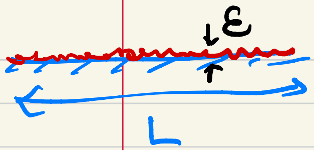
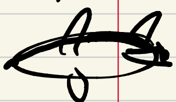


ε : roughness

비행기



$L = 50\,m$

$U = 300\,m/s$

$Re_L = \frac{UL}{\nu} \doteqdot 10^9$

$Re_\delta = 0.16\, Re_x^{6/7} = 1.6 \times 10^8$

자동차

$L = 5\,m$

$U = 30\,m/s$

$Re_L = 10^7$

$Re_\delta = 1.6 \times 10^5$

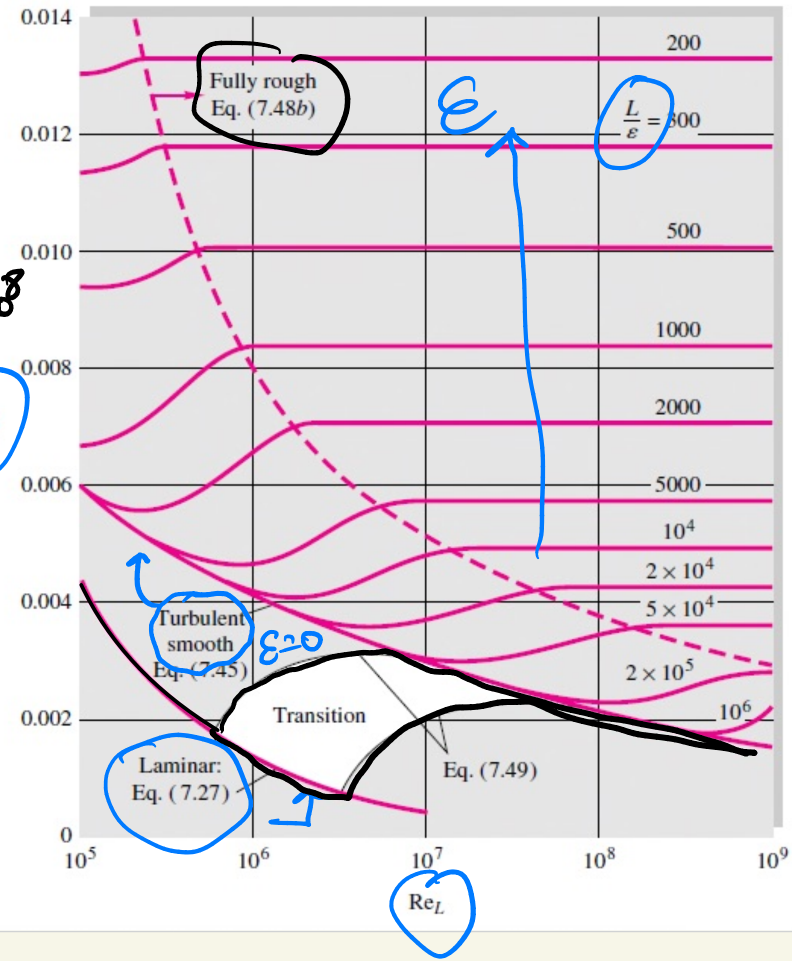
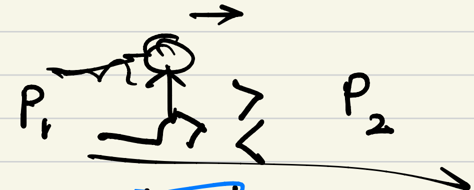


Fig. 7.6 Drag coefficient of laminar and turbulent boundary layers on smooth and rough flat plates. This chart is the flat-plate analog of the Moody diagram of Fig. 6.13.

