EE 252: Measurement and Instrumentation

Lecture 1: Flow Measurement

Lecturer: Rishikesh Kulkarni *Scribes:*

Disclaimer: *These notes have not been subjected to the usual scrutiny reserved for formal publications. They should not be distributed outside this class.*

Flow measurement deals with the quantification of rate of flow of materials in solid, liquid or gaseous state. In case of solids, the quantification is expressed as mass flow rate whereas in case of liquids and gases, it is commonly expressed as volume flow rate. Mass flow rate is most accurate way of flow quantification because mass in invariable quantity while volume of material can change. Flow of liquids and gases can be of two forms: laminar or turbulent. In laminar flow, the flow velocity is low and constant. Material flow is parallel to the pipe. The flow velocity is not exactly constant. It decreases continuously as from the center of the pipe to the pipe wall. In most situations, the laminar flow is assumed in flow measurement. However, turbulent flow is observed when the flow is restricted or flow velocity is above certain threshold. In that case, that section of pipe is chose for flow measurement where the turbulence is minimum.

1.1 Mass flow rate

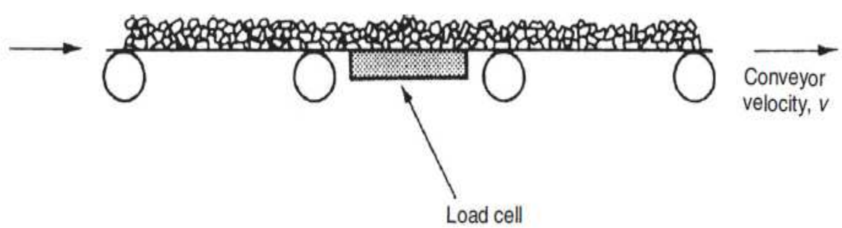


Figure 1.1

1.1.1 Conveyor based methods

This method is suitable flow measurement of bulk or powders or granular objects. It is mainly used for transportation and control of materials in processes at mine sites, paper mills, and power plants, loading and unloading of trucks, barges, and railcars to and from plants. The heart of belt conveyor based flow measurement is the load cell. Load cell is a transducer which consists of a structure which undergoes deformation under loading (tension or compression). The strain gauges attached to the structure coverts the deformation into electrical signal. Along with load cell, the system consists of speed measurement device as well. A load cell measures the mass, M, of material distributed over a length, L, of the conveyor. If the conveyor velocity is v, the mass flow rate, Q, is given by

$$Q = Mv/L \tag{1.1}$$

Advantages: Less expensive, Very wide range of weight measurement, Very wide conveyor belts. Limitations: High maintenance cost, Difficult to relocate, Frequent calibration checks are must, Susceptible to vibrations. Some of the limitations are removed by modular belt scale design by Siemens: `https://www.youtube.com/watch?v=jqXDbWvCfcY`

1.1.2 Radiation based method

Figure 1.2

A radiation-based sensor consists of a sealed radioactive source in a source holder and a scintillation detector. The source and detector are mounted on opposite sides of the conveyor (Fig. 1.2). A fan-shaped collimated beam of radiation is transmitted from the source through the process material and the conveyor to the detector. The amount of absorbed radiations is proportional to the mass. The method provides extremely stable measurement with very little required maintenance. The measurement precision is independent of process material effects such as dust, corrosion, and spillage. It can be easily relocated. However, due to radiations, it involves safety concerns.

1.1.3 Coriolis Flowmeter

Coriolis mass flowmeters measure the force resulting from the acceleration caused by mass moving toward (or away from) a centre of rotation. As related to flowmeters, the effect can be demonstrated by flowing water in a loop of flexible hose that is "swung" back and forth in front of the body with both hands. Because the water is flowing toward and away from the hands, opposite forces are generated and cause the hose to twist. In the meter design, either two parallel tubes are used or a single tube is used which is twisted in such a manner that there are two sections of the tube which are parallel to each other. When the fluid flows through pipes, the vibratory motion of each tube causes forces on the particles in the flowing fluid. These forces induce motion of the fluid particles in a direction that is orthogonal to the direction of flow, which produces a Coriolis force. This Coriolis force causes a deflection of the tubes that is superimposed on top of the vibratory motion. The net deflection of one tube relative to the other is given by $d = kfQ$, where k is a constant, f is the frequency of the tube vibration, and Q is the mass flow rate of the fluid inside the tube. This deflection is measured by a suitable sensor. Thus, in a Coriolis mass flowmeter, the "swinging" is generated by vibrating the tube(s) in which the fluid flows. The amount of twist is proportional to the mass flow rate of fluid passing through the tube(s). Sensors and a Coriolis mass flowmeter transmitter are used to measure the twist and generate a linear flow signal. Coriolis flowmeters are popular and represent about 21% of all flowmeters sold. Measurement uncertainty: $\pm 0.2\%$

