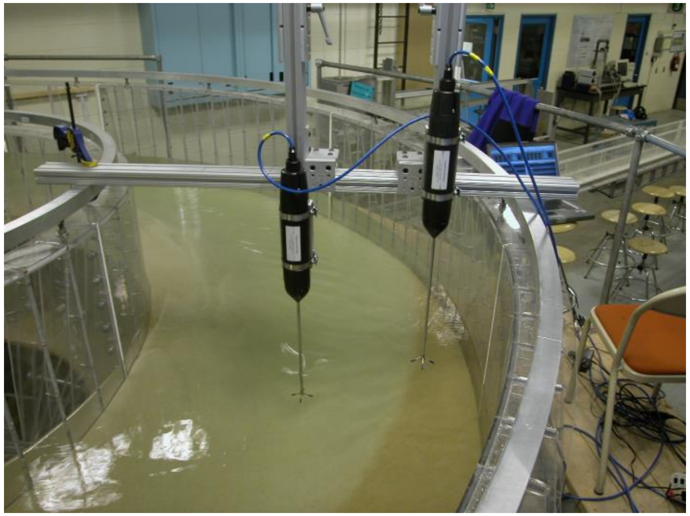
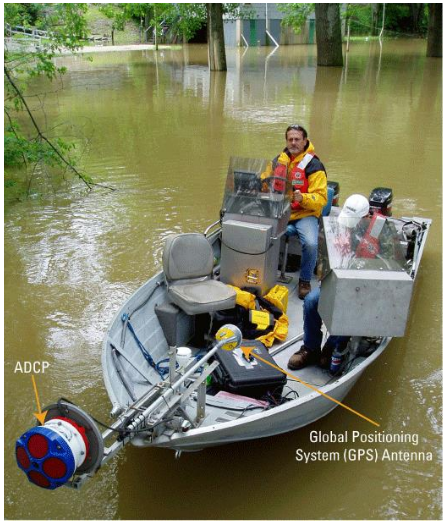
Lecture 2
Fluid Measurements

Contents

Objectives

- Learn how to measure properties of diverse fluids
- Introduce flow measuring devices for both laboratory and field experiments based on the fluid mechanics theory



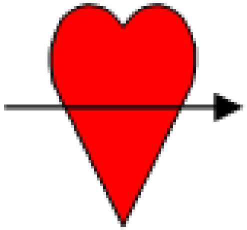


2.1 Density measurement

- There are many properties of fluids, but we only pay attention to the **density and viscosity** since other properties are measured by other disciplines (physics, chemistry).

- Density measurements

$$\rho = \frac{M}{V}$$



1) Weighing a known volume: pycnometer (비중병)
2) Hydrostatic weighing: plummet, Westphal balance
3) Hydrometer (비중계)

1) Weighing method

- Pycnometer (specific gravity bottle; 비중병)
  - Equipment to weigh accurately a known volume of liquid.
  - The specific weight of the liquid is calculated as

$$\gamma_t = \frac{W_2 - W_1}{V_l} \qquad (2.1)$$

  - W_2 = total weight of the pycnometer,
  - W_1 = weight of empty pycnometer
  - γ_t = specific weight of the liquid
  - V_l = volume of the liquid

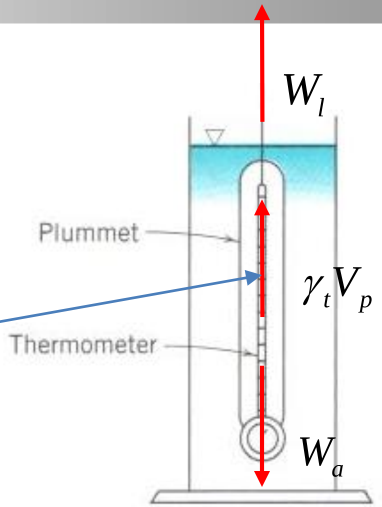
    - density depends on the temperature

2) Plummet (or density ball)

- Based on the Archimedes principle

Buoyant force

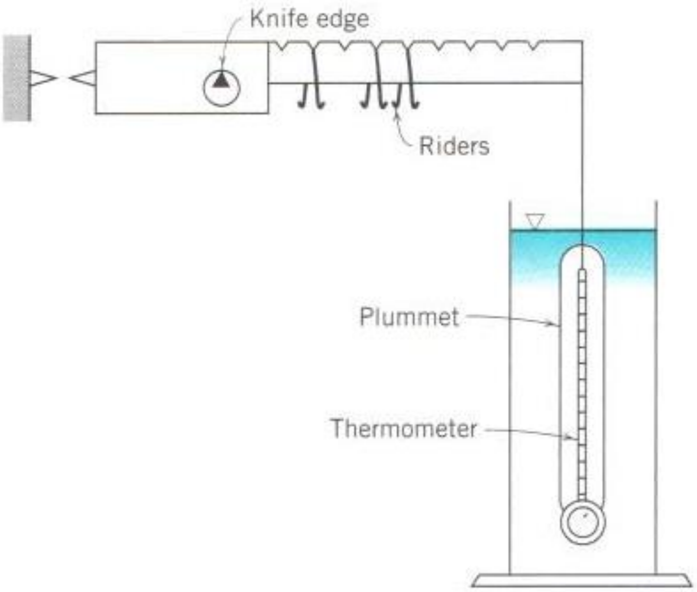
$$W_l + \gamma_t V_p = W_a \qquad (2.2)$$



W_a = weight of the plummet in air
W_l = weight of the plummet when suspended in the liquid
V_p = volume of the plummet
γ_t = specific weight of the liquid

Westphal balance

- Utilize the buoyant force on a plummet



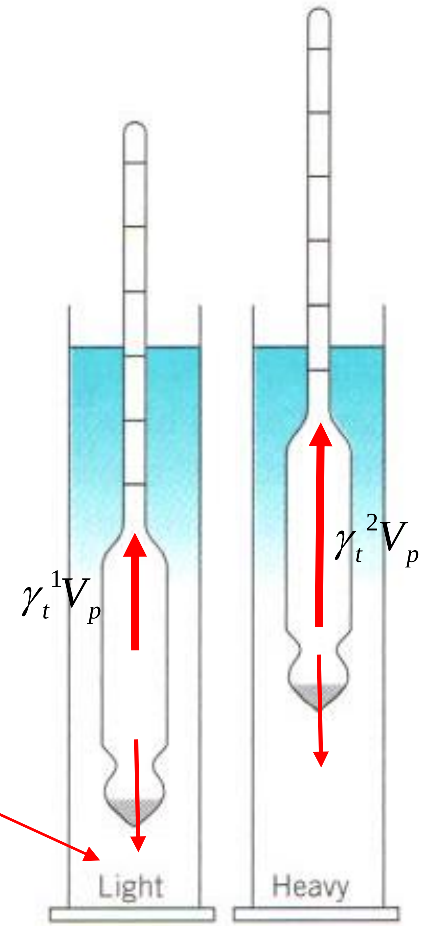
(b) Westphal balance.

3) Hydrometer (비중계)

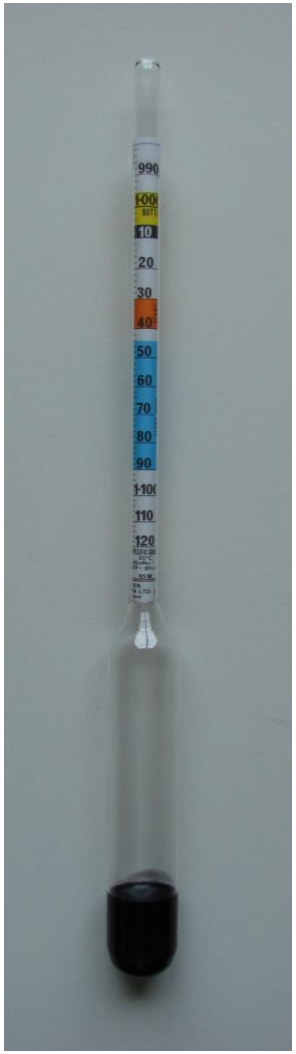
- The most common method
- Float with different immersions in liquids of different densities

Light liquid

$\gamma_t^1 < \gamma_t^2$



(c) Hydrometers.



2.2 Viscosity measurement

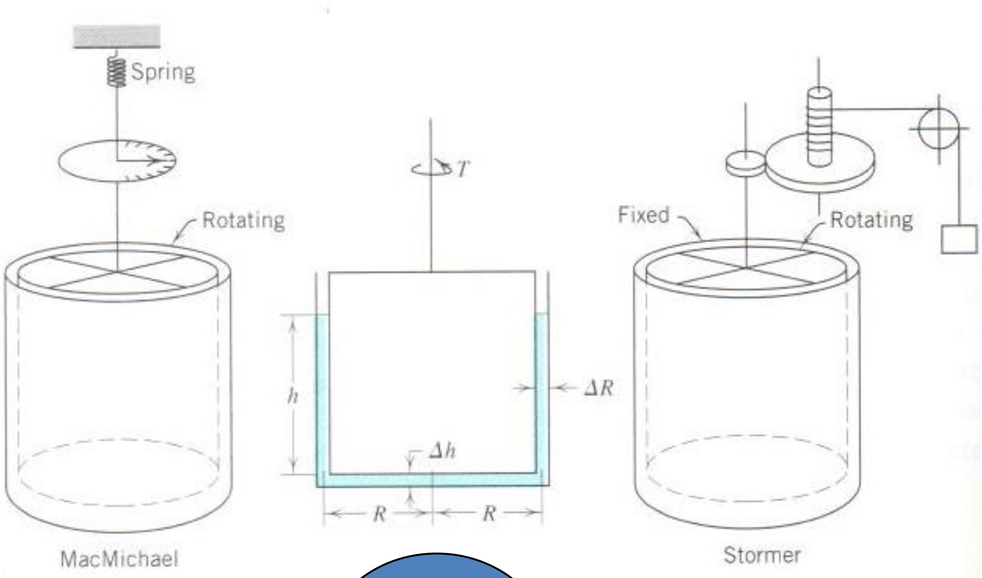
- Viscosity measurements are made with devices known as viscosimeters or viscometers

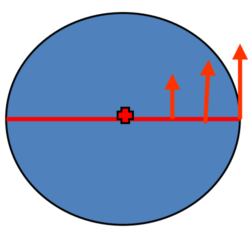
  1) Rotational viscometer

  2) Tube viscometer

- The operation of theses viscometers depends on the existence of laminar flow.
- Viscosity depends on the temperature and when it is measured, done in constant temperature.

