Fluid Mechanics: Fluid Flow Measurement

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Training for Engineers on Geothermal Power Plant

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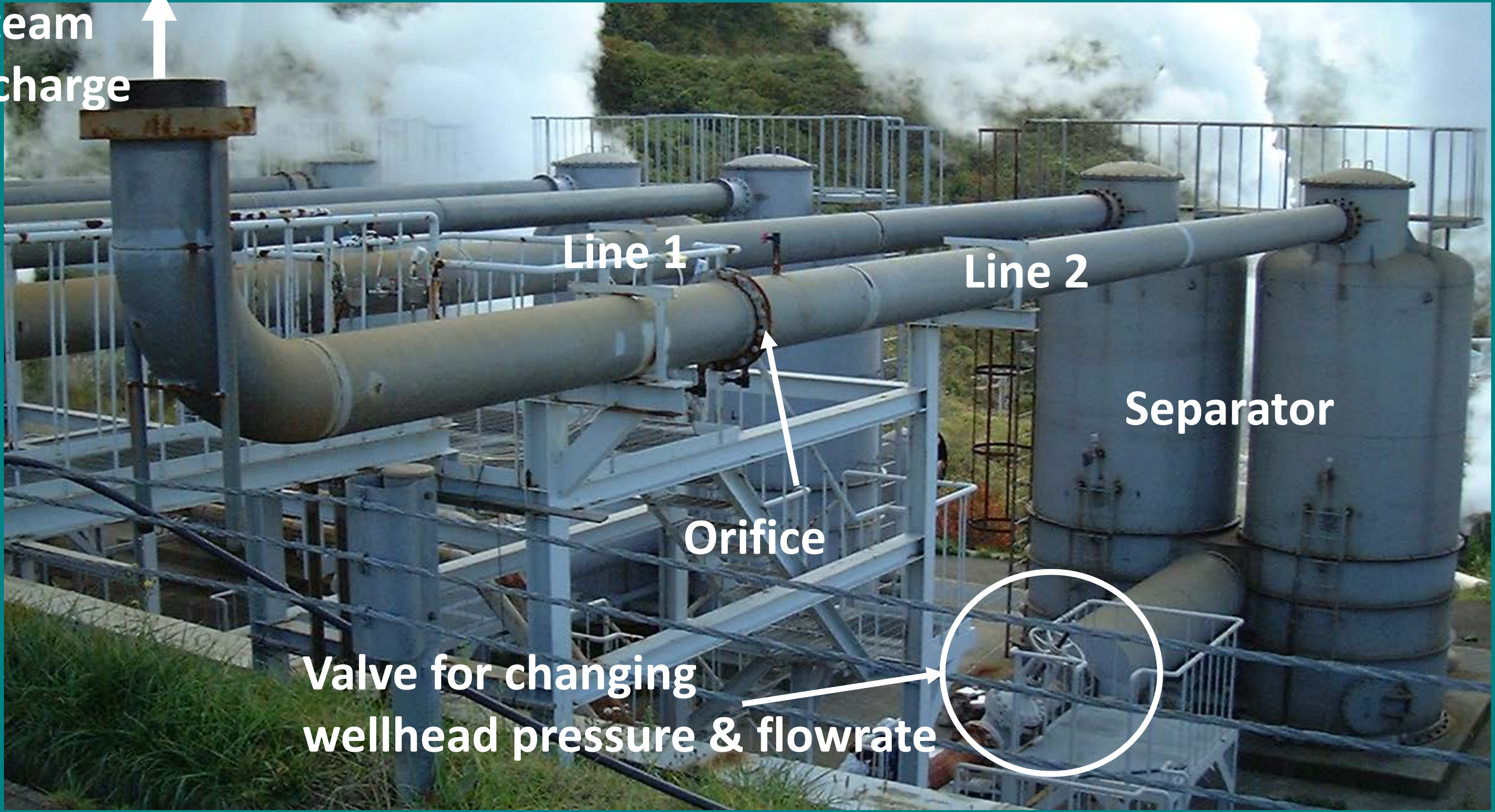
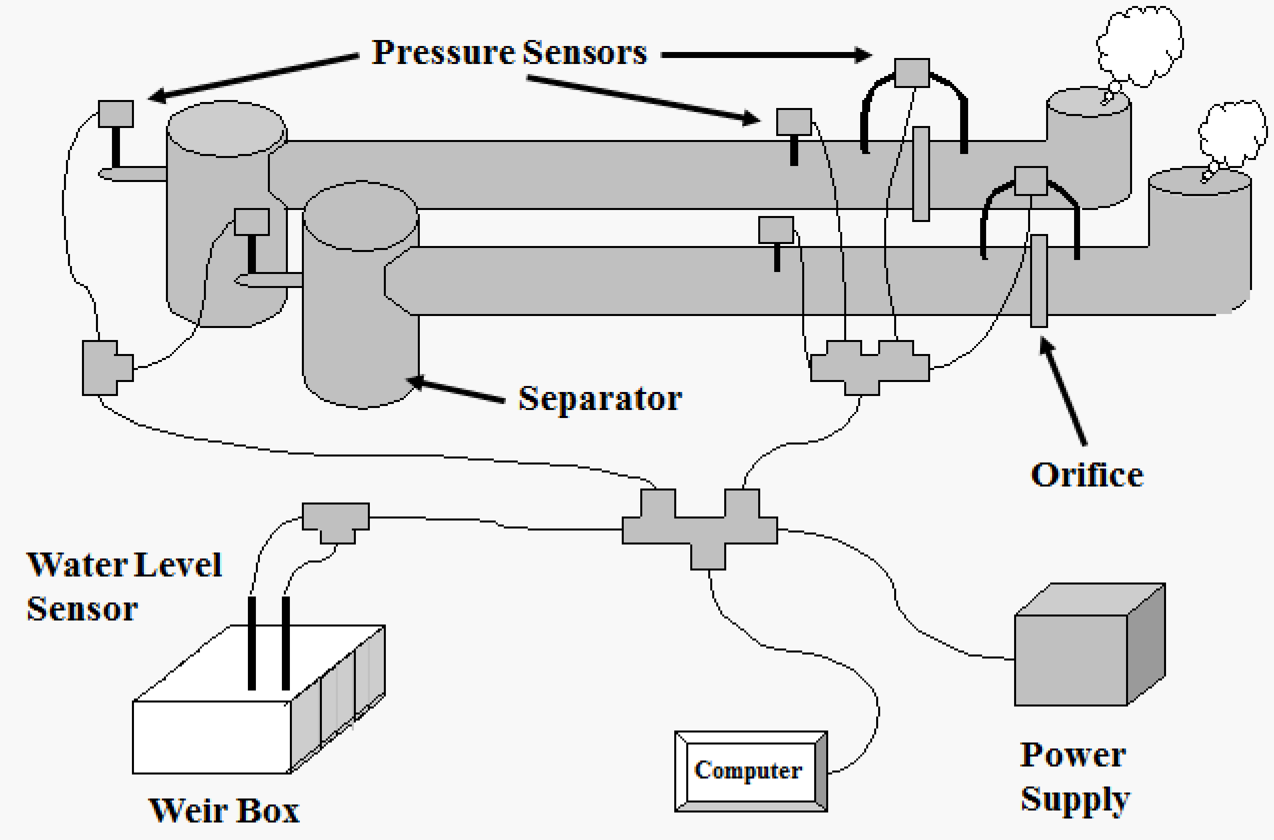
GEOCAP
Geothermal Capacity Building Program Indonesia - Netherlands

What & where should we measure?



Measurement Layout



Weir box for water flow rate measurement

Stainless 2 rod electrodes

Basic Type of Measurement

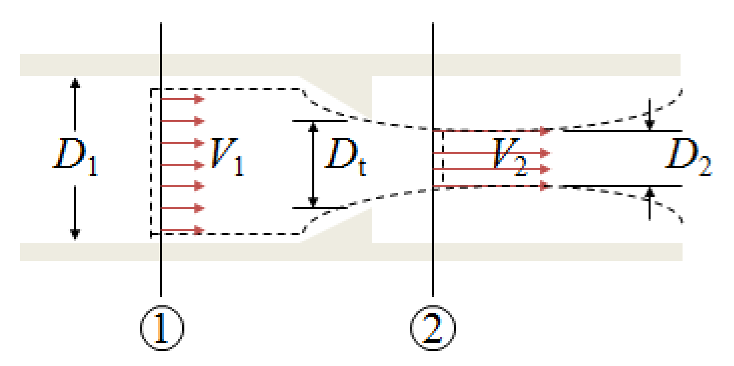
- Differential pressure producers (obstruction)
- Direct discharge measurement
- Positive volume displacement measurement
- Flow velocity-area measurement

Flow meter

- Venturi type meter
- Orifice meter
- Propeller type meter
- Magnetic flow meter
- Ultrasonic flow meter
- Vortex meter
- Rotameter (variable-area meter)
- Flumes
- Weirs

