

Flow of Fluids

Meenakshi Chauhan and Yasmin Sultana

FLUID MECHANICS

Fluid mechanics is the study of fluids and the forces on them. Fluids include liquids, gases, and plasmas. Fluid mechanics is classified into: fluid kinematics, the study of fluid motion, and fluid dynamics, the study of the effect of forces on fluid motion, which can further be divided into fluid statics, the study of fluids at rest, and fluid kinetics, the study of fluids in motion (Fig. 1.1). It is a branch of continuum mechanics which is a subject that models matter without using the information that it is been made out of atoms. Its models does not matter from a microscopic view point but rather than matter from a macroscopic viewpoint.

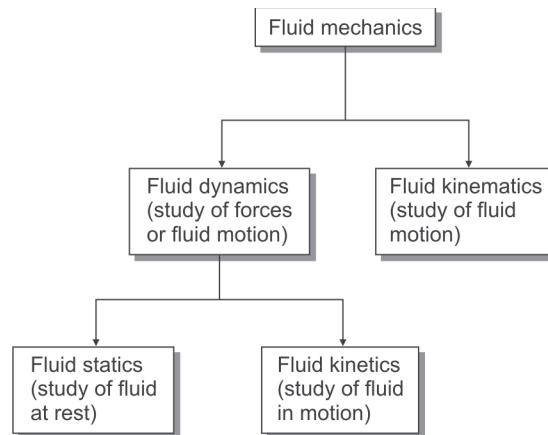


Fig. 1.1: Fluid mechanics (scheme)

A fluid is a substance which can flow. A continuous relative motion between different particles of a substance is the description of flow in technical terms. Under influence of shear forces the relative motion between particles make the fluid to flow. The particles starts moving when they cannot resist the shear force. Under shear stress a fluid without returning to its original position can deform indefinitely.

A fluid is defined as a material continuum which is unable to withstand a static shear stress. A fluid responds with an irrecoverable flow unlike an elastic solid which

responds to a shear stress with a recoverable deformation. Variables needed to define a fluid and its environment are shown in Table 1.1

Table 1.1: Variables needed to define a fluid and its environment

<i>Quantity</i>	<i>Symbol</i>	<i>Object</i>	<i>Units</i>
Pressure	<i>P</i>	Scalar	N/m ²
Velocity	<i>V</i>	Vector	m/s
Density	<i>R</i>	Scalar	kg/m ³
Viscosity	<i>M</i>	Scalar	kg/m-s
Body force	<i>B</i>	Vector	N/kg
Time	<i>T</i>	Scalar	S

Euler Equations

In fluid dynamics, the Euler equations govern the motion of a compressible, inviscid fluid. They correspond to the Navier-Stokes equations with zero viscosity. They directly represent conservation of mass, momentum, and energy.

Laplace's Equation

The Laplace equations describes the behaviour of gravitational, electric, and fluid potentials.

The Bernoulli Equation

A statement of the conservation of energy in a form useful for solving problems involving fluids. For a non-viscous, incompressible fluid in steady flow, the sum of pressure, potential and kinetic energies per unit volume is constant at any point.

Conservation Laws

- The conservation laws states that particular measurable properties of an isolated physical system do not change as the system evolves.
- Conservation of energy (including mass)
- Fluid mechanics and conservation of mass—The law of conservation of mass states that mass can neither be created nor destroyed.
- The continuity equation—It is a statement that mass is conserved.

Ideal Gas Law

- The ideal gas law—For a perfect or ideal gas the change in density is directly related to the change in temperature and pressure as expressed in the ideal gas law.
- Properties of gas mixtures—Special care must be taken for gas mixtures when using the ideal gas law, calculating the mass, the individual gas constant or the density.
- The individual and universal gas constant—It is common in fluid mechanics and thermodynamics.

Navier-Stokes Equations

The motion of a non-turbulent, Newtonian fluid is governed by the Navier-Stokes equations. The equation can be used to model turbulent flow, where the fluid parameters are interpreted as time-averaged values.

PROPERTIES OF FLUIDS

The term fluid includes both liquid and gases. Whereas, liquids are considered to be incompressible, while gases are considered to be compressible.

A liquid can take the shape of a surface in contact and a gas completely occupies the available space. As the liquid is the fluid for consideration in hydraulics so we examine properties of the liquid.

Mass density: It is the mass of the fluid per unit volume. Its unit is kg per cubic meter.

Specific weight: It is the weight per unit volume of fluid. Its units are Newton per cubic meter.

Compressibility: The property of the fluid by virtue of which its volume decrease on application of pressure is called compressibility.

Elasticity: The property by virtue of it the fluid returns to its original volume, when the force which is generating pressure is released.

Vapour pressure: Vapour pressure of the liquid is the pressure which is attained when molecule of liquid escape from surface to fill the space above the liquid surface and container till their pressure is equal to pressures due to these molecules.

Surface tension: Surface tension is caused due to cohesive force between molecules of the liquid, it is the weak force at the interface between liquid and air.

Capillarity: There are two type of forces acting on molecules of liquid. Cohesive forces are forces acting on molecules of liquid and adhesive forces are forces acting between liquid and container walls. When adhesive forces are greater than cohesive forces, liquid sticks to the wall of the container and results in capillary rise. When cohesion is more than adhesion, the capillary level dips.

Types of Fluids—Newtonian and Non-Newtonian Fluids

Those fluids which shows linear relationship between shearing stress and rate of shearing strain. Shear actions, such as agitation or pumping at a constant temperature do not change viscosity τ consistency of Newtonian liquids, hence they are called true liquids. Some example of Newtonian fluids are water and oils.

A Newtonian fluid the term coined by Isaac Newton which is defined to be a fluid whose shear stress is linearly proportional to the velocity gradient in the direction perpendicular to the plane of shear. This definition means no matter of the forces acting on a fluid as it *continues to flow*. For example, water is a Newtonian fluid as it continues to display its fluid properties regardless of how much it is stirred or mixed. Under normal conditions important fluids and most gases behaves as a Newtonian fluid.

Non Newtonian fluids are exemplified by materials, such as pudding, which while stirring leaves a hole which gradually fills up overtime.

Equations for a Newtonian Fluid

The proportionality constant between the shear stress and the velocity gradient is known as the viscosity. A simplest equation to describe Newtonian fluid behaviour is:

$$\tau = \mu v$$

where,

τ = shear stress exerted by the fluid ("drag")

μ = fluid viscosity (a constant of proportionality)

v = velocity gradient perpendicular to the direction of shear.

The viscosity of a Newtonian fluid does not depend on forces acting upon it, and depends on temperature and pressure.

Fluids are of two types: Ideal and non-ideal fluids. An ideal fluid does not exist in reality but in some calculations this assumption is justified. An ideal fluid is not viscous and offers no resistance to shearing force. Real fluids are of two types, Newtonian and non-Newtonian. Newtonian fluids agree with Newton's Law of viscosity while non-Newtonian liquids can be plastic, pseudoplastic, dilatant, thixotropic and rheopectic and viscoelastic.

Shear-thinning/pseudoplastic liquids: Shear-thinning or pseudoplastic liquids are those whose apparent viscosity decreases with increasing shear rate. Their structure is time-independent.

Thixotropic fluids: Thixotropic liquids have a time-dependent structure. The apparent viscosity of a thixotropic liquid decreases with increasing time, at a constant shear rate.

Example: Ketchup and mayonnaise are thixotropic materials that appear thick or viscous but are quite easily possible to pump.

Dilatant fluids: These are also known as shear thickening fluids which increase their viscosity with agitation. Some of these liquids can even become almost solid within a pump or pipe line. Cream becomes butter with agitation and even candy compounds, clay slurries and similar heavily filled liquids do exhibit same behaviour.