1) Rotational Viscometers





Outer cylinder is rotating at constant angular velocity (각속도), ω

Measure torque (회전모멘트) on the inner cylinder

- Rotational Viscometers – based on Couette (laminar) flow

– Measure torque, *T* on the inner tank (side + bottom)

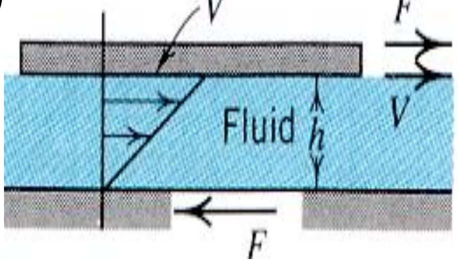
$$T = F\,r = \tau A r$$

$$T = T_1 + T_2$$

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

$$V = \omega R$$

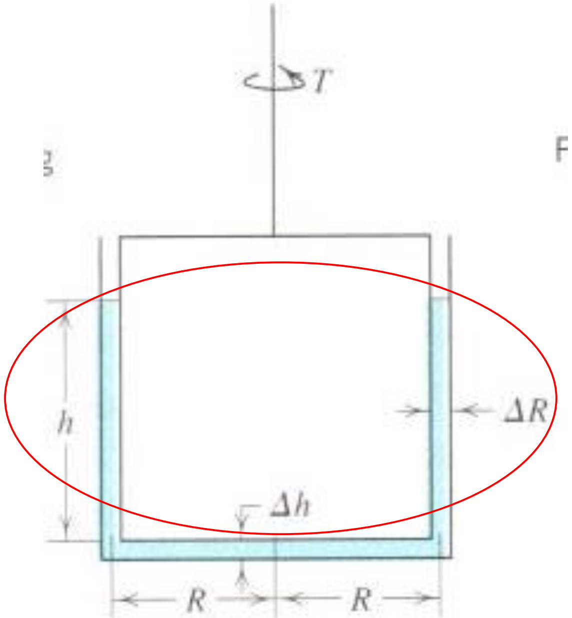
$$\tau = \mu \frac{V}{h}$$



$$T_1 = F_1 r_1 = \tau_1 A_1 r_1$$

$$\tau_1 = \mu \frac{dV}{dy} = \mu \frac{V}{\Delta R};\ A_1 = 2\pi R_i h;\ r_1 = R_i$$

$$T_1 = \frac{2\pi\mu R_i^2 hV}{\Delta R} \quad (2.3)$$



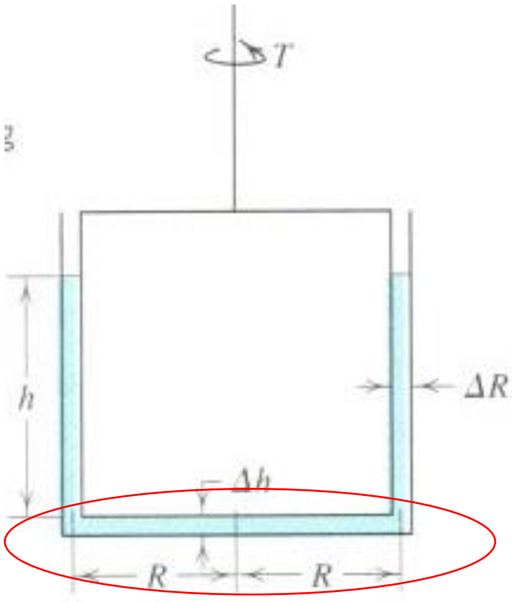
$$T_2 = \int_0^R dT = \int_0^R \tau dA \cdot r$$

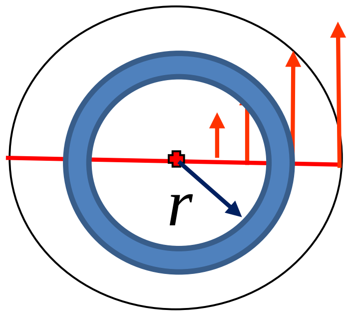
$$\tau = \mu \frac{dv}{dy} = \mu \frac{V}{\Delta h} = \mu \frac{\omega r}{\Delta h}$$

$$T_2 = \int_0^R \left(\mu \frac{\omega r}{\Delta h} \right) (2\pi r \cdot dr) \cdot r = \frac{2\pi\mu\omega}{\Delta h} \int_0^R r^3 dr$$

$$= \frac{\pi\mu\omega}{2\Delta h} R^4 = \frac{\pi R^3 \mu V}{2\Delta h} \qquad (2.4)$$

$$T = \frac{2\pi R^2 h \mu V}{\Delta R} + \frac{\pi R^3 \mu V}{2\Delta h} \qquad (2.5)$$



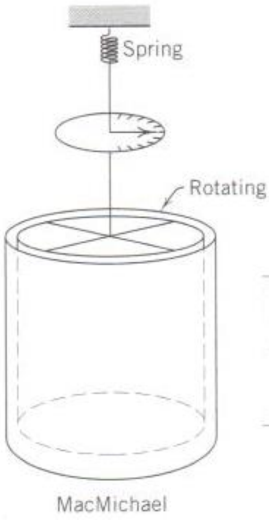


MacMichael viscometer

- Torque is proportional to the torsional deflection θ

$$T = K_1 \theta$$

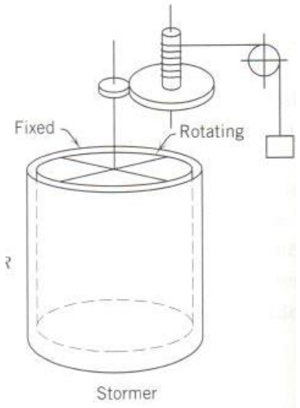
$$\mu = \frac{K_1 \theta}{KN} \qquad (2.6)$$



Stormer viscometer

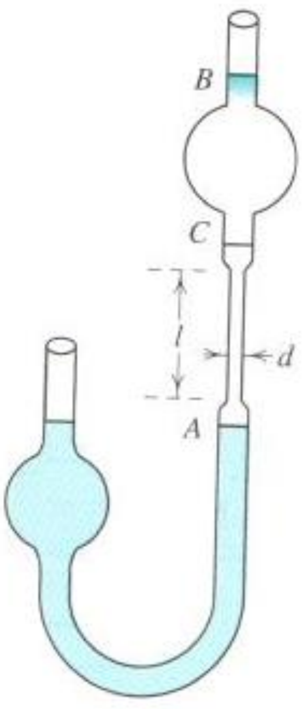
- Torque is constant since it is proportional to the weight *W*, and the time *t* required for a fixed number of revolutions is inversely proportional to *N*

$$\mu = \frac{T}{KN} = \frac{T}{KK_2} t \qquad (2.7)$$

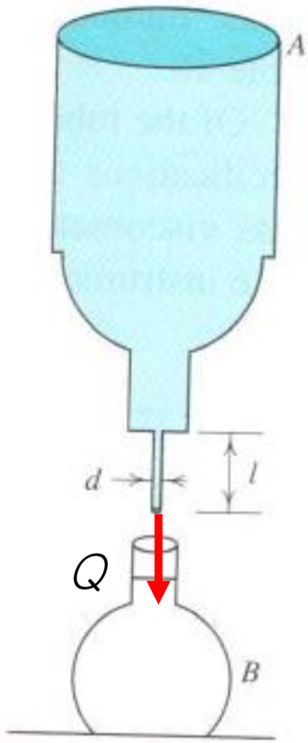


2) Tube-type viscometer

- Ostwald – low viscosity
- Saybolt instrument – medium to high viscosity



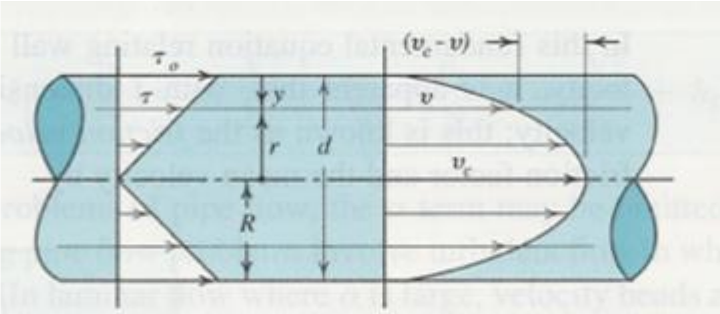
Ostwald



Saybolt

- The tube-type viscometers involve the unsteady laminar flow of a fixed volume of liquid through a small tube under standard head conditions.
- The time for the quantity of liquid to pass through the tube becomes a measure of the kinematic viscosity of the liquid.
- Apply the Hagen-Poiseuille law for laminar flow in a circular tube

$$Q = \frac{\pi d^4 \gamma h_L}{128 \mu l}$$



$$Q = \frac{V_l}{t}$$

$$\mu = \left(\frac{\pi d^4 h_L}{128 V_l l} \right) \gamma t \qquad (2.8)$$

V_l is volume of liquid passed in time *t*

d, l, V_l, h_L are constants of the instrument

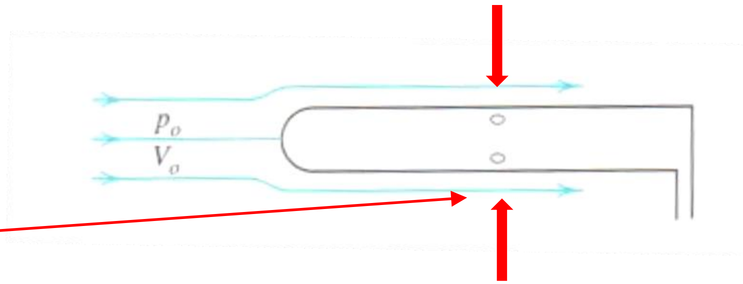
2.3 Pressure measurement

- Static pressure
  - The accurate measurement of static pressure in a fluid at rest may be accomplished with comparative ease.

  → manometer, pressure gages

  - To measure static pressure in a flowing fluid a device is required within fits the streamline picture and causes no flow disturbance.
  - It should contain a small hole whose axis is normal to the diction of motion, which usually is not known in advance.

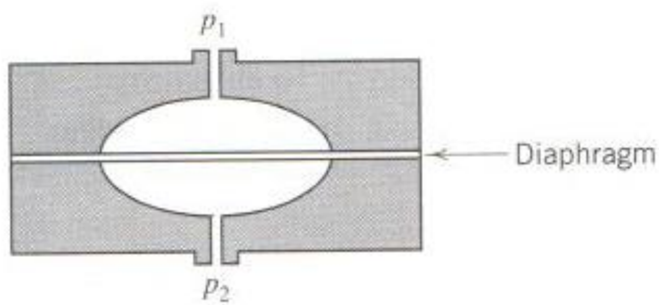
- Static tube
  - Assuming that it is aligned to the direction



$$V_{measured} > V_0 \rightarrow p_{measured} < p_0$$

  - This error is minimized by making the tube as small as possible.

- Transducers (connect to the manometer)
  - Transducer (diaphragm gage) convert pressure differential to an electric output.

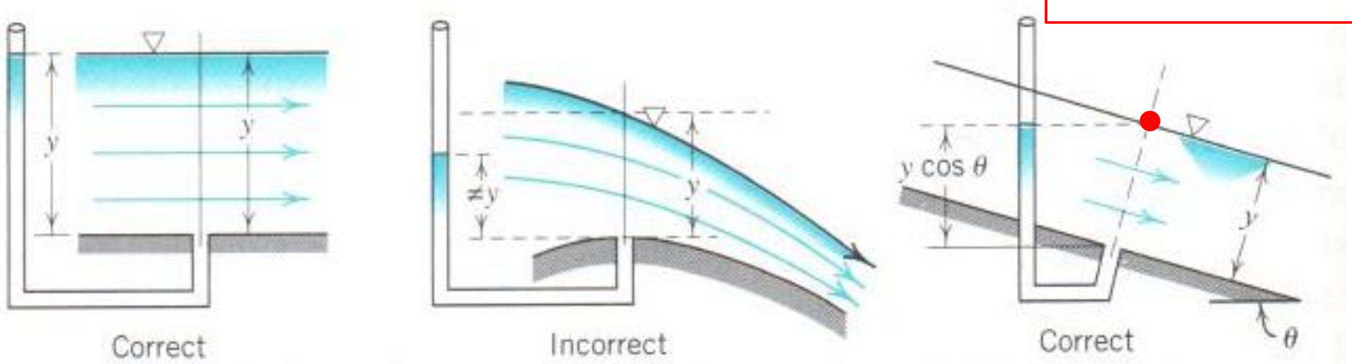


2.4 Surface elevation

1) *Manometer, piezometer column, pressure-gage:*

- The elevation of the surface of a liquid at rest may be determined
- The same methods may be applied to flowing liquids.
- The piezometer method is used only where the streamlines are essentially straight and parallel.

