LECTURE NO.1

INTRODUCTION – INSTRUMENTATION, PROCESS CONTROL - MEASUREMENTS - METHODS OF MEASUREMENTS - DIRECT METHODS- IN-DIRECT METHODS

Instrumentation

Instrumentation is defined as "the art and science of measurement and control". Instrumentation can be used to refer to the field in which Instrument technicians and engineers work in, or it can refer to the available methods and use of instruments.

Instruments are devices which are used to measure attributes of physical systems. The variable measured can include practically any measurable variable related to the physical sciences. These variables commonly include: pressure , flow , temperature , level , density , viscosity , radiation , current , voltage , inductance , capacitance , frequency ,chemical composition , chemical properties , various physical properties, etc.

Instruments can often be viewed in terms of a simple input-output device. For example, if we "input" some temperature into a thermocouple, it "outputs" some sort of signal. (Which can later be translated into data.) In the case of this thermocouple, it will "output" a signal in millivolts.

Process control

The purpose of process control is to reduce the variability in final products so that legislative requirements and consumers' expectations of product quality and safety are met. It also aims to reduce wastage and production costs by improving the efficiency of processing. Simple control methods (for example, reading thermometers, noting liquid levels in tanks, adjusting valves to control the rate of heating or filling), have always been in place, but they have grown more sophisticated as the scale and complexity of processing has increased. With increased mechanization, more valves need to be opened and more motors started or stopped. The timing and sequencing of these activities has become more critical and any errors by operators has led to more serious quality loss and financial consequences. This has caused a move away from controls based on the operators' skill and judgment to technology-based control systems. Initially, manually operated valves were replaced by electric or pneumatic operation and switches for motors were relocated onto control panels. Measurements of process variables, such as levels of liquids in tanks, pressures, pH, temperatures, etc., were no longer taken at the site of equipment, but were sent by transmitters to control panels and gradually processes became more automated.

Automatic control has been developed and applied in almost every sector of the industry. The impetus for these changes has come from:

- increased competition that forces manufacturers to produce a wider variety of products more quickly
- escalating labour costs and raw material costs
- increasingly stringent regulations that have resulted from increasing consumer demands for standardized, safe foods and international harmonization of legislation and standards.

For some products, new laws require monitoring, reporting and traceability of all batches produced which has further increased the need for more sophisticated process control.

All of these requirements have caused manufacturers to upgrade the effectiveness of their process control and management systems. Advances in microelectronics and developments in computer software technology, together with the steady reduction in the cost of computing power, have led to the development of very fast data processing. This has in turn led to efficient, sophisticated, interlinked, more operator-friendly and affordable process control systems being made available to manufacturers. These developments are now used at all stages in a manufacturing process, including:

- ordering and supplying raw materials
- detailed production planning and supervision
- management of orders, recipes and batches

- controlling the flow of product through the process
- controlling process conditions
- evaluation of process and product data (for example, monitoring temperature profiles during heat processing or chilling
- control of cleaning-in-place procedures
- packaging, warehouse storage and distribution.

MEASUREMENTS

Measurements provide us with a means of describing various phenomena in quantitative terms. It has been quoted "whatever exists, exists in some amount". **The determination of the amount is measurement all about**. There are innumerable things in nature which have amounts. The determination of their amounts constitutes the subject of Mechanical Measurements. The measurements are not necessarily carried out by purely mechanical means. Quantities like pressure, temperature, displacement, fluid flow and associated parameters, acoustics and related parameters, and fundamental quantities like mass, length, and time are typical of those which are within the scope of mechanical measurements. However, in many situations, these quantities are not measured by purely mechanical means, but more often are measured by electrical means by transducing them into an analogous electrical quantity.

The Measurement of a given quantity is essentially an act or result of comparison between a quantity whose magnitude (amount) is **unknown**, with a similar quantity whose magnitude (amount) is **known**, the latter quantity being called a Standard.

Since the two quantities, the amount of which is unknown and another quantity whose amount is known are compared, the result is expressed in terms of a numerical value. This is shown in the Fig. 1.1.

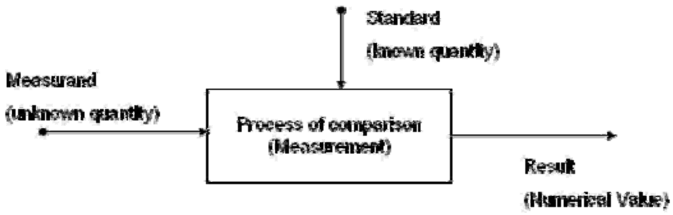


Fig. 1.1 Fundamental Measuring Process.

In order that the results of measurement are meaningful, the basic requirements are:

(i) the standard used for comparison purposes must be accurately defined and should be commonly acceptable,

(ii) the standard must be of the same character as the measurand (the unknown quantity or the quantity under measurement).

(iii) the apparatus used and the method adopted for the purposes of comparison must be provable.

METHODS OF MEASUREMENT

The methods of measurement may be broadly classified into two categories:

Direct Methods.

In-Direct Methods.

Direct Methods.

In these methods, the unknown quantity (also called the measurand) is directly compared against a standard. The result is expressed as a numerical number and a unit. Direct methods are quite common for the measurement of physical quantities like length, mass and time.

Indirect Methods

Measurements by direct methods are not always possible, feasible and, practicable. These methods in most of the cases, are inaccurate because they involve human factors. They are also less sensitive. Hence direct methods are not preferred and are less commonly used.

In engineering applications Measurement Systems are used. These measurement systems use indirect methods for measurement purposes.

A measurement system consists of a transducing element which converts the quantity to be measured into an analogous signal. The analogous signal is then processed by some intermediate means and is then fed to the end devices which present the results of the measurement.

LECTURE NO.2

PRIMARY MEASUREMENTS - SECONDARY MEASUREMENTS – TERTIARY MEASUREMENT -INSTRUMENTS AND MEASUREMENT SYSTEMS - MECHANICAL INSTRUMENTS - ELECTRICAL INSTRUMENTS - ELECTRONIC INSTRUMENTS

PRIMARY, SECONDARY AND TERTIARY MEASUREMENTS

Measurements may be classified as primary, secondary and tertiary based upon whether direct or indirect methods are used.

Primary Measurements:- A primary measurement is one that can be made by direct observation without involving any conversion (translation) of the measured quantity into length.

Example:-

(i) the matching of two lengths, such as when determining the length of an object with a metre rod,

(ii) the matching of two colors, such as when judging the color of red hot metals

Secondary Measurements:- A secondary measurement involves only one translation (conversion) to be done on the quantity under measurement to convert it into a change of length. The measured quantity may be pressure of a gas, and therefore, may not be observable. Therefore, a secondary measurement requires,

(i) an instrument which translates pressure changes into length changes, and

(ii) a length scale or a standard which is calibrated in length units equivalent to known changes in pressure.

Therefore, in a pressure gauge, the primary signal (pressure) is transmitted to a translator and the secondary signal (length) is transmitted to observer's eye.

Tertiary Measurements :-A tertiary measurement involves two translations. A typical example of such a measurement is the measurement of temperature of an object by thermocouple. The primary signal (temperature of object) is transmitted to a translator which generates a voltage which is a function of the temperature. Therefore, first translation is temperature to voltage. The voltage, in turn, is applied to a voltmeter through a pair of wires. The second translation is then voltage into length. The tertiary signal (length change) is transmitted to the observer's brain. This tertiary measurement is depicted in, Fig. 2.1.

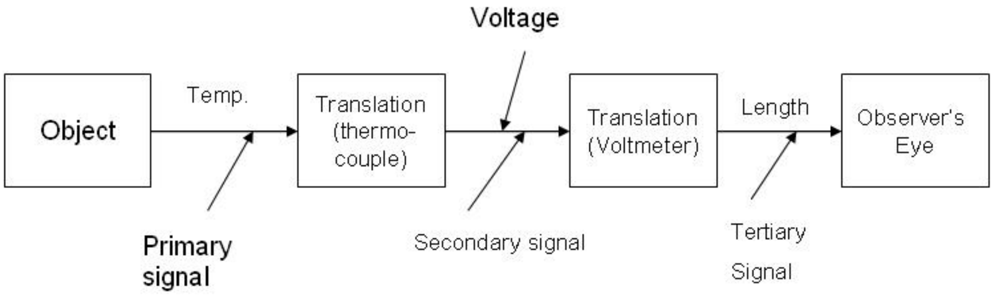


Fig. 2.1 A typical tertiary measurement.

INSTRUMENTS AND MEASUREMENT SYSTEMS

Measurements involve the use of instruments as a physical means of determining quantities or variables. The instrument enables the man to determine the value of unknown quantity or variable. *A measuring instrument exists to provide information about the physical value of some variable being measured.* In simple cases, an instrument consists of a single unit which gives an output reading or signal according to the unknown variable (measurand) applied to it. In more complex measurement situations, a measuring instrument may consist of several separate elements. These elements may consist of **transducing elements** which **convert the measurand to an analogous form**. The analogous signal is then processed by some intermediate means and then fed to the end devices to present the results of the measurement for the purposes of display, record and control. Because of this modular nature of the elements within it, it is common to refer the measuring instrument as a measurement system.

MECHANICAL, ELECTRICAL AND ELECTRONIC INSTRUMENTS

The history of development of instruments encompasses **three phases of instruments**, viz. : (i) mechanical instruments, (it) electrical instruments and (iii) electronic instruments.

The three essential elements in modern instruments are :

(i) a detector,

(ii) an intermediate transfer device, and

(iii) an indicator, recorder or a storage device.

Mechanical Instruments. These instruments are very reliable for static and stable conditions. Major disadvantage is unable to respond rapidly to measurements of dynamic and transient conditions. This is due to the fact that these instruments have moving parts that are rigid, heavy and bulky and consequently have a large mass. Mass presents inertia problems and hence these instruments cannot follow the rapid changes which are involved in dynamic measurements. Thus it would be virtually impossible to measure a 50 Hz voltage by using a mechanical instrument but it is relatively easy to measure a slowly varying pressure using these instruments. Another disadvantage of mechanical instruments is that most of them are a potential source of noise and cause noise pollution.

Electrical Instruments. Electrical methods of indicating the output of detectors are more rapid than mechanical methods. Electrical system normally depends upon a mechanical meter movement as indicating device. This mechanical movement has some inertia and therefore these instruments have a limited time (and hence, frequency) response. For example, some electrical recorders can give full scale response in 0.2 s, the majority of industrial recorders have responses of 0.5 to 24 s.

Electronic Instruments.: The necessity to step up response time and also the detection of dynamic changes in certain parameters, which require the monitoring time of the order of ms and many a times, μs , have led to the design of today's electronic instruments and their associated circuitry. These instruments require use of semiconductor devices. **Since in electronic devices, the only movement involved is that of electrons,** the response time is extremely small on account of **very small inertia of electrons**. For example, a Cathode Ray Oscilloscope (CRO) is capable of following dynamic and transient changes of the order of a few ns (10^{-9} s).

Another advantage of using electronic devices is that very weak signals can be detected by using pre-amplifiers and amplifiers. The foremost importance of the electronic instruments is the power amplification provided by the electronic amplifiers, which results in higher sensitivity. This is particularly important in the area of **Bio-instrumentation** since **Bio-electric potentials** are very weak i.e., lower than **1 mV**. Therefore, these signals are too small to operate electro-mechanical devices like recorders and they must be amplified. **Additional power** may be fed into the system to provide an increased power output beyond that of the input. Another advantage of electronic instruments is the ability to obtain indication at a **remote location** which helps in monitoring inaccessible or hazardous locations. The most important use of electronic instrument is their **usage in measurement of non-electrical quantities**, where the non-electrical quantity is converted into electrical form through the use of transducers.

Electronic instruments are light, compact, have a high degree of reliability and their power consumption is very low.

Communications is a field which is entirely dependent upon the electronic instruments and associated apparatus. **Space communications,** especially, makes use of air borne transmitters and receivers and job of interpreting the signals is left entirely to the electronic instruments.

In general electronic instruments have (i) a higher sensitivity (ii) a faster response, (iii) a greater flexibility, (iv) lower weight, (v) lower power consumption and (vi) a higher degree of reliability

LECTURE NO.3

CLASSIFICATION OF INSTRUMENTS: DEFLECTION AND NULL TYPES, MANUALLY OPERATED AND AUTOMATIC TYPES, ANALOG AND DIGITAL TYPES, SELF-GENERATING AND POWER-OPERATED TYPES, CONTACTING AND NON-CONTACTING TYPES, DUMB AND INTELLIGENT TYPES

CLASSIFICATION OF INSTRUMENTS

Instruments may be classified according to their application, mode of operation, manner of energy conversion, nature of output signal and so on. The instruments commonly used in practice may be broadly categorized as follows:

Deflection and Null Types

A deflection type instrument is that in which the physical effect generated by the measuring quantity produces an equivalent opposing effect in some part of the instrument which in turn is closely related to some variable like mechanical displacement or deflection in the instrument. For example, the unknown weight of an object can be easily obtained by the deflection of a spring caused by it on the spring balance as shown in Fig. 3.1. Similarly, in a common Bourdon gauge, the pressure to be measured acts on the C-type spring of the gauge, which deflects and produces an internal spring force to counter balance the force generated by the applied pressure.

Deflection instruments are simple in construction and operation.

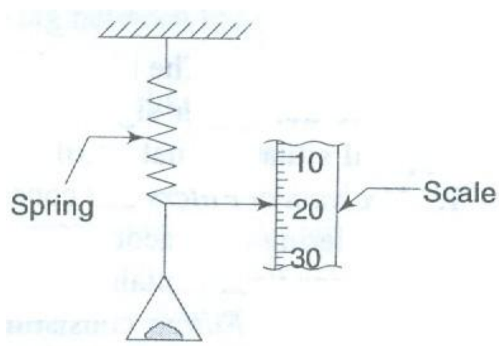


Fig. 3.1 A typical spring balance – A deflection type weight measuring instrument

A null type instrument is the one that is provided with either a manually operated or automatic balancing device that generates an equivalent opposing effect to nullify the physical effect caused by the quantity to be measured. The equivalent null-causing effect in turn provides the measure of the quantity. Consider a simple situation of measuring the mass of an object by means of an equal-arm beam balance. An unknown mass, when placed in the pan, causes the beam and pointer to deflect. Masses of known values are placed on the other pan till a balanced or null condition is obtained by means of the pointer. The main advantage of the null-type devices is that they do not interfere with the state of the measured quantity and thus measurements of such instruments are extremely accurate.

Manually Operated and Automatic Types

Any instrument which requires the services of human operator is a manual type of instrument. The instrument becomes automatic if the manual operation is replaced by an auxiliary device incorporated in the instrument. An automatic instrument is usually preferred because the dynamic response of such an instrument is fast and also its operational cost is considerably lower than that of the corresponding manually operated instrument.

Analog and Digital Types

Analog instruments are those that present the physical variables of interest in the form of continuous or stepless variations with respect to time. These instruments usually consist of simple functional elements. Therefore, the majority of present-day instruments are of analog type as they generally cost less and are easy to maintain and repair.

On the other hand, digital instruments are those in which the physical variables are represented by digital quantities which are discrete and vary in steps. Further, each digital number is a fixed sum of equal steps which is defined by that number. The relationship of the digital outputs with respect to time gives the information about the magnitude and the nature of the input data.

Self-Generating and Power-Operated Types

In self-generating (or passive) instruments, the energy requirements of the instruments are met entirely from the input signal.

On the other hand, power-operated (or active) instruments are those that require some source of auxiliary power such as compressed air, electricity, hydraulic supply, etc. for their operation.

Contacting and Non-Contacting Types

A contacting type of instrument is one that is kept in the measuring medium itself. A clinical thermometer is an example of such instruments.

On the other hand, there are instruments that are of non-contacting or proximity type. These instruments measure the desired input even though they are not in close contact with the measuring medium. For example, an optical pyrometer monitors the temperature of, say, a blast furnace, but is kept out of contact with the blast furnace. Similarly, a variable reluctance tachometer, which measures the rpm of a rotating body, is also a proximity type of instrument.

Dumb and Intelligent Types

A dumb or conventional instrument is that in which the input variable is measured and displayed, but the data is processed by the observer. For example, a Bourdon pressure gauge is termed as a dumb instrument because though it can measure and display a car tyre pressure but the observer has to judge whether the car tyre air inflation pressure is sufficient or not.

Currently, the advent of microprocessors has provided the means of incorporating Artificial Intelligence (AI) to a very large number of instruments. Intelligent or smart instruments process the data in conjunction with microprocessor (μP) or an on-line digital computer to provide assistance in noise reduction, automatic calibration, drift correction, gain adjustments, etc. In addition, they are quite often equipped with diagnostic subroutines with suitable alarm generation in case of any type of malfunctioning.

An intelligent or smart instrument may include some or all of the following:

1. The output of the transducer in electrical form.
2. The output of the transducer should be in digital form. Otherwise it has to be converted to the digital form by means of analog-to-digital converter (A-D converter).
3. Interface with the digital computer.
4. Software routines for noise reduction, error estimation, self-calibration, gain adjustment, etc.
5. Software routines for the output driver for suitable digital display or to provide serial ASCII coded output.

LECTURE NO.4

PERFORMANCE CHARACTERISTICS - STATIC AND DYNAMIC PERFORMANCE CHARACTERISTICS – ACCURACY - PRECESSION - RESOLUTION - THRESHOLD - STATIC SENSITIVITY - DEFLECTION FACTOR

PERFORMANCE CHARACTERISTICS

The measurement system characteristics can be divided into two categories:

(i) Static characteristics and (ii) Dynamic characteristics.

Static characteristics of a measurement system are, in general, those that must be considered when the system or instrument is used to measure a condition not varying with time.

However many measurements are concerned with rapidly varying quantities and, therefore, for such cases the dynamic relations which exist between the output and the input are examined. This is normally done with the help of differential equations. Performance criteria based upon dynamic relations constitute the **Dynamic Characteristics.**

Static characteristics

Accuracy

Accuracy of a measuring system is defined as the closeness of the instrument output to the true value of the measured quantity. It is also specified as the percentage deviation or inaccuracy of the measurement from the true value. For example, if a chemical balance reads 1 g with an error of 10^{-2}g, the accuracy of the measurement would be specified as 1%.

Accuracy of the instrument mainly depends on the inherent limitations of the instrument as well as on the shortcomings in the measurement process. In fact, these are the major parameters that are responsible for **systematic or cumulative errors**. For example, the accuracy of a common laboratory micrometer depends on **instrument errors like zero error, errors in the pitch of screw, anvil shape, etc**. and in the measurement process errors are caused due to temperature variation effect, applied torque, etc.

The accuracy of the instruments can be specified in either of the following forms:

$$1.\ \text{Percentage of true value} = \frac{\text{measured value - true value}}{\text{true value}} \times 100$$

$$2.\ \text{Percentage of full - scale deflection} = \frac{\text{measured value - true value}}{\text{maximum scale value}} \times 100$$

Precision

Precision is defined as the ability of the instrument to reproduce a certain set of readings within a given accuracy. For example, if a particular transducer is subjected to an accurately known input and if the repeated read outs of the instrument lie within say ± 1 %, then the precision or alternatively the precision error of the instrument would be stated as ± 1%. Thus, a highly precise instrument is one that gives the same output information, for a given input information when the reading is repeated a large number of times.

