Chapter 3. Fluid Flow Phenomena

: 유체의 거동은 고체 경계(solid boundaries)의 유무에 따라 영향을 받음

Potential flow ↔ Boundary layer flow
(포텐셜 흐름) (경계층 흐름)

Potential flow: 벽의 영향이 적은 지역(전단응력 무시 가능)

incompressible & zero viscosity인 ideal fluid 거동으로 해석

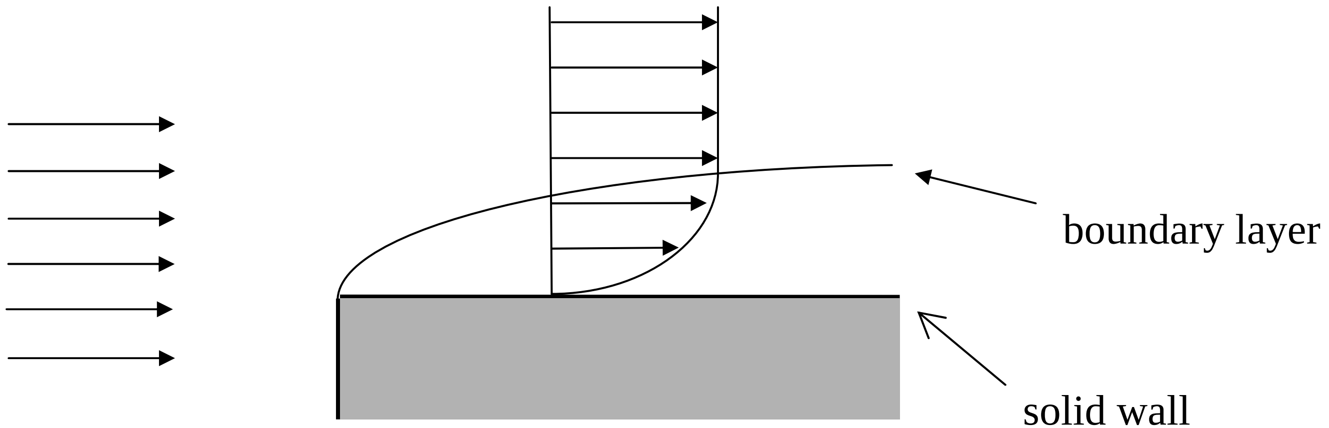
→ Newton 역학으로 기술 가능

(circulations나 eddies가 없는 irrotational flow,
friction이 없어 heat dissipation이 없음)

Boundary layer flow: 고체 벽면의 영향 하에 있는 유체의 흐름

→ 이 경우 다음의 효과가 나타남

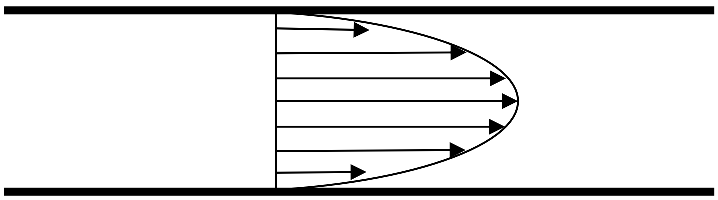
(coupling of velocity-gradient and shear-stress fields,
onset of turbulence,
formation and growth of boundary layers
separation of boundary layers from solid boundary)



Velocity at wall: zero (no-slip boundary condition)

One-dimensional flow: A flow that has only one velocity component

(ex. Steady flow through straight pipe)