1.1.4 Thermal mass flowmeter

These meters are used to measure gaseous material flow rate. They operate either by introducing a known amount of heat into the flowing stream and measuring an associated temperature change or by maintaining a probe at a constant temperature and measuring the energy required to do so. Thermal mass flow meters measure the mass flow-rate of gases and liquids directly where measurements are unaffected by changes in viscosity, density, temperature, or pressure. Depending on the manner in which the heat is introduced into the flow stream, there are two types: Immersion and externally-heated tube. (See Fig. 1.4). These meters provides wide rangeability with measurement uncertainty of $\pm 1 - 2\%$. They are used in controlling mass-related processes such as chemical reactions. An important advantage of these meterss is that they are useful in low flow rate measurement: micro to nano liters/min. The relationship between flow rate Q, heating power

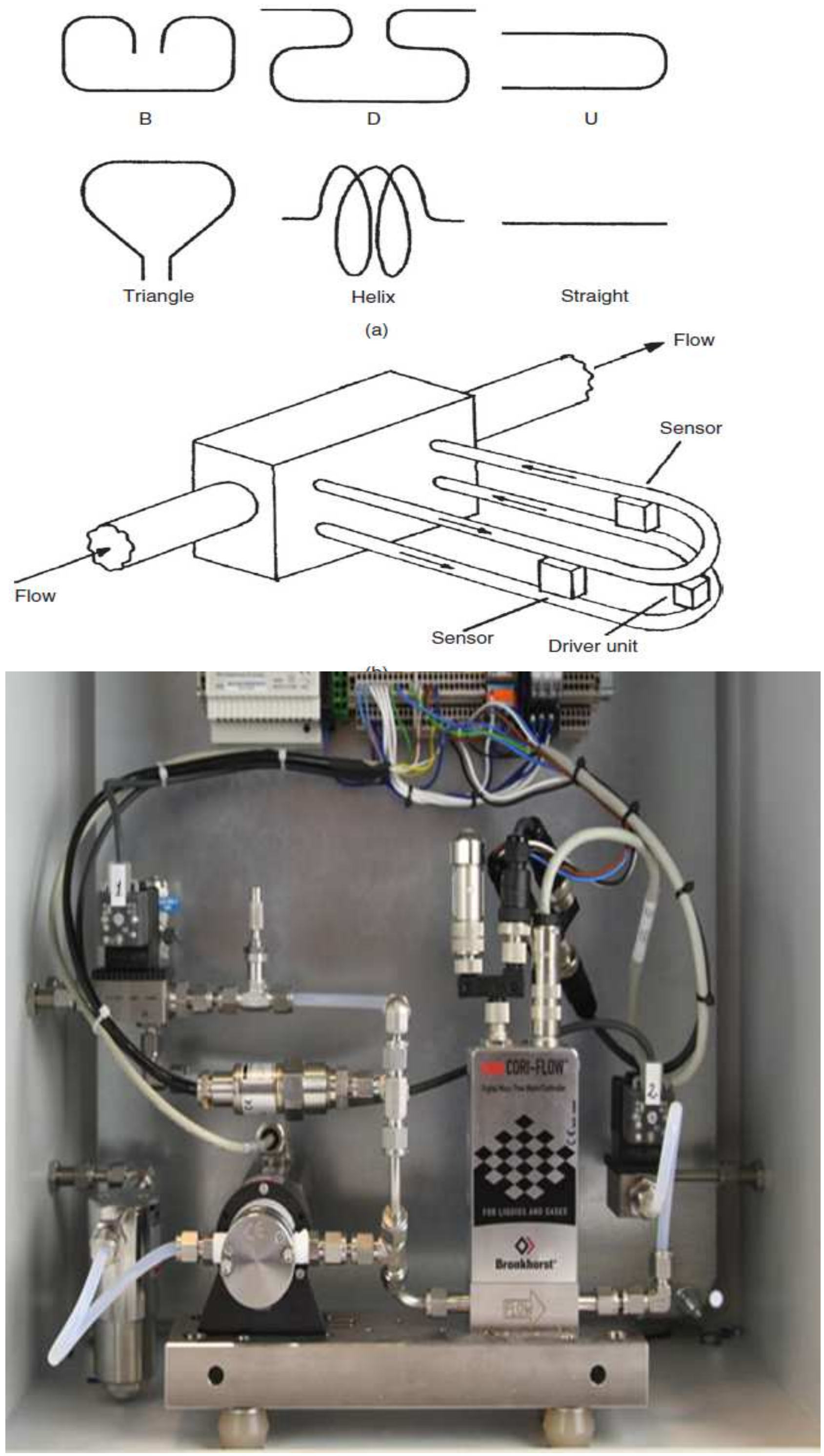

B
D
U
Triangle
Helix
Straight
(a)
Flow
Sensor
Flow
Sensor
Driver unit
CORI-FLOW

Figure 1.3

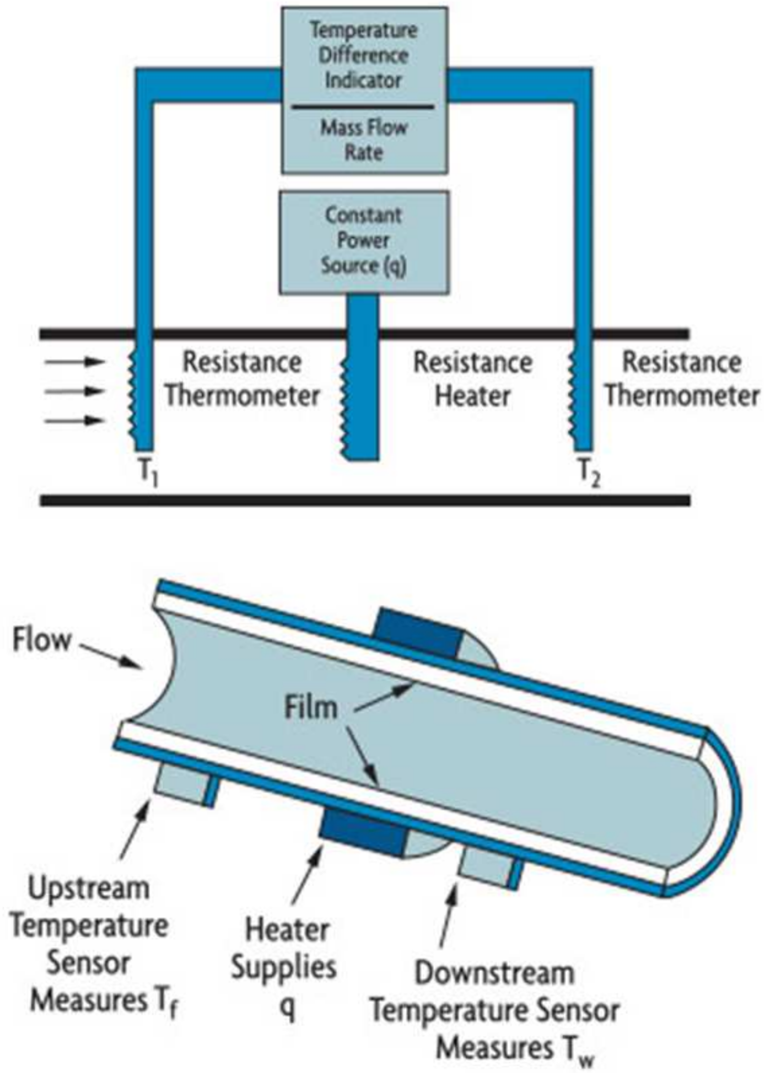
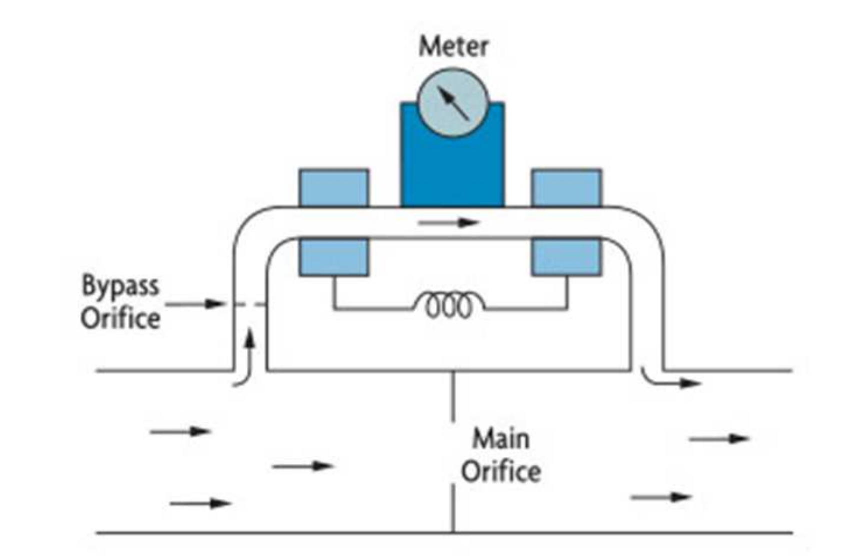


Figure 1.4

P, the temperature difference between upstream and downstream of the meter $T_2 - T_1$, specific heat C_p is given as

$$Q = \frac{Kq}{C_p(T_2 - T_1)} \tag{1.2}$$

where, K is proportionality constant. Another by-pass type configuration of thermal mass flowmeter is shown in Fig. 1.5. It consists of a thin-walled capillary tube connected in parallel with the pipe. A self-heating RTDs is placed inside the pipe. The change in resistance is caused by change in flow temperature. The change in temperature is result of heat-carried away by the flowing fluid. The temperature profile along the tube is also shown in the figure.