Mass Flow Rate Measurement

Bernoulli principle

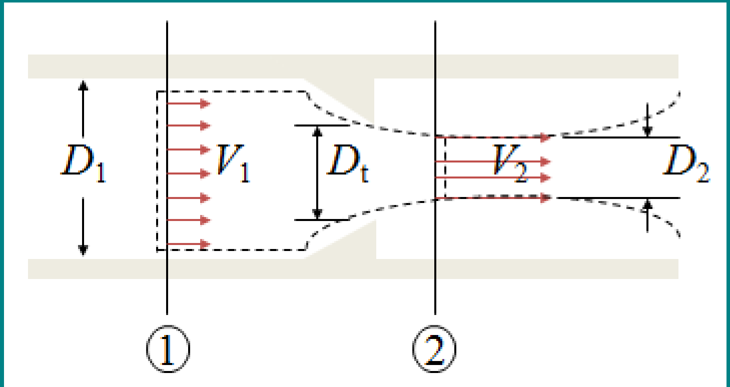


$$\frac{1}{2}mv^2 + mgh + mg\frac{P}{\rho g} = cte$$

Assumptions:

- Steady flow
- Flow along streamline
- Incompressible flow
- No friction

Bernoulli Equation

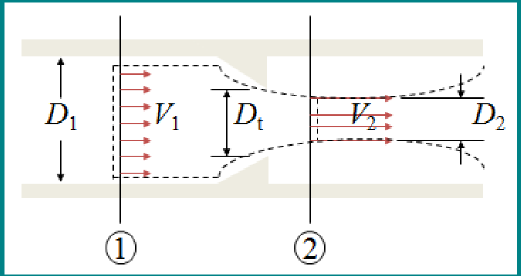


$$\frac{1}{2}mV_1^{\,2} + mgh_1 + mg\frac{P_1}{\rho g} = \frac{1}{2}mV_2^{\,2} + mgh_2 + mg\frac{P_2}{\rho g}$$

Assuming: $h_1=h_2$

$$V_1^{\,2} - V_2^{\,2} = \frac{2}{\rho}(P_1 - P_2)$$

$$\dot{m}_1 = \dot{m}_2 = \rho V_1 A_1 = \rho V_2 A_2$$



$$V_1 A_1 = V_2 A_2$$

$$V_1^{\,2} - V_2^{\,2} = \frac{2}{\rho}(P_1 - P_2)$$

$$V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho[1-(A_2/A_1)^2]}}$$

$$\dot{m}_{\text{theoretical}} = \rho V_2 A_2 = \frac{A_2}{[1-(A_2/A_1)^2]^{1/2}} \sqrt{2\rho(p_1 - p_2)}$$

Modified Bernoulli Equation

$$\dot{m}_{\text{actual}} = \frac{C_d . A_t}{[1-(A_t/A_1)^2]^{1/2}} \sqrt{2\rho(p_1 - p_2)}$$

C_d: Discharge Coefficient

If $\beta = D_t / D_1$, then $(A_t / A_1)^2 = (D_t / D_1)^4 = \beta^4$

$$\dot{m}_{\text{actual}} = \frac{CA_t}{[1-\beta^4]^{1/2}} \sqrt{2\rho(p_1 - p_2)}$$

Volume Flow Rate Measurement

Basic equations:

a) Continuity:

mass in = mass out

b) Bernoulli equation

Total pressure is
constant along the flow

Continuity Equation:

$$\dot{m}_1 = \dot{m}_2$$

$$\dot{m} = \rho A v$$

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

Incompressible

$$\rho_1 = \rho_2$$

$$A_1 v_1 = A_2 v_2$$

Bernoulli Equation:

$$P_0 = \text{Total Pressure} = \text{Const.} = \frac{1}{2}\rho v^2 + P$$

$$\frac{1}{2}\rho_1 v_1{}^2 + P_1 = \frac{1}{2}\rho_2 v_2{}^2 + P_2 = P_0$$

$$P = static\ \ pressure$$

$$P_0 = total\ \ pressure$$

$$\frac{1}{2}\rho v^2 = dynamic\ \ pressure$$

$$v_2 = \frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{2\,\Delta P}{\rho}}$$

Flow Rate

$$Q = A_2 v_2 = A_2 \frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{2\,\Delta P}{\rho}} \qquad Ideal$$

For Real Flow

$$Q = YCA_2 \frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{2\,\Delta P}{\rho}}$$

Venturi Type Flow Meter

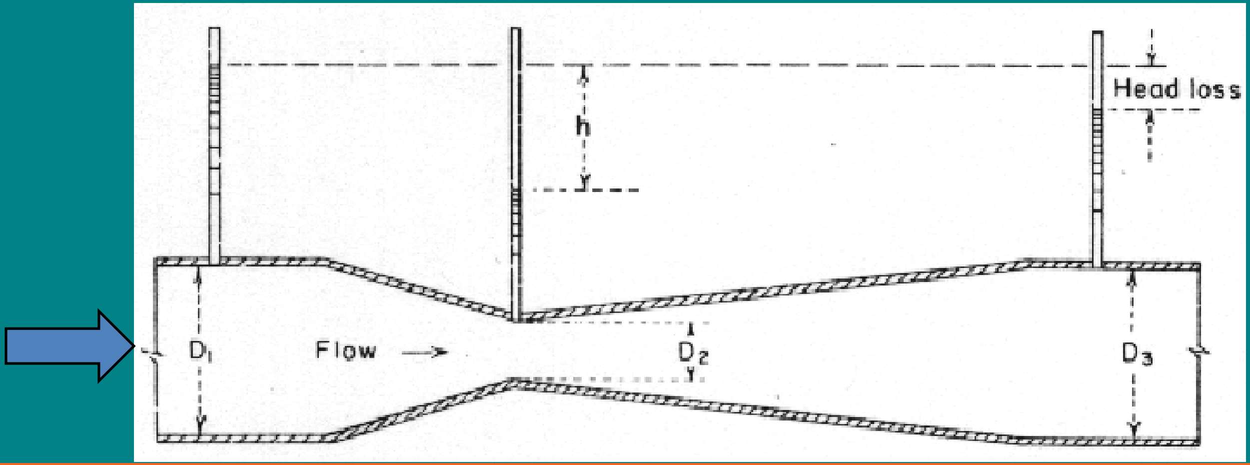
- Measure differential pressure
- Consists of converging section, throat, and diverging recovery section
- Difference in two heads is analyzed by electrical or electro-mechanic instrument
- Accuracy: ±1%

$\dot{m}_1$

ρ_1

A_1

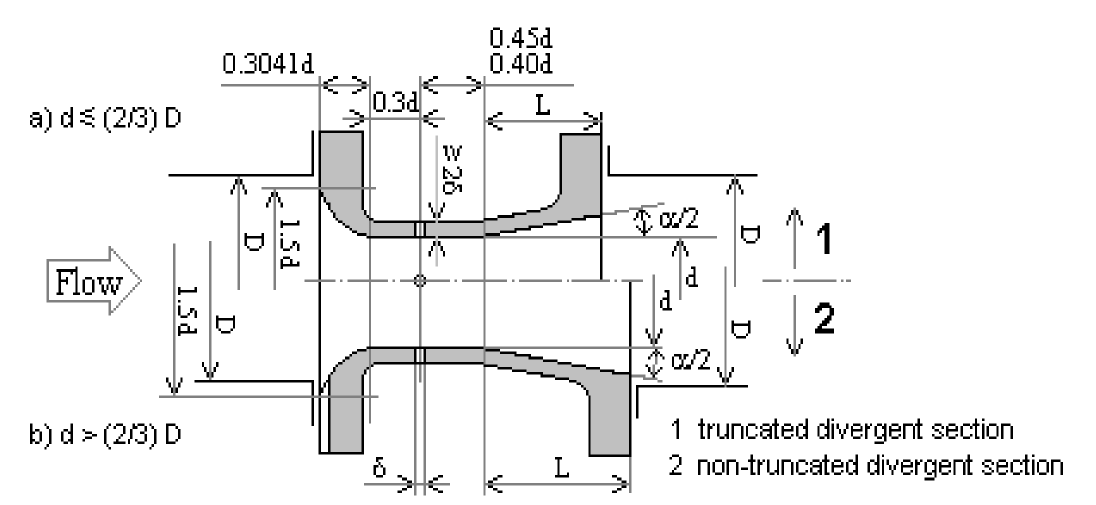
v_1

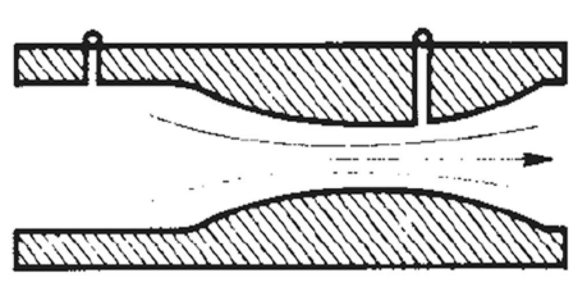


Mass Rate

$$\dot{m}_{\text{actual}} = \frac{CA_t}{[1-\beta^4]^{1/2}}\sqrt{2\rho(p_1 - p_2)}$$

Discharge coefficient (C_d) varies 0.98 s/d 0.995 for high Reynolds number.





