Lecture 4

Flow Patterns and Wind Forces

Tokyo Polytechnic University
The 21st Century Center of Excellence Program

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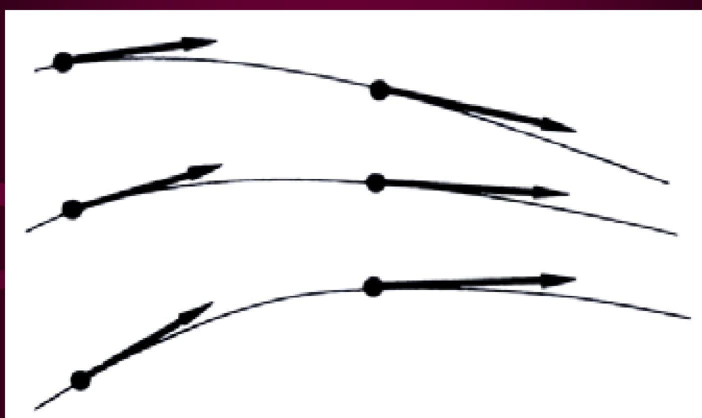
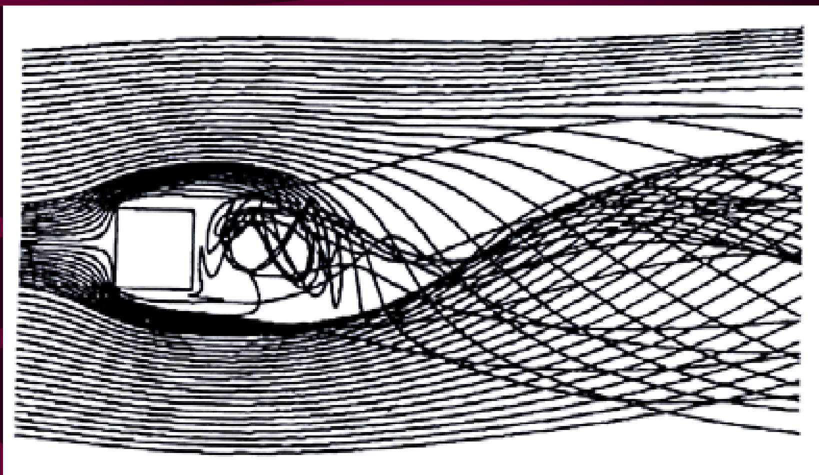
Flows Around Bluff Bodies

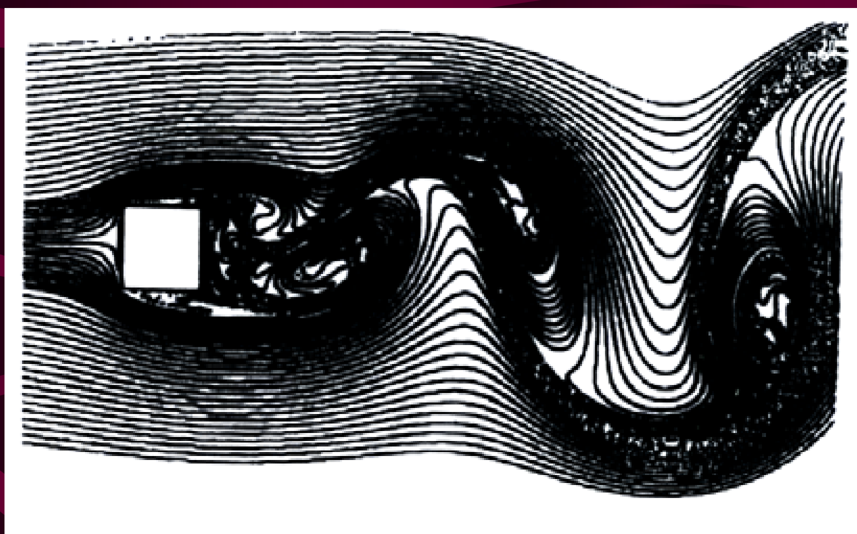
Flow Patterns Around Bluff Bodies



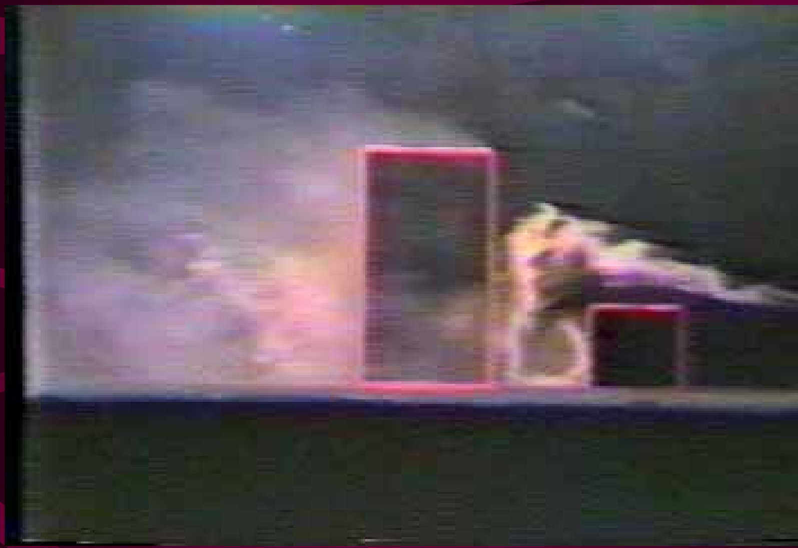
Stream Lines



Flow pattern around a square prism (Particle paths, 2D, Uniform flow, CFD)

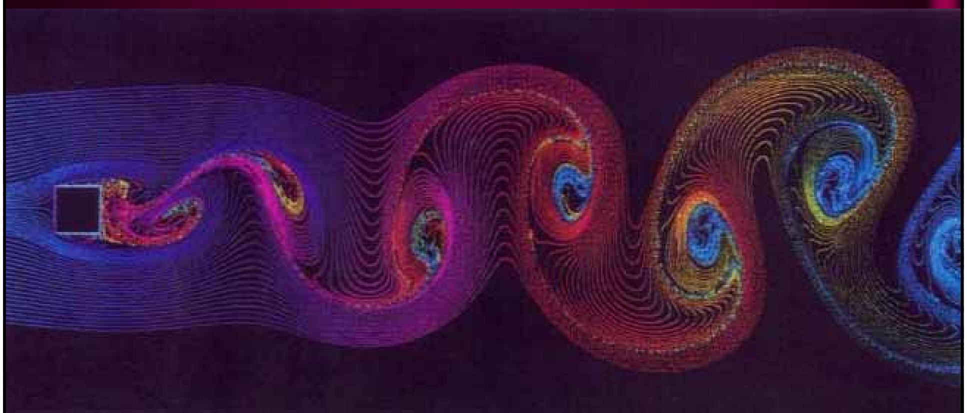


Flow pattern around a square prism (Streak Lines, 2D, Uniform Flow, CFD)

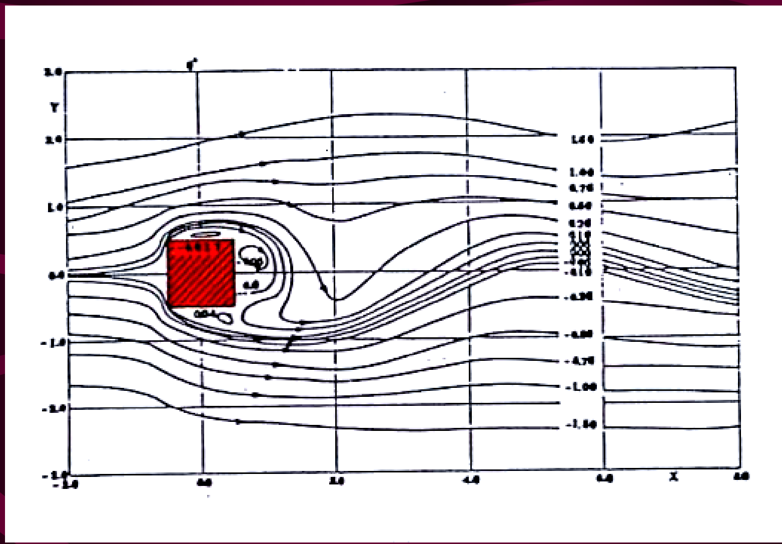


Flow pattern between building models
(Streak Lines)

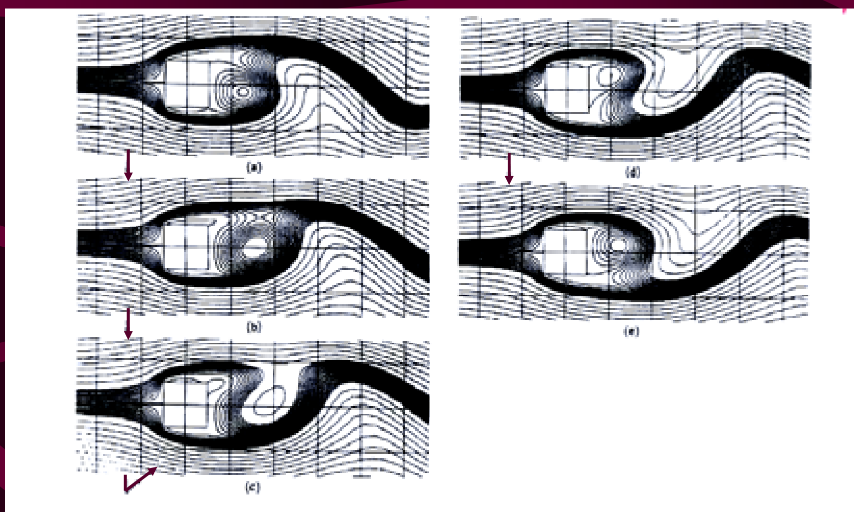
K. Shimada



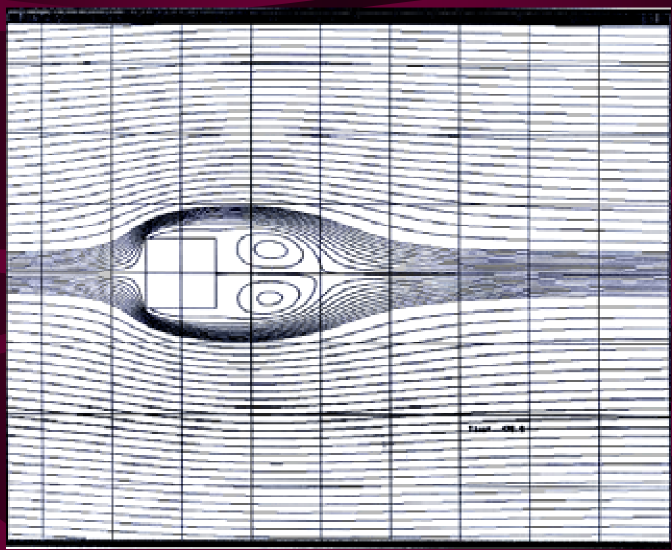
Periodic vortices shed from a square prism
(Streak Lines, CFD)



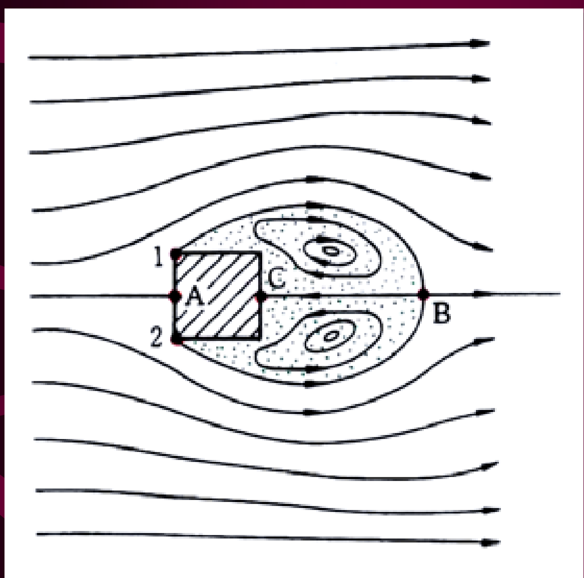
Flow pattern around a square prism
(Stream lines, Wind tunnel, by T. Mizota)



Temporal variation of flow pattern around a square prism (Stream lines, 2D, Uniform flow, CFD)

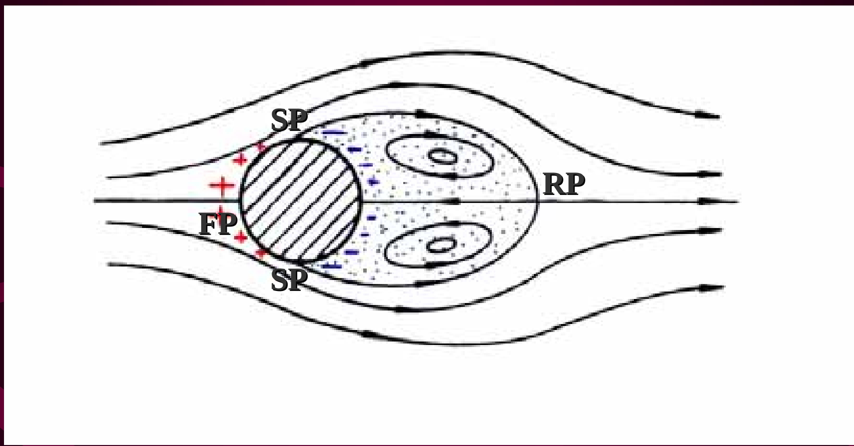


Temporally averaged flow pattern around a square prism (Stream lines, 2D, Uniform flow, CFD)

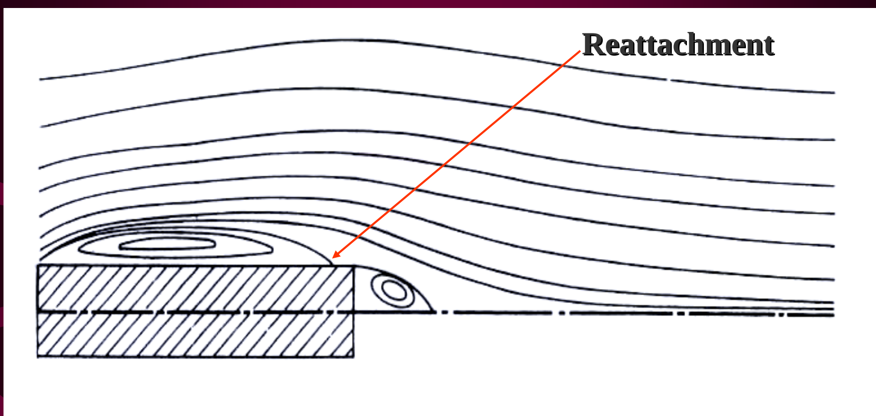


- A: Front stagnation point
- B: Rear stagnation point
- 1, 2: Separation point

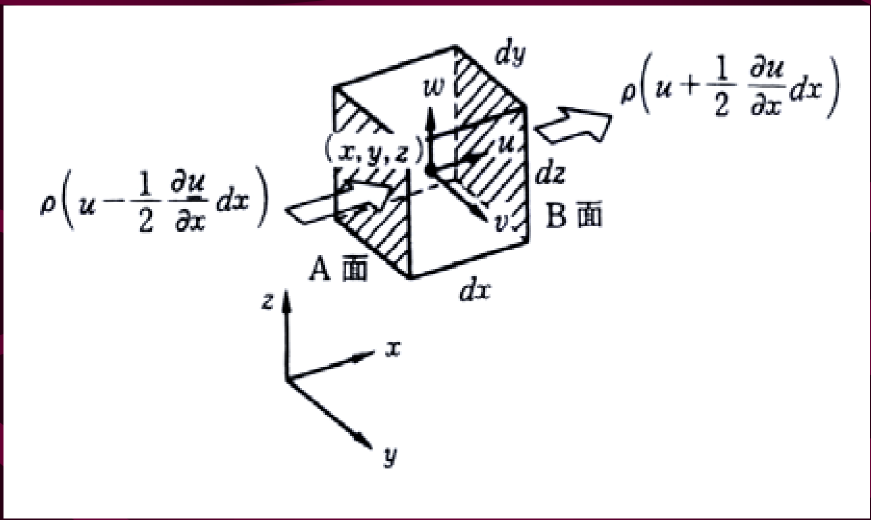
Temporally averaged flow pattern around a square prism



