Abu Dhabi National Oil Co.

ADNOC Technical Institute

INSTRUMENTATION

INSTRUMENTATION 1

UNIT 4

FLOW MEASUREMENT

UNITS IN THIS COURSE

TABLE OF CONTENTS

4.0 COURSE OBJECTIVES

The student will be able to:

- Explain the difference between total flow and rate of flow measurements.
- Explain the difference between mass and volume flow units.
- Use volumetric and mass conversion tables.
- Explain with the aid of a sketch how positive displacement flow meters work.
- Explain with the aid of a sketch how velocity flow meters work.
- Explain, with the aid of sketches, the use of a pipe restriction to produce a differential pressure for rate of flow measurement

$$Q = C_P \sqrt{P_1 - P_2}$$

- Sketch the following rate of flow measuring devices and list their advantages and disadvantages.

  The orifice plate

  The Venturi

  The Venturi - nozzle.

  The nozzle

- Sketch a variable area meter.
- State the calibration procedures that can be used to calibrate flow meters.

4.1 INTRODUCTION

The aims of this unit are:

i) to explain the measurement of liquid flow

ii) describe devices used to measure liquid flow.

4.2 UNITS OF FLOW

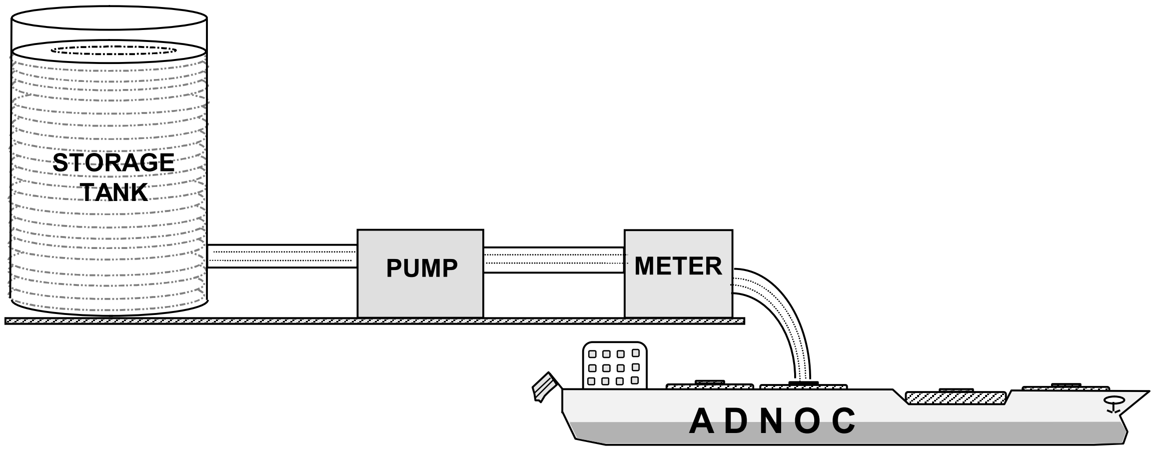


Figure 4-1 Flow Measurements

Figure 4-1 shows a tanker being loaded from a storage tank. The amount of oil loaded must be accurately measured to know how much it costs (fiscal purposes). The total flow (quantity) of oil into the tanker can be measured in two ways:

- by volume, in barrels or cubic meters.
- by mass, in metric or imperial tons (the international standard for oil/gas transfer).

For control purposes the rate of flow (how fast the ship is loaded) is also measured. Rate of flow units can also be given in either volumetric or mass units.

For example

- Rate of flow by volume (volumetric)

  Barrels / Hour

  Cubic Feet / Min.

  Cubic Meters / Sec.

- Rate of flow by mass

  Tons / Hour

  Kilograms / Sec.

  Pounds / Min.

The petrochemical industry uses many different units and there is no common standard. The following list gives some of the units and their conversion.

VOLUME	
Barrel (bbl)	= 42 US gallons = 34.97 Imperial gallons = 163 litres.
Cubic foot (ft^3)	= 0.0929 m^3
Cubic meters (m^3)	= 10.76 ft^3
Cubic meter (m^3)	= 1000 litres
1 Litre	= 1000 cubic centimetres (millilitres).
MASS	
Pound (lb.)	= 0.454 kg
Kilogram (kg)	= 2.2 lb.
Imperial ton	= 2240 lb. (long ton)
Metric tonne	= 1000 kg
American ton	= 2000 lb. (short ton)
Long ton	= 1.016 Metric tonne
Metric tonne	= 0.984 long ton

VELOCITY			
ft/sec	**ft/min**	**metre/sec**	**metre/min**
1	60	0.3048	18.29
0.01667	1	0.005080	0.3048
0.03281	1.9685	0.01	0.600
3.281	196.85	1	60
0.0547	3.281	0.01667	1

ABBREVIATIONS	
Bopd	= Barrels oil per day

Blpd	= Barrels liquid per day
Bcpd	= Barrels condensate per day
Scfpd	= Standard cubic feet per day
MScfpd	= Thousand standard cubic feet per day
MMScfpd	= Million standard cubic feet per day
Nm^3pd	= Normalised meters cubed per day
l/m or Lit/m	= Litres per minute
500 ml/s	= 500 millilitres per second.

Note : Sometimes the p (per) is omitted in the abbreviation. Standard and normalised refer to a standard temperature and pressure. This is normally fixed between buyer and seller. Common standards are:

14.7 psi at 68°F and 1.013 Bar at 15°C.

4.3 QUANTITY METERS

There are two basic methods used to measure quantity (total flow)

(a) Positive displacement.

(b) Velocity meters (semi-positive displacement)

4.3.1 Positive Displacement

The simplest form of positive displacement meter is the gasoline (petrol) pump. It will release an exact amount of gasoline in either imperial gallons or litres. A simple diagram to show its operation is shown in Figure 4-1.