Bingham plastic fluids: They have a yield value which must be exceeded before it will start to flow like a fluid. And from that point the viscosity will decrease with increase in agitation, e.g. toothpaste, mayonnaise and tomato ketchup.

Basic Equations of Fluid Flow

Viscosity: It is a measure of resistance to the flow of fluids and it defines the interaction between moving particles of the fluid. Due to difference in viscosity, the flow or rate of deformation of fluids under shear stress is different for different fluids.

The viscosity of a fluid is an essential property in the analysis of liquid behaviour and in fluid motion near solid boundaries. The fluid resistance is viscosity that is to shear or flow and is used to measure the adhesive/cohesive or frictional fluid property. The intermolecular friction causes resistance which is exerted when layers of fluids attempt to slide by one another. For proper design of required temperatures for storage, pumping or injection of fluids, the knowledge of viscosity is needed.

The fluid viscosity can be measured by dynamic (or absolute) and kinematic viscosity. Absolute or dynamic viscosity is the tangential force per unit area which is

required to move one horizontal plane with respect to the other at unit velocity while maintaining a unit distance apart by the fluid (Fig. 1.2). The dynamic or absolute viscosity can be expressed as:

$$\tau = \mu \, dc/dy$$

Equation is known as the **Newtons Law of Friction**.

where,

τ = shearing stress

μ = dynamic viscosity

In the SI system the dynamic viscosity units are N s/m^2 , Pa s or kg/m s , where $1 \text{ Pa s} = 1 \text{ N s/m}^2 = 1 \text{ kg/m s}$

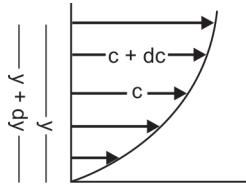


Fig. 1.2: Dynamic viscosity

The dynamic viscosity is often expressed in the metric CGS (centimeter-gram-second) system as g/cm.s , dyne.s/cm^2 or poise (p) , where $1 \text{ poise} = \text{dyne s/cm}^2 = \text{g/cm s} = 1/10 \text{ Pa s}$

To use practically, the *Poise* is too large and its usually divided by 100 into the smaller unit called the *centi Poise (cP)*, where $1 \text{ p} = 100 \text{ cP}$.

For example: Water at 68.4°F (20.2°C) has an absolute viscosity of one *-1-centi-poise*.

Kinematic Viscosity: It is defined as a ratio of absolute or dynamic viscosity to density, i.e. a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid by its mass density.

$$\nu = \mu/\rho$$

where,

ν = kinematic viscosity

μ = absolute or dynamic viscosity

ρ = density

In the SI-system the theoretical unit is m^2/s or commonly used *Stoke (St)* Where, $1 \text{ St} = 10^{-4} \text{ m}^2/\text{s}$.

Since, the *Stoke* is an impractical large unit, it is usual divided by 100 to give the unit called *Centistokes (cSt)*.

where,

$$1 \text{ St} = 100 \text{ cSt}$$

$$1 \text{ cSt} = 10^{-6} \text{ m}^2/\text{s}$$

Since, the specific gravity of water at 68.4°F (20.2°C) is almost *one (1)*.

For practical purposes, kinematic viscosity of water at 68.4 F is 1.0 Cst. Viscosity and temperature: For dynamic or kinematic viscosity, the reference temperature must be quoted as viscosity is highly temperature dependant. The kinematic viscosity decrease at higher temperature while in gas the kinematic viscosity increase at higher

temperature. Other units of viscosity are Saybolt Universal Seconds (SUS) kinematic viscosity versus dynamic or absolute viscosity can be expressed as:

$$\nu = 4.63 \mu / SG$$

where,

ν = kinematic viscosity (SSU)

μ = dynamic or absolute viscosity (cP)

SG = Specific Gravity

Degree engler: It is used as a scale to measure kinematic viscosity, in Great Britain. Unlike the Saybolt and Redwood scales, this scale is based on comparing a flow of the substance being tested to the flow of another substance, i.e. water. Viscosity in Engler degrees is the ratio of the time of a flow of 200 cm³ of the fluid whose viscosity is being measured, to the time of flow of 200 cm³ of water at the same temperature (mostly 20°C but sometimes 50°C or 100°C) in a standardized Engler viscosity meter (Table 1.2).

Centi stokes (cSt)	Typical liquid
1	Water (20°C)
4.3	Milk
15	Oil
20	Cream
43	Vegetable oil
220	Tomato juice
1100	Glycerine (20°C)
2200	Honey
6250	Mayonnaise
19,000	Sour cream

Viscosity and Temperature

It should be noted that for liquids viscosity decreases with temperature and for gases viscosity increases with temperature.

FLUID STATICS—MEASUREMENT OF PRESSURE

Pressure in Fluid and its Variation

Relationship between depth and pressure: When we dives under water surface, it is noticed that the pressure on ear drums is considerably higher than atmospheric pressure. For a given depth liquid exerts same pressure in all directions. The pressure of a liquid is directly proportional to the depth. As shown in Fig. 1.3, the fluid leave the tank at varying velocities. This is due to variation in pressure of fluid at different levels. Pressure is defined as the force per unit area. The force is due to the weight of the water above the point.

The pressure at any point of fluid increase with the depth. Down the column of a fluid, the increase in pressure is due to weight of fluid column above that level. To understand relation between pressure and depth of liquid column, consider a vertical column of liquid with constant cross-sectional area. It is assumed that the liquid is at rest (so no shear forces) and it is in equilibrium (all forces are balanced in the column).

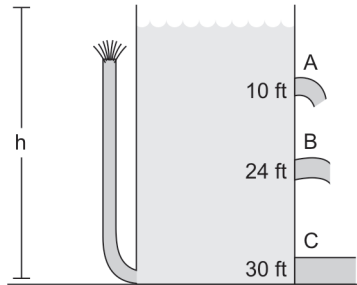


Fig. 1.3: Pressure versus depth

At any particular depth of the column, the weight of the column is balanced by force due to pressure at that point. Thus, the pressure at that point is equal to weight of column at that point divided by area of cross-section of liquid column.

Weight of column = Volume \times Density \times Acceleration due to gravity

Volume of liquid column = Height of column \times Area of cross-section

Thus, pressure at any depth = Density of liquid \times Acceleration due to gravity \times Height of the liquid column above that point

In hydraulics, as per above equation as density and acceleration due to gravity are constant, the pressure varies with depth in liquid bodies.

The atmospheric pressure is the pressure acting on fluids over the surface of earth. The pressure measurement is done to find the weight of air column above the level. Thus, the absolute pressure in any fluid is equal to atmospheric pressure plus the pressure due to weight of fluid column above level of measurement. The pressure measured by pressure gauges is the quantity in excess to the atmospheric pressure. The calibration of the pressure gauges are done, so that they indicate zero at atmospheric pressure.

Pressure reading above atmospheric pressure is positive and pressure reading below atmospheric pressure is negative. The pressure reading and difference of these devices from atmospheric pressure is known as gauge pressure. The absolute pressure is equal to the sum of the gauge pressure and the atmospheric pressure.

Pressure Measurement Devices

Different types of pressure measurement devices are available which ranges from simple gauges with low accuracy to complex gauges with high accuracy. Apart from this, other types of gauges are, gauges using fluids, gauges without fluids, electrical gauges, optical gauges and mechanical gauges.

A few commonly used pressure gauges are discussed below:

Manometer: It is a device used for measure the pressure of a fluid by balancing it with against a column of a liquid.

