ENT 286
Instrumentation & Measurement

Chapter 9

Fluid Flow Instrumentation

Basic of Fluid Flow

- Important parameter in industrial process.
- Measured primarily to determine the amount of fluid flow in a system.
- Three basics principles/concepts:
  1) Principle of momentum (equations of fluid force)
  2) Conservation of energy, Bernoulli Equations (First Law of Thermodynamics)
  3) Conservation of mass (Continuity equation)

Flow Measurement Methods

1) Mechanical flow meters

- Bucket-and-stopwatch
- Piston meter/Rotary piston
- Variable area meter
- Turbine flow meter
- Woltmann meter
- Single jet meter
- Paddle wheel meter
- Multiple jet meter
- Pelton wheel
- Oval gear meter
- Nutating disk meter

2) Pressure-based meters

- Venturi meter
- Orifice plate
- Dall tube
- Pitot tube
- Multi-hole pressure probe
- Flow Nozzles

3) Optical flow meters

4) Open channel flow measurement

- Level to flow
- Area / velocity
- Dye testing
- Acoustic Doppler velocimetry

Flow Measurement Methods

5) Thermal mass flow meters

6)Vortex flowmeters

7) Electromagnetic, ultrasonic and coriolis flow meters

- Magnetic flow meters
- Ultrasonic (Doppler, transit time) flow meters
- Coriolis flow meters

8) Laser Doppler flow measurement

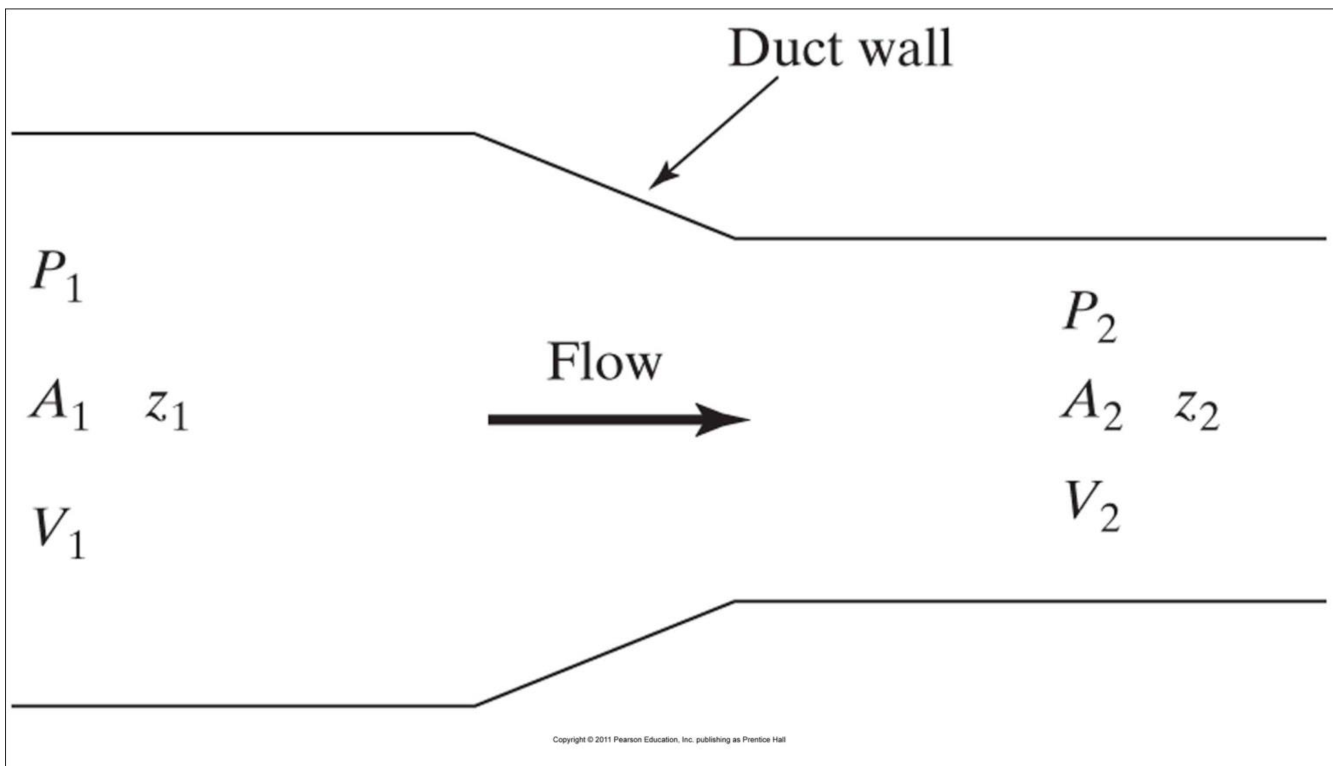
System for Measuring Fluid Flow Rate

Pressure Differential Devices:

- Venturi Tube
- Flow Nozzle
- Orifice Meter

System for Measuring Fluid Flow Rate

Technical Basis



System for Measuring Fluid Flow Rate

Technical Basis

The Bernoulli equation describe the flow of an incompressible fluid inside a duct/pipe if frictional and other losses are negligible.

$$\frac{V_1^2}{2} + \frac{P_1}{\rho} + gz_1 = \frac{V_2^2}{2} + \frac{P_2}{\rho} + gz_2$$

Conservation of mass

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 = \dot{m}$$

System for Measuring Fluid Flow Rate

Technical Basis

For incompressible fluid, density *ρ* is normally

constant, thus $\dot{m}$ become ***Q***

$$V_1 A_1 = V_2 A_2 = Q$$

System for Measuring Fluid Flow Rate

Technical Basis

Velocity at section 2

$$V_2 = \frac{1}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2[(P_1+g\rho z_1)-(P_2+g\rho z_2)]}{\rho}}$$

Equation for the flow rate

$$Q = \frac{A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2[(P_1+g\rho z_1)-(P_2+g\rho z_2)]}{\rho}}$$

System for Measuring Fluid Flow Rate

Technical Basis

The equation is the theoretical basis for a type of flowmeters known as *obstruction meters* or *head meters.* Three well-known flowmeters → venturi tube, orifice and flow nozzle

This is because the flow rate is determine from the pressure change causes by variation of conduit/duct's area.