Precision of an instrument is in fact, dependent on the repeatability. The term repeatability can be defined as the ability of the instrument to reproduce a group of measurements of the same measured quantity, made by the same observer, using the same instrument, under the same conditions. The precision of the instrument depends on the factors that cause **random or accidental errors**. The extent of random errors of alternatively the precision of a given set of measurements can be quantified by performing the statistical analysis.

Accuracy v/s Precision

The accuracy represents the degree of correctness of the measured value with respect to the true value and the precision represents degree of repeatability of several independent measurements of the desired input at the same reference conditions.

Accuracy and precision are dependent on the systematic and random errors, respectively. Therefore, in any experiment both the quantities have to be evaluated. **The former is determined by proper calibration of the instrument and the latter by statistical analysis**. However, it is instructive to note that a precise measurement may not necessarily be accurate and vice versa. To illustrate this statement we take the example of a person doing shooting practice on a target. He can hit the target with the following possibilities as shown in Fig. 4.1.

1. One possibility is that the person hits all the bullets on the target plate on the outer circle and misses the bull's eye [Fig. 4.1(a)]. This is a **case of high precision but poor accuracy**.
2. Second possibility is that the bullets are placed as shown in Fig. 4.1 (b). In this case, the bullet hits are placed symmetrically with respect to the bull's eye but are not spaced closely. Therefore, this is **case of good average accuracy but poor precision**.
3. A third possibility is that all the bullets hit the bull's eye and are also spaced closely [Fig. 4.1 (c)]. As is clear from the diagram, this is a **case of high accuracy and high precision**.
4. Lastly, if the bullets hit the target plate in a random manner as shown in Fig. 4.1 (d), then this is a case of poor precision as well as poor accuracy.

Fig. 4.1 Illustration of degree of accuracy and precision in a typical target shooting experiment

Based on the above discussion, it may be stated that in any experiment the accuracy of the observations can be improved but not beyond the precision of the apparatus.

Resolution (or Discrimination)

It is defined as the smallest increment in the measured value that can be detected with certainty by the instrument. In other words, it is the degree of fineness with which a measurement can be made. The least count of any instrument is taken as the resolution of the instrument. For example, a ruler with a least count of 1 mm may be used to measure to the nearest 0.5 mm by interpolation. Therefore, its resolution is considered as 0.5 mm. A high resolution instrument is one that can detect smallest possible variation in the input.

Threshold

It is a particular case of resolution. *It is defined as the minimum value of input below which no output can be detected.* It is instructive to note that resolution refers to the *smallest measurable input above the zero value*. Both threshold and resolution can either be specified as absolute quantities in terms of input units or as percentage of full scale deflection.

Both threshold and resolution are not zero because of various factors like friction between moving parts, play or looseness in joints (more correctly termed as backlash), inertia of the moving parts, length of the scale, spacing of graduations, size of the pointer, parallax effect, etc.

Static sensitivity

Static sensitivity (also termed as scale factor or gain) of the instrument is determined from the results of static calibration. This static characteristic is defined as the ratio of the magnitude of response (output signal) to the magnitude of the quantity being measured (input signal), i.e.

$$\text{Static sensitivity, } K = \frac{\text{change of output signal}}{\text{change in input signal}}$$

$$= \frac{\Delta q_o}{\Delta q_i}$$

where q_o and q_i are the values of the output and input signals, respectively.

In other words, sensitivity is represented by the slope of the input-output curve if the ordinates are represented in actual units. With a linear calibration curve, the sensitivity is constant (Fig. 4.2(a)]. However, if the relationship between the input and output is not linear, the sensitivity varies with the input value and defined as [Fig. 4.2(b)]:

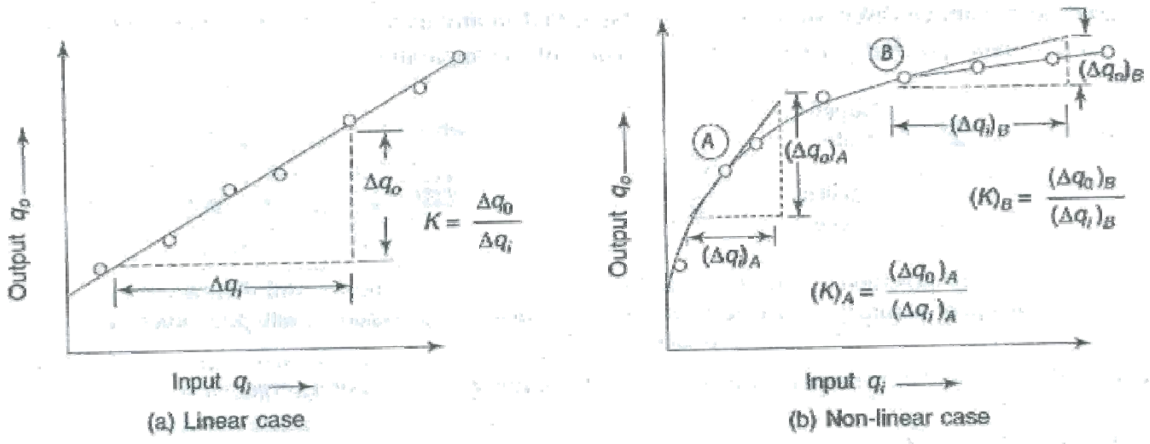


Fig. 4.2 Static sensitivity of linear and non-linear instruments

$$\text{Static sensitivity} = \left.\frac{\Delta q_o}{\Delta q_i}\right|_{q_i}$$

The sensitivity of a typical linear spring, whose extension is directly proportional to the applied force can be defined as say, 450 N/mm. Similarly, the sensitivity of a non-linear type of copper / constantan thermocouple is found to be maximum at 350 °C and is 60 $\mu V / {}^oC$.

It may be noted that in certain applications, the reciprocal of the sensitivity is commonly used. This is termed inverse sensitivity or the deflection factor.

LECTURE NO.5

PERFORMANCE CHARACTERISTICS- LINEARITY, RANGE AND SPAN, HYSTERESIS, DEAD BAND, BACKLASH, DRIFT

Linearity

A linear indicating scale is one of the most desirable features of any instrument. Therefore, manufacturers of instruments always attempt to design their instruments so that the output is a linear function of the input. In commercial instruments, the maximum departure from linearity is often specified in one of the following ways.

Independent of the input (5.1 (a))

Proportional to input (5.1 (b))

Combined independent and proportional to the input (5.1 (c))

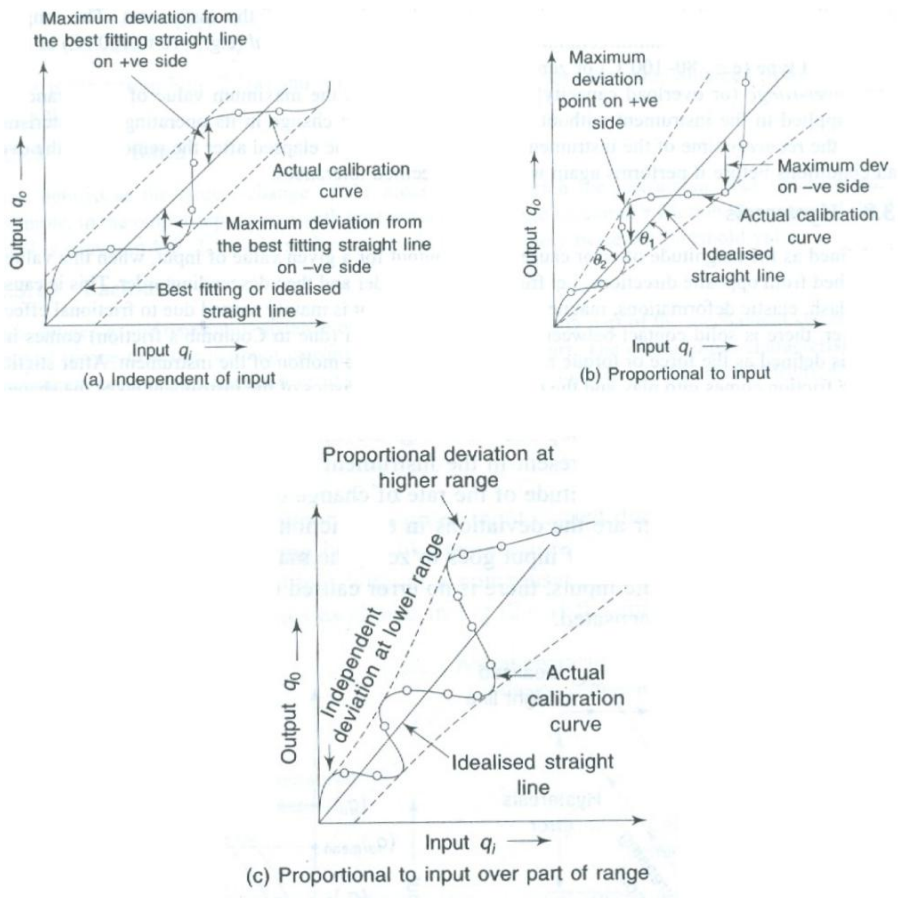


Fig. 5.1 Typical specifications of non-linearity

The non-linearity of a complex type of calibration curve is obtained as say ± y % of full-scale deflection and also as ± x % of the input value. The non-linearity of the instrument is then stated as ± y % of full scale or ± x % of the input, whichever is greater.

Range and Span

The range of the instrument is specified by the lower and upper limits in which it is designed to operate for measuring, indicating or recording the measured variable. The algebraic difference between the upper and lower range values is termed as the span of the instrument. The range of the instrument can either be unidirectional (e.g., 0-100°C) or bidirectional (e.g., -10 to 100°C) or it can be expanded type (e.g., 80 -100°C) or zero suppressed (e.g., 5 - 40°C).

The over-range (or overload capacity) of the instrument is the maximum value of measurand that can be applied to the instrument without causing a perceptible change in its operating characteristics. Further, the recovery time of the instrument is the amount of time elapsed after the removal of the overload conditions before it performs again within the specified tolerances.

Hysteresis

It is defined as the magnitude of error caused in the output for a given value of input, when this value is approached from opposite directions, i.e. from ascending order and then descending order. This is caused by backlash, elastic deformations, magnetic characteristics, but is mainly caused due to frictional effects.

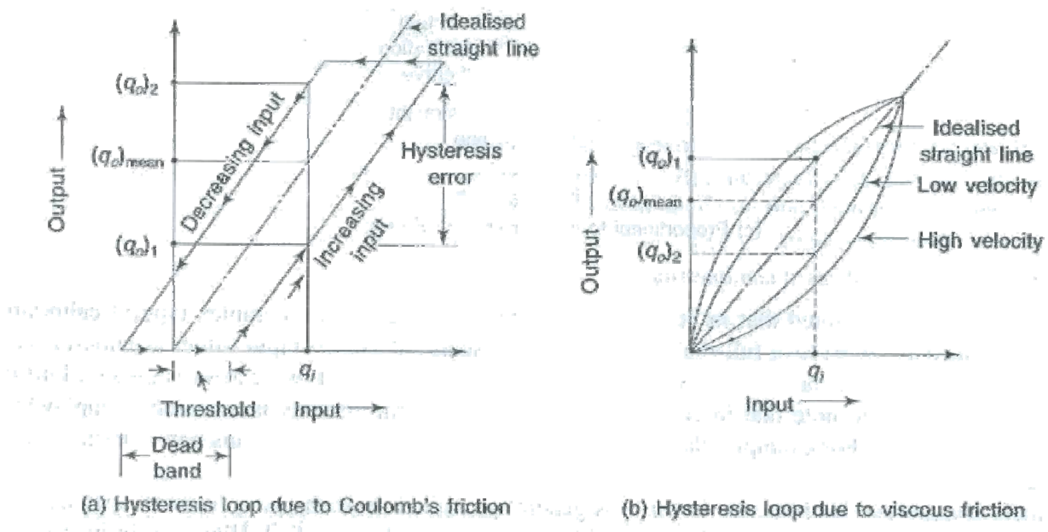


Fig.5.2 Typical output-input curves showing hysteresis effects

Hysteresis effects are best eliminated by taking the observations both for ascending and descending values of input and then taking the arithmetic mean. For example, in Fig. 5.2(a) and (b), for a value of input q_i, the output in ascending order is $(q_o)_1$ and in descending order is $(q_o)_2$. Then the mean value is:

$$(q_o)_{mean} = \frac{(q_o)_1 + (q_o)_2}{2}$$

As is clear from Figs. 5.2 (a) and (b), this value is more or less the value obtained from the idealised straight line.

Dead Band

It is defined as the largest change of the measurand to which the instrument does not respond. For example, in the output-input curve with hysteresis effect due to Coulomb's friction, the extent of the dead band is shown in Fig. 5.2 (a). In such a case, it is approximately twice the threshold value.

Backlash

It is defined as the maximum distance or angle through which any part of the mechanical system may be moved in one direction without causing motion of the next part. The output-input characteristics of an instrument system with backlash error is similar to hysteresis loop due to Coulomb's friction shown in Fig. 5.2 (a). Backlash error can be minimized if the components are made to very close tolerances.

Drift

It is defined as the variation of output for a given input caused due to change in the sensitivity of the instrument due to certain interfering inputs like temperature changes, component instabilities, etc.

LECTURE NO.6

PRESSURE SENSITIVE PRIMARY DEVICES: SOME OF THE COMMONLY USED FORCE SUMMING DEVICES, BOURDON TUBES, DIAPHRAGMS AND BELLOWS

PRESSURE SENSITIVE PRIMARY DEVICES

Most pressure measuring devices use elastic members for sensing pressure at the primary stage. These elastic members are of many types and **convert the pressure into mechanical displacement** which is later converted into an electrical form using a secondary transducer. These devices are many a time known as force summing devices. Fig. 6.1 shows some of the commonly pressure sensitive primary devices

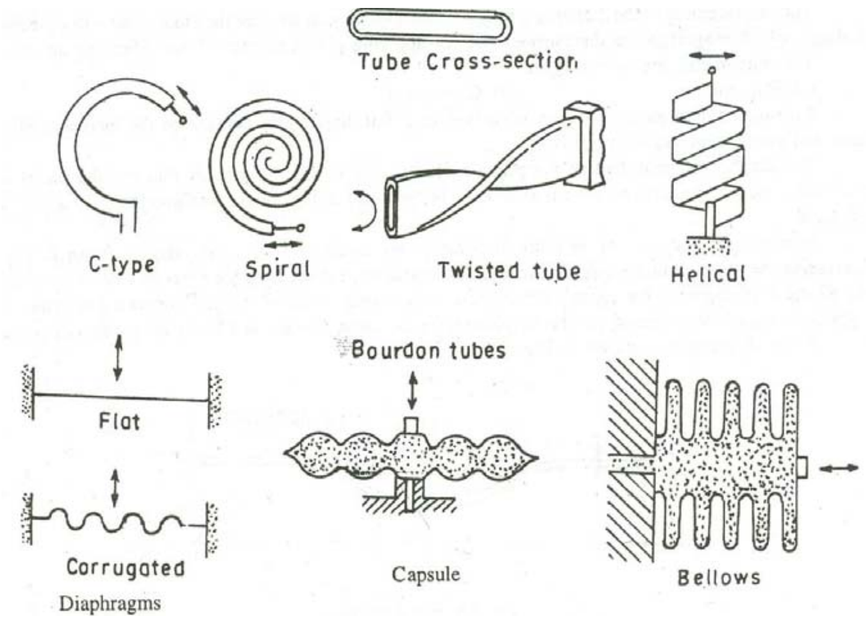


Fig. 6.1 Pressure sensitive primary devices

The principle of working of these devices is: the fluid whose pressure is to be measured is made to press the pressure sensitive element and since the element is an elastic member, it deflects causing a mechanical displacement. The displacement is proportional to the pressure applied. The displacement is then measured with the help of electrical transducers. The output of the electrical transducers is proportional to the displacement and hence to the applied input pressure.

Some of the commonly used force summing devices are,

(i) Bourdon tubes,

(ii) Diaphragms and

(iii) Bellows

Bourdon Tubes

These are designed in various forms like:

(i) C type (ii) spiral (iii) twisted tube and (iv) helical

The Bourdon tubes are made out of an elliptically sectioned flattened tube bent in such a way as to produce the above mentioned shapes. One end of the tube is sealed or closed and physically held. The other end is open for the fluid to enter. When the fluid whose pressure is to be measured enters the tube, the tube tends to straighten out on account of the pressure. This causes the movement of the free end and the displacement of this end is amplified through mechanical linkages. The amplified displacement of the free end is used to move a pointer over a scale calibrated in units of pressure. Bourdon tubes normally measure gauge pressure. The materials used for Bourdon tubes are brass, phosphor bronze, beryllium copper, and steel.

Diaphragms

The movement of a diaphragm is a convenient way of sensing **low pressures**. A diaphragm is a circular disc of thin, springy metal firmly fixed at its rim. The unknown pressure is applied to one side of the diaphragm and since the rim of the diaphragm is rigidly fixed there is a deflection of the diaphragm. The displacement of the centre of the diaphragm is directly proportional to the pressure and therefore can be used as a measure of pressure.

The displacement of the diaphragm may be transmitted by an arm fastened to its centre to a mechanical linkage, which magnifies the displacement before applying it to a pointer of the indicating device.

The diaphragms are of two types:

(i) Flat, and (ii) Corrugated.

Corrugated diaphragms have an advantage over flat diaphragms because of the increased effective area and consequent greater sensitivity.

In many applications two or more diaphragms are joined to form a capsule. A flat diaphragm is shown in Fig. 6.2.

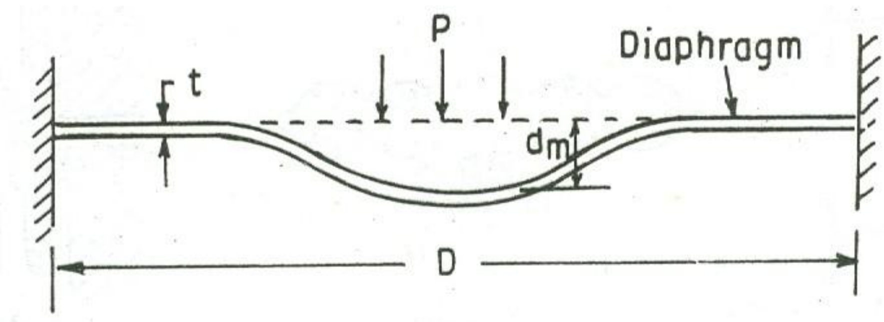


Fig. 6.2 Flat diaphragm

The pressure (P) is given by:

$$P = \frac{256\, Et^3\ d_m}{3\,(1-v^2)\,D^4}\ N/m^2$$

where

E = Young's modulus, N/m^2

D, t = diameter and thickness of diaphragm respectively, m

v = Poisson's ratio

$d_m =$ deflection at the centre of the diaphragm, m

The above relationship, between pressure, P, and the deflection at the centre d_m, is linear. But linearity holds good as long as $d_m < 0.5$ t.

