IoT 4211: Sensor Technology

Flow Measurement

Contents

PRINCIPLE OF HEAD TYPE FLOW METERS

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2$$

$$\Rightarrow P_1 + \frac{\rho V_1^2}{2} + \rho g Z_1 = P_2 + \frac{\rho V_2^2}{2} + \rho g Z_2$$

$$\Rightarrow P_1 + \frac{\rho V_1^2}{2} + \gamma Z_1 = P_2 + \frac{\rho V_2^2}{2} + \gamma Z_2$$

Bernoulli's equation can be written as

$$P_1 + \frac{\rho {V_1}^2}{2} + \gamma Z_1 = P_2 + \frac{\rho {V_2}^2}{2} + \gamma Z_2$$

We assume the flow is horizontal

$$Z_1 = Z_2$$

And the Bernoulli equation becomes

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

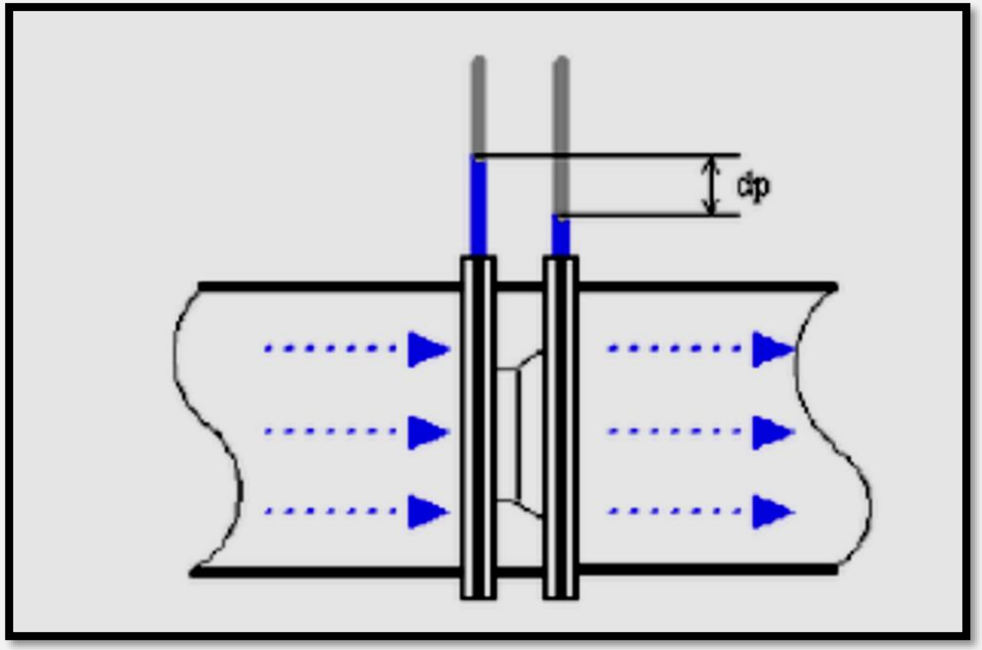
We also assume the velocity profiles are uniform at sections 1 and 2. The continuity equation and be written as

$$Q = A_1 V_1 = A_2 V_2$$

Where A_2 is the smaller flow area $(A_2 < A_1)$. Combining these equations gives and equation for the flow rate in the pipe.

$$Q = A_2 \sqrt{\frac{2(P_1 - P_2)}{\rho\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]}}$$

ORIFICE PLATE



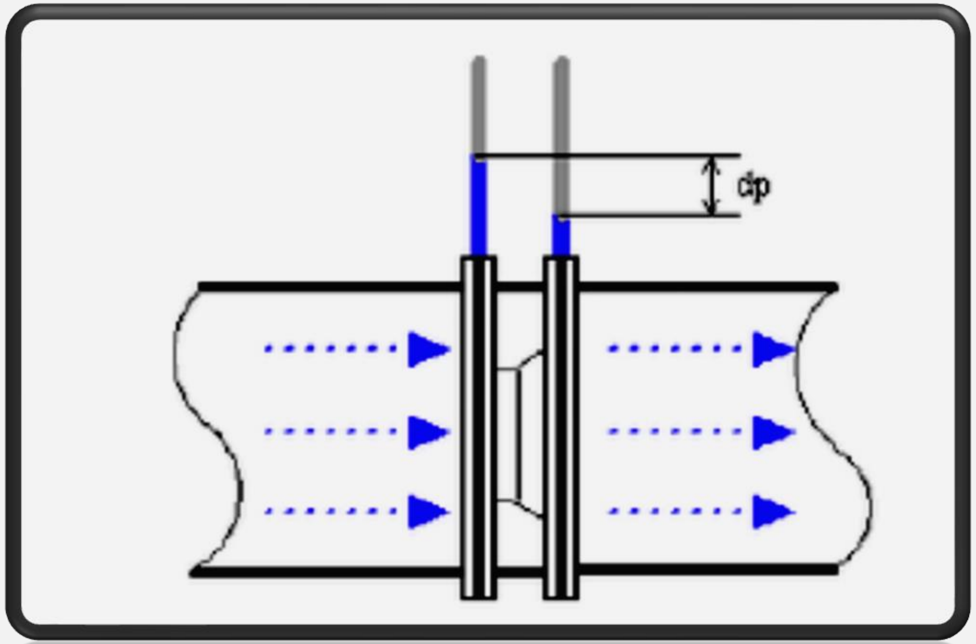
- An orifice flow meter is a type of differential pressure flow meter that measures the flow rate of a fluid (liquid or gas) by introducing a restriction in the flow. The restriction, typically in the form of an orifice plate, creates a pressure drop across the plate, and the difference in pressure before and after the orifice is related to the flow rate.

Orifice Plate: A thin plate with a hole (orifice) in the middle, which restricts the flow.

Pressure Taps: These are located upstream and downstream of the orifice plate to measure the pressure differential.

Differential Pressure Transmitter: Measures the pressure difference across the orifice. uses manometer

ORIFICE PLATE



- **Disadvantages:**

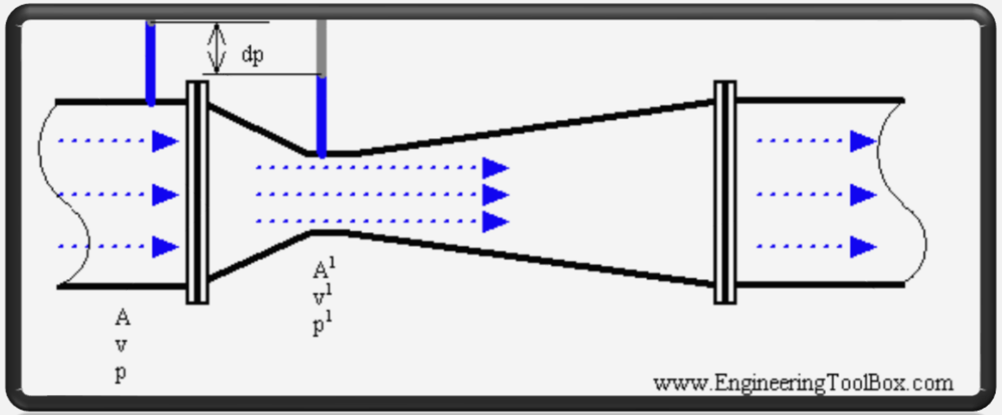
1. Permanent pressure loss in the downstream

2. Wear of the sharp edge on account of long use or by abrasive particles can change the discharge coefficient and hence the calibration.

3. The flow rate is non-linear with respect to the pressure drop.

VENTURI TUBES

- A **Venturi tube** is a flow measurement device that uses the principles of fluid dynamics to measure the flow rate of a fluid.
- It works based on Bernoulli's principle, which relates the velocity and pressure of a fluid moving through a constriction in a pipe.
- The Venturi tube consists of three sections: a converging section, a throat (narrow section), and a diverging section.

