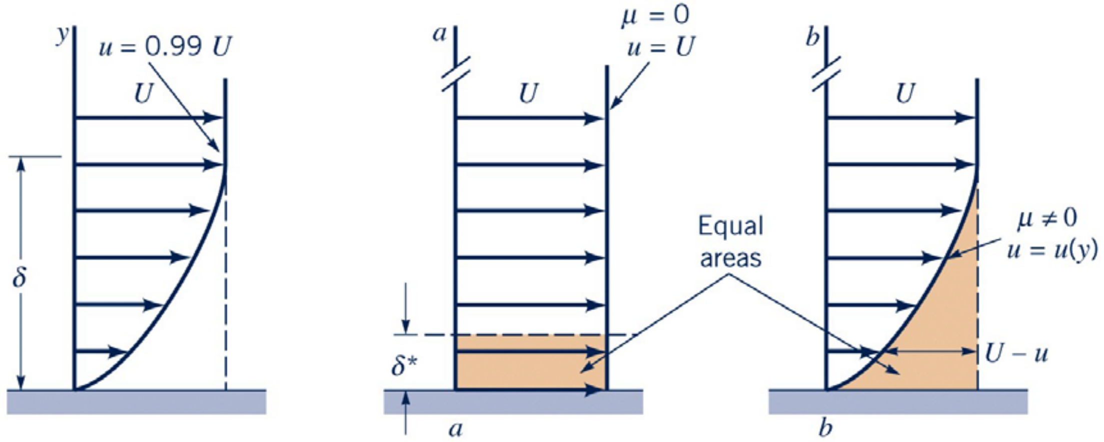
Chapter 9

Turbulent Boundary-Layer Flows



Chapter 9 Turbulent Boundary-Layer Flows

Contents

Objectives

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

9.1 Introduction

- Turbulence occurs most commonly in shear flows.
- Shear flow: spatial variation of the mean velocity

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

- Turbulent motion in shear flows is self-sustaining: Turbulence arises as a consequence of the shear and shear persists as a consequence of the turbulent fluctuations.
- Wall turbulence:

1) Non-uniform boundary layers on immersed bodies

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

9.1 Introduction

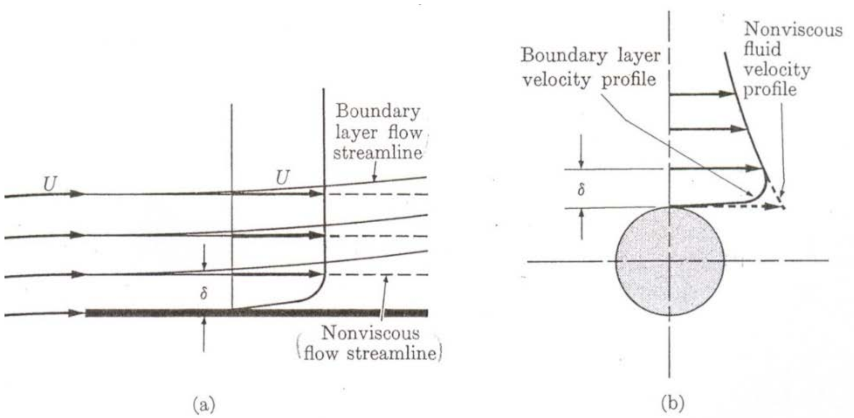


FIG. 8–4. Boundary layer versus slip flow: (a) flat plate; (b) cylinder.

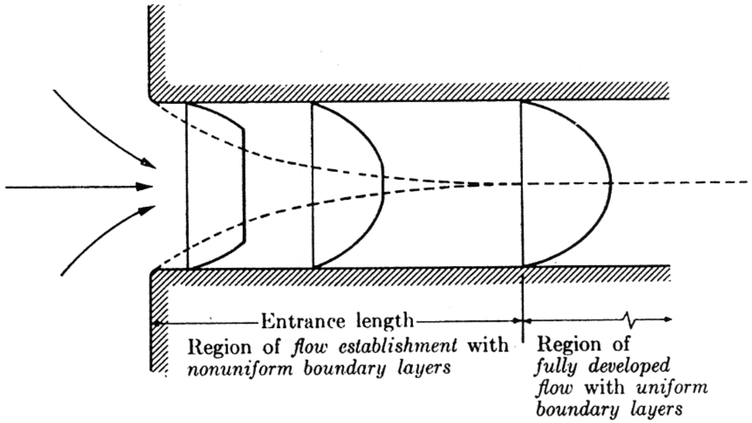


FIG. 8–5. Boundary layers in ducts.