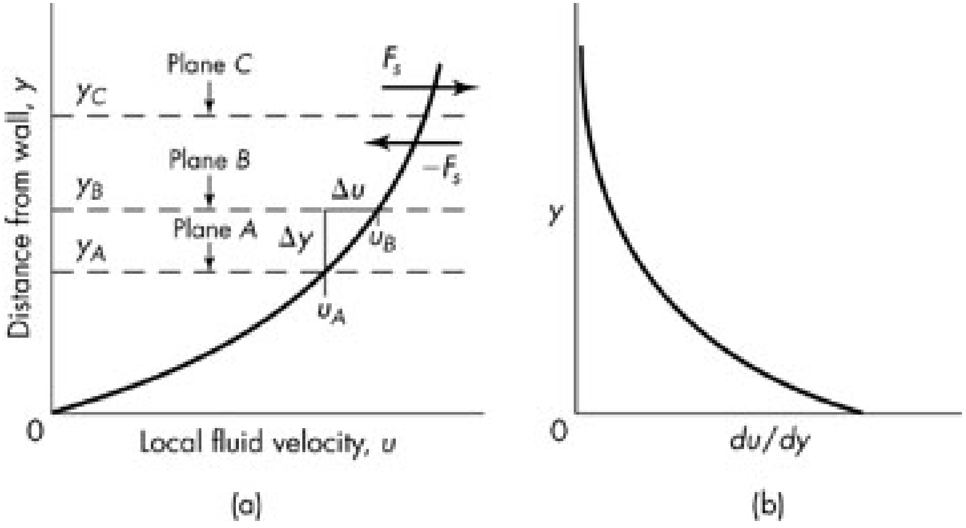
Steady (state) flow: flow invariant with time (the velocity at each location is constant)

Laminar Flow (층류)

← At low velocities, fluids flow without lateral mixing, cross-current and eddies.

Velocity gradient (or shear rate): 속도기울기 (전단속도)

: $\frac{du}{dy}$ (or $\dot{\gamma}$)



velocity

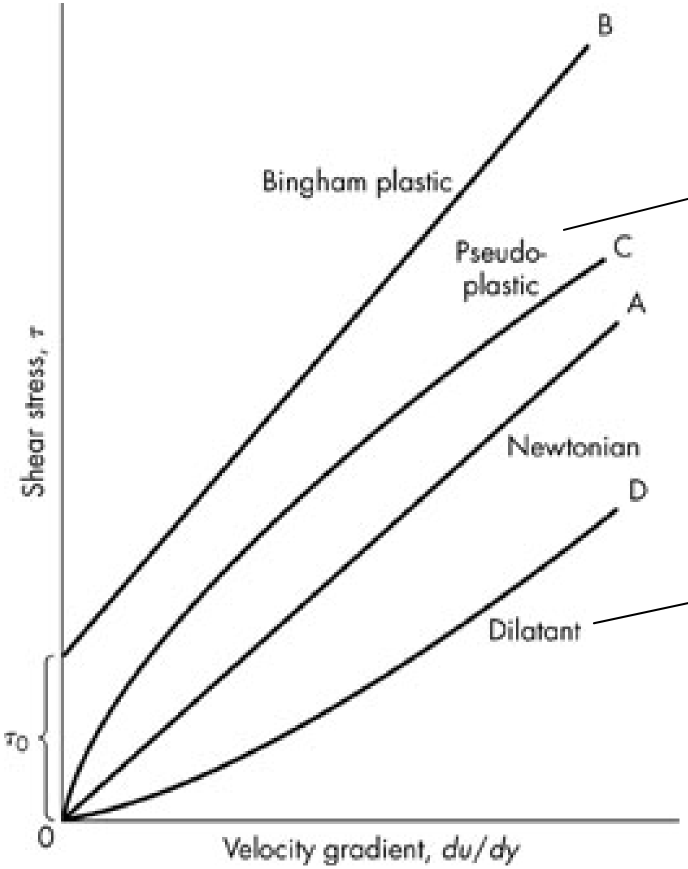
velocity gradient
(or shear rate)

Shear stress (전단응력)

: $\tau = \frac{F_s}{A_s}$

Rheological Properties (유변물성)

Newtonian & non-Newtonian fluids



or shear thinning
(전단담화)

yield stress
(항복응력)

or shear thickening
(전단농화)

Time-dependent flow

Thixotropic: shear stress (τ) decreases with time for a given shear rate (du/dy)

Rheopectic: shear stress increases with time for a given shear rate

Viscosity (점도), μ

: shear stress와 shear rate 그래프의 기울기, shear stress와 shear rate간의 비례상수

$$\boxed{\tau = \mu \frac{du}{dy}}$$: Newton's law ----- (3.3)

점도의 단위: Pa·s (kg/m·s), P (poise: g/cm·s), cP (1 Pa·s = 10 P = 1,000 cP 의 관계)