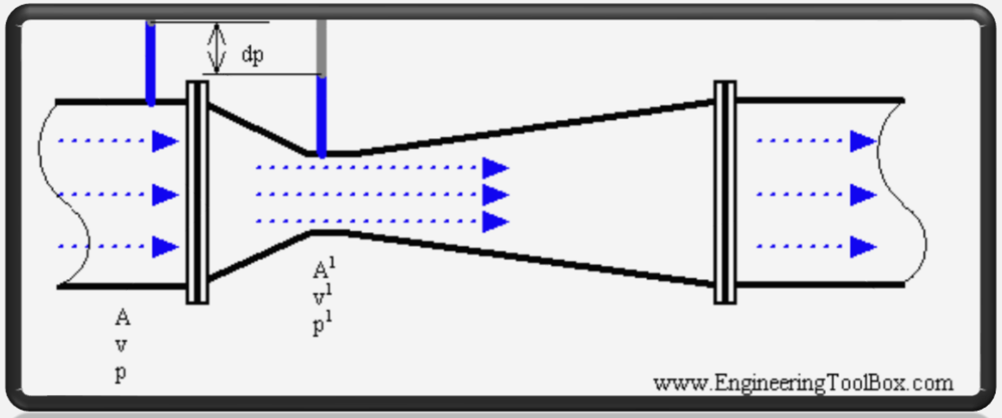


VENTURI TUBES

Converging Section: The fluid enters this section, where the pipe diameter decreases, causing the velocity of the fluid to increase and the pressure to drop.

Throat: This is the narrowest section of the Venturi tube, where the fluid reaches its maximum velocity and experiences the lowest pressure.

Diverging Section: After the throat, the pipe diameter increases again, causing the fluid velocity to decrease and the pressure to recover (partially, though never to the initial level due to energy losses).



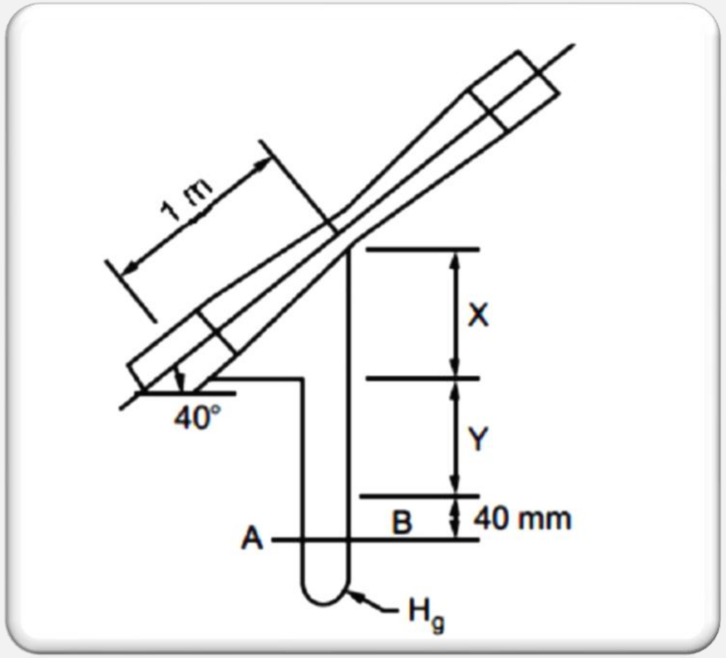
Working Principle:

The operation of the Venturi tube is based on **Bernoulli's equation**, which states that an increase in the velocity of a fluid results in a decrease in pressure. As the fluid flows through the converging section, it accelerates and the pressure drops. The pressure difference between the upstream section (before the constriction) and the throat (narrow section) is proportional to the flow rate.

A venturimeter is fitted in a pipe of 30 cm diameter inclined at 40° to the horizontal to measure the flow rate of petrol having a specific gravity of 0.8. The ratio of areas of main pipe and throat is 5 and the throat is at 1 m from the inlet along its length. The difference in manometer head is 40 mm of mercury. Assuming the coefficient of discharge as 0.96. Calculate the discharge through the venturimeter and the pressure difference between the throat and the entry point of the venturimeter.

Hints:

$$Q = C_d \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \sqrt{2gh_m\left(\frac{\rho_m}{\rho} - 1\right)}$$



Coefficient of discharge: ratio of the actual discharge to the ideal discharge

A venturimeter is fitted in a pipe of 30 cm diameter inclined at 40° to the horizontal to measure the flow rate of petrol having a specific gravity of 0.8. The ratio of areas of main pipe and throat is 5 and the throat is at 1 m from the inlet along its length. The difference in manometer head is 40 mm of mercury. Assuming the coefficient of discharge as 0.96. Calculate the discharge through the venturimeter and the pressure difference between the throat and the entry point of the venturimeter.

Solutions:

$$A_1 = \frac{\pi}{4} \times 0.3^2 = 0.0707 \text{ m}^2$$

$$A_1/A_2 = 5$$

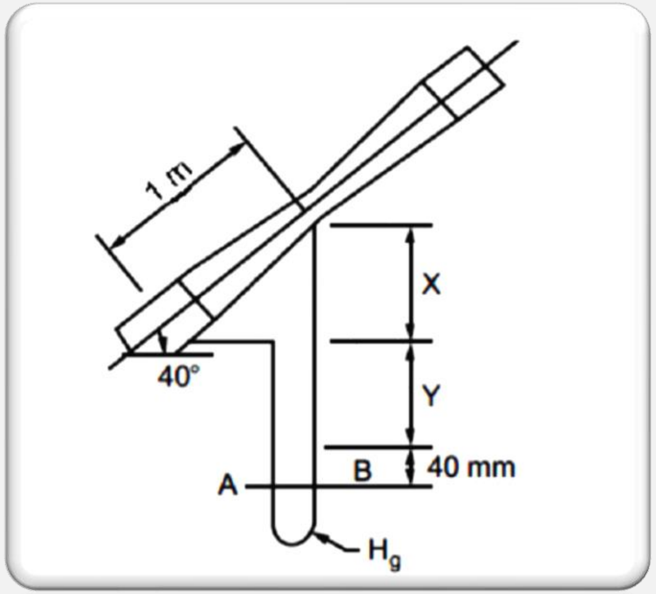
$$A_2 = 0.0707/5 = 0.0141 \text{ m}^2$$

$$Q = \frac{0.96 \times 0.0141 \times 0.0707}{\sqrt{0.0707^2 - 0.0141^2}} \sqrt{2 \times 9.81 \times 0.04 \times \left(\frac{13.6}{0.8} - 1\right)}$$

$$= 0.0486 \text{ m}^3/\text{s}$$

A venturimeter is fitted in a pipe of 30 cm diameter inclined at 40° to the horizontal to measure the flow rate of petrol having a specific gravity of 0.8. The ratio of areas of main pipe and throat is 5 and the throat is at 1 m from the inlet along its length. The difference in manometer head is 40 mm of mercury. Assuming the coefficient of discharge as 0.96. Calculate the discharge through the venturimeter and the pressure difference between the throat and the entry point of the venturimeter.

Solutions:



$$P_A + \rho g y + \rho g(0.04) = P_B + \rho g x + \rho g y + \rho_m g\,(0.04)$$

$$P_A - P_B = \rho g x + 0.04 \times g \times (\rho_m - \rho)$$

$$= \rho g\,(1 \times \sin 40) + 0.04 \times 9.81 \times (13600 - 800)$$

$$= 10067.32\ \text{N/m}^2 \text{ or } 10.07\ \text{kN/m}^2$$

A venturimeter is used to measure liquid flow rate of 7500 litres per minute. The difference in pressure across the venturimeter is equivalent to 8 m of the flowing liquid. The pipe diameter is 19 cm. Calculate the throat diameter of the venturimeter. Assume the coefficient of discharge for the venturimeter as 0.96.