Bellows

The bellows element consists of a cylindrical metal box with corrugated walls of thin springy material like brass, phosphor bronze, or stainless steel. The thickness of walls is typically 0.1 mm. Bellows are used in applications where the pressures involved are low.

The pressure inside the bellows tends to extend its length. This tendency is opposed by the springiness of the metals, which tends to restore the bellows to its original size. Pressure on the outside of the bellows tends to reduce its length and this tendency also, is opposed by the springiness of metal. When the pressures are small the springiness of the metal sufficient. However, when, the pressures are high, the springiness of the walls may not be sufficient to restore the bellows to its original size. For such applications springs are located inside the bellows to provide additional springiness to restore the bellows to its original size.

The action of the bellows is as under:

The pressure to be measured is applied from the left end as shown in Fig.6.1. The pressure inside the bellows extends its length. Since the left hand end is fixed, there is a displacement of the right hand end to which a rod is connected. The displacement of this rod is directly proportional to the pressure inside the bellows. The displacement of the rod is small and may be amplified by using mechanical linkage and then transferred to a pointer moving over a calibrated scale.

LECTURE NO.7

TEMPERATURE MEASUREMENT: INTRODUCTION- TEMPERATURE SCALES- INTERNATIONAL PRACTICAL TEMPERATURE SCALE (IPTS)

INTRODUCTION

Temperature is a very widely measured and frequently controlled variable used in numerous industrial applications. In general, **chemical reactions** in the industrial processes and products are temperature dependent and the desired quality of a product is possible only if the temperature is accurately measured and maintained. In the **heat treatment of steel and aluminum alloys**, temperature measurement and control plays a crucial role in incorporating the **desired material properties** in the finished heat-treated products. The other areas where measurement and control of temperature is essential are: plastic manufacturing, nuclear reactor components, milk and dairy products, plant furnace and molten metals, heating and air-conditioning systems, space shuttle components, blades of gas turbines, etc.

The temperature is defined as the degree of hotness or coldness of a body or an environment measured on a definite scale. Definition of temperature is also defined based on its equivalence to a driving force or potential that caused the flow of energy as heat. Thus, we can *define temperature as a condition of a body by virtue of which heat is transferred to or from other bodies*.

It may be noted that there is a difference between the quantities **temperature** and **heat**. **Temperature** may be defined as 'degree' of heat whereas heat is taken to mean as 'quantity' of heat. For example, a bucket of warm water would melt more ice than a small spoon of boiling water. The warm water in the bucket obviously contains greater quantity of heat than that in the spoon containing boiling water. **But its temperature is lower than the boiling water, a fact that is readily apparent if a finger is dipped in both the vessels**.

Temperature is a fundamental quantity, much the same way as mass, length and time. *The law that is used in temperature measurement is known as the* **Zeroth law of thermodynamics**.

Zeroth law of thermodynamics

Zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, then they are all in thermal equilibrium with each other.

TEMPERATURE SCALES

Two temperature scales in common use are the **Fahrenheit** and **Celsius scales**. These scales are based on a specification of the **number of increments** between **freezing point** and **boiling point** of water at the standard atmospheric temperature.

The Celsius scale has **100 units** between these points, while the **Fahrenheit scale has 180 units**. The Celsius scale is currently more in use because of the adoption of metric units. However, the **absolute temperature scale** based on the thermodynamic ideal Carnot cycle has been correlated with the Celsius and Fahrenheit scales as follows:

K (Absolute temperature, Kelvin scale) = °C + 273.15

where

°C is temperature on Celsius scale.

R (Absolute temperature, Rankine scale) = °F + 459.69

where

°F is the temperature on the Fahrenheit scale.

The zero points on both the scales represent the same physical state and the ratio of two values is the same, regardless of the absolute scale used i.e.

$$\left[\frac{T_2}{T_1}\right]_{Rankine} = \left[\frac{T_2}{T_1}\right]_{Kelvin}$$

The boiling and freezing points of water at a pressure of one atmosphere ($101.3\ kN / m^2$) are taken as 100° and 0° on the Celsius scale and 212° and

32° on the Fahrenheit scale. The relationships between Fahrenheit and Celsius and Rankine and Kelvin scales are as follows:

$$^{o}F = 32 + \frac{9}{5}\,^{o}C\ R$$

$$= \frac{9}{5} K$$

with SI units, the kelvin temperature scale (which is also termed as absolute temperature scale or 'thermodynamic' temperature scale) is used in which the unit of temperature is the kelvin (K).

INTERNATIONAL PRACTICAL TEMPERATURE SCALE (IPTS)

To enable the accurate calibration of a wide range of temperatures in terms of the Kelvin scale, the International Practical Temperature Scale (IPTS-68) has been devised. This lists 11 primary 'fixed' points which can be reproduced accurately. Some typical values are:

Table 14.1 Typical Values of Primary 'Fixed' points

S. No.	Primary fixed point	Temperature (K)	Temperature (^{o}C)
1	Triple point of equilibrium hydrogen (equilibrium between solid, liquid, and vapour phases of equilibrium hydrogen)	6.18	-259.34
2	Boiling point of equilibrium hydrogen	20.28	-252.87
3	Triple point of oxygen	54.361	-218.789
4	Boiling point of oxygen	90.188	-182.962
5	Triple point of water (equilibrium between solid, liquid and vapor phases of water)	273.16	0.01
6	Boiling point of water	373.15	100
7	Freezing point of zinc	692.73	412.58
8	Freezing point of silver	1235.58	961.93
9	Freezing point of gold	1337.58	1064.43

Apart from the primary standard points, there are 31 secondary points on the International Practical Temperature Scale which forms the convenient working standard for the workshop calibration of the temperature measuring devices. Some typical values of these points are given in **Table 14.2**.

Table 14.2 Typical Values of Secondary Points

S. No.	**Secondary points**	**Temperature (K)**	**Temperature (^{o}C)**
1	Sublimation point of carbon dioxide	194.674	-74.476
2	Freezing point of mercury	234.288	-38.862
3	Equilibrium between ice and water (ice point)	273.15	0
4	Melting point of bismuth	544.592	271.442
5	Melting point of lead	600.652	327.502
6	Boiling point of pure sulphur	717.824	444.674
7	Melting point of antimony	903.87	630.74
8	Melting point of aluminium	933.52	660.37
9	Melting point of copper	1357.6	1084.5
10	Melting point of platinum	2045	1772
11	Melting point of tungsten	3660	3387

LECTURE NO.8

MEASUREMENT OF TEMPERATURE: CLASSIFICATION OF TEMPERATURE MEASURING DEVICES - BIMETALLIC THERMOMETERS - GLASS THERMOMETERS AND PRESSURE GAUGE THERMOMETERS - THERMOCOUPLES

MEASUREMENT OF TEMPERATURE

Temperature is measured by observing the effect that temperature variation causes on the measuring device. Temperature measurement methods can be broadly classified as follows:

1. non-electrical methods,
2. electrical methods, and
3. radiation methods.

NON-ELECTRICAL METHODS

The non-electrical methods of temperature measurement can be based on anyone of the following principles:

1. change in the physical state,
2. change in the chemical properties, and
3. change in the physical properties.

BIMETALLIC THERMOMETER

This type of thermometer also employs the principle of solid expansion and consists of a 'bimetal' strip usually in the form of a cantilever beam [Fig.8.1 (a)]. This comprises strips of two metals, having different coefficients of thermal expansion, **welded or riveted together so that relative motion between them is prevented**. An increase in temperature causes the deflection of the free end of the strip as shown in Fig.8.1 (b), assuming that metal A has the higher coefficient of expansion. The deflection with the temperature is nearly linear, depending mainly on the coefficient of linear thermal expansion. **Invar** is commonly employed as the **low expansion metal**. This is an iron-nickel alloy containing 36% nickel. Its coefficient of thermal expansion is around

1/20th of the ordinary metals. **Brass** is used as **high expansion material** for the measurement of low temperatures, whereas nickel alloys are used when higher temperatures have to be measured. A plain bimetallic strip is somewhat insensitive, but the sensitivity is improved by using a longer strip in a helical form as shown in Fig.8.2.

Bimetallic thermometers are usually employed in the range of -30 to 550 °C. Inaccuracies of the order of ± 0.5 to ± 1.0% of full-scale deflection are expected in bimetallic thermometers of high accuracies.

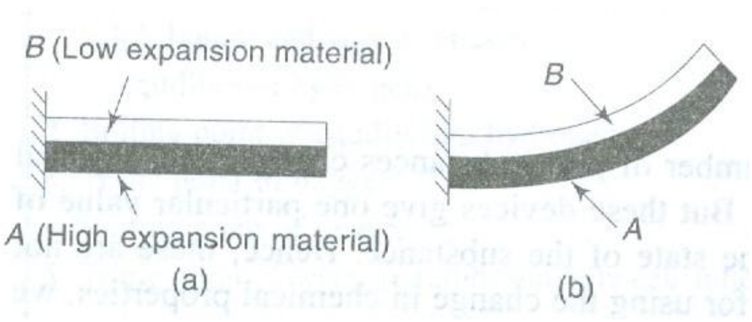


Fig.8.1 Bimetallic Thermometer

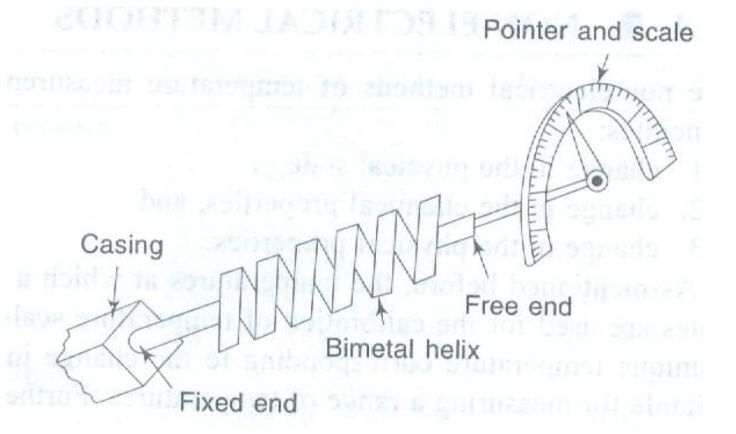


Fig.8.2 Bimetallic Helix Thermometer

The bimetallic strip has the **advantage** of being self-generating type instrument with low cost practically no maintenance expenses and stable operation over extended period of time. However, its **main disadvantage** is its inability to measure rapidly changing temperatures due to its relatively higher thermal inertia.

LIQUID-IN-GLASS THERMOMETER/MERCURY-IN-GLASS THERMOMETER

The liquid-in-glass thermometer is one of the most common temperature measuring devices. **Both liquid and glass** expand on heating and their **differential expansion** is used to indicate the temperature. The lower temperature limit is **-37.8** ºC for mercury, down to **–130 °C** for pentane. The higher temperature range is 340 °C (boiling point of mercury is 357 °C) but this range may be extended to 560 °C C by filling the space above mercury with CO_2 or N_2 at high pressure, thereby increasing its boiling point and range. The precision of the thermometer depends on the care used in calibration. *A typical instrument is checked and marked from two to five reference temperatures*. Intermediate points are marked by interpolation. The calibration of the thermometer should be occasionally checked against the ice point to take into account the aging effects. Precision thermometers are sometimes marked for partial or total immersion and also for horizontal or vertical orientation. The accuracy of these thermometers does not exceed **0.1°C**. However, when increased accuracy is required, a **Beckmann range thermometer** can be used. It contains a big bulb attached to a very fine capillary. The range of the thermometer is limited to **5 – 6 °C** with an accuracy of **0.005°C**.

Liquid-in-glass thermometers have notable qualities like *low cost, simplicity in use, portability and convenient visual indication* without the use of any external power. However, their use is limited to certain laboratory applications. It is not preferred in industrial applications because of its **fragility** and its **lack of adaptability to remote indication**. Further, it introduces **time lag** in the measurement of dynamic signals because of relatively high heat capacity of the bulb.

PRESSURE THERMOMETERS / PRESSURE <u>SPRING</u> THERMOMETERS

Pressure thermometer is based on the principle of fluid expansion due to an increase in the pressure in a given volume of the temperature measuring system. It is one of the most economical, versatile and widely used devices in industrial temperature measurements. It has a relatively large metal bulb (often stainless steel) instead of glass. This results in a robust, easy-to-read thermometer that may be read remotely by connecting the bulb to a Bourdon gauge or any other pressure measuring device by means of a capillary tube as illustrated in Fig.3.

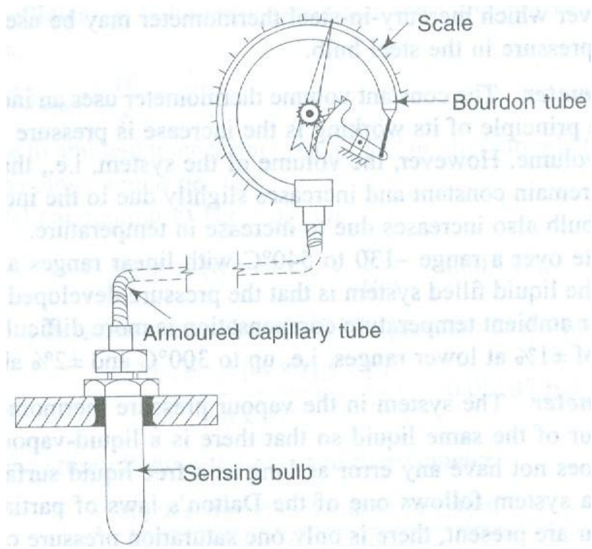


Fig.8.3 A schematic diagram of pressure thermometer

The entire assembly of the bulb, capillary and gauge is calibrated directly **on the basis of pressure change corresponding to the temperature change**. The bulb of the thermometer may be filled with either a liquid (usually mercury) or gas or a liquid-vapor mixture and depending upon the type of fluid, the thermometer is termed as **mercury-in-steel thermometer** or **constant volume gas thermometer** or **vapour pressure thermometer** respectively.

Fluid expansion thermometers are low in cost, self-operated type, rugged in construction, with no maintenance expenses, stable in operation and accurate to **±1°C**. Further, the response of these instruments can be increased by using a small bulb connected to an electrical type of pressure sensor connected through a short length of capillary tube.

LECTURE NO.9

ELECTRICAL RESISTANCE THERMOMETERS - RESISTANCE-TEMPERATURE DETECTORS (RTDS) - THERMOCOUPLE - THERMOCOUPLE MATERIALS

ELECTRICAL METHODS

Electrical methods are **in general preferred** for the measurement of temperature as they furnish a signal which can be easily detected, amplified or used for control purposes. There are **two main electrical methods** used for measuring temperature. They are:

1. Thermo-resistive type i.e., variable resistance transducers and
2. Thermo-electric type i.e., emf generating transducers.

ELECTRICAL RESISTANCE THERMOMETERS

In resistance thermometers, the **change in resistance of various materials**, which varies in a reproducible manner **with temperature**, *forms the basis* of this important sensing technique. The **materials** in actual use fall in two classes namely, **conductors** (metals) and **semiconductors**. In general, the *resistance of the highly conducting materials (metals) increases with increase in temperature* and the coils of such materials are called **metallic resistance thermometers**. Whereas the **resistance of semiconductor materials** generally (not always) **decreases with increase in temperature**. Thermo-sensitive resistors having such negative temperature characteristics are commonly known as NTC thermistors. Figure 9.1 illustrates the typical variation of specific resistance of the metals (platinum for example) and the NTC thermistor.

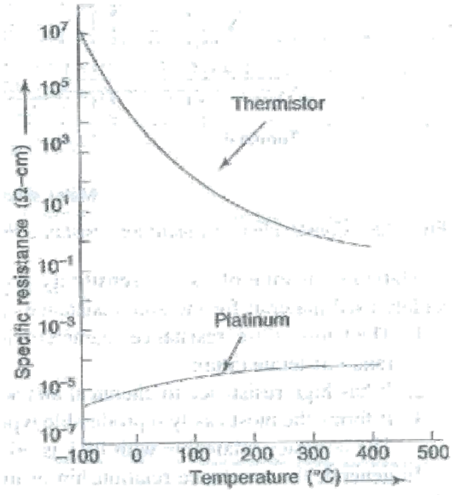


Fig. 9.1 Resistance- temperature characteristics of platinum and a typical NTC thermistor

METALLIC RESISTANCE THERMOMETERS OR RESISTANCE-TEMPERATURE DETECTORS (RTDS)

Metals such as platinum, copper, tungsten and nickel exhibit small increases in resistance as the temperature rises because they have a positive temperature coefficient of resistance. Platinum is a very widely used sensor and its operating range is from 4K to 1064 °C. Because it provides extremely reproducible output, it is used in establishing International Practical Temperature Scale from 13.81 K to 961.93 °C. However for the measurement of lower temperatures up to 600°C, RTD sensor is made of nickel.

Metallic resistance thermometers are constructed in many forms, but the temperature sensitive element is usually in the form of a coil of fine wire supported in a stress-free manner. A typical construction is shown in Fig. 9.2, where the wire of metal is wound on the grooved hollow insulating ceramic former and covered with protective cement.

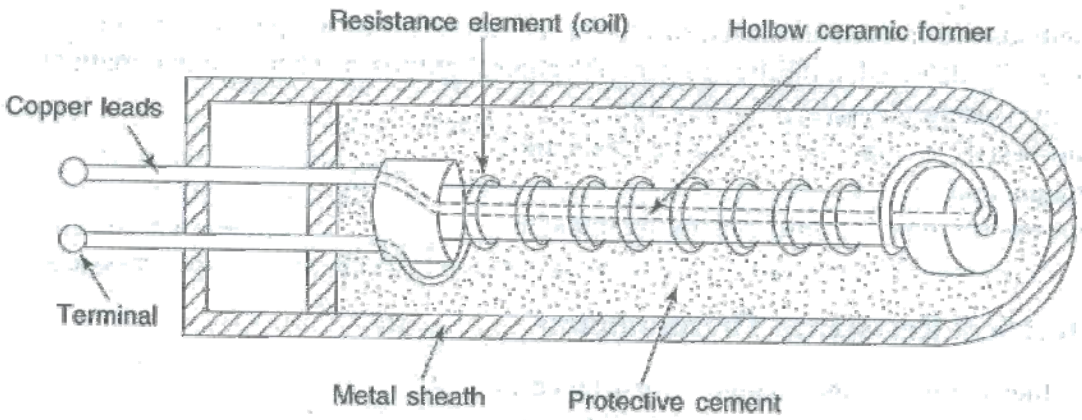


Fig. 9.2 Construction of a platinum resistance thermometer (PRT)

THERMO-ELECTRIC SENSORS / THERMOCOUPLE

The most common electrical method of temperature measurement uses the thermo-electric sensor, also known as the **thermocouple (TC)**. The **thermocouple** is a **temperature transducer** that **develops an emf** which is a function of the temperature between **hot junction** and **cold junction**. The construction of a thermocouple is quite simple. It consists of two wires of different metals twisted and brazed or welded together with each wire covered with insulation which may be either.

1. mineral (magnesium oxide) insulation for normal duty, or

2. ceramic insulation for heavy duty.