Classification of Manometer

- I. **Simple manometers** are those which measure pressure at a point in a fluid contained in the pipe or a vessel. They are of many types:
 - a. Piezometer
 - b. U-tube manometer (simple manometer)
 - c. Single column manometer.

II. Differential manometers measure the difference of pressure between any two points in a fluid contained in a pipe or vessel. They are of following types:

- a. U-tube differential manometer
- b. Inclined or sloping U-tube differential manometer
- c. Micromanometer
- d. Inverted U-tube manometer.

I. Simple Manometers

a. Piezometer: It is a tube connected vertically to the liquid system which pressure is to be measured. The liquid rises in the tube up to the point, where the weight of the liquid column in the tube is balanced by the gauge pressure of the system. Pressure shown by the piezometer is the gauge pressure as the tube is open to the atmosphere on the other side as shown in Fig. 1.4.

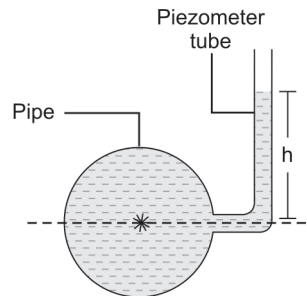


Fig. 1.4: Piezometer

Disadvantages

- It can measure gauge pressures only.
- It is not suitable for measuring negative pressures.
- They cannot be employed when large pressures in the lighter liquids are to be measured as this would require very long tubes that cannot be handled conveniently.
- Gas pressures cannot be measured by it.

Note: These limitations can be overcome by the use of U-tube manometers.

b. U-tube manometer: It operates on the **principle of hydrostatic balance**. It is a U-shaped tube filled with an immiscible liquid, opens at both ends. In it, one end is attached to the fluid system and its pressure is to be measured whereas the other end is open to the atmosphere. At first, when the liquid enters the manometer the level of liquid is same in both the arms of manometer. As one arm of the manometer is under examination, the liquid falls in one arm and the level increases in the other arm. The gauge pressure of the system can be determined by the variation in the levels of the liquid as one of the ends is open to the atmosphere as it is shown in Fig. 1.5. For measuring high pressures a liquid used is heavy manometer, and for measuring low pressures liquid used is a light manometer.

Depending upon the pressure of the source it measures, the liquid in the column of manometer will either increase or decrease when a manometer is attached to a process. Therefore, it becomes essential to have information about the type of the liquid and its height in the column in order to determine the pressure of the liquid. This is because the amount to which the level of the liquid will increase or decrease due to pressure depends on type of the liquid and also the specific gravity is important to measure the pressure correctly.

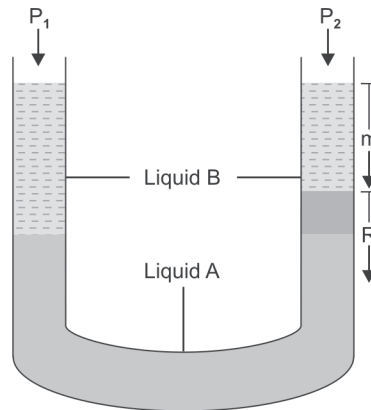


Fig. 1.5: U-tube manometer

The correctness of the manometer is influenced by the shape of liquid at the interface between the liquid and air in the column. This level of the liquid is known as meniscus and it varies with the shape of the liquid. Hence, the shape of the liquid can predict the type of the liquid that is being used.

In order to avoid the errors the shape of the liquid is determined at the centre of the column. The liquid should have the following characteristics:

- Low viscosity
- Low surface tension
- Non adherent to the walls of the container
- It should not evaporate
- The two liquids used should be immiscible.

The filled liquid must be clean and have a known specific gravity.

Advantages

- It is very simple in construction
- Cost-effective
- Accurate and sensitive
- Other process variables can be measured.

Disadvantages

- It is fragile in construction
- Shows too much sensitivity to temperature changes.

Applications

- Low pressure ranges can be calculated.
- It has extensive use in the laboratories.
- Venturi meter and orifice meter use it for flow determination.
- Calibration of gauges and various other instruments can be done.
- The fall of pressure in different valves and joints can be measured.

c. Single column manometer: It is a remodelled form of a U-tube manometer as shown in Fig. 1.6 which has a shallow reservoir attached to one end of the manometer. The shallow reservoir that is connected has a large cross-sectional area about 100 times in contrast to the area of the tube.

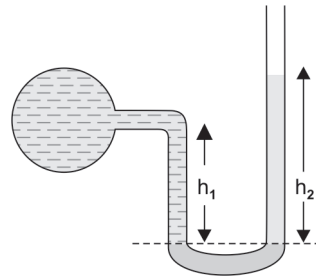


Fig. 1.6: Single column manometer

II. Differential Manometer

a. **U-tube differential manometer:** It is also called two-fluid U-tube manometer. It is also a U-tube manometer as shown in Fig. 1.7 having the two ends, connected to the two systems between which pressure difference is to be measured. It depends on the range of pressure differences, i.e. to be measured, a suitable liquid or combination of liquids can be filled in the two arms of the U-tube. If large pressure differences are to be measured a heavy manometer liquid is filled in the U-tube. And to measure very small pressure difference U-tube with long arms is used and two light liquids are filled in the two arms of the U-tube. It usually contains two immiscible liquids A and B having almost same densities.

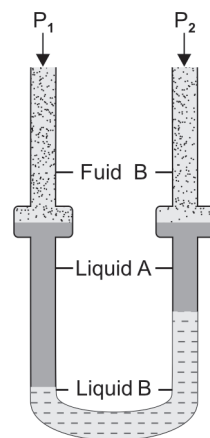


Fig. 1.7: Differential U-tube manometer

b. **Inclined or sloping U-tube manometer:** It is used for measuring the minute differences of two pressures (where accuracy is the major consideration). It is basically similar as differential U-tube manometer, but the tube is inclined at certain angle this time as shown in Fig. 1.8. The construction involves enlarged vertical leg so that due to movement of meniscus this enlargement becomes negligible. Although leg having meniscus is inclined in such a manner that for a small value 'r' it moves a considerable distance along the tube. It results in more deflection in the liquid level (in the tube) for the same change in pressure. Thus enables the measurement of small pressure changes with high accuracy.

c. **Micromanometer:** It is a different form of liquid column manometers. It is based on the inclined tube manometer and is useful in calculating the very small pressure

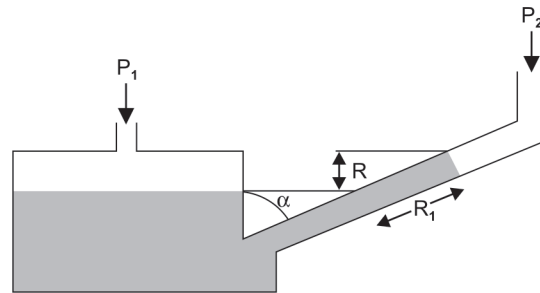


Fig. 1.8: Inclined manometer

variations. The meniscus of the inclined tube is at reference level as shown in Fig. 1.9, observed with a magnifier having a cross hair line. This is performed for the condition when $p_1 = p_2$ and the adjustment can be made by moving well high and low across a micrometer. Similarly, when p_1 is not equal to p_2 the well can be moved high and low to keep the meniscus at zero and the pressure can be measured by the difference between the two readings. Considering manometric fluid as a free body, the following forces are acting on it namely:

- Weight dispersion over the whole fluid.
- The drag force because of the movement of fluid and the resulting tube wall shearing stress.
- Force created because of differential pressure.
- Surface tension at both ends of manometer.