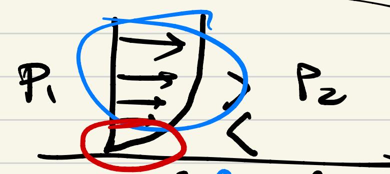
7.5 Boundary layers w/ pressure gradients

flat plate : $U = \text{const} \rightarrow \frac{dU}{dx} = 0 \rightarrow \frac{dp}{dx} = 0$

$\frac{dp}{dx} > 0$: adverse press. grad.
역 압력 구배



$\frac{dp}{dx} < 0$: favorable press. grad.
순 압력 구배

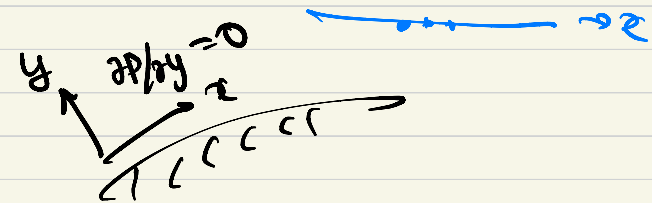


- N-S eq :

$$\cancelto{0}{\frac{\partial u}{\partial t}} + \cancelto{0}{u}\frac{\partial u}{\partial x} + \cancelto{0}{v}\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\cancel{\frac{\partial^2 u}{\partial x^2}} + \frac{\partial^2 u}{\partial y^2}\right)$$

@ $y=0$ (wall), $u = v = 0$ (no slip)

$$\Rightarrow \quad 0 = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2}\bigg|_w$$



$$\Rightarrow \quad \boxed{\frac{\partial^2 u}{\partial y^2}\bigg|_w = \frac{1}{\mu}\frac{\partial p}{\partial x}}$$

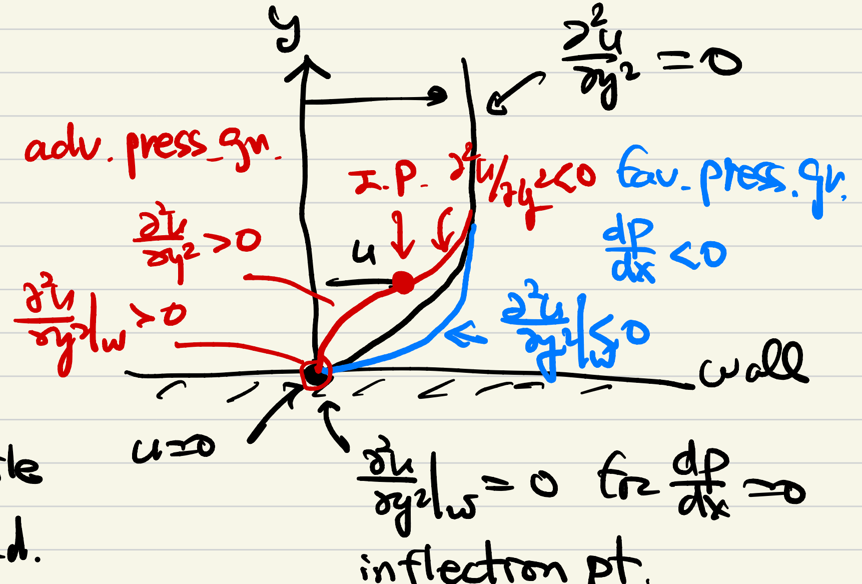
curvature

$$\left.\frac{\partial^2 u}{\partial y^2}\right|_w = \frac{1}{\mu}\frac{dp}{dx}$$

if $\frac{dp}{dx} = 0$, $\left.\frac{\partial^2 u}{\partial y^2}\right|_w = 0$

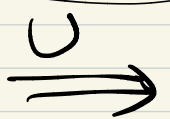
$\frac{dp}{dx} < 0$, $\left.\frac{\partial^2 u}{\partial y^2}\right|_w < 0$

$\frac{dp}{dx} > 0$, $\left.\frac{\partial^2 u}{\partial y^2}\right|_w > 0$



→ Any boundary layer profile in an adverse press. grad. exhibits a characteristic S shape.

flow Separation 유동 박리

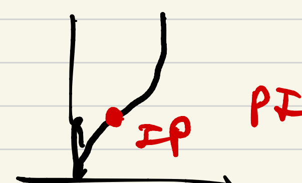


zero press. gr. $\frac{dp}{dx} = 0$, $\frac{dU}{dx} = 0$, no sep.