수심 = y
수위 = ycosθ

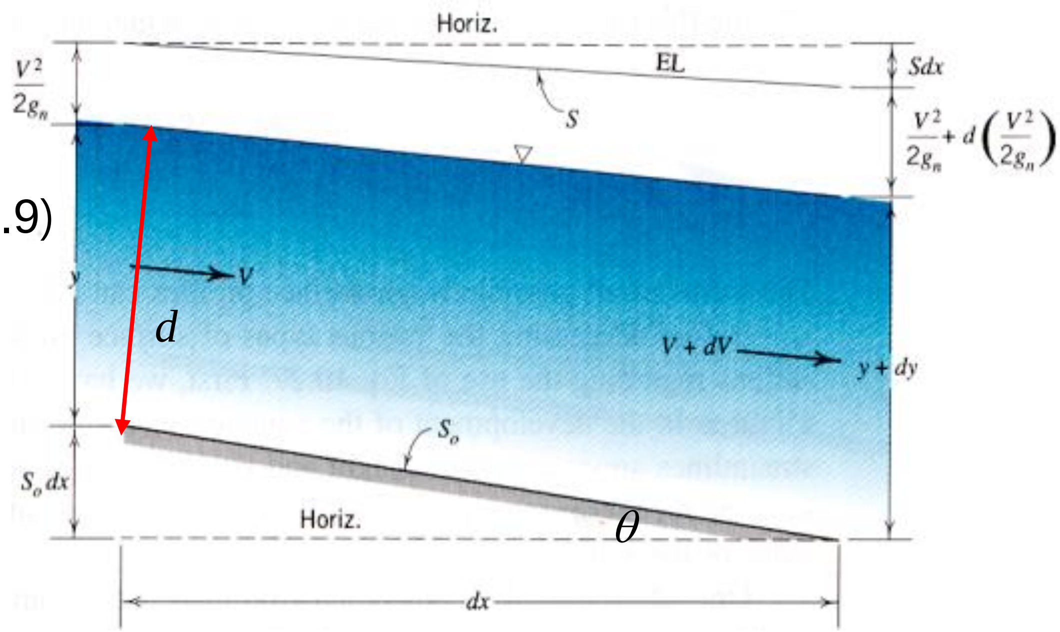


[Re] Derivation of gradually varied flow equation

dx = length of a channel segment
y ~ *d* = depth of flow (varies by *dy*);
V = average velocity (varies by *dV*)
S_0 = bed slope
S = energy (friction) slope

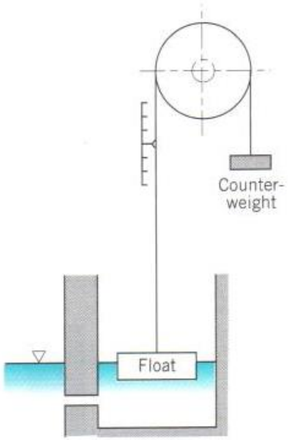
$$H = z + d\cos\theta + \frac{V^2}{2g} \approx z + y + \frac{V^2}{2g} \quad (2.9)$$

$$when\ \theta\ is\ small \rightarrow d\cos\theta \approx y$$



2) Floats:

used for measuring the surface



3) Staff gages:

crude but direct measurements of liquid-surface elevation

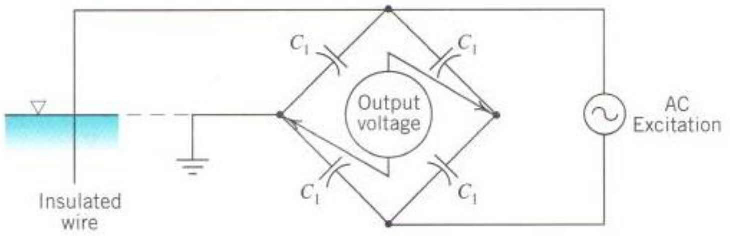
4) Wading rod:

- Depth is shallow enough or measuring from a low footbridge

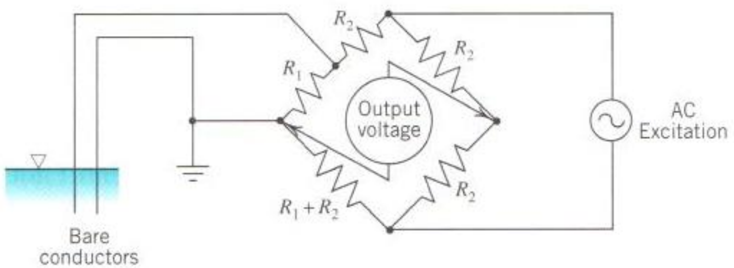
- Wading rod to be placed firmly on the streambed

5) Insulated wire and bare conductors (전도체)

- output bridge voltage is proportional to the change in depth



(a) Capacitive sensor.



(b) Resistive sensor.

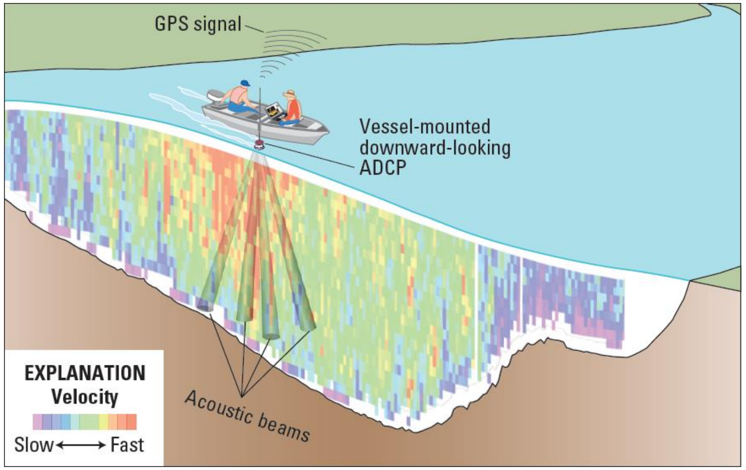
6) Sonic devices

- Measure the time necessary for a sound pulse to travel to the surface and return to its source

- Echo sounder (MBES/ADCP)

Measuring depth when making a moving boat measurement

Records a continuous trace of the streambed on a digital or analog chart.



2.5 Velocity measurement

1) Pitot-static tube (피토관)

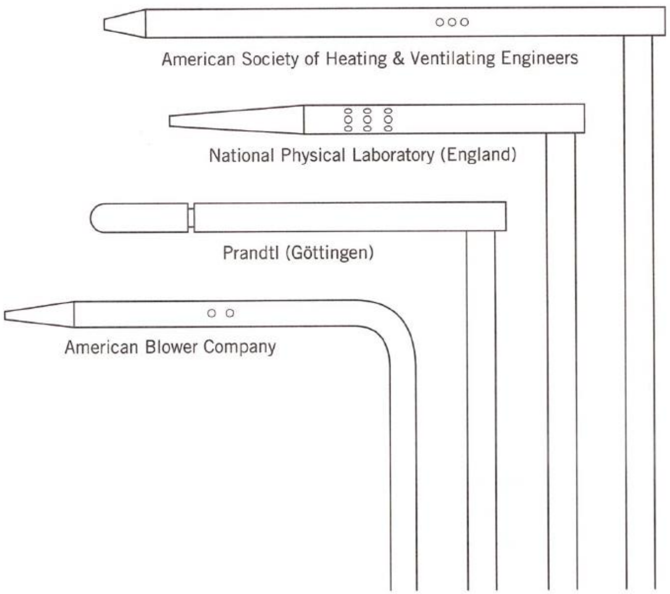
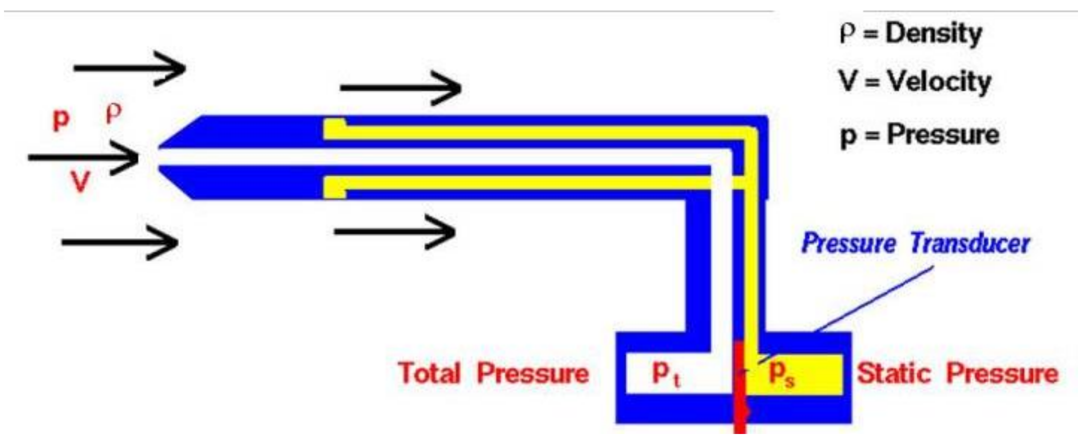
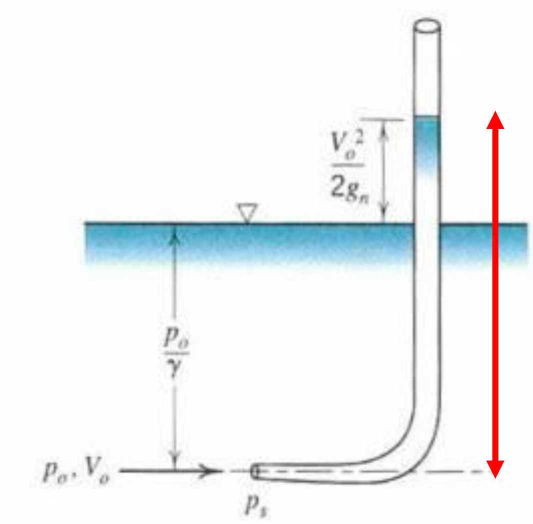


Fig. 14.12 Pitot-Static tubes (to scale).



- Stagnation pressure (total pressure) 정체압력
  - Aligned to the flow direction
  - Apply Bernoulli equation



$$\frac{p_s}{\gamma} = \frac{p_0}{\gamma} + \frac{V_0^{\ 2}}{2g} \qquad (2.10)$$

Total pressure 정체압력

Static pressure 정압력

Dynamic pressure 동압력

$$V_0 = \sqrt{\frac{2g(p_s - p_0)}{\gamma}} \qquad (2.11)$$

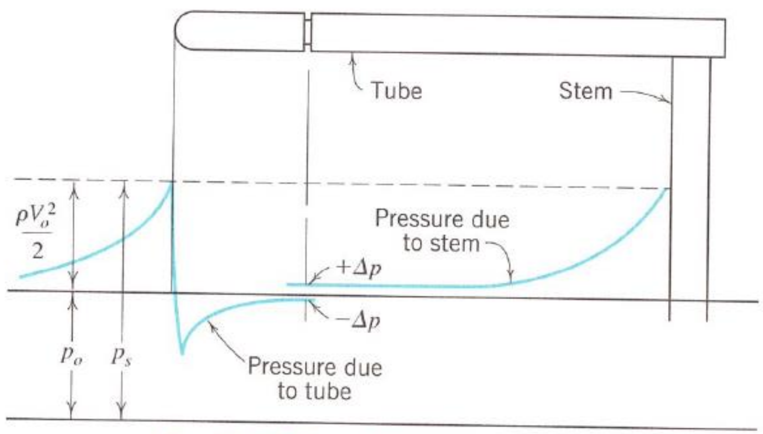


Fig. 14.13 Prandtl's pitot-static tube.

