- The energy balance equation–flow measuring devices

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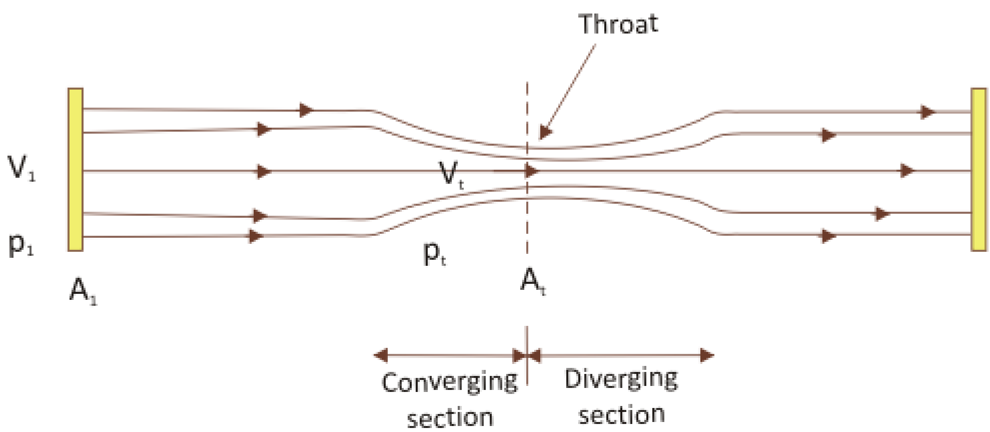
The energy balance equation–flow measuring devices

In this lecture, we discuss a few common devices, which are mostly based on the principle of general mechanical energy balance, to measure the volumetric flow rate of a fluid:

1. Venturimeter
2. Orificemeter
3. Pitot tube
4. Rotameter*

The first three devices are based on the mechanical energy balance. *The last instrument is based on a simple force balance.

(a) Venturimeter: it is a simple instrument having a converging–diverging section installed in a pipe. Pressure-drop is measured across two sections and is correlated to the flow rate, accounting for the viscous (minor) loss.



(Fig. 22a)

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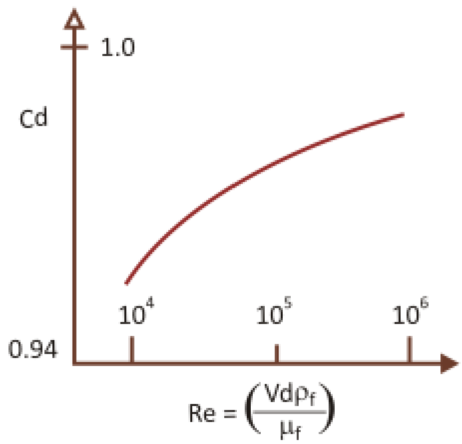
$Q = V_1 A_1 = V_t A_t$

$\frac{P_1}{\rho} + \frac{V_1^2}{2} = \frac{p_t}{\rho} + \frac{V_t^2}{2}$ (Neglecting minor-loss)

(Minor–loss can be minimized by slowly or gradually expanding the diverging section. That is why, the venturimeters are long, bulky, and expensive)

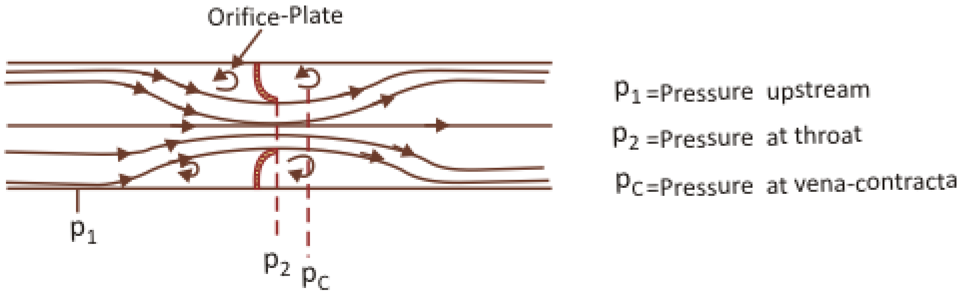
Q_{ideal} (without loss) $= A_1 V_1 = A_t \sqrt{\frac{2(p_1 - p_t)/\rho}{\left(1-\left(A_2/A_1\right)^2\right)}}$

For Venturimeters, Q_{real} or actual flowrate is calculated as, $Q_{real} = C_d \; Q_{ideal}$, where C_d is called the discharge coefficient and accounts for minor–loss or viscous–loss, because of non-uniform flow– patterns in the converging–diverging sections and at throat. The supplier of the instrument provides a plot to calculate C_d:



(Fig. 22b)

(b) Orifice meter: The instrument has an orifice–plate (circular plate with a small hole) inserted across the section of the pipe or tube:



(Fig. 22c)

In such a device, the flow from the upstream–section accelerates as the flow-area decreases from the section 1 to 2 at the orifice. The flow continues to accelerate, or the main flow area continues to decrease till the section 2 and further downstream of the orifice at C, before it starts increasing downstream. The section at C contains the minimum flow area, known as vena–contracta.

