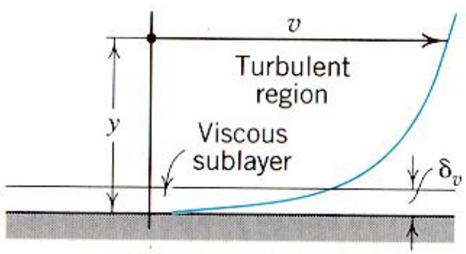
$x < x_{crit}$, total friction = laminar shear stress

$x > x_{crit}$, total friction = laminar + turbulent shear stress

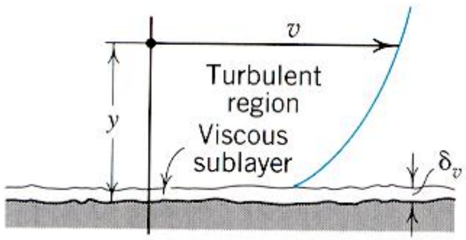
23.2 Structure of a Turbulent Boundary Layer

(2) Rough boundary

- Turbulent boundary layer is established near the leading edge of the boundary without a preceding stretch of laminar flow.
- Laminar sublayer is destroyed by the roughness elements.



(a) Smooth boundary



(b) Rough boundary

23.2 Structure of a Turbulent Boundary Layer

23.2.2 Comparison of laminar and turbulent boundary-layer profiles

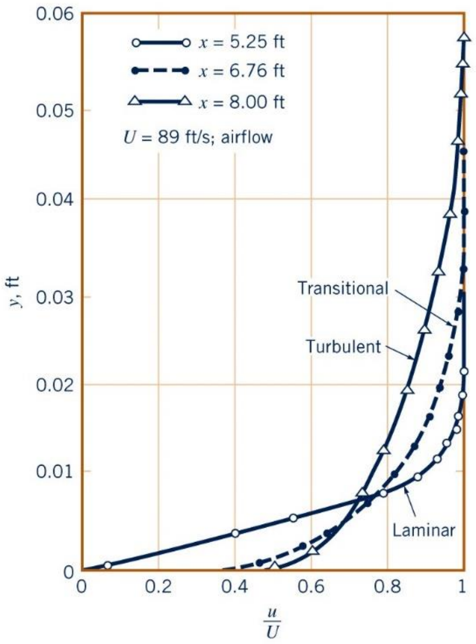
Compare thickness of boundary layer for the laminar and turbulent flows of the same Reynolds number, $\mathrm{Re}_x = 500{,}000$ on the smooth wall

From LC17, we have

$$\delta_{lam} = \frac{5x}{\mathrm{Re}_x^{1/2}} \tag{17.18}$$

$$\delta^*_{lam} = \frac{1.73x}{\mathrm{Re}_x^{1/2}} \tag{17.19}$$

$$\theta_{lam} = \frac{0.664x}{\mathrm{Re}_x^{1/2}} \tag{17.20}$$



23.2 Structure of a Turbulent Boundary Layer

1) Boundary layer thickness

$$\frac{\delta_{turb}}{\delta_{lam}} = 3.9 \qquad (23.4)$$

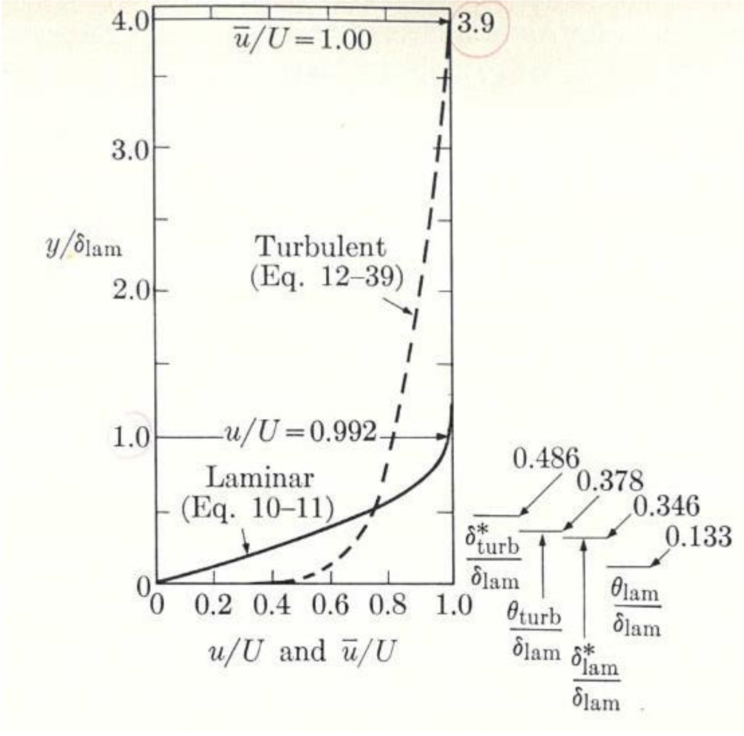
$$\delta_{tur} = \frac{0.318x}{\mathrm{Re}_x^{\ 1/5}} \qquad (23.5)$$