Temporally averaged flow pattern around a circular cylinder



Temporally averaged flow pattern around a rectangular cylinder with a large side ratio



Inflow and outflow into an infinitesimal hexahedron

Inflow through the ($dy \times dz$) plane:

$$\rho\left(u-\frac{1}{2}\frac{\partial u}{\partial x}dx\right)dydz-\rho\left(u+\frac{1}{2}\frac{\partial u}{\partial x}dx\right)dydz$$

$$=-\rho\frac{\partial u}{\partial x}dxdydz \qquad (1)$$

Inflow through the ($dz \times dx$) plane:

$$=-\rho\frac{\partial v}{\partial y}dxdydz \qquad (2)$$

Inflow through the ($dx \times dy$) plane:

$$=-\rho\frac{\partial w}{\partial z}dxdydz \qquad (3)$$

Law of Conservation of Mass

(Incompressive Fluid) : Eq.(1)+Eq.(2)+Eq.(3)=0

$$-\rho\frac{\partial u}{\partial x}dxdydz-\rho\frac{\partial v}{\partial y}dxdydz-\rho\frac{\partial w}{\partial z}dxdydz=0$$

Equation of Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

$$(\text{div}\ \vec{v}=0)$$

Vorticity Vector $\vec{\omega}$:

$$\vec{\omega}=(\xi,\ \eta,\ \zeta)=\text{rot}\ \vec{v}$$

$$\xi=\frac{\partial w}{\partial y}-\frac{\partial v}{\partial z}$$

$$\eta=\frac{\partial u}{\partial z}-\frac{\partial w}{\partial x}$$

$$\zeta=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}$$

$\xi,\ \eta,\ \zeta=2\omega_x, 2\omega_y, 2\omega_z$: Vorticity

$\omega_x, \omega_y\ \omega_z$: Rotational angular velocity about x, y and z axes

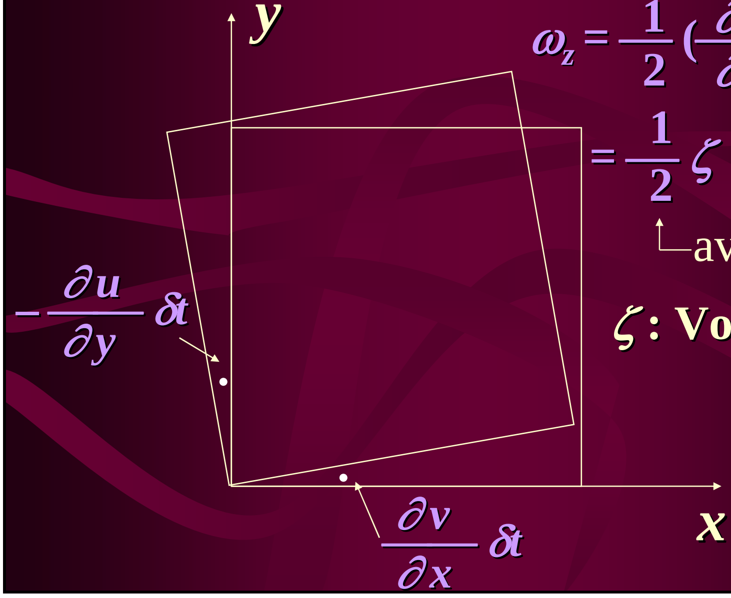
Angular Velocity of Rotation

$$\omega_z = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$$

$$= \frac{1}{2}\zeta$$

└average

ζ: Vorticity



- **Non-viscous and Irrotational Fluid**

$$\vec{\omega} = \text{rot}\,\vec{v} = 0$$

- **Velocity potential ϕ can be assumed:**

$$u = \frac{\partial \phi}{\partial x},\ v = \frac{\partial \phi}{\partial y},\ w = \frac{\partial \phi}{\partial z}$$

- **Equation of Continuity:**

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

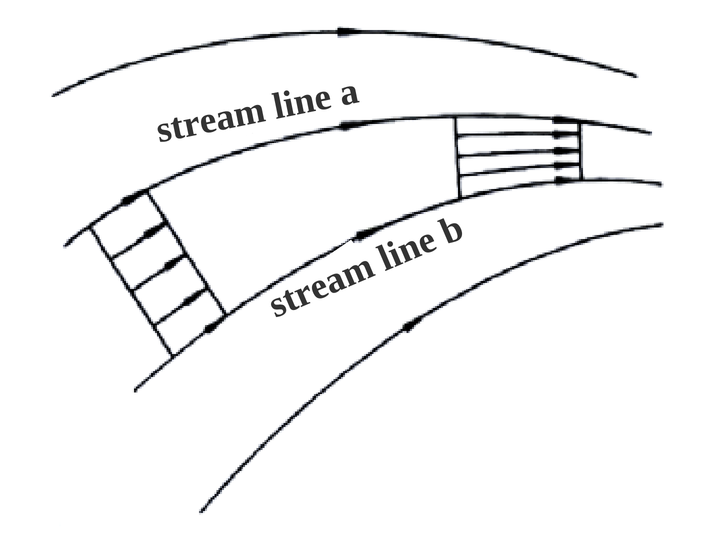
$$u = \frac{\partial \phi}{\partial x}, \quad v = \frac{\partial \phi}{\partial y}, \quad w = \frac{\partial \phi}{\partial z}$$

ϕ : Velocity potential

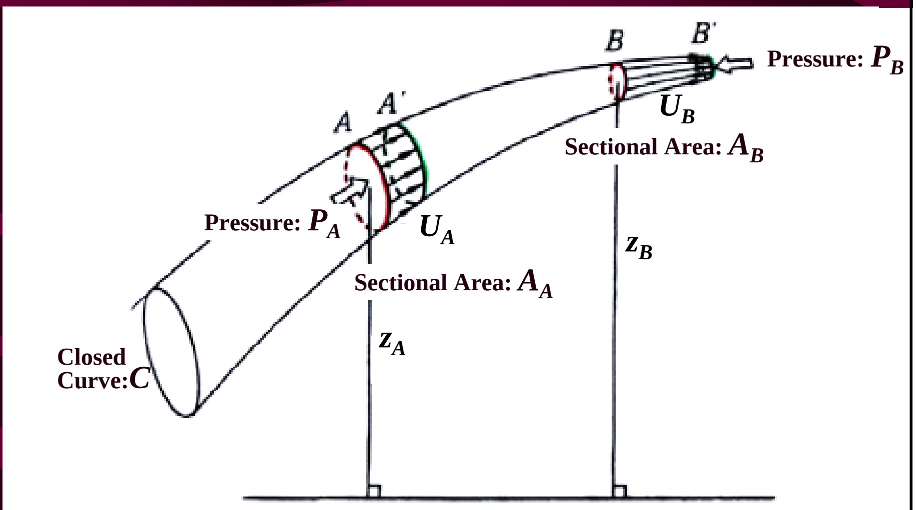
- **Laplace Equation:**

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

Flow Pattern and Pressure



Stream line and flow velocity



Stream tube and flow velocity

Incompressive Flow (Law of conservation of mass)

$$\rho A_A U_A = \rho A_B U_B = m$$

m : Air mass of inflow and outflow portions

Increase of kinetic energy during unit time

$$\frac{m}{2}(U_B^2 - U_A^2) \qquad (1)$$

Increase of potential energy during unit time

$$mg\,(z_B - z_A) \qquad (2)$$

Work done by pressure difference during unit time

$$(P_A A_A)U_A - (P_B A_B)U_B \qquad (3)$$

ρ : Air density, U_i : Wind speed at point i
P_i : Pressure at point i, g : Gravity acceleration
z_i : Altitude of point i

For the same stream tube:

$$\frac{1}{2}\rho U_A^2 + P_A + \rho g z_A$$
$$= \frac{1}{2}\rho U_B^2 + P_B + \rho g z_B$$

ρ : Air density
U_i : Wind speed at point i
P_i : Pressure at point i
g : Gravity acceleration
z_i : Altitude of point i

Eq.(1)+Eq.(2)= Eq.(3)

Bernoulli's Equation (Steady / Ideal flow)

$$\frac{1}{2}\rho U^2 + P + \rho g z = H_T \quad \text{(constant)}$$

- ρ : Air density
- U : Wind speed
- P : Pressure
- g : Gravity acceleration
- z : Altitude
- H_T : Total pressure

(On Stream

Bernoulli's equation:

$$\frac{1}{2}\rho U^2 + P_S = H_T \quad \text{(constant)}$$

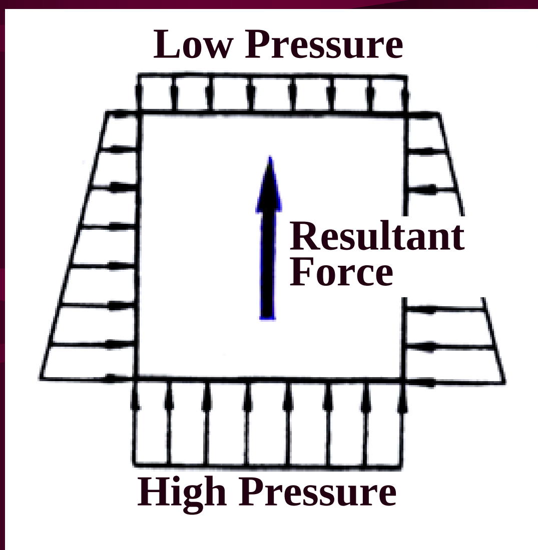
- ρ : Air density
- U : Wind speed
- P_S : Static pressure = $P + \rho g z$
- $\frac{1}{2}\rho U^2$: Dynamic pressure
- H_T : Total pressure

Bernoulli's equation:

$$\frac{1}{2}\rho U^2 + P_S = H_T \text{ (constant)}$$

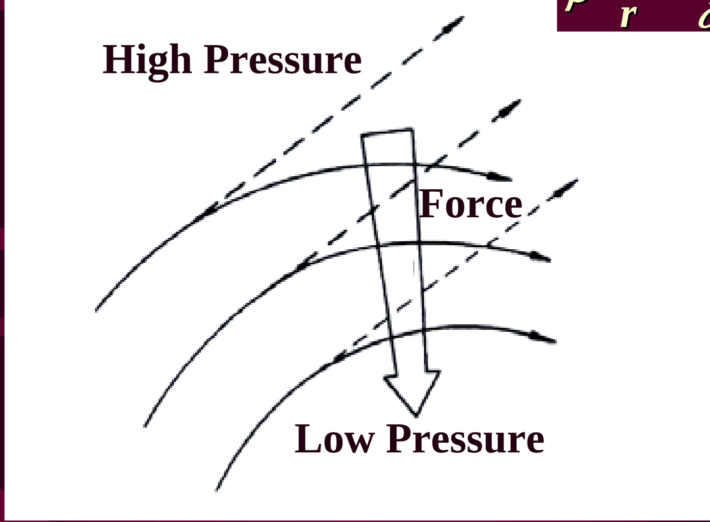
U : Large (Small)

P_S : Small (Large)



Pressure distribution and resultant force acting on a fluid cell

$$\rho \frac{U^2}{r} + \frac{\partial P}{\partial n} = 0$$



Curved stream line and pressure gradient

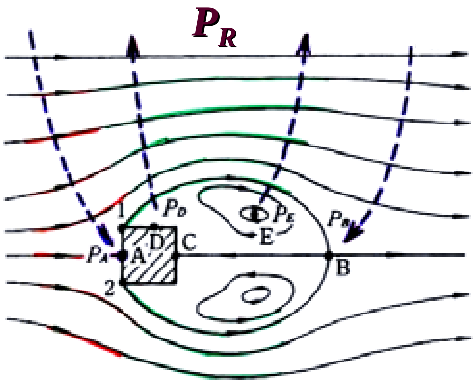
Wind Pressure at point *i*

$$p_i = P_i - P_R$$

P_i : Pressure at point *i*

P_R : Pressure at reference point *R* far away from the body, where there is no effect of the body on the flow field

Wind Pressure : $p_i = P_i - P_R$



$P_A > P_R$ $(p_A > 0)$

$P_B > P_R$ $(p_B > 0)$

$P_D < P_R$ $(p_D < 0)$

$P_E < P_R$ $(p_E < 0)$

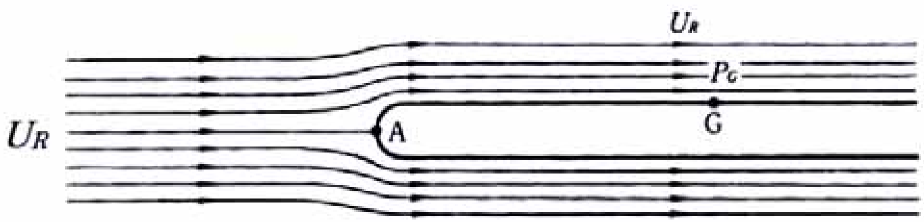
Stream lines around a square prism and spatial variation of pressure

$p_A = P_A - P_R = P_A - P_G =$

$= (1/2)\rho U_R^2$: Dynamic pressure (Velocity pressure) of the reference point

→ $U_R = \sqrt{2p_A/\rho}$ (Reference wind speed)

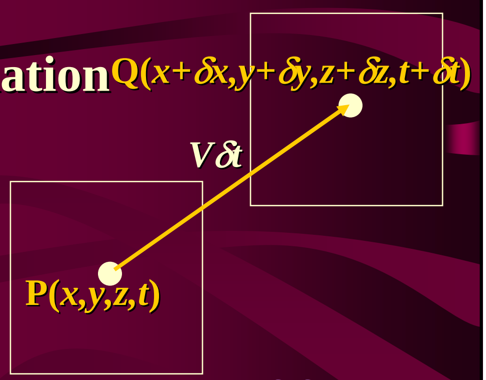
→ *Anemometer*



Flow around Pitot static tube and pressure

Navier-Stokes Equation

Substantial Differentiation



Velocity components

$u = u(x,y,z,t)$
$v = v(x,y,z,t)$
$w = w(x,y,z,t)$

Displacement of a small element of fluid at point P during an infinitesimal interval δt

$$\left.\begin{aligned} \delta x &= u(x,y,z,t)\delta t \\ \delta y &= v(x,y,z,t)\delta t \\ \delta z &= w(x,y,z,t)\delta t \end{aligned}\right\} \quad \text{Eq.(a)}$$

35

Changing rate ($\delta f / \delta t$) of a property f

$$f + \delta f = f(x + \delta x, y + \delta y, z + \delta z, t + \delta t)$$

$$= f(x, y, z, t) + \frac{\partial f}{\partial x}\delta x + \frac{\partial f}{\partial y}\delta y + \frac{\partial f}{\partial z}\delta z + \frac{\partial f}{\partial t}\delta t + O(\delta t^2)$$

$\delta t \to 0$, substituting Eq.(a)

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} + w\frac{\partial f}{\partial z}$$

