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Program : **B.Tech**

Subject Name: **Fluid Mechanics I**

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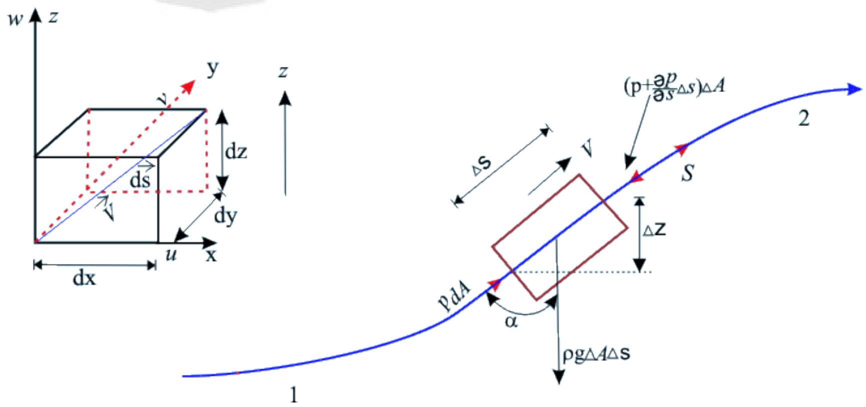
UNIT-3

Dynamics of Flow: Euler's equation of motion along a streamline and derivation of Bernoulli's equation, application of Bernoulli's equation, energy correction factor, linear momentum equation for steady flow; momentum correction factor. The moment of momentum equation, forces on fixed and moving vans and other applications. Fluid Measurements: Velocity Measurement (Pitot tube, prandtl tube, current meters etc.); flow measurement (orifices, nozzles, mouth pieces, orifice meter, nozzle meter, venturimeter, weirs and notches).

- **Euler's equation of motion along a streamline**

The Euler's equation for steady flow of an ideal fluid along a streamline is a relation between the velocity, pressure and density of a moving fluid. It is based on the Newton's Second Law of Motion. The integration of the equation gives Bernoulli's equation in the form of energy per unit weight of the following fluid.

1. **It is based on the following assumptions:**
2. **The fluid is non-viscous (i,e., the frictional losses are zero).**
3. **The fluid is homogeneous and incompressible (i.e., mass density of the fluid is constant).**
4. **The flow is continuous, steady and along the streamline.**
5. **The velocity of the flow is uniform over the section.**
6. **No energy or force (except gravity and pressure forces) is involved in the flow.**



Derivation

Euler's equation along a streamline is derived by applying Newton's second law of motion to a fluid element moving along a streamline. Considering gravity as the only body force component acting vertically downward (Fig.), the net external force acting on the fluid element along the directions can be written as

$$F_s = -\frac{\partial p}{\partial s}\Delta s \Delta A - \rho \Delta s \Delta A g \cos\alpha \qquad \text{------------------------3.1}$$

Where ΔA is the cross-sectional area of the fluid element. By the application of Newton's second law of motion in s direction, we get

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$$\rho \Delta s \Delta A \frac{DV}{Dt} = -\frac{\partial p}{\partial s} \Delta s \Delta A - \rho \Delta s \Delta A g \cos\alpha \quad \text{---------------------------------3.2}$$

From geometry we get

$$\cos\alpha = \lim_{\Delta s \to 0} \frac{\Delta z}{\Delta s} = \frac{dz}{ds}$$

Hence, the final form of Eq.

$$\rho \frac{DV}{Dt} = -\frac{\partial p}{\partial s} - \rho g \frac{dz}{ds}$$

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial s} = -\frac{1}{\rho} \frac{\partial p}{\partial s} - g \frac{dz}{ds} \quad \text{---3.3}$$

Above Equation is the Euler's equation along a streamline.