- Aribus-380
- Helicopter

2) Current meters

$$V = aN + b$$

- Anemometers and current meters

N = 회전수

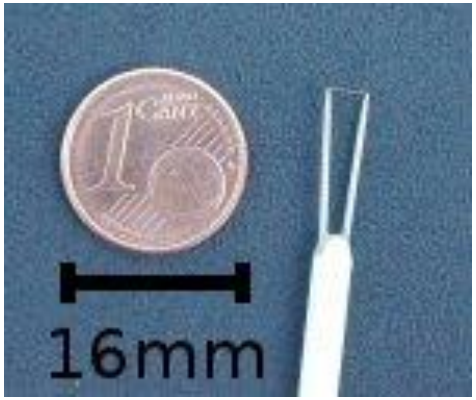
Current meters – propeller type

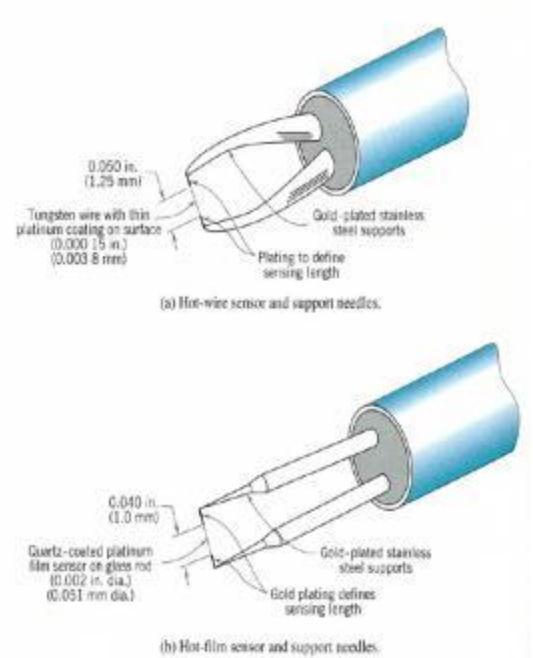
Current meters – cup type

Anemometers -air

3) Hot wire anemometer

- Change of temperature affects the electric current flow or voltage drop through wire.
- Fine platinum wire (film) is heated electrically by a circuit that maintains voltage drop constant.
- When inserted into the stream, the cooling, which is a function of the velocity, can be detected as variations in voltage.



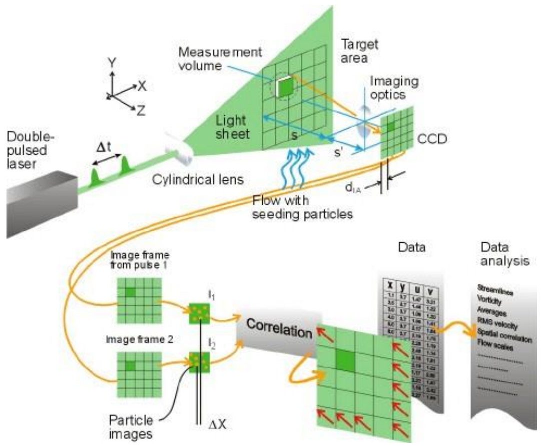


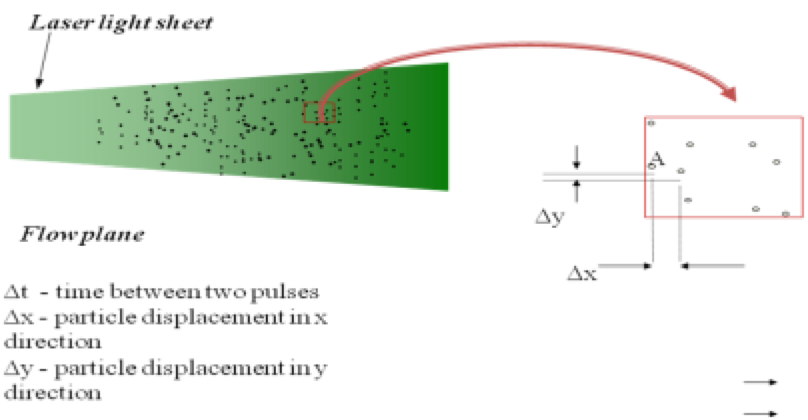
(a) Hot-wire sensor and support needles.

(b) Hot-film sensor and support needles.

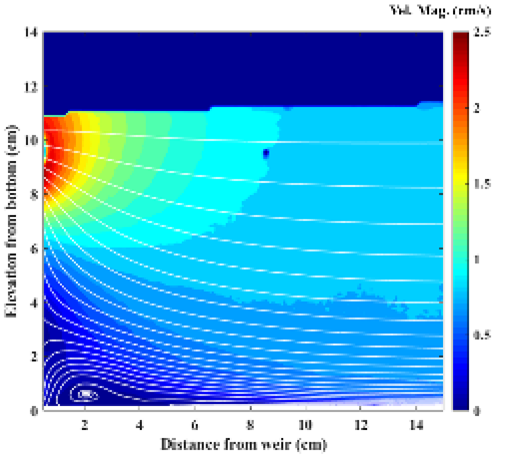
4) Laser techniques

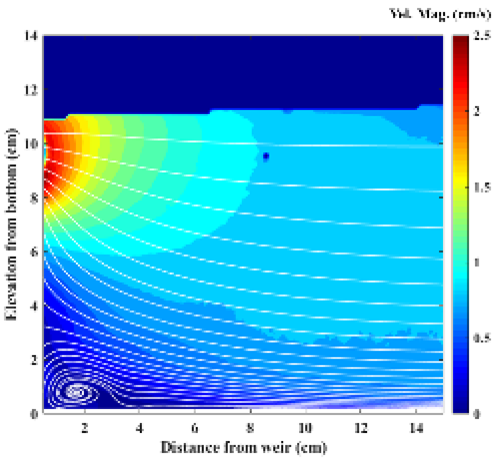
1) PIV (Particle Image Velocimetry)



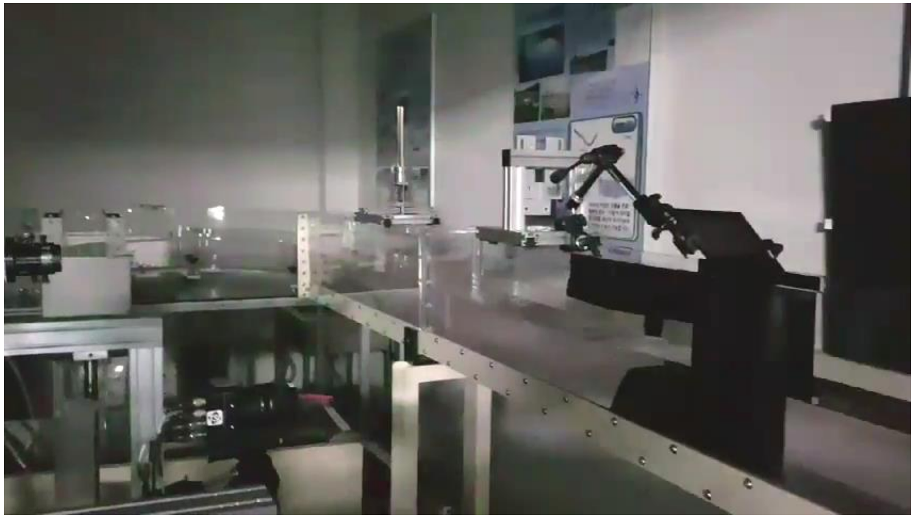


Δt - time between two pulses
Δx - particle displacement in x direction
Δy - particle displacement in y direction

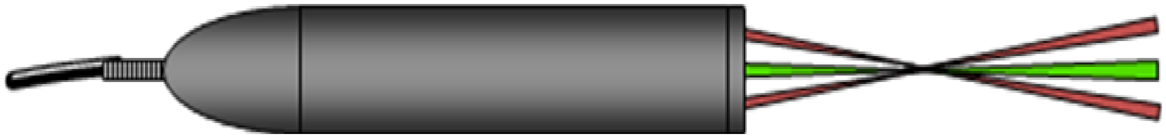


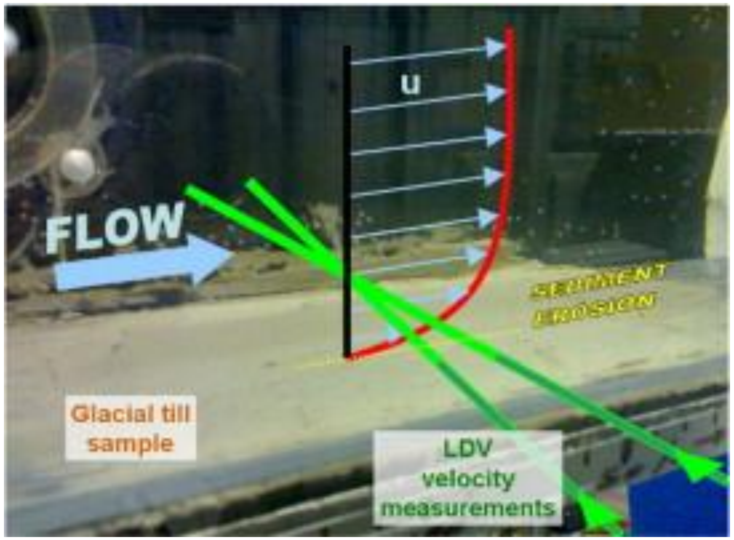


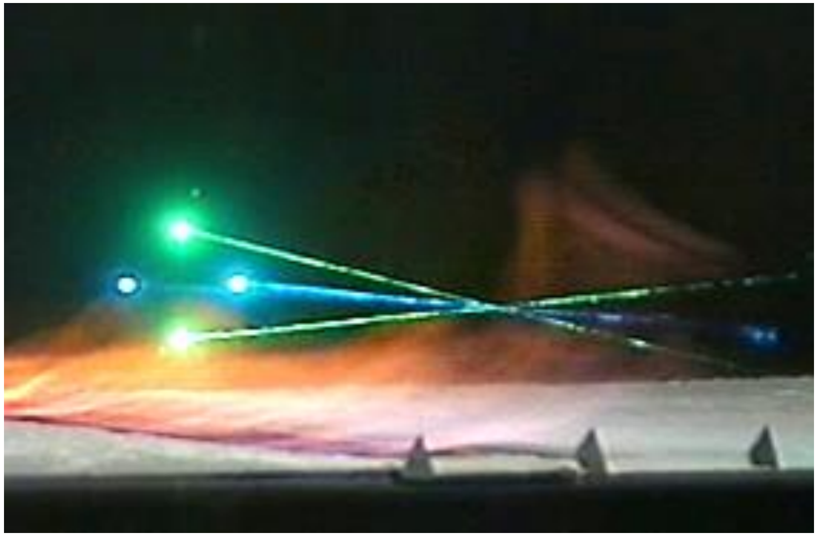
- Weir tests



2) LDV (Laser Doppler Velocimeter)







~ use Doppler effect

~ A laser (ultrasonic) beam transmitted into the fluid will be reflected by impurities or bubbles in the fluid to a receiving sensor at a different frequency.

→ The transmitted and reflected signals are then compared by electronic means to calculate the Doppler shift which is proportional to the velocity.

~ non-intrusive sensing (immersible LDA)

~ sampling frequency is up to 20,000 Hz

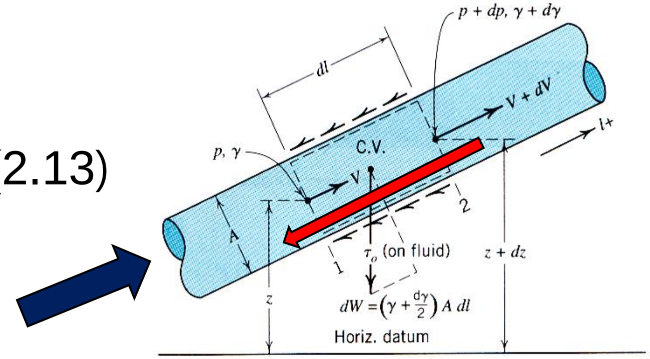
$$F_{doppler} = -F_{source} \frac{V}{C} \qquad (2.12)$$

2.6 Shear measurements

- Shear determined by inference
  - No device has yet been invented which is capable of measuring the stress between moving layers of fluid.
  - measure wall shear τ_0
  - From τ_0 the shear between moving layers may be deduced using shear stress equations.
  - For a cylindrical pipe of uniform roughness, the wall shear can be obtained from pressure measurements as given below:

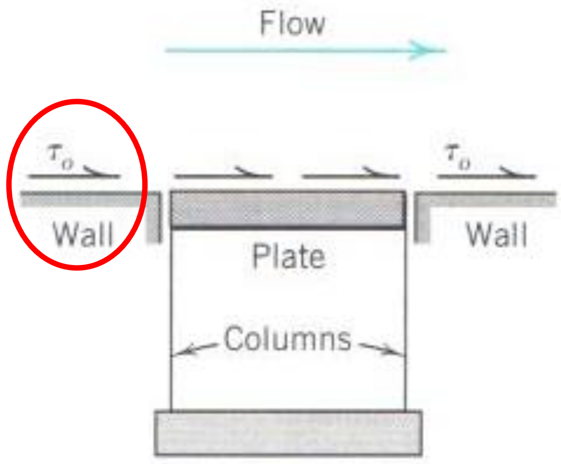
$$\tau_0 = \frac{\gamma d}{4l}\left(\frac{p_1}{\gamma} + z_1 - \frac{p_2}{\gamma} - z_2\right) = \frac{\gamma d}{4l} h_L \quad (2.13)$$