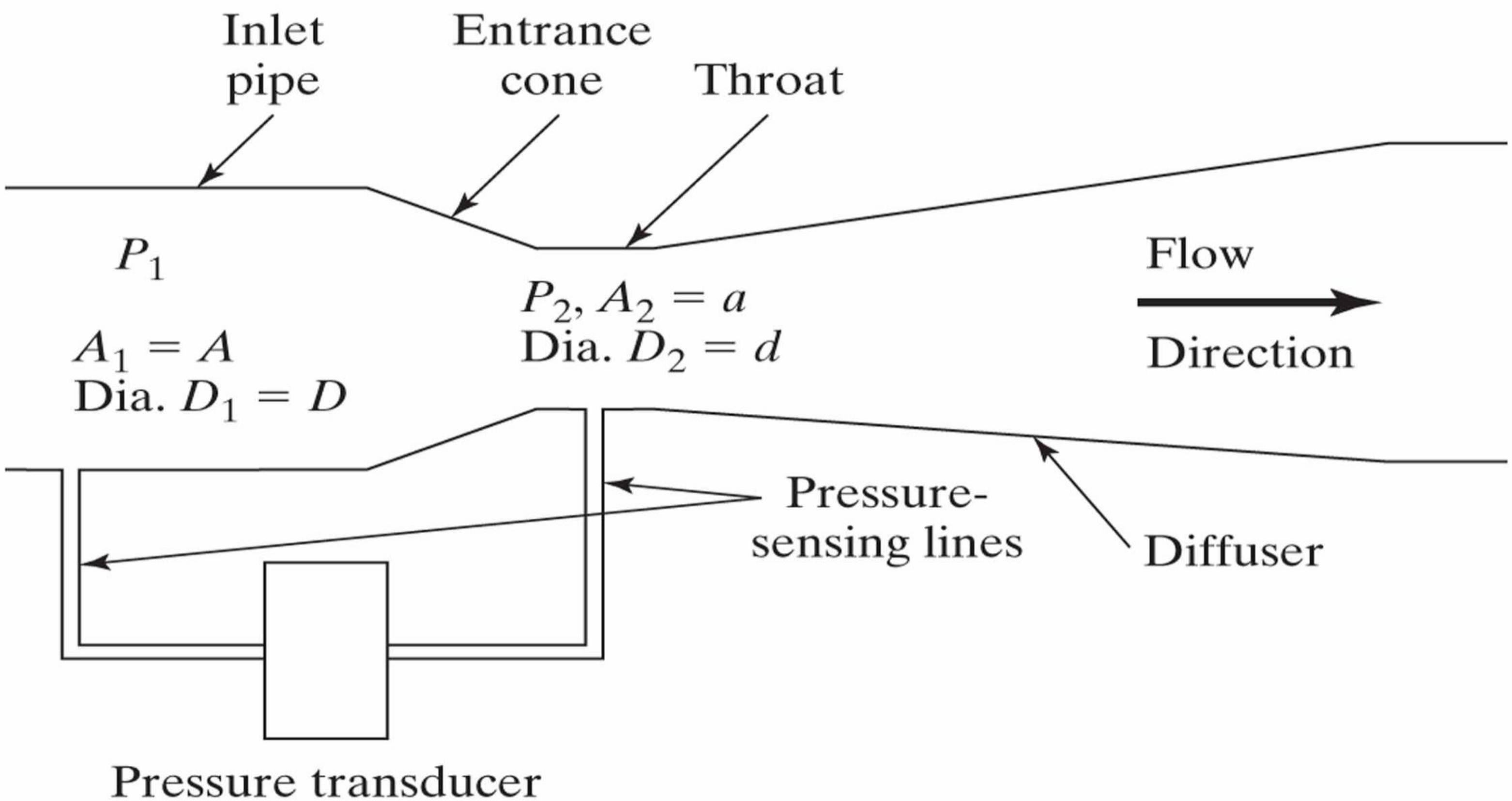
ASME prepared details documentation of this matter.

System for Measuring Fluid Flow Rate

Venturi Tube

System for Measuring Fluid Flow Rate

Venturi Tube



System for Measuring Fluid Flow Rate

Venturi Tube

- Area of pipe contracts from A_1 to A_2 (throat).

- If oriented horizontally, elevation term *z* can be cancelled out.

$$\Delta P_{trans} = (P + g\rho z)_1 - (P + g\rho z)_2$$

System for Measuring Fluid Flow Rate

Venturi Tube

Volume flow rate for venturi meter

$$Q = \frac{CA_2}{\sqrt{1-(A_2/A_1)^2}} \sqrt{\frac{2[(P_1 + g\rho z_1) - (P_2 + g\rho z_2)]}{\rho}}$$

Where ***C*** is the discharge coefficient, related to Reynolds number , Re.

C is standardize for venturi meter constructed That follows the ASME standard

System for Measuring Fluid Flow Rate

Venturi Tube

$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

, $\boldsymbol{\mu}$ is the liquid viscosity.

- The flow in a pipe is either laminar, turbulent, or transitional.
- Using Reynolds number,
  - Turbulent flow: $R_e > 4000$
  - Laminar flow: $R_e < 2000$

System for Measuring Fluid Flow Rate

Venturi Tube

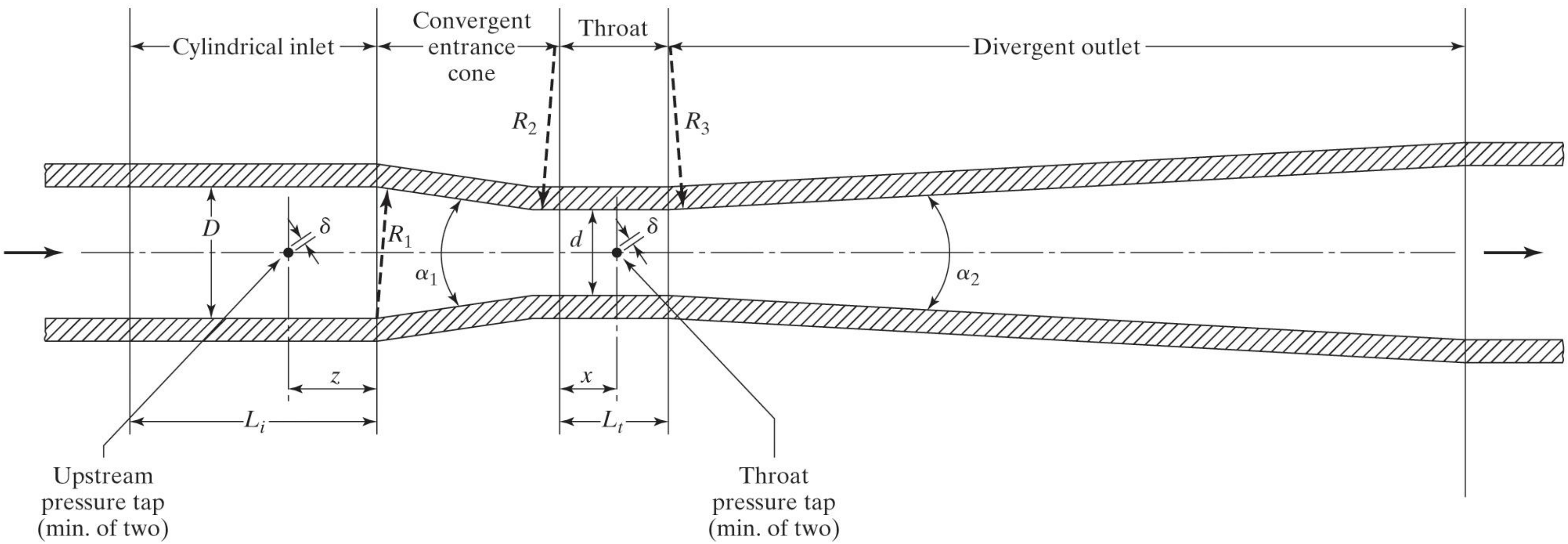
TABLE 10.1 Discharge Coefficients for Venturi Tubes

Rough-Cast Entrance Cone and Rough-Welded Sheet-Metal Cone	Machined Entrance Cone
$C = 0.984 \pm 1.0\%$	$C = 0.995 \pm 1.0\%$
$4 \text{ in.} \leq D \leq 48 \text{ in.}$	$2 \text{ in.} \leq D \leq 10 \text{ in.}$
$0.3 \leq \beta \leq 0.75$	$0.3 \leq \beta \leq 0.75$
$2 \times 10^5 \leq {}^{*}\text{Re} \leq 2 \times 10^6$	$2 \times 10^5 \leq \text{Re} \leq 2 \times 10^6$

Source: ASME (1989).