Volume Rate

$$Q = YCA_2 \frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

Y = Compressibility Factor

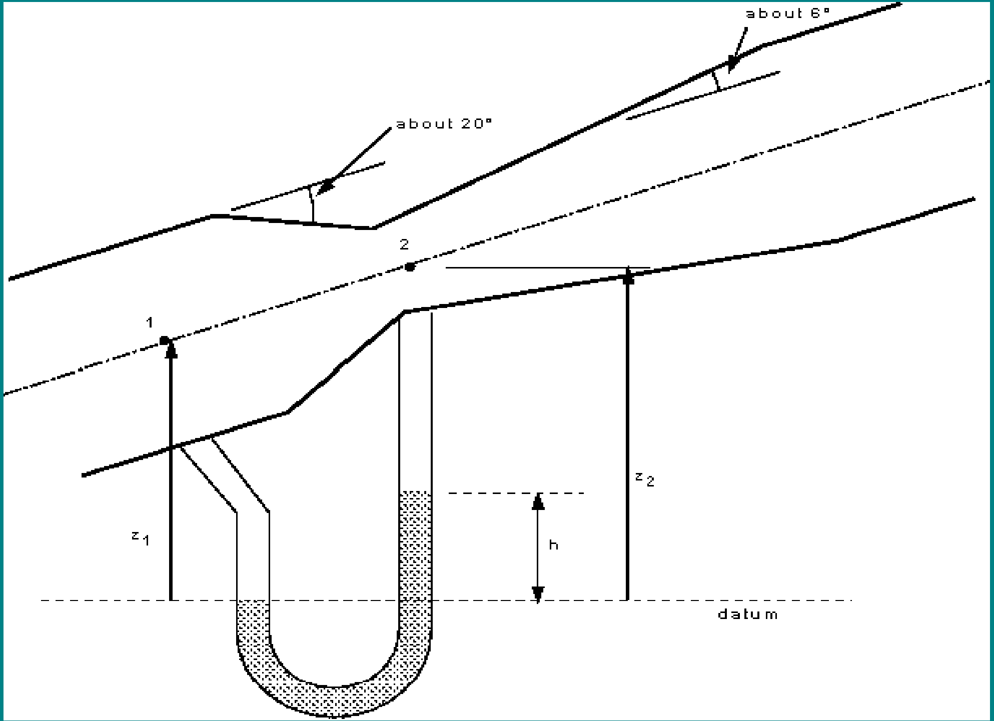
= 1 for incompressible

flow or when $\Delta P \ll P_{abs}$

C = Discharge Coefficient

= f(Re) and the specific condition

for flow meter

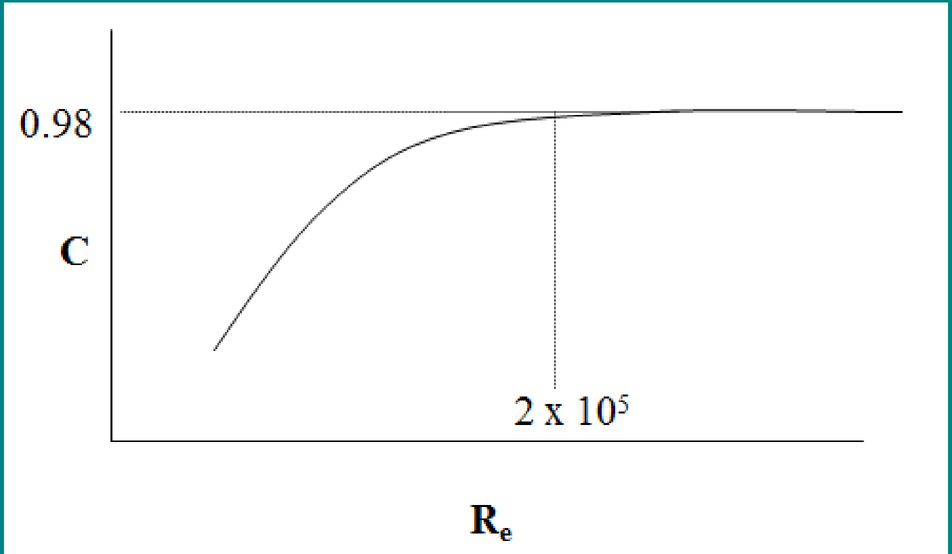


$$\Delta P = P_1 - P_2 = \frac{1}{2}\rho_2 v_2^2 - \frac{1}{2}\rho_1 v_1^2$$

$$= \frac{1}{2}\rho_2 v_2^2 - \frac{1}{2}\rho_1 \left(\frac{A_2}{A_1}\right)^2 v_2^2$$

$$= \frac{1}{2}\rho v_2^2 \left[1 - \left(\frac{A_2}{A_1}\right)^2\right]$$

for $\rho_1 = \rho_2$



- For venturi, 0.95 < C < 0.98
- Advantages:

  Pressure recovery

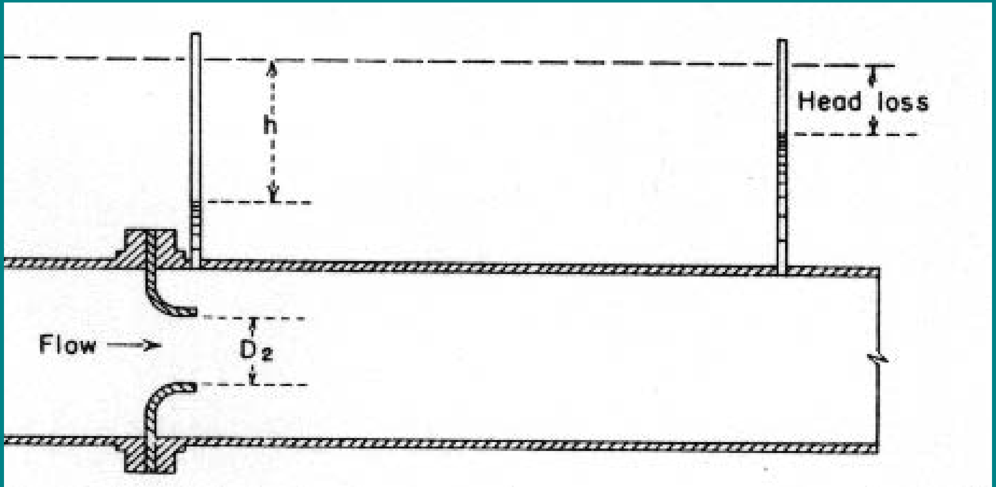
  Small power used

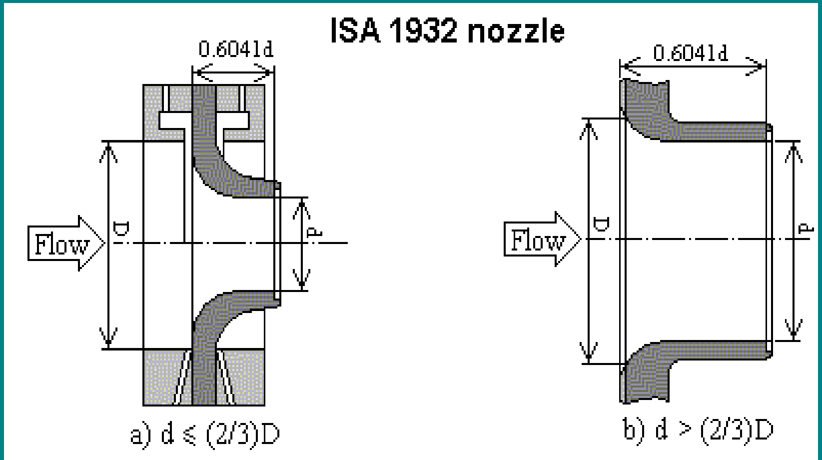
$$R_e = \frac{\rho d_1 v_1}{\mu}$$

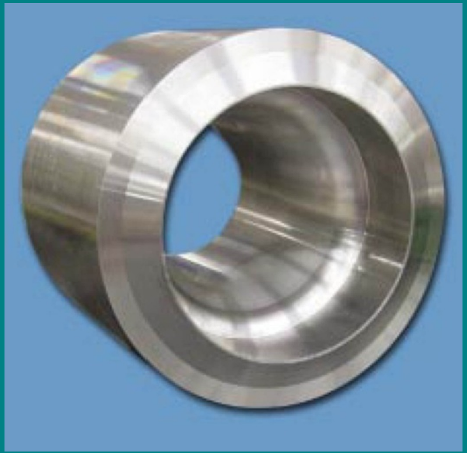
Based on the condition inside the pipe close to the meter

Flow Nozzle Meter

- Measure differential pressure
- Similar to Venturi meter without diverging recovery section
- Cheaper than Venturi meter but high head loss
- Accuracy: < ±1%