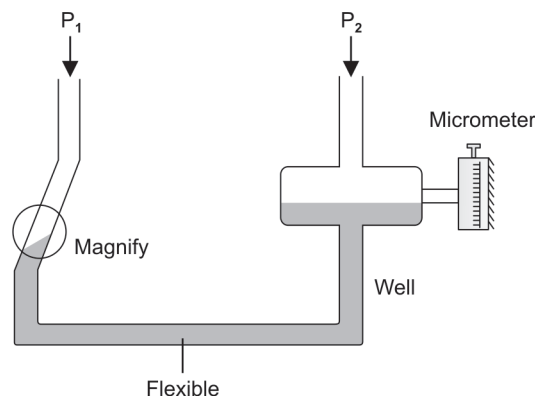


Fig. 1.9: Micromanometer

d. Inverted U-tube manometer: It is used when the difference between the densities of the two liquids is small. 'A' and 'B' are points at different levels with liquids having different specific gravity. It consists of a glass tube-shaped like an inverted letter 'U' and seems similar to two piezometers connected end-to-end to which air is present at the center of the two limbs as shown in Fig. 1.10. As the two points in consideration are at different pressures the liquid raises in the two limbs. Air or mercury is used as the manometric fluid.

2. Mechanical pressure measurement gauges: It involves the measurement of pressure with the help of a solid object like a tube, plate or diaphragm instead of measuring it by the deviation of fluid level in the tube. The object whose pressure has to be measured is attached to the deviating object. The change in the pressure deviates the object and

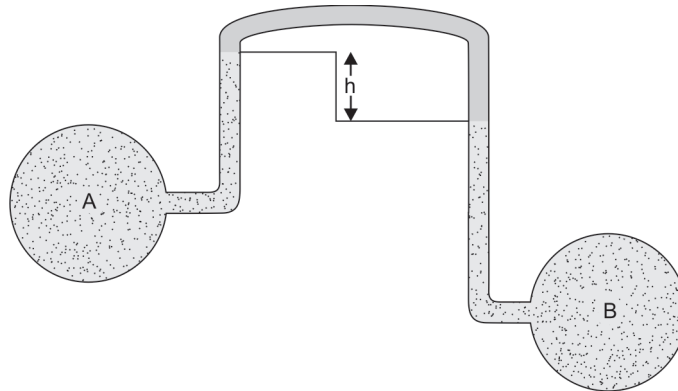


Fig. 1.10: Inverted U-tube manometer

the deviation produced is magnified with the help of a suitable gear and linkage mechanism and is depicted on the calibration dial.

3. Bourdon gauge: It involves a coiled tube in which one end is attached to the system and the other is sealed. The coil straightens up and results in the deviation of the sealed end by applying pressure in the tube.

The indicating needle is attached to the sealed end with the help of gear and linkage mechanism. The deviation produced at the sealed end leads to the movement of the needle on a calibrated dial. It is used to determine the wide ranges of pressure.

4. Diaphragm gauge: It resembles Bourdon gauge but it has a diaphragm that deviates when the pressure is changed and is depicted on calibrated scale.

5. Bellows gauge: This is used for determining very low pressures. In this gauge the indicating needle moves by the deviation of bellows chamber.

6. Pressure transducers: In this the pressure changes are converted into electrical signals with the help of an electrical system that is attached along with the mechanical gauges. They determine pressure continuously in a manner so that the electrical signals are delivered to some control system that can be used to determine the pressure changes. The types of pressure transducers are piezoelectric, magnetic, resistive, or capacitive.

FLUID DYNAMICS

The Bernoulli Equation

Daniel Bernoulli (1700–1782) was the first scientist who contributed in a fundamental way to the development of it. After Bernoulli, others who contributed to the development of the ideas were d' Alembert (1717–1783) but the theory was put on a firm foundation by the work of Euler (1707–1783). The conservation theorems which are closely related to the conservation of energy when applied to flow of fluids are collectively called Bernoulli theorems.

Bernoulli's theorem states that in an ideal flow state of an incompressible fluid the total energy per unit mass, which consists of pressure energy, kinetic energy and datum energy, at any point of fluid is constant.

Assuming a horizontal flow (neglecting minor elevation differences between measuring points) the Bernoulli equation can be modified to:

$$p_1 + 1/2 \rho v_1^2 = p_2 + 1/2 \rho v_2^2$$

where,

p = pressure

ρ = density

v = flow velocity

The equation can be adapted to vertical flow by adding elevation heights h_1 and h_2 .

Assume a horizontal flow that neglects minor elevation differences between the measuring points and the Bernoulli equation then can be modified into:

$$p_1 + 1/2 \rho v_1^2 = p_2 + 1/2 \rho v_2^2$$

where,

p = pressure

ρ = density

v = flow velocity

The equation can be adapted to vertical flow by adding elevation heights h_1 and h_2 .

Assuming a uniform velocity profiles in the upstream and downstream flow – then the continuity equation is expressed as:

$$q = v_1 A_1 = v_2 A_2$$

where,

q = flow rate

A = flow area

Combining these two equations and let assume $A_2 < A_1$, gives the “ideal” equation:

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

For a given geometry (A), the flow rate can be known by measuring the difference in pressure $p_1 - p_2$.

The theoretical flow rate q will show smaller in practice be (2–40%) because of geometrical conditions.

The ideal equation can be changed with a discharge coefficient by:

$$q = c_d A_2 [2(p_1 - p_2) / \rho(1 - (A_2/A_1)^2)]^{1/2}$$

where,

c_d = discharge coefficient

c_d (discharge coefficient) is a function of the jet size or orifice opening

$$\text{Area ratio} = A_{vc} / A_2$$

where,

A_{vc} = area in “vena contracta”

“Vena contracta” is explained as the minimum jet area which appears immediately to downstream of restriction. The viscous effect is usually expressed in terms of the Reynolds Number— Re which is a non-dimensional parameter.

In “Vena contracta” the velocity of the fluid will be highest and the pressure at the lowest due to the two equations Bernoulli and Continuity equation. The velocity will decrease to the similar extent after the metering device as before the obstruction. A head loss to the flow is added as the pressure recovers to a pressure level lower than the pressure before the obstruction.

The above equation can be modified with diameters to:

$$q = c_d \pi / 4 D_2^2 [2(p_1 - p_2) / \rho (1 - d^4)]^{1/2}$$

where,

D_2 = orifice, venturi or nozzle inside diameter

D_1 = upstream and downstream pipe diameter

$d = D_2 / D_1$ diameter ratio

$\pi = 3.14$

The above equation can be converted into mass flow for fluids by just simply getting it multiply with density:

$$m = c_d \pi / 4 D_2^2 \rho [2(p_1 - p_2) / \rho (1 - d^4)]^{1/2}$$

While measuring the mass flow in gases it is required to consider the pressure reduction and changes in density of the fluid. The formula above can be used for applications but with limitations that to bring relatively small changes in pressure and density.

Applications

- It is applied in the measurement of the rate of fluid flow using orifice meter, venturi meter, etc.
- It is applied in the working of centrifugal pumps
- It is easy to measure heights and apply them as energy terms.
- It can be used to calculate pressure or velocity of the fluid.
- It works in air flight and helps to fly by dragging against thrust force.

Types of Flow

Reynolds number is defined as the ratio between inertial and viscous forces and is denoted by Re. It is a well suitable parameter to determine whether the condition of flow is laminar or turbulent. It can be explained as when the viscous forces are dominant to keep all the fluid particles flow in line that is slow flow and low Re then the flow is termed laminar flow. The very low Re shows viscous motion and inertia effects are considered to be negligible. Similarly when the inertial forces are dominant over the viscous forces that is fast flow and high Re then the flow is termed turbulent flow.