Hints:

$$Q = C_d \frac{A_1 A_2 \sqrt{2gh}}{\sqrt{A_1^2 - A_2^2}},$$

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Hints:

$$A_1 = \frac{\pi}{4} \times 0.19^2 = 0.0284 \text{ m}^2$$

$$\frac{7500 \times 10^{-3}}{60} = \frac{0.96 \times 0.0284\ A_2}{\sqrt{0.0284^2 - A_2^2}} \sqrt{2 \times 9.81 \times 8}$$

$$A_2 = 0.0098 \text{ m}^2$$

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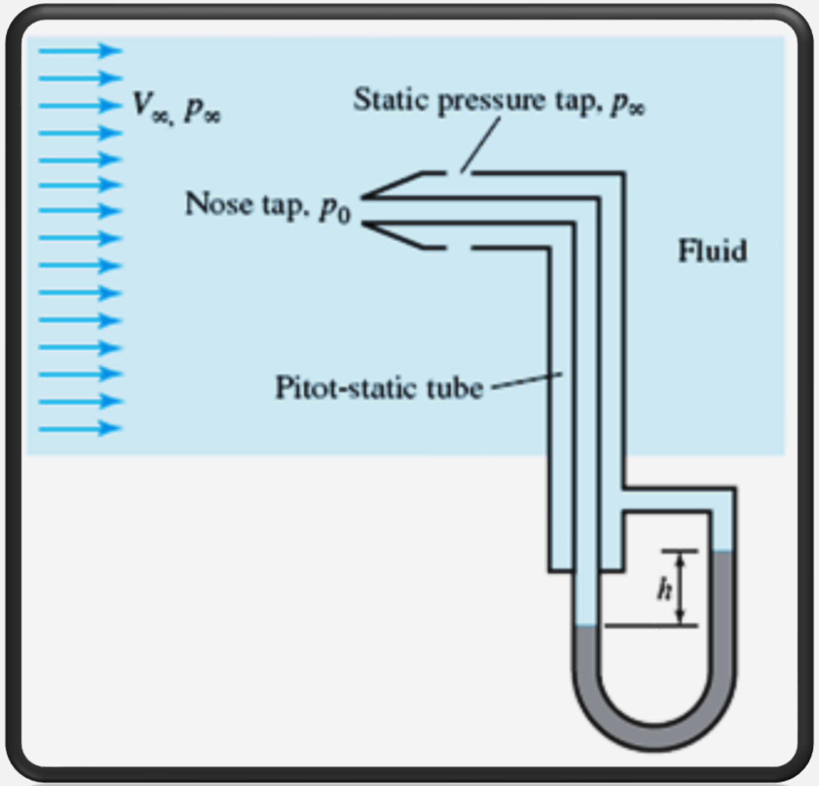
Hints:

Let the diameter be *d*, $\frac{\pi}{4} \times d^2 = 0.0098$

$$d = \sqrt{\frac{4 \times 0.0098}{\pi}} = 9.9 \text{ cm}$$

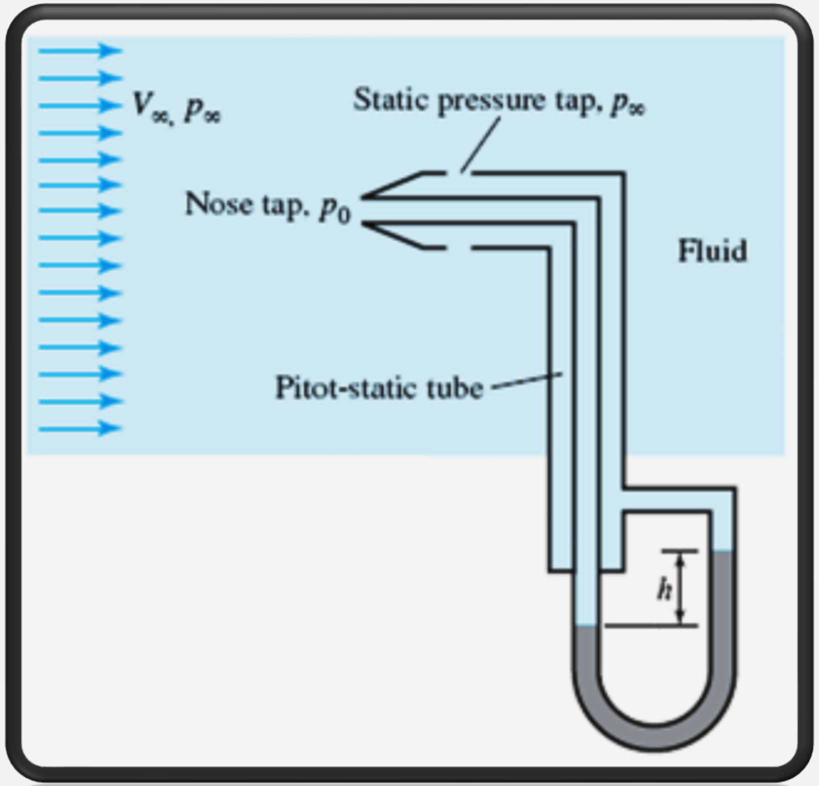
PITOT TUBES



A **Pitot tube** is a device used to measure the velocity of a fluid (usually air or water) by converting the kinetic energy of the flow into potential energy (pressure).

Impact Port (Stagnation Port): This is the opening at the front of the Pitot tube, which faces directly into the fluid flow. It measures the total (stagnation) pressure—the sum of the fluid's static pressure and dynamic pressure caused by the fluid's velocity.
Static Ports: Small holes on the side of the Pitot tube (or on a separate tube in a combined setup), perpendicular to the flow, which measure the static pressure (the pressure exerted by the fluid when it is not moving).
Differential Pressure Sensor: Measures the difference between the stagnation pressure and static pressure. This difference is the dynamic pressure, which is related to the velocity of the fluid.

PITOT TUBES



Working Principle:
The Pitot tube works based on **Bernoulli's principle**, which relates the pressure and velocity of a fluid. When the fluid enters the stagnation port, it comes to a stop, converting its velocity into pressure. The static ports measure the pressure without the contribution of fluid velocity.

The **dynamic pressure** is the difference between the stagnation pressure (P_0) and the static pressure (P_s):

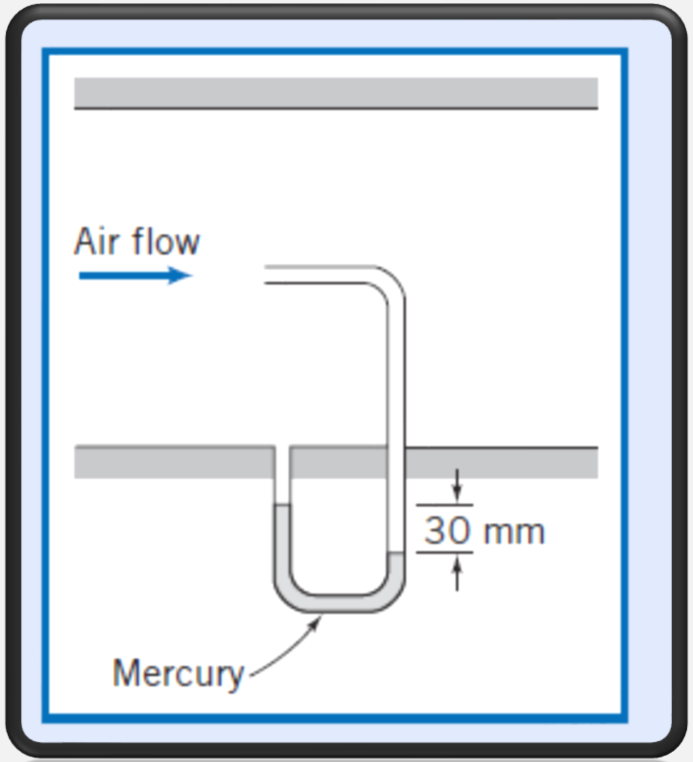
$$P_d = P_0 - P_s$$

A pitot tube is inserted in an air flow (at STP) to measure the flow speed. The tube is inserted so that it points upstream into the flow and the pressure sensed by the tube is the stagnation pressure. The static pressure is measured at the same location in the flow, using a wall pressure tap. If the pressure difference is 30 mm of mercury, determine the flow speed.

Hints:

Governing equation: $\frac{p}{\rho} + \frac{V^2}{2} + gz = \text{constant}$

Specific gravity of mercury = 13.6



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Solution:

Assumptions:
(1) Steady flow.
(2) Incompressible flow.
(3) Flow along a streamline.
(4) Frictionless deceleration along stagnation streamline.