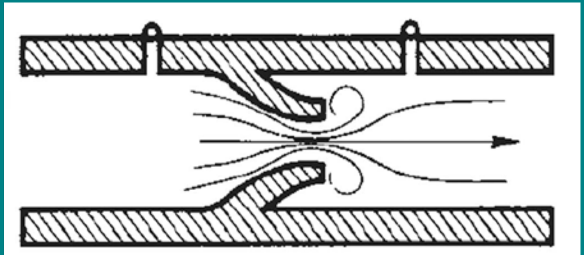


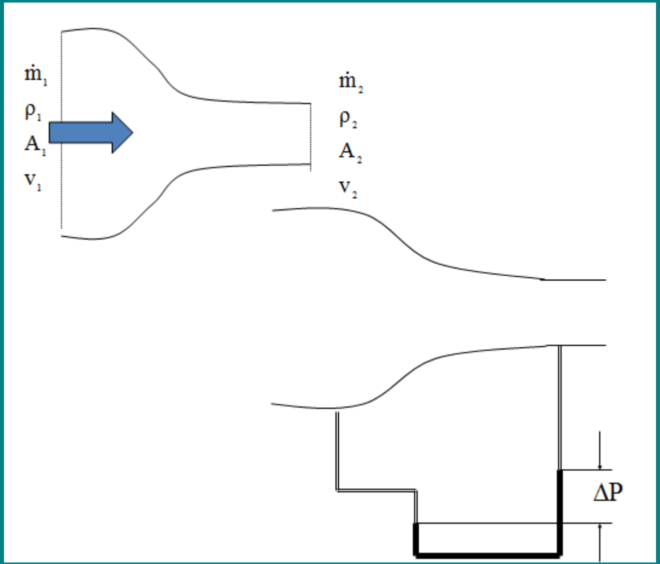


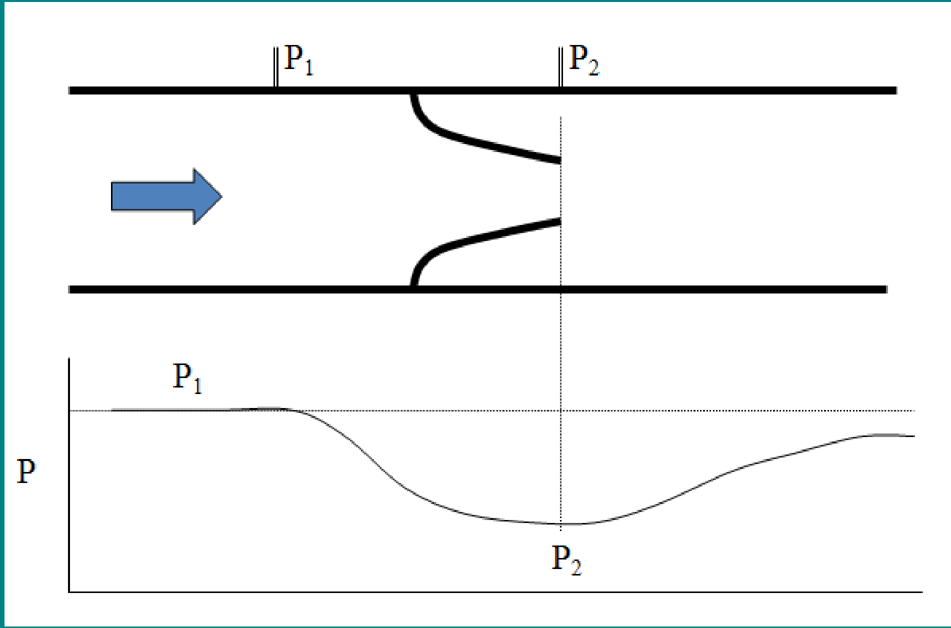
$$\dot{m}_{\text{actual}} = \frac{CA_t}{[1-\beta^4]^{1/2}} \sqrt{2\rho\left(p_1 - p_2\right)}$$

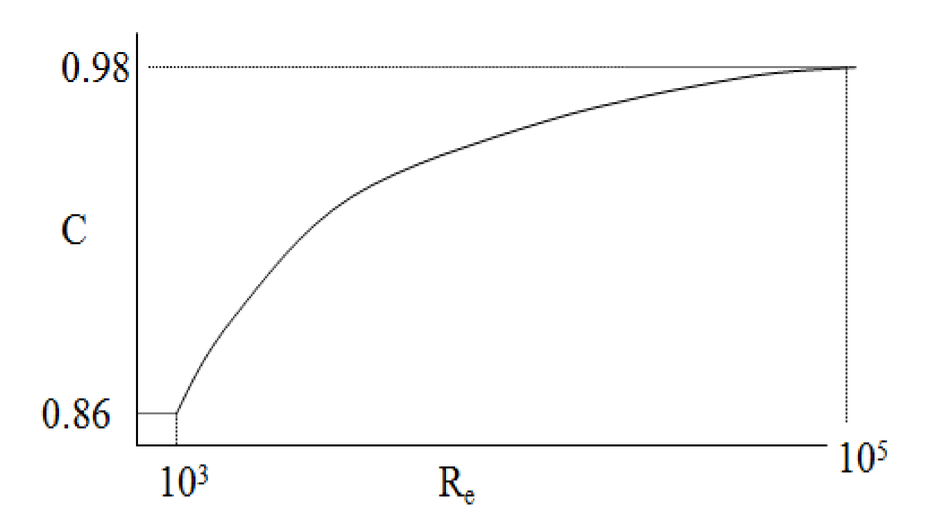
For $0.2 < \beta < 0.75$ and $10^4 < R_e < 10^7$

$$C_d = 0.9975 - \frac{6.53\beta^{0.5}}{R_e^{0.5}}$$




ṁ1
ρ1
A1
v1
ṁ2
ρ2
A2
v2
ΔP

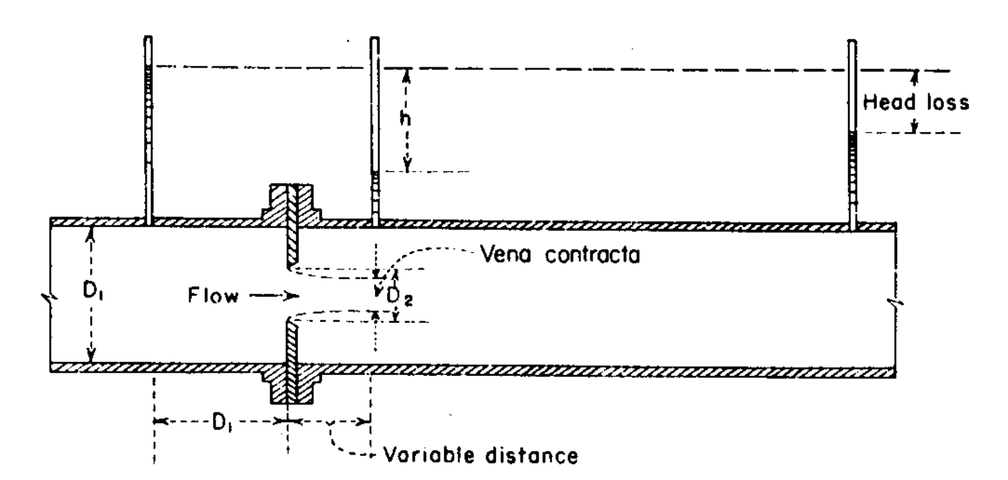

P1
P2
P
P1
P2



- Shorter and cheaper than venturi
- High pressure drop
- More losses on the power during operation.

Orifice Meter

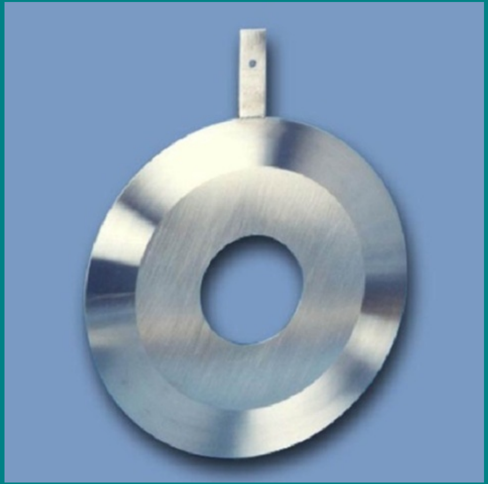
- Measure differential pressure
- Easy to install and manufacture
- Advantages: cheaper than all types of differential pressure and has *good accuracy* (±1%)
- Disadvantages: less efficient, high headloss, easy clogging, and small flow range.