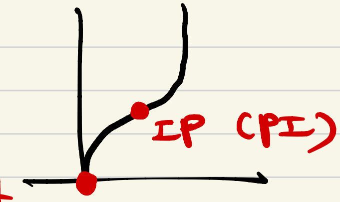
weak adv. press grad.

$\frac{dp}{dx} > 0 \rightarrow \frac{dU}{dx} < 0$

no sep.



critical adv. press. gr. $\frac{dp}{dx} > 0$ $\frac{du}{dx} < 0$



↓

separation starts

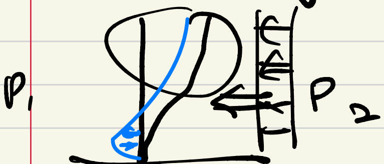
separation pt.
박리점

$\Rightarrow \left.\frac{\partial u}{\partial y}\right|_w = 0$

$\tau_w = 0$

↓

boundary layer thickness ↑

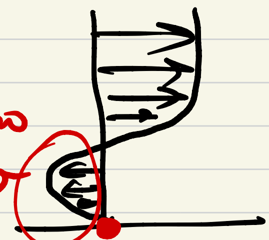


bdry layer approx X

reattach-ment point
재부착점

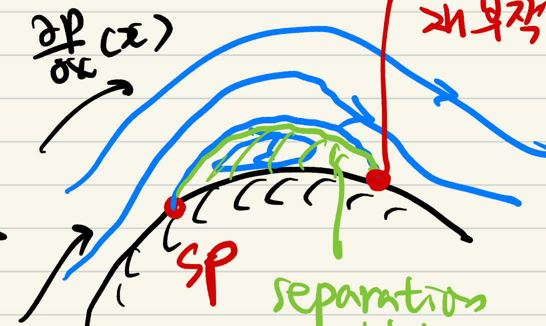
excessive adv. press gr.