Substantial Acceleration

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}$$

Changing rate ($\delta f / \delta t$) of a property f

$$f + \delta f = f(x + \delta x, y + \delta y, z + \delta z, t + \delta t)$$

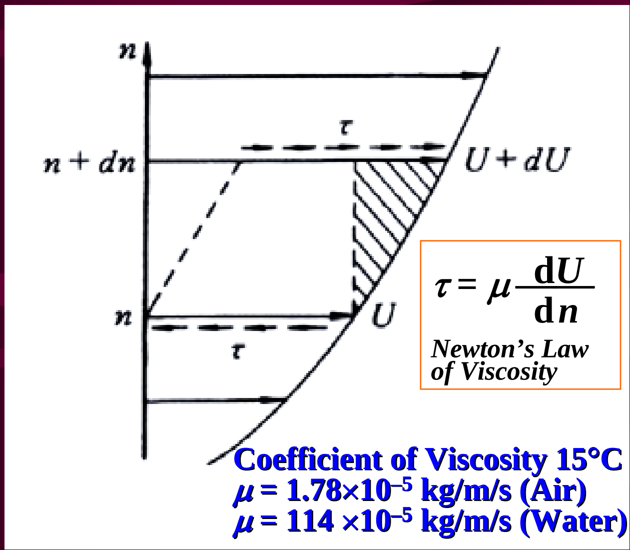
$$= f(x, y, z, t) + \frac{\partial f}{\partial x}\delta x + \frac{\partial f}{\partial y}\delta y + \frac{\partial f}{\partial z}\delta z + \frac{\partial f}{\partial t}\delta t + O(\delta t^2)$$

$\delta t \to 0$, substituting Eq.(a)

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} + w\frac{\partial f}{\partial z}$$

Substantial Acceleration

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}$$



$$\tau = \mu \frac{\mathrm{d}U}{\mathrm{d}n}$$

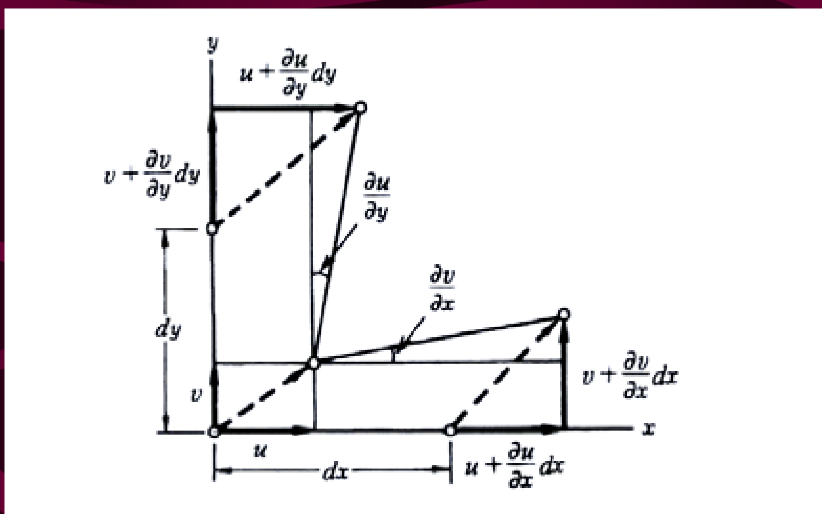
Newton's Law of Viscosity

Coefficient of Viscosity 15°C

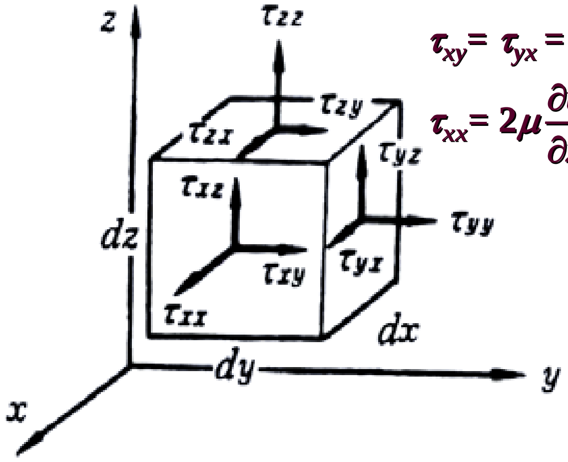
$\mu = 1.78\times10^{-5}$ kg/m/s (Air)

$\mu = 114 \times10^{-5}$ kg/m/s (Water)

Velocity gradient and viscous stress (Newtonian fluid)



Shear deformation velocity in *xy* - plane



$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)$$

$$\tau_{xx} = 2\mu\frac{\partial u}{\partial x}$$

Shear stresses acting on an infinitesimal hexahedron of fluid

■ **Total shear forces acting *x*-direction:**

$$\left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) dxdydz$$

Navier Stokes Equations:

Convective acceleration

Inertial force per unit volume

$$\rho\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right]$$

Substantial acceleration

Local (Instantaneous) acceleration

$$= -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right]$$

Pressure gradient   *Viscous stress*

Navier Stokes Equations:

$$\rho\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right] = -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right]$$

$$\rho\left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right] = -\frac{\partial p}{\partial y} + \mu\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right]$$

$$\rho\left[\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right] = -\frac{\partial p}{\partial z} + \mu\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right]$$

Non-dimensional expression of Navier Stokes Equations:

$$\frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} + w^* \frac{\partial u^*}{\partial z^*}$$

$$= -\frac{\partial p^*}{\partial x^*} + \frac{1}{Re}\left[\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\partial^2 u^*}{\partial z^{*2}}\right]$$

$$x^* = \frac{x}{L},\quad y^* = \frac{y}{L},\quad z^* = \frac{z}{L},\quad t^* = \frac{tU}{L},\quad p^* = \frac{p}{\rho U^2}$$

$$u^* = \frac{u}{U},\quad v^* = \frac{v}{U},\quad w^* = \frac{w}{U},\quad Re = \frac{\rho UL}{\mu}$$

Reynolds Number

T = 15°C, P = 1013hPa
ρ = 1.22 kg/m^3
μ = 1.78×10^{-5} kg/m/s (Air)
μ = 114 ×10^{-5} kg/m/s (Water)
Dynamic Viscosity
$\nu = \mu/\rho$ = 1.45×10^{-5} m^2/s (A)
$\nu = \mu/\rho$ = 1.14×10^{-6} m^2/s (W)

$$Re = \frac{\rho UL}{\mu} = \frac{UL}{\nu}$$

$$= \frac{\rho L^3 \; U^2/L}{L^2 \quad \mu U/L}$$

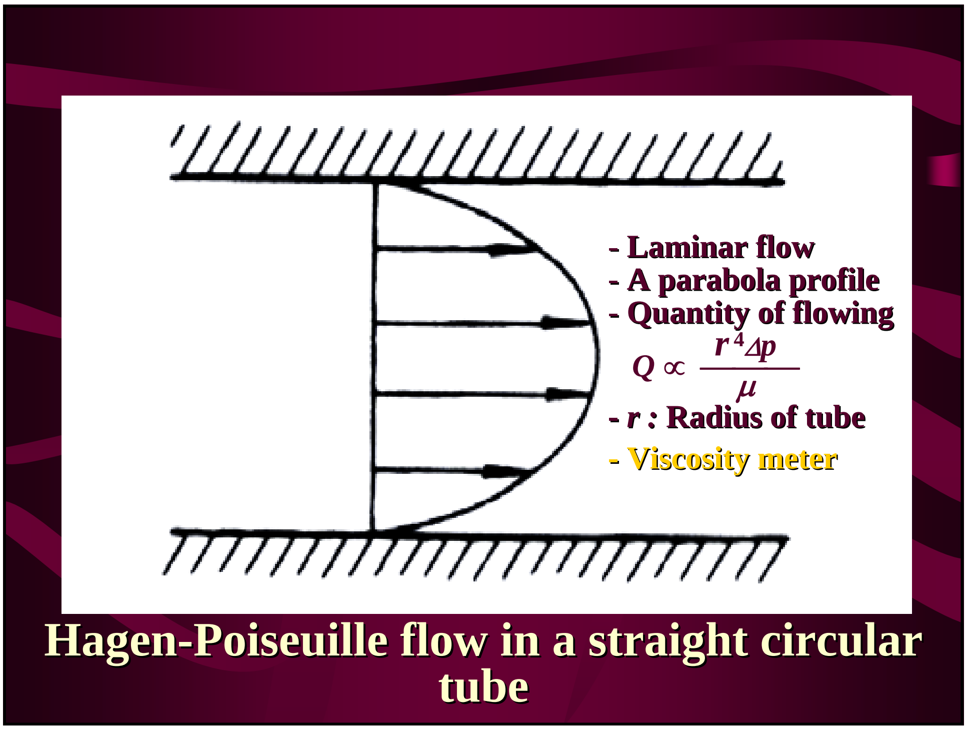
$$= \frac{\text{Inertial Force}}{\text{Viscous Force}}$$

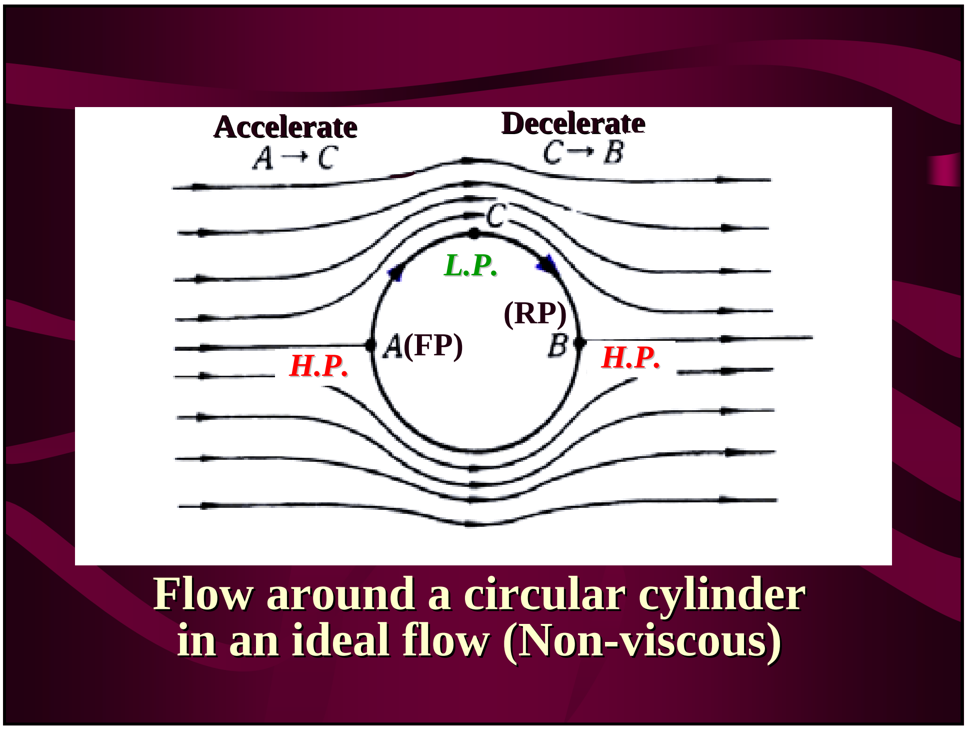
$\approx 7 \times 10^4\, L\, U$ (Air)

U: (m/s) Reference Speed

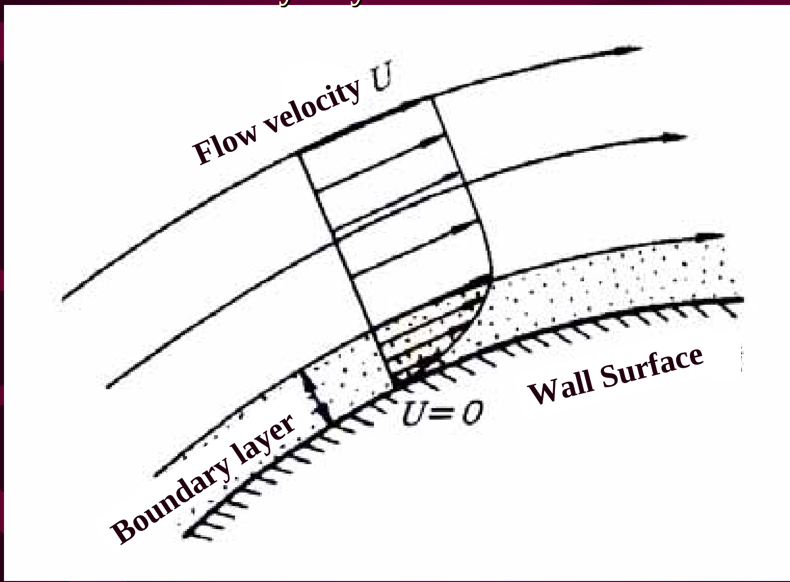
L: (m) Reference Length

$\approx 9 \times 10^5\, L\, U$ (Water)

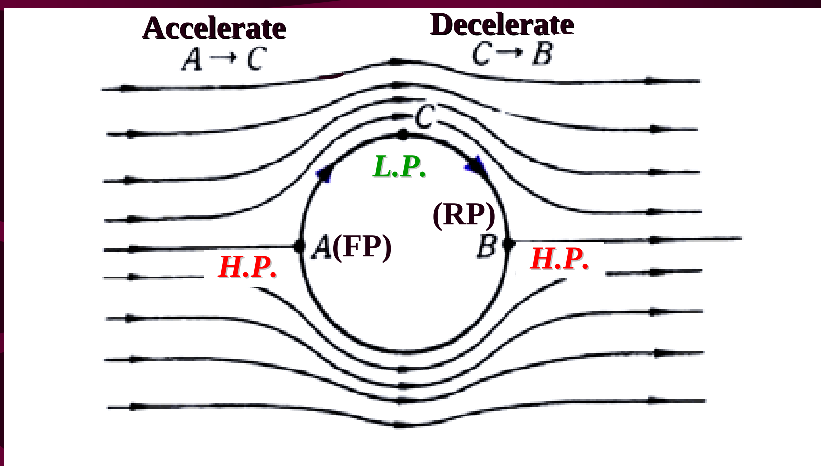

- Laminar flow
- A parabola profile
- Quantity of flowing
$Q \propto \frac{r^4 \Delta p}{\mu}$
- r : Radius of tube
- Viscosity meter
Hagen-Poiseuille flow in a straight circular tube


Accelerate
A → C
Decelerate
C → B
C
L.P.
(RP)
A(FP)
B
H.P.
H.P.
Flow around a circular cylinder in an ideal flow (Non-viscous)