System for Measuring Fluid Flow Rate

Venturi Tube



$L_i > D$ or $L_i > (D/4 + 250$ mm (10 in.))
$z = D/2\ (+0.0\ D,\ -D/4)$, minimum of 2 taps
$L_t \geq d/3$
$x = 0.5\ d \pm 0.02\ d$, minimum of two taps
4 mm (5/32 in.) $\leq \delta \leq$ 10 mm (25/64 in.) and $\delta < 0.1D$ or $0.13\ d$

$R_1 = 1.375\ D \pm 20\%$
$R_2 = 3.625\ d \pm 0.125\ d$
$5d \leq R_3 \leq 15\ d$
$\alpha_1 = 21° \pm 1°$
$7° \leq \alpha_2 \leq 15°$

System for Measuring Fluid Flow Rate

Flow Nozzle

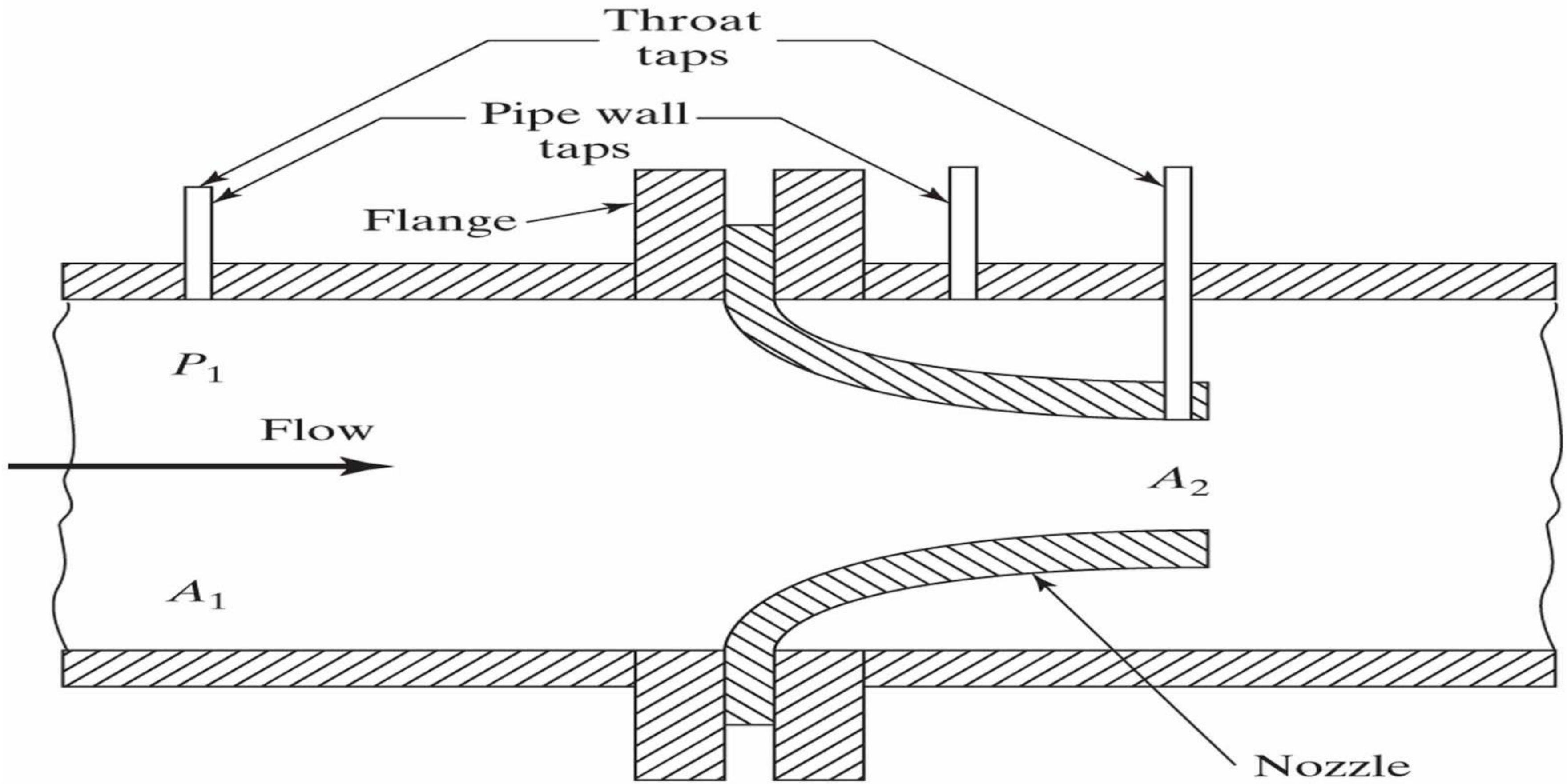
System for Measuring Fluid Flow Rate

Flow Nozzle

- Using similar concept with the venturi tube.
- The fluid passes through the minimum flow area is then go through expended pipe area.
- Larger energy losses.
- Construction follows ASME specification.