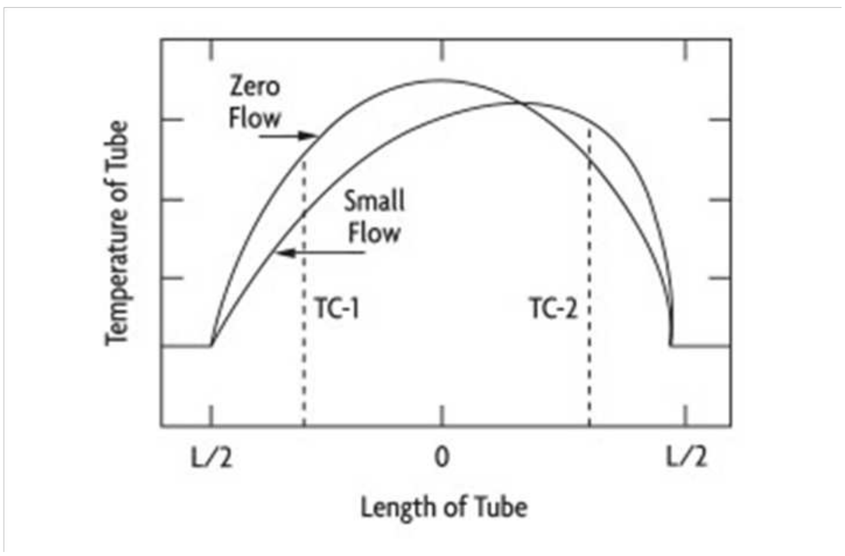


Figure 1.5

Advantages: Small size, minimum energy consumption, Low maintenance Low cost, Popular in semiconductor industry **Limitations**: Filters are essential to prevent plugging, High pressure applications, Low accuracy: 2%
Nice video demonstration: `https://www.youtube.com/watch?v=YfQSf2NBGqc`

1.2 Volume flow measurement

In case of liquid and gaseous materials, volume flow rate measurement is performed under the assumption of laminar flow. Different techniques for volume flow measurement are discussed below:

1.2.1 Differential pressure/ Obstruction type meters

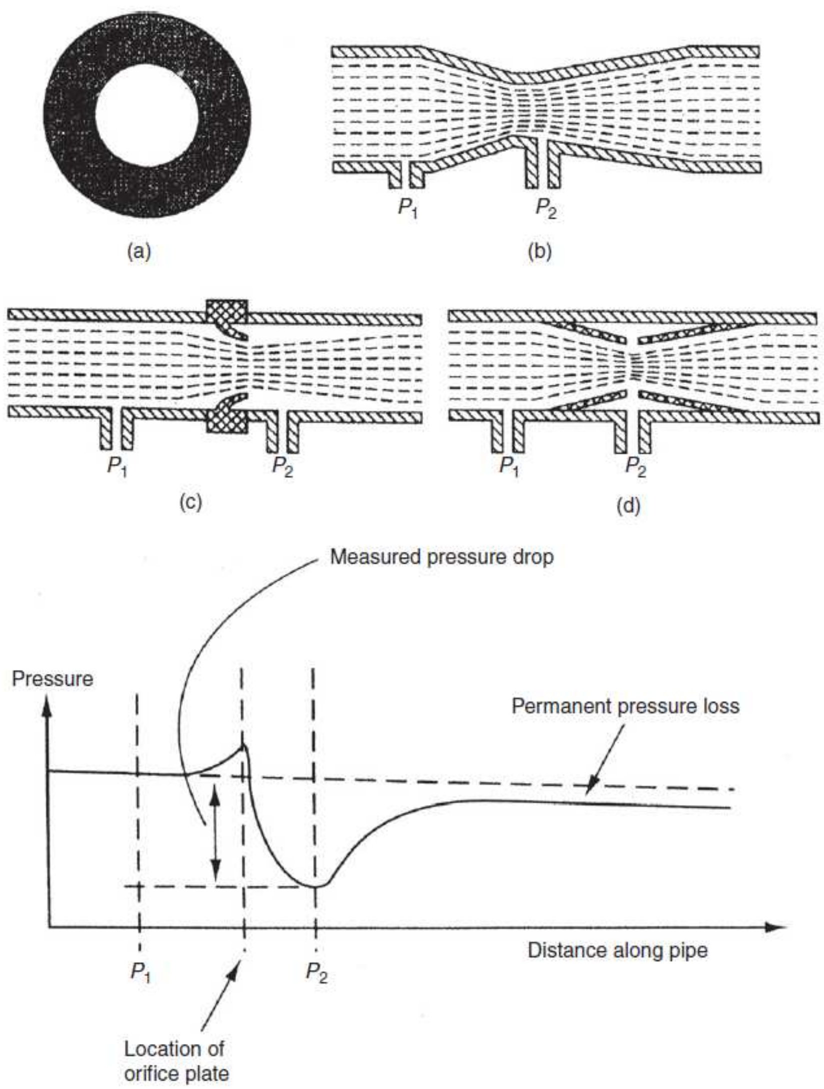


Figure 1.6

These type of meters involve an obstruction in flow created by a specific device inserted along the pipe. The pressure difference is created on both side of the device. Different types of obstruction devices used in practice are (a) *orifice plate*, (b) *venturi tube*, (c) *flow nozzle* and (d) *Dall flow tube* (See Fig. 1.6). The profile of pressure on both side of the obstruction is also shown in the figure. It can be seen that the pressure drops after the obstructing plate. The flow rate Q is proportional to the pressure difference as given below:

$$Q = \frac{A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{\frac{2(P_1-P_2)}{\rho}} \tag{1.3}$$

where A_1 and P_1 are the cross-sectional area and pressure of the fluid flow before the obstruction, A_2 and P_2 are the cross-sectional area and pressure of the fluid flow at the narrowest point of the flow beyond the obstruction, and ρ is the fluid density. Note that positioning of pressure sensors at upstream and downstream is done depending the pressure profile. It can also be seen from the pressure profile that A_1 and A_2 are not exactly equal to the area of pipe and area of obstruction, respectively. However, they are not measurable. Moreover, presence of fringe force also need to be taken into account. Accordingly, the flow rate expression is modified as

$$Q = C_d\frac{A_2'}{\sqrt{1-(A_2'/A_1')^2}}\sqrt{\frac{2(P_1-P_2)}{\rho}} \tag{1.4}$$

where, A_1' and A_2' are actual pipe and obstruction areas, respectively; C_d is the discharge coefficient that corrects for the friction force and the difference between the pipe and flow cross-section diameters.

Can you observe that this system is analogous to the current measurement in electrical system? A known small resistance (obstruction) is placed in series with the circuit. The voltage drop (pressure difference) across the resistor is measured which is proportional to the current.

The advantage of obstruction type meters is that they are no moving parts which make them robust and reliable. However, they have significant disadvantage that their is a permanent pressure loss at the downstream side of the device. It is evident from the pressure profile shown in Fig. 1.6. Sometimes, this pressure loss is bearable. However, in other cases, additional pumping system is required to boost the pressure level back to the desired level. The different structures of the obstruction device basically aim to minimize the pressure loss. For example, high pressure loss is observed in the case of Orifice. This is caused by abrupt reduction in the flow area. The pressure loss is reduced in venturi meter where the change in flow area is varied smoothly. However, note that the total size of venturi meter is more compared to orifice plate. In general, 50% flowmeters are of orifice plate because their simplicity, low cost and low maintenance.

Nice video demonstration on obstruction type flowmeters: `https://www.youtube.com/watch?v=oUd4WxjoHKY&pbjreload=10`

Pitot tubes are also commonly used flow meters in many applications which work on the principle of flow obstruction and Bernoulli's principle. As shown in Fig. 1.7, the pitot tube is inserted into the flow. There are two opening on the pitot tube, one is placed directly against the flow and other is in parallel with it. Accordingly, the pressure in one column of the tube is static pressure + dynamic