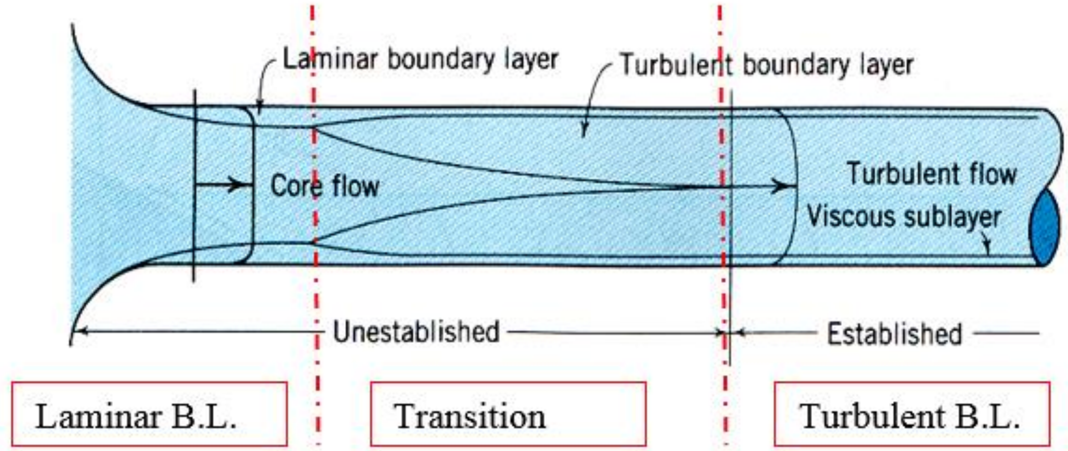
Head loss

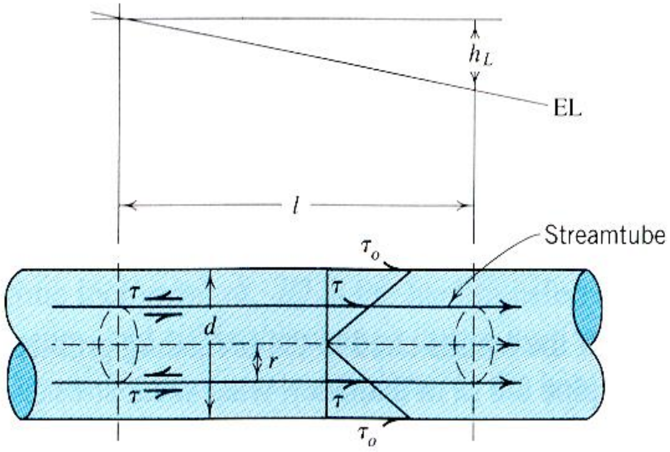


1) Wall probes

- A movable plate mounted on elastic columns fastened to a rigid support
- The columns are deflected slightly by the shearing force of fluid on plate.
- This small deflection measured by strain gages, and the wall shear stress deduced from this deflection.



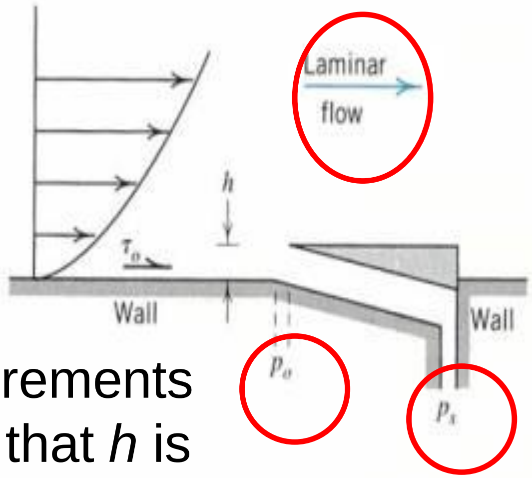


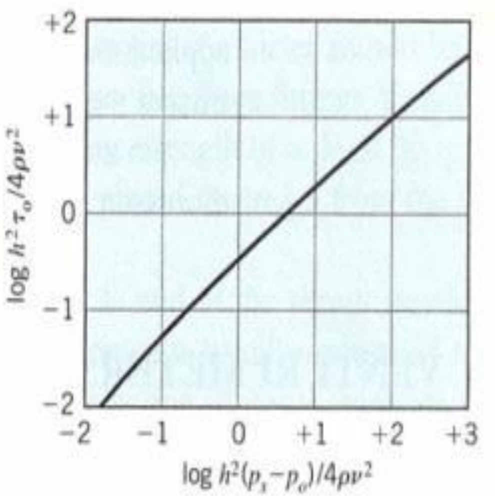


2) Wall Pitot tubes

- Stanton tube
  - To measure wall shear, Stanton invented the wall pitot tube of which the wall forming one side of the pitot tube.
  - Calibration in laminar flow and in the viscous sublayer of the turbulent pipe flow showed that

$$\frac{\tau_0 h^2}{4\rho\nu^2} = fn\left(\frac{(p_s - p_0)h^2}{4\rho\nu^2}\right) \tag{2.14}$$

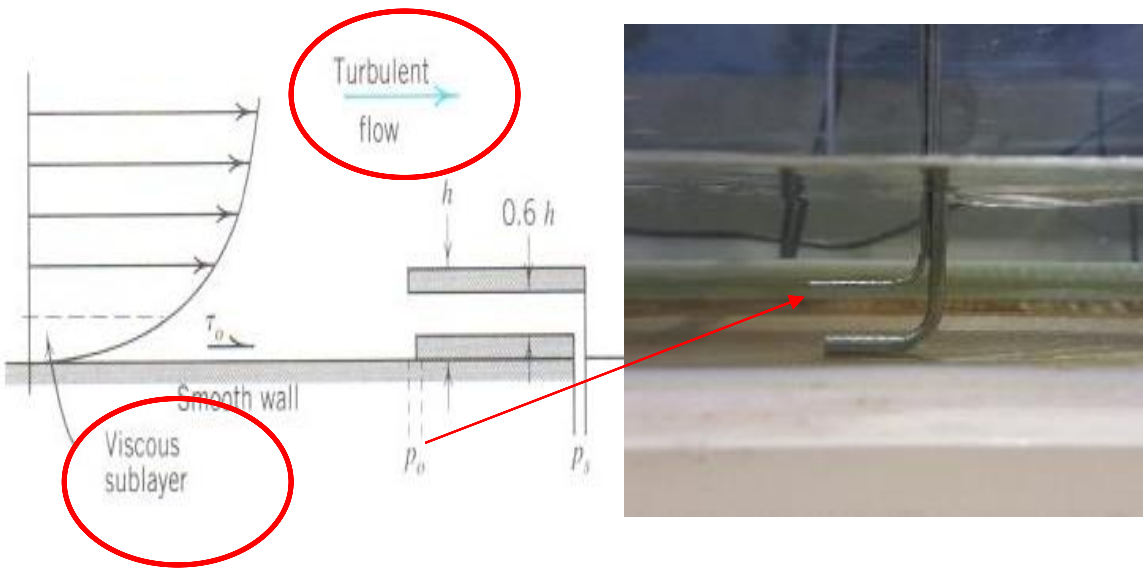


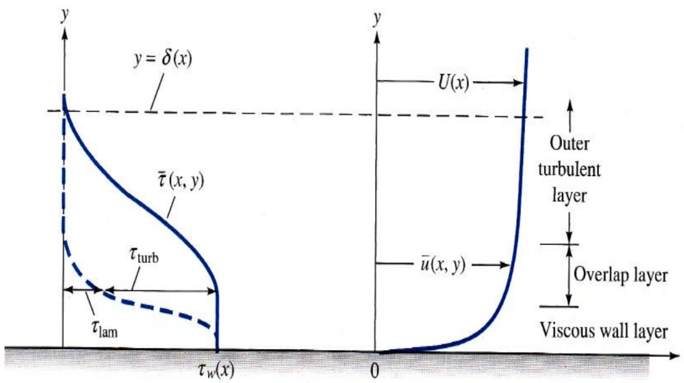


τ_0 can be calculated from measurements of $(p_s - p_0), \rho, \nu, h$ providing that *h* is smaller than the thickness of viscous region.

- Preston tubes

- Preston applied idea to turbulent flow over smooth surface
- This tube is not submerged in the viscous sublayer
- Its performance depends on the similarity of the velocity profiles through the buffer zone between the viscous sublayer and the turbulent region.

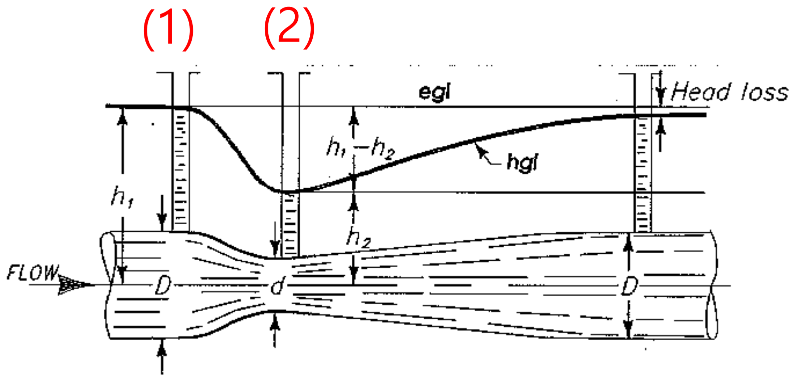




2.7 Flowrate measurement

1) Differential measurement system

i) Venturi meter



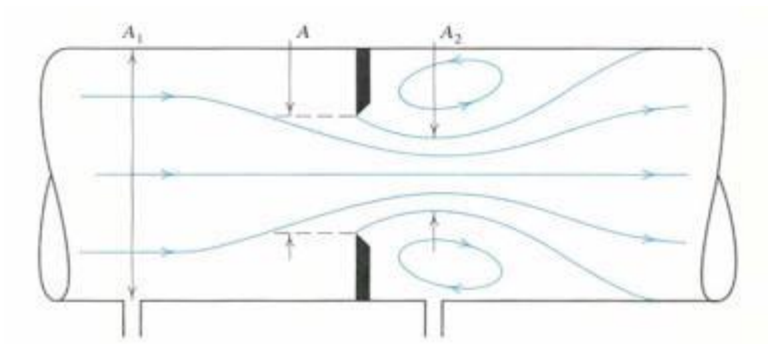
- Consider head loss at the constriction using Bernoulli equation

$$Q = \frac{C_v A_2}{\sqrt{1 - \left(A_2 / A_1 \right)^2}} \sqrt{2g \left(\frac{p_1}{\gamma} + z_1 - \frac{p_2}{\gamma} - z_2 \right)} \qquad (2.15)$$

C_v = coefficient for Venturi meter (Fig. 14.24)

ii) Pipe orifice meter

- The minimum section occurs at section 2 (Vena contracta)



$$Q = \frac{C_v A_2}{\sqrt{1 - C_c^{\,2}\left(A_2/A_1\right)^2}} \sqrt{2g\left(\frac{p_1}{\gamma} + z_1 - \frac{p_2}{\gamma} - z_2\right)} = CA\sqrt{2g\left(\frac{p_1}{\gamma} + z_1 - \frac{p_2}{\gamma} - z_2\right)} \qquad (2.16)$$