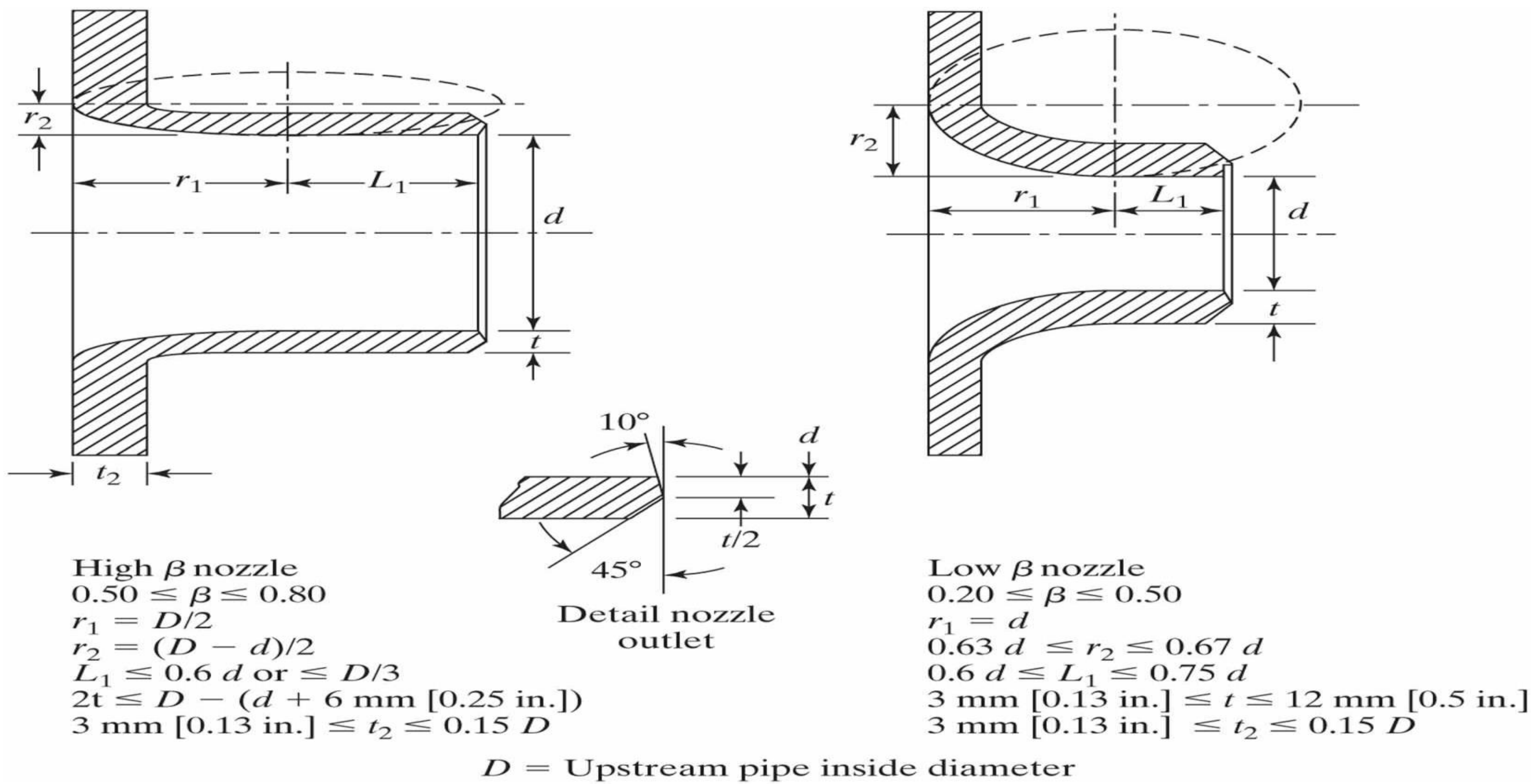
System for Measuring Fluid Flow Rate

Flow Nozzle



System for Measuring Fluid Flow Rate

Flow Nozzle



System for Measuring Fluid Flow Rate

Flow Nozzle

$$Q = \frac{CA_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2[(P_1+g\rho z_1)-(P_2+g\rho z_2)]}{\rho}}$$

$$C = 0.9975 - 0.00653\left(\frac{10^6\beta}{\mathrm{Re}_D}\right)^{0.5}$$

System for Measuring Fluid Flow Rate

Flow Nozzle

Flow nozzle also applicable for gasses:

$$\dot{m} = \rho_2 V_2 A_2 = \frac{CYA_2}{\sqrt{1-\left(A_2/A_1\right)^2}}\sqrt{2\rho_1(P_1 - P_2}$$

$$Y = \left(r^{\frac{2}{\gamma}} \frac{\gamma}{\gamma - 1} \frac{1 - r^{(\gamma-1)/\gamma}}{1 - r} \frac{1 - \beta^4}{1 - \beta^4 r^{2/\gamma}} \right)^{\frac{1}{2}}$$

Except that Y has some tolerance, given by:

$$Y = \pm\left[2\left(P_2 - P_1\right)/P_1\right]\%$$

System for Measuring Fluid Flow Rate

Flow Nozzle

- Critical flow nozzle for measuring mass flow rate in gases, including steam.
- If the pressure downstream of the nozzle throat is sufficiently low, then the velocity in the minimum area of the nozzle will become equal to the local speed of sound.
- The flow is said to be choked (critical)

$$P_{crit} = \frac{P_0}{[(\gamma+1)/2]^{\gamma/(\gamma-1)}}$$

- The critical flow rate for an ideal gas can be determine from the equation (Shapiro, 1953)

$$\dot{m} = \frac{A_2 P_0}{\sqrt{T_0}} \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$$

System for Measuring Fluid Flow Rate

Orifice Meter

- One of the inexpensive and easy to install type .

- Fluid energy losses larger than in venturi tube.

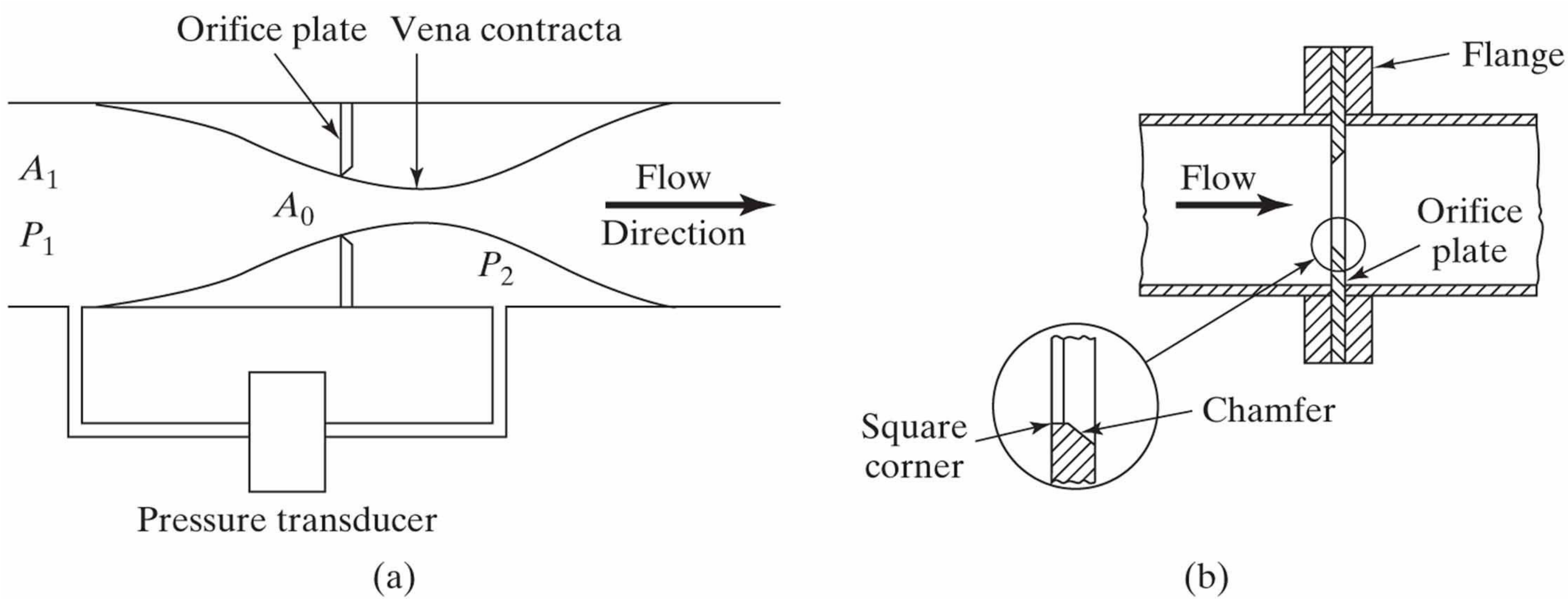
- The minimum fluid flow area does not occur at the orifice plate but at location further downstream.