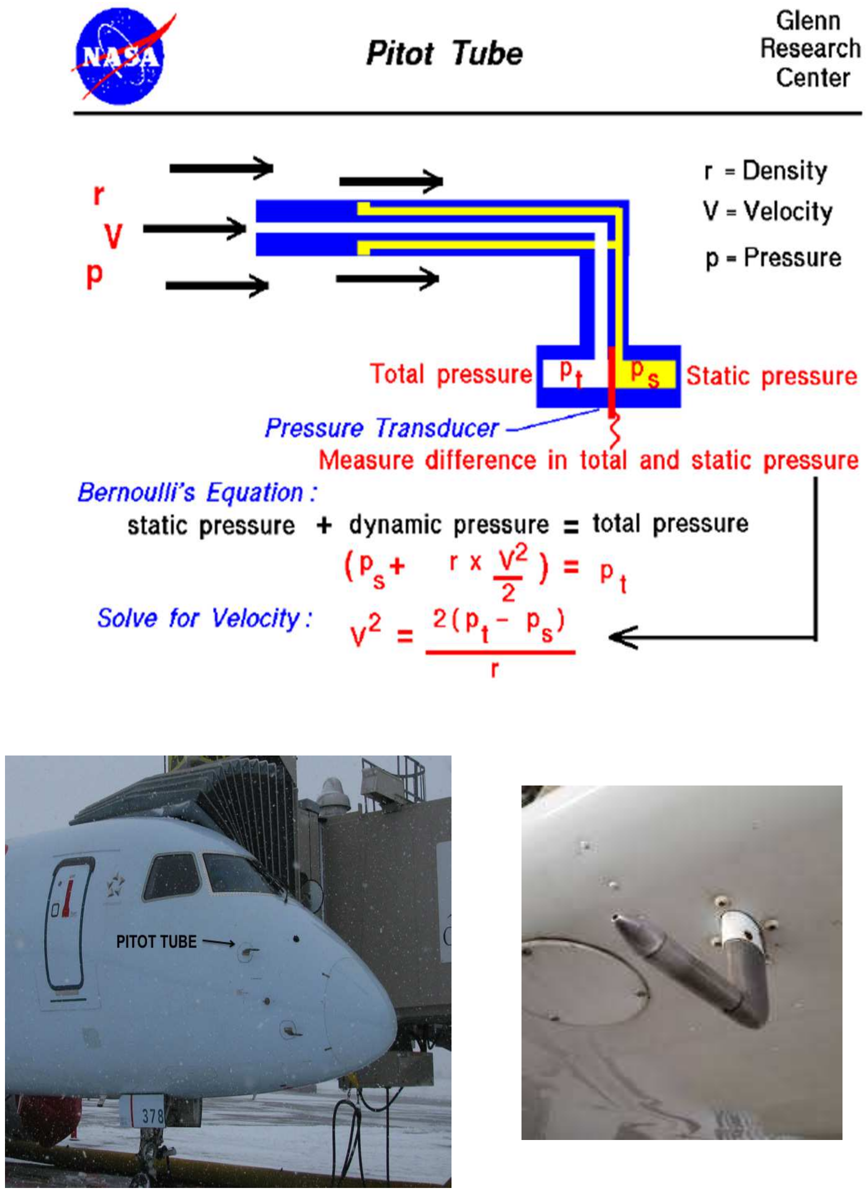


Figure 1.7

pressure whereas in the other column it is only static in nature. Thus, the difference between the two pressure measurements provide the dynamic pressure only which is proportional to the flow velocity. An example of use of pitot tubes on aircrafts is shown in the figure.

Nice video demonstration on pitot tubes: `https://www.youtube.com/watch?v=D6sbzkYq3_c`

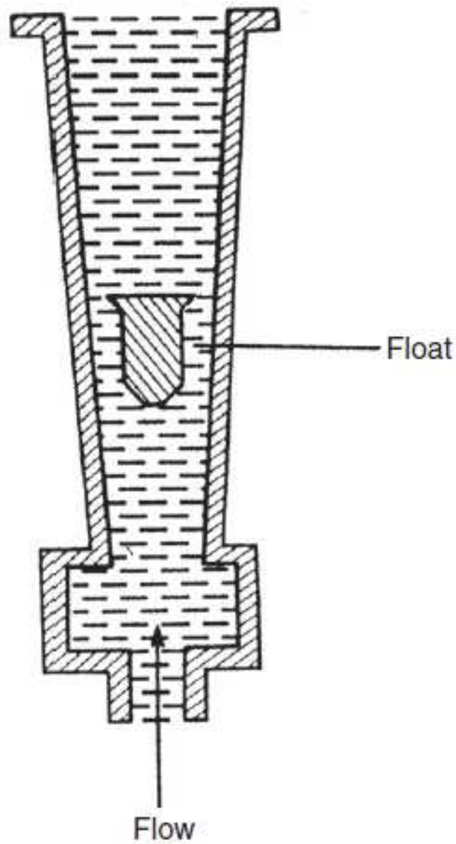


Figure 1.8

1.2.2 Variable area flowmeter

This is one of the simplest flowmeters available in market. Due to their simplicity and low cost, they have about 20% market in flowmeters. The variable area flowmeters, also referred as rotameters, consist of a tapered glass tube through which the fluid (liquid or gas) flows. A tapered float is placed inside the glass tube which is free to within the tube. As this float moves within the tube as fluid flows through it, it creates a variable aperture within the glass tube. Consequently, the differential pressure is generated across the float. For a given flow rate, the float comes to an equilibrium position where the force due to float weight is balanced by buoyancy force and flow force. In a given system, the weight force and buoyancy force are constant. Consequently, the float position is proportional to the flow force and in turn flow velocity. Thus, the rotameter glass tube is marked with scale indicating the flow rate. Note that these meter can be used for manual observation only and they can not be used in automation applications.