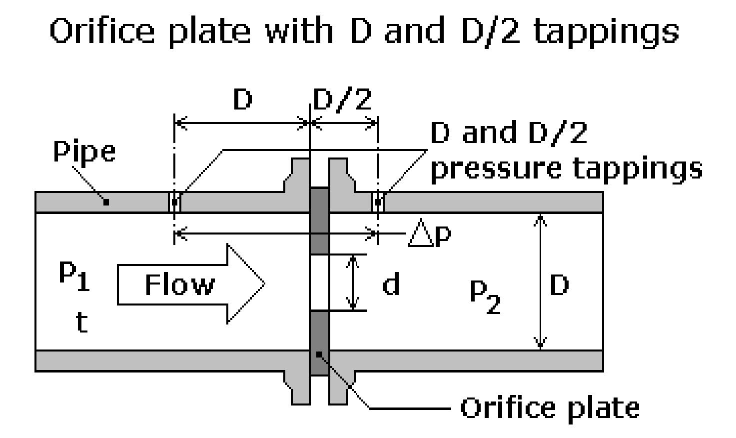


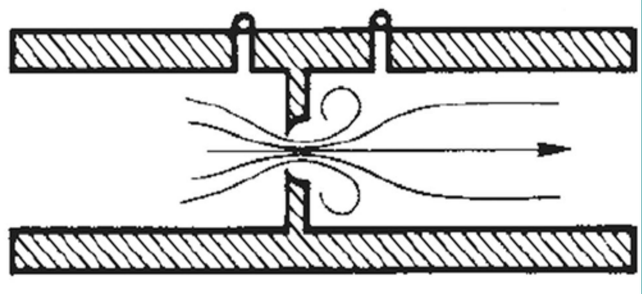
$$\dot{m}_{\text{actual}} = \frac{CA_t}{[1-\beta^4]^{1/2}} \sqrt{2\rho(p_1 - p_2)}$$

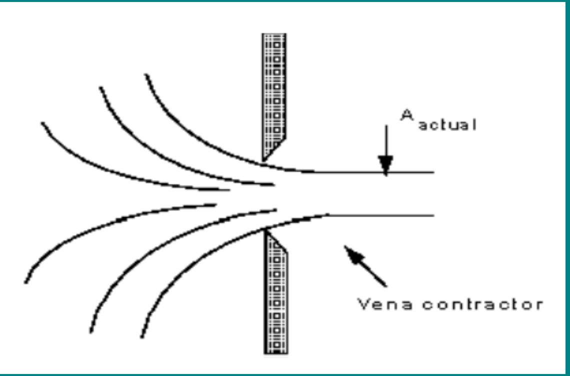
$$\text{For } 0.2 < \beta < 0.75 \text{ and } 10^4 < R_e < 10^7$$

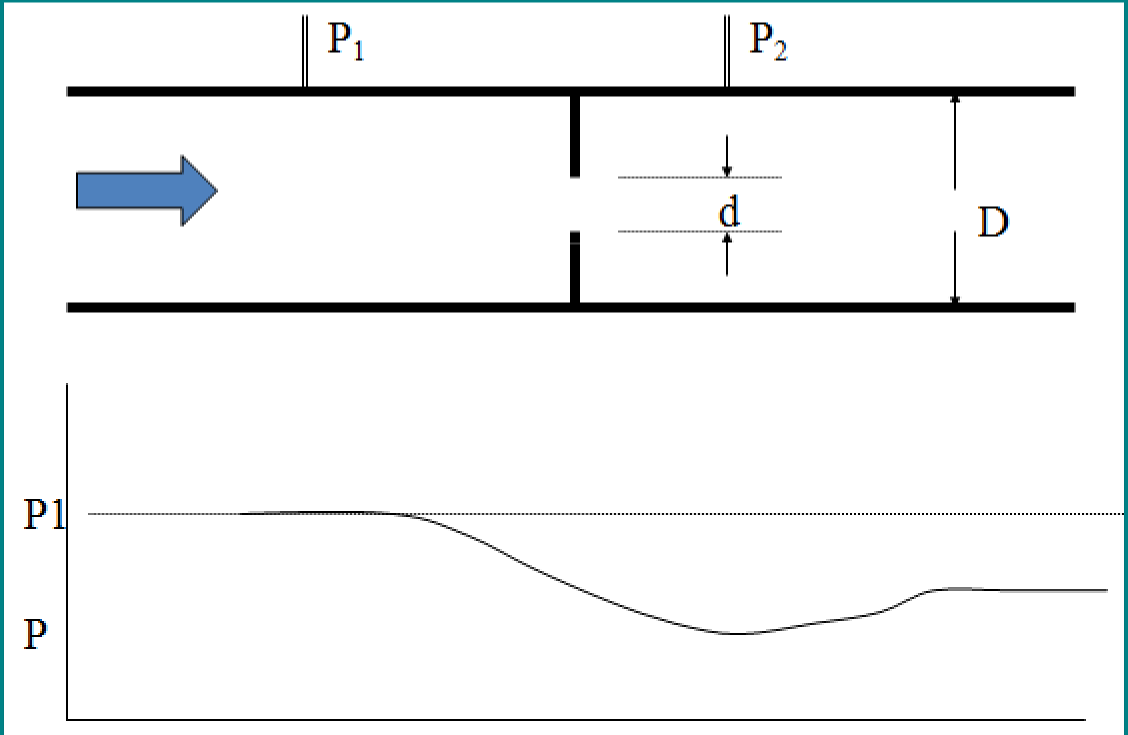
$$C_d = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + \frac{91.71\beta^{2.5}}{R_e^{0.75}}$$







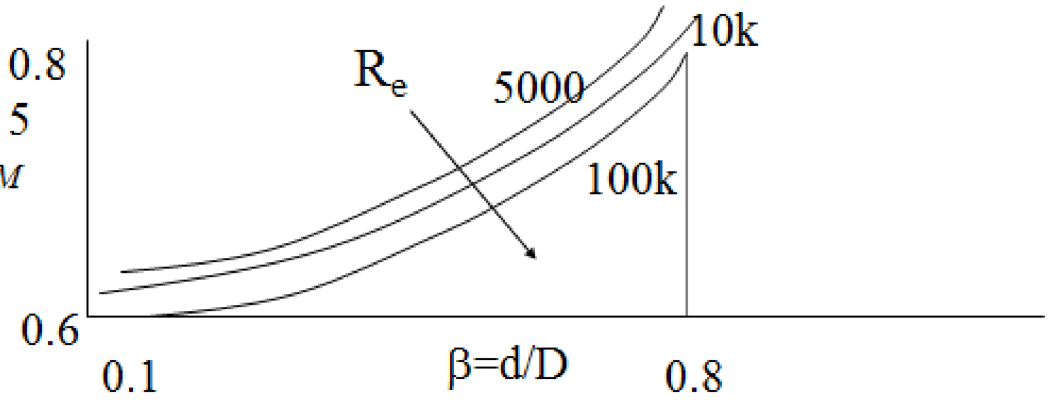

A actual
Vena contractor


P_1
P_2
d
D
P1
P

- Very cheap and simple
- High pressure drop and power lost (C~0.6 - 0.7)
- Notes:

  Pressure drop is due to friction and turbulence from shear layer downstream from vena contracta