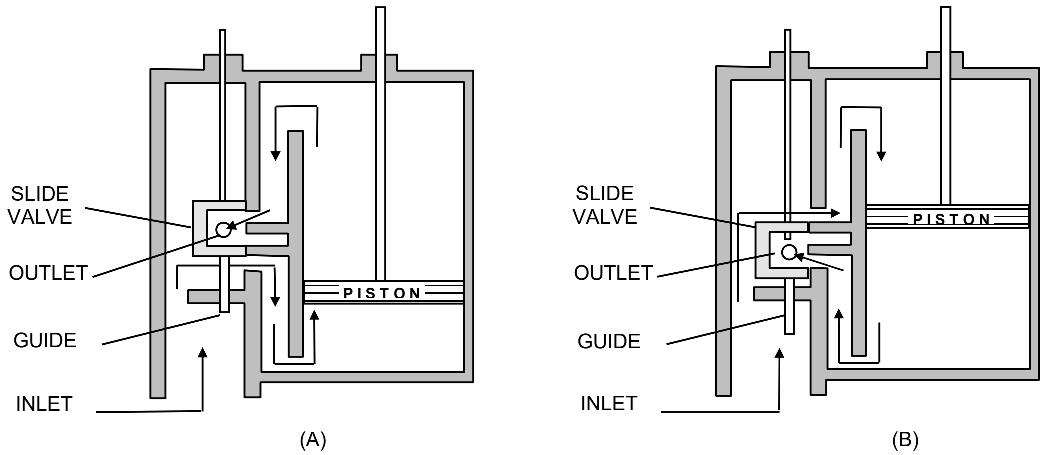


Figure 4-2 Reciprocating Piston Meter

Operation:

When the piston is at the bottom of its stroke (see Figure (A)) the slide valve opens the inlet vent to the bottom of the cylinder. The liquid (petrol) flows into the cylinder below the piston and pushes the piston upwards. As the piston rises the liquid in the top half of the cylinder is pushed through the outlet vent into the outlet pipe. When the piston is at the top of its stroke the slide valve closes the outlet at the top of the cylinder and opens the inlet vent. At the same time the slide valve opens the outlet vent at the bottom of the cylinder and closes the inlet (see Figure (B)). The pressure of the liquid coming into the top of the cylinder pushes the liquid at the bottom of the cylinder into the outlet pipe. The amount of liquid coming out of the cylinder during each stroke is measured. Each time the piston makes a stroke a meter connected to the top of the piston indicates how much liquid has been delivered.

The oil industry's positive displacement meter is the sliding vane meter. It can be used for measuring large quantities of liquid flow; eg, oil being loaded onto a tanker. A typical example is shown in Figure 4-3.

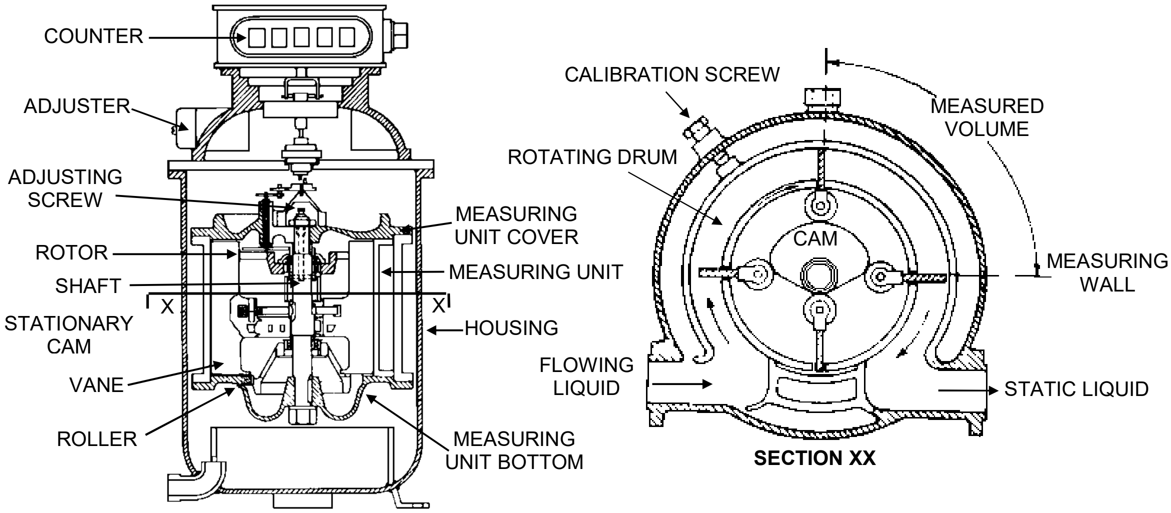


Figure 4-3 The Sliding Vane Meter

Operation:

This meter consists of a rotating drum with four sliding vanes (long blades) set inside it. The vanes move around a cam which is fixed in the centre of the drum. The liquid flowing through the meter pushes the vanes round with the drum. As the vanes rotate with the drum the cam pushes them in and out against the measuring wall. As the vanes are pushed against the measuring wall, they trap a measured volume of liquid between the drum and the measuring wall. Each revolution of the drum will measure 4 lots of the measured volume. The number of revolutions of the drum is counted and displayed. This gives the total flow passing through the meter. The calibration nut is used to adjust the side of the measurement chamber so that the volume of liquid passing through the meter can be measured exactly.

Note: A static liquid chamber is added so that there is no differential pressure across the measurement wall.

4.3.2 Velocity Meters (semi-positive displacement)

The sliding-vane type meter is not used much nowadays because it is slow. Most loading meters for shipping are now of the velocity type. The velocity meter measures the speed of the flow and works out the volume of flow using calibration figures.