Video demonstration: `https://www.youtube.com/watch?v=Pz-Mvdc6nf4`

1.2.3 Turbine meters

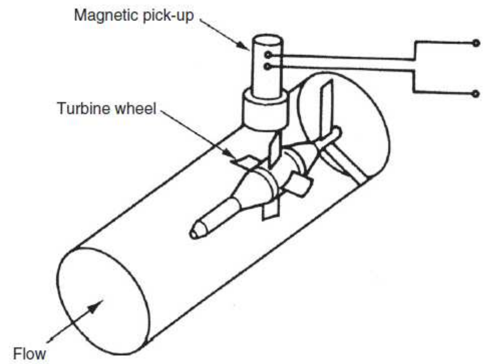


Figure 1.9

A turbine flowmeter consists of a multi-bladed wheel mounted in the pipe such that the axis of rotation is in parallel with the flow direction. In the presence of flow, the wheel rotates. The frequency of rotation is proportional to the flow rate. Considering this fact, the blades are made up of ferromagnetic material. A permanent magnet is part of meter which generates a magnetic field. A coils is also placed in the meter such that when the rotating blades create changes in magnetic flux, electric pules are generated in the coil. The frequency of pulses are directly proportional to the flow rate. The moving parts of these meters make them less rugged and reliable compared to obstruction type meters. In addition, the accuracy is severely affected in the presence of any particulate matter and multiphase fluid.

Video demonstration: `https://www.youtube.com/watch?v=0nrHinGZi5A`

1.2.4 Electromagnetic flow meter

If the fluid is electrically conducting then electromagnetic flow meters can be considered as an option for flow measurement. In these meters, a stainless pipe is equipped with electromagnetic coils outside the pipe surface (See Fig. 1.10) which create a magnetic field inside the pipe when powered with ac mains. The magnetic field direction is maintained such that it is perpendicular to the direction of flow. Consequently, as per the Faraday's law of electromagnetic induction, a voltage is generated in the direction perpendicular to both the magnetic field and the direction of flow. That is,

$$V = BLv \tag{1.5}$$

where, V: voltage; B: magnetic field; v: flow velocity; L distance between electrode, that is, pipe diameter. voltage is measured by electrodes placed inside the pipe at inner surface. The inner surface is made up of an insulating material and has to be corrosion resistant. Similarly, the electrodes are also exposed to fluids so the electrode material should also be corrosion resistance apart from being conductive. This requirement increases the purchase and maintenance cost of

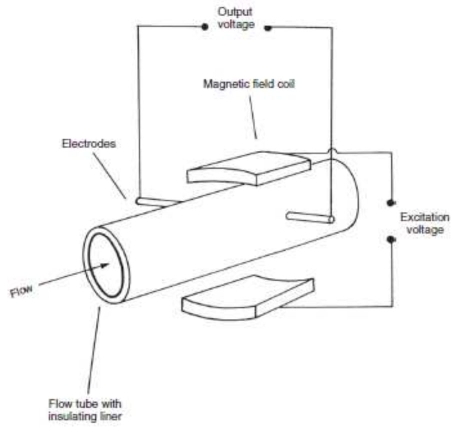


Figure 1.10

the meter significantly. Since there is no obstruction to flow introduced during the measurement operation, there is no pressure loss. The market share of these meters is increasing as battery operated compact meters have been designed.

Video demonstration: `https://www.youtube.com/watch?v=f949gpKdCI4`

1.2.5 Ultrasonic flowmeter

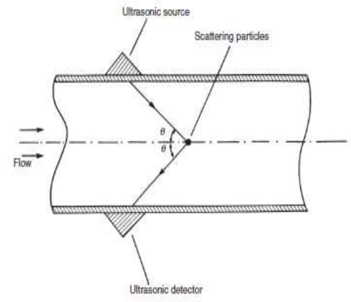
Ultrasonic technology has found numerous applications with audio frequency used as probing medium (Ultransonic machine used in sonography, same principle). Ultrasonic flowmeters have been penetrating flowmeter market for some time now. The unique advantage it provide over many other flowmeters is that it is entirely non-destructive and non-contact as well. Since it can be installed into the process without disturbing the pipeline, a huge cost benefit is achieved. Two distinct versions of flowmeter exists:

1.2.5.1 Doppler shift ultrasonic flowmeter

Figure 1.11 describes the principle of doppler flowmeter. An ultrasonic transmitter sends burst of sinusoidal signal into the flow with frequencies between 0.5 to 20 MHz. The particles in the flow scatters the ultrasonic waves which are received by the receiver. The transmitter and receiver are basically made up of piezoelectric materials. The change in frequency of received ultrasonic signal is proportional to the flow velocity as

$$v = \frac{c(f_t - f_r)}{2 f_t \cos\theta} \tag{1.6}$$

where, f_t and f_r: transmitted and received ultrasonic frequency; θ: angle of transmission and reception with respect to direction of flow. It is obvious that presence of scattering particle is