2) Mass displacement thickness,

$$\frac{\delta^*_{\ turb}}{\delta^*_{\ lam}} = 1.41 \qquad (23.6)$$

3) Momentum thickness, θ

$$\frac{\theta_{turb}}{\theta_{lam}} = 2.84 \qquad (23.7)$$



→ Because of the <u>higher flux of mass and momentum through the zone nearest the wall</u> for turbulent flow, increases of and θ rate are not as large as δ.

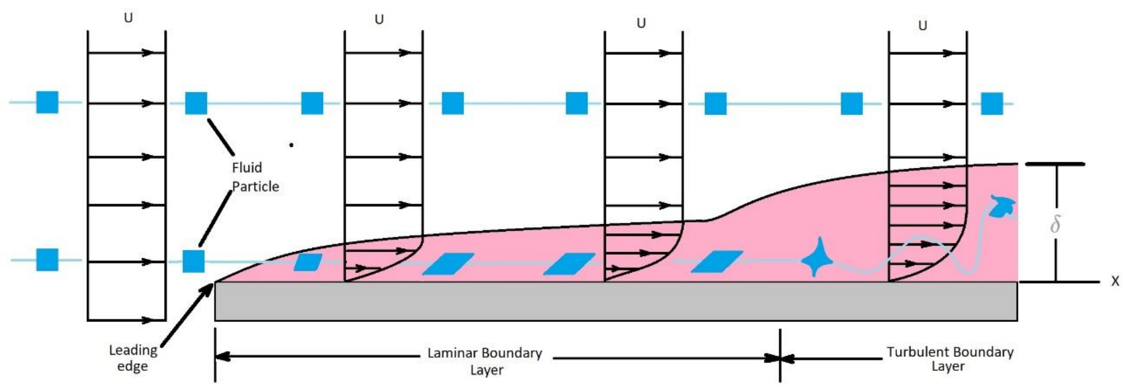
23.2 Structure of a Turbulent Boundary Layer

23.2.3 Intermittent nature of the turbulent layer

- Outside a boundary layer

- free-stream shearless flow of velocity U → potential flow (inviscid) → slightly turbulent flow

- considered to be <u>non-turbulent flow</u> relative to higher turbulence inside a turbulent boundary layer



23.2 Structure of a Turbulent Boundary Layer

- Interior of the turbulent boundary layer

- consist of regions of different types of flow (laminar, buffer, turbulent)

- Instantaneous border between turbulent and non-turbulent fluid is irregular and changing.

- Border consists of fingers of turbulence extending into the non-turbulent fluid and fingers of non-turbulent fluid extending deep into the turbulent region.