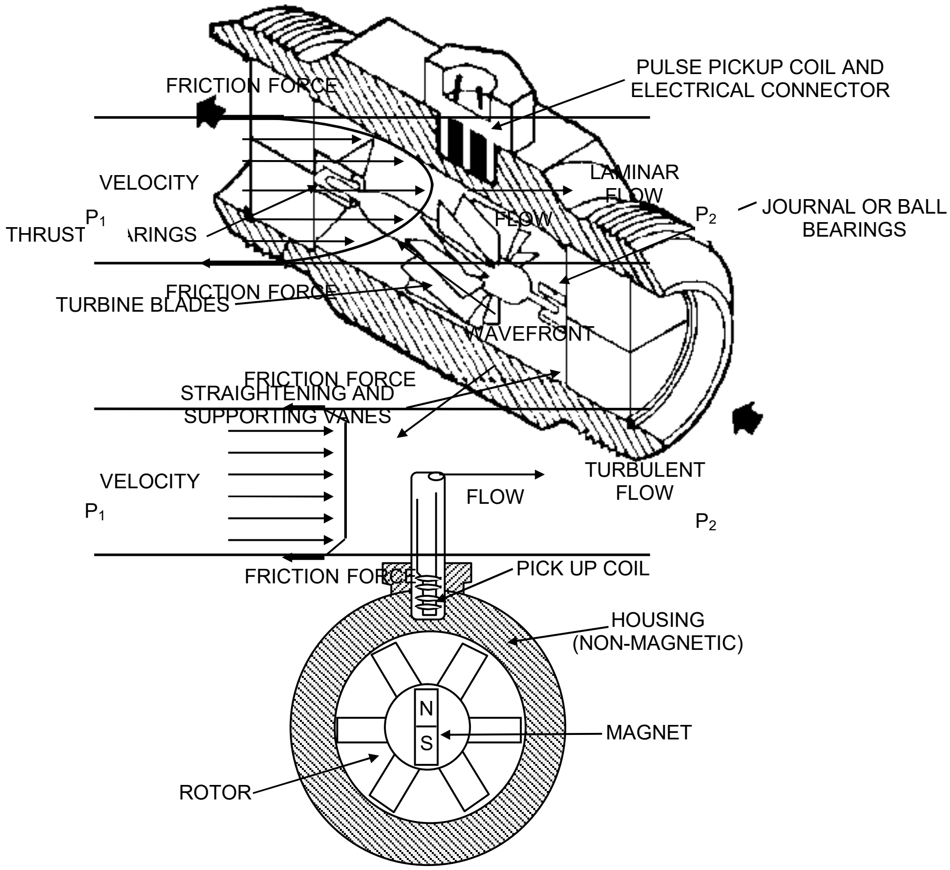


Figure 4-4 The Turbine Meter

Operation:

The velocity (speed) at which the rotor turns depends on the flow rate. The pick-up coil gets a pulse induced for every rotation. The number of pulses is counted by an electronics unit. This unit displays the total quantity of flow.

Note :- In the oil/gas industry these two quantity meters are only for liquid measurements.

4.4 RATE OF FLOW MEASUREMENT

The previous two quantity meters are used to calculate how much oil the customer pays for, so they must be extremely accurate. A modern turbine meter will measure to within $\pm$ 0.1% of the true reading. Devices for measuring the rate of flow do not need to be so accurate. They are used mainly to give a flow signal to a controller.

4.4.1 Flow Basics

Figure 4-5 Flow in a Pipe

Figure 4-5 shows the flow of a fluid (gas or liquid) down a pipe. The flow is produced by the differential pressure across the ends of the pipe ($P_1 - P_2$). The walls of a pipe are not perfectly smooth. The frictional force at the walls will cause the fluid to go slower at the edge than at the centre.

This leads to two different types of flow.

- LAMINAR FLOW

  The fluid flow rate is slow and the velocity of the wavefront down the pipe is much higher in the centre of the pipe than at the edges.

- TURBULENT FLOW

  The fluid flow rate is high and the velocity of the wavefront is the same across the pipe. However, the flow is a little slower at the edges against the wall.

The velocity lines on the diagram are called STREAMLINES. Engineers assume the streamlines are straight and parallel to each other.

4.4.2 Flow Measurement by Differential Pressure

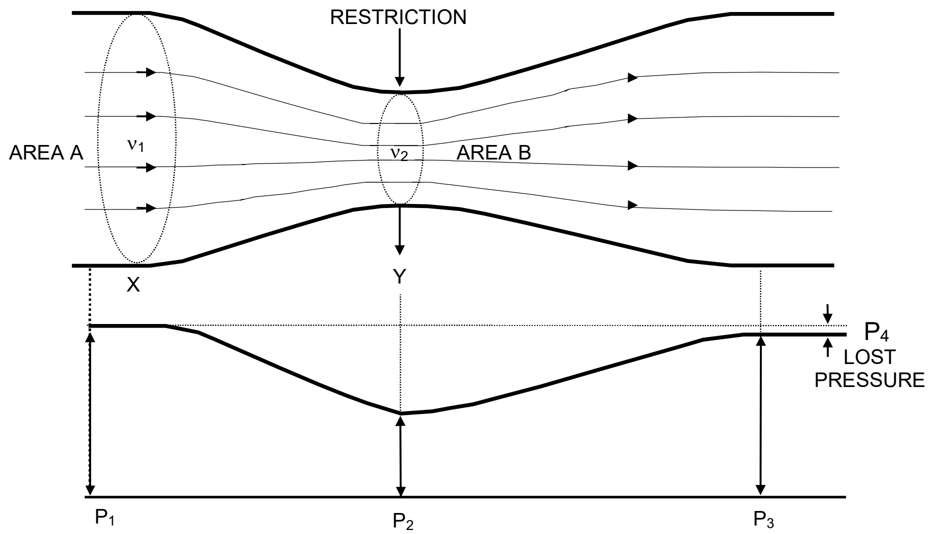


Figure 4-6 Flow through a Restriction

Figure 4-6 shows the flow of a fluid through a closed pipe full of liquid or gas. It has a restriction in the pipe.