- The minimum flow area is known as *vena contracta.*

- ASME-described orifice specification is the *square-edged orifice type*

System for Measuring Fluid Flow Rate

Orifice Meter

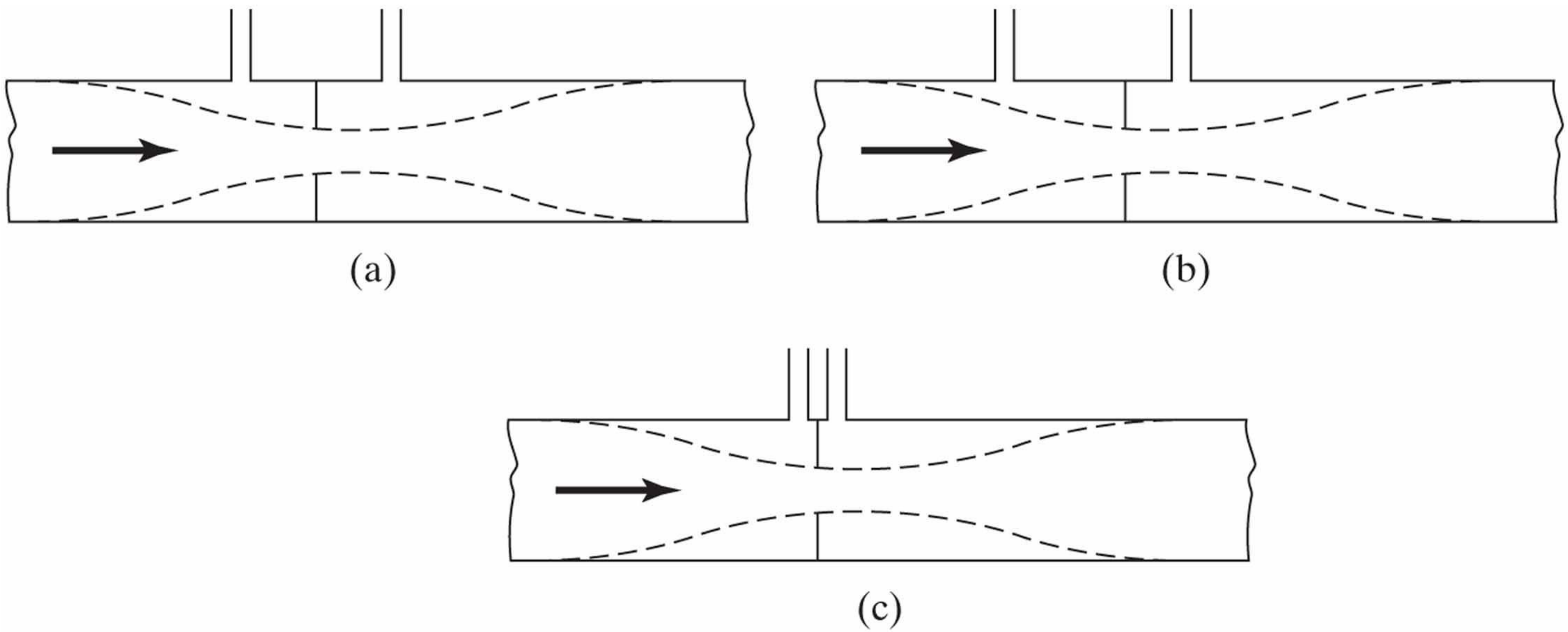


**Vena contracta* is the point in a fluid stream where the diameter of the stream is the least

System for Measuring Fluid Flow Rate

Orifice Meter

Figure 10.7 Location of orifice meter pressure taps: (a) flange taps; (b) *D*-1/2*D* taps; (c) corner taps.



System for Measuring Fluid Flow Rate

Orifice Meter

$$Q = \frac{CA_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2[(P_1+g\rho z_1)-(P_2+g\rho z_2)]}{\rho}}$$

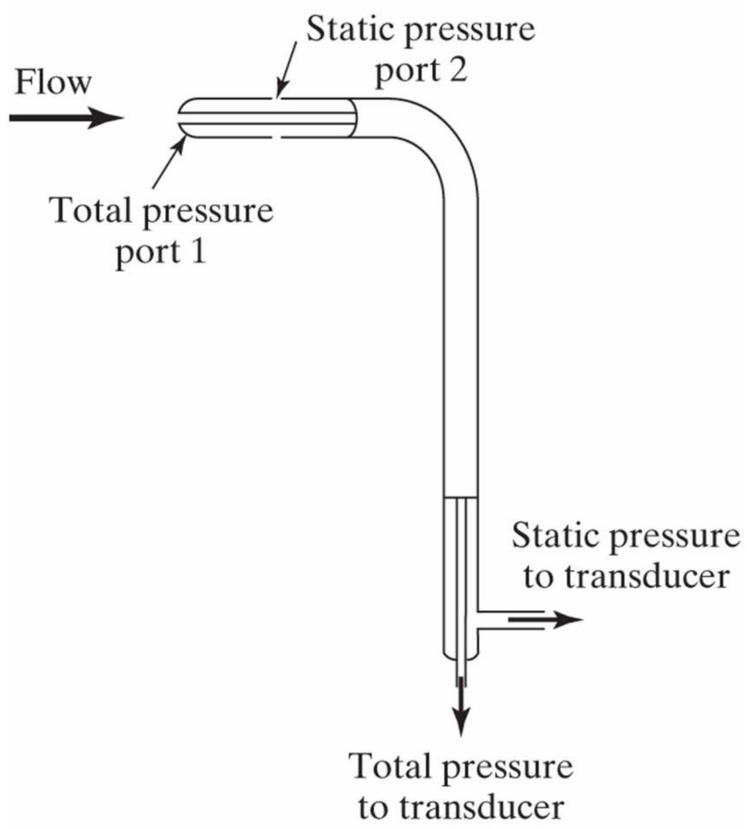
$$C = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + \frac{91.71\beta^{2.5}}{\mathrm{Re}_D^{0.75}}$$