9.2 Structure of a Turbulent Boundary Layer

9.2.1 Boundary layer flows

(i) Smooth boundary

Consider a fluid stream flowing past a smooth boundary.

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

1) $\mathrm{Re} < \mathrm{Re}_{crit}$

→ The boundary-layer is initially laminar.

$\rightarrow \; u = u(y)$

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

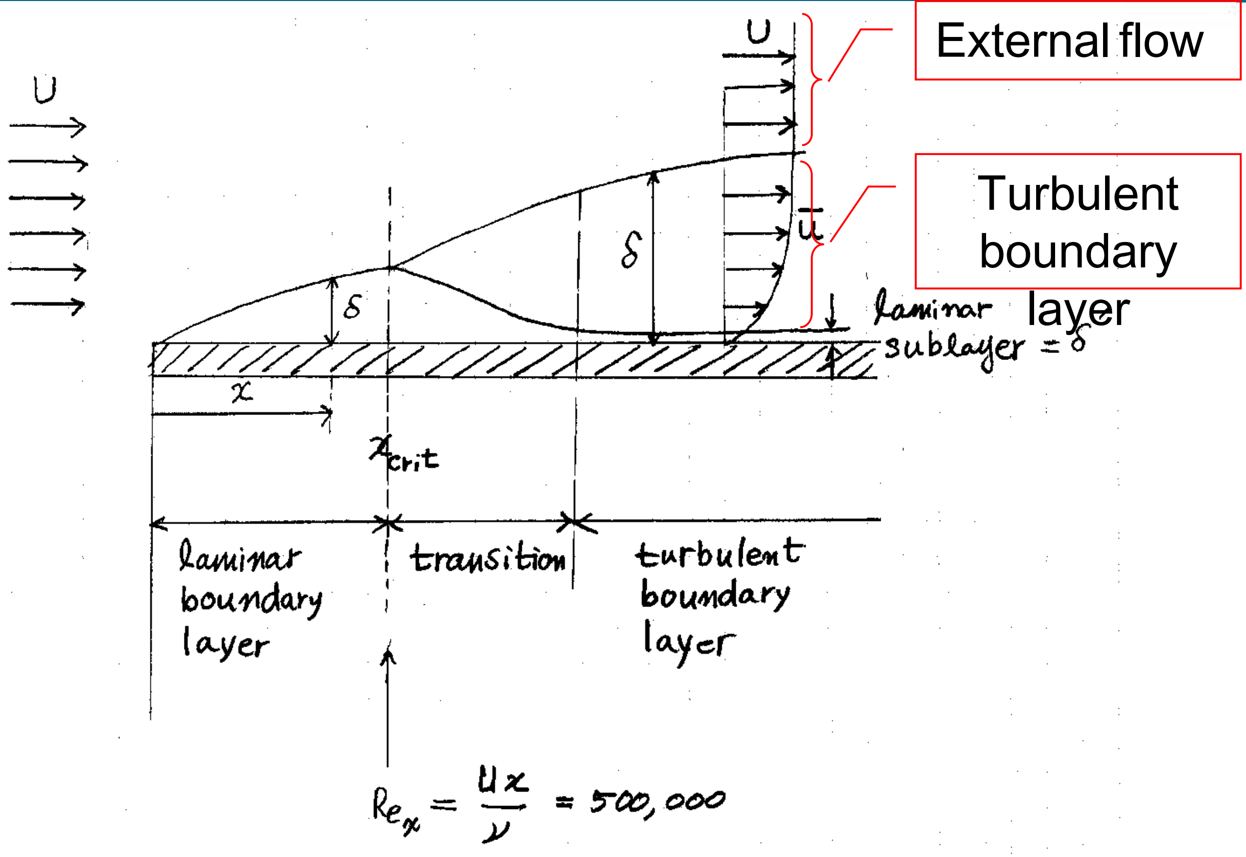
→ The boundary-layer is turbulent.