Because there is a restriction, there is a difference between the pressure at the centre of the restriction (position Y) and the pressure in the normal pipeline (position X)

The difference in pressure between the centre of the restriction and the normal pipeline pressure (P_1-P_2) is proportional to the square root of the flow rate (Q) given as an equation.

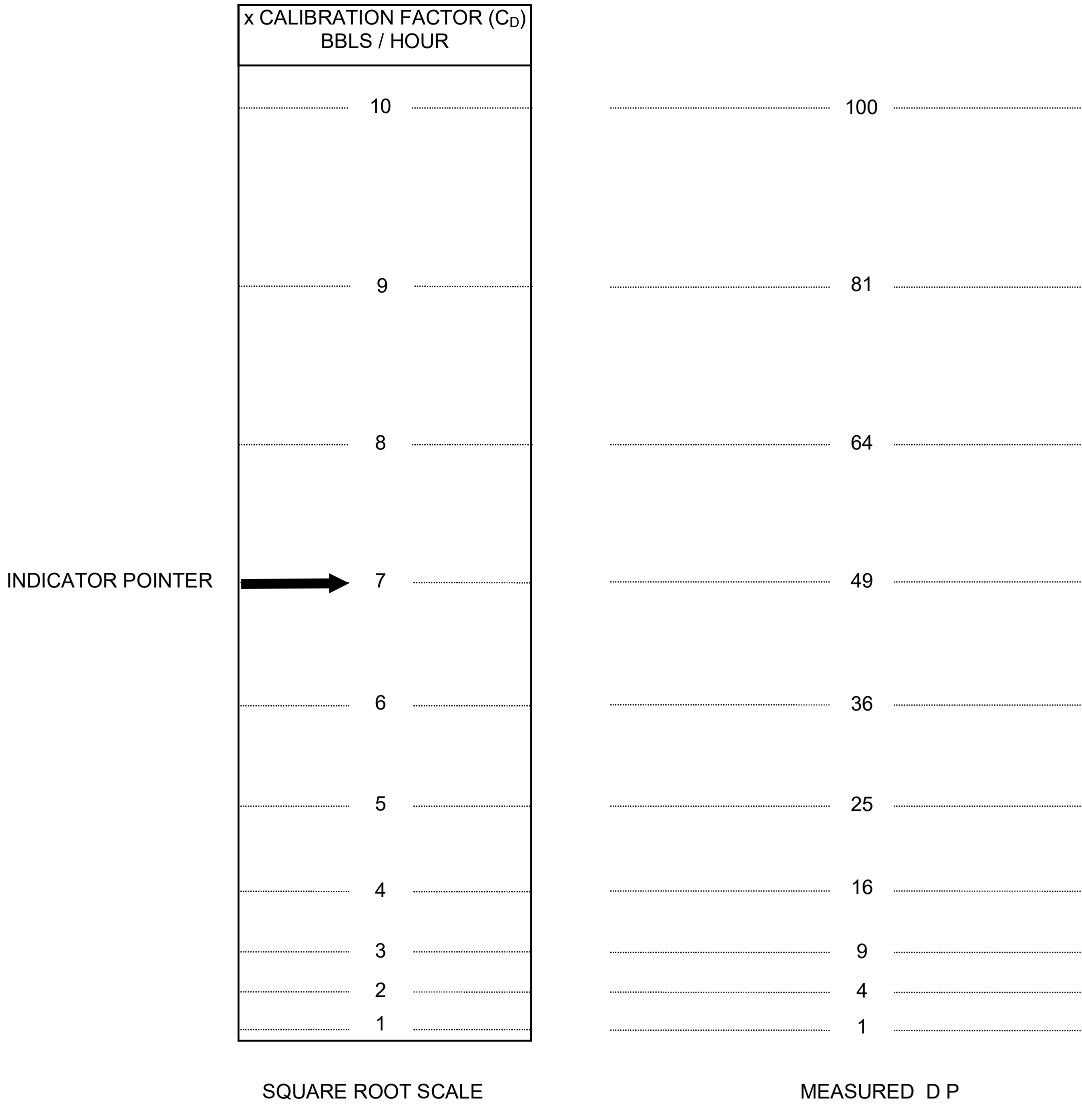
$$Q \propto \sqrt{P1 - P2}$$

$$\text{or } Q = C_D \sqrt{P_1 - P_2}$$

C_D is called the "coefficient of discharge". We can get this from tables. It depends on what is used to make the restriction.

Note :- P_1-P_2 is often written as DP (Differential Pressure) or ΔP (Delta P).

The above equation means that the measured DP has to be square rooted before the flow rate can be calculated. Modern electronic transmitters do this automatically and a linear 4-20 mA signal for flow rate is produced. The older pneumatic systems produce a flow rate indication by using a square root scale or chart. A typical square root scale is shown below.



Theory

The equation $Q \propto \sqrt{\Delta P}$ comes from Bernoulli's theory.

Bernoulli said "The sum of the kinetic energy (velocity energy) and pressure energy at any point in a closed pipe is a constant", i.e. the sum of these two types of energy is always the same.

This is true if the pipe is horizontal and the temperature of the fluid does not change.