(물의 점도: 약 1 cP)

Kinematic viscosity (동점도, or 운동학 점도)

$$\nu \equiv \frac{\mu}{\rho}$$

동점도의 단위: St (Stokes: cm^2/s) ($1\ m^2/s = 10^4$ St 의 관계)

Viscosity models

Newtonian fluids:

$$\tau = \mu \frac{du}{dy}$$

Power-law fluids:

$$\tau = K \frac{du}{dy}^{n} = K \left| \frac{du}{dy} \right|^{n-1} \frac{du}{dy}$$

K: flow consistency index

n: power-law index (or flow behavior index)

n=1, Newtonian fluids ($K = \mu$)

n<1, pseudo-plastic (shear thinning) fluids

n>1, dilatant (shear thickening) fluids

Bingham plastics:

$$\tau - \tau_o = K \frac{du}{dy} \qquad \text{at } \tau > \tau_o$$

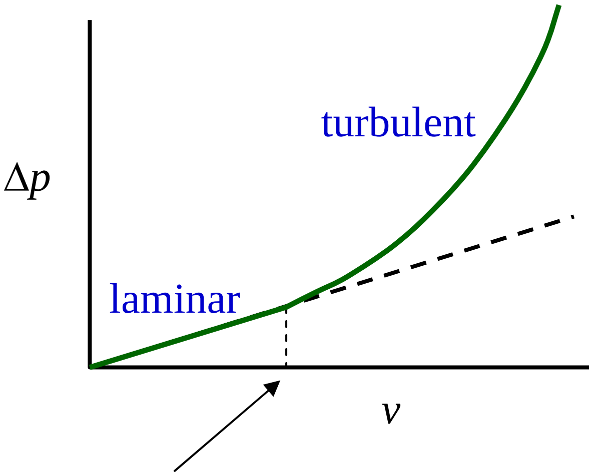
$$\frac{du}{dy} = 0 \qquad \text{at } \tau < \tau_o$$

τ_o: yield stress

Turbulence (난류)

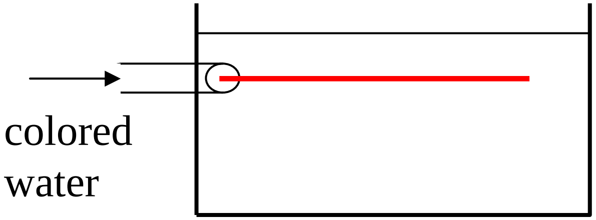
Pressure drop (Δp)

$$\propto \begin{cases} v & \text{at low flow rates} \\ v^2 & \text{at high flow rates} \end{cases}$$

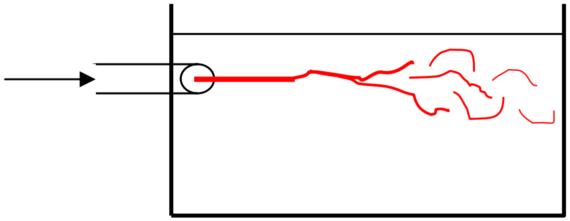


critical velocity

* An experiment by Osborne Reynolds



straight line, no cross mixing
→ laminar flow



wavy and gradually disappeared
→ turbulent flow

Reynolds number, Re : a dimensionless group

$$\boxed{\mathrm{Re} = \frac{D\bar{V}\rho}{\mu} = \frac{D\bar{V}}{\nu}} \quad : \text{------ (3.10)}$$