backward flow
reverse flow

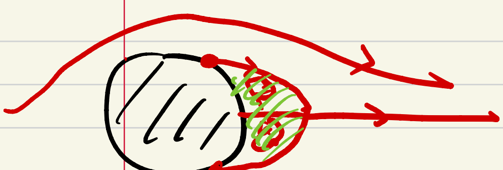


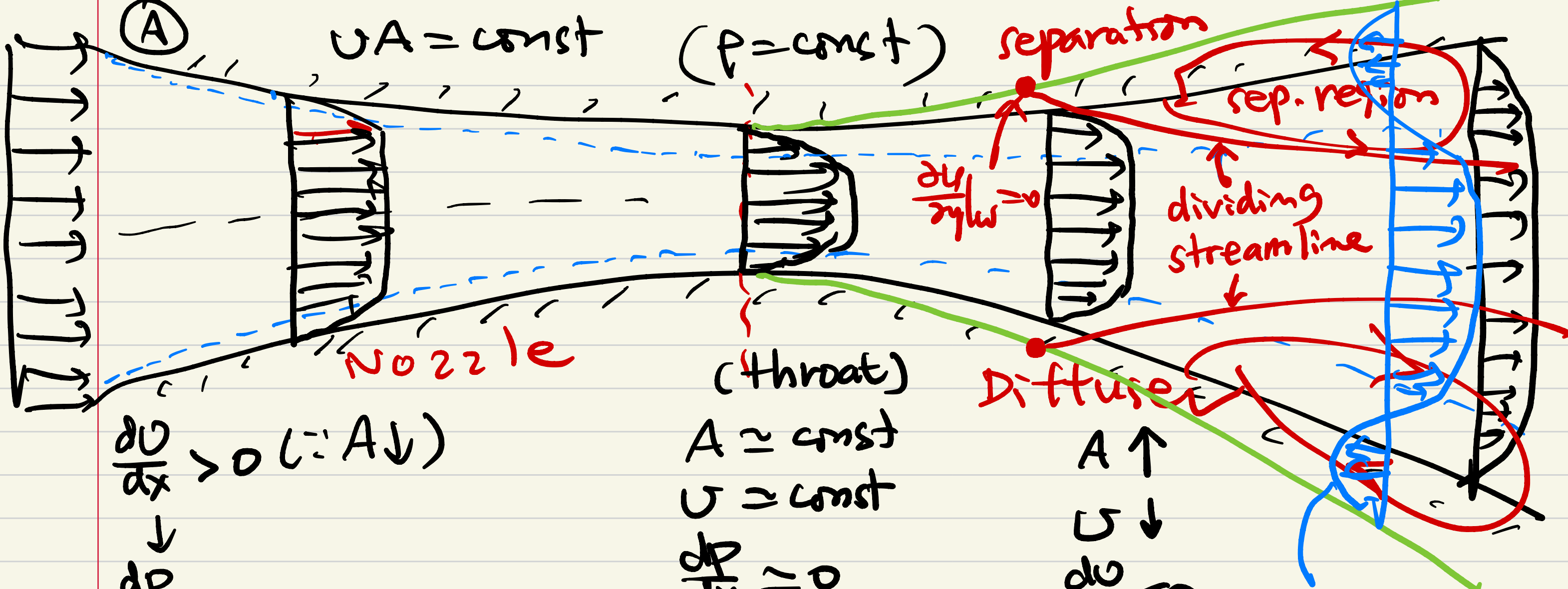
$\left.\frac{\partial u}{\partial y}\right|_w < 0$

$\tau_w < 0$



separation regime





$\frac{dU}{dx} > 0$ ($\because A \downarrow$)

$\downarrow$

$\frac{dp}{dx} < 0$

fav. pres. gr.

$A \simeq$ const

$U \simeq$ const

$\frac{dp}{dx} \simeq 0$

zero pres. gr.

$A \uparrow$

$U \downarrow$

$\frac{dU}{dx} < 0$

$\frac{dp}{dx} > 0$ $\quad p \uparrow$

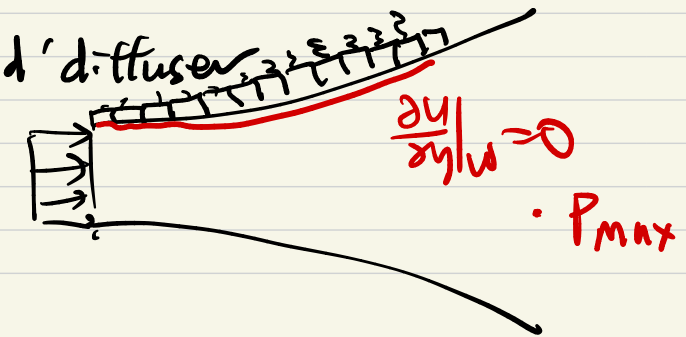
adv. pres. gr.

stall

$\downarrow$

heavy flow loss

'Stratford' diffuser



Boundary layer theory ($u \gg v$, $\frac{\partial}{\partial y} \gg \frac{\partial}{\partial x}$, $\frac{\partial^2}{\partial y^2} \gg \frac{\partial^2}{\partial x^2}$)
is valid only up to the separation pt.