Let us consider $d\vec{s}$ **along the streamline so that**

$$d\vec{s} = \vec{i}dx + \vec{j}dy + \vec{k}dz$$

Again, we can write from Fig.

$$\frac{dx}{ds} = \frac{u}{V}, \quad \frac{dy}{ds} = \frac{v}{V} \text{ and } \frac{dz}{ds} = \frac{w}{V}$$

The equation of a streamline is given by

$$\vec{V} \times d\vec{S} = 0$$

$$\begin{vmatrix} i & j & k \\ u & v & w \\ dx & dy & dz \end{vmatrix} = 0$$

or, which finally leads to

$$udy = vdx; \qquad udz = wdx; \qquad vdz = wdy$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = X_x - \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = X_y - \frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = X_z - \frac{1}{\rho}\frac{\partial p}{\partial z}$$

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Multiplying Eqs above by dx, dy and dz respectively and then substituting the above mentioned equalities, we get

$$\rho\left(u\frac{\partial u}{\partial t}\cdot\frac{ds}{V}+u\frac{\partial u}{\partial x}dx+u\frac{\partial u}{\partial y}dy+u\frac{\partial u}{\partial z}dz\right)=-\frac{\partial p}{\partial x}dx+X_x dx$$

$$\rho\left(v\frac{\partial v}{\partial t}\cdot\frac{ds}{V}+v\frac{\partial v}{\partial x}dx+v\frac{\partial v}{\partial y}dy+v\frac{\partial v}{\partial z}dz\right)=-\frac{\partial p}{\partial y}dy+X_y dy$$

$$\rho\left(w\frac{\partial w}{\partial t}\cdot\frac{ds}{V}+w\frac{\partial w}{\partial x}dx+w\frac{\partial w}{\partial y}dy+w\frac{\partial w}{\partial z}dz\right)=-\frac{\partial p}{\partial z}dy+X_z dz$$

Adding these three equations, we can write

$$\rho\left(\frac{ds}{V}\cdot\frac{\partial}{\partial t}\left(\frac{u^2}{2}+\frac{v^2}{2}+\frac{w^2}{2}\right)+\frac{\partial}{\partial x}\left(\frac{u^2}{2}+\frac{v^2}{2}+\frac{w^2}{2}\right)dx+\frac{\partial}{\partial y}\left(\frac{u^2}{2}+\frac{v^2}{2}+\frac{w^2}{2}\right)dy+\frac{\partial}{\partial z}\left(\frac{u^2}{2}+\frac{v^2}{2}+\frac{w^2}{2}\right)dz\right)$$

$$=\rho\left(\frac{ds}{V}\cdot\frac{\partial}{\partial t}(\frac{V^2}{2})+\frac{\partial}{\partial x}\left(\frac{V^2}{2}\right)dx+\frac{\partial}{\partial y}\left(\frac{V^2}{2}\right)dy+\frac{\partial}{\partial z}\left(\frac{V^2}{2}\right)dz\right)$$

$$=\rho\left[\frac{\partial V}{\partial t}+V(\frac{\partial V}{\partial x}\cdot\frac{dx}{ds}+\frac{\partial V}{\partial y}\cdot\frac{dy}{ds}+\frac{\partial V}{\partial z}\cdot\frac{dz}{ds})\right]=-\left(\frac{\partial p}{\partial x}\cdot\frac{dx}{ds}+\frac{\partial p}{\partial y}\cdot\frac{dy}{ds}+\frac{\partial p}{\partial z}\cdot\frac{dz}{ds}\right)-\rho g\frac{dz}{ds}$$

Hence, $$\boxed{\rho\left[\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial s}\right]=-\frac{\partial p}{\partial s}-\rho g\frac{dz}{ds}}$$

This is the more popular form of Euler's equation because the velocity vector in a flow field is always directed along the streamline.