D: tube diameter

$\bar{V}$: average velocity

ρ: density

μ: viscosity

ν: kinematic viscosity

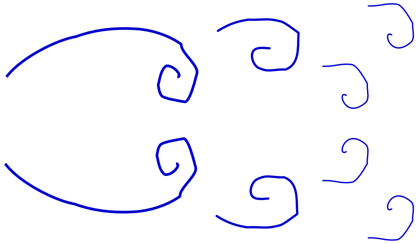
In a pipe flow,

Laminar region at Re<2,100

Turbulent region at Re>4,000

Transition region at 2,100<Re<4,000

Turbulent flow consists of eddies

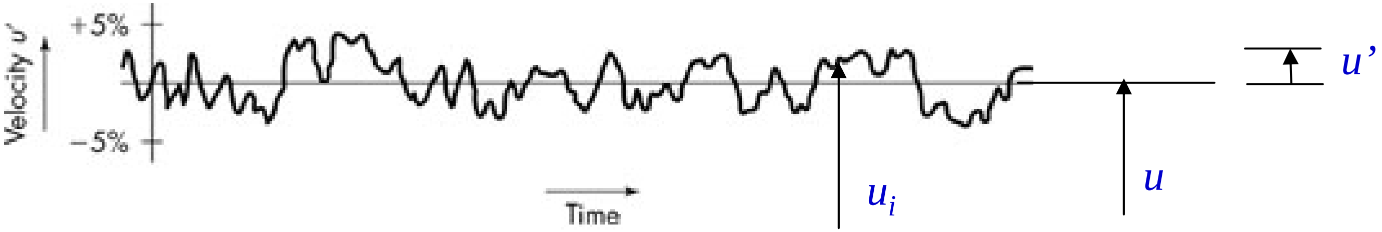


energy dissipation

largest -- dimension of stream

smallest -- 10-100 μm

- Deviating velocity (편차속도)



In one-dimensional turbulent flow,

$$u_i = u + u' \qquad v_i = v' \qquad w_i = w'$$

cf.) In laminar flow,

$$u_i = u \quad v_i = 0 \quad w_i = 0$$

u_i, v_i, w_i: instantaneous velocities (순간속도)

u, *v*, *w*: average velocities (평균속도)

u', *v*', *w*': deviating velocities (or fluctuating velocities) (편차속도 or 변동속도)

. *time average of u*': $\frac{1}{t_0}\int_0^{t_0} u'dt = 0$

. *time average of mean square of u*': $\frac{1}{t_0}\int_0^{t_0} (u')^2 dt = \overline{(u')^2}$

Isotropic turbulence (등방성 난류): $\overline{(u')^2} = \overline{(v')^2} = \overline{(w')^2}$

- Reynolds stress (or turbulent shear stress), τ_t

← 난류에서는 층류 보다 훨씬 큰 shear force가 존재 (deviating velocity 때문)

따라서 점성응력 이외에 추가적인 난류전단응력(Reynolds 응력)을 고려해야 함.

$$\tau_t = \rho\overline{u'v'}$$

- Eddy viscosity, E_v

← 난류전단응력과 전단속도와의 관계에서 정의되는 점도

(eddy viscosity E_v는 shear viscosity μ와 유사하게 정의됨)

$$\tau_t = E_v \frac{du}{dy}$$

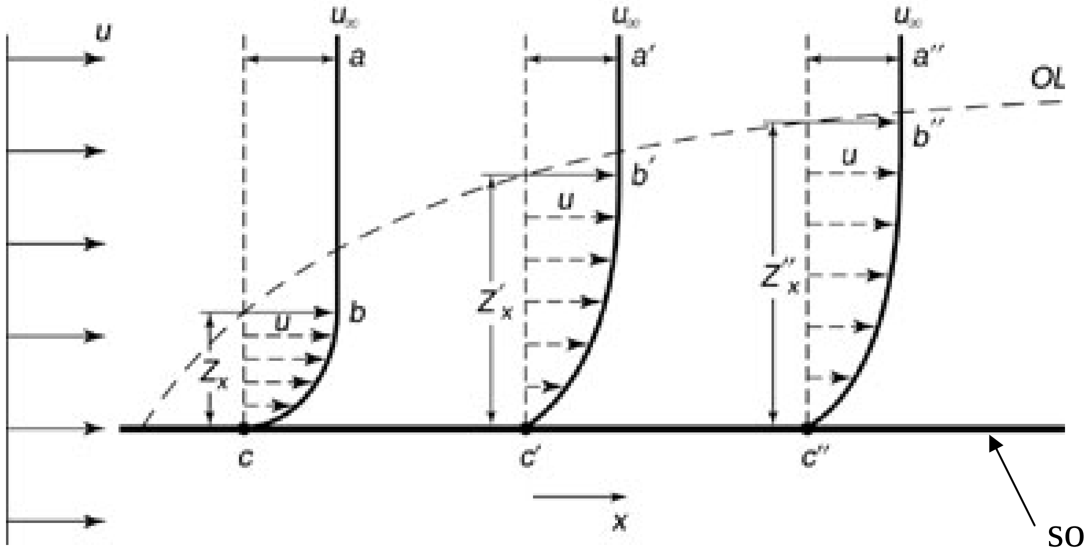
- Total shear stress in turbulent flow

← viscous stress와 turbulent stress의 합

$$\tau = \tau_v + \tau_t = (\mu + E_v)\frac{du}{dy}$$

Boundary Layers (경계층)