- Laminar bdry layer integral theory (Karman)

$$\frac{\tau_w}{\rho U^2} = \boxed{\frac{C_f}{2} = \frac{d\theta}{dx} + (2+H)\frac{\theta}{U}\frac{dU}{dx}} \quad \left(\frac{dU}{dx} = -\frac{1}{\rho U}\frac{dp}{dx}\right)$$

C_f, θ, H open form

separation occurs @ $H = 3.5$ laminar flow
($C_f = 0$) $= 2.4$ turbulent "

laminar turbulent

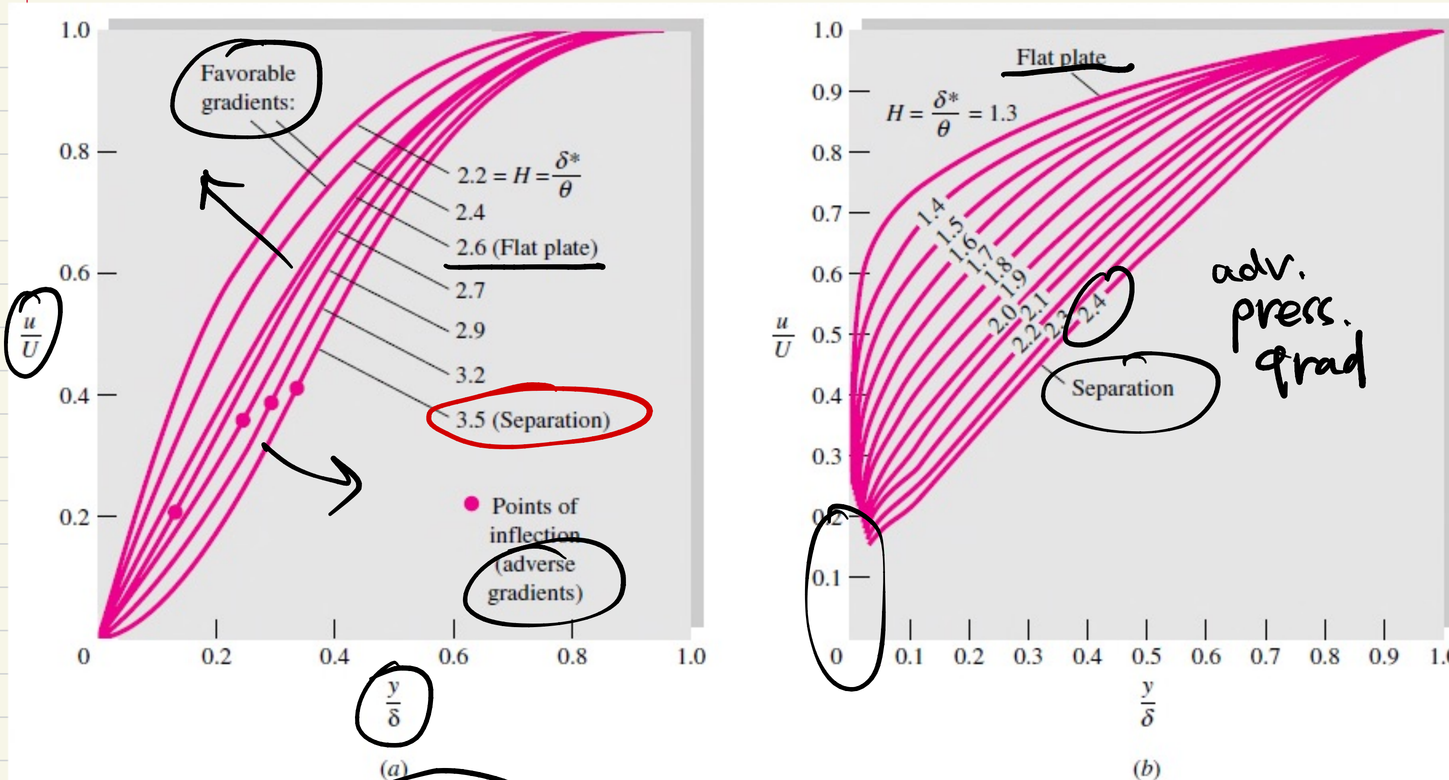


Fig. 7.9 Velocity profiles with pressure gradient: (a) laminar flow; (b) turbulent flow with adverse gradients.

7.6 Experimental external flows