Bernoulli's Equation

Energy Equation of an ideal Flow along a Streamline

Euler's equation (the equation of motion of an inviscid fluid) along a stream line for a steady flow with gravity as the only body force can be written as

$$V\frac{dV}{ds}=-\frac{1}{\rho}\frac{dp}{ds}-g\frac{dz}{ds}$$

Application of a force through a distance ds along the streamline would physically imply work interaction. Therefore an equation for conservation of energy along a streamline can be obtained by integrating the Eq. (13.6) with respect to ds as

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$$\int V\frac{dV}{ds}ds = -\int\frac{1}{\rho}\frac{dp}{ds}ds - \int g\frac{dz}{ds}ds$$

$$\text{or,}\quad \frac{V^2}{2} + \int\frac{dp}{\rho} + gz = C$$

Where C is a constant along a streamline. In case of an incompressible flow, Eq. (13.7) can be written as

$$\frac{P}{\rho} + \frac{V^2}{2} + gz = C$$

The Eqs (13.7) and (13.8) are based on the assumption that no work or heat interaction between a fluid element and the surrounding takes place. The first term of the Eq. (13.8) represents the flow work per unit mass, the second term represents the kinetic energy per unit mass and the third term represents the potential energy per unit mass. Therefore the sum of three terms in the left hand side of Eq. (13.8) can be considered as the total mechanical energy per unit mass which remains constant along a streamline for a steady inviscid and incompressible flow of fluid. Hence the Eq. (13.8) is also known as Mechanical energy equation.

This equation was developed first by Daniel Bernoulli in 1738 and is therefore referred to as Bernoulli's equation. Each term in the Eq. (13.8) has the dimension of energy per unit mass. The equation can also be expressed in terms of energy per unit weight as

$$\frac{P}{\rho g} + \frac{V^2}{2g} + z = C_1(\text{constant})$$

In a fluid flow, the energy per unit weight is termed as head. Accordingly, equation 13.9 can be interpreted as

Pressure head + Velocity head + Potential head =Total head (total energy per unit weight).

Bernoulli's Equation with Head Loss

The derivation of mechanical energy equation for a real fluid depends much on the information about the frictional work done by a moving fluid element and is excluded from the scope of the book. However, in many practical situations, problems related to real fluids can be analysed with the help of a modified form of Bernoulli's equation as

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f$$

Where, hf represents the frictional work done (the work done against the fluid friction) per unit weight of a fluid element while moving from a station 1 to 2 along a streamline in the direction of flow. The term hf is usually referred to as head loss between 1 and 2, since it amounts to the loss in total mechanical energy per unit weight between points 1 and 2 on a streamline due to the effect of fluid friction or viscosity. It physically signifies that the difference in the total mechanical energy between stations 1 and 2 is dissipated into intermolecular or thermal energy and is expressed as loss of head hf in

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Eq. (13.10). The term head loss, is conventionally symbolized as hL instead of hf in dealing with practical problems. For an in viscid flow hL = 0, and the total mechanical energy is constant along a streamline.

PRACTICAL APPLICATIONS OF BERNOULLI'S EQUATION

Bernoulli's equation finds wide applications in all types of problems of incompressible flow where there is involvement of energy considerations. The other equation, which is commonly used in the solution of the problems of fluid flow, is the continuity equation. In this section, the applications of Bernoulli's equation and continuity equation will be discussed for the following measuring devices.

1. **Venturi meter**
2. **Nozzle**
3. **Orifice meter**
4. **Pitot tube**

ENERGY CORRECTION FACTOR

The energy equation for ideal flow has a kinetic energy term with a velocity square factor. We consider ideal flows to be in viscid. For in viscid flow shear effects are not present, hence the flow is uniform across the area of cross section of the flow. It means that the velocity is uniform or the same across the cross section of flow. Therefore the average velocity is equal to the velocity at any point on the section. The total kinetic energy at the section can be written for the ideal flow using the average velocity.

We prefer to use average velocity to calculate kinetic energy because it is easy to find average velocity. Average velocity at any cross section of flow is equal to the rate of flow divided by the area of flow. Energy Correction Factor

We have assumed in the derivation of Bernoulli equation that the velocity at the end sections (1) and (2) is uniform. But in a practical situation this may not be the case and the velocity can very across the cross section. A remedy is to use a correction factor for the kinetic energy term in the equation. If $\overline{V}$ is the average velocity at an end section then we can write for energy,

$$\int_A \frac{V^2}{2}\rho V.dA = \alpha\dot{m}\frac{\overline{V}^2}{2}$$

After simplification we find that

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$$\alpha = \frac{1}{A} \int_A \left(\frac{u}{\bar{V}} \right)^3 dA$$

Consequently, Eqn.3.70 (Low Speed Application) is written as

$$\left(\frac{p}{\gamma} + z + \alpha_1 \frac{V^2}{2g} \right)_1 = \left(\frac{p}{\gamma} + z + \alpha_2 \frac{V^2}{2g} \right)_2 + h_{friction} - h_{pump} + h_{turbine}$$

Where α is the Kinetic Energy Factor? Its value for a fully developed laminar pipe flow is around 2, whereas for a turbulent pipe flow it is between 1.04-1.11. It is usual to take it is 1 for a turbulent flow. It should not be neglected for a laminar flow.