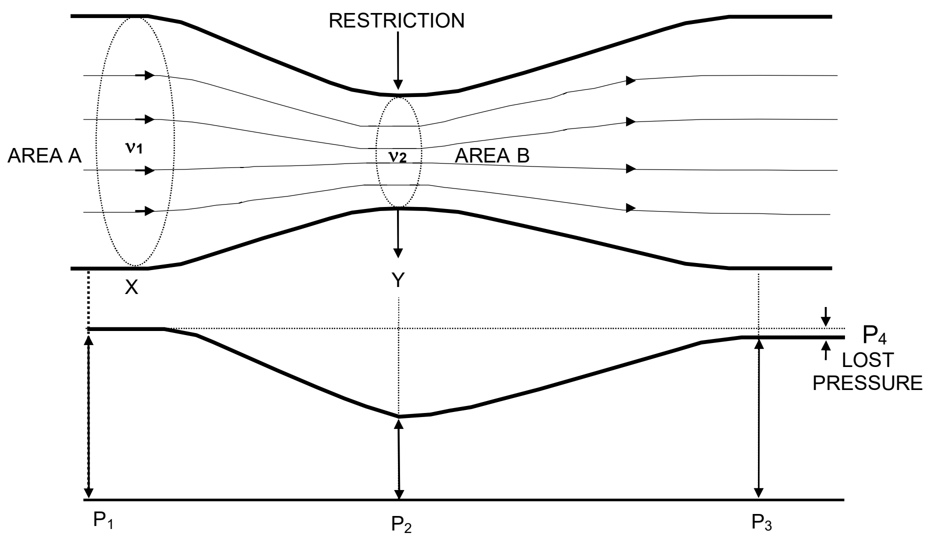
Kinetic Energy = $\frac{1}{2}m\nu^2$ where m = Mass of fluid

ν = Velocity of the fluid

Pressure Energy = P m / *p* P = Pressure of fluid

p = Density of fluid

As the fluid flows through the restriction, it gets faster (the velocity increases). This is because FLOW = VELOCITY x AREA. If the area is smaller, the velocity is bigger. So, the pressure must fall and from the diagram;



Energy at point A = Energy at point B

$$\frac{1}{2}m\nu_1^2 + \frac{P_1\,m}{\rho} = \frac{1}{2}m\nu_2^2 + \frac{P_2\,m}{\rho}$$

or

$$\frac{P_1\,m}{\rho} - \frac{P_2\,m}{\rho} = \frac{1}{2}m\nu_2^2 - \frac{1}{2}m\nu_1^2$$

In this equation m can be cancelled, so that

$$P_1 - P_2 = \frac{1}{2}\rho(\nu_2^2 - \nu_1^2)$$

The flow is constant so that

$$Q = AV_1 = BV_2$$

$$V_2 = \frac{A}{B} V_1$$

$$P_1\text{-}P_2 = \tfrac{1}{2}\rho \left(\left(\frac{A}{B} V_1\right)^2 V_1^2\right)$$

$$P_1\text{-}P_2 = \tfrac{1}{2}\rho \, (V_1)^2 \left(\frac{A^2}{B^2} \text{-}1\right)$$

This equation means that the velocity at the restriction is given by;

$$V_1 \; \alpha \; \sqrt{P_1 - P_2} \quad (\rho \text{ constant})$$

The flow rate will be V_1 multiplied by the area B to give the equation;

$$Q = C_D \sqrt{P_1 - P_2}$$

C_D is called the "coefficient of discharge". We can get this from tables. It depends on what is used to make the restriction.

4.4.3 Differential Pressure Devices

There are many devices used to make a restriction in a pipeline so that rate of flow can be measured. The design of each device is fixed by either ISO or ISA (Instrument Society of America) standards. There are standard tables which are used to calculate flow. In the petroleum industry engineers assume the flow is turbulent. However, you can get tables for laminar flow if you need them. A field technician will only need to calibrate the differential pressure transmitter. An engineer will give a technician the figures he needs to do this. Some of the more common devices are given below together with their uses.

- The Orifice Plate

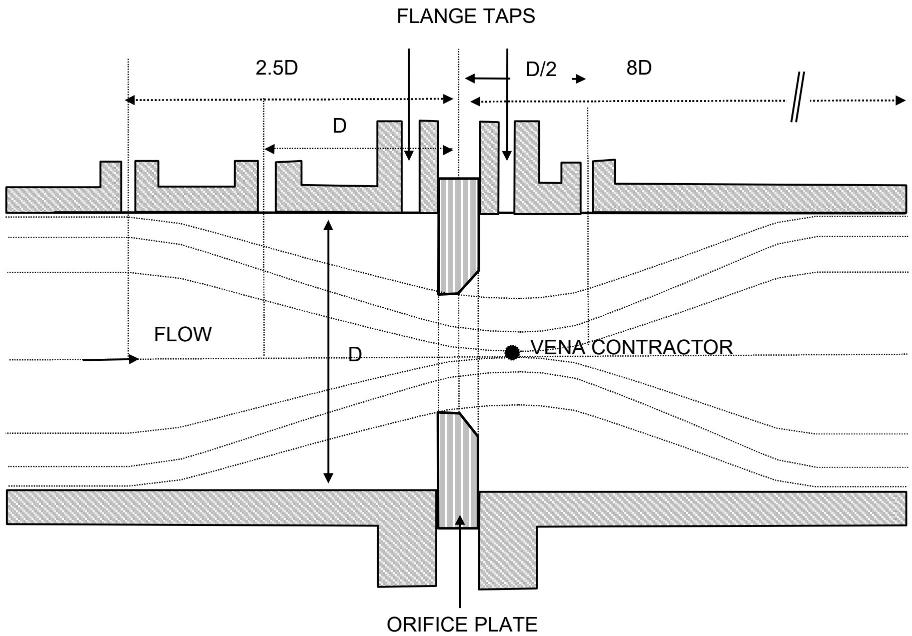


Figure 4-7 The Orifice Plate and Tappings

Figure 4-7 shows an orifice plate fitted into a pipeline to make a differential pressure. The orifice plate is a flat disc with a hole in it shaped as shown. The front edge is sharp and the back edge is chamfered. The fluid is squeezed as it passes through the hole and has a maximum velocity at a point called the VENA CONTRACTOR.