It is a dimensionless number comprised of the physical characteristics of the flow. An increasing Reynolds number indicates an increasing turbulence of flow.

$$R = \frac{\rho V D}{\mu}$$

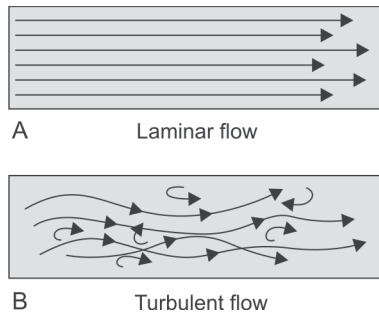
where,

V = velocity

D = distance

For example, as shown in Fig. 1.11 for fluid flowing in a pipe, V is the average fluid velocity, and D is the pipe diameter, excessive fluid inertia tends to disrupt organized flow leading to chaotic turbulent behaviour, whereas viscous stresses within a fluid tend to stabilize and organize the flow.

Reynolds numbers up to 2000 are laminar fluid flow. Reynolds number above 4000 is entirely turbulent flow. There is a transition in flow between laminar and turbulent in a range among 2000 and 4000, and makes possible to acquire sub-regions of both flow types within a flow field provided.



Figs 1.11A and B: A. Reynolds number equation; B. Laminar flow and turbulent flow

The fluid is governed by the laws of fluid statics when the flow is zero or it can be said statics.

Navier-Stokes equation is used in describing the laminar fluids flow and the Bernoulli equation is used to describe the viscous flow.

Significance

It is used to determine nature of flow, i.e. viscous or turbulent:

- Whether viscous/turbulent.
- It is helpful in determining the physical stability of suspensions or emulsions by studying type of flow.
- It is used to study the rate of heat transfer of liquids also depends on the flow.
- It is an important part in the calculation of the friction factor in equations of fluid mechanics, including the Darcy-Weisbach equation.
- It is used when modelling the movement of any organisms swimming through water.
- It is used to calculate atmospheric air which is considered to be a fluid and makes it possible to apply it in wind tunnel testing to study the aerodynamic properties of various surfaces.
- It also shows an important part in the testing of wind lift on aircraft, in cases of supersonic flights where the high speed causes a localized increase in the density of air surrounding the aircraft.

ENERGY LOSSES

Whenever a fluid is flowing through a pipe then the fluid experiences some resistance due to which some of the energy of the fluid is lost. The Bernoulli's equation includes the term energy losses in the pipe. Hence, it is very necessary to determine the energy losses. For the pipe system, the overall head loss of the head consists of loss due to viscous effects in the straight pipes and are termed the major loss and denoted $h_{L-major}$. The head loss in various others pipe components, termed the minor loss and denoted $h_{L-minor}$.

$$H_1 = h_{L-major} + h_{L-minor}$$

They are classified as in Fig. 1.12.

1. **Major energy losses:** The viscosity causes loss of energy in the flows which is known as frictional losses or major energy loss. The fluid flow can either be viscous or turbulent that influences losses. It can be calculated by:

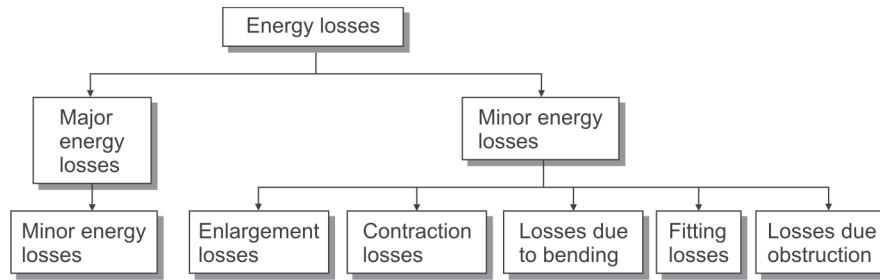


Fig. 1.12: Classification of energy losses

- a. *The Darcy-weisbach formula*: It is valid for any fully developed, steady, incompressible pipe flow, whether the pipe is horizontal or on hill

$$h_f = 4 f L V^2 / (2gD)$$

where,

h_f = Loss of head due to friction

f = Co-efficient of friction which is a function of Reynolds number
 $= 64/R_e$ (for $Re < 2000$) (laminar flow)

L = Length of pipe

V = Mean velocity of flow

D = Diameter of pipe

- b. *Moody chart*: It is universally valid for all steady, fully developed, incompressible pipe flows.

The following equation from *Colebrook* is valid for the entire non-laminar range of the *Moody* chart. It is called *Colebrook formula*.

$$\frac{1}{f} = -2.0 \log \frac{\epsilon/D}{3.7} + \frac{2.51}{Re \sqrt{f}}$$

- c. *Fanning equation*: It is applicable when fluid is passing through a straight pipe and the nature of the fluid flow is viscous or turbulent. The roughness of the inner surface of the pipe is also a factor of consideration.

$$\Delta P_f = \frac{2f_u^2 l \rho}{D}$$

where,

ρ = Density of the fluid

DP_f = Pressure drop

Friction losses can be reduced by the addition of soluble and high molecular weight polymers in a low concentration. Friction losses are permanent, since potential and kinetic energies are converted into heat.

2. **Minor energy losses**: The loss of energy due to change of velocity of the flowing fluid in magnitude or direction is called minor loss of energy. The minor loss of energy includes the following cases:

- a. **Enlargement Losses**: Figure 1.13, the cross-section of the pipe enlarges gradually; the fluid adapts itself to the changed section without any disturbance

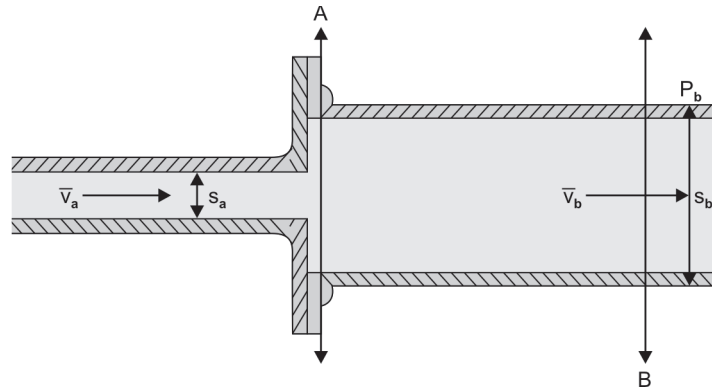


Fig. 1.13: Energy losses due to enlargement

resulting in loss of energy. But if the cross-section changes suddenly then loss of energy is seen due to eddies. Such disturbances causes loss of head.

The equation for head loss due to sudden expansion is:

$$h_e = (V_1 - V_2)^2 / 2g$$

where,

V_1 = The velocity at section 1

V_2 = The velocity at section 2

- b. Contraction losses:** (Figure 1.14) when the cross-section of the pipe is reduced at sudden the fluid flow becomes disturbed. The velocity of fluid at smaller cross-section known as vena-contracta will be far greater than that at larger section. The losses are observed due to additional eddying.

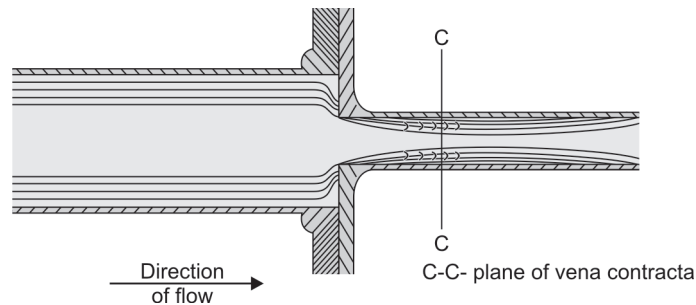


Fig. 1.14: Energy losses due to contraction

The equation for head loss due to sudden contraction is

$$h_c = k (V_2^2 / 2g)$$

where,

$$k = ((1/C_c) - 1)^2$$

V_2 = The velocity at section 2

- c. Losses due to bending in pipe:** Change in direction causes fluid separation from the inner wall and a larger angle causes a greater head loss (Fig. 1.15). The radius of the bend and diameter of the pipe also contribute to the losses.