Surface Boundary Layer

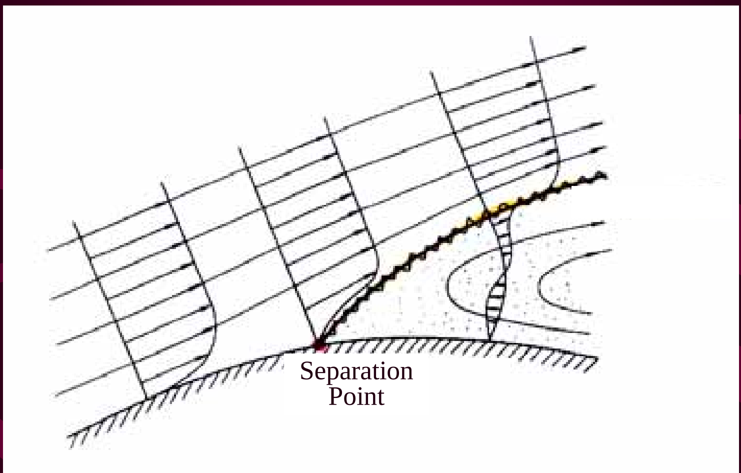


Flow near surface of body



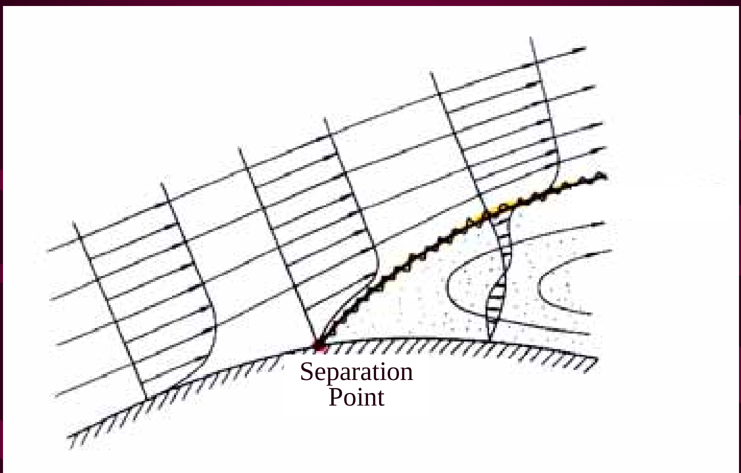
Flow around a circular cylinder
in an ideal flow (Non-viscous)

- Separated shear layer
- Vortex sheet
- Shear layer instability

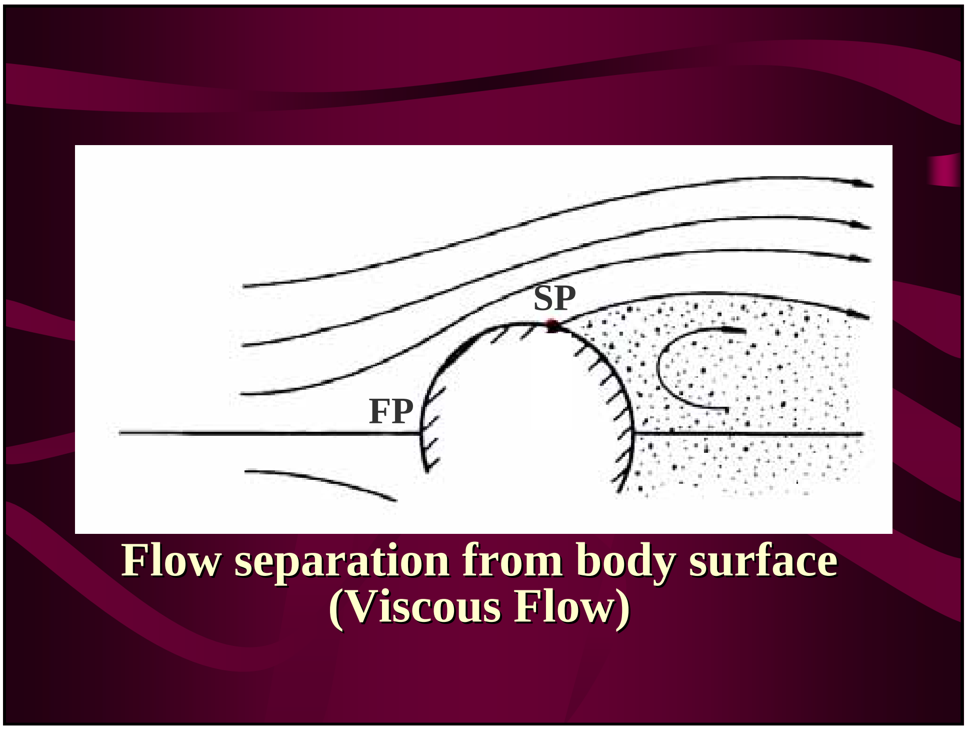


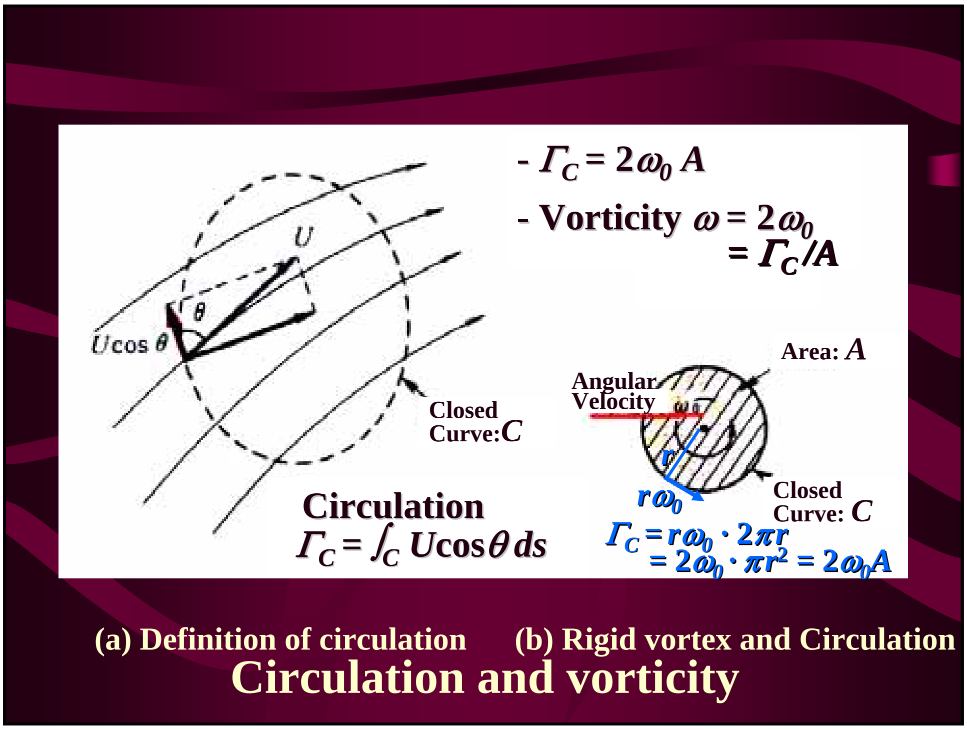
Flow near the separation point

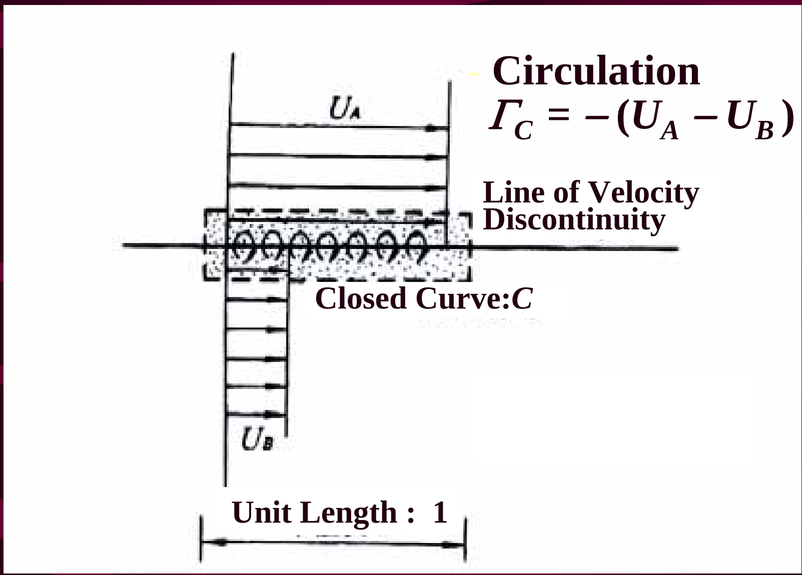
- Separated shear layer
- Vortex sheet
- Shear layer instability



Flow near the separation point

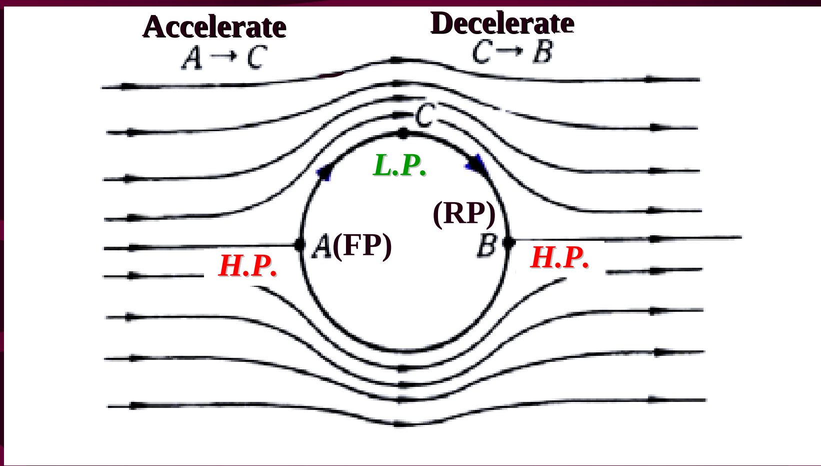

SP
FP
Flow separation from body surface
(Viscous Flow)


- Γ_C = 2ω_0 A
- Vorticity ω = 2ω_0
= Γ_C/A
U
θ
Ucos θ
Closed
Curve:C
Circulation
Γ_C = ∫_C Ucosθ ds
Area: A
Angular
Velocity
r
rω_0
Closed
Curve: C
Γ_C = rω_0 · 2πr
= 2ω_0 · πr² = 2ω_0A
(a) Definition of circulation
(b) Rigid vortex and Circulation
Circulation and vorticity



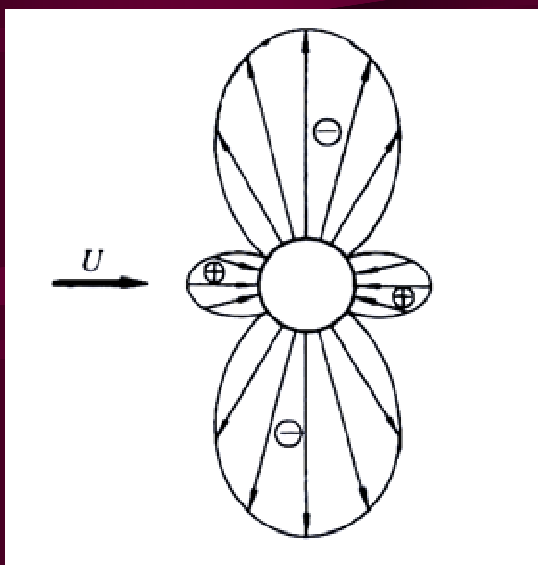
Circulation along a line of velocity discontinuity

Causes of Wind Forces

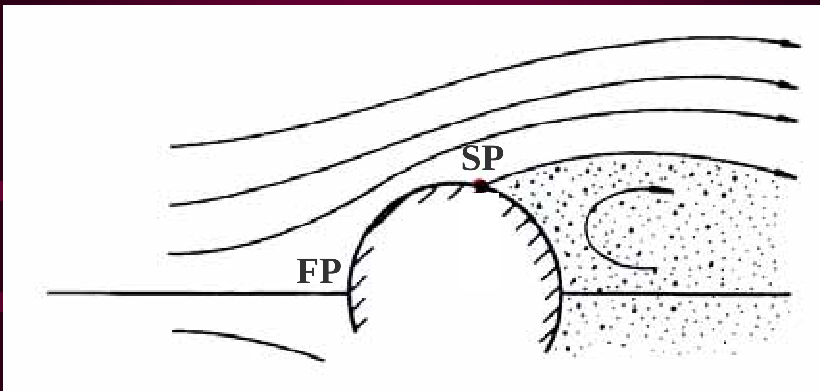


Flow around a circular cylinder in an ideal flow (Non-viscous)

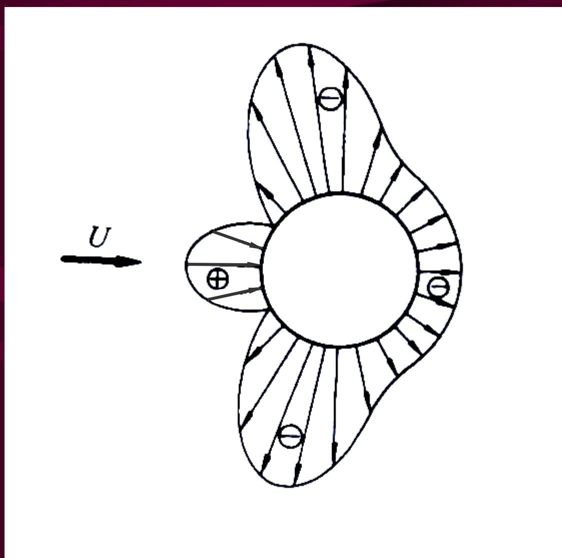
- D'Alambert's Paradox



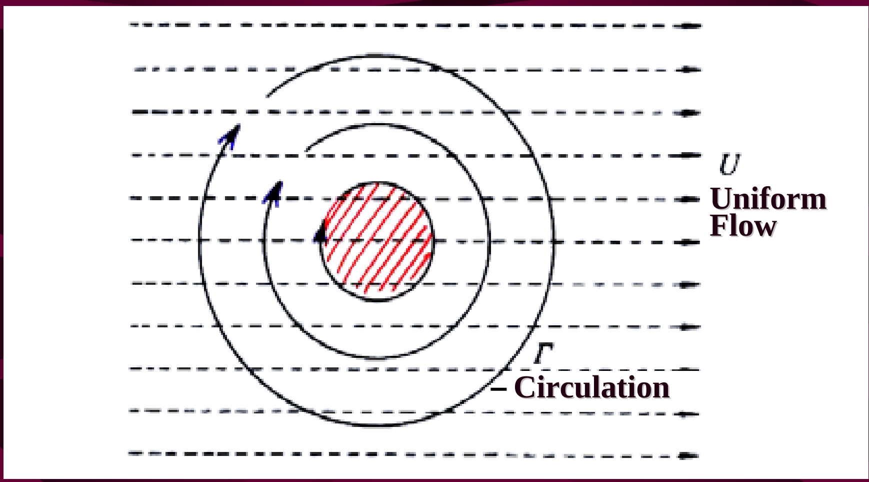
Pressure distribution on a circular cylinder in the ideal non-viscous flow



Flow separation from body surface
(Viscous Flow)