Writing Bernoulli's equation along the stagnation streamline (with $\Delta z = 0$) yields

$$\frac{p_0}{\rho} = \frac{p}{\rho} + \frac{V^2}{2}$$

$$V = \sqrt{\frac{2(p_0 - p)}{\rho_{\text{air}}}}$$

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Solution:

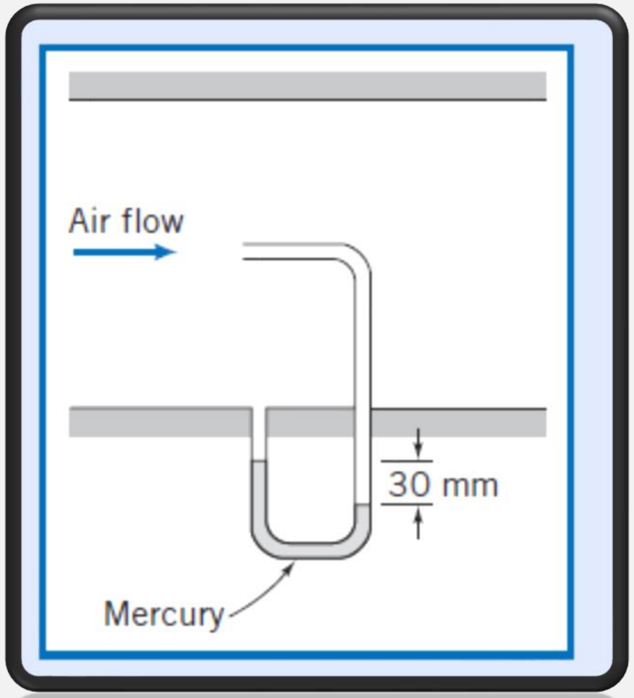
From the diagram,

$$p_0 - p = \rho_{Hg} g h = \rho_{H_2O} g h SG_{Hg}$$

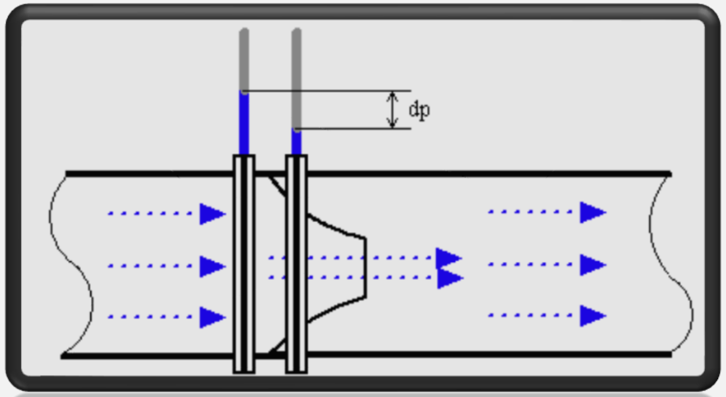
$$V = \sqrt{\frac{2\rho_{H_2O} g h SG_{Hg}}{\rho_{air}}}$$

$$= \sqrt{2 \times 1000 \frac{kg}{m^3} \times 9.81 \frac{m}{s^2} \times 30\ mm \times 13.6 \times \frac{m^3}{1.23\ kg} \times \frac{1\ m}{1000\ mm}}$$

$$V = 80.8\ m/s$$



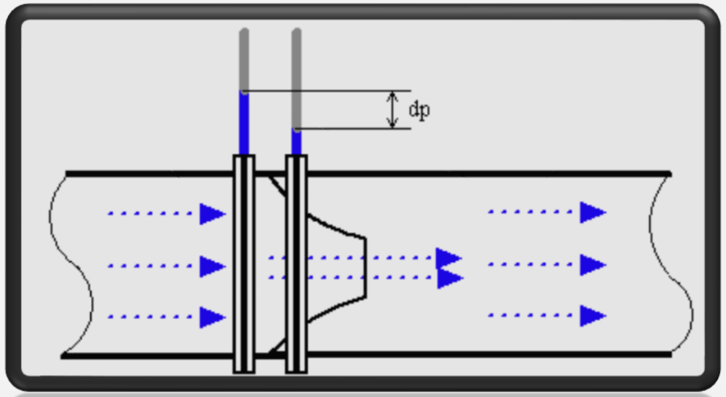
FLOW NOZZLE



A **flow nozzle** is a type of differential pressure flow meter used to measure the flow rate of fluids (both gases and liquids). Like the orifice plate and Venturi tube, it relies on the principle of creating a pressure drop as the fluid flows through a constriction. However, the flow nozzle has a streamlined design, which reduces energy losses and makes it more suitable for certain applications, especially high-velocity flows.

Inlet Section: The part where the fluid enters the nozzle. The pipe diameter is uniform at this section.
Converging Section: A curved, converging part of the nozzle where the fluid is accelerated as it flows into a smaller area. The nozzle's shape minimizes flow separation, making it more efficient than an orifice plate.
Throat: The narrowest part of the flow nozzle, where the fluid reaches its highest velocity and the pressure is at its lowest.
Pressure Taps: These are located before and after the nozzle to measure the pressure drop, which is used to calculate the flow rate.

FLOW NOZZLE



Working Principle:
The flow nozzle operates based on **Bernoulli's principle**, which states that an increase in the velocity of a fluid results in a decrease in pressure. As the fluid passes through the nozzle's throat, its velocity increases and pressure decreases, creating a pressure differential between the upstream (inlet) and downstream (throat) sections. This pressure drop is proportional to the flow rate.

FLOW NOZZLE VS. ORIFICE PLATE VS. VENTURI TUBE:

•**Pressure Loss**: Flow nozzles cause less permanent pressure loss than orifice plates but more than Venturi tubes.

•**Accuracy**: Flow nozzles provide better accuracy at high velocities compared to orifice plates but slightly lower accuracy than Venturi tubes.

•**Cost**: Flow nozzles are more expensive than orifice plates but less expensive than Venturi tubes.

Flow nozzles offer a good balance of performance, durability, and efficiency, particularly in applications with high-velocity or erosive fluids.

Air flows steadily at low speed through a horizontal *nozzle* (by definition a device for accelerating a flow), discharging to atmosphere. The area at the nozzle inlet is 0.1 m^2. At the nozzle exit, the area is 0.02 m^2. Determine the gage pressure required at the nozzle inlet to produce an outlet speed of 50 m/s.

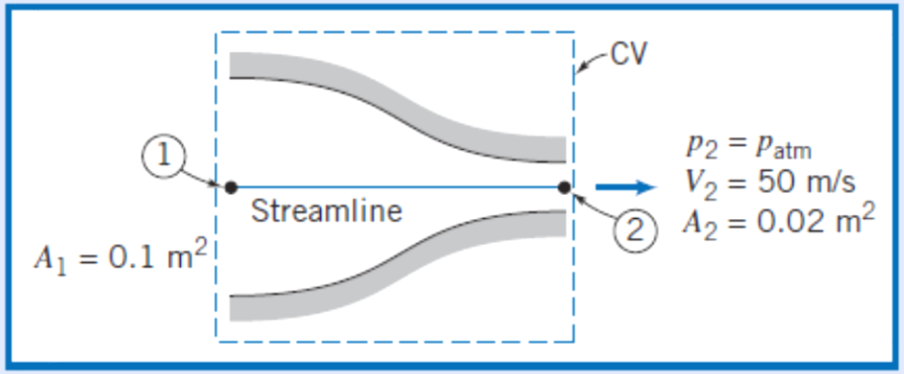
Hints:

Governing equations:

$$\frac{p_1}{\rho} + \frac{V_1^2}{2} + gz_1 = \frac{p_2}{\rho} + \frac{V_2^2}{2} + gz_2$$

Continuity for incompressible and uniform flow:

$$\sum_{CS} \vec{V} \cdot \vec{A} = 0$$



For air at standard conditions, $\rho = 1.23\ kg/m^3$.