<u>Moment of momentum equation</u>

Moment of momentum equation is derived from moment of momentum principle which states that the resulting torque acting on a rotating fluid is equal to the rate of chance of moment of momentum.

Let V1V1 = velocity of fluid at section 1

r1r1 = radius of curvature at section 1

Q = rate of flow of fluid

ρρ = density of fluid

and V2V2 and r2r2 = velocity and radius of curvature at section 2

Momentum of fluid at section 1 = mass x velocity = PQ×V1/sPQ×V1/s

Moment of momentum per second at section 1 = PQ×V2×r2PQ×V2×r2

Rate of change of moment of momentum

= PQV2r2−PQV1r1=PQ[v2r2−v1r1]PQV2r2−PQV1r1=PQ[v2r2−v1r1]

According to moment of momentum principle

Resultant torque = rate of change of moment of momentum

T=PQ[V2r2−V1r1]T=PQ[V2r2−V1r1] ----- (1)

Eq (1) is known as moment of momentum equation.

Analysis Of Finite Control Volumes - the application of momentum theorem

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We'll see the application of momentum theorem in some practical cases of inertial and non-inertial control volumes.

Inertial Control Volumes

Applications of momentum theorem for an inertial control volume are described with reference to three distinct types of practical problems, namely

Forces acting due to internal flows through expanding or reducing pipe bends.

Forces on stationary and moving vanes due to impingement of fluid jets.

Jet propulsion of ship and aircraft moving with uniform velocity.

Non-inertial Control Volume

A good example of non-inertial control volume is a rocket engine which works on the principle of jet propulsion.

We shall discuss each example separately in the following slides.

Application of Moment of Momentum Theorem

Let us take an example of a sprinkler like turbine as shown in Fig. 12.2. The turbine rotates in a horizontal plane with angular velocity ω. The radius of the turbine is r. Water enters the turbine from a vertical pipe that is coaxial with the axis of rotation and exits through the nozzles of cross sectional area 'a' with a velocity Ve relative to the nozzle.

A control volume with its surface around the turbine is also shown in the fig below.

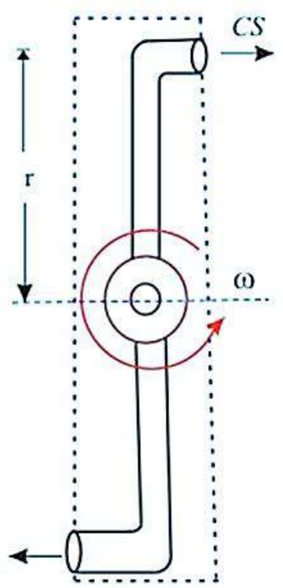

Fig 12.1 A Sprinkler like Turbine

Application of Moment of Momentum Theorem (Eq. 10.20b) gives

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$$M_{zc} = \dot{m}\left(\vec{r} \times \vec{V}\right)$$

When Mzc is the moment applied to the control volume. The mass flow rate of water through the turbine is given by

$$\dot{m} = \rho 2 V_e a$$

The velocity must be referenced to an inertial frame so that

$$\vec{r} \times \vec{V} = -r\vec{i}_r \times \left(V_e - \omega r\right)\vec{i}_\theta = -r\left(V_e - \omega r\right)\vec{i}_z$$

$$M_{zc} = -\dot{m}r\left(V_e - \omega r\right)$$

The moment M_z acting on the turbine can be written as

$$M_z = -M_{zc} = \dot{m}r\left(V_e - \omega r\right)$$

The power produced by the turbine is given by

$$P = M_z \omega$$

VELOCITY MEASUREMENT

The methods of measuring the velocity of liquids or gases can be classified into three main groups: kinematic, dynamic and physical.