$$C\left[\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\right] = CM$$



Electromagnetic Meter

- The fluid is conductor, it must transfer electricity
- E = BDVx10^{-8}

  E = voltage, volt

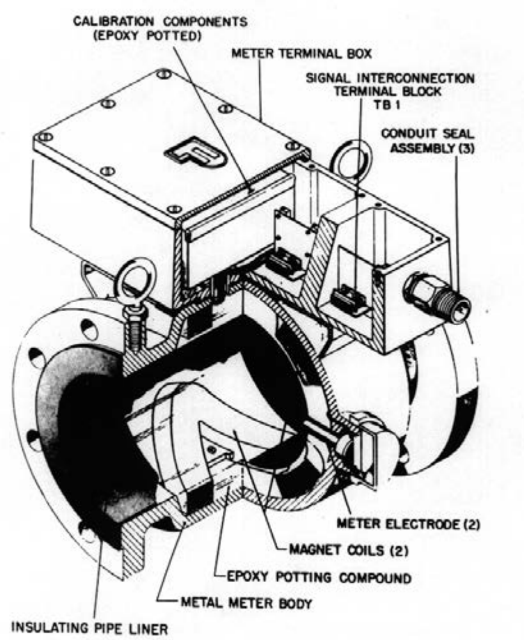
  B = magnetic flux density, gauss

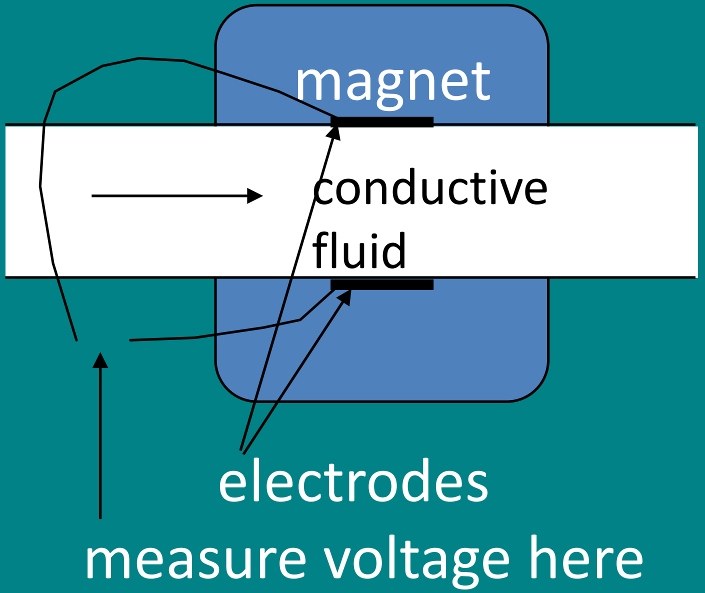
  D = conductor length, cm

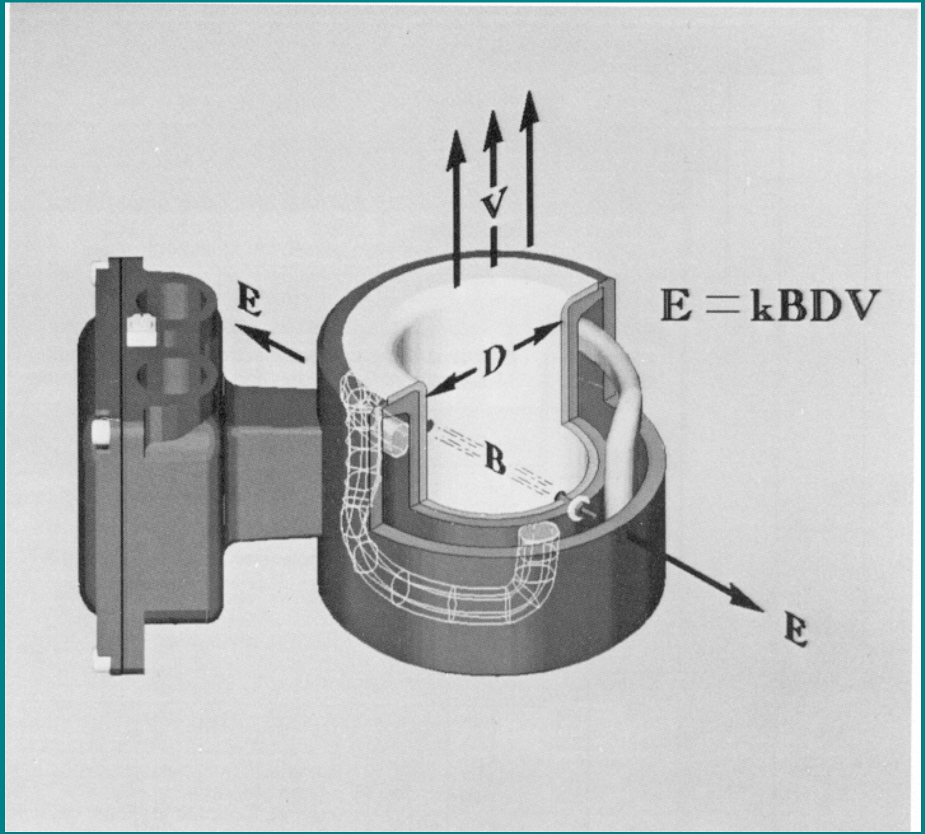
  V = conductor velocity, cm/s

$$E = -NB\frac{dA}{dt} = -NB\frac{dl}{dt}D = -NBVD$$

$$V = \frac{E}{K}$$

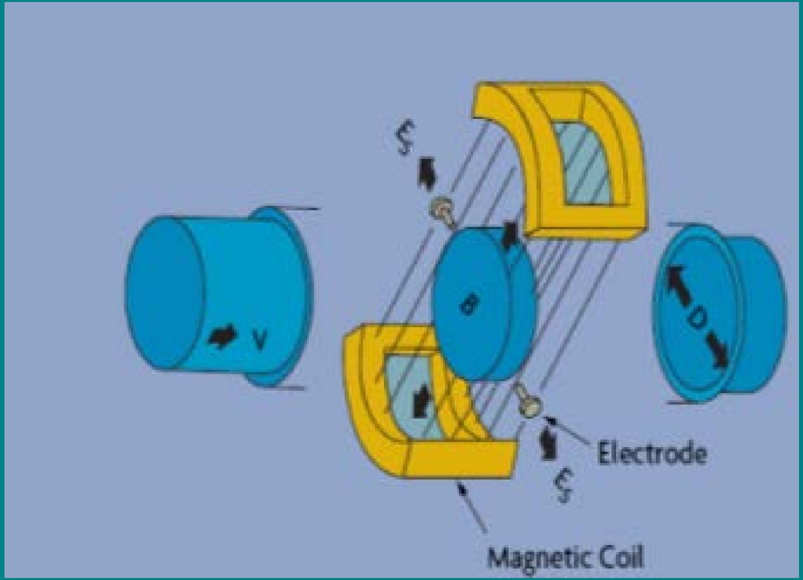



magnet
conductive
fluid
electrodes
measure voltage here


V
E
D
B
E = kBDV
E

How it works

- Electromagnetic flowmeter measures fluid flow by measuring induced voltage change from conducting fluid that passes through controlled magnetic field.

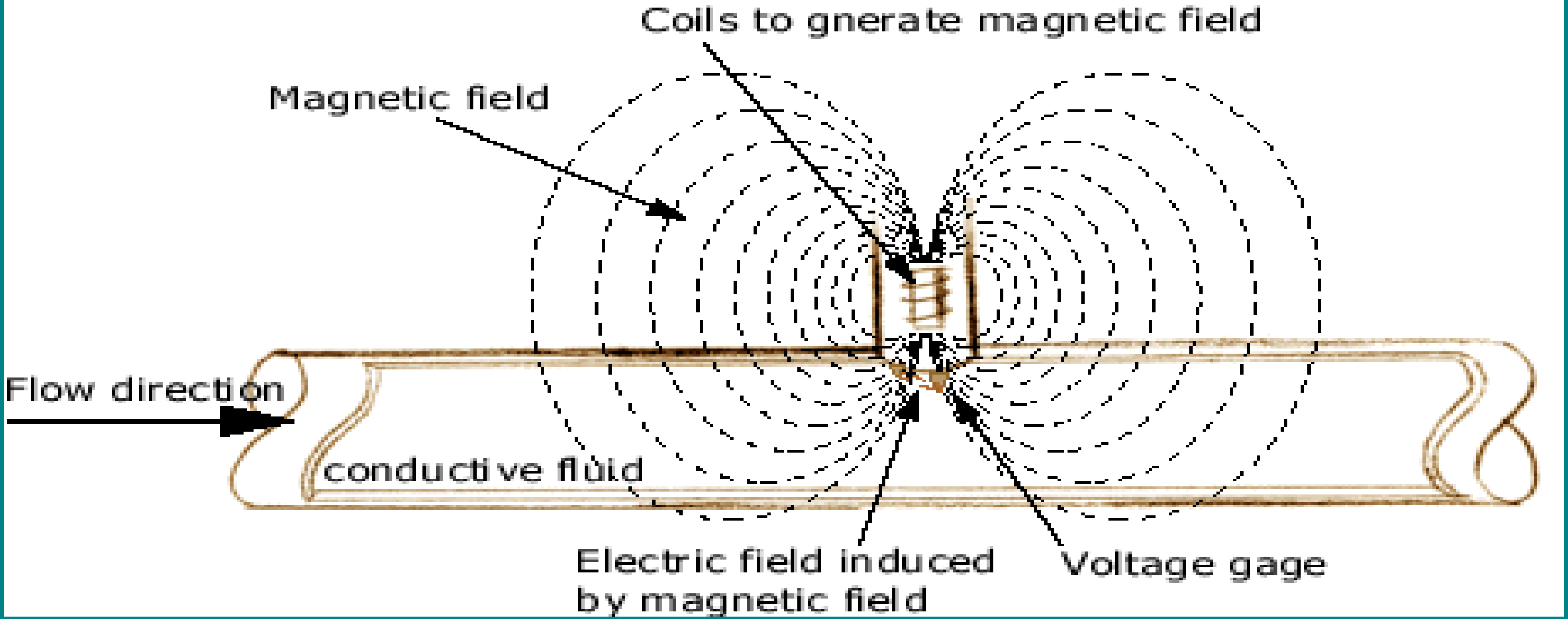


- Faraday’s Law: produced voltage by moving the conductor through a magnetic field is proportional to the conductor velocity.