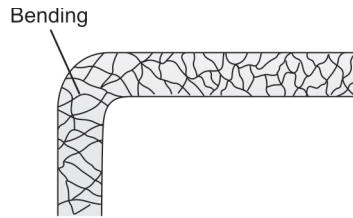


Fig. 1.15: Energy losses due to bending of pipe

The equation for head loss due to bending is

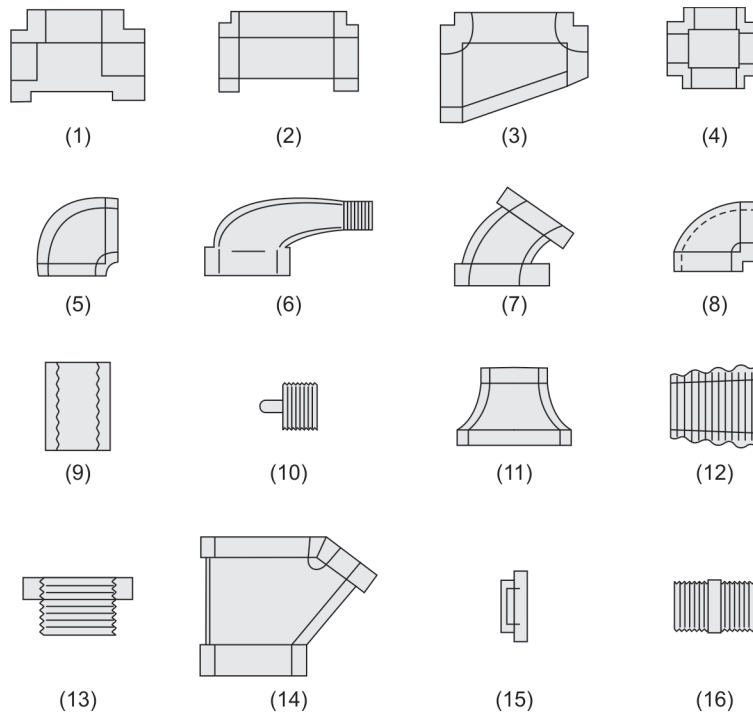
$$h_b = k (V^2/2g)$$

where,

V = The velocity of the flow

k = The co-efficient of the bend, which depends on the angle of the bend, radius of curvature of bend and diameter of the pipe

d. Head loss due to pipe fittings: A large number of fittings are included in pipe, such as coupling, union, tee fitting, valve, elbow, etc. fittings causes disturbances in flow resulting in loss of energy causing head loss as shown in Fig. 1.16.



- | | |
|----------------------------|-------------------|
| (1) Tee | (9) Coupling |
| (2) Tee reducing on outlet | (10) Plug |
| (3) Tee reducing on run | (11) Reduces |
| (4) Cross | (12) Close nipple |
| (5) Elbow | (13) Bushing |
| (6) Street elbow | (14) T-branch |
| (7) 45° elbow | (15) Cap |
| (8) Reducing elbow | (16) Short nipple |

Fig. 1.16: Energy losses due to pipe fittings

The equation for head loss due to fitting losses is

$$h_f = K_L (V^2 / 2g)$$

where,

V = The velocity of the flow

K = The coefficient of pipe fitting

Measures for Reducing Head Loss

- Replace pipes through the project lifetime by solids that will accumulate along the pipe walls, constricting the diameter and altering surface roughness
- Minimize pipe lengths and number of components as they both are directly proportional to head loss
- A uniform pipe diameter
- Operate at design velocity to reduce head loss.

Transportation of Fluids

Pipe, tubing, hose, fittings and accessories are used for the closed transfer of materials, typically liquids but also solids and gases. Pipes and tubes are often, but not always, cylindrical in shape. Products with a square cross-section are less common, but are also available. Pipes are designated mainly by their inner diameter (ID) while tubes are designated mainly by their outer diameter (OD). Hoses are flexible and often reinforced. Fittings and accessories are used to join pipes to pipes, pipes to tubes, or pipes to hoses.

Pipes and tubes may be used to transfer water and liquid chemicals, gases, such as propane and nitrogen, and solids, such as granular plastics and cereal grains. Although pipes are designated by ID and tubes are designated by OD, measured diameter is not the only distinction between the piping and tubing. Typically, pipes can withstand higher temperatures and higher pressures. Pipes are also used in closed systems with fittings, such as in a chemical processing facility. Tubes may be used with more open systems (e.g. drainage).

Measurement of flow of fluids: Flow measurement is required in many industries, e.g. oil industry, power plants, chemical industry, food and beverages industry, water and waste treatment plants. It is essential for determining the quantity of a fluid, gas, or steam, which passes through a check point, either through a closed conduit or by an open channel in daily processing operation. It is helpful in evaluation of volume, flow rate, mass flow rate, flow velocity, or other quantities.

The instrument that is used in measurement of flow is called flowmeter. The development of a flowmeter involves a wide variety such as flow sensors, the use of computation techniques in the sensor and fluid interactions, the signal processing units and the associated transducers, and in the assessment of an overall system in both the laboratory and the field under various conditions, such as ideal, disturbed, harsh, or potentially explosive.

Depiction of flowmeters: Flowmeters are integrated instruments that are used to measure the different flow quantities by using different technologies. Many features can be referred in categorizing the flowmeters. Flow metering mainly comprises of— orifice meter, venturi meter, nozzles flow, pitot tubes, positive displacement, turbine, vortex, electromagnetic, ultrasonic Doppler, etc.

In a flow metering device based on the Bernoulli equation the downstream pressure after an obstruction will be lower than the upstream pressure before. To understand

orifice, nozzle and venturi meters it is therefore necessary to explore the Bernoulli equation.

THE ORIFICE METER

Principle: It consists of a thin plate containing a narrow and sharp aperture and when the fluid stream is allowed to pass through the narrow constriction, the velocity of the fluid increases as compared to upper stream resulting in the corresponding decrease in the pressure head. As it can be correlated by Bernoulli's theorem that the increase in velocity head with the decrease in pressure heads between two points that can be measured by manometer.

Construction

The orifice meter consists of a flat orifice plate made of stainless steel with a circular hole drilled in it as shown in Fig. 1.17. There are two pressure taps one at upstream from the orifice plate and another at just downstream. Generally, there are three methods of inserting the taps and the position of taps determines the coefficient of the meter. From face of orifice the tap location *1 inch* upstream and *1 inch* downstream is termed as Flange location. Similarly from face of orifice tap location *1 pipe diameter* (actual inside) upstream and *0.3 to 0.8 pipe diameter* downstream is called "*Vena Contracta*" location. And from face of orifice tap location *2.5 times nominal pipe diameter* upstream and *8 times nominal pipe diameter* downstream is a pipe location.