In kinematic measurements, a specific volume, usually very small, is somehow marked in the fluid stream and the motion of this volume (mark) is registries by appropriate instruments. Dynamic methods make use of the interaction between the flow and a measuring probe or between the flow and electric or magnetic fields. The interaction can be hydrodynamic, thermodynamic or magneto hydrodynamic.

For physical measurements, various natural or artificially organized physical processes in the flow area under study, whose characteristics depend on velocity, are monitored.

Kinematic Methods

The main advantage of kinematic methods of velocity measurements is their perfect character, and also their high space resolution. By these methods, we can find either the time the marked volume covers a given path, or the path length covered by it over a given time interval. The mark can differ from the surrounding fluid flow in temperature, density, charge, degree of ionization, luminous admittance, index of refraction, radioactivity, etc.

The marks can be created by impurities introduced into the fluid flow in small portions at regular intervals. The mark must follow the motion of the surrounding medium accurately. The motion of marks is distinguished by the method of their registration, into non optical and optical kinematic methods. In the probe (no optical) method which traces thermal non uniformities, a probe consisting of three filaments located in parallel plates (see Anemometers, Thermal) is used. The thermal trace is registered by two receiving wires located a distance 1 from the central wire. By registering the time Δt between the

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pulse heat emitted from the central wire and the thermal response of the receiving wire, we can determine the velocity u = l/Δt. Depending on which receiving wire receives a thermal pulse, we can define the direction of flow.

Marks consisting of regions of increased ion content are also widely used. To create ion marks, a spark or a corona discharge or an optical breakdown under the action of high-pulse laser radiation is used. In tracing by radioactive isotopes, the marks are created by injecting radioactive substances into the fluid flow; the times of passing selected locations by the marks are registered with the help of ionizing-radiation detectors.

Optical kinematic methods use cine and still photography to follow the motion of marks. Three main types of photography are used: cine photography, still photography with stroboscopic lighting and photo tracing. In cine photography, to determine the velocity, successive frames are aligned and the distance between the corresponding positions of the mark is measured. In the stroboscopic visualization method, several positions of the mark are registered on a single frame (a discontinuous track), which correspond to its motion between successive light pulses. Two components of the instantaneous velocity vector are determined by the distance between the particle positions. Typical of the marks used are 3-5 mm aluminum powder particles or small bubbles of gas generated electrolytic ally in the circuit of the experimental plant. Of vital importance in this method is the accuracy of measurement of the time intervals between the flashes.

In the photo tracing method, the motion of the mark is recorded by projecting the image of the mark through a diaphragm (in the form of a thin slit oriented along the fluid flow) onto a film located on a drum rotating at a certain speed. The mark image leaves a trace on the film whose trajectory is determined by adding the two vectors: the vector of mark motion and the vector of film motion. The slope angle of a tangent to this trajectory is proportional to the velocity of mark motion. Further information on the photographic technique is given in the article on Tracer Methods.

Laser Doppler anemometers can also be classified as kinematic techniques (see Anemometers, Laser Doppler).

Dynamic Methods

Among the dynamic methods the most generally employed are, because of the simplicity of the corresponding instruments, the methods based on hydrodynamic interaction between the primary converter and the fluid flow. The Pitot tube is used most often (see Pitot tube) whose function is based on the velocity dependence of the stagnation pressure ahead of a blunt body placed in the flow.

The operating principle of fiber-optic velocity converters is based on the deflection of a sensing element, in the simplest case, made in the form of a cantilever beam of diameter D and length L and placed in the fluid flow between the receiving and sending light pipe, depends on the velocity of fluid flowing around it. The change in the amount of light supplied to a receiving light-pipe is measured by a photo detector.