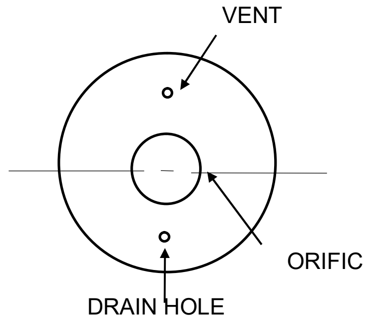
Taps (holes) are drilled into the pipeline and a differential pressure transmitter connected across the orifice plate. The differential pressure is measured. The square root of the differential is used to produce a flow signal which is proportional to the flow.

Standard tables are produced for the tapping places as shown.

D & D/2	For maximum dp
Flange Taps	The most common tapping place. It produces a high D.P. These can be drilled accurately in the workshop. The taps can be vertical as shown on the diagram or they can be at an angle of 45° (corner taps).
2.5D & 8D	Not much used nowadays. This is because it is difficult to place them exactly on the pipeline. They measure the pressure loss across the plate.

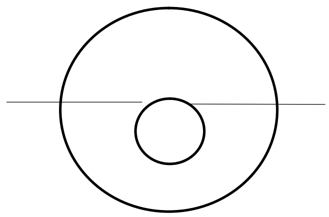
The position of the hole in the plate depends on the fluid being measured. The diagram below shows typical plates and their uses.

CONCENTRI



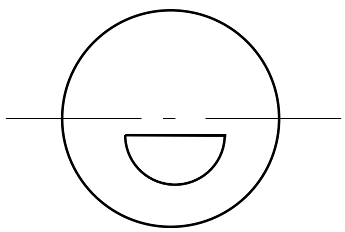
This is the standard orifice plate. The venthole is for gases in a liquid. The drainhole is for liquids in a gas.

ECCENTRIC



This is used when the flow of thick dirty liquids is being measured, e.g. engine cooling oil.

SEGMENTAL



This is used when the liquids contain solids, e.g. cement.

All orifice plates must be made to an exact standard to fit the reference tables. A typical example is given below for a D and D/2 tap fitting.

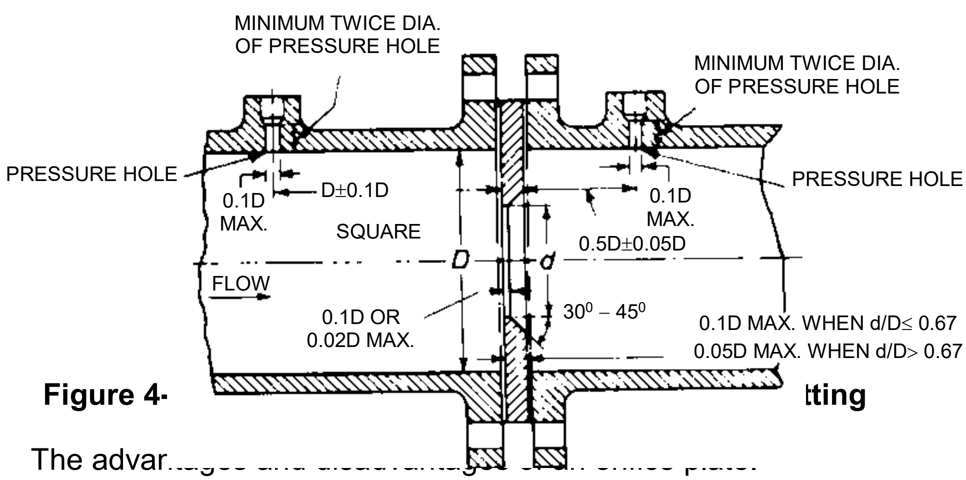


Figure 4- ... tting

The advar...

Advantages

1. Simple in operation
2. No moving parts
3. Reliable for a long time
4. Not expensive

Disadvantages

1. Square root relationship
2. Difficult to install
3. Range of measurement small. Operator has to change plate (hole size) to change the range.

Note :- The orifice plate is the only suitable device when measuring high gas flow rates.

- THE VENTURI

This is a very expensive device. It is used when the energy of the flow is so low that the restriction could stop the flow (low pressure loss). The diagram below shows a typical Venturi with its pressure tappings (see Figure 4-9).

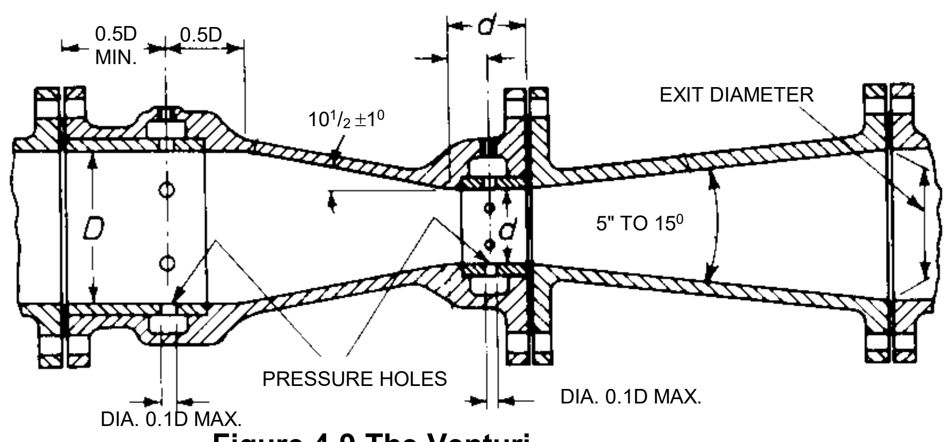


Figure 4-9 The Venturi

The advantages and disadvantages of the venturi.