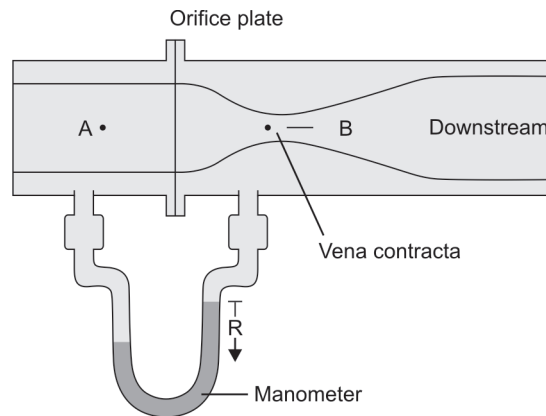


Fig. 1.17: Orifice meter

Working: It is used to the pressures across affixed constriction placed in the path of flow consisting of a constant area. According to Bernoulli's theorem, there must be a corresponding reduction in pressure at this point. The difference in pressure between the point of constriction and the main channel can be read using a manometer and this pressure difference can be related to the rate of flow of fluid. If manometer is connected to the Point A and B, the pressure at B will be less than at A and this pressure difference can be read from the manometer. If the two points A and B are chosen and Bernoulli's equation written between these two points:

The discharge coefficient— c_d —varies considerably with changes in area ratio and the Reynolds number. A discharge coefficient $c_d = 0.60$ may be taken as standard, but the value varies noticeably at low values of the Reynolds number. The pressure recovery is limited for an orifice plate and the permanent pressure loss depends primarily on

the area ratio. For an area ratio of 0.5, the head loss is about 70–75% of the orifice differential.

Applications

- It has a wide applicability as it is standardized.
- Concentric orifice plates are used to measure flow rates of pure fluids.
- To measure flow rates of fluids containing suspended materials, such as solids, oil mixed with water and wet steam eccentric and segmental orifice plates are used.

Advantages

- The orifice meter is recommended for clean and dirty liquids and some slurry services.
- The rangeability is 4 to 1.
- The pressure loss is *medium*.
- Typical accuracy is 2 to 4% of full scale.
- The required upstream diameter is 10 to 30.
- The viscosity effect is *high*.
- The relative cost is *low*.

Disadvantages

- Poor pressure recovery at downstream
- Gets easily clogged when the suspended fluids flow
- Inaccuracy occurs as the orifice plate gets corroded
- The orifice plate has low physical strength
- Low coefficient of discharge.

The venturi meter: It is also known as restriction type flow meter. Its work is based on Bernoulli's principle. In it, pressure energy (PE) converted into kinetic energy (KE) to calculate flow rate (discharge) in a closed pipeline.

Principle: It consists of two tapered sections in the pipeline with a gradual constriction at its centre and when the fluid is allowed to pass through the narrow throat, the velocity of the fluid increases as compared to upper stream resulting in the corresponding decrease in the pressure head. As it can be correlated by Bernoulli's theorem that the increase in velocity head with the decrease in pressure heads between two points can be measured by manometer.

Construction: The venturi meter, as shown in Fig. 1.18, is usually made of cast iron, bronze or steel. The converging part is made shorter by employing large cone angle (19–21°) while diverging section is longer with lower cone angle (5–15°). The high-pressure tap is located at starting of the venturi and low-pressure tap located in the middle of throat sections that are inserted in the pipeline, with the tapers smooth enough and gradual enough so that there are no serious losses.

Working: In it the fluid is accelerated through a converging cone having an angle of 15–20°. The pressure difference between the throat and upstream side of the cone is measured and signal for the rate of flow is provided. Most of the kinetic energy is converted back to pressure energy as the fluid slows down in a cone with a smaller angle of 5–7°. No "Vena Contracta" is found because of the cone and a gradual reduction in the area. At the throat it is observed that flow area is at minimum. High pressure

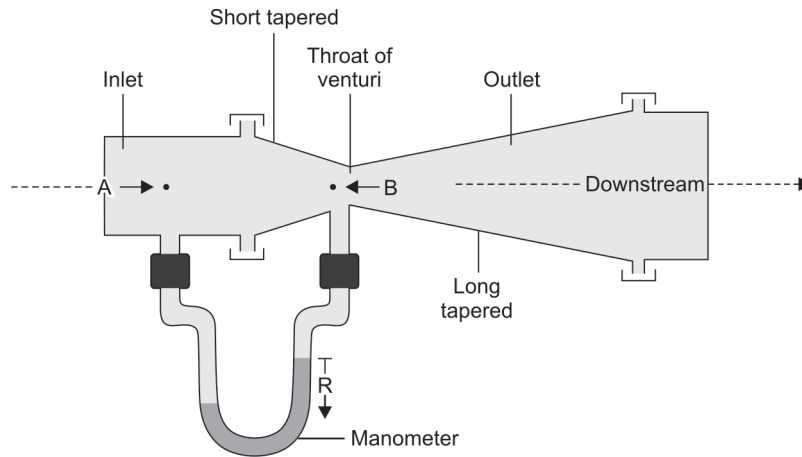


Fig. 1.18: Venturi meter

and energy recovery makes it very useful in cases where only small pressure heads are available.

As a standard discharge coefficient is $c_d = 0.975$, but this value fluctuates at low values of Reynolds number. In it pressure recovery is better than the orifice meter.

Applications

- It is used for measurement of fluids, gas, liquids, slurries, suspended oils and other processes
- It is also widely used in large diameter pipes such as in the waste treatment process
- They are suitable for measurement of dirty fluid as it allows solid particles flow through it because of their gradually sloping smooth design.

Advantages

- The venturi tube is suitable for clean, dirty and viscous liquid and some slurry services
- The rangeability is 4 to 1
- Pressure loss is low
- Typical accuracy is 1% of full range
- Required upstream pipe length 5 to 20 diameters
- Viscosity effect is high
- Relative cost is medium.

Disadvantages

- It is quite expensive
- Requires more space
- Ratio of throat diameter to pipe diameter cannot be changed
- Energy losses
- Impossible to clean out the pressure taps if they clog up with dirt or debris.

PITOT TUBE

Principle: It is also known as insertion meter. It consists of a sensing element with a small constriction as compared to the size of the flow channel. As the sensing element is inserted at the centre of stream there is increased in velocity of flow resulting in

decrease in pressure head. Tube at right angles to the flow measures pressure head only whereas the tube that pointed upstream measures pressure head and velocity head. The difference in the readings above determines the velocity head.

Construction: The tubes are connected to the legs of a manometer in which one tube is perpendicular to the flow of direction and the other tube is connected parallel to the direction of flow. The size of the sensing element is very small as compared to the size of the flow channel.

Working: Suppose that two tubes be inserted as shown in Fig. 1.19. If the tube is right angles to the flow be properly designed, it will measure the pressure head only. The tube that points upstream will measure the pressure plus the velocity head. The reading R of the manometer will therefore measure the velocity head and

$$\Delta H_p = u^2/2gc$$

where,

ΔH_p = The velocity head of the fluid corresponding to R .

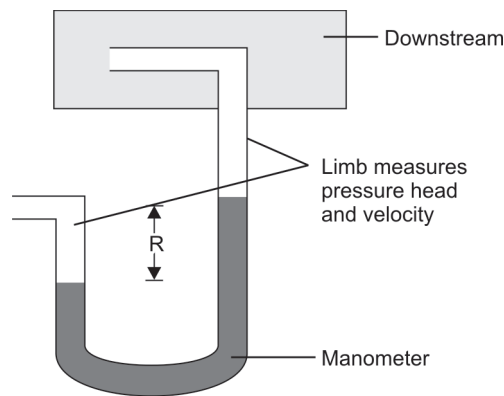


Fig. 1.19: Pitot tube

Whereas the orifice and venturimeter measure the average velocity of the whole stream of fluid, the pitot tube measures the velocity at one point only. Since, the velocity varies over the cross-section of the pipe, average velocity has to be calculated either from the maximum velocity or by taking reading at different points in the cross-section and determining the mean velocity by graphic integration.

Applications

- It is used in utility streams where high accuracy is not necessary
- It is also used in the air duct and pipe system
- It is used in aircraft for measuring the air flow velocity
- They can be used for mapping flow profile in a channel or duct.