$\rightarrow \; \bar{u} = \bar{u}(y)$

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

→ <u>thicker boundary layer</u>:

9.2 Structure of a Turbulent Boundary Layer



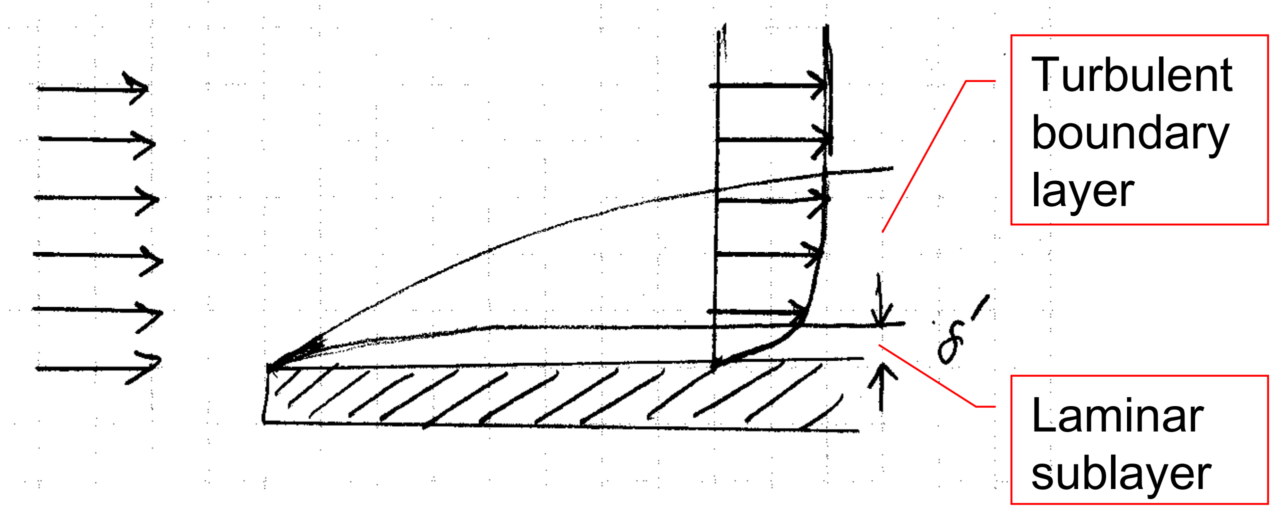
$x < x_{crit}$, total friction = laminar shear stress

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

9.2 Structure of a Turbulent Boundary Layer

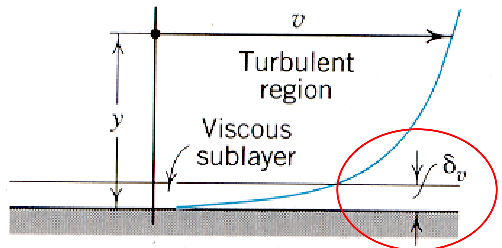
(ii) Rough boundary

- 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.