System for Measuring Fluid Velocity

- Devices – used to measure velocity at a point in a flow field

System for Measuring Fluid Velocity

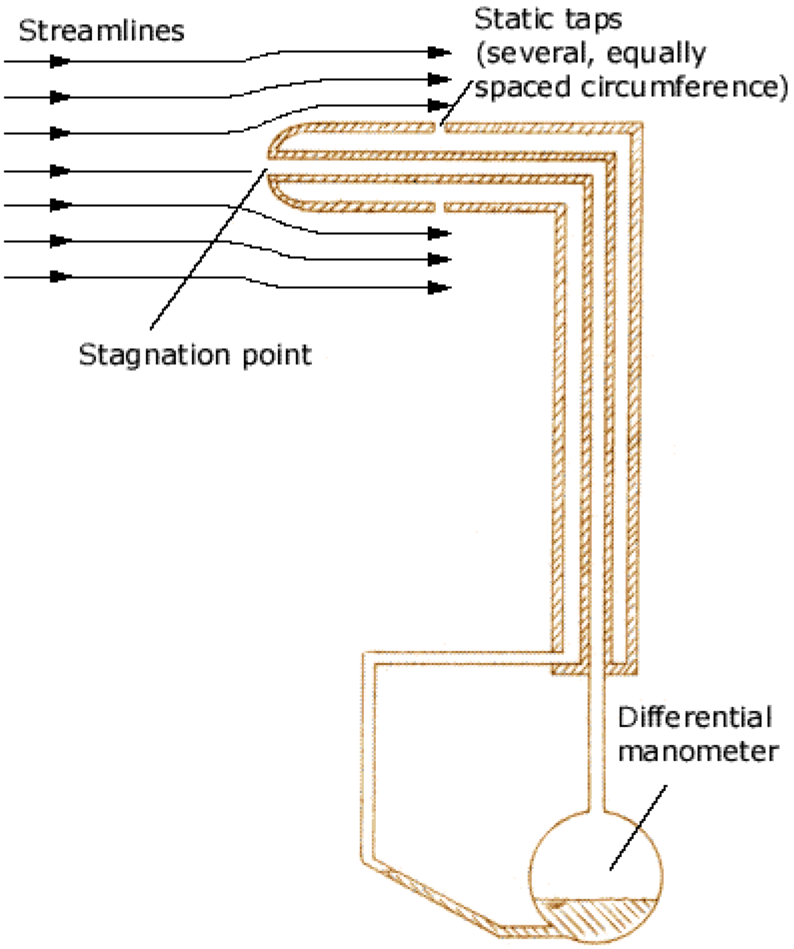
- Pitot-Static Probe: a common device to measure fluid velocity in both liquid and gas flows



Pitot-Static Probe

- It is normally protrudes from the leading edge of aircraft wings in order to measure airspeed (speedometers).
- The probe is placed in the flow with the axis parallel to the flow.
- Pressure sensing locations
    - Port 1 (Total pressure)
    - Port 2 (Static pressure)
- The flow that approaches the total pressure port stops completely so the velocity is zero (Stagnation point)
- The flow that passes to static pressure port has approximately the same velocity as the velocity without the probe present.
- The transducer measures the difference in pressure in the two groups of tubes.

Pitot-Static Probe



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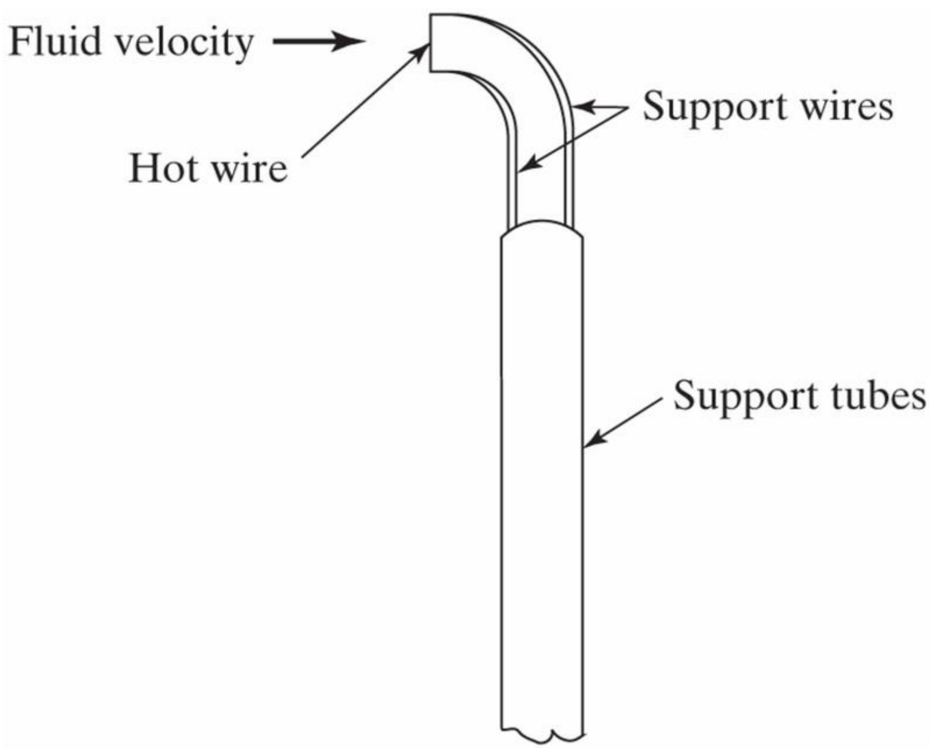
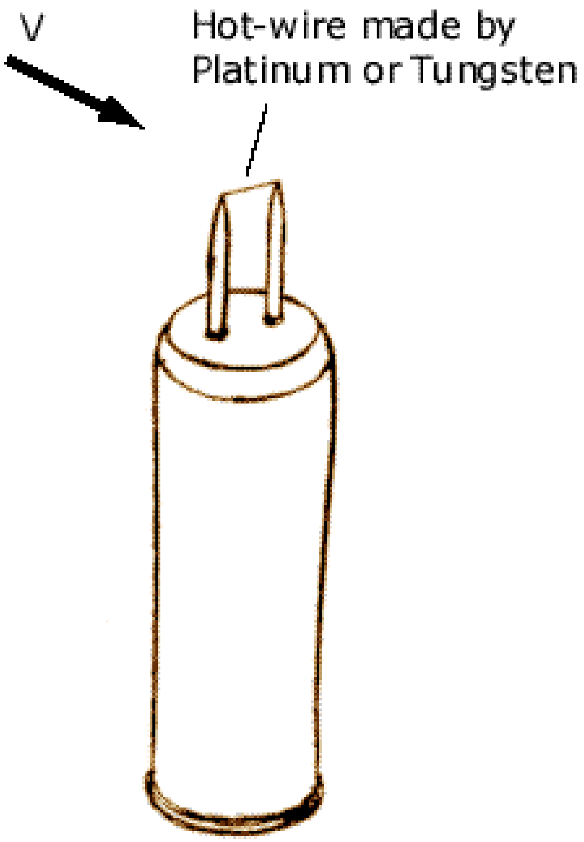
Hot-Wire and Hot-Film Anemometers

- A fluid-velocity-measuring device which is based on the fact that the convective heat transfer from a small-diameter heated wire is a function of fluid velocity.



The wire is 0.04 in long with diameter as small as 0.0002 in.