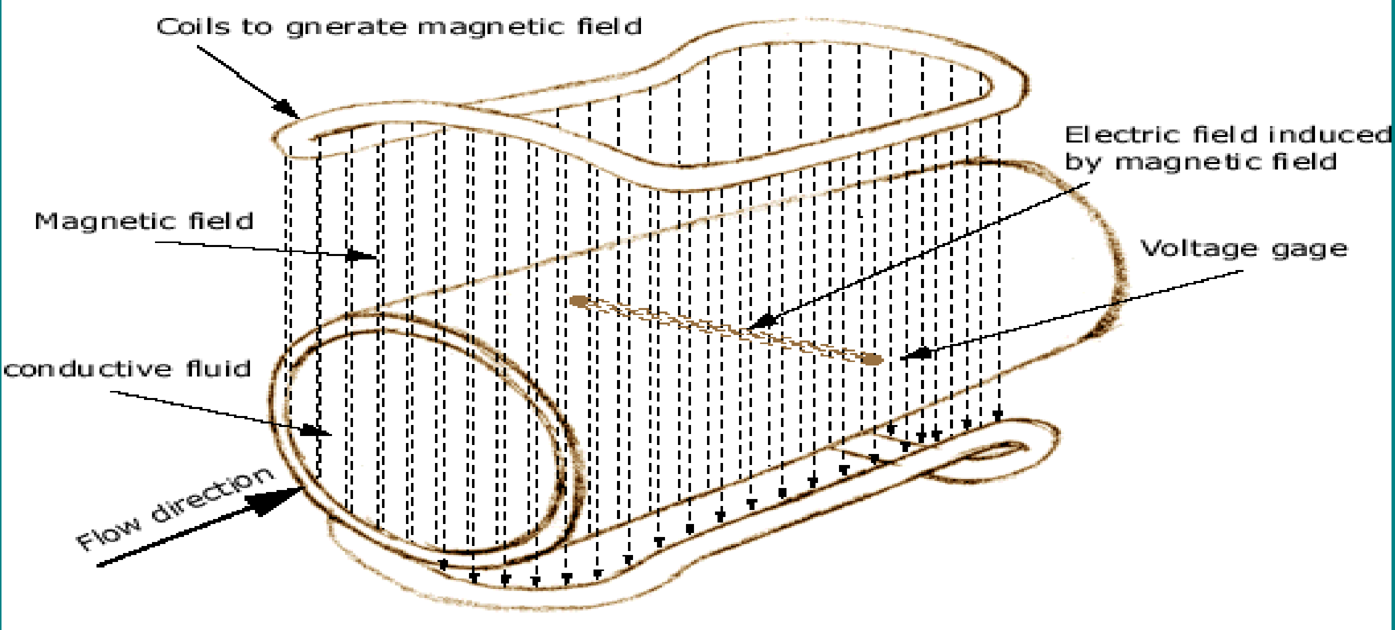
- Advantages: good accuracy (±1~2%), can measure larger flow range, no head loss, not influenced by the temperature, conductivity, viscosity, turbulance, and solids.

- Disadvantages: high initial cost and required trained personnel for routine O&M.

Insertion Electromagnetic Flow meter

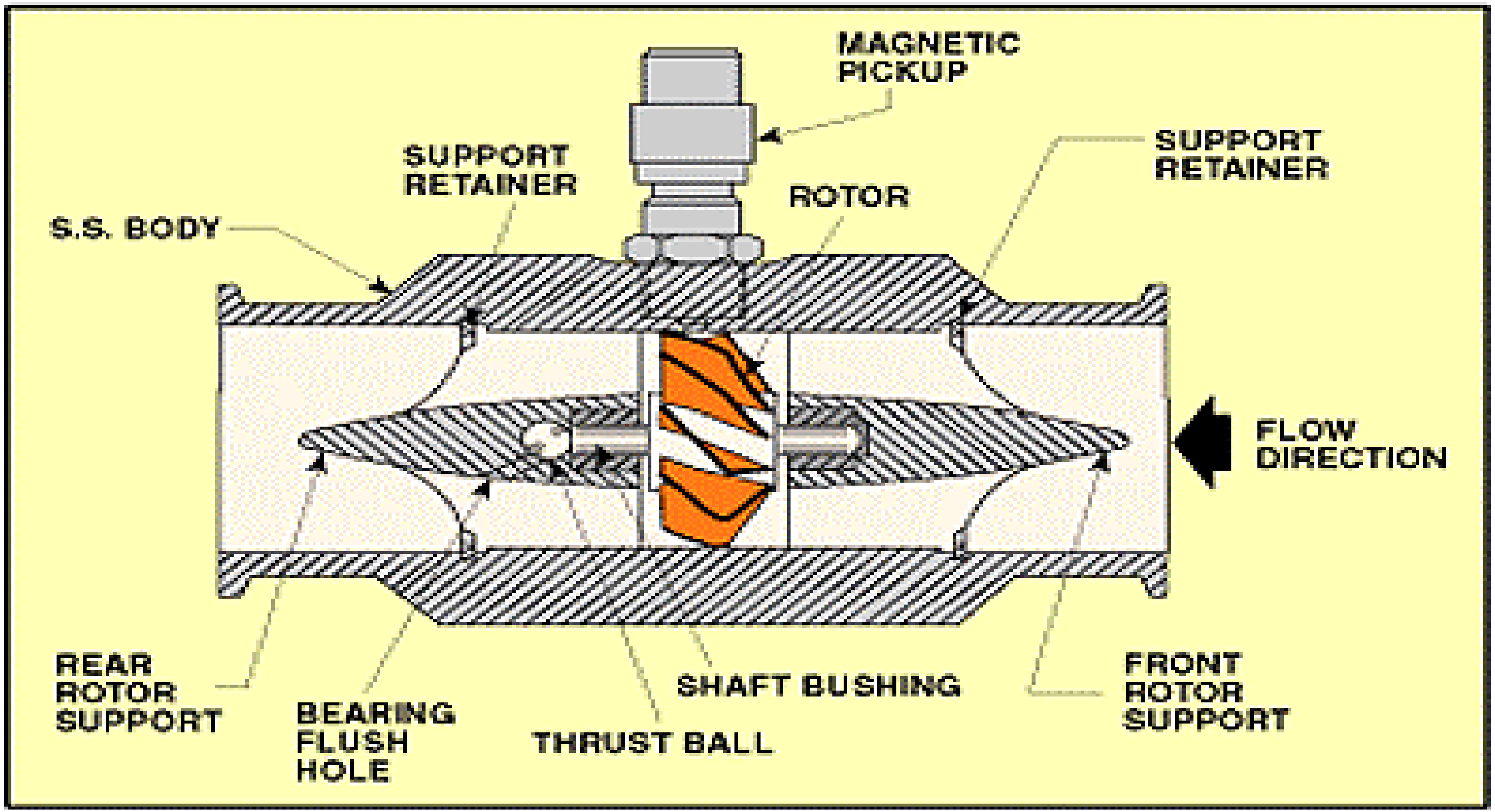


Inline Electromagnetic Flow meter



Turbine meter

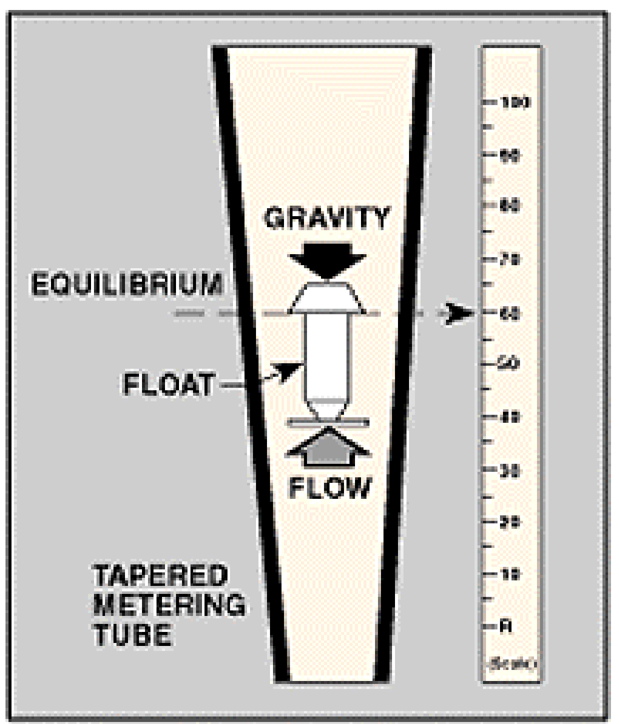
- Use rotating element (turbine).
- Wide application from water to oil, solvent to acid.
- Limited to the pipe fully filled with flow, under pressure.
- Very accurate (±0.25%) and can measure wide flow range.


MAGNETIC
PICKUP
SUPPORT
RETAINER
SUPPORT
RETAINER
ROTOR
S.S. BODY
FLOW
DIRECTION
REAR
ROTOR
SUPPORT
BEARING
FLUSH
HOLE
SHAFT BUSHING
THRUST BALL
FRONT
ROTOR
SUPPORT

How it works

- Fluid entering the channel or impeller- producing inert moment that will cause torque.
- Liquid in the impeller produces pressure. It turns the wheel mover.
- Balanced by the spring.
- Rotational pickup is connected.
- Torque is proportional to the flow.
- Besides *spring retarding disc*, magnetic assembly can be used.