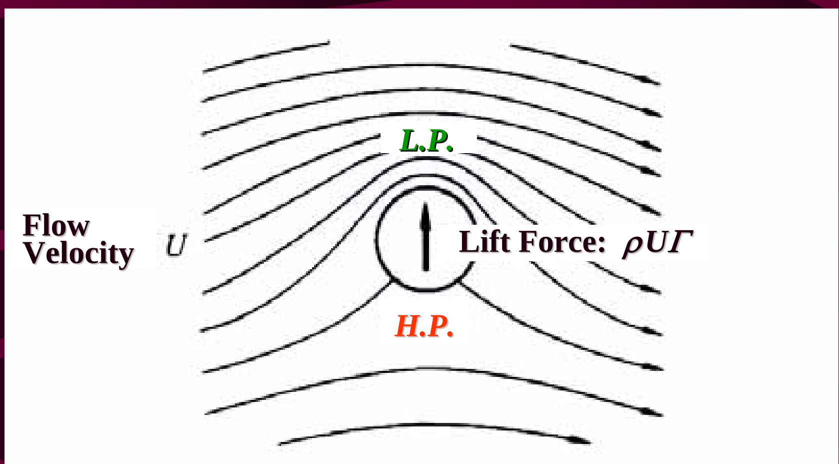


Pressure distribution on a circular cylinder in actual viscous flow



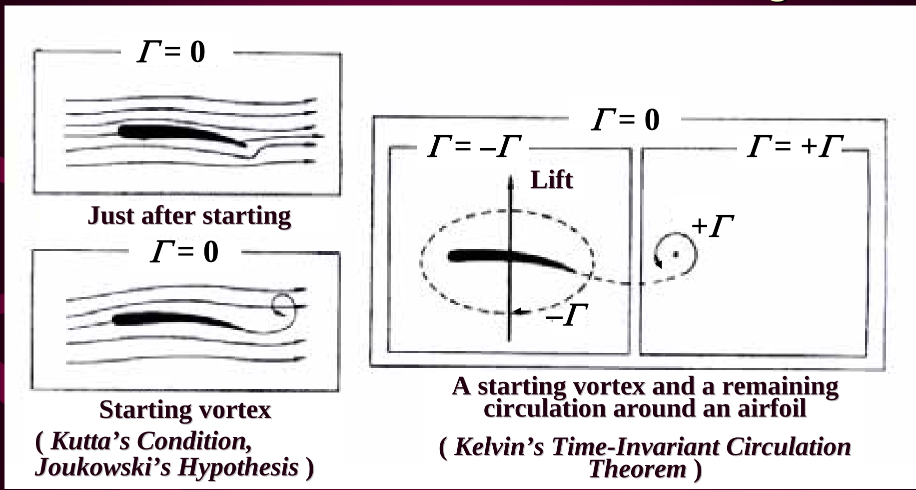
Superimposition of a rotational flow around a circular cylinder with a uniform flow

Kutta-Joukowski's Theorem

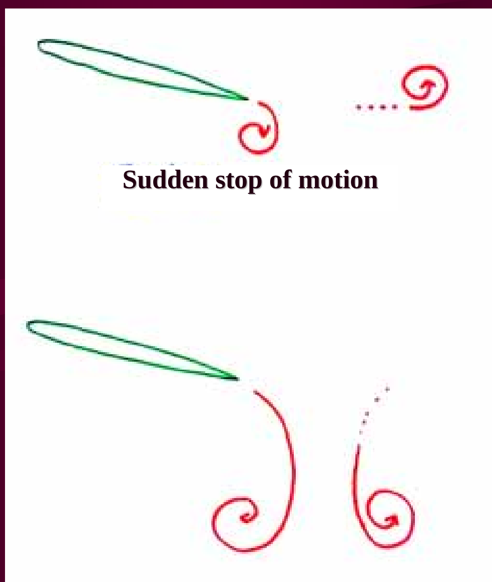


Stream lines around a circular cylinder in a uniform ideal flow superimposed on a clockwise circulation

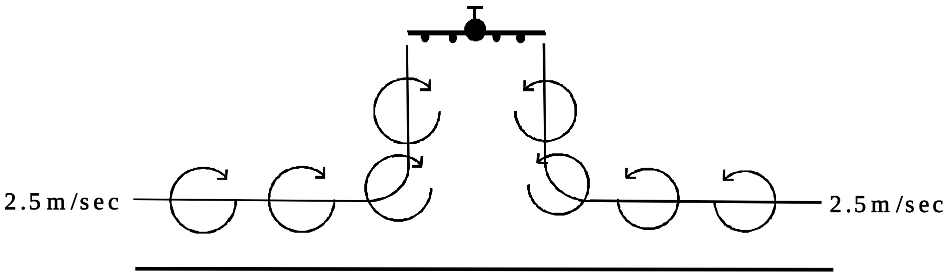
- Starting vortex



A vortex generated when an airfoil starts to move in a stationary flow

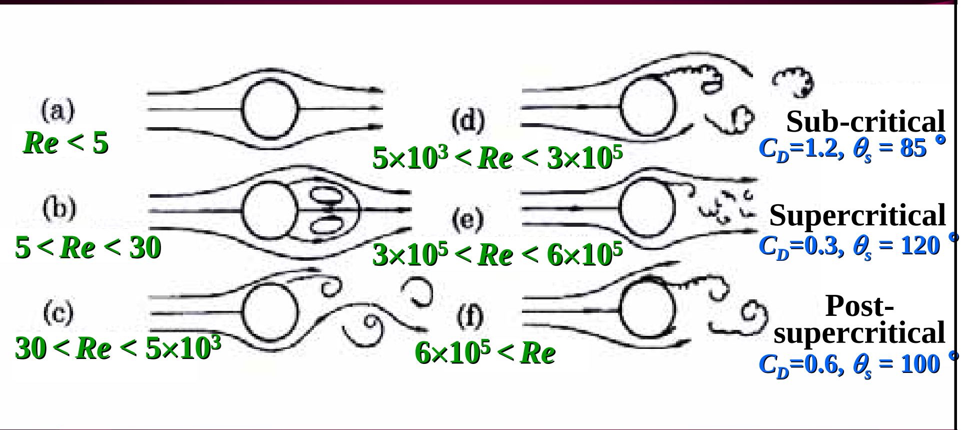


Release of a vortex stuck to an airfoil by sudden stop of motion



Turbulence after airplane

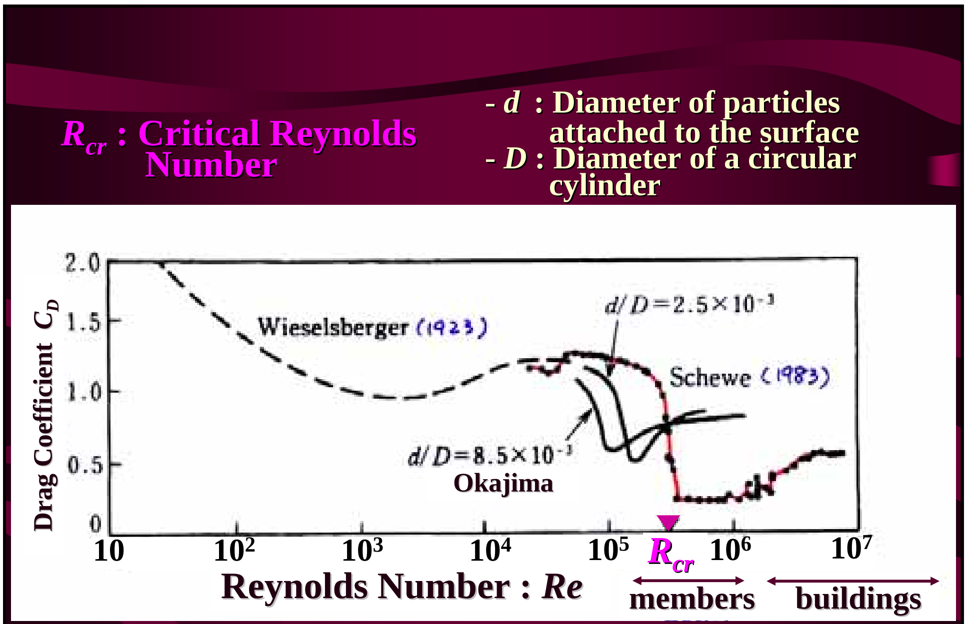
Reynolds Number and Flow Patterns



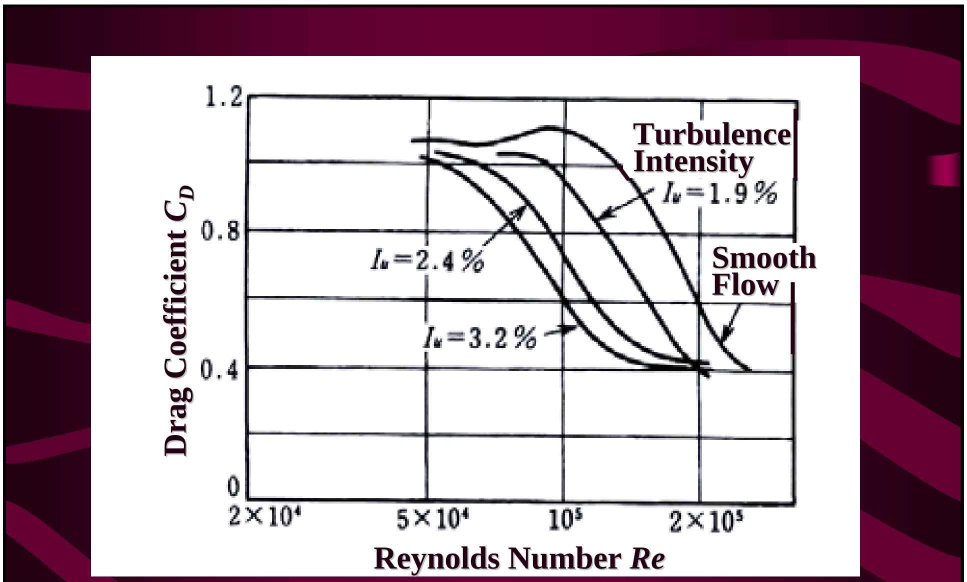
Variation of flow pattern around a circular cylinder due to Reynolds number

Important Regimes for Structures

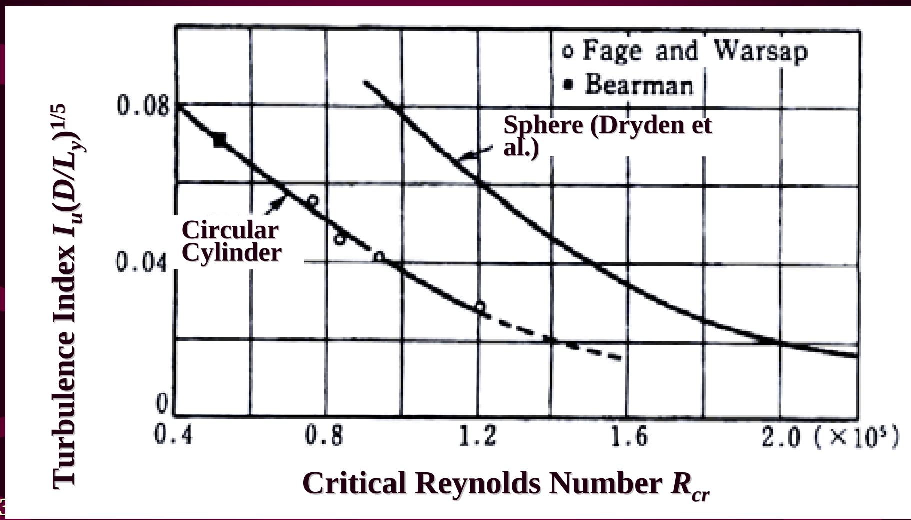
- **Sub-critical** $5\times10^3 < Re < 3\times10^5$
  - Surface boundary layer : Laminar
  - Separation points: $\theta_S = 85^o$
  - Separated shear layer: Turbulent in wake (Widest wake)
  - Drag Coefficient : $C_D = 1.2$
  - Vortices : Very periodic
- **Supercritical** $3\times10^5 < Re < 6\times10^5$
  - Surface boundary layer : Laminar →Turbulent $\theta > 85^o$
  - Separation points: $\theta_S = 120^o$
  - Separated shear layer: Narrow Wake-width
  - Drag Coefficient : $C_D = 0.3$
  - Vortices : Lose periodicity
- **Post-supercritical** $6\times10^5 < Re$
  - Surface boundary layer : Fully turbulent
  - Separation points: $\theta_S = 100^o$
  - Separated shear layer: Wider wake-width
  - Drag Coefficient : $C_D = 0.6$ ($Re \approx 4 \times 10^6$)
  - Vortices : Periodic



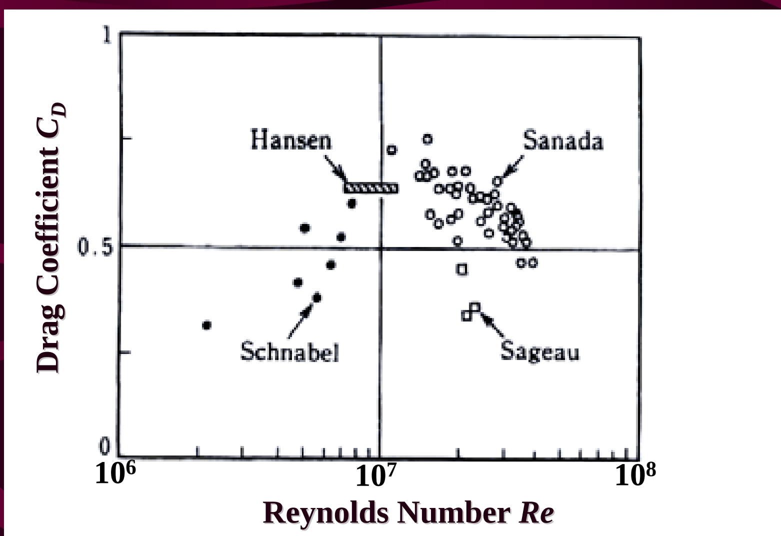
Variation of drag coefficient of a circular cylinder due to Reynolds number



Variation of mean drag coefficient of a circular cylinder with turbulence intensity and Reynolds number (2D)



Variation of the critical Reynolds numbers of a sphere and a circular cylinder with turbulence index $I_u(D/L_v)^{1/5}$(Bearman, 1968)

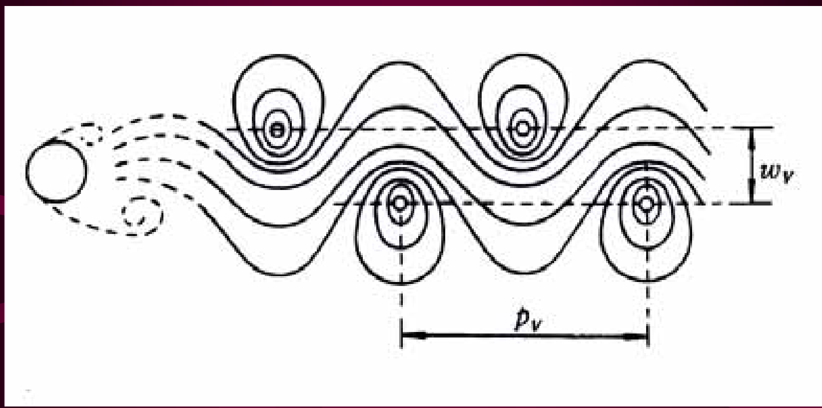


Field data of mean drag coefficients of actual circular structures (chimneys etc.)