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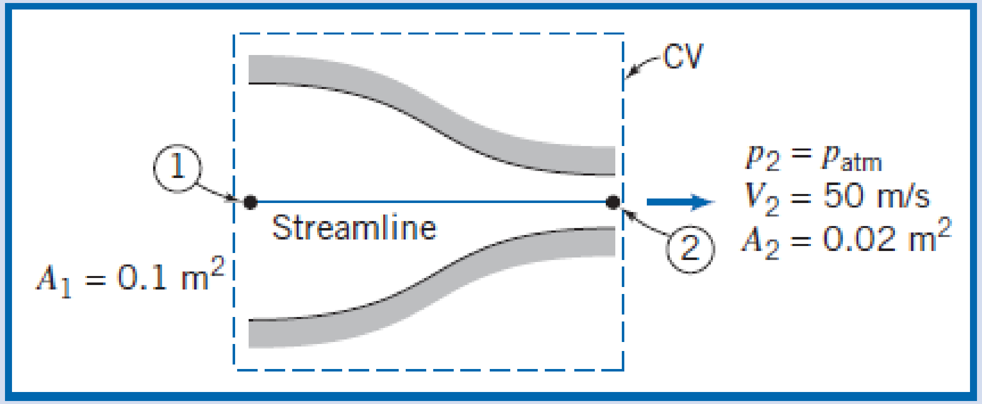
Solution:

Assumptions:
(1) Steady flow.
(2) Incompressible flow.
(3) Frictionless flow.
(4) Flow along a streamline.
(5) $z_1 = z_2$.
(6) Uniform flow at sections 1 and 2.



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Solution:

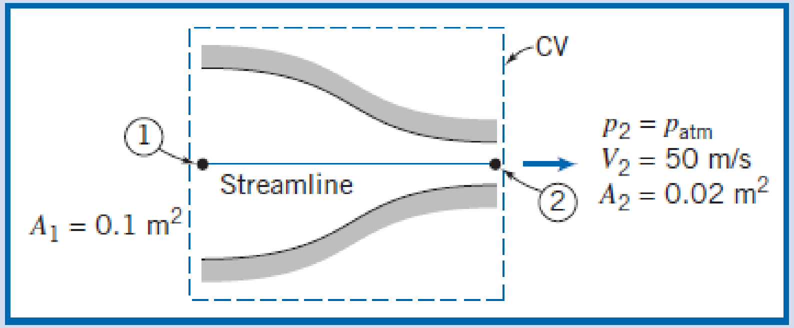
Apply the Bernoulli equation along a streamline between points (1) and (2) to evaluate p_1. Then

$$p_1 - p_{atm} = p_1 - p_2 = \frac{\rho}{2}(V_2^2 - V_1^2)$$

Apply the continuity equation to determine V_1,

$$(-\rho V_1 A_1) + (\rho V_2 A_2) = 0 \qquad \text{or} \qquad V_1 A_1 = V_2 A_2$$

$$V_1 = V_2 \frac{A_2}{A_1} = 50 \frac{\text{m}}{\text{s}} \times \frac{0.02\ \text{m}^2}{0.1\ \text{m}^2} = 10\ \text{m/s}$$



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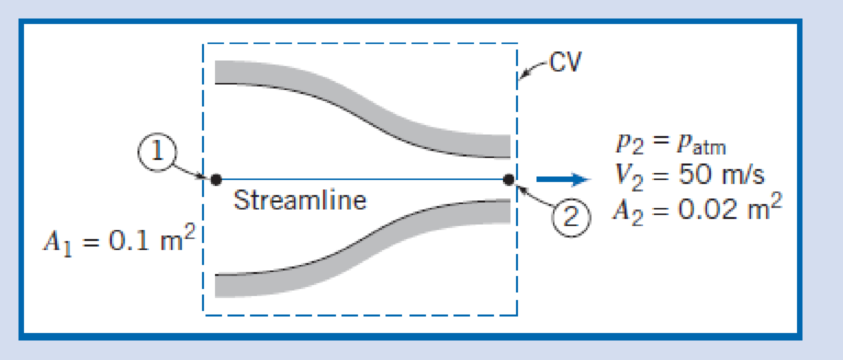
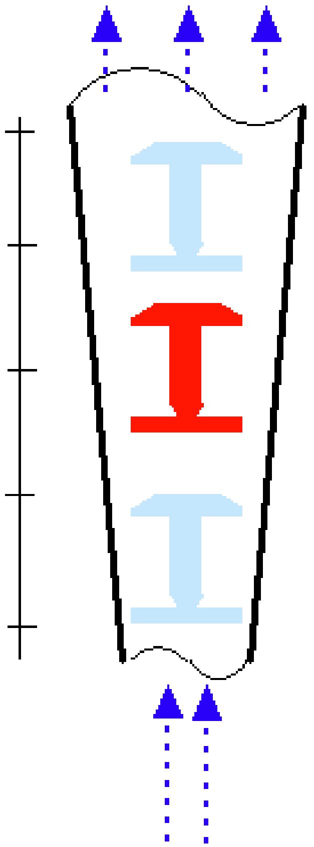
Solution:

$$p_1 - p_{atm} = \frac{\rho}{2}(V_2^2 - V_1^2)$$
$$= \frac{1}{2} \times 1.23 \frac{\text{kg}}{\text{m}^3}\left[(50)^2 \frac{\text{m}^2}{\text{s}^2} - (10)^2 \frac{\text{m}^2}{\text{s}^2}\right] \frac{\text{N} \cdot \text{s}^2}{\text{kg} \cdot \text{m}}$$

$$p_1 - p_{atm} = 1.48 \text{ kPa}$$



Rotameter



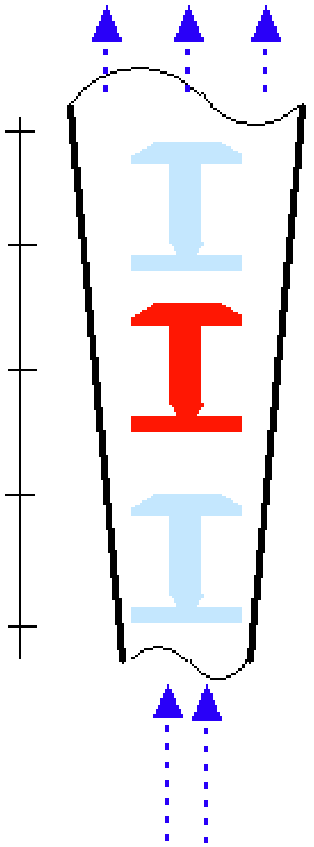
A **rotameter** is a type of variable area flow meter used to measure the flow rate of liquids and gases. It consists of a vertically oriented, tapered tube and a float that moves up and down inside the tube depending on the flow rate. The position of the float is used to determine the flow rate, with the reading typically displayed on a scale alongside the tube.

Tapered Tube: A transparent tube that gradually widens from bottom to top. The tube is typically made of glass, plastic, or metal and is calibrated for a specific fluid and flow range.

Float: A small object (usually made of metal, glass, or plastic) that is lifted by the fluid as it flows through the tube. The float rises or falls depending on the flow rate.

Scale: A graduated scale alongside the tube allows the user to directly read the flow rate based on the float's position.

Rotameter



Working Principle:

The rotameter operates on the principle of a variable area flow meter, where the area through which the fluid flows changes as the float moves. As fluid flows upward through the tapered tube, it exerts an upward force on the float, which is counteracted by the downward force of gravity. When the forces balance, the float reaches a stable position.