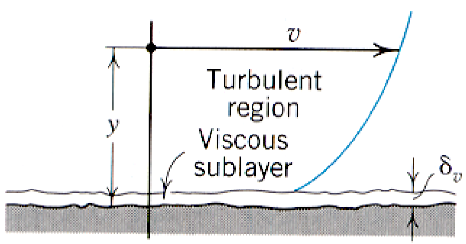


9.2 Structure of a Turbulent Boundary Layer

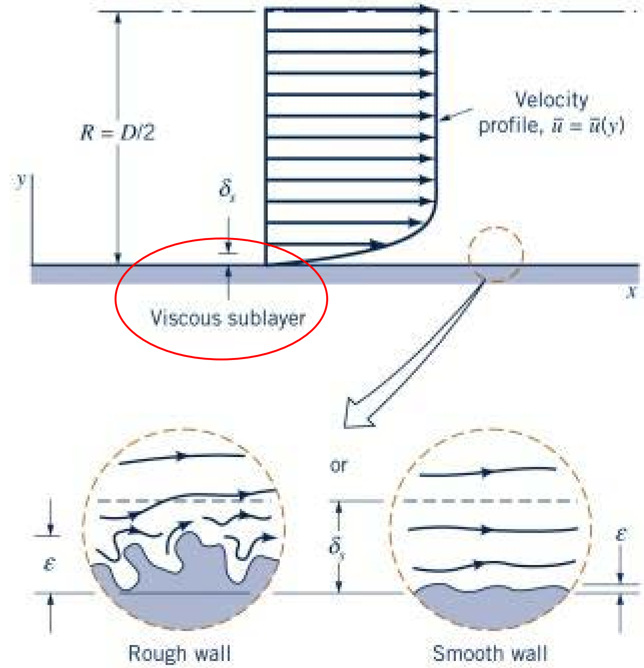
smooth vs rough boundary



(a) **Smooth boundary**



(b) **Rough boundary**



9.2 Structure of a Turbulent Boundary Layer

9.2.2 Comparison of laminar and turbulent boundary-layer profiles

Compare thickness of boundary layer for the laminar and turbulent flows of the same Reynolds number on the smooth wall

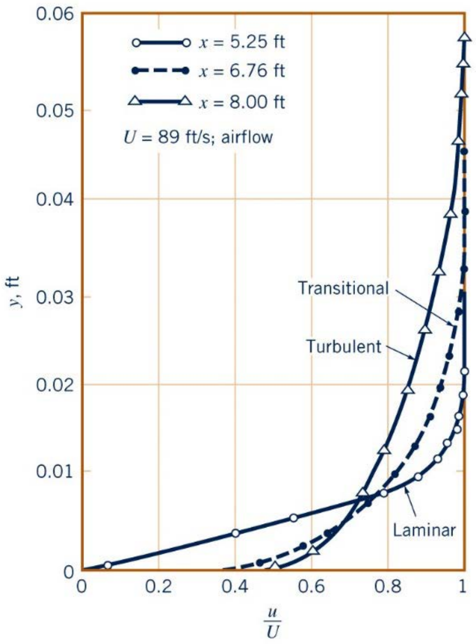
$$Re_x = \frac{Ux\rho}{\mu} = 500,000$$

From Ch. 10 (D&H), we have

$$\delta_{lam} = \frac{5x}{Re_x^{1/2}}$$

$$\delta^*_{lam} = \frac{1.73x}{Re_x^{1/2}}$$

$$\theta_{lam} = \frac{0.664x}{Re_x^{1/2}}$$



9.2 Structure of a Turbulent Boundary Layer

1) Boundary layer thickness

$$\frac{\delta_{turb}}{\delta_{lam}} = 3.9$$

2) Mass displacement thickness,

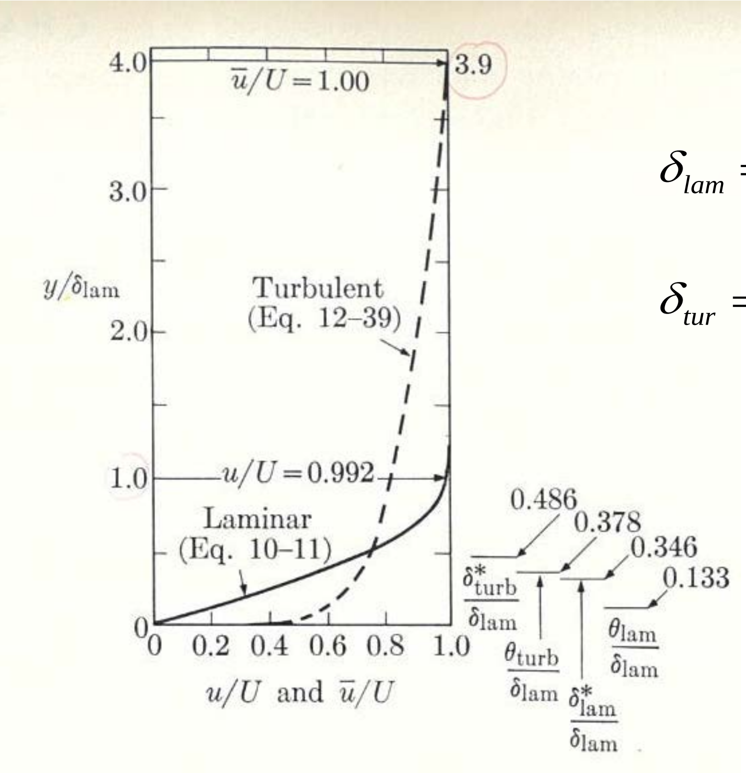
Eq. (8.9): $$\delta^* = \int_0^h \left(1 - \frac{u}{U}\right) dy$$