The basic principle of temperature measurement using a thermo-electric sensor was discovered by **Seebeck in 1821** and is illustrated in Fig. 9.3. When two conductors of **dissimilar metals**, say A and B, are joined together to form a loop (thermocouple) and two unequal temperatures T_1 and T_2 are interposed at two junctions J_1 and J_2, respectively, Then an infinite resistance voltmeter detects the electromotive force E, or if a low resistance ammeter is connected, a current flow I is measured Experimentally, it has been found that the magnitude of E depends upon the materials as well as the temperature T_1 and T_2. Now, the overall relation between emf E and the temperatures T_1 and T_2 forms the basis for thermoelectric measurements and is called the Seebeck effect. Thus, in practical applications, a suitable device is incorporated to indicate the emf E or the flow of current I. For convenience of measurements and standardization, one of the two junctions is usually maintained at some known temperature. The measured emf E then indicates the temperature difference relative to the reference temperature, such as ice point which is very commonly used in practice.

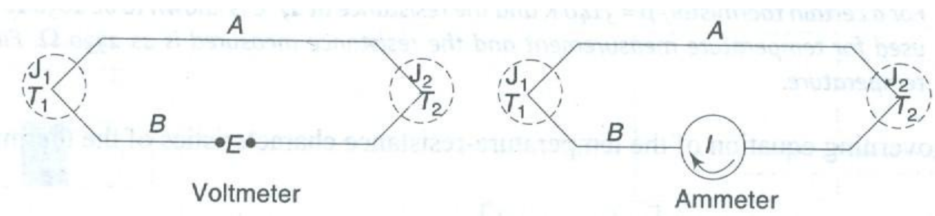


Fig. 9.3 Basic thermo-electric circuit

It may be noted that temperatures T_1 and T_2 of junctions J_1 and J_2 respectively are slightly altered if the thermo-electric current is allowed to flow in the circuit. Heat is generated at the cold junction and is absorbed from the hot junction thereby heating the cold junction slightly and cooling the hot junction slightly. This phenomenon is termed **Peltier** effect. If the thermocouple voltage is measured by means of potentiometer, no current flows and Peltier heating and cooling are not present. Further, these heating and cooling effects are proportional to the current and are fortunately quite negligible in a thermocouple circuit which is practically a millivolt range circuit. In addition, the junction emf may be slightly altered if a temperature gradient exists along either or both the materials. This is known as **Thomson effect**.

The actual application of **thermocouples** to the measurements requires consideration of the **laws of thermo-electricity**.

LAW OF INTERMEDIATE TEMPERATURES

This states that the emf generated in a thermocouple with junctions at temperatures T_1 and T_3 is equal to the sum of the e.m.f. 's generated by similar thermocouples, one acting between temperatures T_1 and T_2 and the other between T_2 and T_3 when T_2 lies between T_1 and T3 (Fig.9.4).

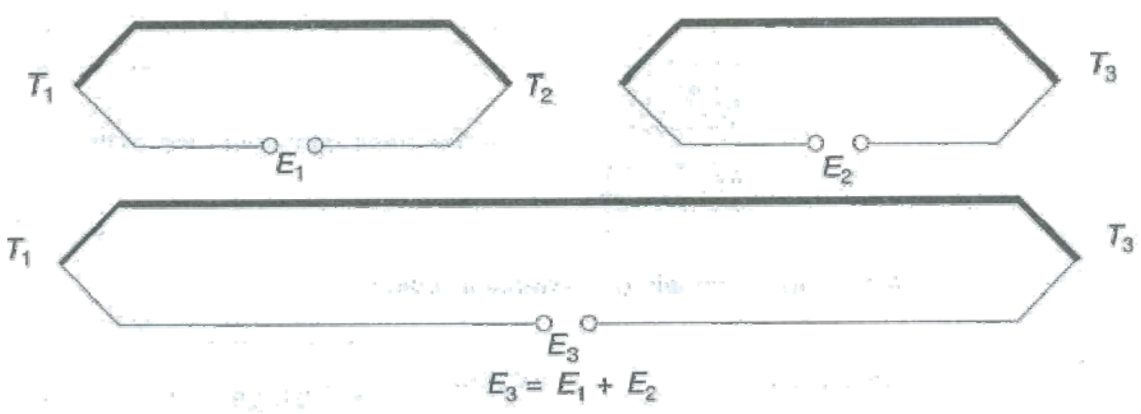


Fig. 9.4 Law of intermediate temperatures

Law of Intermediate Metals

The basic thermocouple loop consists of two dissimilar metals A and B [Fig.9.5 (a)]. If a third wire is introduced, then three junctions are formed as shown in Fig. 9.5(b). The emf generated remains unaltered if the two new junctions *B-C* and *C-A* are at the same temperature.

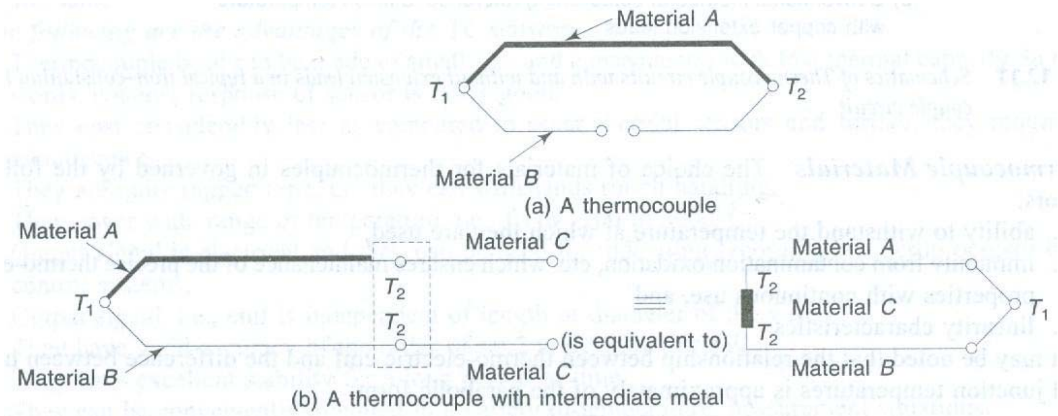
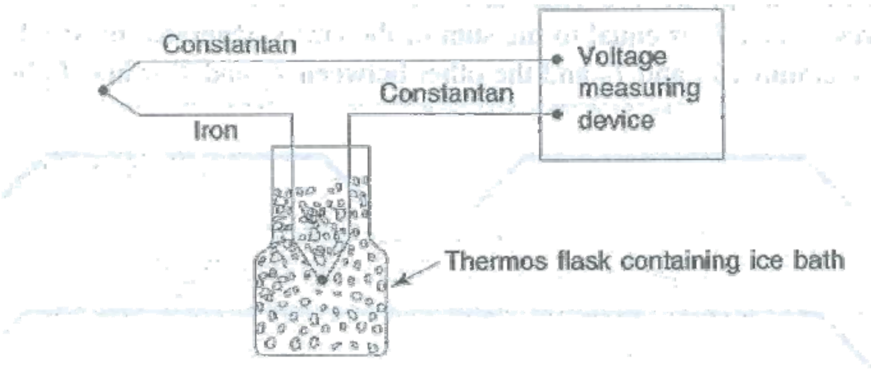
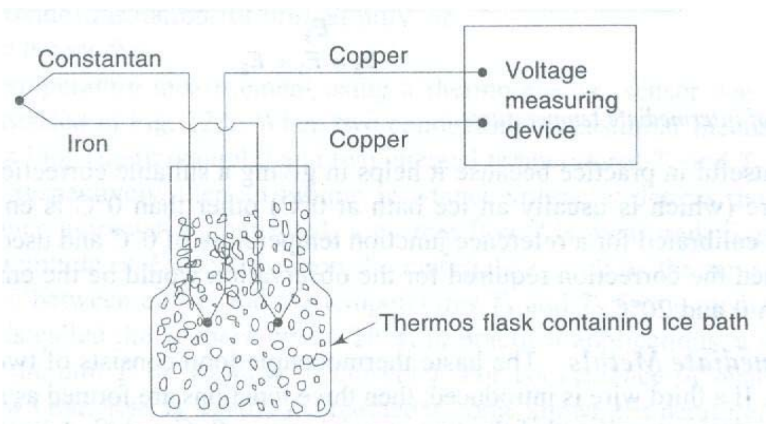


Fig.9.5 Law of intermediate metal

It may be noted that extension wires are needed when the measuring instrument is to be placed at a considerable distance from the reference junction. Maximum accuracy is obtained when the leads are of the same material as the thermocouple element [Fig.9.6 (a)]. However, this approach is not economical while using expensive thermocouple materials. Therefore, it is preferable to employ the system shown in Fig. 9.6 (b) to keep the copper-iron and copper-constantan junctions in the thermos flask at 0°C and provide binding posts of copper. This ensures maximum accuracy in the thermocouple operation.



(a) A thermocouple without extension leads



(b) Conventional method of establishing reference function temperature with copper extension leads

Fig.9.6 Schematics of Thermocouple circuits with and without extension leads in a typical iron-constantan thermocouple circuit

(a) A thermocouple without extension leads

(b) Conventional method of establishing reference function temperature with copper extension leads

THERMOCOUPLE MATERIALS

The choice of materials for thermocouples in governed by the following factors:

1. Ability to withstand the temperature, at which they are used,

2. Immunity from contamination / oxidation, etc. which ensures maintenance of the precise thermo-electric properties with continuous use, and

3. Linearity characteristics.

It may be noted that the relationship between thermo-electric emf and the difference between hot and cold junction temperatures is approximately of the parabolic form:

$$E = aT + bT^2$$

Thermocouple can be broadly **classified** in two categories:

1. base-metal thermocouples, and
2. rare-metal thermocouple.

Base-metal thermocouples use the combination of **pure metals** and **alloys of iron, copper and nickel** and are used for temperature up to **1450 K**. These are most **commonly used** in practice as they are **more sensitive, cheaper** and have **nearly linear characteristics**. Their **chief limitation** is the **lower operating range** because of their *low melting point* and *vulnerability to oxidation*.

On the other hand, **rare-metal thermocouples** use a **combination of pure metals and alloys of platinum** for temperatures up to l600 °C and **tungsten, rhodium and molybdenum for temperatures up to 3000 °C**.

LECTURE NO.10

PRESSURE - GAUGE PRESSURE, ABSOLUTE PRESSURE, DIFFERENTIAL PRESSURE, VACUUM - UNITS OF PRESSURE - PRESSURE SCALES - CONVERSION OF UNITS- TYPES OF PRESSURE MEASUREMENT DEVICES

PRESSURE MEASUREMENT

INTRODUCTION

Pressure means force per unit area, exerted by a fluid on the surface of the container.

Pressure measurements are one of the most important measurements made in industry especially in continuous process industries such as chemical processing, food and manufacturing. The principles used in measurement of pressure are also applied in the measurement of temperature, flow and liquid level.

Pressure is represented as **force per unit area**.

Fluid pressure is on account of exchange of momentum between the molecules of the fluid and a container wall.

Static and Dynamic Pressures

When a fluid is in equilibrium, the pressure at a point is identical in all directions and is independent of orientation. This is called ***static pressure***.

However, when pressure gradients occur within a continuum (field) of pressure, the attempt to restore equilibrium results in fluid flow from regions of higher pressure to regions of lower pressure. In this case the pressures are no longer independent of direction and are called ***dynamic pressures.***

Velocity and Impact Pressures

Pressure components of different nature exist in a flowing fluid. For example, in case a small tube or probe for sampling, it is found that the results depend upon how the tube is oriented. In case, the tube or probe is so aligned that there is a direct impact of flow on the opening of the tube or probe as shown in Fig.10.1 *(a)* it senses a ***total or stagnation pressure.*** If the tube or probe is oriented as shown in Fig.10.1 *(b),* the results are different and what we obtain is called ***static pressure***.

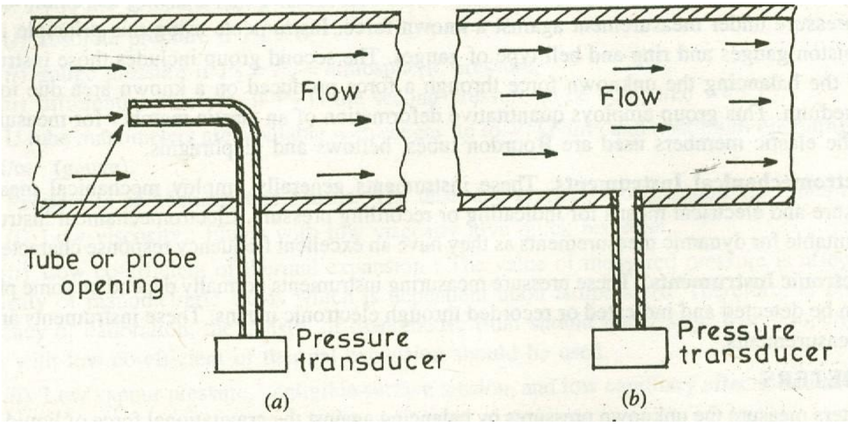


Fig.10.1 Impact and Static Pressure tubes

Static Pressure

Static pressure is considered as the pressure that is experienced if moving along the stream and the total pressure may be defined as the pressure if the stream is brought to rest is entropically. The difference of the two pressures is the pressure due to fluid motion commonly referred as the *velocity pressure.*

$$\text{Velocity pressure} = \text{stagnation (total) pressure} - \text{static pressure}$$

Therefore, in order to properly interpret flow measurements, consideration must be given how the pressure is being measured.

Absolute pressure.

Absolute pressure means the fluid pressure above the reference value of a perfect vacuum or the absolute zero pressure.

Gauge pressure.

It represents the difference between the absolute pressure and the local atmospheric pressure.

Vacuum

Vacuum on the other hand, represents the amount by which atmospheric pressure exceeds the absolute pressure.

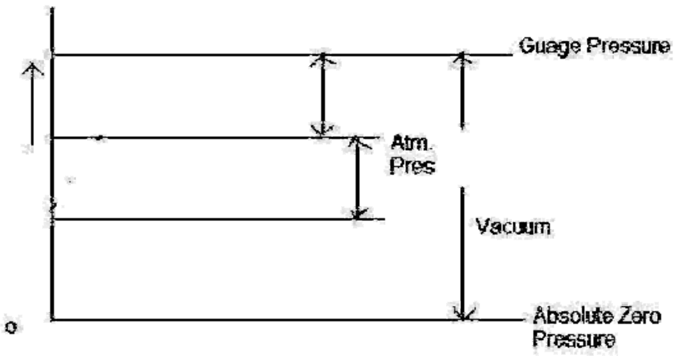


Fig.10.2 Various Pressure Terms used in Pressure Measurement From the above definitions, we have:

$$P_g = P_a - P_s$$

$$P_v = P_s - P_a$$

where

P_a, P_g, P_s and P_v are absolute, gauge, atmospheric and vacuum pressures, respectively.

The absolute pressure represents a positive gauge pressure and vacuum represents a negative gauge pressure.

Units of Pressure

Some of the commonly used units of pressure are:

1 mmof mercury	= 1 torr	
1 atm	= 1.0I3X10^5 N/m^2	760 mmof Hg at °C
1 atm	= 1.0132 bar	
1 N/m 2	= 1 Pascal	
1 bar	0.987 atm	

The atmospheric pressure at sea level is 1.0I3 X10^5 N/m^2 or 760 mm of mercury.

Pressures higher than 1000 atm are usually regarded as very high while those of the order of 1 mm of Hg or below are regarded as very low.

TYPES OF PRESSURE MEASUREMENT DEVICES

A number of devices can be used for measurement of pressure. In industrial applications pressure is normally measured by means of **indicating**

gauges and recorders. These instruments are

- mechanical,
- electromechanical
- electrical or electronic in operation

(i) **Mechanical Pressure Measuring Instruments.**

Pressure can be easily transduced to force by allowing it to act on a known area. Therefore, basic methods of measuring force and pressure are essentially the same except for the pressures in the high vacuum region. Mechanical instruments used for pressure measurement are based on comparison with known dead weights acting on known areas or on the deflection of elastic elements subjected to unknown pressures.

Instruments using this principle include **manometers.** And the elastic members used are Bourdon tubes, bellows and diaphragms.

(ii) **Electromechanical Instruments.** These instruments generally employ mechanical means for detecting pressure and electrical means for indicating or recording pressure. Electromechanical instruments are very well suitable for dynamic measurements as they have an excellent frequency response characteristics.

(iii) **Electronic Instruments.** These pressure measuring instruments normally depend on some physical change that can be detected and indicated or recorded through electronic means. These instruments are used for vacuum measurements.

LECTURE NO.11

MEASUREMENT OF PRESSURE: MANOMETERS - U TUBE MANOMETER - INCLINED TUBE MANOMETER - WELL TYPE MANOMETER - PROPERTIES OF MANOMETRIC FLUIDS

MANOMETERS

Manometers measure the unknown pressures by balancing against the gravitational force of liquid heads. Manometers are self-balancing deflection type of instruments and have continuous rather than stepwise output. These are used in plant systems, as **differential pressure devices**. They are used as primary standards for pressure measurements from low vacuum range to about 0.1 MN/m^2.

Construction of Manometers. Manometer bodies are usually made of brass, steel, aluminum or stainless steel. Tubes are made of **pyrex**. Scales are provided which read pressures in terms of mm of water or in mm of mercury. They can be provided to read in terms of kN/m^2 (kPa).

Types of Manometers

The various types of manometers are:

U tube manometer, Well type Manometer, Inclined tube

Manometer. **U tube manometer**

The U tube manometer is shown in Fig. 11.1. This is used for measurement of liquid or gas pressures. The manometer is filled with a manometric fluid whose specific gravity is known. The difference between the pressures on two limbs of the manometer is a function of h (the difference between the levels of the manometric fluid in the two limbs).

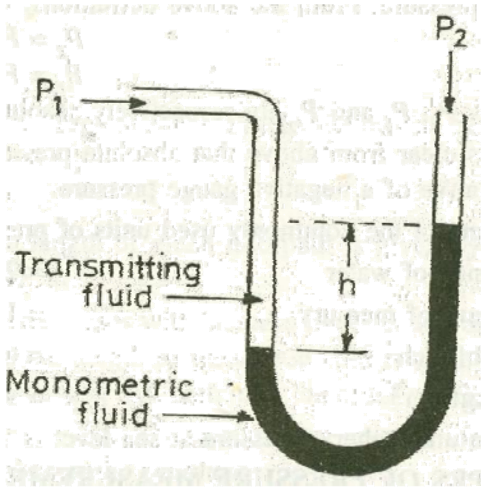


Fig. 11.1 U Tube Manometer

The pressure balance equation is,

$$P_1 + gh\rho_f = P_2 + gh\rho_m$$

Differential pressure, $P = P_1 - P_2 = gh(\rho_m - \rho_f)$

where

g is the gravitational constant (9.81 m/s^2) and

ρ_m and ρ_f are respectively the specific gravities of manometric fluid and the transmitting fluid in kg/m^3.