Advantages

- Economical
- Minimum frictional loss
- Easy to install as having small size and in extreme environment, high temperature and pressure conditions

- Loss of pressure is negligible
- It measures the velocity at only one point.

Disadvantages

- Eddies within the pressure tube disturb the readings and creates more disturbances themselves
- It does not give average velocity
- It has low sensitivity and poor accuracy
- It is not suitable for dirty or sticky fluid like sewage disposal
- They can easily become clogged with foreign materials in the liquid.

ROTAMETER

The orifice and venturi meters depend on the measurement of a variable differential pressure across a fixed constriction placed in the flow. Since velocity varies with the pressure differential, these types sometimes referred to as “variable head” meters. In the rotameter, the area of flow is varied so as to produce a constant head differential, so it is also called “variable-area” meter.

Principle: A rotameter (Fig. 1.20) consists of a vertical, slightly tapered tube within which is placed a solid plummet or a float smaller in diameter than the narrowest part of the tube. As the flow of the liquid is increased or decreased, the plummet rises and falls freely, thereby varying the area of the annular space between it and the tube in such a way that head loss across this annulus is equal to the weight of plummet. The volumetric flow of the fluid may be directly read using the upper edge of the plummet as the index.

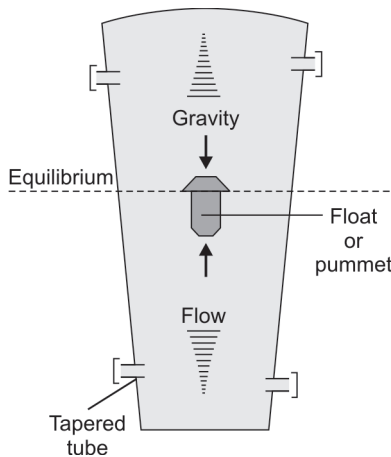


Fig. 1.20: Rotameter

Construction: It consists of a vertical shaped tapered tube, which is mounted with a narrow end down. The tube is usually made of glass and a nearly linear scale is etched and having solid plummet placed on a tube. The diameter of plummet is always smaller than the narrow end of the tube. Recording can be made by electric and electronic transmitters. Floats can be made of aluminium, lead, glass and plastic of different densities, so that a 200-fold range of flow can be measured accurately.

Working: The flow of fluid varies as the flow is upward through a tapered tube. The plummet which got surrounded by the fluid may rise and falls depending upon the rate of flow. The higher the plummet rises, the greater will be flow. In rotameters, the pressure drop is constant or nearly constant.

During the fluid flow, the area of the annular space between the plummet and the tube varies having an area is properly calibrated to the flow rate. These readings may be transmitted, for recording, integrating and controlling.

Applications

- It is used in chemical industries such as bulk drugs
- It has also been used in fermenters, the supply of air has controlled through it
- It is used both for gases and liquids at high and low pressures.

Advantages

- Direct visual readings
- Wide range
- Nearly linear scale
- Constant head loss
- It requires no straight pipe runs before and after the meters.

Disadvantages

- It will only be accurate for a given substance at a given temperature only.
- Resolution is relatively poor due to the direct flow indication.
- They are not generally manufactured in sizes greater than 6 inches/150 mm.

VERY SHORT QUESTIONS

1. Why is mercury used as a liquid in the manometer?
2. Write the following equations, explain its terms and mention its importance.
 - a. Fanning equation
 - b. Hagen-Poiseuille's equation
3. Briefly explain Reynold's number and its importance.
4. How is energy losses of energy due to enlargement in cross-section measured? Give relevant equation explaining all terms.
5. Define fluid mechanics and classify it.
6. Explain the fluid flow meter which gives point velocity.

SHORT QUESTIONS

1. Differentiate between fluid dynamics and fluid statics with suitable equation.
2. Compare and contrast the advantages and disadvantages of pitot tube and rotameter.
3. Explain types of fluid and the characteristic of different types of fluid.
4. What are merits and demerits of venturi meter over orifice meter?
5. Explain energy losses and mention essential measures to avoid it.

LONG QUESTIONS

1. Explain fluid and mention all relevant equations for calculation of flow rates.
2. Explain the working, principle, construction, advantages, disadvantages and uses of the following in detail:
 - a. Venturimeter
 - b. Pitot tube
 - c. Orifice meter
 - d. Rotometer
3. Elaborate energy losses that occur when a fluid flows through a pipe with suitable equations.
4. Explain in detail Bernoulli's theorem and its significance.
5. Write a note on pressure measuring devices and explain working and principle of orifice meter.

MULTIPLE CHOICE QUESTIONS

1. The fluid flow in which the fluid particles in one layer do not mix with the fluid particles in the other layer is called:
 - a. Laminar flow
 - b. Turbulent flow
 - c. Layer flow
 - d. None of the above
2. Why is large reservoir used in single column manometer?
 - a. In order to enhance the change in level of liquid in reservoir
 - b. In order to negate the effects of change in level due to pressure variation
 - c. In order to reduce the effect due to dynamic pressure variation due to motion
 - d. None of the mentioned
3. Viscosity of a fluid can be defined as:
 - a. Change in density of the fluid per unit temperature
 - b. Flow resistance offered by the fluid
 - c. Flow velocity change
 - d. None of the above
4. Which of the following fluid can be considered as an ideal fluid?
 - a. Viscous fluid
 - b. Non-viscous fluid
 - c. Compressible fluid
 - d. All of the above
5. What is the SI unit for absolute or dynamic viscosity (μ)?
 - a. Ns/m^2
 - b. Nm^2/s
 - c. $\text{N/m}^2\text{s}$
 - d. N/m^2
6. Which of the following does not require manometer in the construction of flow of meters:
 - a. Orifice meter
 - b. Rotameter
 - c. Venturimeter
 - d. Pitot tube

7. **Venturi relation is one of applications of:**
- Equation of continuity
 - Bernoulli's equation
 - Light equation
 - Speed equation
8. **If every particle of fluid has irregular flow, then flow is said to be:**
- Laminar flow
 - Turbulent flow
 - Fluid flow
 - Both a and b
9. **The average drag coefficient for turbulent boundary layer flow past a thin plate is given by $C_f = 0.455 / (\log_{10} R_{el})^{2.58}$. Where R_{el} is the Reynolds number based on plate length. A plate 50 cm wide and 5 m long is kept parallel to the flow of water with free stream velocity 3 m/s. Calculate the drag force on both sides of the plate. For water, kinematic viscosity = 0.01 stokes:**
- 53.38 N
 - 63.38 N
 - 73.38 N
 - 83.38 N
10. **Consider the above problem, estimate the value of Reynolds number:**
- 0.12
 - 0.13
 - 0.14
 - 0.15
11. **The distance moved by liquid will be more in which type of manometer?**
- Inclined single column manometer
 - Vertical single column manometer
 - Horizontal single column manometer
 - None of the mentioned
12. **Which device is popularly used for measuring difference of low pressure?**
- Inverted U-tube differential manometer
 - U-tube differential manometer
 - Inclined single column manometer
 - Vertical single column manometer
13. **Which of the following uses direct reading of flow of fluids?**
- Orifice meter
 - Rotameter
 - Venturimeter
 - Pitot tube
14. **What is kinematics viscosity of a fluid?**
- Dynamic viscosity per unit volume of the fluid
 - Dynamic viscosity per unit weight of the fluid
 - Dynamic viscosity per unit density of the fluid
 - None of the above
15. **Generally, all the fluid particles in flowing fluid**
- Flow at a constant velocity
 - Flow at various velocities
 - Flow at a velocity as high as possible
 - None of the above