Hot-Wire and Hot-Film Anemometers



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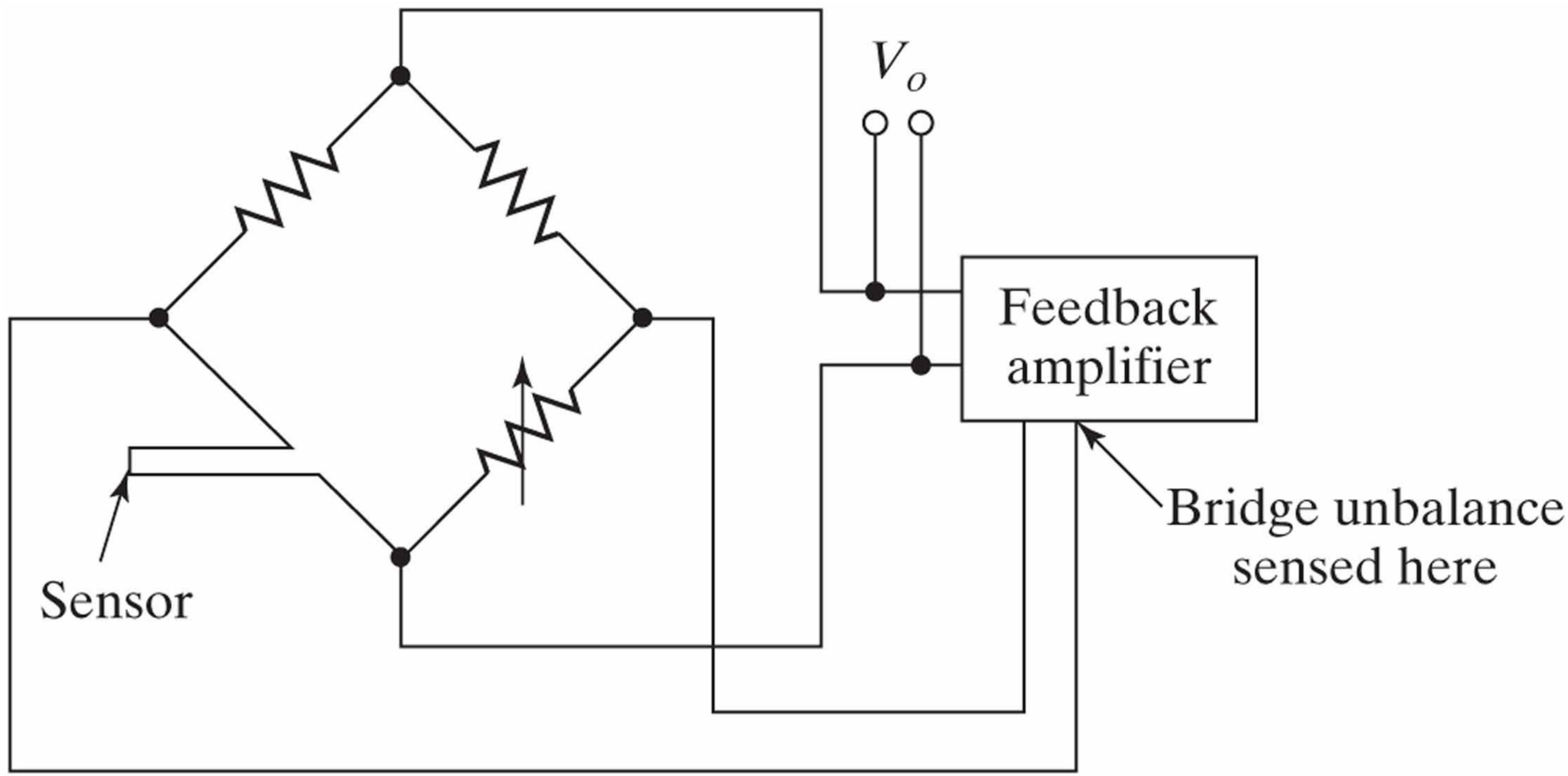
Hot-Wire and Hot-Film Anemometers

- The physical size of the probe is quite small
- Therefore the probe does a minimum to disturb the flow
- The wire is heated up electrically or maintained at a constant temperature
- Heat lost can be measured by obtaining the change in wire temperature
- The heat lost can be converted into fluid velocity (convective theory)

Hot-Wire and Hot-Film Anemometers

- Constant-temperature hot-wire anemometer
  - Operate the hot-wire sensor such that its temperature is held constant
  - Holding temperature and resistance constant, indicates that voltage V will only be function of the fluid velocity U.

Hot-Wire and Hot-Film Anemometers

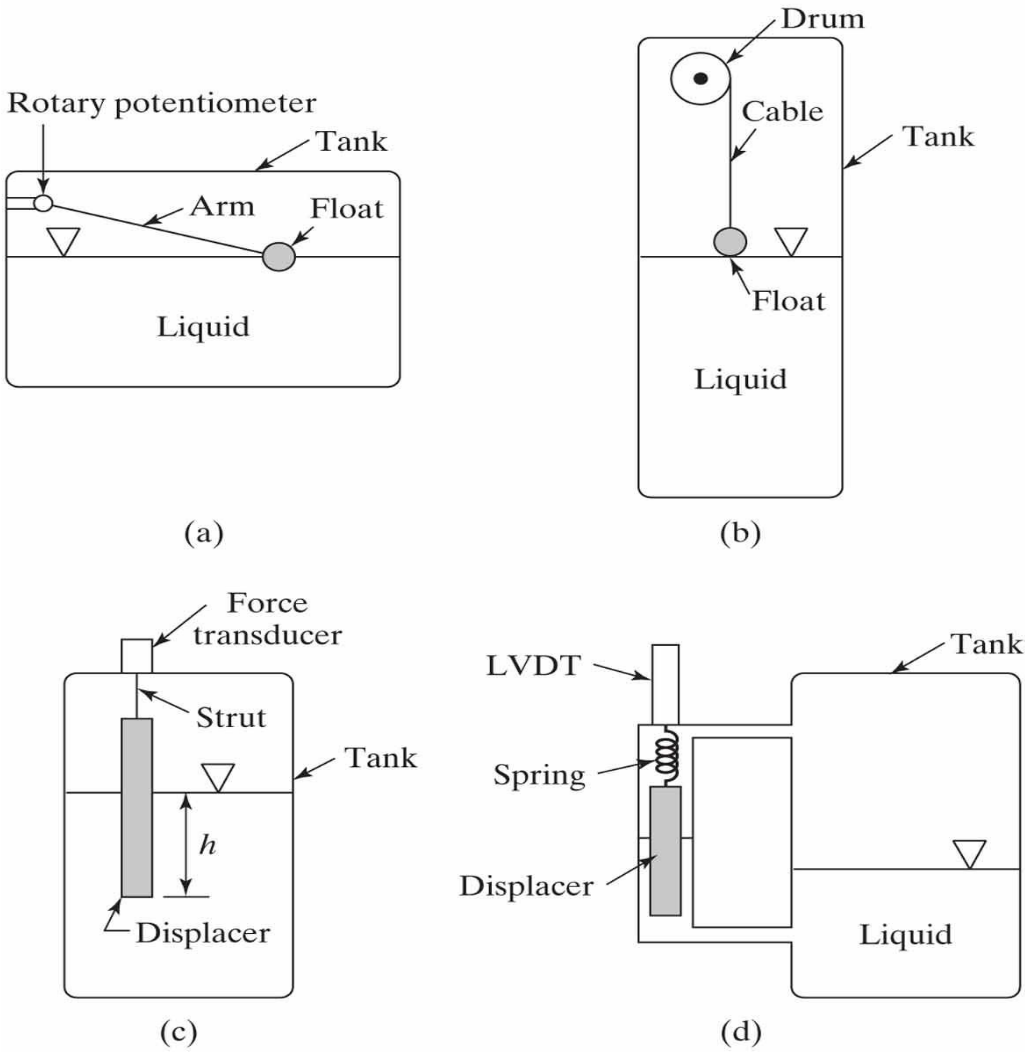


Constant-temperature hot-wire anemometer system.