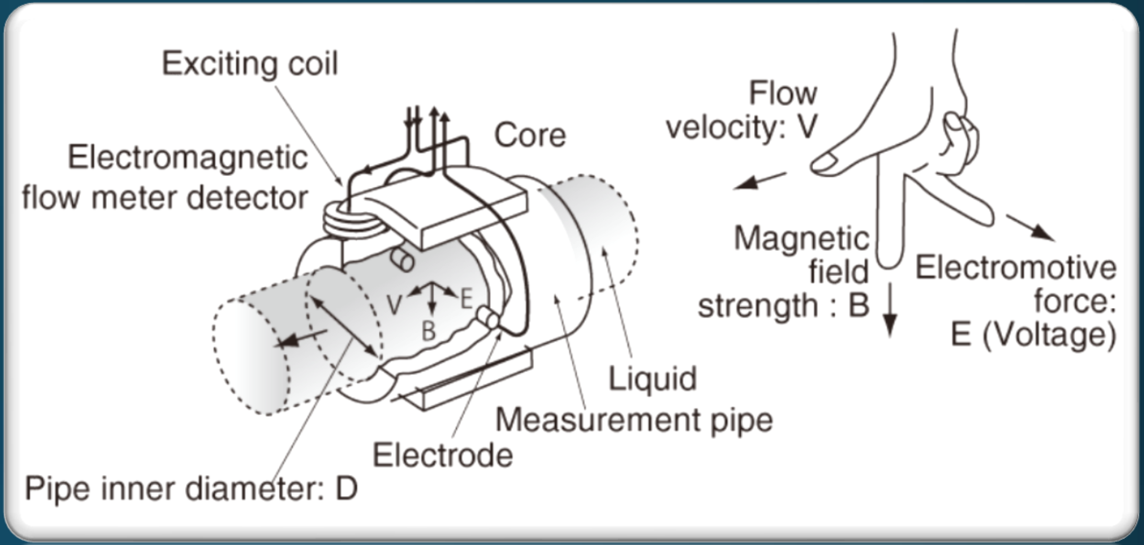
•**Low flow rate**: The float rests near the bottom of the tube where the area is smaller.

•**High flow rate**: The float rises as the flow increases, moving to a wider section of the tube where the area is larger.

The height of the float is proportional to the flow rate, and the flow rate can be read directly from the scale.

Electro-magnetic Flow Meter

An **electromagnetic flow meter** (also known as a **magmeter**) is a type of flow meter that measures the flow rate of conductive liquids (like water, slurries, or corrosive chemicals) based on **Faraday's law of electromagnetic induction**. It has no moving parts, which makes it suitable for measuring the flow of liquids that are dirty, corrosive, or contain solids.



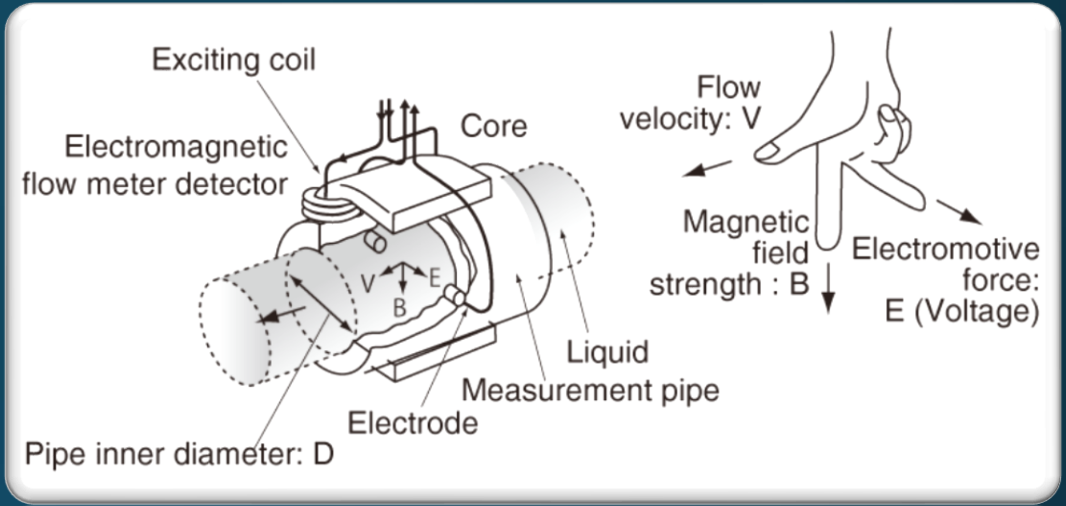
Electromagnetic Coils: Two coils generate a magnetic field that interacts with the conductive fluid as it flows through the meter.
Electrodes: Two or more electrodes are placed on the inner walls of the flow tube to detect the voltage generated by the fluid moving through the magnetic field.
Flow Tube: The section of pipe through which the fluid flows. It is typically non-conductive (often made of plastic or rubber lining) to ensure accurate readings of the induced voltage.
Signal Processor: A device that converts the voltage detected by the electrodes into a flow rate reading

Electro-magnetic Flow Meter

Working Principle:

The electromagnetic flow meter operates based on **Faraday's Law of Electromagnetic Induction**, which states that a voltage is induced when a conductive fluid flows through a magnetic field. The magnitude of this induced voltage is directly proportional to the velocity of the fluid.

When a conductive fluid moves through the magnetic field generated by the coils, it induces a voltage across the electrodes. The faster the fluid flows, the greater the voltage. This induced voltage is proportional to the fluid's velocity, and with the cross-sectional area of the pipe known, the flow rate can be determined.



Governing Equation:

The flow rate Q is calculated based on the induced voltage E, using Faraday's law:

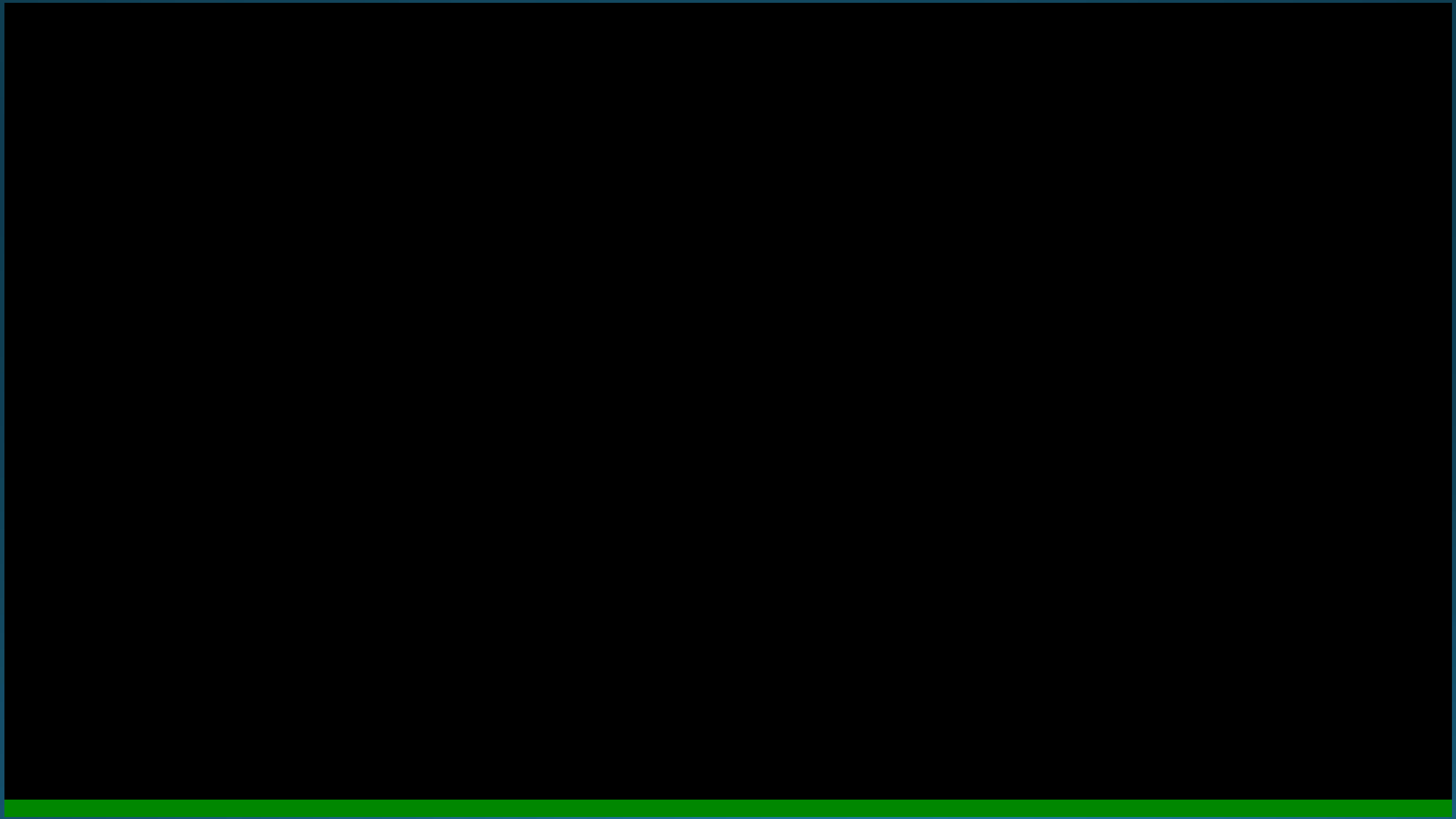
$E = B \cdot v \cdot D$ Where:

- E = Induced voltage
- B= Magnetic field strength (constant for a given meter)
- v = Fluid velocity
- D = Distance between the electrodes (essentially the diameter of the flow tube)

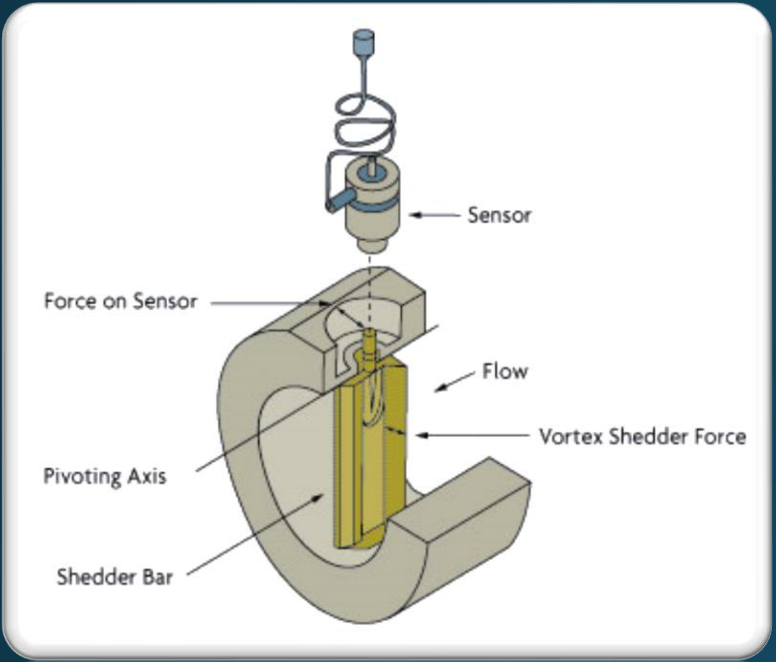
The volumetric flow rate Q is related to the velocity of the fluid v and the cross-sectional area of the pipe A:

$$Q = A \cdot v$$

Magnetic Flow Meter



Vortex Flow Meter



A **vortex flow meter** is a type of flow measurement device that determines the flow rate of liquids, gases, or steam by detecting the vortices shed by a bluff body placed in the flow stream. The device operates based on the principle known as the **von Kármán vortex street**, where alternating vortices are generated downstream of the bluff body when fluid flows around it.

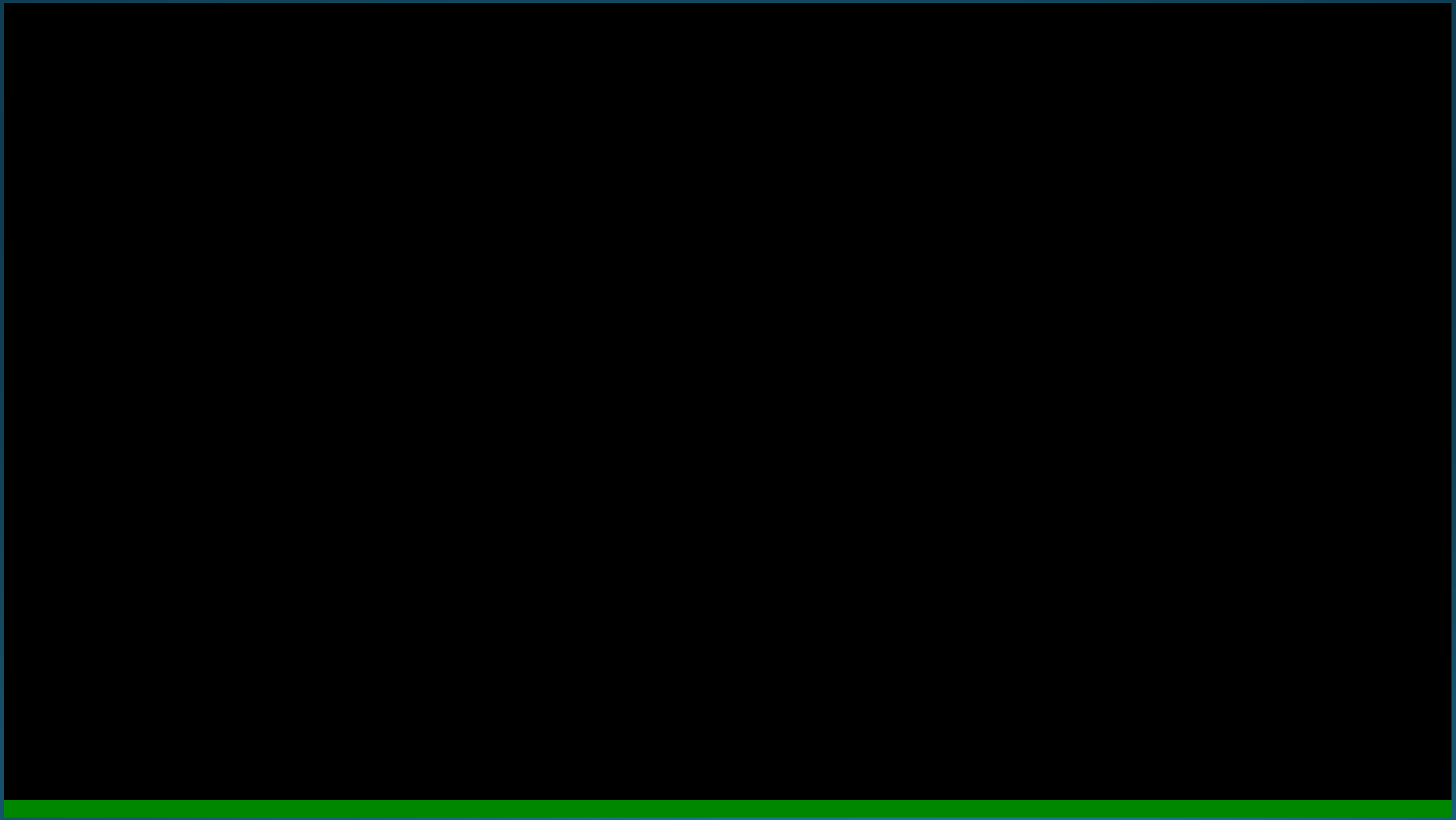
Bluff Body: A non-streamlined object placed in the flow path that disrupts the fluid flow and causes the formation of vortices. The size and shape of the bluff body are critical to ensure consistent vortex shedding.

Sensor: The sensor detects the frequency of the vortices, which is proportional to the flow rate. Sensors can be piezoelectric, capacitive, or ultrasonic, depending on the design.