Well type Manometer

Unlike in the case of a U tube manometer, the two legs do not have the same area. In the well type manometer (Fig. 11.2), one of the legs of a U tube is substituted by a large well or reservoir. The cross-sectional area of the well (used **on the high pressure side**) is very large as compared to the area of the other leg. This means that even for a small displacement of liquid level in the well there will be a very large change of height of liquid column in the other limb. This results in increase of sensitivity.

A well type manometer operates in the same manner as the U-tube manometer except that the construction is as shown in Fig.11.2. Since, the well area is large compared to that of the tube, only a single leg reading may be noted and the change in level in the well may be ignored.

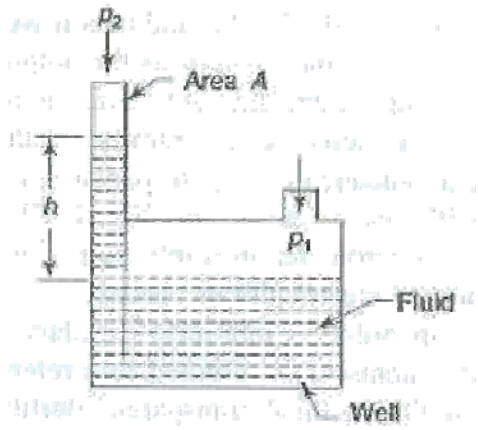


Fig. 11.2 Well type Manometer

If, P_1 and P_2 are absolute pressures applied as shown, force equilibrium gives:

$$P_1 A - P_2 A = A h\rho g$$

ρ being mass density of the liquid.

$$\frac{p_1 - p_2}{\rho g} = h$$

If P_2 is atmospheric, h is a measure of the guage pressure applied at the well.

Inclined Tube Manometer

An inclined tube manometer is a modified version of a well-type manometer wherein the vertical leg is placed in an almost horizontal position so that a very small change in pressure in the well causes a very large change in the measured level of liquid in the inclined leg.

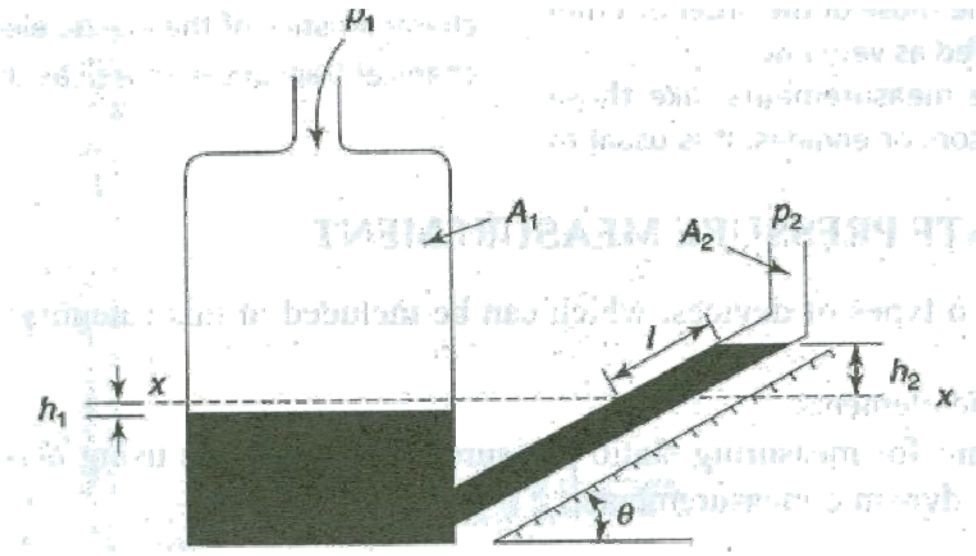


Fig.11.3 Inclined tube manometer

Fig. 11.3 shows an inclined tube manometer. Suppose a tube is inclined at a slope of 1: 20 to the horizontal, the 20 units being measured as shown. A rise of h mm in the liquid would mean that the displacement of liquid along the tube is 20 h mm. Thus, the movement for a small change in level is easily detected in an inclined tube manometer than in a vertical limbed manometer. Hence, the inclined tube manometers have a much higher sensitivity than that of vertical limbed manometers.

In these type of manometers, the length l along the inclined tube is read as a measure of the pressure difference ($p_1 - p_2$) and l is derived as follows:

When pressure in the two limbs are the same, the levels of the liquid are at equilibrium position xx. On application of pressure p_1 *and* p_2 , difference in levels between the two limbs is

$$h_1 + h_2 = \frac{p_1 - p_2}{\rho g}$$

If A_1 and A_2 are the respective areas of the two limbs,

$$A_1 h_1 = A_2 l$$

$$h_2 = l \sin \theta$$

From the above equations,

$$p_1 - p_2 = \rho g l \left(\frac{A_2}{A_1} + \sin \theta \right)$$

If $A_1 >> A_2$ or A_2 / A_1 is negligible,

$$p_1 - p_2 = \rho g l \sin \theta = \rho g h_2$$

If $\theta = 30^0$, $l = 2h_2$ and thus it would be more accurate to read l rather than h_2 as the output. Since $A_1 >> A_2$, the reading on one side only, viz. l is required.

Properties of Manometric Fluids

The desirable properties of manometric fluids are:

i. Low viscosity: Fluids with low viscosity give quick response.
ii. Low co-efficient of thermal expansion: The value of measured pressure is affected by changes in density of manometreric fluids which is dependent upon temperature.
iii. Low vapor pressure, negligible surface tension, and low capillary effects, and non-sticky effects.
iv. Non-corrosive, non-poisoness
v. Long term stability

Some of the manometric fluids are: water, Mercury, transformer oil (suitable for ammonia gas flow meters and measurements of small pressure differences), Aniline (suitable for low pressure air or gas flow meters with the exception of ammonia and chlorine)

Advantages of Manometers.

i. The advantages of manometers are:
ii. They are simple in construction, high accuracy, and good repeatability.
iii. Wide range of manometric fluids can be used

iv. They can be used both as measuring instruments and also as primary standards for pressure measurement on account of their inherent accuracy.
v. The accuracy level of manometers is quite good.

Disadvantages of Manometers.

The disadvantages of manometers are:

i. They are fragile in construction and hence lack portability.
ii. When visual reading of height h is used, corrections must be applied for effect of temperature on the engraved (fixed) scale.
iii. The value of gravitational constant g is dependent upon the altitude of the place
iv. Accurate leveling is required in order to have good accuracy.
v. Poor dynamic response.

Several types of modified manometers are available which have the advantages of ease in use and high sensitivity.

LECTURE NO.12

ELASTIC PRESSURE ELEMENTS - BOURDON TUBE – BELLOWS - DIAPHRAGMS

ELASTIC PRESSURE ELEMENTS

Elastic elements when subjected to pressure get deformed. The deformation, when measured, gives an indication of the pressure. These elements are in the form of diaphragms, capsules, bellows, Bourdon or helical tubes (Fig. 12.1). The deformation may be measured by mechanical or electrical means. These devices are convenient to use and can cover a wide range of pressures, depending on the design of the elastic elements.

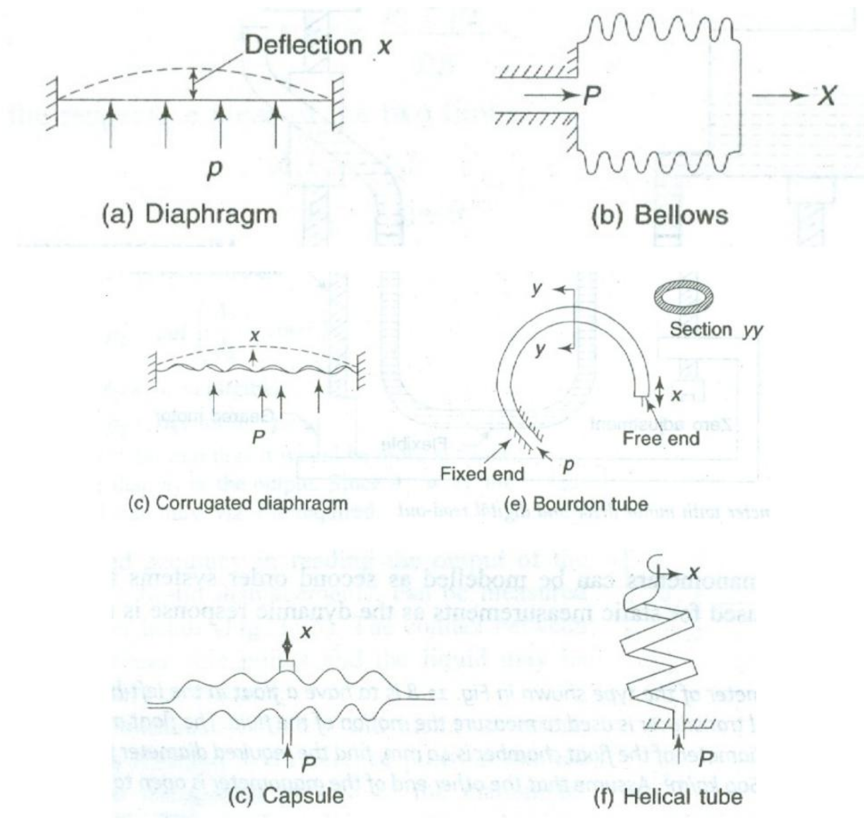


Fig. 12.1 Elastic elements / Pressure Elements

Among the elastic pressure elements, the three main types are:

(i) Bourdon Tube, *(ii) Bellows, and* *(iii) Diaphragm.*

BOURDON TUBE

A bourdon gauge is commonly used for measuring pressure. The Bourdon tubes find wide applications because of their simple design and low cost. There are three types of Bourdon elements and they are,

(i) C- type, (ii) spiral type, and (iii) helical type.

(i) C- type Bourdon element:

The tube which is oval in section is formed into an arc of *250_0* and hence the name C for the configuration which is shown in Fig. 12.2. One end called the tip of the tube is sealed and is called **free end**. This is attached by a light link-work to a mechanism which operates the pointer. The other end of the tube is fixed to a socket where the pressure to be measured is applied. The internal pressure tends to change the section of the tube. The degree of linearity depends upon the quality of gauge from oval to circular, and this tends to straighten out the tube. **The movement of the tip is ideally proportional to the pressure applied**. The tip is connected to a spring loaded link-work and a geared sector and pinion arrangement which amplifies the displacement of tip and converts into the deflection of the pointer. The linkage is constructed so that the mechanism may be constructed for optimum linearity and minimum hysteresis, as well as to compensate for wear which may develop over the time.

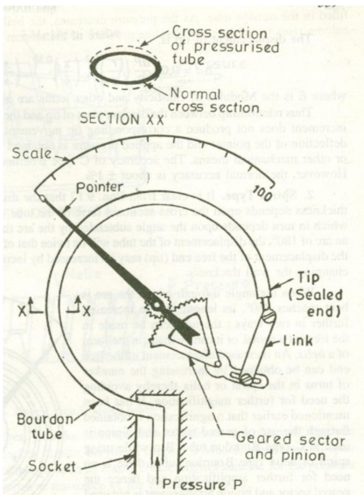


Fig. 12.2 C type Bourdon tube

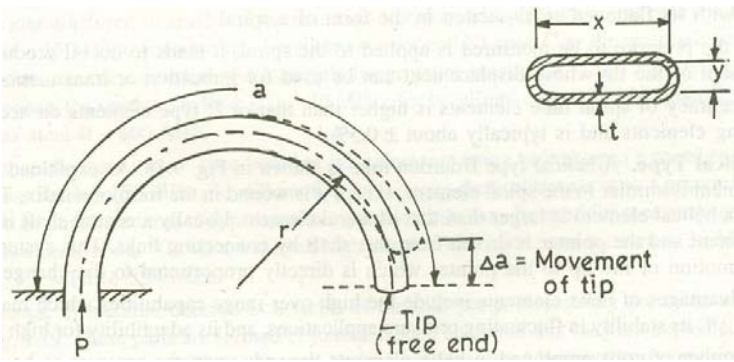


Fig. 12.3 Displacement at the free end of Bourdon Tube

The displacement of tip is,

$$\Delta a = 0.05\,\frac{aP}{E}\left(\frac{r}{t}\right)^{0.2}\left(\frac{x}{y}\right)^{0.33}\cdot\left(\frac{x}{t}\right)^{3}$$

Where

E is the Modulus of Elasticity and other terms are as shown in the above fig.

The normal accuracy of C type Bourdon tube is about ± 1 %.

(ii) Spiral type Bourdon tube

Spiral tubes are made by winding several turns of the tube with its flattened cross-section in the form of a spiral. When the pressure to be measured is applied to the spiral, it tends to uncoil producing a relatively long movement of the tip whose displacement can be used for indication or transmission. The accuracy of spiral tube elements is higher than that of C type elements on account of absence of magnifying elements and is typically about ± 0.5%.

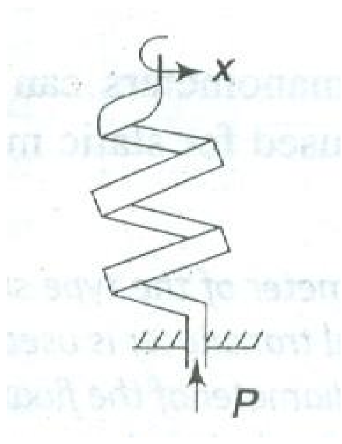


Fig. 12.4 Helical type Bourdon tube

(iii) Helical Type. A helical type Bourdon tube is shown in Fig. 12.4. Helical and Spiral bourdon tube elements are similar, except it is wound in the form of a helix. The displacement of the tip of a helical clement is larger than that of spiral element. Usually a central shaft is installed within a helical clement and the pointer is driven from this shaft by connecting links. This system transmits only the circular motion of the tip to the pointer which is directly proportional to the changes in pressure.

The advantages of helix elements include its stability in fluctuating pressure applications, and its adaptability for high pressure service. The number of coils employed in helix elements depends upon the pressure to be measured. Helix type of pressure elements use as few as three coils while elements used for measurement for high pressures may have as many as 16 coils or even more. The accuracies obtainable from helical elements may vary from ± 0.5 % to ± 1 %.

Materials used for constructing Bourdon Tubes

Bourdon tubes are made up of different materials which include brass, alloy steel, stainless steel, bronze, phosphor bronze, beryllium, copper, and monel.

Phosphor bronze is used in low pressure applications where the atmosphere is non-corrosive while in applications where corrosion and / or high pressure is a problem, **stainless steel or Monel are used**.

Pressure gauges using bourdon tube elements are made with ranges from 760 mm of mercury to 700 M Pa or higher for special applications with the minimum span being about 70 kPa.

Bellows

A metallic bellows consists of a series of circular parts, resembling the folds shown in Fig.12.5. These parts are formed or joined in such a manner that they are **expanded or contracted axially by changes in pressure**.

The metals used in the construction of bellows must

be thin enough to be flexible,

ductile enough for reasonably easy fabrication,

and have a high resistance to fatigue failure.

Materials commonly used are brass, bronze, beryllium copper, alloys of nickel and copper, steel and monel.

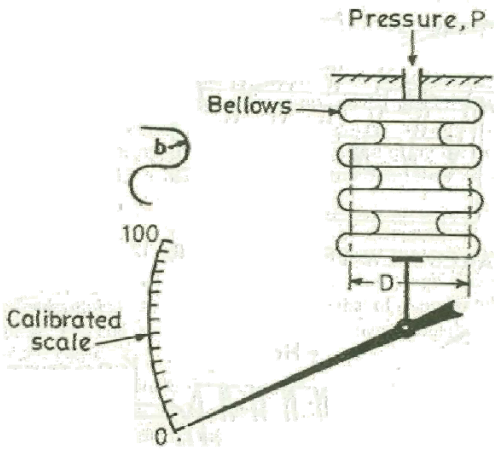


Fig.12.5 Bellows Pressure Element

The displacement of bellows element is given by.

$$d = \frac{0.453\ Pb\ n\ D^2 \quad \sqrt{1-v^2}}{Et^3}$$

Where,

P = Pressure, N/m^2

b = radius of each corrugation, m

n = number of semi-circular corrugations

t =thickness of wall, m

D = mean diameter, m

E = Modulus of elasticity, N/m^2

v = Poisson's ratio

The **advantages of bellows include** their simple and rugged construction, moderate price, their usefulness for measurement of low, medium and high pressures, and their applicability for use in measurement of absolute, gauge and differential pressures. Bellows are useful to measure vacuum and low pressures.

The disadvantages of bellows are that they are not suited for dynamic measurements on account of their greater mass and longer relative movement. Also they need temperature compensating devices to avoid errors resulting from changes in ambient temperature.

DIAPHRAGMS

The operating principle of diaphragm elements is similar to that of the bellows. The pressure to be measured is applied to the diaphragm, causing it to deflect, the deflection being proportional to the applied pressure. The movement of the diaphragm depends on its thickness and diameter.

The diaphragm element is essentially a flexible disc which may be either flat or corrugated as shown in Fig. 12.6.

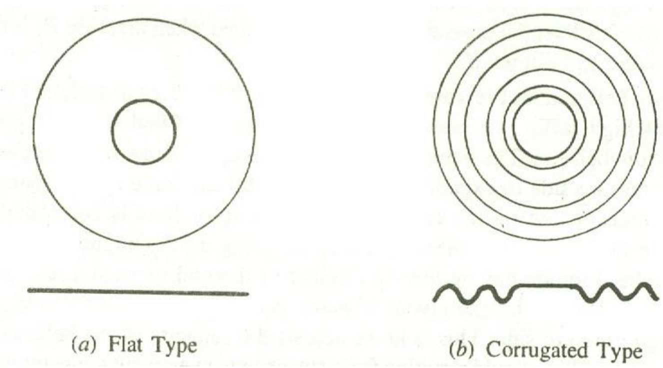


Fig. 12.6 Single Diaphragm elements

For the arrangement of a flat diaphragm shown in Fig. 12.7 the maximum deflection, d_m and the deflection at any radius, d_r , are given by following expressions:

$$d_m = \frac{3P}{16\,Et^3} R^4 (1 - v^2)$$

and

$$d_r = \frac{3P(1-v^2)}{16\,Et^3} (R^2 - r^2)^2$$

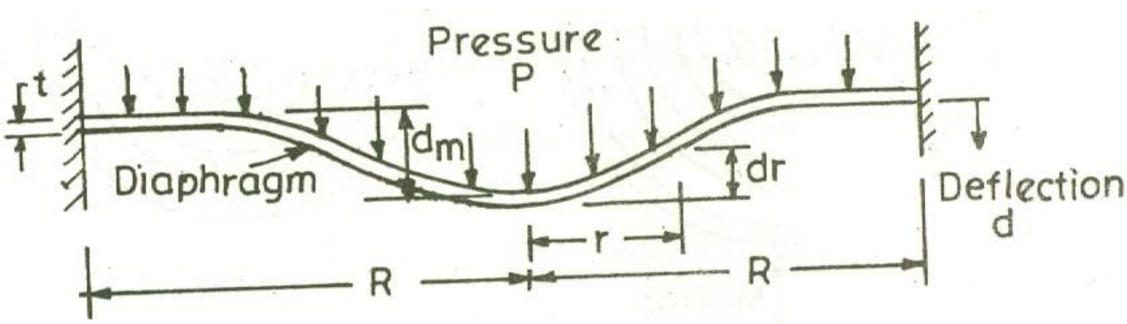


Fig.12.7 Deflection of flat diaphragm.