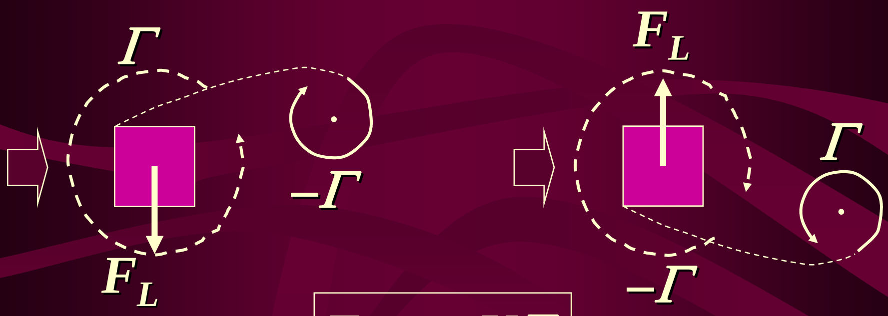
Vortices Shed From Bluff Bodies

Karman vortices shed from a square prism

$w_v / p_v = 0.281$



Karman vortex streets



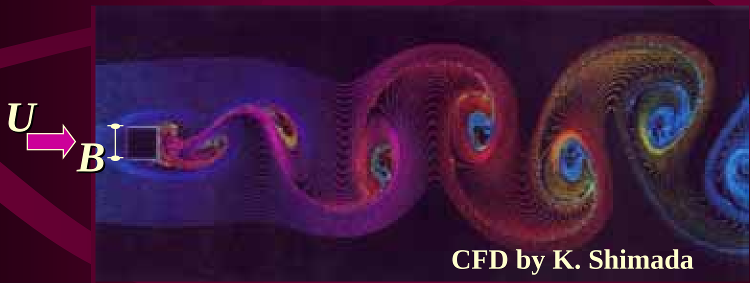
$$F_L = \rho U \Gamma$$

Kutta-Joukowski's Theorem

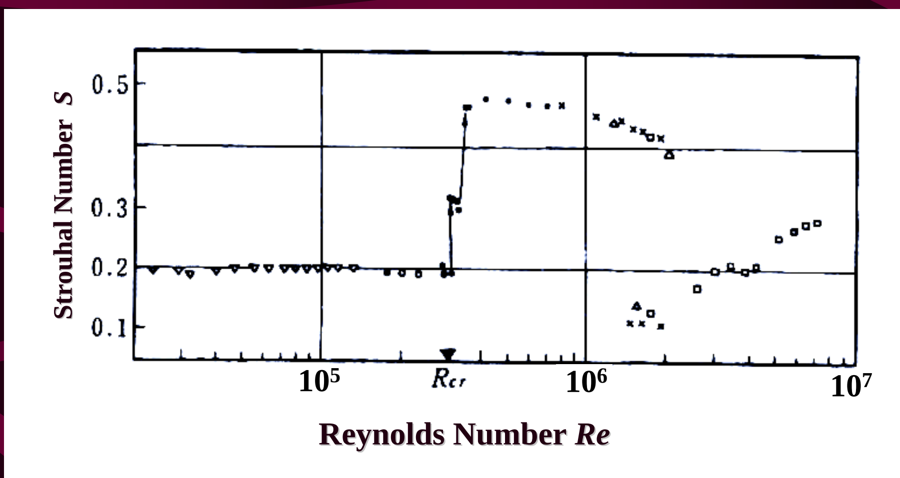
Periodic lateral force due to alternate vortex shedding

$$f_v = S\frac{U}{B}, \quad S = \frac{f_v B}{U}$$

- f_v : Shedding frequency of Karman vortices
- S : Strouhal number
- U : Wind Speed
- B : Reference Length

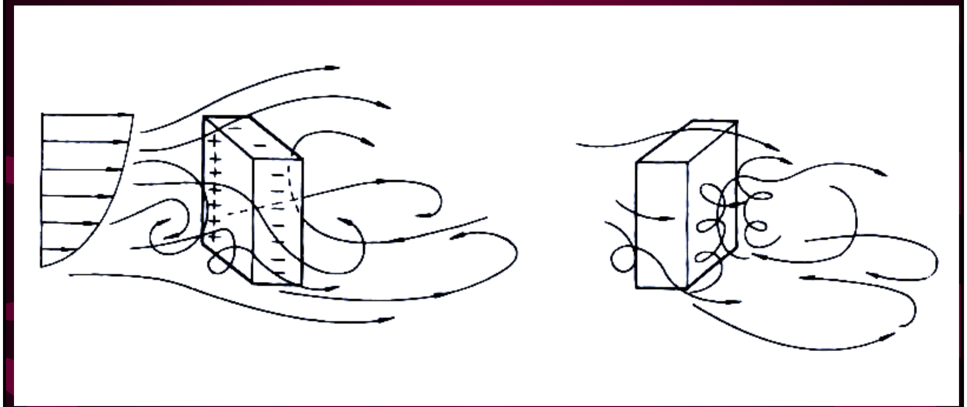


Vortex shedding and Strouhal Number



Variation of Strouhal number with Reynolds number

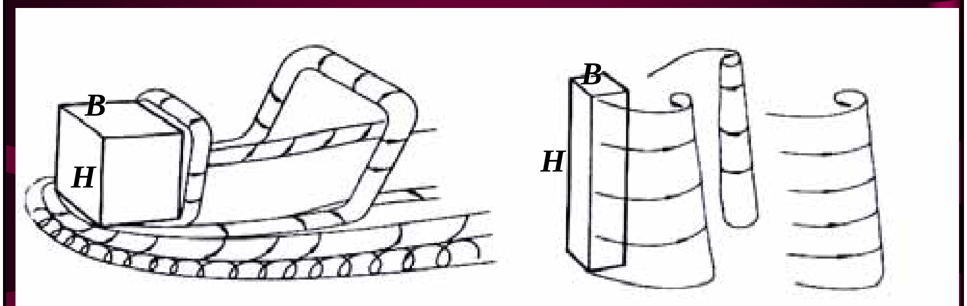
(Circular cylinder, 2D, Uniform flow, Shewe 1983)



(a) front side (b) rear side

Flow around a building

(T.Tamura)

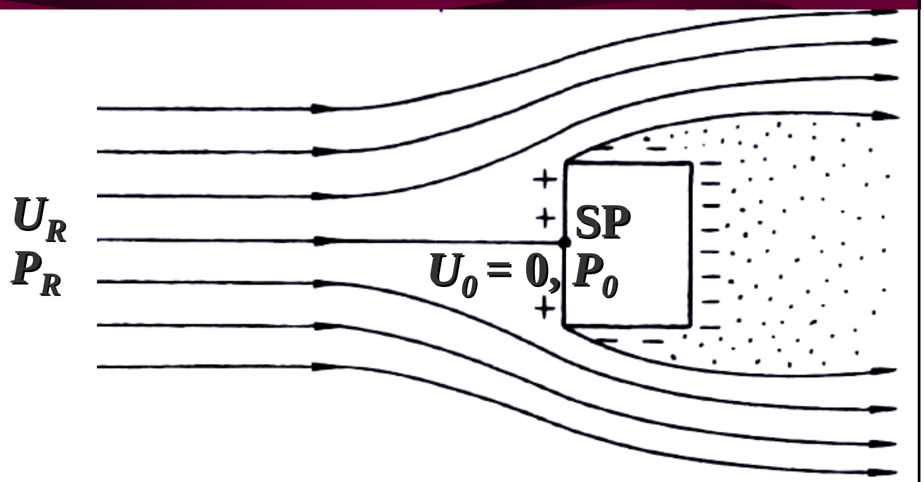


(a) Small *H/B* (Aspect Ratio) (b) Large *H/B*

Vortex formation behind building models

Static Wind Forces

Velocity Pressure
and
Wind Pressure Coefficient



Wind Pressure at Stagnation Point

$$p_0 = P_0 - P_R = (1/2)\rho U_R^2$$

Velocity Pressure (Dynamic

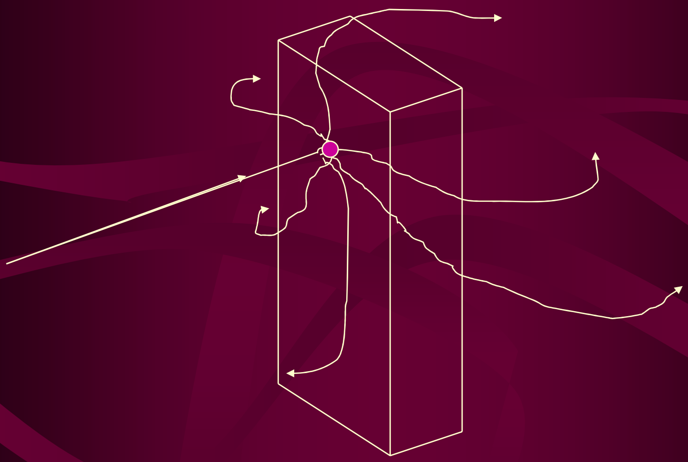
■ Wind Pressure Coefficient

$$C_{pk} = \frac{p_k}{\frac{1}{2}\rho U_R^2}$$

← Velocity Pressure : q_R

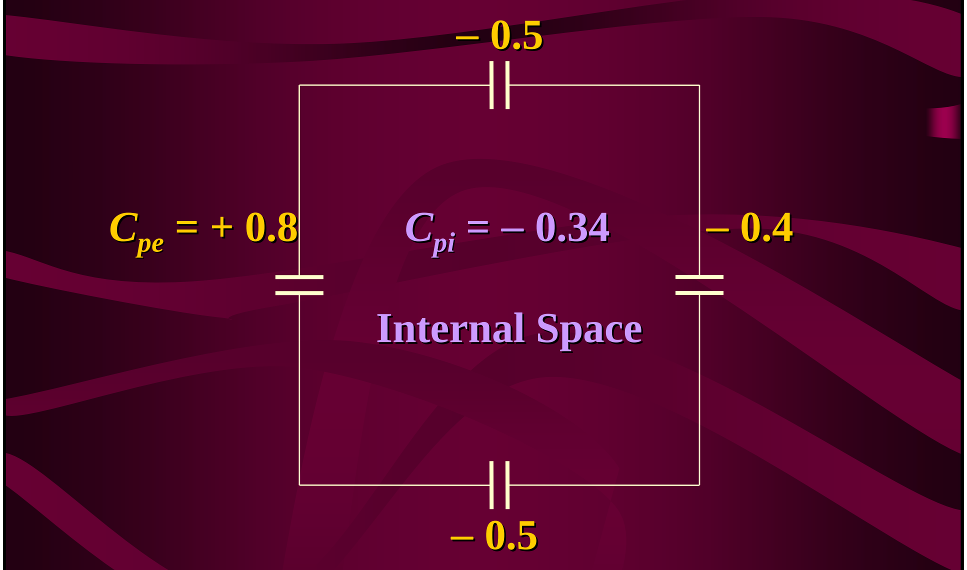
$$p_k = P_k - P_R$$

p_k : Wind pressure at point k
P_k : Static pressure at point k
P_R : Reference static pressure
ρ : Air density
U_R : Reference wind speed



Stagnation point of a 3D building

Internal Pressure Coefficient
and
External Pressure Coefficient



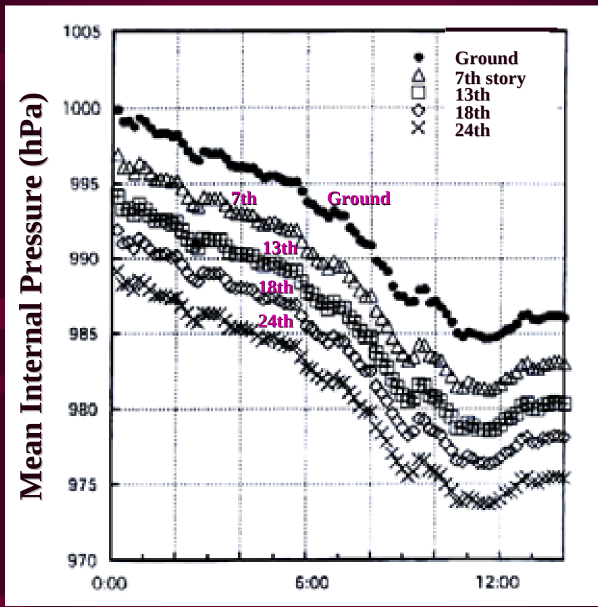
External pressure coefficient C_{pe} and internal pressure coefficient C_{pi}

Equilibrium Equation of Flows Through Gaps:

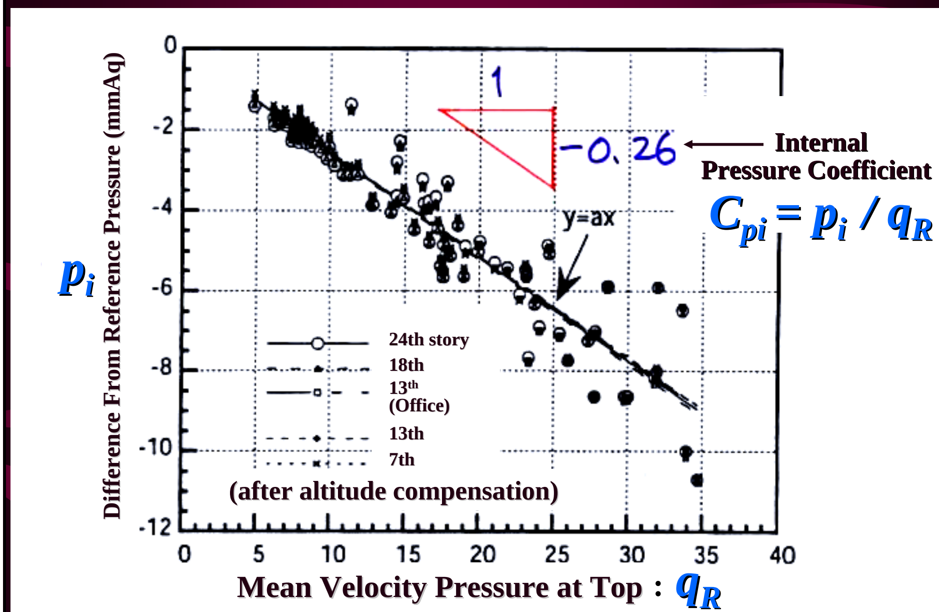
- The flow is proportional to the velocity at each gap.
- The velocity is assumed to be proportional to the square root of the pressure difference between the gap.

$$\sqrt{|0.8 - C_{pi}|} = 2\sqrt{|C_{pi} + 0.5|} + \sqrt{|C_{pi} + 0.4|}$$

$\longrightarrow C_{pi} = -0.34$

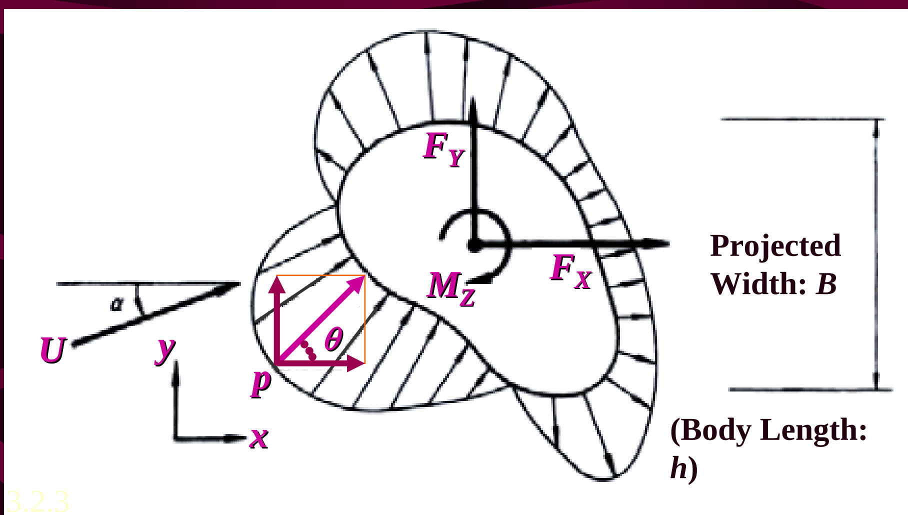


Temporal variations of mean internal pressures (Full-scale, Kato et al., 1996)



Variation of mean internal pressures with reference velocity pressure (Full-scale, Kato et al., 1996)

Wind Force Coefficient



Wind pressure and wind forces defined for axes fixed to body

Wind Forces

$$F_X = \int_S p \cos\theta h\, ds$$

$$F_Y = \int_S p \sin\theta h\, ds$$

h : Body length

Wind Force Coefficients

$$C_{FX} = \frac{F_X}{\frac{1}{2}\rho U_R^2 A}, \quad C_{FY} = \frac{F_Y}{\frac{1}{2}\rho U_R^2 A}$$