Advantages

1. Simple in operation
2. Low pressure loss

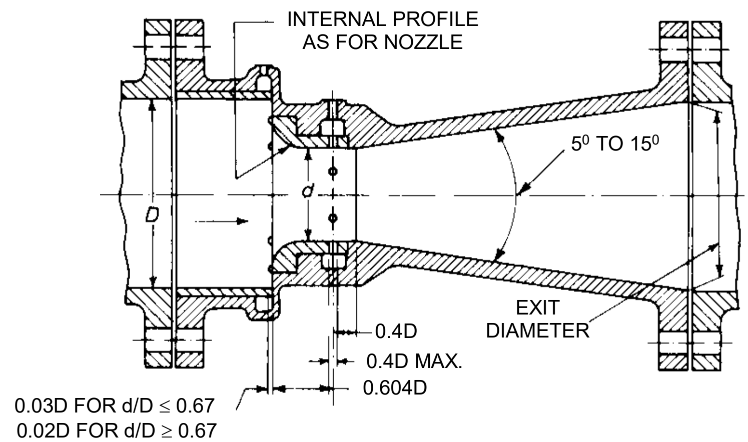
3. Can be used with liquids that contain solids
4. Reliable for a long time
5. No moving parts

Disadvantages

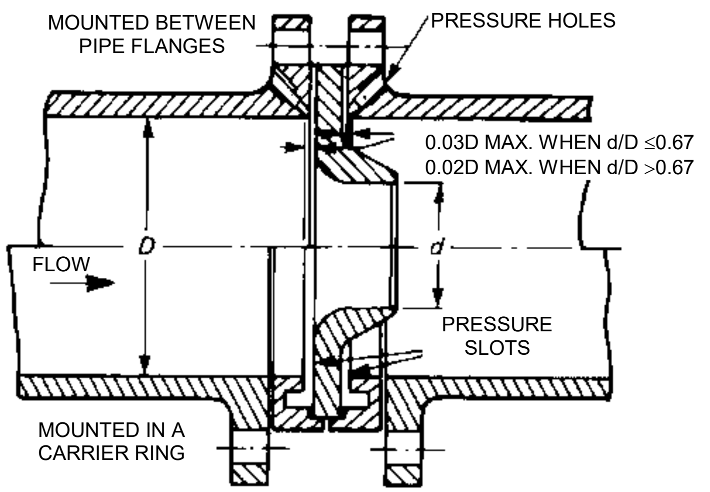
1. Expensive
2. Square root relationship
3. Poor range. Designed for one job only
4. Difficult to install

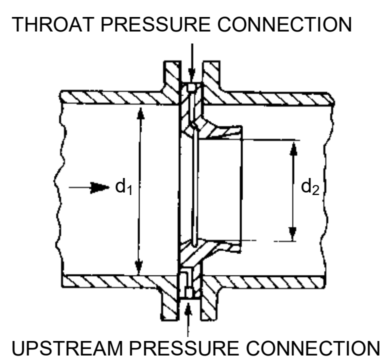
- NOZZLES

These are a compromise between the orifice plate and the venturi. They are cheaper than a venturi but have a high pressure loss. They are more expensive than an orifice plate, but have lower pressure loss. A few examples are shown below.



VENTURI - NOZZLE





FLOW NOZZLE INSERT **DALL TUBE**

- PRESSURE LOSS GRAPH

The graph below (see Figure 4-10) shows how much pressure is lost when these devices are used. The Y axis shows the hole size and the X axis shows the percentage of pressure lost. This shows the advantages of the venturi over the orifice plate. It also shows how the nozzle is between the two.