$$\frac{\delta^*_{turb}}{\delta^*_{lam}} = 1.41$$

3) Momentum thickness, θ

Eq. (8.10): $$\theta = \int_0^h \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$$

$$\frac{\theta_{turb}}{\theta_{lam}} = 2.84$$



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

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

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

9.2 Structure of a Turbulent Boundary Layer

9.2.3 Intermittent nature of the turbulent layer

• Outside a boundary layer

→ free-stream shearless flow (*U*) → potential flow (inviscid)

→ slightly turbulent flow

→ considered to be non-turbulent flow relative to higher turbulence inside a turbulent boundary layer

• Interior of the turbulent boundary layer (δ)

~ 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

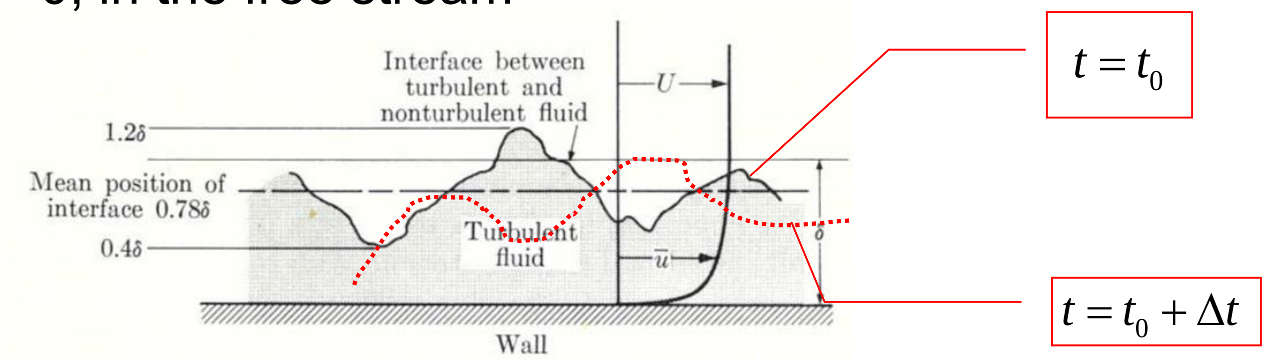
9.2 Structure of a Turbulent Boundary Layer

- 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



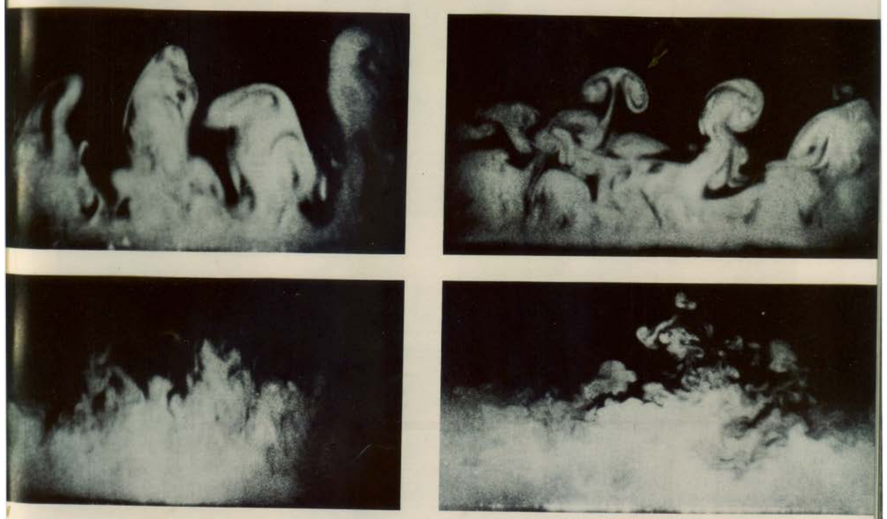
①Average position of the turbulent-nonturbulent interface = 0.78 δ