In some cases, a diaphragm element may consist of a single disc, while in others, two diaphragms are bonded together at their circumference by soldering or pressure welding to form **a capsule**. A diaphragm element may consist of one capsule or two or more capsules connected together with each capsule deflecting on the application of pressure. The total deflection is the sum of the deflections of individual capsules. Fig. 12.8 shows a diaphragm element consisting of three capsules. In this assembly, the individual capsule is connected axially with the next one and is allowed to expand without any restraints.

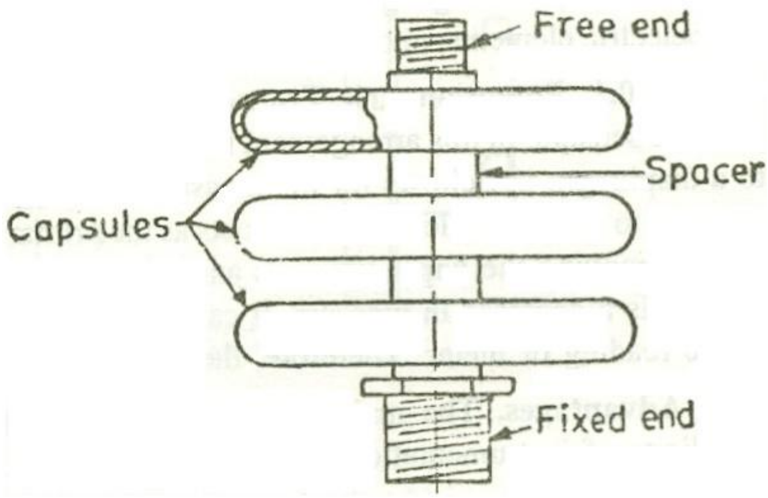


Fig.12.8 Diaphragm element using three capsules

LECTURE NO.13

TYPES OF FLUID FLOW: STEADY FLOW AND UNSTEADY FLOW-UNIFORM FLOW AND NON-UNIFORM FLOW - ONE-DIMENSIONAL FLOW, TWO DIMENSIONAL FLOW AND THREE DIMENSIONAL FLOW-ROTATIONAL FLOW AND IRROTATIONAL FLOW - LAMINAR FLOW AND TURBULENT FLOW.

TYPES OF FLUID FLOW

Fluid flows are classified in several ways as indicated below:

I. Steady flow and Unsteady flow.
II. Uniform flow and Non-uniform flow.
III. One-dimensional flow, two dimensional flow and three dimensional flow.
IV. Rotational flow and Irrotational flow
V. Laminar flow and Turbulent flow.

Steady Flow

Fluid flow is said to be steady if at any point in the flowing fluid various characteristics such as velocity, pressure, density, temperature etc., which describe the behavior of the fluid in motion, do not change with time. The various characteristics of the fluid in motion are independent of time.

However, these characteristics may be different at different points in the flowing fluid.

Unsteady Flow

Fluid flow is said to be unsteady if at any point in the flowing fluid any one or all the characteristics which describe the behaviour of the fluid in motion change with time.

Steady flow is simpler to analyze than unsteady flow. Most of the practical problems of engineering involve only steady flow conditions.

Uniform Flow

When the velocity of flow of fluid does not change, both in magnitude and direction, from point to point in the flowing fluid, for any given instant of time, the flow is said to be uniform.

For example flow of liquids under pressure through long pipe lines of constant diameter is uniform flow.

Non-uniform Flow

If the velocity of flow of fluid changes from point to point in the flowing fluid at any instant, the flow is said to be non-uniform.

For example, flow of liquids under pressure through long pipelines of varying diameters is non-uniform flow.

All these types of flows can exist independent of each other so that any of the four types of combinations of flows is possible, viz., (a) steady-uniform flow; (b) steady-non-uniform flow; (c) unsteady uniform flow; and (d) unsteady-non-uniform flow. Examples of these combinations of flows are:

flow of liquid through a long pipe of constant diameter at a constant rate is steady uniform flow;

flow of liquid through a long pipe line of constant diameter, at either increasing or decreasing rate is unsteady-uniform flow;

flow of liquid through a tapering pipe at a constant rate is steady-non-uniform flow and

flow through a tapering pipe at either increasing or decreasing rate is unsteady-non-uniform flow.

One-dimensional, Two-dimensional and Three-dimensional Flows

The various characteristics of flowing fluid such as velocity, pressure, density, temperature etc, are in general the functions of space and time i.e., *these may vary with the coordinates of any point x, y and z and time t*. Such a flow is known as a three-dimensional flow. If any of these characteristics of flowing fluid does not vary with respect to time, then it will be a steady three-dimensional flow.

When the various characteristics of flowing fluid are the functions of only any two of the three coordinate directions, and time t, i.e., these may not vary in anyone of the directions, then the flow is known as **two-dimensional flow**. For example, if the characteristics of flowing fluid do not vary in the coordinate direction Z, then it will be a two-dimensional flow having flow conditions identical in the various planes perpendicular to the Z-axis.

When the various characteristics of flowing fluid are the functions of only one of the three coordinate directions and time t, i.e., these may vary only in one direction, then the flow is known as one dimensional flow. Similarly, it will be a steady one dimensional flow if the characteristics of flowing fluid do not vary with respect to time. Considering one of the characteristics of flowing mass of fluid, say velocity of flow V, the following expressions may be written which clearly exhibit the difference between these three types of flows:

Types of Flow	**Unsteady**	**Steady**
Three dimensional	$V = f(x, y, z, t)$	$V = f(x, y, z)$
Two dimensional	$V = f(x, y, t)$	$V = f(x, y)$
One dimensional	$V = f(x, t)$	$V = f(x)$

Rotational Flow

A flow is said to be rotational if the fluid particles while moving in the direction of flow rotate about their mass centres. The liquid in the rotating tanks illustrates rotational flow where the velocity of each particle varies directly as the distance from the centre of rotation.

Irrotational Flow

A flow is said to be irrotational if the fluid particles while moving in the direction of flow do not rotate about their mass centres.

Laminar Flow

A flow is said to be laminar when the various fluid particles move in layers (or laminae) with one layer of fluid sliding smoothly over an adjacent layer. Thus in the development of a laminar flow, the viscosity of the flowing fluid plays a significant role.

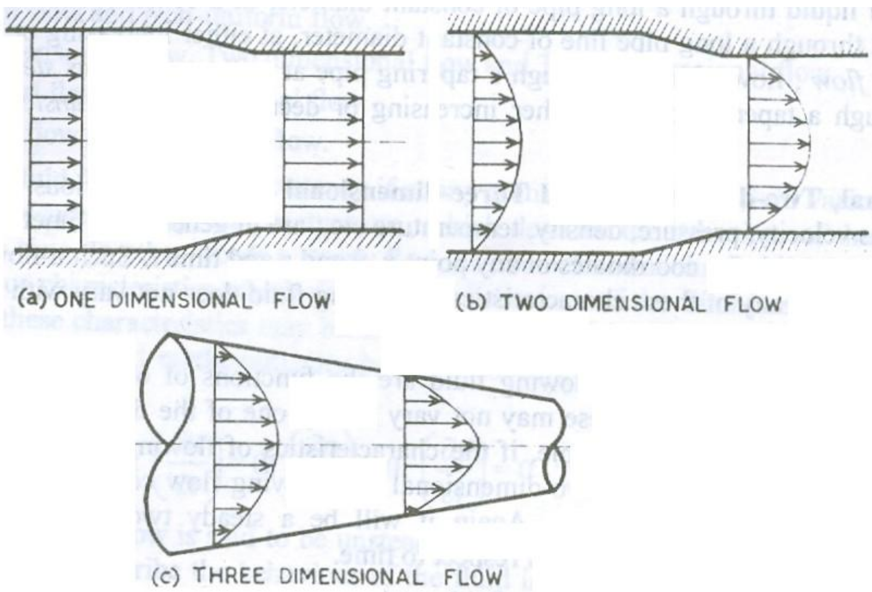


Fig. 13.1 One, Two and Three-dimensional flows

Turbulent Flow

A fluid motion is said to be turbulent when the fluid particles move in an entirely haphazard or disorderly manner that results in a rapid and continuous mixing of the fluid leading to momentum transfer as flow occurs. In such a flow eddies or vortices of different sizes and shapes are present which move over large distances. This eddies and their random movement give rise to fluctuations in the velocity and pressure at any point in the flow field, which are necessarily the functions of time.

LECTURE NO.14

FLOW MEASUREMENT: INTRODUCTION - PRIMARY OR QUANTITY METERS - POSITIVE-DISPLACEMENT METERS - SECONDARY OR RATE METERS - VARIABLE HEAD METERS

FLOW MEASUREMENT: Introduction

Flow measurements are essential in many applications such as transportation of solids as slurries, compressed natural gas in pipelines, water and gas supply systems to domestic consumers, irrigation systems and a number of industrial process control systems. The types of flows encountered in the measurements may be any one or combination of the following types:

- clean or dirty/opaque,
- wet or dry,
- hazardous/corrosive or safe,
- single-phase, two-phase or multiphase,
- laminar or transitional or turbulent,
- pressure may vary from vacuums to high pressures of many atmospheres,
- temperature may vary from cryogenic levels to hundreds of centigrade,
- flow rate may be of miniscule type, i.e., few drops per minute or massive type involving thousands of litres per minute.

The selection of a particular flow-measuring equipment depends primarily on the nature of the metered fluid and the demands of the associated plant. Many industrial flow meters have to work with fluids which may be corrosive in nature or may contain foreign matters, but the equipment may be relatively large and of fixed type. Additionally, the other factors that govern the choice of a particular flow metering device are the various performance parameters like range, accuracy, repeatability, linearity, dynamic response, type of output like analog / digital, etc. Further, another requirement may be to indicate or record the rate of flow, total flow or may be both these quantities.

Flow measuring devices generally fall into one of the two categories, namely, *primary devices or quantity meters* and **secondary devices known as rate meters**. The distinction between the two is based on the character of the sensing element that interacts with the fluid flow. Quantity measurements, by mass or volume, are usually accomplished by counting successive isolated portions, whereas rate measurements are inferred from effects of flow rates on pressure, force, heat transfer, flow area, etc. The quantity meters are generally used for the calibration of rate meters.

PRIMARY OR QUANTITY METERS

Quantity or total flow measurement signifies the amount of fluid in terms of mass or volume that flows past a given point in a definite period of time. In other words, in this technique, the time required to collect a particular amount of fluid is determined accurately and then the average flow rate can be evaluated.

The flow meter calibration procedures using the quantity measurements fall into the following two categories.

1. Voumetric Method
2. Gravimetric Method

Volumetric Method

In this technique, the fluid flowing in the flow meter which is being calibrated is diverted into a tank of known volume. When the tank is completely filled, then this known volume is compared with the integrated, volumetric quantity registered by the flow meter under test.

Gravimetric Method

In this technique also, the fluid flowing in the flow meter, which is being calibrated, is diverted into a vessel which can be weighed either continuously or in the vessel after a pre-determined time. The weight of the liquid collected is compared with the gravimetric quantity registered by the flow meter under test.

POSITIVE-DISPLACEMENT METERS

The term positive displacement meter is applied to a flow measuring device so designed that the metered fluid is repeatedly filled and emptied from a space of known volume. **The principle of this measurement is that the liquid flows through a meter and moves the measuring element that seals the measuring chamber into a series of measuring compartments each holding a definite volume.** Each element is successively filled from the flow at the inlet and emptied at the outlet of the meter. In other words, it is said that positive-displacement meters chop the flow into ‘pieces' of known size and then count the number of ‘pieces’.

Positive-displacement meters are widely used in low flow rate metering applications where high accuracy and repeatability under steady flow conditions are required. Further, they are easy to install and maintain and have moderate cost. These types of meters are generally used by the water and oil undertakings for accounting purposes. However, since there are moving parts in these devices, the wear of the components may alter the accuracy. Therefore, these instruments need calibration/adjustment over an interval of time. Another limitation of such meters is their suitability to clean fluids only. Further, these devices are generally flow totalizers and do not give instantaneous rate of flow.

SECONDARY OR RATE METERS

The secondary or rate meters are also termed as ***inferential*** type of flow measuring devices. This is because of the fact that they do not measure the flow directly but instead measure another physical quantity which is related to the flow. These devices fall into **two categories**, namely, the **flow rate meters** and the **velocity meters**.

The transduction principle of some typical flow rate meters is as follows:

(i) Variable head meters: These are also termed as obstruction type of meters in which the obstruction to the flow consists of an engineered constriction in the metered fluid which causes a reduction in the flow pressure.

(ii) Variable area meters: The change in area causes change in the drag force of a body placed in the flowing fluid.

(iii) Variable head and variable area meters: In these devices, a specified shaped restriction is placed in the path of the flow which causes a rise in the upstream liquid level, which is a function of the rate of flow.

(iv) Constant head device: In this device a constant head is applied to cause a laminar flow in the capillary tube. In this device, the applied head is lost in fluid friction but it causes a flow rate which can be metered.

Variable Head Meters

These meters essentially **introduce an engineered constriction** in the flow passage. The, devices in general can be termed as obstruction type of flow meters. The term 'obstruction meter' applies to the devices that act as obstacles placed in the path of the flowing fluid, causing **localized changes in the velocity**. Concurrently with the velocity change, there is a corresponding pressure change in the flow. This variation in pressure change is correlated with the rate of flow of the fluid. It is noted that these devices cause a loading error in the metered value because obstruction introduces extra resistance in the flow system consequently, the flow rate reduces somewhat. The main forms of restriction used in the flow are

venturi tube,

orifice plate and

a nozzle.

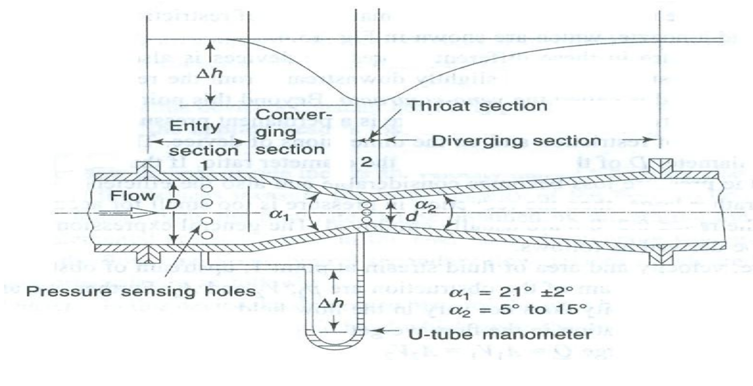


Fig. (a) Venturi meter

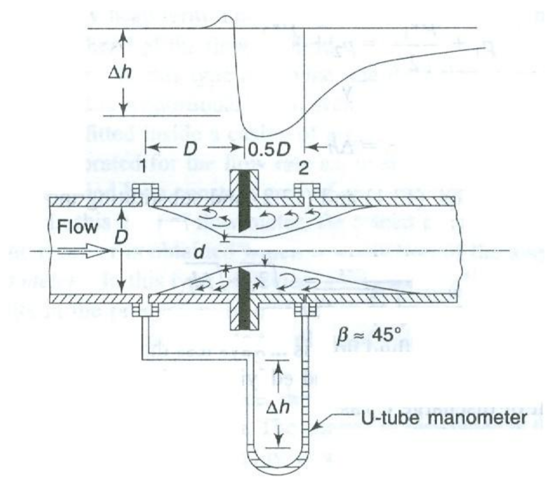


Fig.(b) Orifice meter

Fig. 14.1 Different types of variable head meters

The variation of pressure in these differential pressure devices is indicated in Fig.14.1 (a) and Fig.14.1 (b). The position of minimum pressure is located slightly downstream from the restriction at a point where the stream is the narrowest and is called the ***vena-contracta***. Beyond this point, the pressure again rises but does not return to the upstream value and thus there **is a permanent pressure loss**. The magnitude of this loss depends on the type of restriction and on the dimensions of device. The ratio of the diameter at the constriction to the diameter D of the pipe is called the ***diameter ratio***. If this ratio is too small, the opening is narrow and the pressure loss becomes considerable and also the efficiency of the measurement is low. If the ratio is rather large, then the reduction in pressure is too small for accurate measurements. In practice, ratios in the range 0.2-0.6 are usually employed.

LECTURE NO.15

THE GENERAL EXPRESSION FOR THE RATE OF FLOW- CONSTRUCTION OF VENTURI METER

The general expression for the rate of flow in these devices can be derived as follows:

Say, the pressure, velocity and area of fluid stream at point 1, upstream of obstruction are p_1, V_1 and A_1 and at point 2 just downstream of the obstruction are p_2, V_2 and A_2. Further, we assume the flow to be **incompressible**, i.e., its density does not vary in the flow field.

Applying the continuity equation in the flow we get

Rate of discharge $Q = A_1V_1 = A_2V_2$ ------ (15.1)

Applying Bernoulli's equation (assuming the flow to be ideal) we get,

$$P_1 + \frac{\rho V_1^2}{2} = P_2 + \frac{\rho V_2^2}{2} \quad (15.2)$$

The differential pressure head Δh is given by

$$\frac{p_1 - p_2}{\rho g} = \Delta h \quad (15.3)$$

Eliminating V_1 and V_2 from Eqs. (15.1) and (15.2) and substituting the value of Δh from eq. (3) we get the ideal rate of discharge as

$$Q_{ideal} = \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} . \sqrt{2g} \sqrt{\Delta h} \quad (15.4)$$

In actual practice, the actual rate of fluid flow is always less than Q_{ideal} as given by eq.(15.4), because of the losses in the fluid flow due to friction and eddying motions. To account for this discrepancy, we define the term coefficient of discharge C_d as

$$C_d = \frac{Q_{actual}}{Q_{ideal}} \qquad (15.5)$$

Thus, we can write the actual rate of fluid flow as

$$Q_{actual} = C_d \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} . \sqrt{2g} \sqrt{\Delta h} \qquad (15.6)$$

Equation (15.6) can be rewritten in the simplified from as

$$Q_{actual} = C_d \; K (\Delta h)^{1/2}$$

(15.6)

Where K is the constant of low obstruction device and

$$K = \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} . \sqrt{2g}$$

where C_d is the coefficient of discharge which depends on the type of flow, obstruction type configuration and also on the Reynolds number of the flow.

Reynolds number = $\frac{\rho V D}{\mu}$

The venturimeter offers the best accuracy, least head loss as compared to the orifice meter. Because of the smooth surface, it is not much affected by the wear and abrasion from dirty fluids. Further, due to low value of losses, the coefficient of discharge is high and approaches unity under favourable conditions. However, it is expensive and occupies substantial space.

An orifice meter consists of thin orifice plate which may be clamped between pipe flanges. Since its geometry is simple, it is low in cost, easy to install or replace and takes almost no space. However, it suffers from a head loss which is of the order of 30-40%. Also, it is susceptible to inaccuracies resulting from erosion, corrosion, clogging, etc. due to flow of dirty fluids.