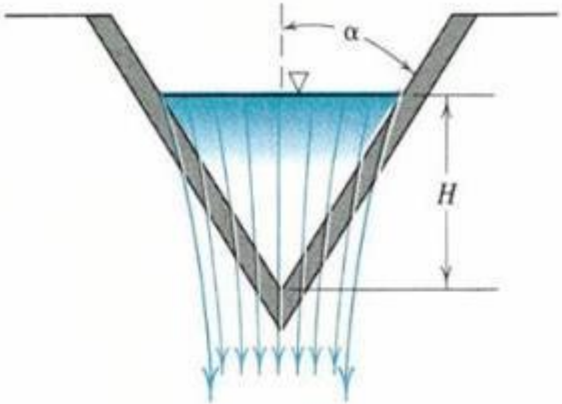
$$C = \frac{C_v C_c}{\sqrt{1 - C_c^{\,2}\left(A/A_1\right)^2}}$$

C – Fig. 14.27

3) Weir

Weir- a regular obstruction over which flow occurs

- Spillway – overflow section of dam
- Sharp-crested weir
- Broad-crested weir
  - – critical-depth meter



Consider energy equation through the strip

$$H + \frac{V_1^2}{2g} = (H - h) + \frac{v_2^{\;2}}{2g}$$

$$v_2 = \sqrt{2g\left(h + \frac{V_1^2}{2g}\right)}$$

$$q = \int_0^H v_2 dh = \frac{2}{3}\sqrt{2g}\left[\left(H + \frac{V_1^2}{2g}\right)^{3/2} - \left(\frac{V_1^2}{2g}\right)^{3/2}\right]$$

$\frac{V_1^{\;2}}{2g}$ can be neglected since $P >> H$ and V_1 is small

$$q \cong \frac{2}{3}\sqrt{2g}H^{3/2}$$

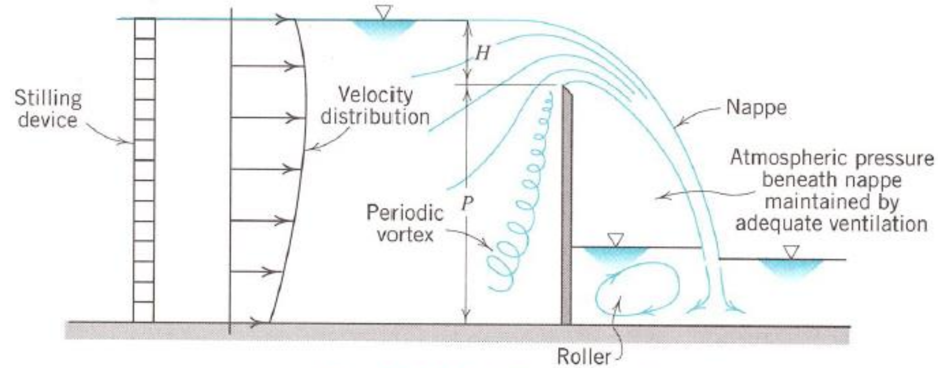
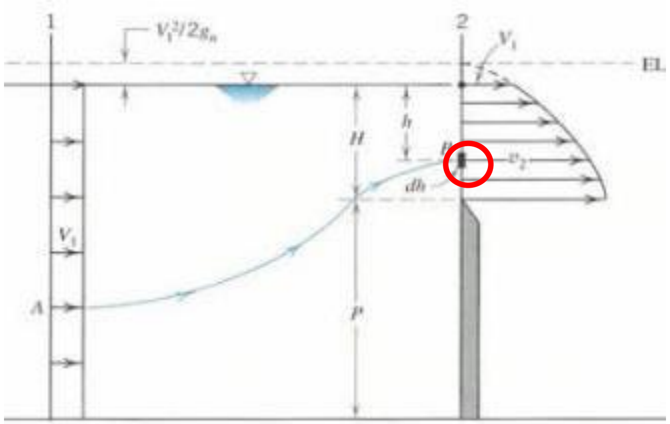


Fig. 14.35 Weir flow (actual).

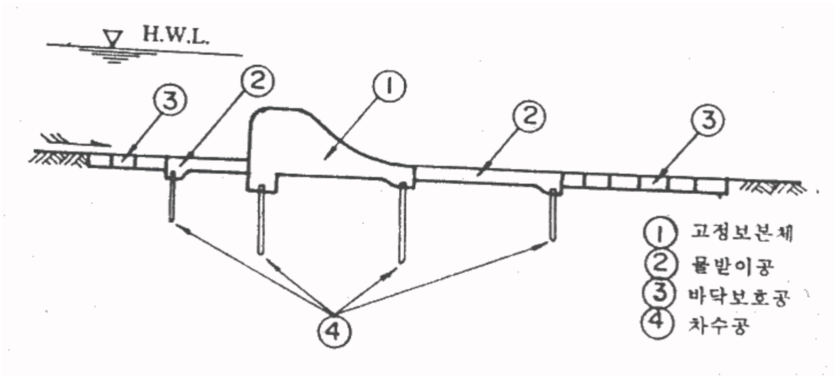


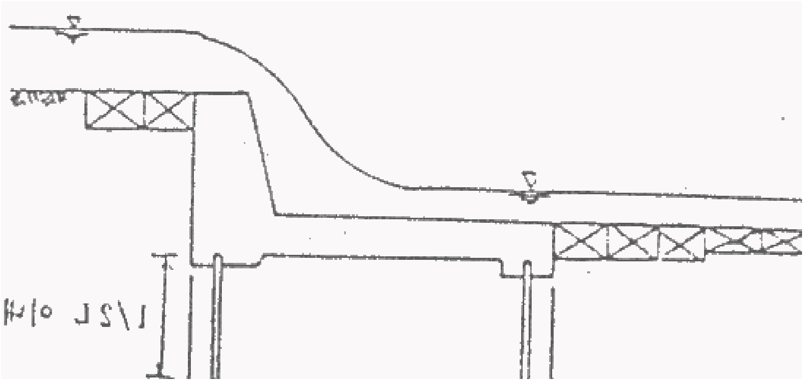
$$q = C_w \frac{2}{3}\sqrt{2g}H^{3/2}$$ (2.17)

C_w = weir coefficient

Dam and Weir

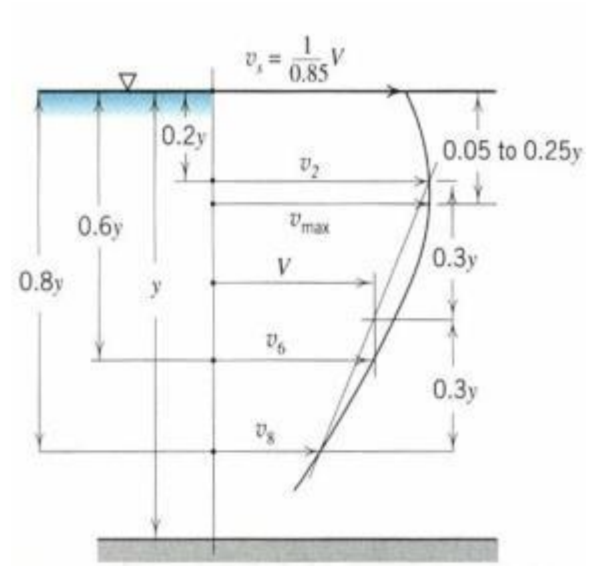
- Large dam 대댐
- Small dam 소댐: H < 15m
- Navigation dam 주운댐
- Weir: 수위 상승
- Drop structure 하상유지공(낙차공)





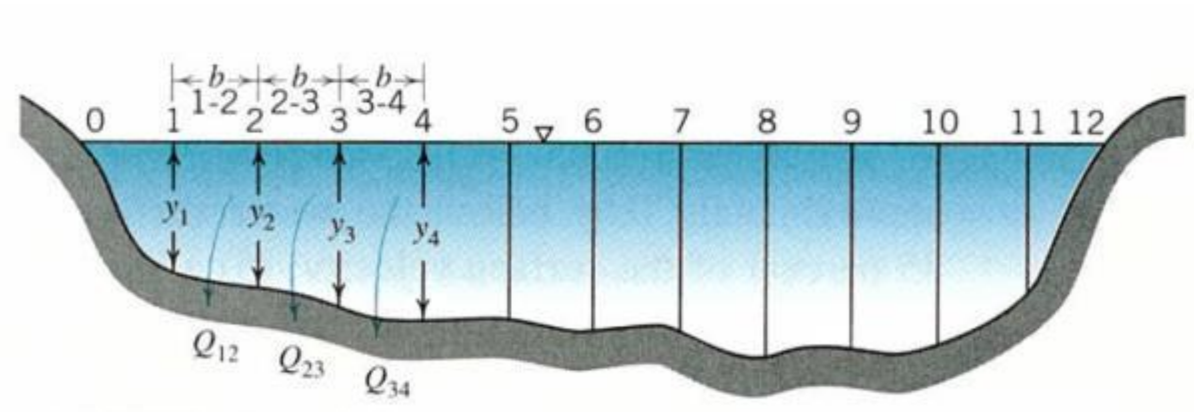
Velocity-area method

The standard method of river flow measurement is to measure the velocity by means of a current meter and integrate the depth-averaged velocity to obtain the flowrate.



$$V = \frac{v_{0.2} + v_{0.8}}{2} \qquad (2.18)$$

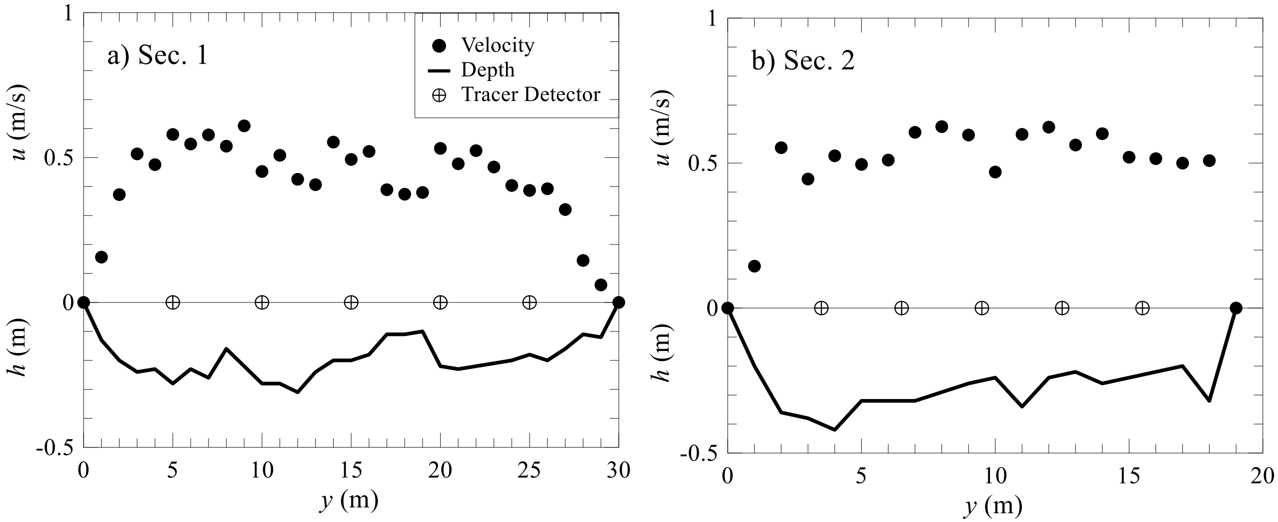
$$Q_{12} = b_{12}\left(\frac{y_1 + y_2}{2}\right)\left(\frac{V_1 + V_2}{2}\right) \qquad (2.19)$$



Velocity profile

- measured by wading with ADV or by dragging boat-mounted ADCP
- Lateral distribution of velocity is obtained