The upper limit of the range of velocities measured u_{max} is limited by the value of $Re = u_{max} D/\nu \ll 50$ and the frequency response is limited by the natural frequency f_0 which depends on the material,

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diameter and length of the sensing element. However, by varying L and D, we can change the velocities over a wide range. Depending on the fluid in which measurements of umax are made, the dimensions of the sensing elements vary within the limits of 5 ≪ D ≪ 50 µm, 0.25 ≪ L ≪ 2.5 mm.

The tachometric methods use the kinetic energy of flow. Typical anemometers using this principle consist of a hydrometric current meter with several semi-spherical cups or an impeller with blades situated at an angle of attack to the direction of flow (see Anemometer, Vane).

What is a pitot tube?

Basically, a pitot tube is used in wind tunnel experiments and on airplanes to measure flow speed. It's a slender tube that has two holes on it. The front hole is placed in the airstream to measure what's called the stagnation pressure. The side hole measures the static pressure. By measuring the difference between these pressures, you get the dynamic pressure, which can be used to calculate airspeed.

On an airplane, the pitot tube can be mounted in a number of ways, including jutting out from the edge of the wing or sticking up from the fuselage.

Flow Through Orifices And Mouthpieces

An orifice is a small aperture through which the fluid passes. The thickness of an orifice in the direction of flow is very small in comparison to its other dimensions.

If a tank containing a liquid has a hole made on the side or base through which liquid flows, then such a hole may be termed as an orifice.The rate of flow of the liquid through such an orifice at a given time will depend partly on the shape, size and form of the orifice.

An orifice usually has a sharp edge so that there is minimum contact with the fluid and consequently minimum frictional resistance at the sides of the orifice. If a sharp edge is not provided, the flow depends on the thickness of the orifice and the roughness of its boundary surface too.

Flow from an Orifice at the Side of a Tank under a Constant Head

Let us consider a tank containing a liquid and with an orifice at its side wall as shown in Fig. 16.5. The orifice has a sharp edge with the bevelled side facing downstream. Let the height of the free surface of liquid above the centre line of the orifice be kept fixed by some adjustable arrangements of inflow to the tank.

The liquid issues from the orifice as a free jet under the influence of gravity only. The streamlines approaching the orifice converges towards it. Since an instantaneous change of direction is not possible, the streamlines continue to converge beyond the orifice until they become parallel at the Sec. c-c (Fig. 16.5).

For an ideal fluid, streamlines will strictly be parallel at an infinite distance, but however fluid friction in practice produce parallel flow at only a short distance from the orifice. The area of the jet at the Sec. c-c is lower than the area of the orifice. The Sec. c-c is known as the vena contracta.

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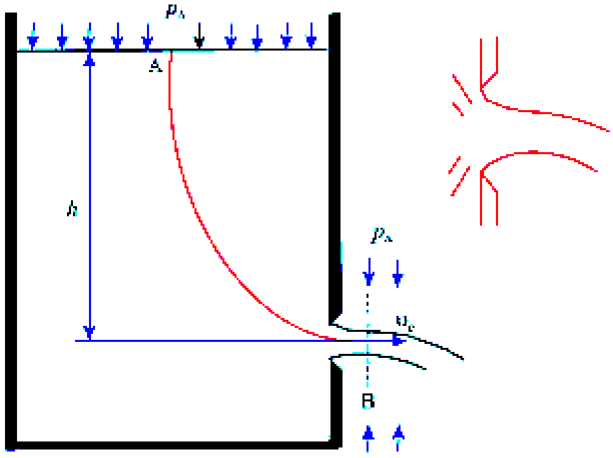
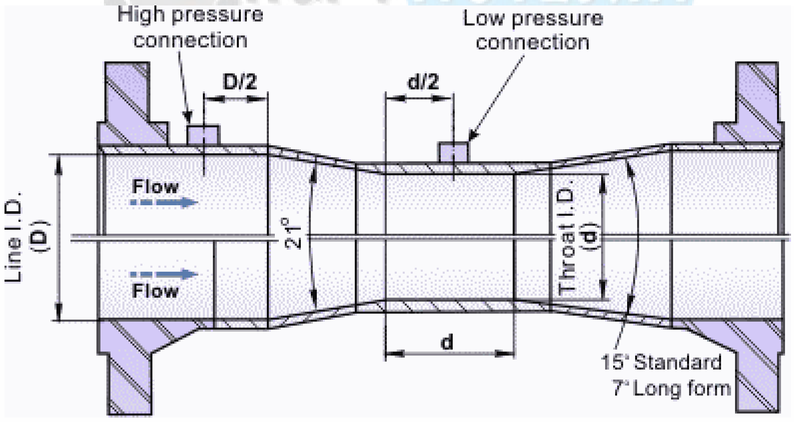