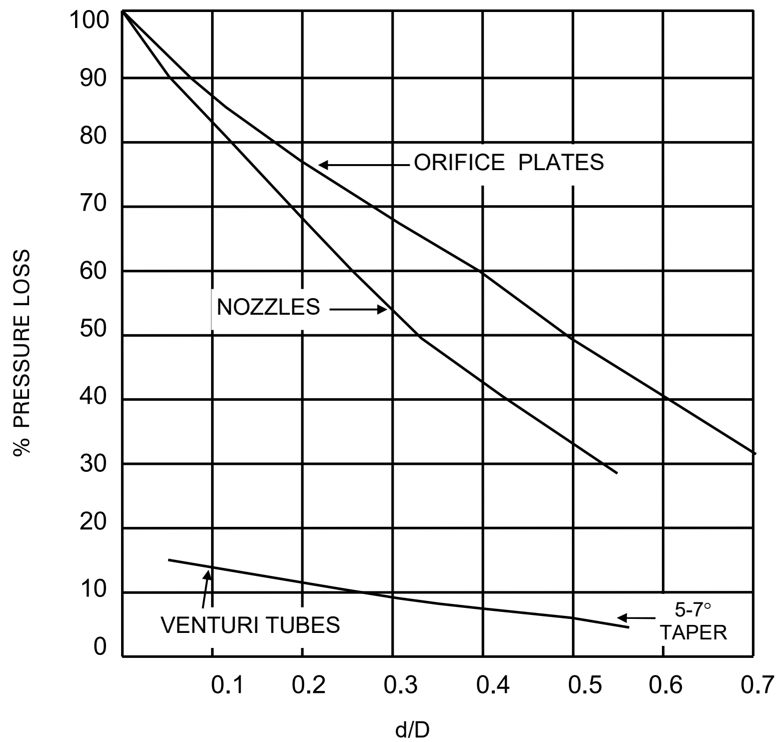


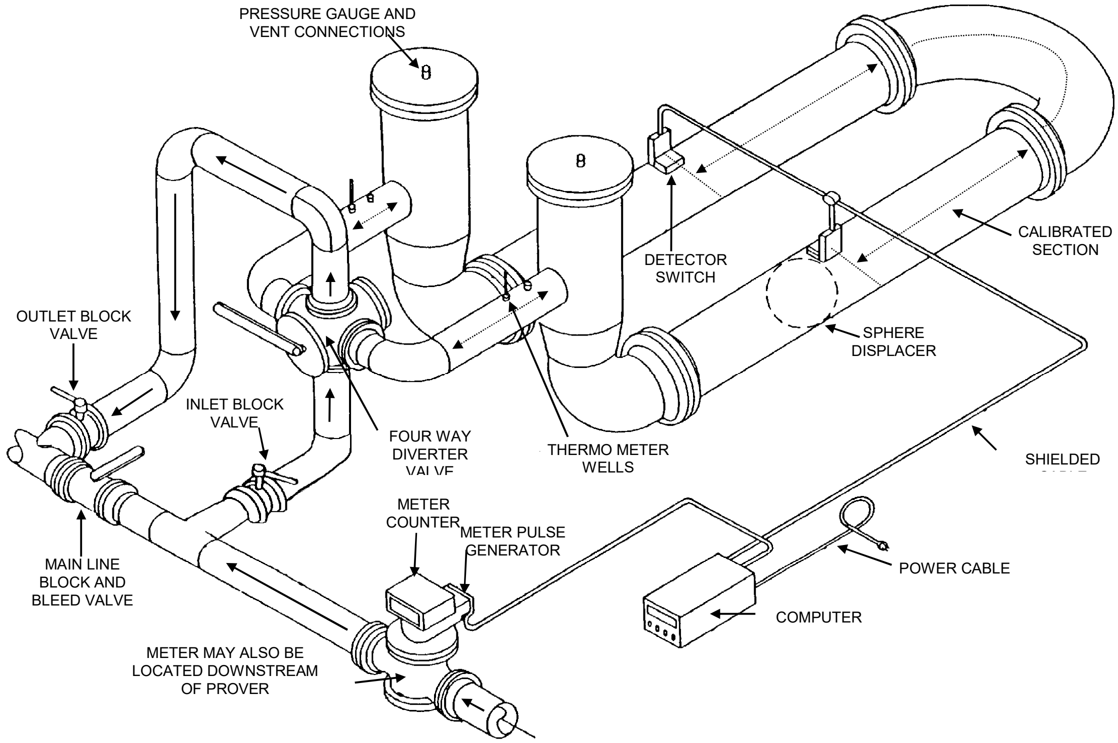
Figure 4-10 Pressure Loss Graph

4.5 VARIABLE AREA METERS

These are simple devices used to indicate small rates of flow. They are used by an operator out in the field. Typical uses are:

- In seal oil and lubrication oil flow lines on large rotating machines; eg, diesel engines and gas compressors.
- In cooling water lines for machines and processes.

Figure 4-11 shows a variable area meter (Rotameter).



The Rotameter is fitted vertically into the flow line. The flow of the fluid is from bottom to top through the cylinder. The cylinder increases in area from bottom to top. With no flow, the float is at the bottom (position A). When the flow increases, the pressure makes the float rise. It will rise to a position where the flow pressure on the float equals the weight of the float, (position B). If the flow gets faster there is more pressure on the float and it will rise higher (position C). The flow rate indicated depends on the size of the device. It is pre-calibrated by the manufacturer. The operator reads the flow rate from the transparent scale using the top of the float as a marker.

4.6 CALIBRATION OF FLOW MEASURING DEVICES

4.6.1 Quantity Meters

The only way to calibrate a flow quantity meter accurately is to use a standard volumetric measure. This is easy when the volumes are small. A gasoline pump is checked by a standard measure; eg, a 10 litre can. When you fill the can the meter on the pump should read 10 litres. This method is impossible when you need to measure thousands of gallons per minute. The system used to check large liquid volumes is called a PROVER LOOP. A simple diagram of the system is shown in Figure 4-12.

Figure 4-12 The Prover Loop

The prover loop consists of a calibrated section of pipe. A tightly fitting rubber ball (sphere displacer) is pushed through the pipe by the flow of a liquid which must be measured. Two detector switches mark the travel of the ball. The computer works out the volume measured by the travelling ball and compares this measurement against the volume measured by the meter. The four way valve lets the operator send the ball in both directions through the calibrated section of pipe. This means that the ball can be passed a number of times to make sure the meter is checked accurately.

4.6.2 Calibration of Differential Pressure Devices

In order to calibrate the differential pressure transmitter, the field technician uses figures given by the design engineer. For control purposes, the actual flow need not be exact. However, the movement of large amounts of gas can only be checked using an orifice plate. The true volume, at standard pressure, is worked out by a special programme on a computer. This work is done by a specialist called a metering engineer.

4.6.3 Flow Straighteners

All flow measuring devices which use a restriction need a stream-lined flow. Flow measuring devices must be placed away from things which disturb the flow; eg elbows, control valves, etc. If this is not possible then the flow is streamlined by flow straighteners. These are groups of small pipes placed in the pipe line as shown in Figure 4-13.

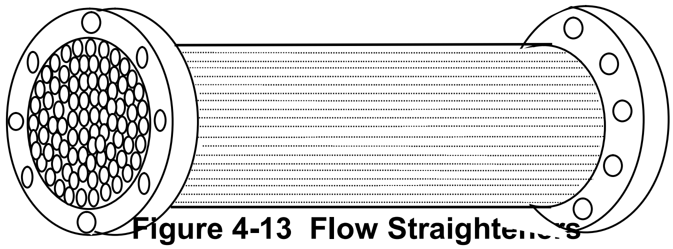


Figure 4-13 Flow Straighteners