Measuring Fluid Level

- Devices – used to measure or control the level of liquid in tanks

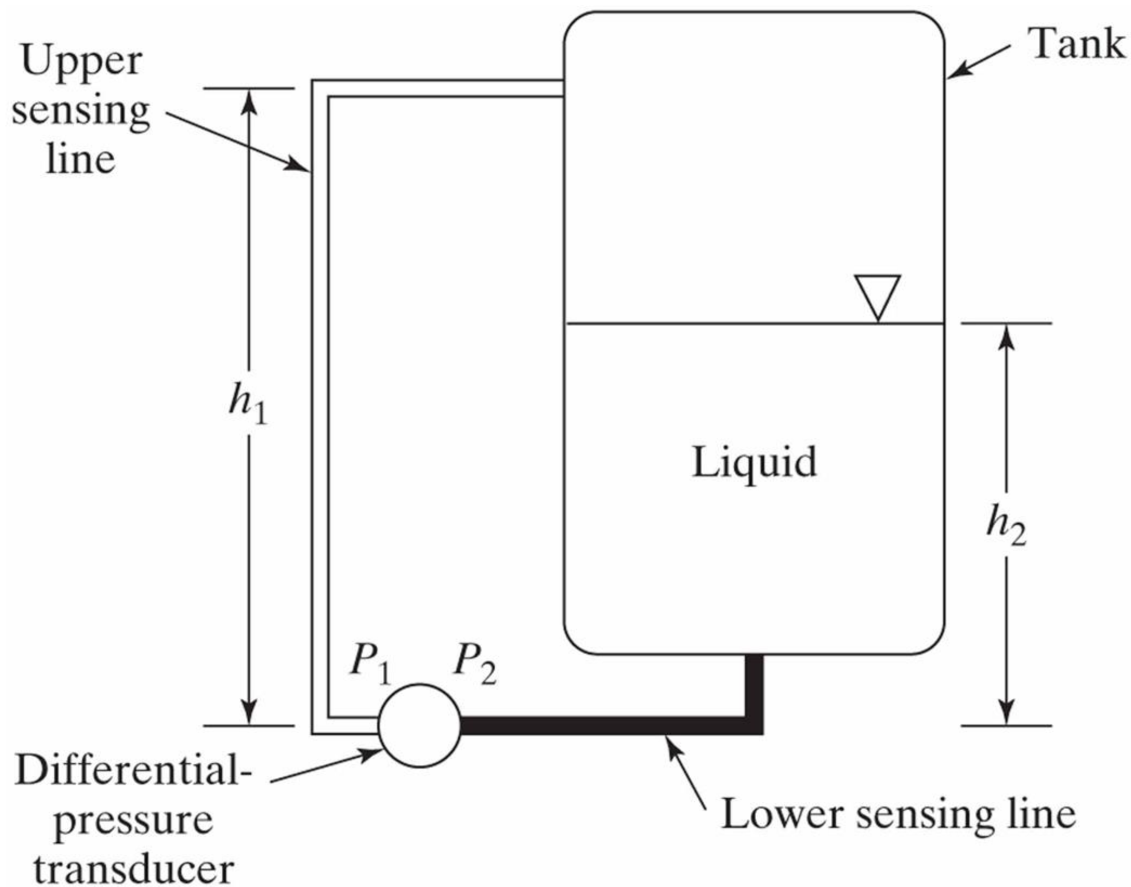
Buoyancy Devices



Float-type level systems.

- Float-type measuring device – measuring level of fuel in the fuel tank (automobile)

Differential Pressure Devices



Differential Pressure Devices

- The difference between the pressure at the surface of a static liquid and the pressure below the surface at a depth h:

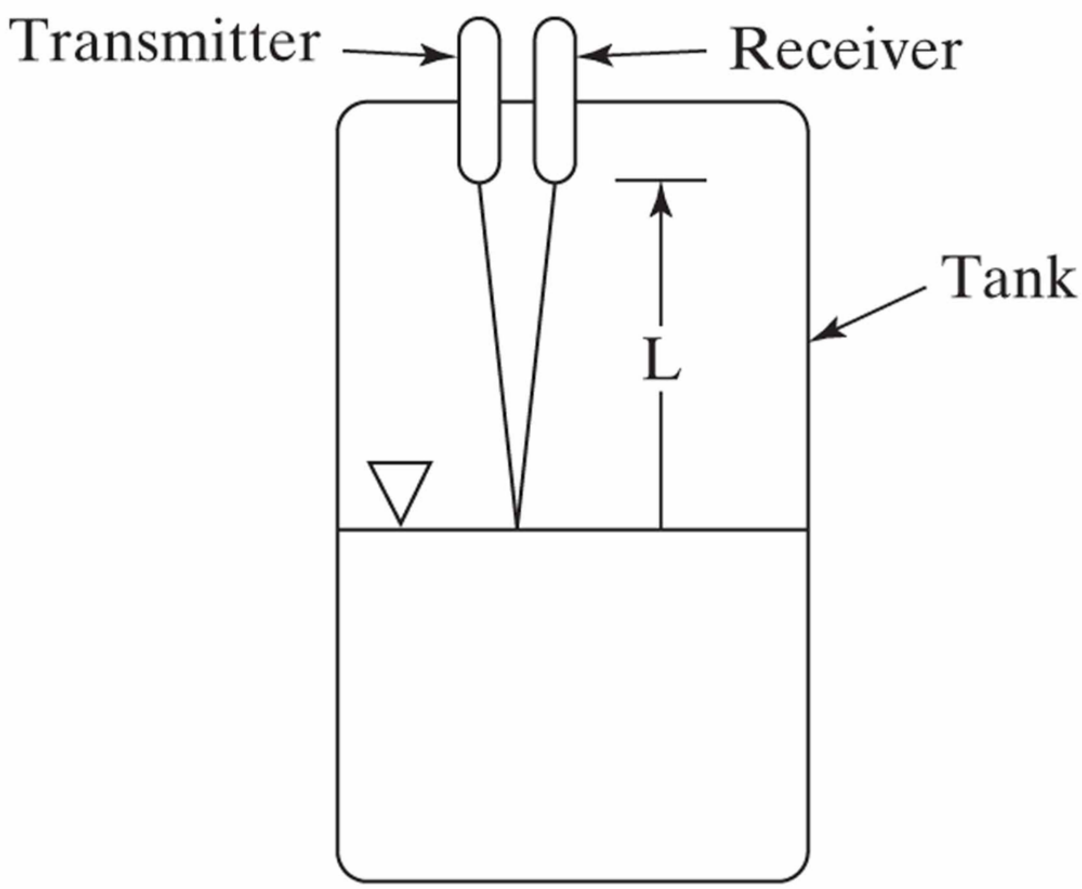
$$\Delta P = \rho g h$$

- Since the air or fluid vapor above the liquid has a very small density, the upper sensing line pressure is the same as the surface pressure.
- h is the depth of the pressure transducer below the fluid surface

Ultrasonic Devices

- Uses same principles as the sonar devices used in ships to locate the bottom of a channel
- A high frequency sound pulse is directed downward toward the surface of the fluid
- It is reflected back and directed back toward the receiver

Ultrasonic Devices



Ultrasonic Devices

- The distance traveled is related to the time t for the pulse to travel the path from the transmitter to the receiver.

$$L = \frac{ct}{2}$$