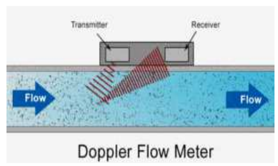


Figure 1.11

essential for the operation of flowmeter. The important limitation of this technique is that the measurement accuracy depends on number of process parameters such as pipe thickness, physical properties of the fluid, such as the sonic conductivity, particle density, and flow profile. Therefore, the calibration is a cumbersome process. Deviation from the calibration parameters significantly affect the measurement accuracy. In many practical designs, the receiver and transmitter are on the same side of the pipe enclosed in the same casing.

1.2.5.2 Transit time ultrasonic flowmeter

In the absence of scattering particles in the flow, transit time principle based ultrasonic flowmeter can be used. Figure 1.12 shows the placement of transducers. Note that each transducer acts as both transmitter and receiver. An ultrasound pulse is sent from the transmitter to receiver in upstream direction. The time of transmission is measured as

$$T_f = \frac{L}{c + v\cos\theta}, \tag{1.7}$$

where, L: distance between transmitter and receiver; c: speed of ultrasound; v: flow velocity. Another ultrasound pulse is sent where the operation of transmitter and receiver are reversed. In that case, the pulse travels in the downstream direction. The time of travel is given as

$$T_r = \frac{L}{c - v\cos\theta} \tag{1.8}$$

Using these two transit times, we get the time difference as

$$\delta T = T_r - T_f = \frac{2vL\cos\theta}{c^2 - v^2\cos^2\theta} \tag{1.9}$$

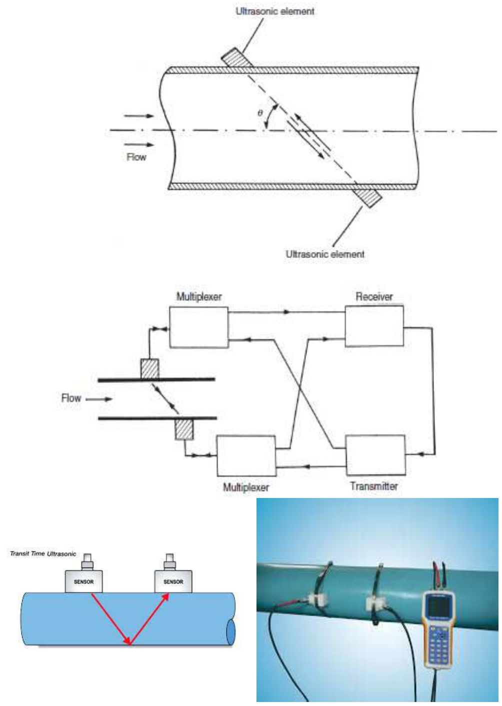


Figure 1.12

With the knowledge of c, we can obtain the measurement of v. This is a limitation since the speed of ultrasound will change based on the fluid properties. This limitation is overcome by another design of calculation of flow velocity given in second diagram in Fig.1.12. In this scheme, once a receiver receives the transmitted pulse, it is immediately triggered to operate as transmitter. The transmitted pulse is received by another transducer which in this condition act as receiver. Thus, appropriate triggering of each transducer generates pulses of frequencies given as

$$F_f = \frac{1}{T_f} = \frac{c + v\cos\theta}{L}; F_r = \frac{1}{T_r} = \frac{c - v\cos\theta}{L} \tag{1.10}$$

Two signals of frequencies F_f and F_r are multiplied together to generate a signal with beat frequency of δF

$$\delta F = F_r - F_f = \frac{2v\cos\theta}{L} \tag{1.11}$$

Thus, the flow velocity is calculated as

$$v = \frac{L\delta F}{2\cos\theta} \tag{1.12}$$

Note here that the velocity is no longer a function of c. The transit-time based flowmeter are more common compared to the doppler type. Especially in case of large diameter pipes, transit-time flowmeter is the only feasible option.

It is important to note that the list of flowmeters discussed here are not the only options. However, they are the most commonly used ones. Read about other types of flowmeters from online resources.

Video demonstration: `https://www.youtube.com/watch?v=Bx2RnrfLkQg`

References

1. E. O. Doebelin, Measurement systems: Application and Design, 2005.
2. Alan Morris, Measurement instrumentation theory and application
3. `https://www.youtube.com/watch?v=gByrUkZUnKo`
4. `https://www.youtube.com/watch?v=_3JVLyMv5II`