: The part of moving fluid in which the fluid motion is influenced by a solid boundary



Z: thickness of boundary layer

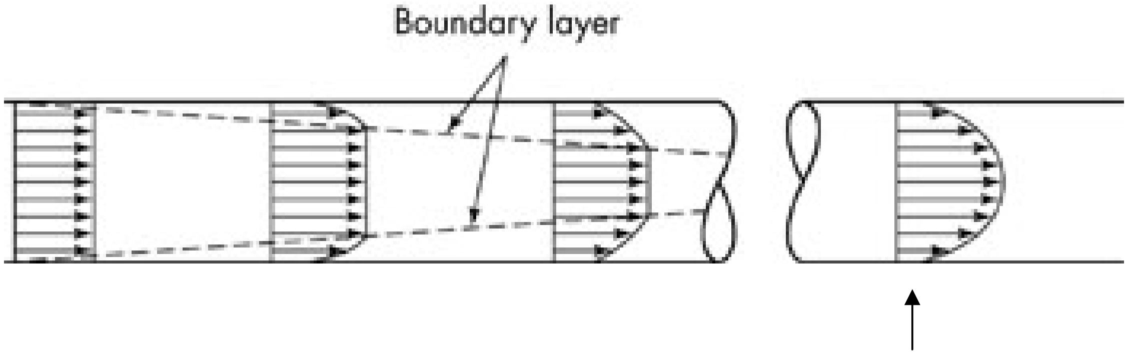
OL: outer limit of boundary layer

solid boundary

일반적으로 99% of u_∞ 지점을 연결한 line을 *OL*로 정의

bulk fluid velocity

Development of boundary layer flow in pipe



fully developed flow (완전발달흐름)
: 속도분포가 더 이상 변하지 않는 흐름

- Approximate length of pipe to reach fully developed flow, for laminar flow:

$$\boxed{\frac{x_t}{D} = 0.05\,\mathrm{Re}}$$

x_t: transition length

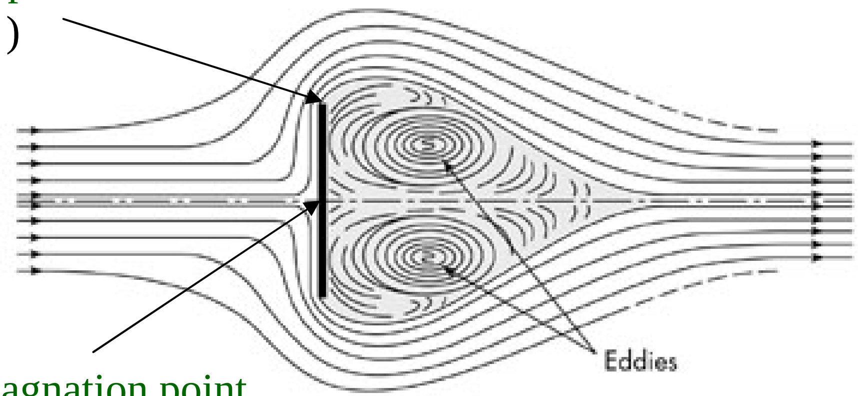
D: diameter of pipe

ex.) ID 50 mm, Re=1,500 → $x_t = 3.75$ m

Boundary layer separation and wake formation

(a) flow parallel with plate

separation point
(정체점)



stagnation point
(정체점)

(b) flow perpendicular to plate

eddy (에디)
vortex (와류)
wake (후류)

Related problems:

(Probs.) 3.1, 3.4, 3.5, 3.9 and 3.12