A : Projected area = Bh

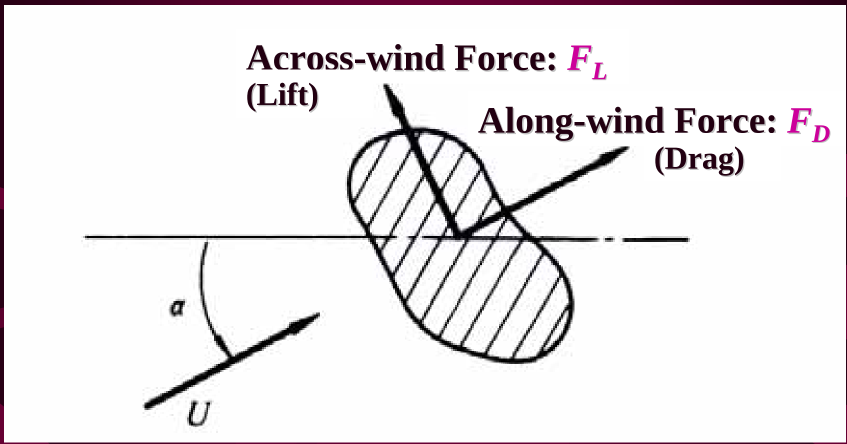
Aerodynamic Moment Coefficients

$$C_{MZ} = \frac{M_Z}{\frac{1}{2}\rho U_R^2 A L}$$

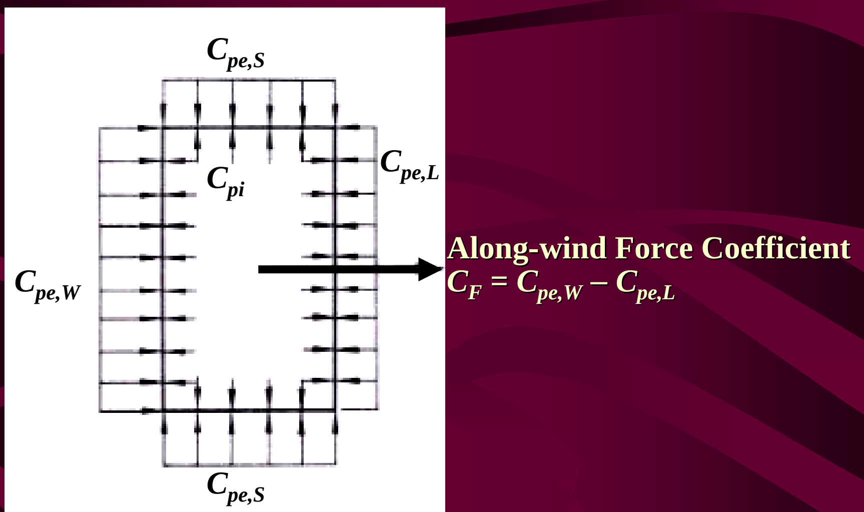
M_Z : Aerodynamic Moment

A : Projected area

L : Reference Length

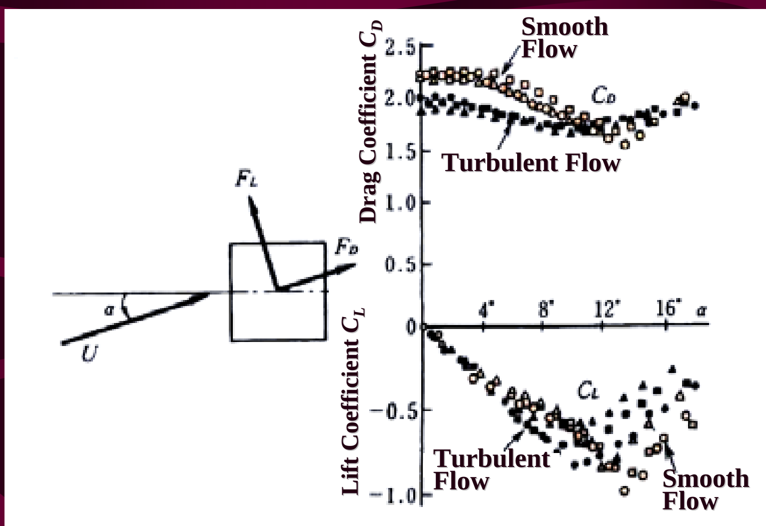


Along-wind force and across-wind force defined for the axes fixed to wind

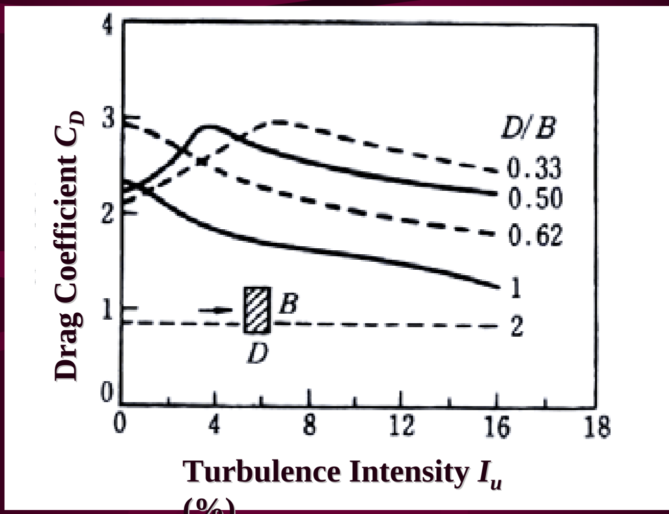


Wind pressure coefficient and wind force coefficient for a building with an internal space

Static Wind Forces Acting On Bluff Bodies

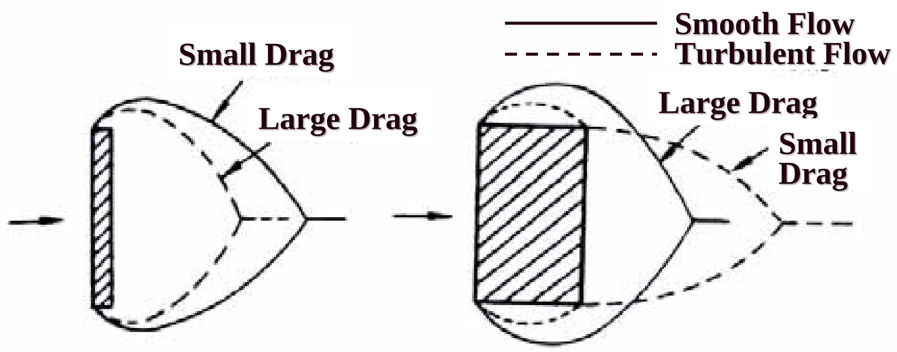


Variations of mean drag and lift coefficients with attacking angle (2D)



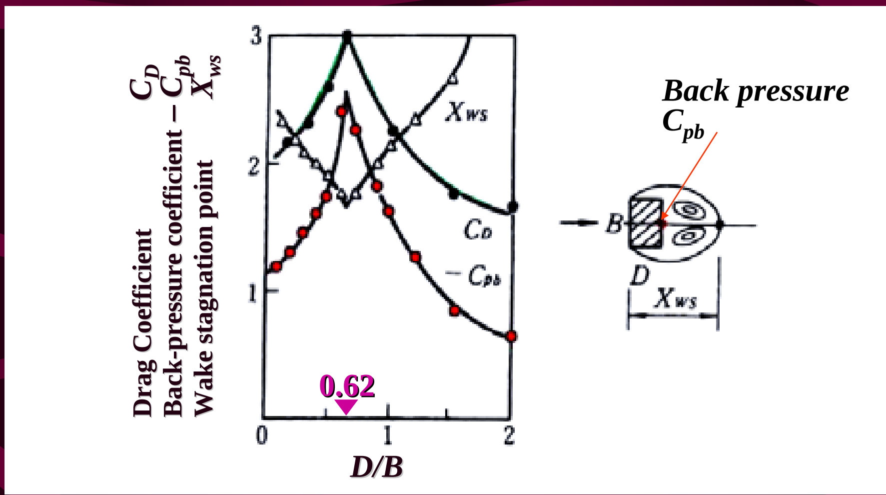
Effects of turbulence on mean drag coefficients of 2D prisms

Entrainment effects of turbulence

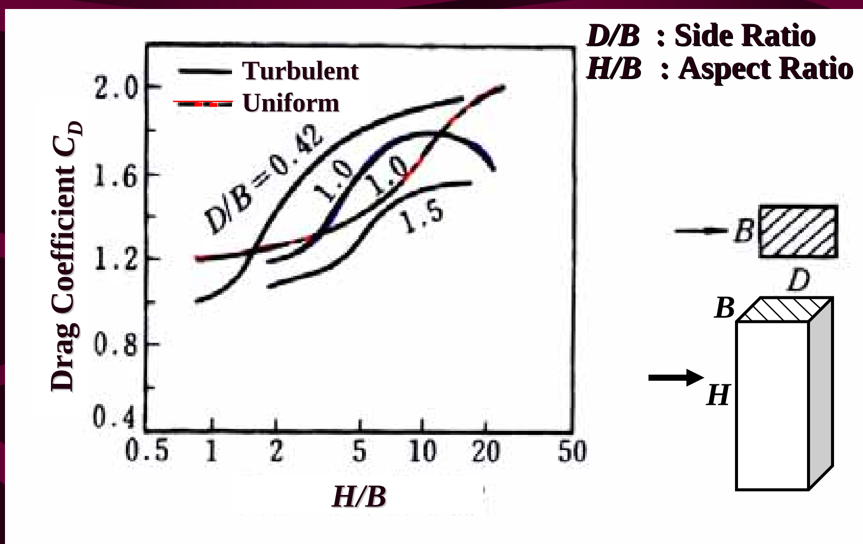


(a)Flat plate (*D/B* = 0.1) (b) Prism (*D/B* = 0.5)

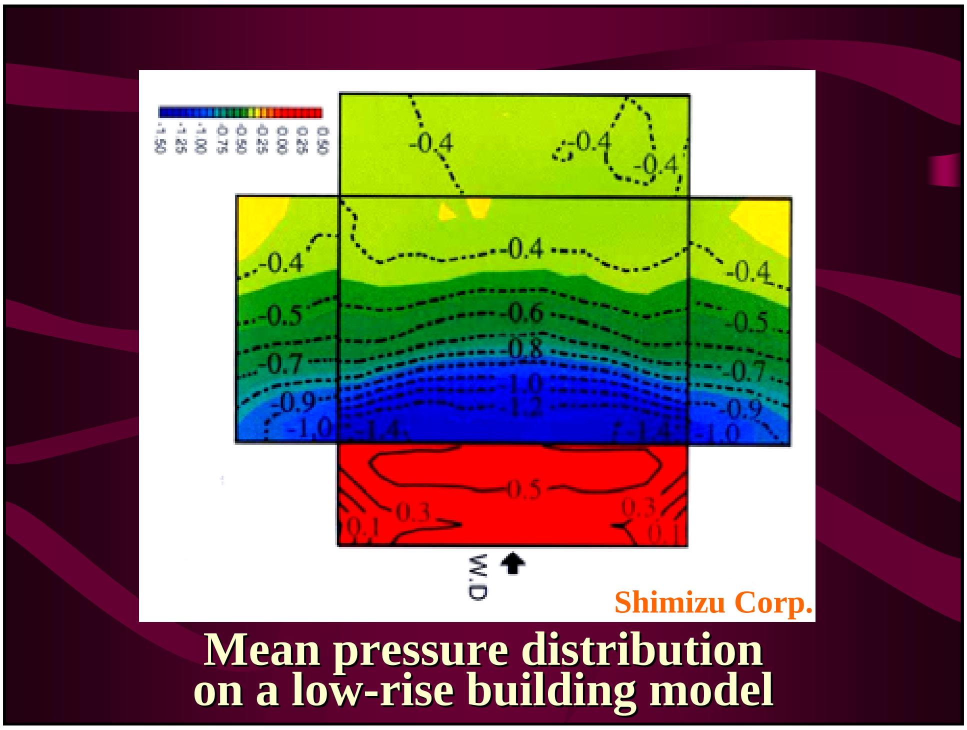
Effects of turbulence on separated shear layers (Laneville et al., 1975)

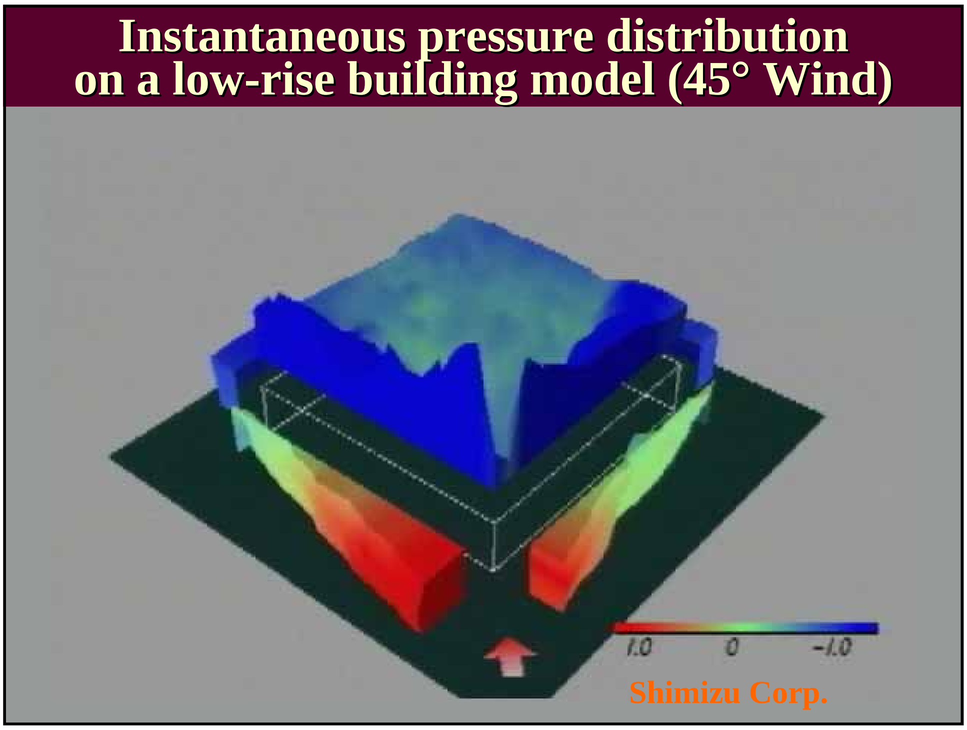


Variation of mean drag coefficient, back-pressure coefficient, and wake stagnation point with side ratio (2D, Uniform flow)