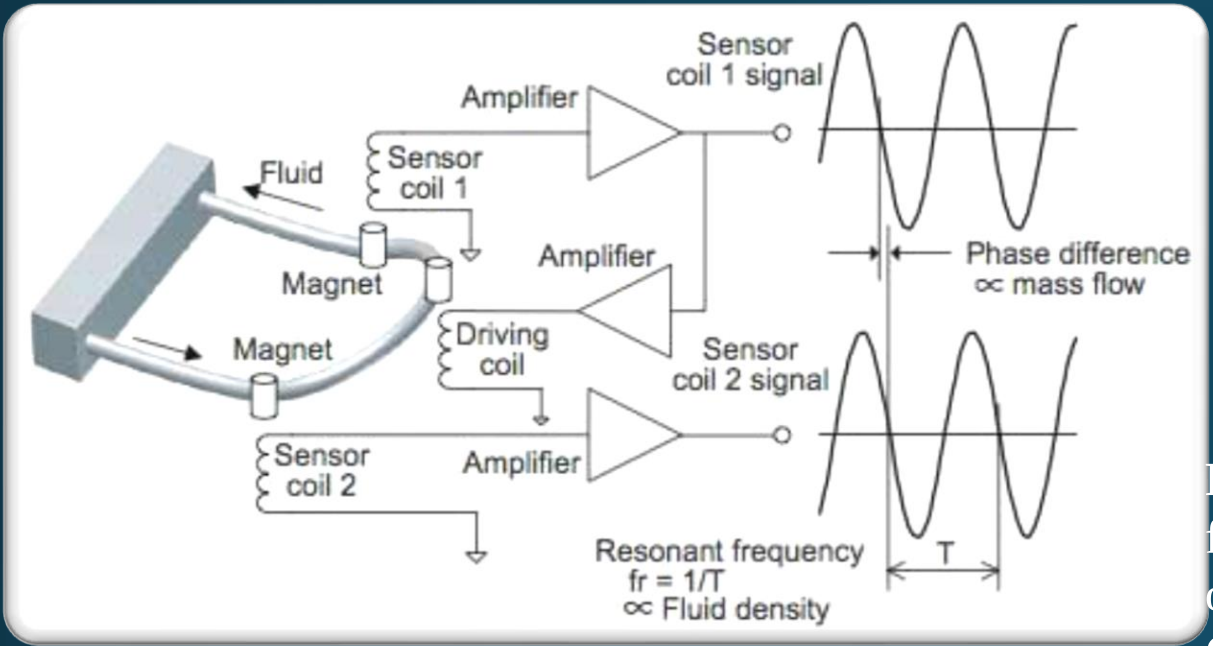
Flow Tube: The section of pipe where the bluff body and sensor are housed.

Transmitter: This converts the frequency signal generated by the sensor into a flow rate reading, which can be displayed

Vortex Flow Meter



Coriolis Flow Meter



A **Coriolis flow meter** is a highly accurate device used to measure the **mass flow rate** of a fluid (liquid or gas). Unlike many other types of flow meters that measure volumetric flow rate, Coriolis meters directly measure the mass flow by leveraging the **Coriolis effect**, which occurs when a fluid flows through oscillating tubes.

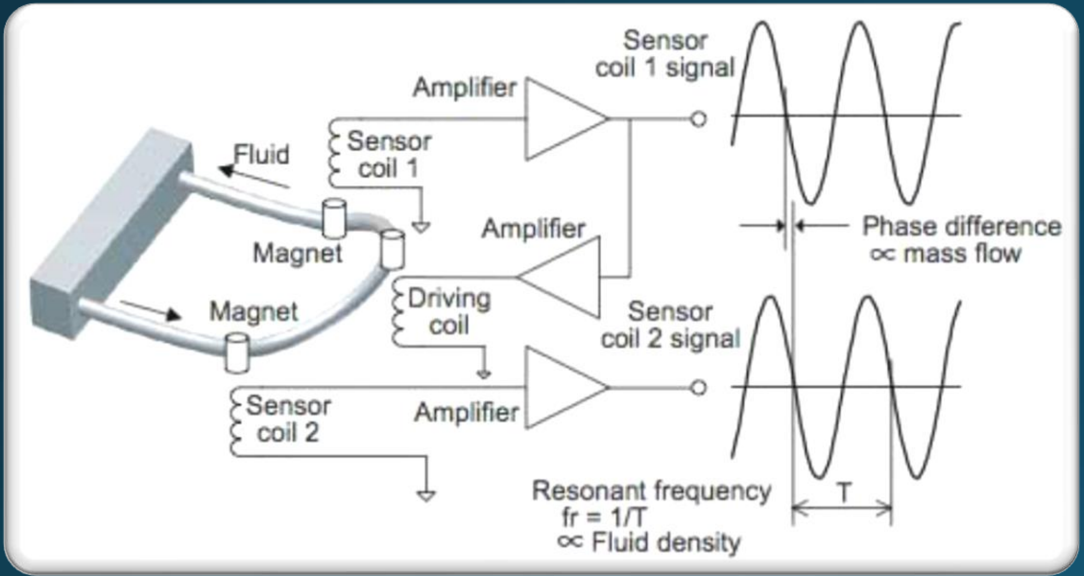
Flow Tubes: Typically, a pair of U-shaped tubes where the fluid flows through. The design of these tubes can vary (single, dual, or multi-tube configurations).

Oscillator: A mechanism that vibrates the flow tubes at a specific frequency, creating a Coriolis effect as the fluid passes through.

Sensors: These detect the vibrations and phase shifts caused by the flowing fluid, usually using strain gauges or accelerometers.

Transmitter: Converts the signals from the sensors into a readable flow rate, typically outputting mass flow and density measurements.

Coriolis Flow Meter



Working Principle:

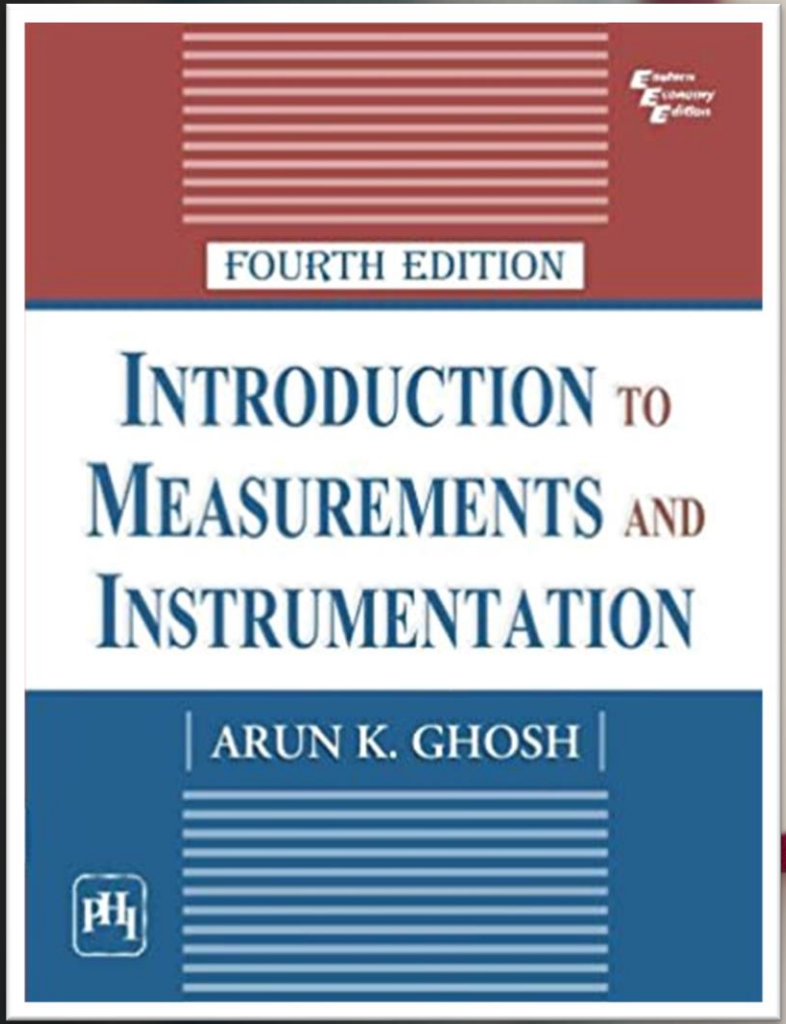
1.Vibration: The flow tubes are oscillated at a specific frequency. As the fluid flows through the vibrating tubes, it experiences a force due to the Coriolis effect.

2.Phase Shift: The movement of the fluid causes a phase shift in the vibration of the tubes. This phase shift is proportional to the mass flow rate of the fluid.

3.Measurement: The flow meter measures both the frequency and the phase shift to determine the mass flow rate. The density of the fluid can also be calculated, allowing for the determination of volumetric flow.

Coriolis Flow Meter

References


FOURTH EDITION
INTRODUCTION TO
MEASUREMENTS AND
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ARUN K. GHOSH
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