- intermittent nature of the turbulent layer

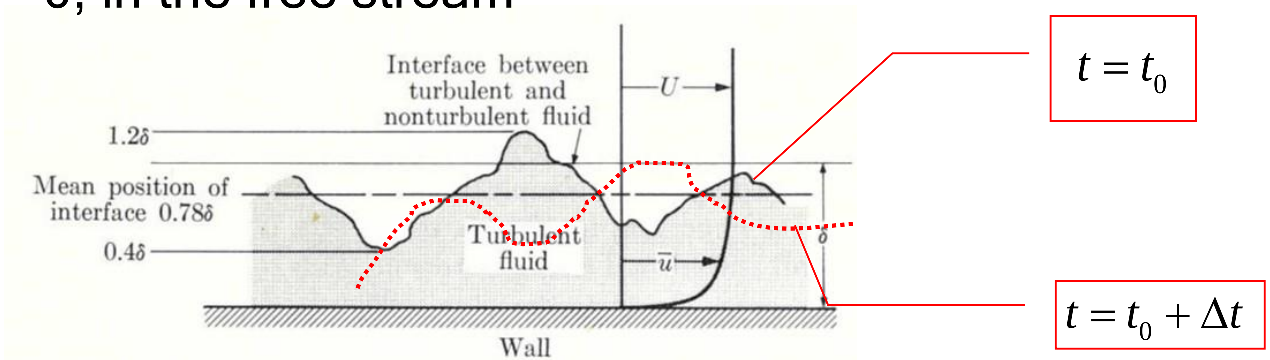
23.2 Structure of a Turbulent Boundary Layer

- Intermittency factor, Ω

Ω = fraction of time during which the flow is turbulent

Ω = 1.0, deep in the boundary layer

= 0, in the free stream



① Average position of the turbulent-non-turbulent interface = 0.78δ

② Maximum stretch of interface = 1.2 δ

③ Minimum stretch of interface = 0.4 δ

23.2 Structure of a Turbulent Boundary Layer

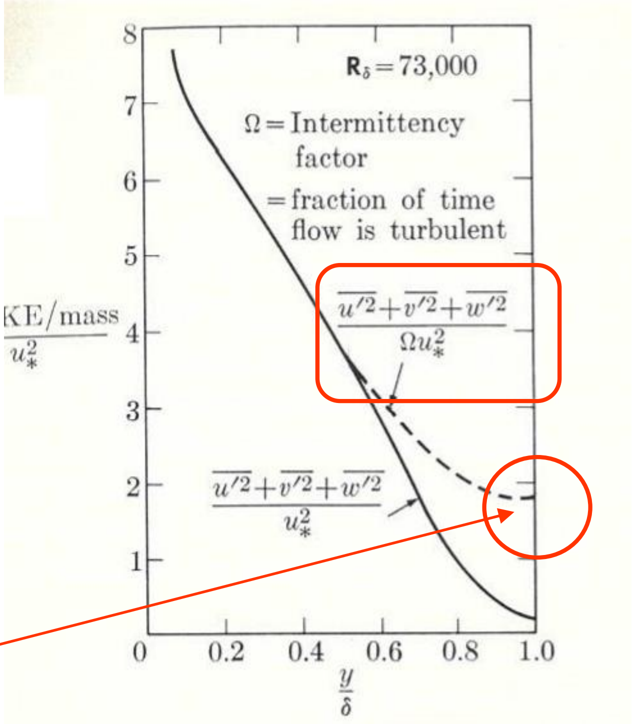
- Turbulent energy in a boundary layer, δ

$$TKE = \frac{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}{u_*^2} \qquad (23.8)$$

where $u_* = \sqrt{\frac{\tau_0}{\rho}}$ = shear velocity

For turbulent layer

$$\mathrm{Re}_\delta = \frac{U\delta}{\nu} = 73{,}000 \iff \mathrm{Re}_x = 4\times10^6$$