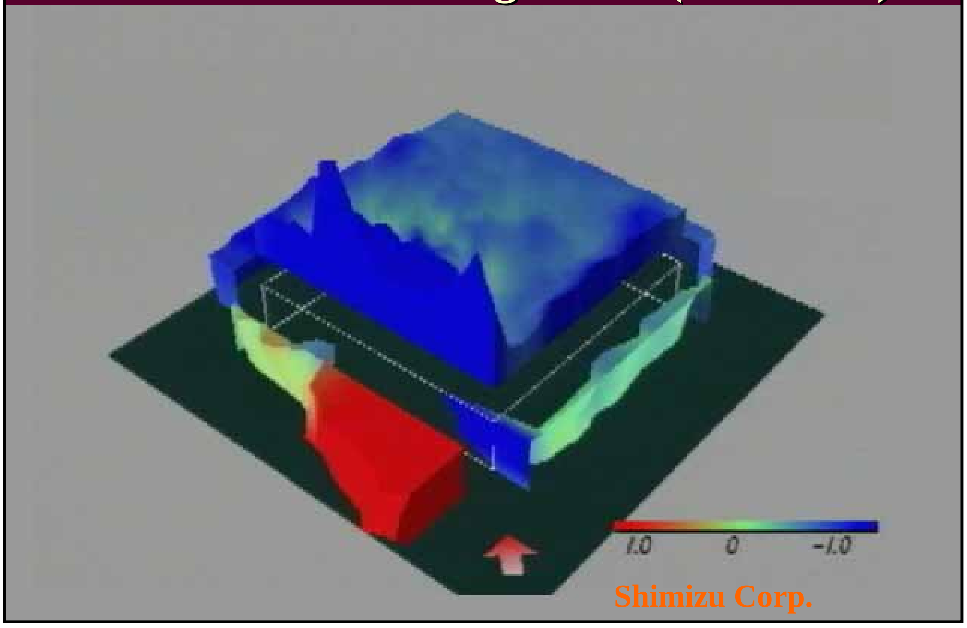


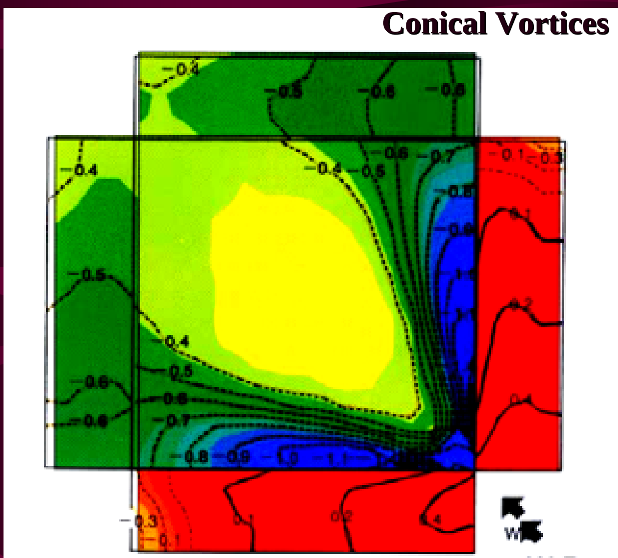
Variation of mean drag coefficients of 3D rectangular prisms with aspect ratio


-0.4
-0.4
-0.4
-0.4
-0.4
-0.4
-0.5
-0.6
-0.5
-0.7
-0.8
-0.7
-0.9
-1.0
-0.9
-1.0
-1.2
-1.4
-1.4
-1.0
-0.5
0.3
0.3
0.1
0.1
W.D
Shimizu Corp.
Mean pressure distribution
on a low-rise building model


Instantaneous pressure distribution
on a low-rise building model (45° Wind)
1.0
0
-1.0
Shimizu Corp.

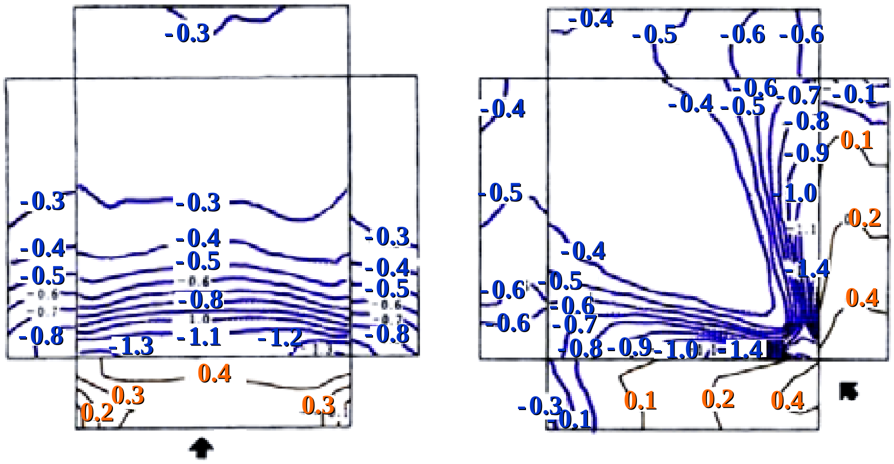
Instantaneous pressure distribution on a low-rise building model (45° Wind)





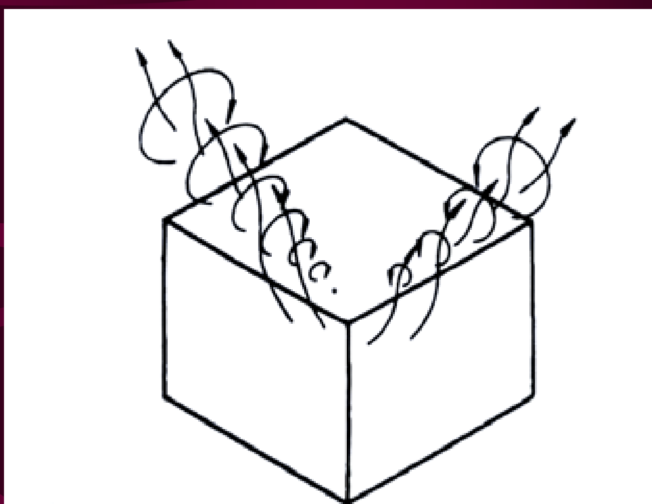
Shimizu Corp

Mean pressure distributions on a low-rise building model (45° Wind)

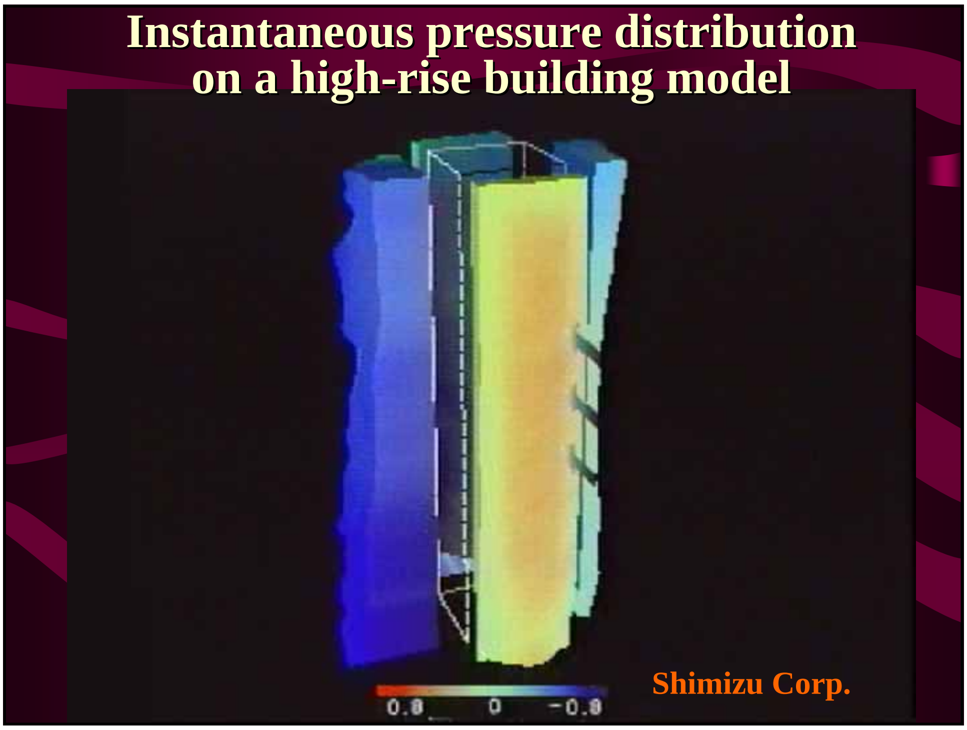


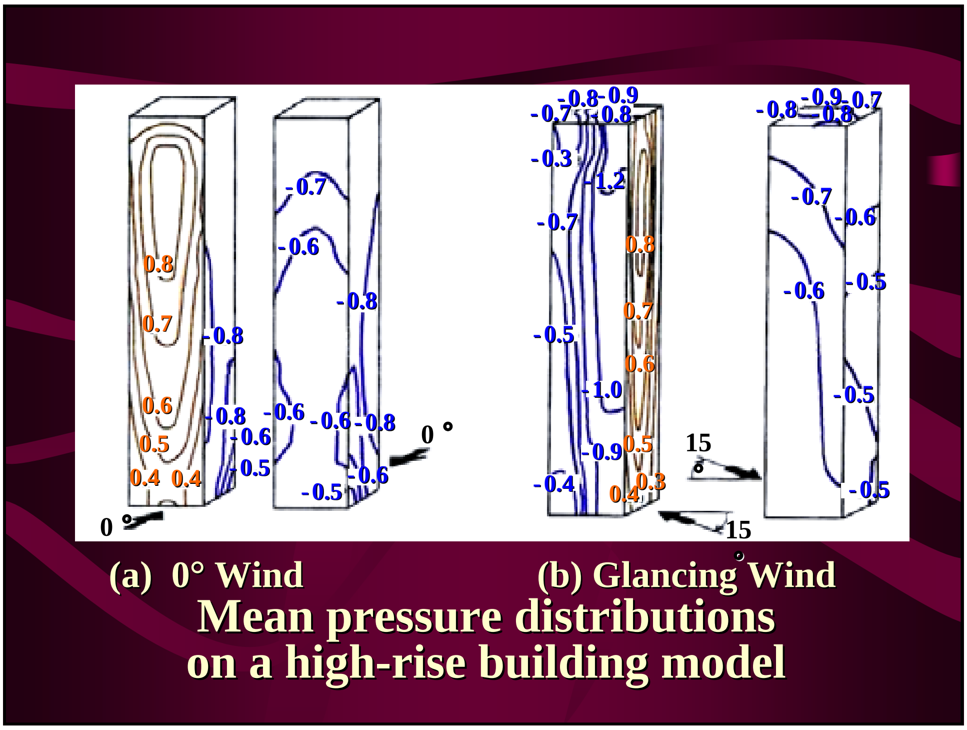
(a) 0° Wind (b) 45° Wind

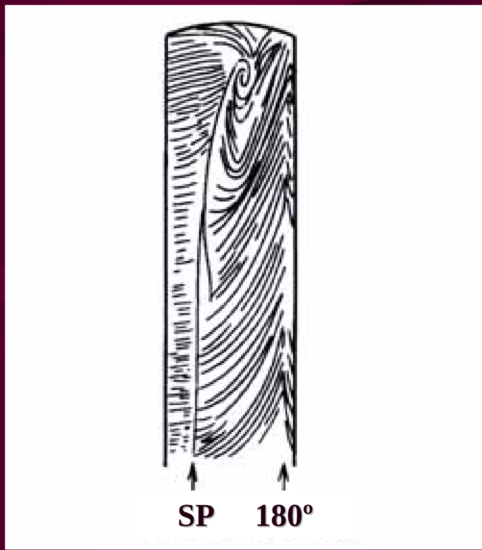
Mean pressure distributions on a low-rise building model



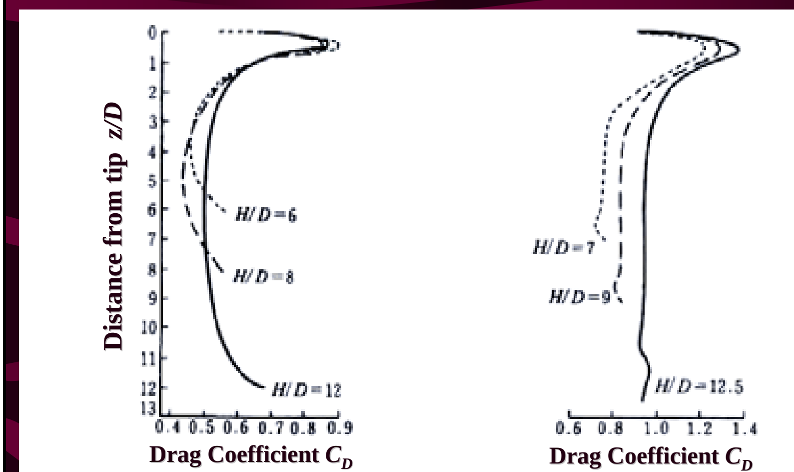
Conical vortices generated from corner eaves

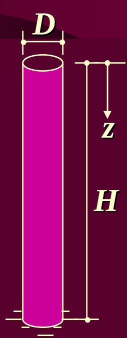

Instantaneous pressure distribution
on a high-rise building model
Shimizu Corp.
0.8
0
-0.8


(a) 0° Wind
(b) Glancing Wind
Mean pressure distributions
on a high-rise building model



Surface flow pattern near the tip of 3D circular cylinder (Oil film technique, view obliquely from behind, Lawson, 1980)

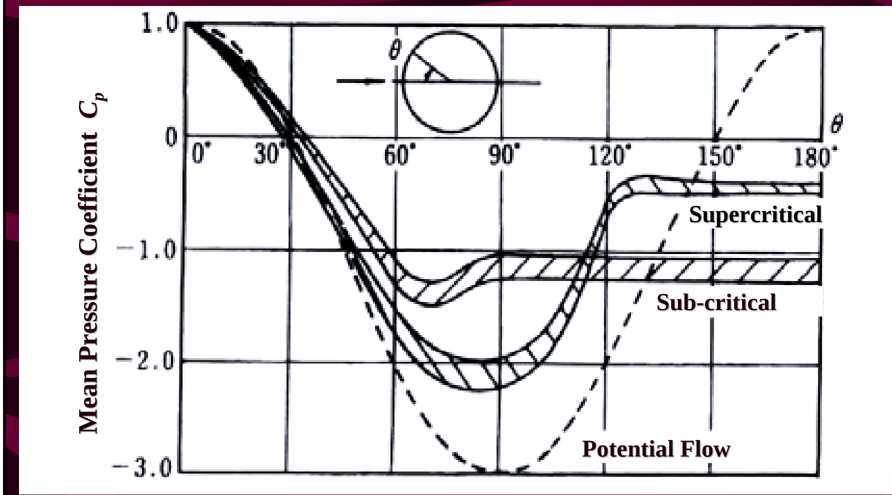




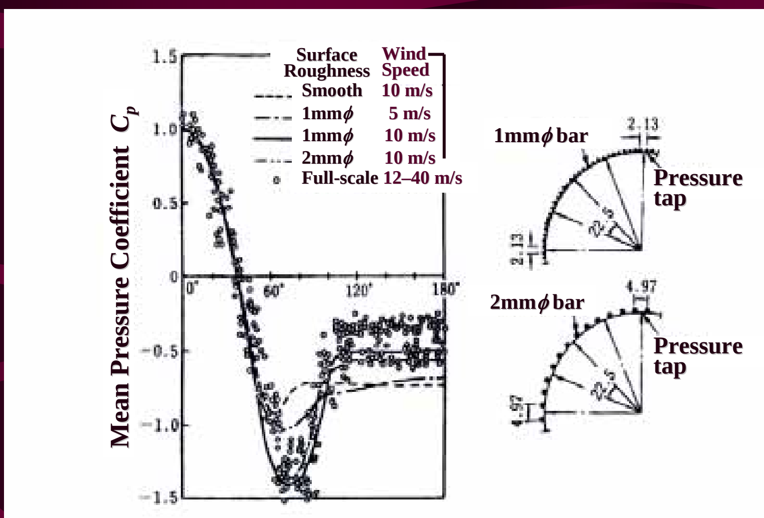
(a) Post-supercritical Regime $Re = 2.7 \sim 5.4 \times 10^6$

(b) Sub-critical Regime $Re = 1.33 \times 10^4$

Vertical distributions of local mean drag coefficients of 3D circular cylinders



Mean pressure distribution on a circular cylinder (Sach, 1972)



Mean pressure distributions on a full-scale chimney and wind tunnel models with different surface roughnesses