Similar to the analysis carried out for venturimeter, one can calculate the ideal or theoretical flow rate:

$$Q = A_c\sqrt{\frac{2(p_1 - p_c)}{\rho\left(1-\left({A_c}/{A_1}\right)^2\right)}}$$

To account for viscous-losses, a parameter $\beta = D_C/D_1$ is defined, so that

$$\left({A_c}/{A_1}\right)^2 = \left(\frac{D_c}{D_1}\right)^4 = \beta^4 \text{ and } Q_{real} = \frac{CA_2}{\sqrt{1-\beta^4}}\sqrt{\frac{2(p_1-p_c)}{\rho}}$$

C is known as the discharge coefficient and $1/\sqrt{1-\beta^4}$ is the velocity-of-approach factor.

A single factor, flow coefficient $K = \frac{C}{\sqrt{1-\beta^4}}$ is used to express

$$Q_{real} = K\,A_t\sqrt{\frac{2(p_1 - p_c)}{\rho}}$$

K is reported in a graph supplied by the manufactures.

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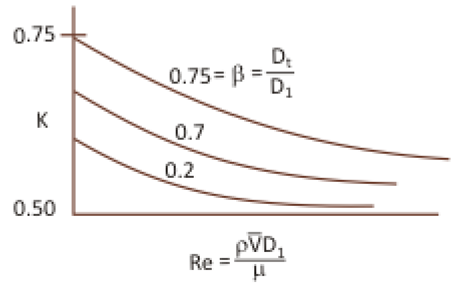
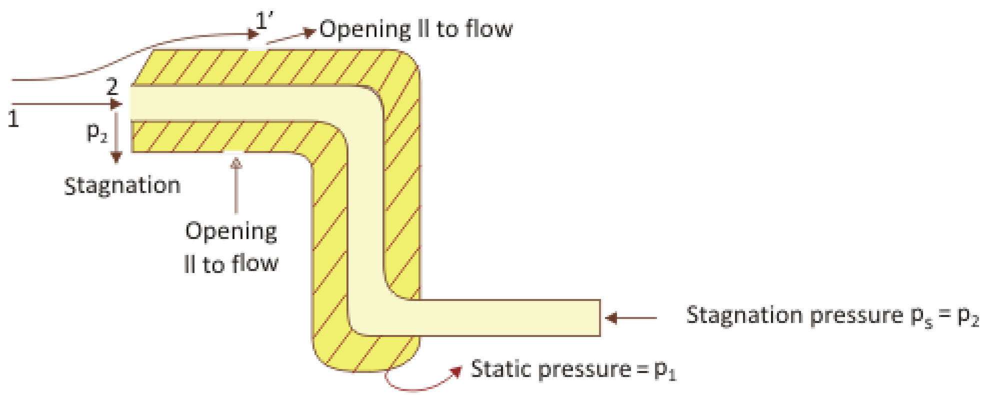


(Fig. 22d)

(C) Pitot tube: In such a device, part of the flow is made stagnant so that the entire KE of the fluid is converted into pressure–energy. A small opening is made in the device, parallel to the flow, where the pressure is the same as the fluid pressure.



(Fig. 22e)

Apply Bernoulli's equation between 1 and 1'

$$\frac{P_1}{\rho}+\frac{V_1^2}{2}=\frac{P'_1}{\rho}+\frac{V_1'^2}{2}$$

$V_1 = V'_1$ (along the same–streamline; flow is parallel to opening)

$P'_1 = P_1 =$ Static pressure

Apply Bernoulli's equation between 1and 2

$$\frac{P_1}{\rho}+\frac{V_1^2}{2}=\frac{p_2}{2}+\frac{V_2^2}{2}$$

But, $p_2 = p_s$

Therefore, $V_1 = \sqrt{\dfrac{2(p_5 - p'_1)}{\rho}}$

By measuring the difference between stagnation and static pressures, one can calculate the velocity and the volumetric flow rate.

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