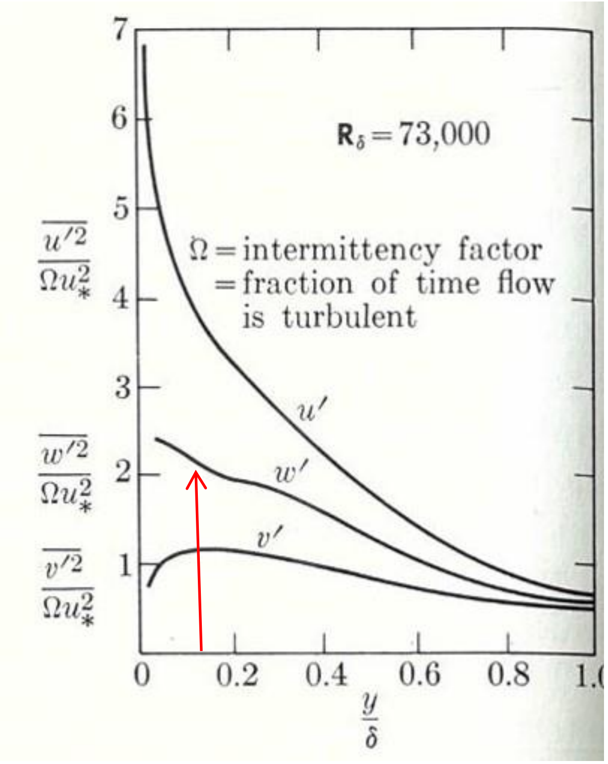


- Turbulent energy average for the turbulent regions only remains finite at $y = \delta$.

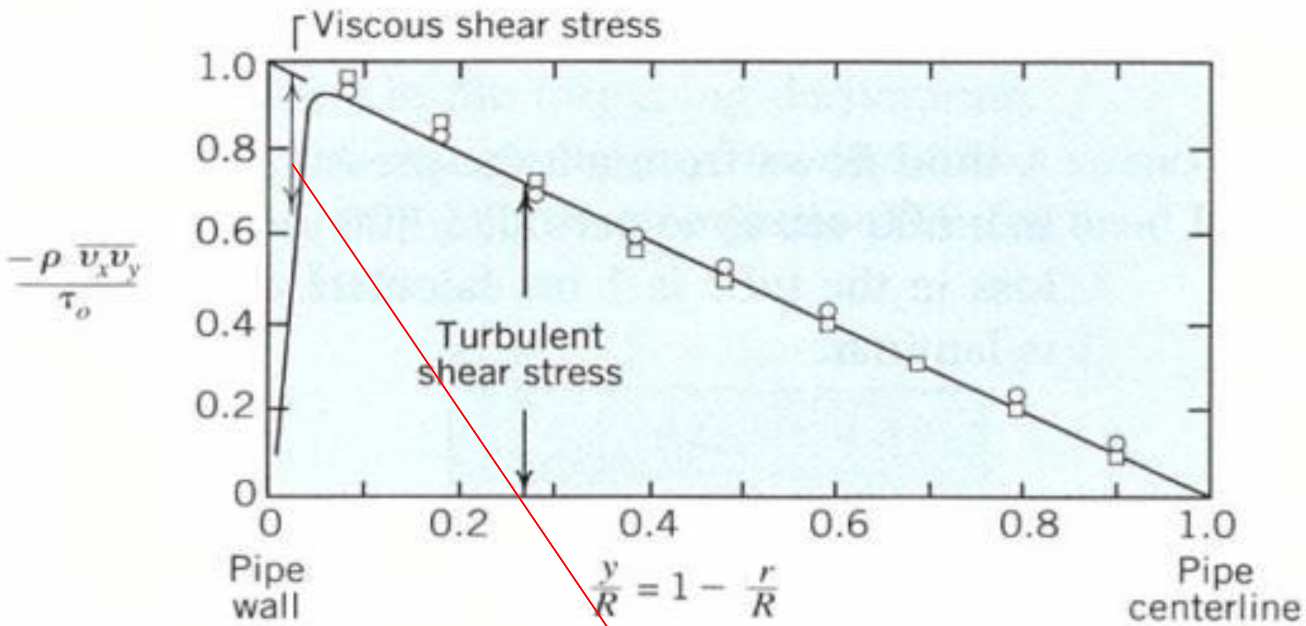
23.2 Structure of a Turbulent Boundary Layer

- Turbulence intensity in the turbulent region only: $\dfrac{\overline{u'^2}}{\Omega u_*^2}, \dfrac{\overline{v'^2}}{\Omega u_*^2}, \dfrac{\overline{w'^2}}{\Omega u_*^2}$

  - Turbulent energy (intensity) has a peak value very near the wall and decreases toward the free stream.



23.2 Structure of a Turbulent Boundary Layer



Near wall, viscous shear is dominant.