②Maximum stretch of interface = 1.2 δ

③Minimum stretch of interface = 0.4 δ

9.2 Structure of a Turbulent Boundary Layer

162. "Typical eddy" in a turbulent boundary layer. Oil fog is illuminated by a sheet of laser light to show the lower two-thirds of a turbulent boundary layer in side view. The vortex-ring structure just below and to the right of center, which resembles a sliced mushroom leaning left, is an example of what Falcò has called a "typical eddy." It scales on wall variables (figure 161) rather than on the boundary-layer thickness. *Photograph by R. E. Falco*



163. Oblique transverse sections of a turbulent boundary layer. The flow is viewed head-on, with smoke illuminated by a sheet of light that is inclined 45° downstream from the wall on the left and 45° upstream on the right. The Reynolds number based on momentum thickness is 600 in the upper pair of photographs and 9400 below. *Head & Bandyopadhyay 1981*

9.2 Structure of a Turbulent Boundary Layer

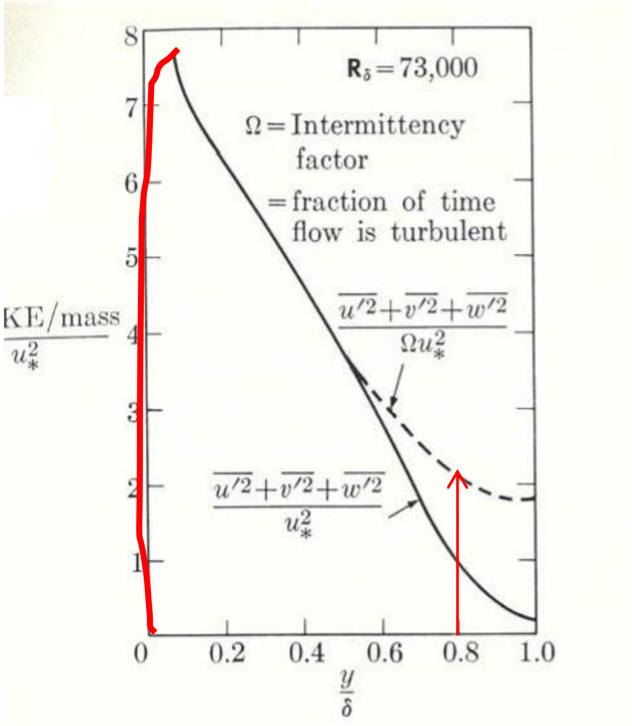
- Turbulent energy in a boundary layer, δ

- Dimensionless energy $= \dfrac{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}{u_*^2}$ (9.1)

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

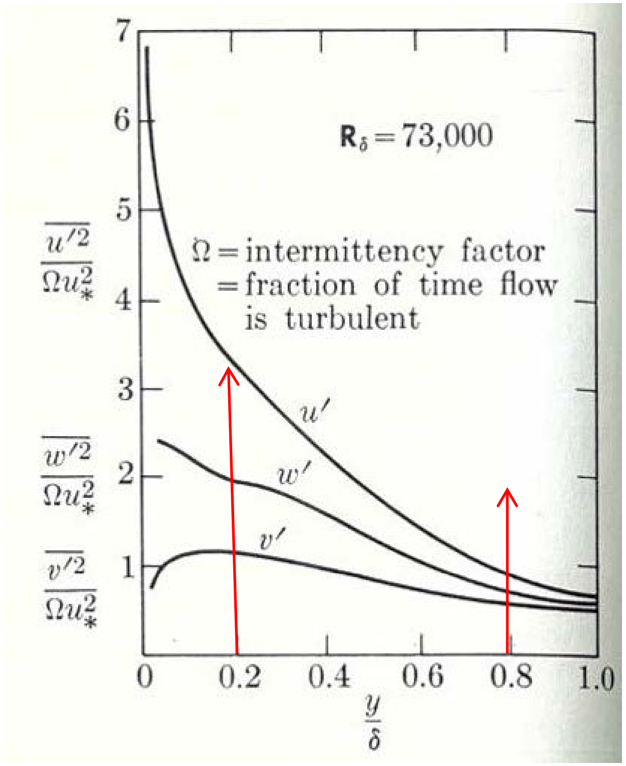
$$\mathrm{Re}_\delta = \frac{U\delta}{\nu} = 73{,}000 \iff \mathrm{Re}_x = 4\times10^6$$