The variable head devices are widely used in practice, because they have no moving parts and require practically no maintenance. Further, they can be used without calibration if made to standard dimensions. However the major disadvantage is the square-root relationship between the pressure loss and the rate of fluid flow. Further, it is not practical to measure the flow below 20% of the rated meter capacity because of the inaccuracies involved in a very low pressure differential measurements.

CONSTRUCTION OF VENTURI METER

A venturi meter is a device which is used for measuring the rate of flow of fluid through a pipe. The basic principle on which a venturi meter works is that by reducing the cross-sectional area of the flow passage, a pressure difference is created and the measurement of the pressure difference enables the determination of the discharge through the pipe.

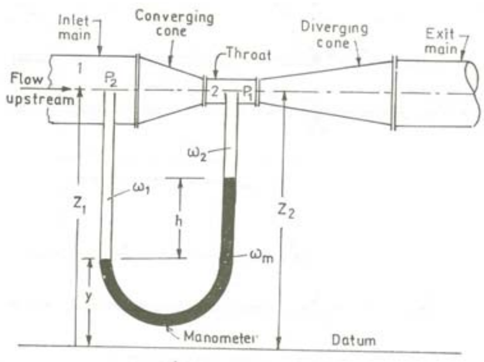


Fig.15.1 Venturi Meter

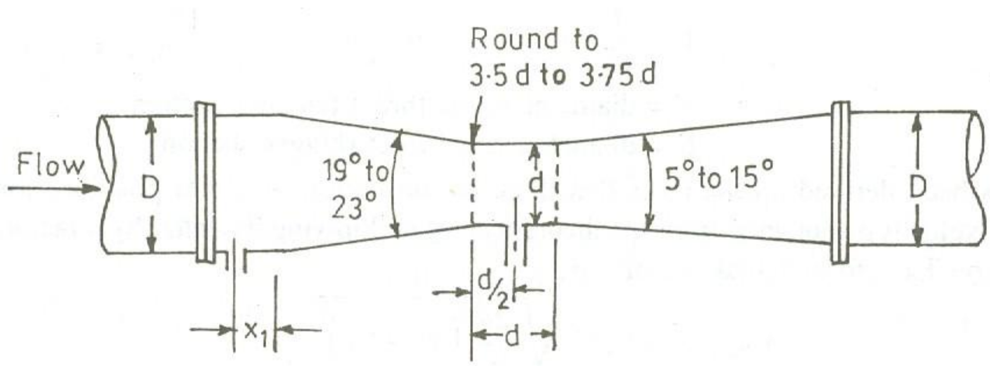


Fig.15.2 Typical dimensions of Venturi Meter

As shown in Fig. 15.1 a venturi meter consists of (1) an inlet section followed by a convergent cone, (2) a cylindrical throat, and (3) a gradually divergent cone. The inlet section of the venturi meter is of the same diameter as that of the pipe which is followed by a convergent cone. The convergent cone is a short pipe which tapers from the original size of the pipe to that of the throat of the venturi meter. The throat of the venturi meter is a short parallel-sided tube having its cross-sectional area smaller than that of the pipe. The divergent cone of the venturi meter is a gradually diverging pipe with its cross-sectional area increasing from that of the throat to the original size of the pipe. At the inlet section and the throat, i.e., sections 1 and 2 of the venturi meter, pressure taps are provided through pressure rings as shown in Fig.15.1.

The convergent cone of a venturi meter has a total included angle of 21°± 1° and its length parallel to the axis is approximately equal to 2.7 (D - d), where D is the diameter of the inlet section and d is the diameter of the throat.

The length of the throat is equal to d. The divergent cone has a total included angle lying between 5° to 15°, (preferably about 6°). This results in the convergent cone of the venturi meter to be of smaller length than its divergent cone.

Since the cross-sectional area of the throat is smaller than the cross-sectional area of the inlet section, the velocity of flow at the throat will become greater than that at the inlet section, according to the continuity equation ($A_1 V_1 = A_2 V_2$). The increase in the velocity of flow at the throat results in the decrease in the pressure at this section as explained earlier. As such a pressure difference is developed between the inlet section and the throat of the venturi meter. The pressure difference between these sections can be determined either by connecting a differential manometer between the pressure taps provided at these sections or by connecting a separate pressure gage at each of the pressure taps. The measurement of the pressure difference between these sections enables the rate of flow of fluid to be calculated as indicated below. Liquids ordinarily contain some dissolved air which is released as the pressure is reduced and it too may form air pockets in the liquid. The formation of the vapour and air pockets in the liquid ultimately results in a phenomenon called cavitation, which is not desirable. Therefore, in order to avoid the phenomenon of cavitation to occur, the diameter of the throat can be reduced only upto a certain limited value which is restricted on account of the above noted factors. In general, the diameter of the throat may vary from $\frac{1}{3}$ to $\frac{3}{4}$ of the pipe diameter and more commonly the diameter of the throat is kept equal to 1/2 of the pipe diameter.

LECTURE NO.16

CONSTRUCTION OF ORIFICE METER

An orifice meter is another simple device used for measuring the discharge through pipes. Orifice meter also works on the same principle as that of venturi meter i.e., by reducing the cross-sectional area of the flow passage a pressure difference between the two sections is developed and the measurement of the pressure difference enables the determination of the discharge through the pipe. However, an orifice meter is a cheaper arrangement for discharge measurement through pipes and its installation requires a smaller length as compared with venturi meter. As such where the space is limited, the orifice meter may be used for the measurement of discharge through pipes.

An orifice meter consists of a flat circular plate with a circular hole called orifice, which is concentric with the pipe axis. The thickness of the plate t is less than or equal to 0.05 times the diameter of the pipe. From the upstream face of the plate the edge of the orifice is made flat for a thickness t_1 less then or equal to 0.02 times the diameter of the pipe and for the remaining thickness of the plate it is bevelled with the bevel angle lying between 30° to 45° (preferably 45°).

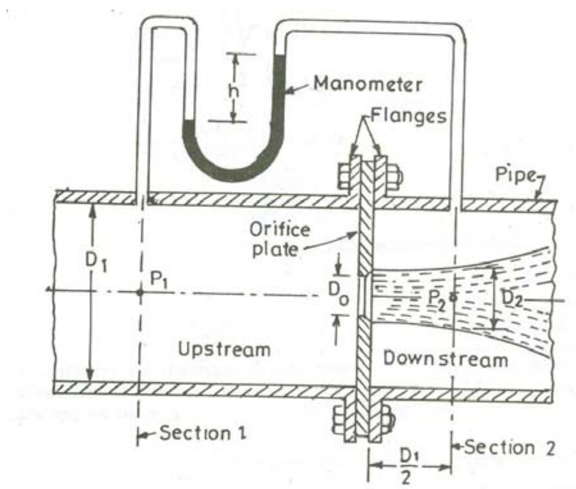


Fig. 16.1 Orifice meter

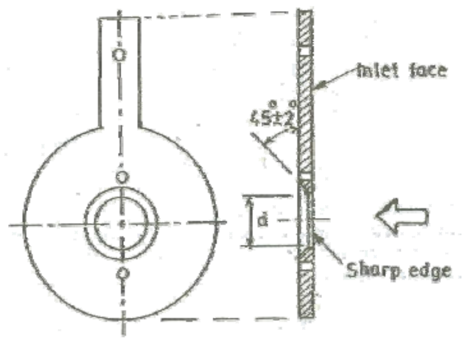


Fig.16.2 Concentric orifice plate with 45 ° bevelled edges

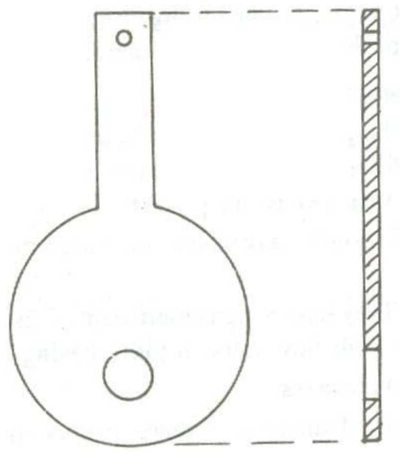


Fig.16.3 Eccentric orifice plate

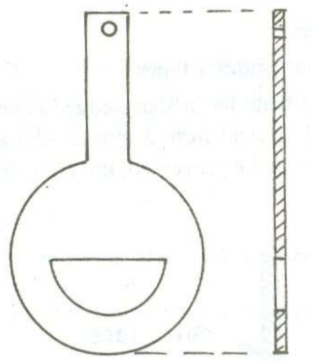


Fig.16.4 Segmental orifice plate

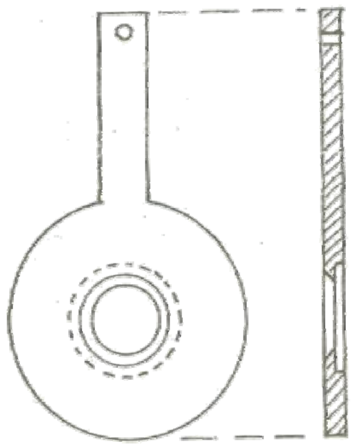


Fig.16.5 Quadrant edge orifice plate

However, if the plate thickness t is equal to t_1 , then no beveling is done for the edge of the orifice. The plate is clamped between the two pipe flanges with the bevelled surface facing downstream. The diameter of the orifice may vary from 0.2 to 0.85 times the pipe diameter, but generally the orifice diameter is kept as 0.5 times the pipe diameter. Two pressure taps are provided, one at section 1 on the upstream side of the orifice plate and the other at section 2 on the downstream side of the orifice plate. The upstream pressure tap is located at a distance of 0.9 to 1.1 times the pipe diameter from the orifice plate. The position of the downstream pressure tap, however, depends on the ratio of the orifice diameter and the pipe diameter. Since the orifice diameter is less than the pipe diameter as the fluid flows through the orifice the flowing stream converges which results in the acceleration of the flowing fluid in accordance with the considerations of continuity. The effect of the convergence of flowing stream extends upto a certain distance upstream from the orifice plate and therefore the pressure tap on the upstream side is provided away from the orifice plate at a section where this effect is non-existent. However, on the downstream side the pressure tap is provided quite close to the orifice plate at the section where the converging jet of fluid has almost the smallest cross-sectional area (which is known as venacontracta) resulting in almost the maximum velocity off low and consequently the minimum pressure at this section. Therefore a maximum possible pressure difference exists between the sections 1 and 2, which is measured by connecting a differential manometer between the pressure taps at these sections, or by connecting a separate pressure gauge at each of the pressure taps. The jet of fluid coming out of the orifice gradually expands from the vena contracta to again fill the pipe. Since in the case of an orifice meter an abrupt change in the cross-sectional area of the flow passage is provided and there being no gradual change in the cross-sectional area of the flow passage as in the case of a venturi meter, there is a greater loss of energy in an orifice meter than in a venturi meter.

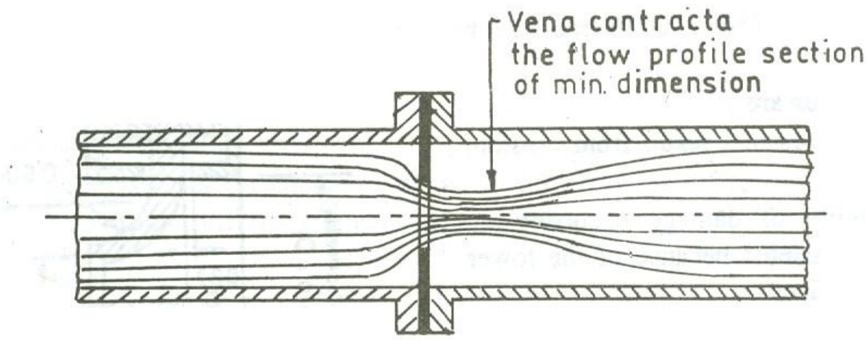


Fig.16.6 Location of Vena contracta point

LECTURE NO.17

VARIABLE AREA METERS- ROTAMETER; PITOT TUBE - ITS ADVANTAGES - ITS LIMITATIONS

VARIABLE AREA METERS

In the variable area meter, the area of the restriction can be altered to maintain a steady pressure difference.

A commonly used variable area flow meter is the **rotameter**.

ROTAMETER

The rotameter also known as variable-area meter is shown in Fig.17.1. It consists of a vertical transparent conical tube in which there is a rotor or float having a sharp circular upper edge. The rotor has grooves on its head which ensure that as liquid flows past, it causes the rotor to rotate about its axis. The rotor is heavier than the liquid and hence it will sink to the bottom of the tube when the liquid is at rest. But as the liquid begins to flow through the meter, it lifts the rotor until it reaches a steady level corresponding to the discharge. This rate of flow of liquid can then be read from graduations engraved on the tube by prior calibration, the sharp edge of the float serving as a pointer. The rotating motion of the float helps to keep it steady. In this condition of equilibrium, the hydrostatic and dynamic thrusts of the liquid on the under side of the rotor will be equal to the hydrostatic thrust on the upper side, plus the apparent weight of the rotor.

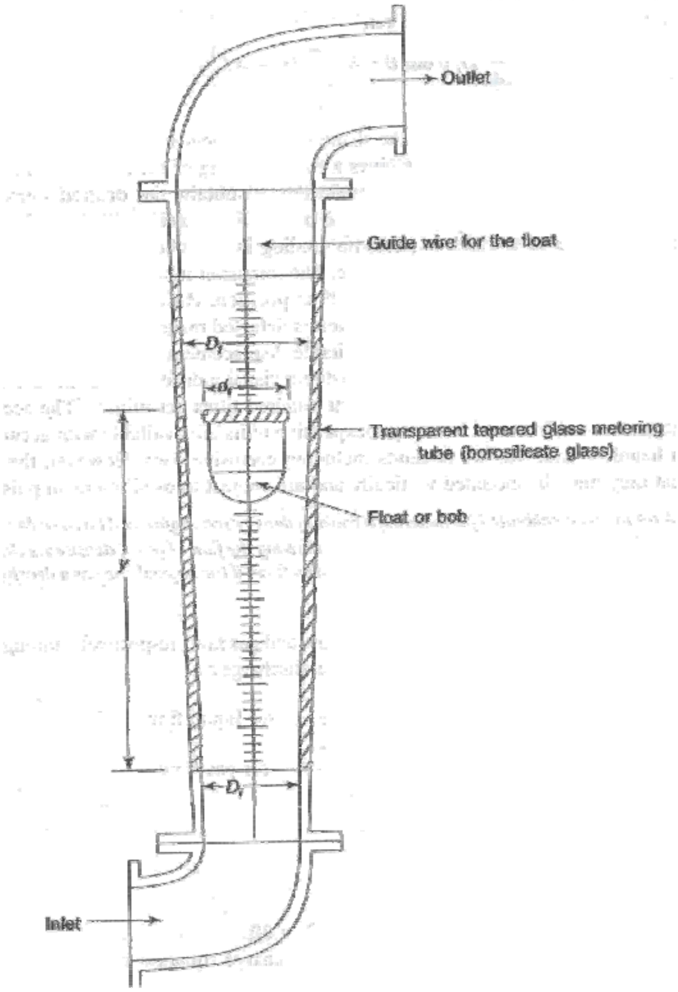


Fig. 17.1 Rotameter

PITOT TUBE

A pitot tube is a simple device used for measuring the velocity of flow. The basic principle used in this device is that if the velocity of flow at a particular point is reduced to zero, which is known as **stagnation point**, the pressure there is increased due to the conversion of the kinetic energy into pressure energy, and by measuring the increase in the pressure energy at this point the velocity of flow may be determined.

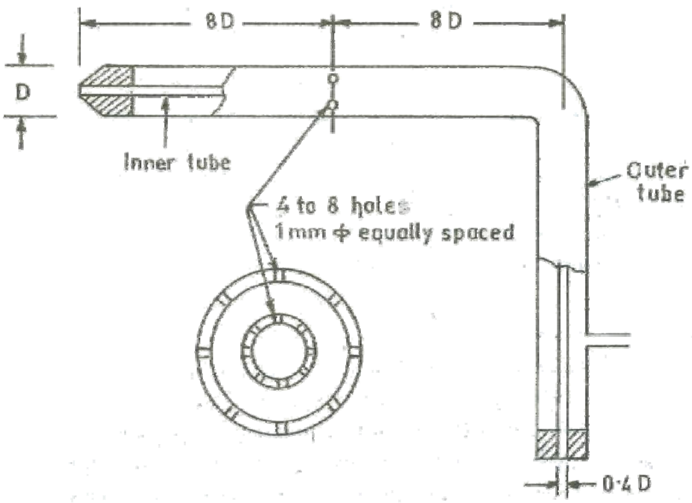


Fig.17.2 A schematic diagram of a pitot tube

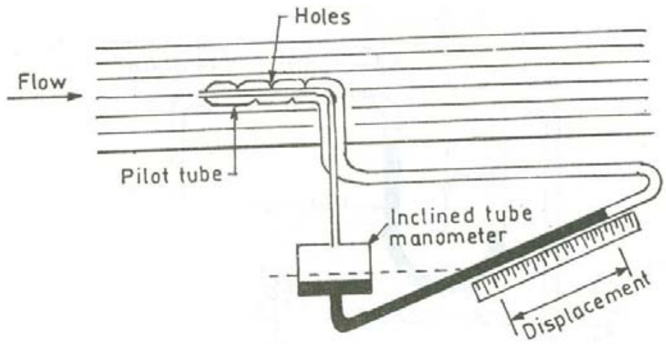


Fig. 17.3 A pitot tube with inclined tube manometer

In its simplest form a pitot tube consists of a glass tube, large enough for capillary effects to be negligible, and bent at right angles. *A single tube of this type may be used for measuring the velocity of flow in an open channel*. The tube is dipped vertically in the flowing stream of fluid with its open end A, directed to face the flow, and the other open end projecting above the fluid surface in the stream as shown in Fig.17.3. The fluid enters the tube and the level of the fluid in the tube exceeds that of the fluid surface in the surrounding stream. This is so because the end A of the tube is a stagnation point where the fluid is at rest, and the fluid approaching the end A divides at this point and passes around the tube. Since at the stagnation point the kinetic energy is converted into the pressure energy, the fluid in the tube rises above the surrounding fluid surface by a height which corresponds to the velocity of flow of fluid approaching the end A of pitot tube. *The pressure at the stagnation point is known* ***as stagnation pressure***.

Consider a point 1 slightly upstream of end A and lying along the same horizontal plane in the flowing stream where the velocity of flow is V. Now if the points 1 and A are at a vertical depth of h_o below the free surface of fluid in the stream and h is the height of the fluid raised in the pitot tube above the free surface, then applying Bernoulli's equation between the points 1 and A and neglecting the loss of energy, we get

$$h_0 + \frac{V^2}{2g} = h_o + h$$

In the above expression (h_o + h), is the stagnation pressure head at point A, which consists of two parts viz., the static pressure head h_o and the dynamic pressure head h. By simplifying the expression, we get

$$\frac{V^2}{2g} = h;$$

or $V = \sqrt{2gh}$

Above equation indicates that the dynamic pressure head h is proportional to the square of the velocity of flow in the stream at the point close to the end A of the Pitot tube. Thus the velocity of flow at any point in the flowing stream may be determined by dipping the pitot tube to the required point and measuring the height h of the fluid raised in the tube above the free surface. However, the velocity of flow given by equation is somewhat more than the actual velocity of flow, because in deriving the above equation no loss of energy has been considered. Moreover, when the flow is highly turbulent the pitot tube records a value of h which is higher than that corresponding to the mean velocity of flow in the direction of the tube axis. As such in order to take into account the errors which may creep in due to the above noted factors the actual velocity of flow may be obtained by introducing a coefficient C (or C_v) called pitot tube coefficient, so that the actual velocity of flow is given by

$$V = C\sqrt{2gh}$$

A probable value for the coefficient of the pitot tube, **C is 0.98**. However, the actual value of the coefficient C for a pitot tube may be determined by calibration.