Velocity measurements with ADV



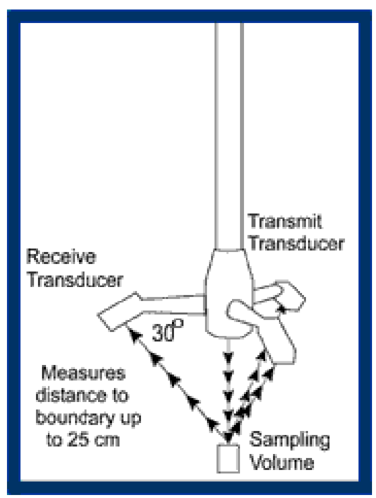
<Velocity profiles>

- Acoustic Doppler Velocimeter

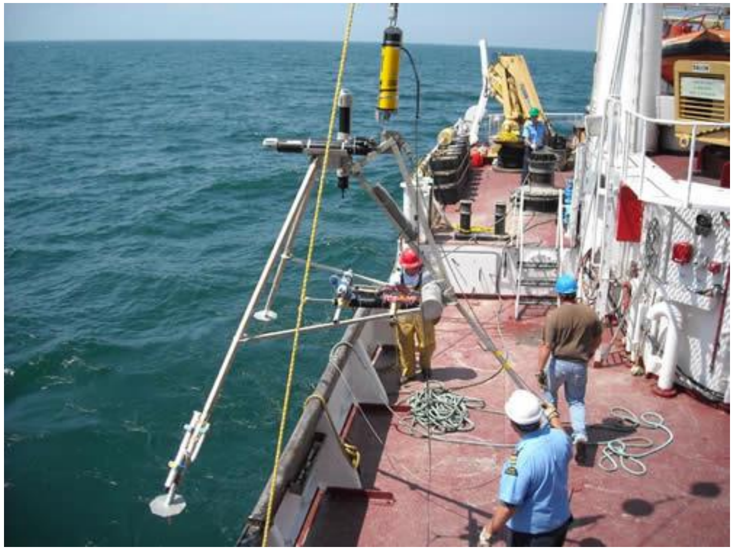
$$V = \frac{F_{Doppler}}{F_{source}} \times \frac{c}{2} \qquad (2.20)$$

$V = \frac{F_{Doppler}}{F_{source}} \times \frac{c}{2}$

C =물에서의 음속



- Acoustic Doppler Velocimeter

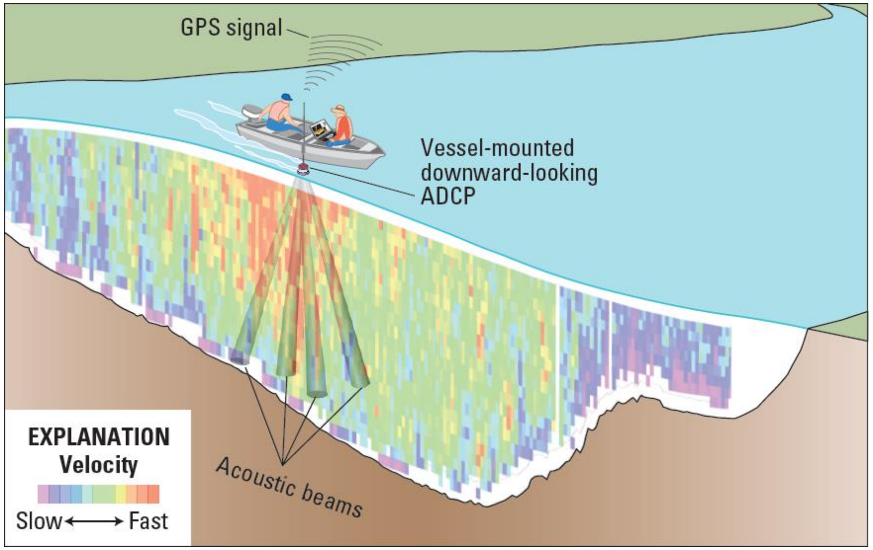


ADCP (Acoustic Doppler Current Profiler)

ADCPs measure non-intrusively 3D velocity and bathymetry

~ applied Doppler principle by bouncing a pulse off particles

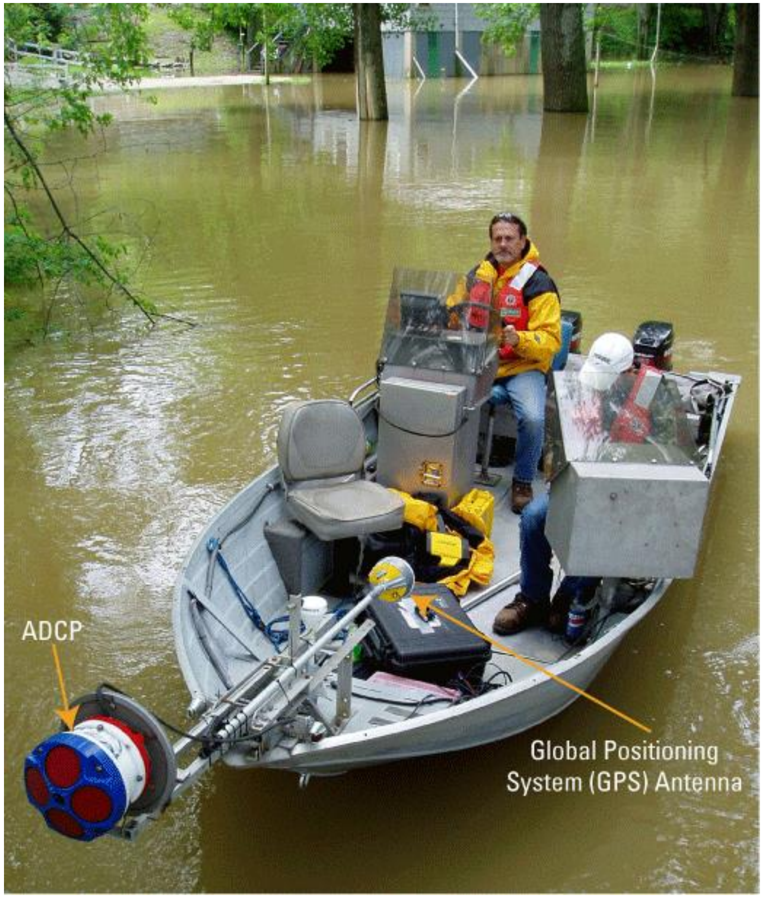
$$F_d = 2F_s \frac{V}{C_s}$$ (two Doppler shift)



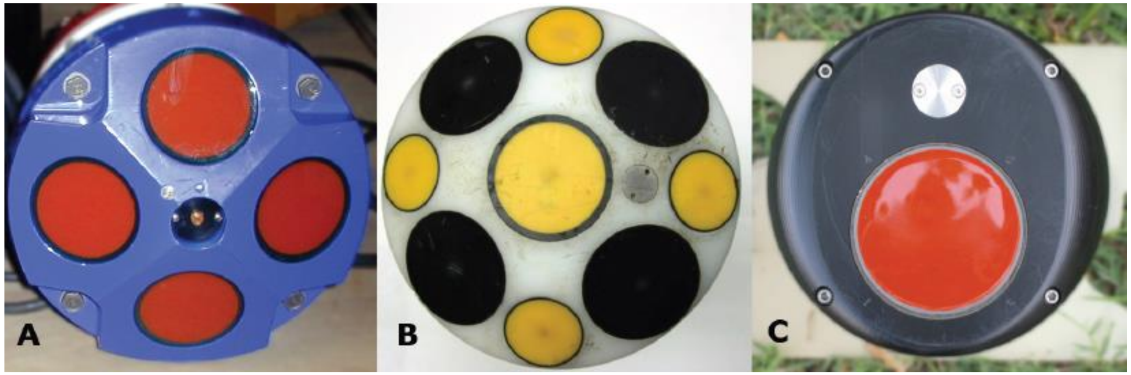
<USGS, 2013>

ADCP

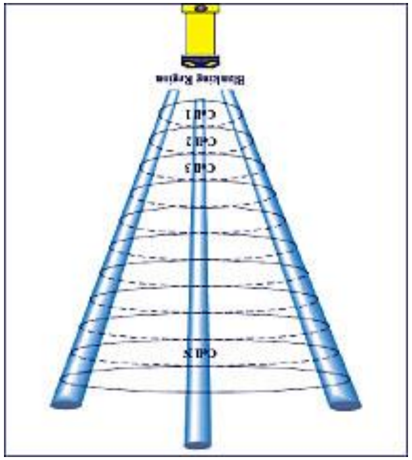
Figure 1.--StreamPro acoustic Doppler current profiler.



ADCP

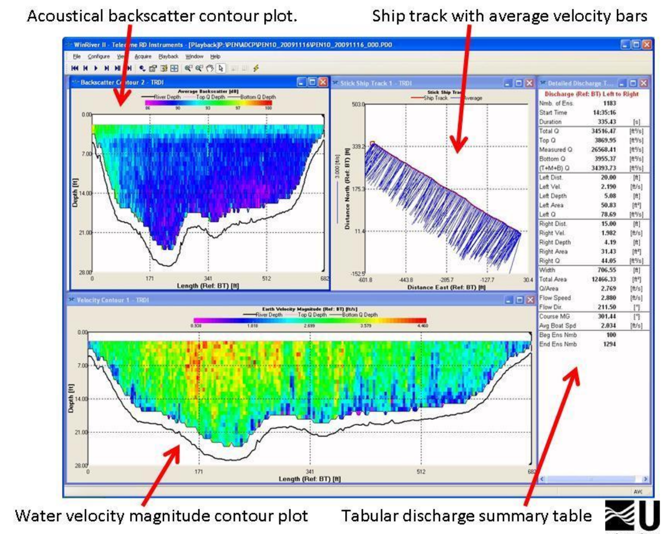


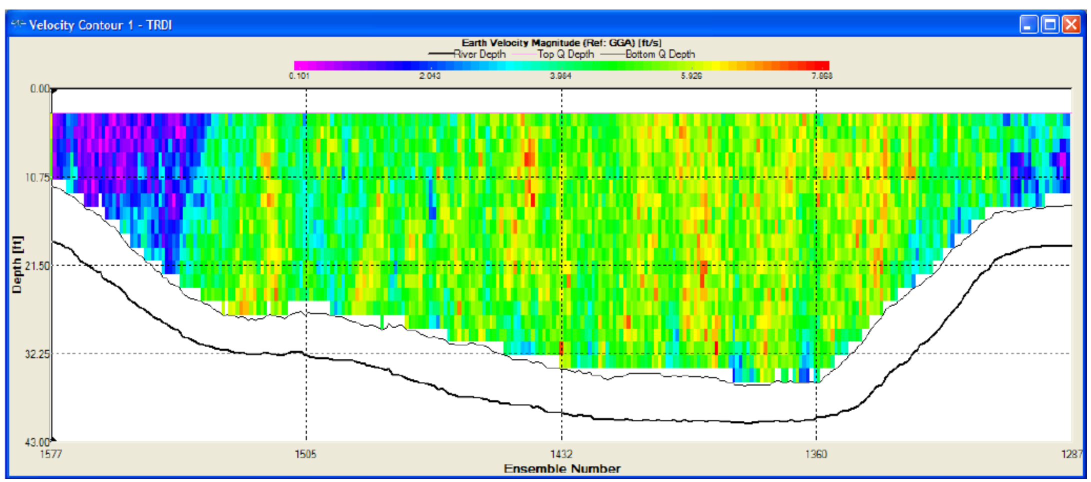
A: TRDI Rio Grande; B: Sontek M9; C: TRDI RiverRay



ADCP

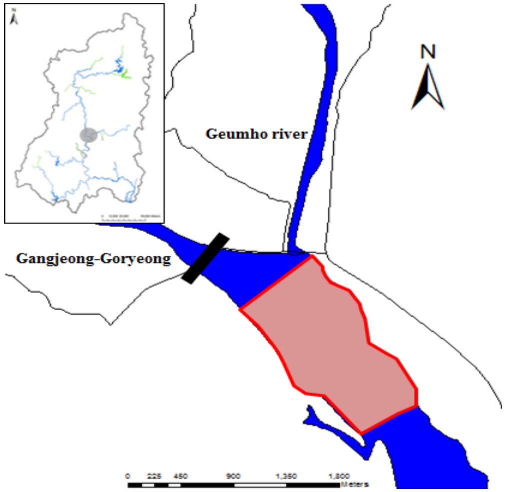

StreamPro
Expert
History
Playback
Transect Comparison Data
Mean Discharge
Mean Velocity
Mean Distance
Mean Area
12.453
0.480
16.21
26.4
Transect
Use
Delta Q
Total Q
Area
004 0.33% 12.494 26.1
003 -0.30% 12.415 26.8
002 -1.83% 12.225 26.1
001 1.80% 12.677 26.8
Tools Help
DataCollection
Transect In Progress
Move to the far edge
Transect Stop
Left Edge 1.20m
Right Edge 1.40m
Abort
Display
Avg Vel [m/s]
0.091
Discharge [m³/s]
-0.013
Bottom Depth [m]
0.300
Dist. Traveled [m]
0.55
File Tools Help