Rotameter, variable-area-flowmeter



- Force balance
  - Drag Force
  - Gravity
  - Buoyancy
    - (generally neglected)

$$\dot{m}_{use} = \dot{m}_{cal}\sqrt{\frac{\rho_{use}}{\rho_{cal}}}$$

Rotameter equations

$$\dot{m} = \rho\, A V$$

$$F = D\rho \frac{V^2}{2} = Mg$$

$$V = \sqrt{\frac{2Mg}{D\rho}}$$

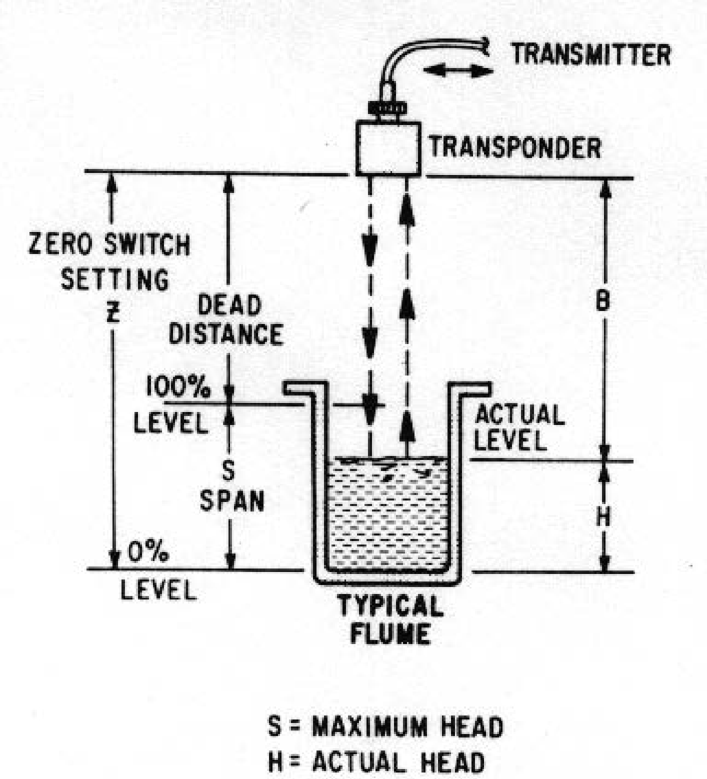
$$\dot{m} = \rho\, A \sqrt{\frac{2Mg}{D\rho}} = \sqrt{\rho}\sqrt{\frac{2MgA^2}{D}}$$

For fixed x-position, A remains fixed.

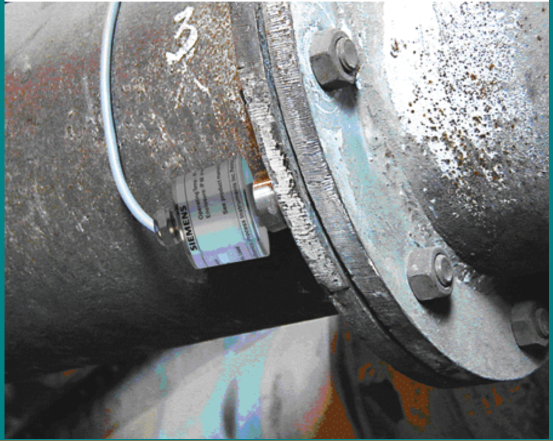
$$\left(\frac{\dot{m}}{\sqrt{\rho}}\right)_{use} = \left(\frac{\dot{m}}{\sqrt{\rho}}\right)_{cal}$$

Acoustic Meter

- Using sound wave to measure flow rate
- Sonic meter or ultrasonic meter depends on whether the sound wave at or beyond the *audible frequency range*
- To determine liquid level, area, and actual velocity
- Advantages: low head loss, excellent accuracy (2~3%), can be used for any pipe size, no fouling to solid, wide flow range
- Disadvantages: high initial cost and needs trained personnel for routine O&M rutin




SURE FLOW
PRODUCTS

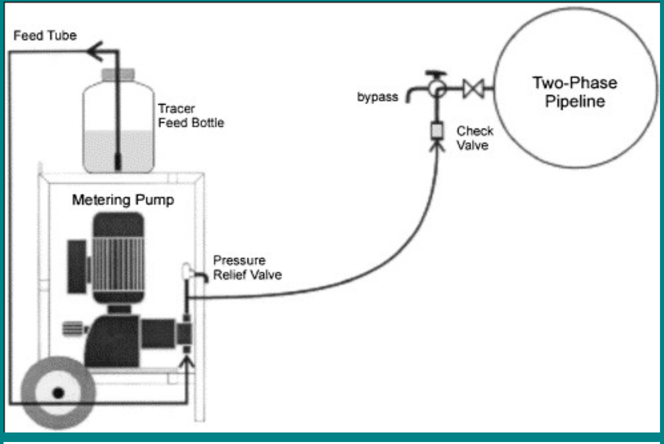

SIEMENS

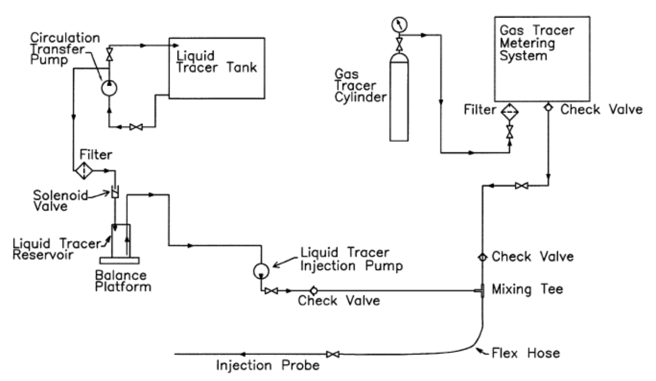
Weirs
(Rectangular, Triangular, or V-Notch)

- Fluid level in weir is measured with float, hook gauge, or level sensor
- Measure flow in open channels
- Accuracy: ±5%; wide range flow
- Advantages: relatively accurate, simple in assembling, cheaper
- Disadvantages: huge head loss, solid deposition in the upstream from weir and heavy maintenance

Tracer Flow Testing (Best Practice-1)

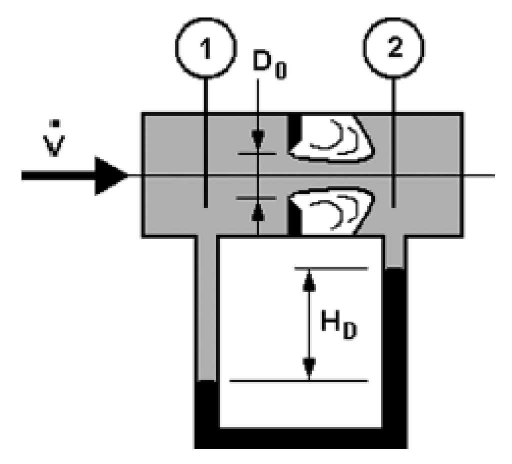
- Using chemical tracers (liquid alcohol/ isopropanol, helium, freon-12 as steam-phase tracers)
- Tracer is injected at a point of two-phase line and sampled at next point)
- Very expensive





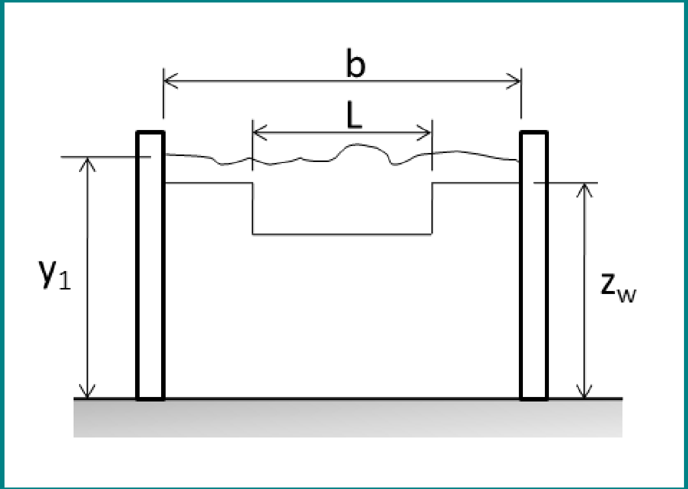
Separator Method (Best Practice-2)

Orifice flow meter (steam)

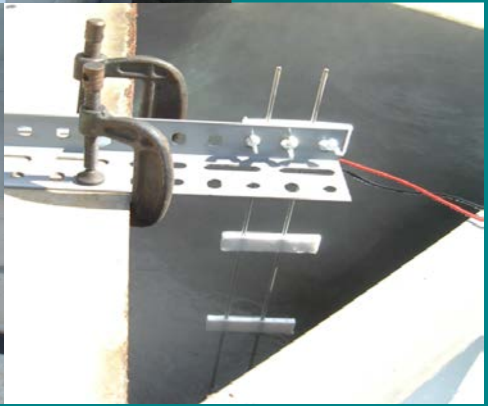


$$\dot{V} = C_0 A_0 \sqrt{2g(P_1 - P_2)/\gamma}\left[1 + \frac{1}{2} C_0^2 \left(\frac{D_0}{D_1}\right)^4\right]$$

Weirbox flow meter (water)



$$\dot{V} = C_d b \left(\frac{L}{b} \right) \sqrt{g} (y_1 - z_w)^{3/2}$$



Thank You