Flow from a Sharp edged Orifice

VENTURI METERS

Venturi meters are flow measurement instruments which use a converging section of pipe to give an increase in the flow velocity and a corresponding pressure drop from which the flow rate can be deduced. They have been in common use for many years, especially in the water supply industry.

The classical Venturi meter, whose use is described in ISO 5167-1: 1991, has the form shown in Figure 1



Classical Vetituri meter design.

For incompressible flow if the Bernoulli Equation is applied between two planes of the tappings,

(1)

$$p_1 + \tfrac{1}{2}\rho\bar{u}_1^2 = p_2 + \tfrac{1}{2}\rho\bar{u}_2^2$$

Where p, ρ and ū are the pressure, density and mean velocity and the subscripts $_1$ and $_2$ refer to the upstream and downstream (throat) tapping planes.

From continuity

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(2)

$$\dot{V} = \tfrac{1}{4}\pi D^2 u_1 = \tfrac{1}{4}\pi d^2 u_2 ,$$

where $\dot{V}$ is the volumetric flow rate and D and d the pipe and throat diameters.

Combining Eqs. (1) and (2)

(3)

$$\dot{V} = \frac{\pi d^2}{4}\frac{1}{\sqrt{(1-\beta^4)}}\sqrt{\left\{\frac{2(p_1-p_2)}{\rho}\right\}},$$

where β is the diameter ratio, d/D. In reality, there is a small loss of total pressure, and the equation is multiplied by the discharge coefficient, C, to take this into account:

(4)

$$\dot{V} = C\frac{\pi d^2}{4}\frac{1}{\sqrt{(1-\beta^4)}}\sqrt{\left\{\frac{2\Delta p}{\rho}\right\}},$$

Where Δp is the differential pressure (≡$p_1 - p_2$). The discharge coefficient of a Venturi meter is typically 0.985, but may be even higher if the convergent section is machined. Discharge coefficients for uncelebrated Venturi meters, together with corresponding uncertainties, are given in ISO 5167-1: 1991.

If the fluid being metered is compressible, there will be a change in density when the pressure changes from p_1 to $p_2$on passing through the contraction. As the pressure changes quickly, it is assumed that no heat transfer occurs and because no work is done by or on the fluid, the expansion is isentropic. The expansion is almost entirely longitudinal and an expansibility factor, ε, can be calculated assuming one-dimensional flow of an ideal gas:

(5)

$$\varepsilon = \left(\left(\frac{\kappa\tau^{2/\kappa}}{\kappa-1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left(\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau}\right)\right)^{1/2}.$$

Where τ is the pressure ratio, p_2/p_1, and κ the isentropic exponent. The expansibility factor is applied to the flow equation in the same way as the discharge coefficient.

Various forms of construction of a Venturi meter are employed, depending on size, but all are considerably more expensive than the orifice plate. However, because most of the differential pressure is recovered by means of the divergent outlet section, the Venturi causes less overall pressure loss in a system and thus saves energy: the overall pressure loss is generally between 5 and 20 per cent of the measured differential pressure. The Venturi meter has an advantage over the orifice plate in that it does not have a sharp edge which can become rounded; however, the Venturi meter is more susceptible to errors due to burrs or deposits round the downstream (throat) tapping.

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The lengths of straight pipe required upstream and downstream of a Venturi meter for accurate flow measurement are given in ISO 5167-1: 1991. These are shorter than those required for an orifice plate by a factor which can be as large as 9. However, Kochen et al. show that the minimum straight lengths between a single upstream 90° bend and a Venturi meter in the Standard are too short by a factor of about 3.

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