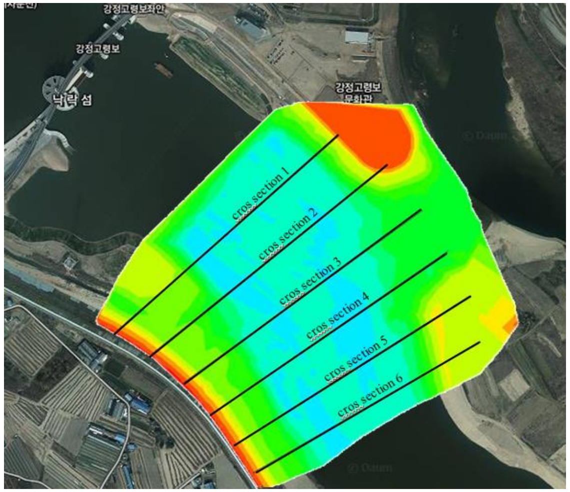

Acoustical backscatter contour plot.
Ship track with average velocity bars
Water velocity magnitude contour plot
Tabular discharge summary table

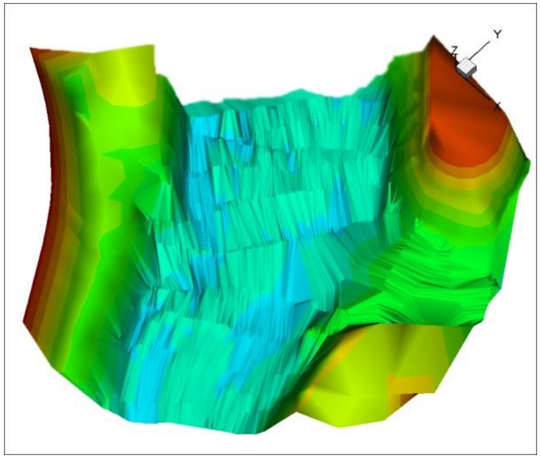

Velocity Contour 1 - TRDI
Earth Velocity Magnitude (Ref: GGA) [ft/s]
River Depth
Top Q Depth
Bottom Q Depth
0.101
2.043
3.984
5.926
7.868
0.00
10.75
21.50
32.25
43.00
Depth [ft]
1577
1505
1432
1360
1287
Ensemble Number

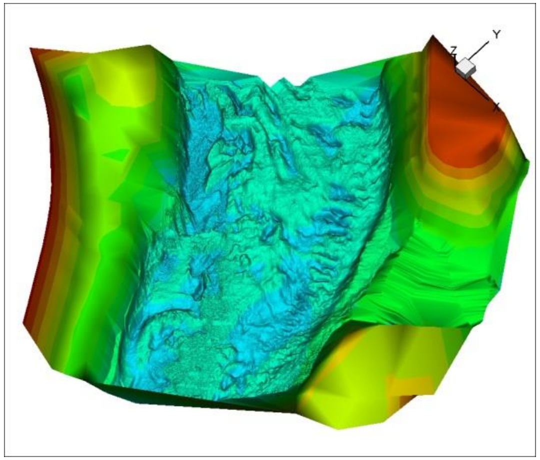
Seoul National University

2.8 River Topography







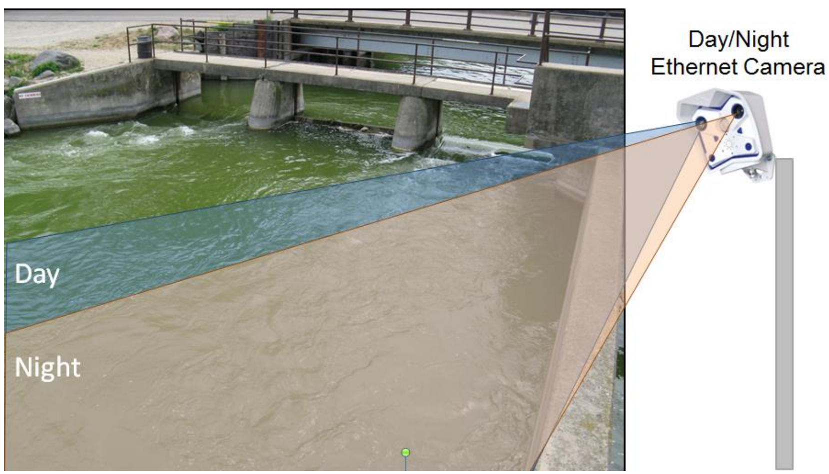


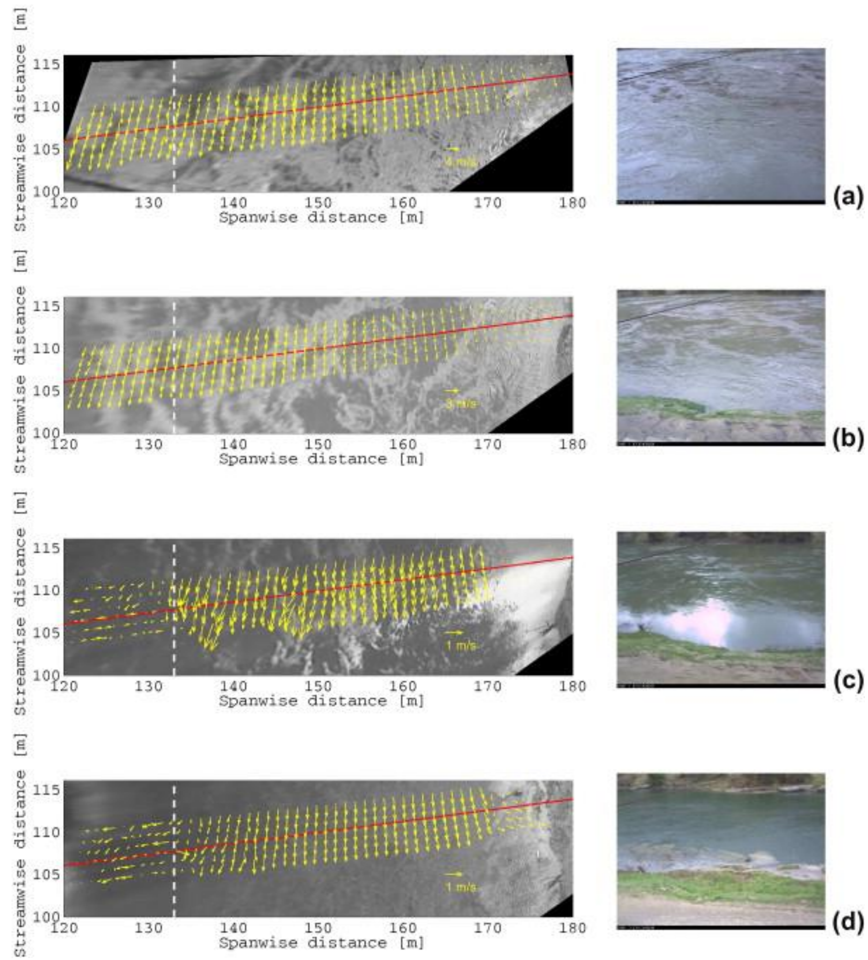
Channel topography measured by ADCP and MBES

2.9 Large scale measurement

- LSPIV

~ use CCD camera in rivers





Remote measurements

- UAV (Unmanned Aerial Vehicle)
- Drone

~ aerial survey

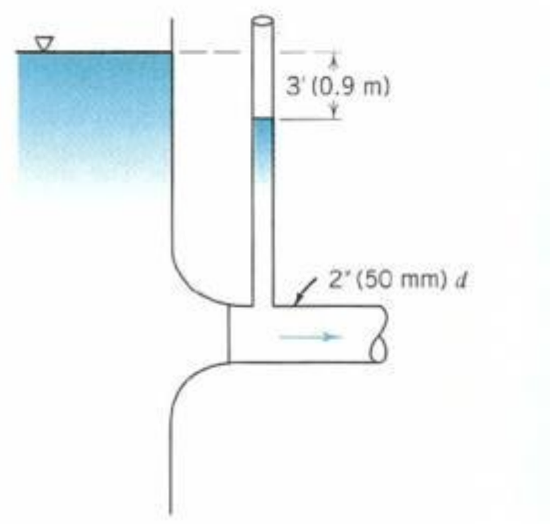
~ river topography, velocity, water quality

Homework Assignment No. 1
Due: 1 week from today
Answer questions in Korean or English

1. (14-8) If the torque required to rotate the inner cylinder of problem 1.69 at a constant speed of 4 *r/min* is 2.7 *N·m*, calculate the approximate viscosity of the oil.

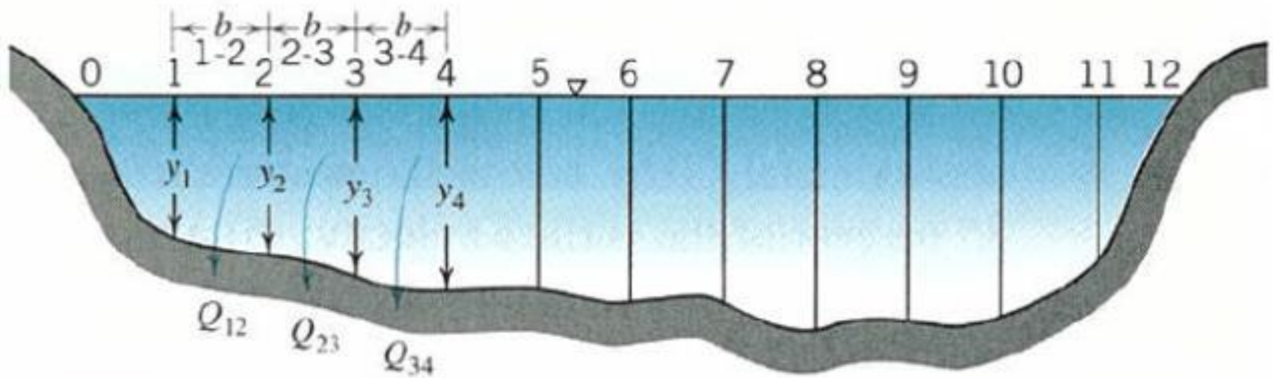
2. (14-37) A Preston tube of 12.7 *mm* outside diameter is attached to the hull if a ship to measure the local shear, When the ship moves through freshwater (20 ℃) the pressure difference is found to be 3.6 *kPa*. Calculate the local shear.

3. (14-61) Calculate the flowrate if C_v for this entrance nozzle is 0.96.



4. (14-82) A rectangular channel 5.4 m wide carries a flowrate of 1.4 m^3/s . A rectangular sharp-crested weir is to be installed near the end of the channel to create a depth of 0.9 *m* upstream from the weir. Calculate the necessary weir height.

5. (14-103) The following data are collected in a current-meter measurement at the river cross section of Fig. 14.44, which is 18 *m* wide at the water surface. Assume $V[m/s] = 0.677 \times (r/s)$ and calculate the flowrate in the river.



Sec. No.	0	1	2	3	4	5	6	7	8	9	10	11	12
Depth (m)	0.0	0.9	0.96	1.05	1.08	1.11	1.17	1.20	1.32	1.32	1.26	1.05	0.0
rpm@ 0.2y	-	40.0	53.5	58.6	63.0	66.7	61.5	56.3	54.0	52.6	50.0	45.0	-
rpm@ 0.8y	-	30.7	42.8	50.0	54.2	58.8	53.3	49.4	46.5	43.2	40.1	32.5	-