for turbulent layer



9.2 Structure of a Turbulent Boundary Layer

• Turbulence intensity in a boundary layer



$$\frac{\overline{u'^2}}{\Omega u_*^2},\ \frac{\overline{v'^2}}{\Omega u_*^2},\ \frac{\overline{w'^2}}{\Omega u_*^2}$$

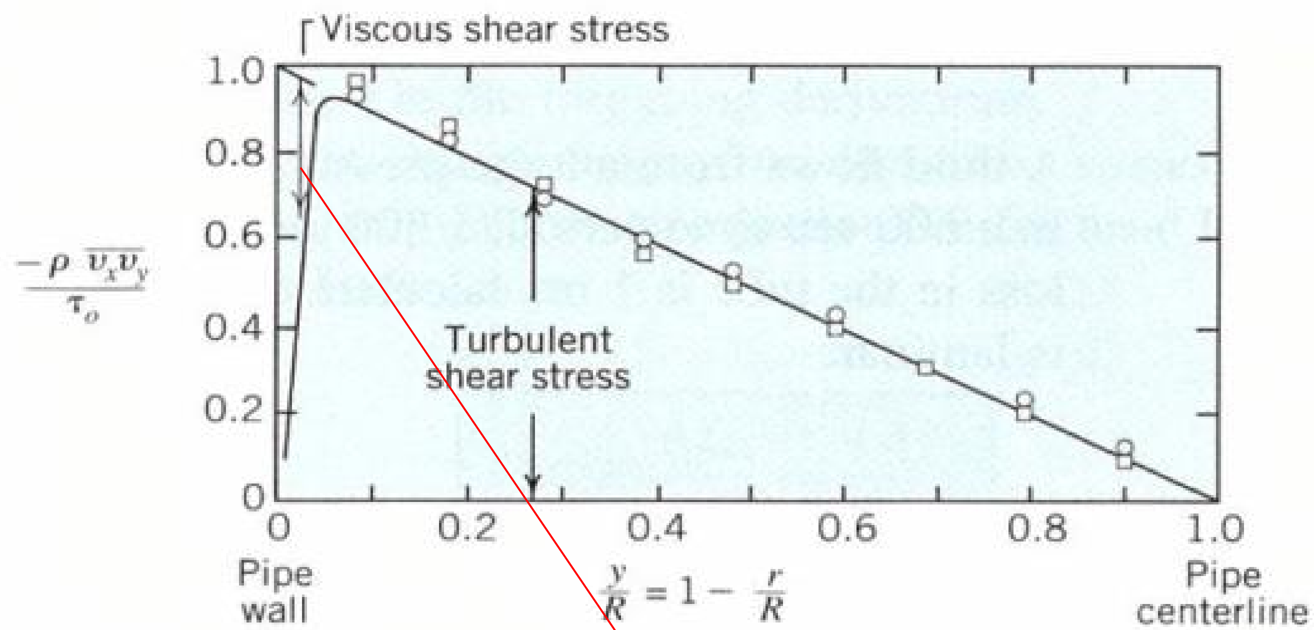
- smooth wall → $v' = 0$ at wall

- rough wall → $v' \neq 0$ at wall

- smooth & rough wall

→ turbulent energy ≠ 0 at y = δ

9.2 Structure of a Turbulent Boundary Layer



Near wall, viscous shear is dominant.