When a pitot tube is used for measuring the velocity of flow in a pipe or any other closed conduit then the pitot tube may be inserted. Since a pitot tube measures the stagnation pressure head (or the total head) at its dipped end, the static pressure head is also required to be measured at the same section where the tip of the pitot tube is held, in order to determine the dynamic pressure head h. For measuring the static pressure head a pressure tap (or a static orifice) is provided at this section to which a piezometer may be connected. Alternatively the dynamic pressure head may also be determined directly by connecting a suitable differential manometer between the pitot tube and the pressure tap meant for measuring the static pressure.

The pitot tube has the following advantages:

1. It is a simple and low-cost device,
2. It produces no appreciable pressure loss in the flow system,
3. It can be easily inserted through a small hole into the pipe or duct, and
4. It is very useful for checking the mean velocities of the flows in venturi, nozzle, orifice plate or any other complex flow field.

The limitations of this device are follows:

1. It is not suitable for measuring low velocities, i.e., below 5 m/s, because of difficulties in the accurate measurement of pressure differential.
2. It is sensitive to misalignment of the probe with respect to free stream velocity. Usually an angle of yaw or misalignment up to 5° has little effect on the velocity values but beyond 20° the error in the velocity determination is of the order of 2%.
3. It is not suitable for the measurement of highly fluctuating velocities, i.e., highly turbulent flows.
4. The use of pitot-tube is limited to exploratory studies. It is not commonly used in industrial applications as numerous pitot tube

traverses are required for velocity distribution data which is quite tedious and time-consuming.

LECTURE NO.18

VARIABLE HEAD AND VARIABLE AREA FLOW METERS (WEIRS) - HOT WIRE ANEMOMETERS - ROTARY VANE METER

VARIABLE HEAD AND VARIABLE AREA FLOW METERS (WEIRS)

Weirs are variable head, variable area flow meters used for measuring large volumes of liquids in open channels. These devices operate on the principle that if a restriction of a specified shape and form is placed in the path of the flow, a rise in the upstream liquid level occurs which is a function of the rate of flow through the restricted section.

Weirs have a variety of forms and are classified according to the shape of the notch or opening. The most commonly used weirs are the rectangular, the triangular or V-notch and the trapezoidal or cipolleti weir. The rectangular weirs are quite suitable for measuring large flows, whereas the V-notch is used for smaller flows below 50 l/s.

HOT WIRE ANEMOMETERS

Hot wire anemometers are hot wire resistance transducers which are used for measurement of flow rates of fluids. Flow rates of non-conducting liquids in open channels and closed pipes and of gases in closed pipes can be measured very conveniently by suitably locating this transducer which is in the form of a wire filament. The hot wire filament is usually a fine wire of platinum or tungsten, and is mounted in the flow channel, by means of supports. The transducer is in the form of a probe as shown in Fig. 18.1.

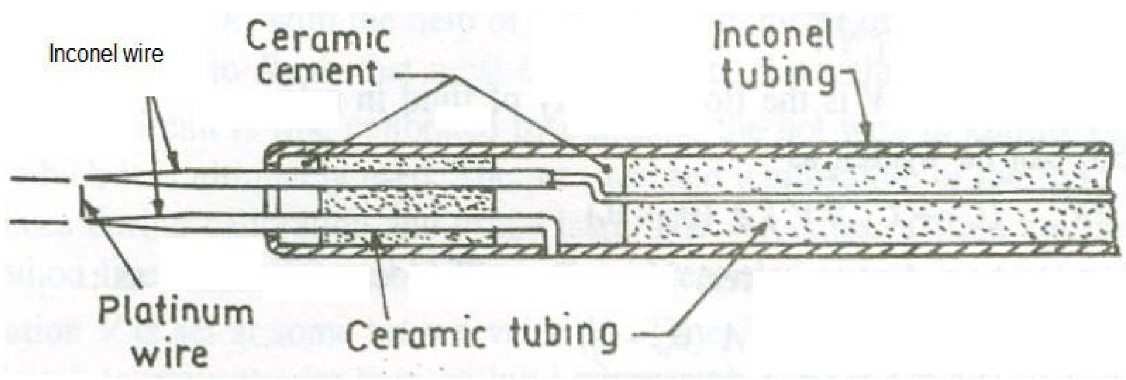


Fig. 18.1 Hot wire anemometer Probe

The diameter and length of wire depends upon the size of the pipe and the maximum flow rate which has to be measured. The diameter of wire varies from 5 μm to 300 μm and length is approximately equal to half the diameter of the pipe. The probe is located at the centre of the pipe with direction of wire perpendicular to the direction of fluid flow.

The hot wire techniques of measuring flow velocities has assumed great significance as the measurement can be done without disturbing the existing conditions. The method can be used for measurement of low velocities. The hot wire probe can be placed in small sized pipes without causing any pressure drop in the fluid stream. However, it can measure only the average velocity of flow. The method is unsuitable for velocity measurements if the fluid is conducting liquid. The main applications of hot wire anemometers are for gas flow and wind velocity measurements and in the laboratory for flow measurements of non conducting liquids and gases.

Hot wire anemometers are commonly used in two different modes i.e.

(i) constant current type and

(ii) constant temperature type.

The two types of anemometers use the same basic principle but in different ways.

In the constant current mode, the fine resistance wire carrying a fixed current is exposed to the flow velocity. The flow of current through the wire generates heat on account of $i^2 R$ loss. This heat is dissipated from the surface of the wire by convection to the surroundings. (The loss of heat due to conduction and radiation is negligible). The wire attains equilibrium temperature when the heat generated due to $i^2 R$ loss is equal to the heat dissipated due to convective loss. The circuit is so designed that $i^2 R$ heat is essentially constant and therefore the wire temperature must adjust itself to change the convective loss until equilibrium is reached. The resistance of the wire depends upon the temperature and the temperature depends the rate of flow. Therefore, the resistance of wire becomes a measure of the flow rate.

In the constant temperature mode, the current through the wire is adjusted to keep the wire temperature, as measured by its resistance, constant. Therefore, the current required to maintain the resistance and hence temperature constant, becomes a measure of flow velocity.

Heat generated = $I^2 R_w$

where

I = current through the wire; A,

R_w = resistance of wire; Ω

Heat dissipated due to convection = $hA(\theta_w - \theta_f)$

where

h = co-efficient of heat transfer; W/m^2-

°C A = heat transfer area; m^2

θ_w = temperature of wire; °C and

θ_f = temperature of flowing fluid; °C

For equilibrium conditions, we can write the energy balance for the hot wire as,

$$I^2 R_w = hA(\theta_w - \theta_f)$$

ROTARY VANE METER

Rotary pumps are capable of furnishing smooth, pulsation free flows at pressures upto 10 kN/m^2 range. Smooth flow is obtained by having more than one vane in action, so that some flow is maintained on a continuous basis. The flow in this type of pump is controlled by valves internally by passing some of the fluid.

A typical vane meter is shown in Fig.18.2. It comprises a casing containing a rotor assembly with four vanes in opposing pairs. Each pair is mounted on rigid tubular rods. The inlet and outlet manifold is bolted above the rotor casing. The direct reading mechanical counter and the calibrating mechanism are bolted on the front cover. The only moving parts in the fluid being the rotor and vanes which are constantly immersed in the fluid.

In operation, fluid enters the meter through inlet manifold and causes the rotor to revolve in a clockwise direction by pressure on centre shaft, while one vane cavity is filled under the line pressure, the backflow is sealed off by the next succeeding vane. Under normal operating conditions one vane discharges its volume in the outlet manifold and at the same time the inlet manifold fills the cavity of the receiving vane. In this flow meter the line pressure keeps the vanes in motion, and no electrical or pneumatic source of power is required. The seal between the vanes and the measuring cavity is maintained by capillary action. The fluid being measured acts as the sealant in the same manner as in the mutating piston meter.

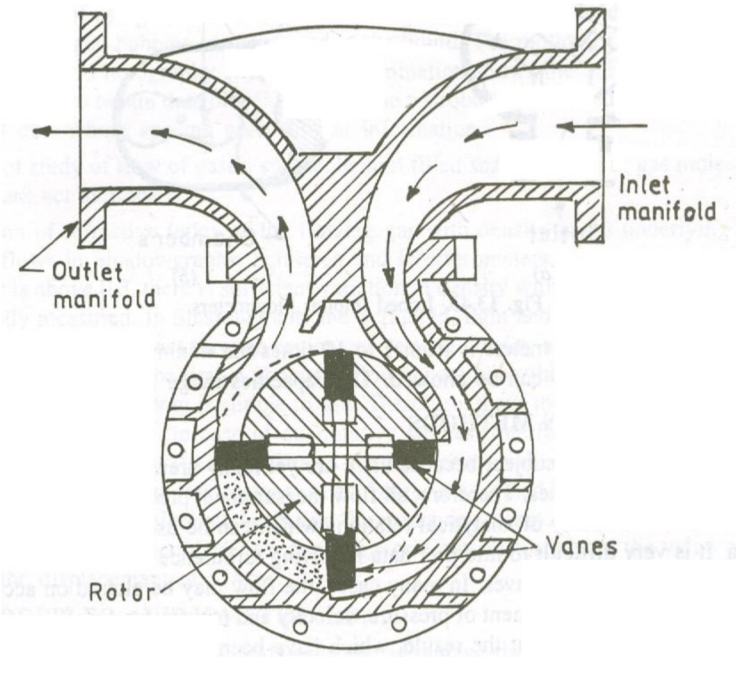


Fig.18.2 Rotary vane meter.

An extension shaft driving through a pressure tight gland in the meter front cover transmits the rotor revolutions through calibrated gearing and thence to a counter or a pulse generator for remote indication.

Materials used in the construction of these meters are different. The standard meters use an aluminium alloy rotor, carbon vanes and stainless steel fittings. High flow rate meters employ cast iron inner capsules and rotor with plastic tipped metal vanes, the other parts are made of stainless steel and brass.

LECTURE NO.19

MEASUREMENT OF LIQUID LEVEL - DIRECT LIQUID LEVEL MEASUREMENTS - DIP-STICK METHOD- SIGHT GLASS METHOD

MEASUREMENT OF LIQUID LEVEL

In industry, usually vast quantities of liquids such as water, solvents, chemicals, etc. are used in a number of industrial processes. Liquid level measurements are *made to ascertain the quantity of liquid held in a container or vessel*. The liquid level affects both pressure and rate of flow in and out of the container and therefore its measurement and / or control becomes quite important in a variety of processes encountered in modern manufacturing plants. Liquid level measurements can be broadly classified as:

1. direct methods and

2. indirect methods

Direct Liquid Level Measurements

In these methods, the actual liquid level is directly measured by means of a simple mechanical type of device.

Dip-stick Method

This is a commonly used method for determining the liquid level is dipping a graduated rod in a liquid. Boatmen usually dip the oars in the canal / river to know the depth of water at a particular place. Similarly, a dip-stick is used to measure the level of oil in a car engine or the height of fuel oil in a uniformly shaped storage tank. This method, though quite economical, is not very accurate specially for moving fluids. Further, it is not possible to get continuous on-line observations in industrial processes.

Sight Glass Method

The sight glass or piezo-meter tube is graduated glass tube mounted on the side of the liquid containing vessel for providing a visual indication of the liquid level (Fig. 19.1). Since the liquids keep level, therefore the rise or fall of the liquid level in a tank / vessel results in a corresponding change in the level indicated by the sight tube.

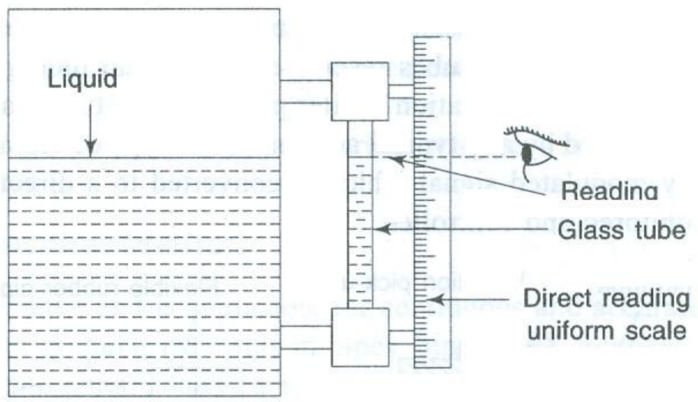


Fig. 19.1 Sight glass level gate

Sight tubes are usually made of toughened glass and are provided with metallic protecting covers around them. Further, the diameter of such tubes is neither too large to change the tank / vessel level, nor too small to cause capillary action in the tube.

The measurement of liquid level with this device is simple and direct for clean and coloured liquids. However, it is rather unsuitable for dirty, viscous and corrosive liquids. Further, an operator is required to record the liquid levels with this device.

LECTURE NO.20

HOOK GAUGE- FLOAT GAUGE - FLOAT-AND-SHAFT LIQUID LEVEL GAUGE

Hook Gauge

Sometimes it becomes necessary to accurately measure very small changes in liquid level in open tanks / containers. In a large tank / reservoir, a small change in level would mean large volumetric changes. For such applications, a simple hook gage is quite suitable. The schematic arrangement of this gauge is shown in Fig. 20.1. In this device, a vertical tubular rod is provided with a vernier scale to be clamped at a suitable height at the upper end and a V-shaped hook at the lower end. This rod moves in a guide bracket fixed to a rigid body at the datum or reference level and has a main graduated scale in it. The movable rod is brought downwards so that the hook is first pushed below the surface of the liquid. It is then gradually raised until the top of the hook breaks through the surface of the liquid. The movable rod is then clamped and the level is read off the scale. The device is accurate up to ± 0.1 mm, the least count of the instrument. Further, the device is manually operated and does not lend itself to automatic reading.

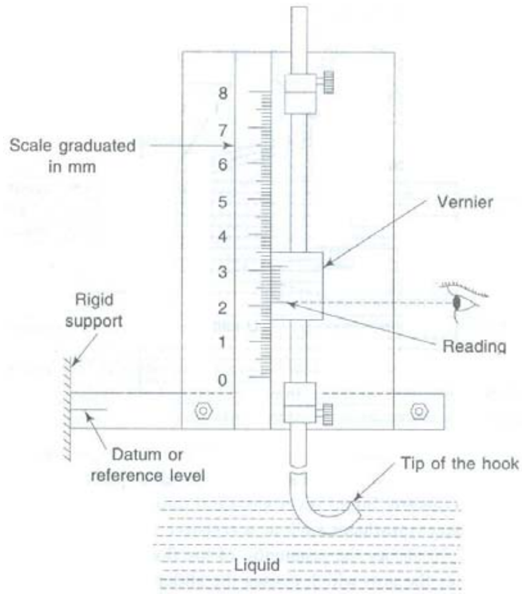


Fig. 20.1 Hook type level indicator

Float Gauge

A floating body, because of its buoyancy, would always follow the varying liquid level. Therefore, float-operated devices are capable of giving continuous, direct liquid level measurements. The floats generally used are hollow metal spheres, cylindrical ceramic floats or / disc shaped floats of synthetic materials. The top of the float is usually made sloping so that any solid suspensions in the liquid do not settle on the float and change its weight. Float gauges are sufficiently accurate when properly calibrated after installation. Further, a proper correction is required if there is a change in the liquid density due to a change in temperature.

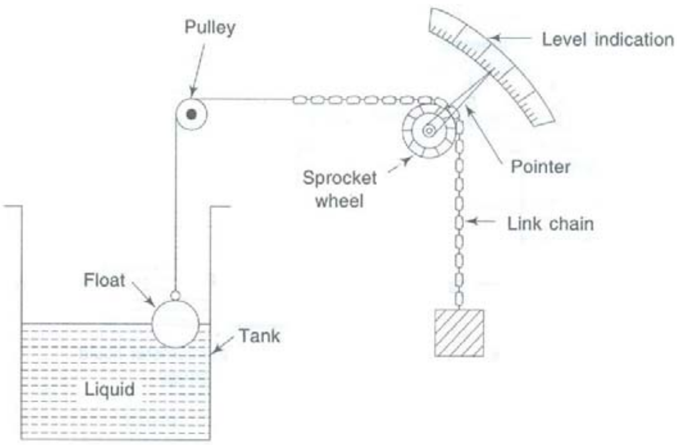


Fig.20.2 Float and chain liquid level gauge

Figure 20.2 illustrates a typical float-and-chain liquid level gauge generally used for directly measuring the liquid level in open tanks. The instrument consists of a float, a counter weight and a flexible connection that may be a chain or a thin metallic perforated tape. The counter weight keeps the chain / tape taut as the liquid rises or falls with any changes in the liquid level. The chain / perforated tape link is wound on a gear or sprocket wheel to which the pointer is attached. Any movement of this wheel would indicate on a suitably calibrated scale the level of the liquid in the tank.

Float-and-Shaft Liquid Level Gauge

Another version of the float-actuated instrument is the float-and-shaft liquid level gauge (Fig.20.3). In this unit, the motion of the float on the surface of the liquid is transferred to the shaft and the level is indicated by the pointer on the dial.

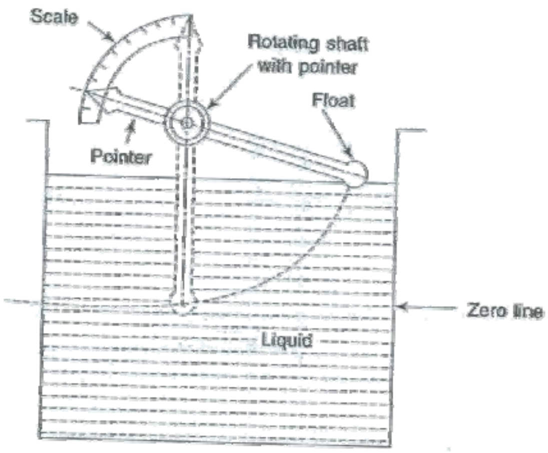


Fig. 20.3 Float-and-shaft liquid level gauge

Further, there are a number of float-operated schemes with electrical read-outs. In these, the float acts as a primary transducer that converts liquid level variation into a suitable displacement. This displacement is sensed by the secondary transducer such as a resistive type of potentiometric device, inductive type of LVDT, etc. Figure 20.4 shows the schematic of the float-actuated rheostatic (resistive) device. The float displacement actuates the arm which causes the slider to move over the resistive element of a rheostat. The circuit resistance changes and this resistance change is directly proportional to the liquid level in the tank.

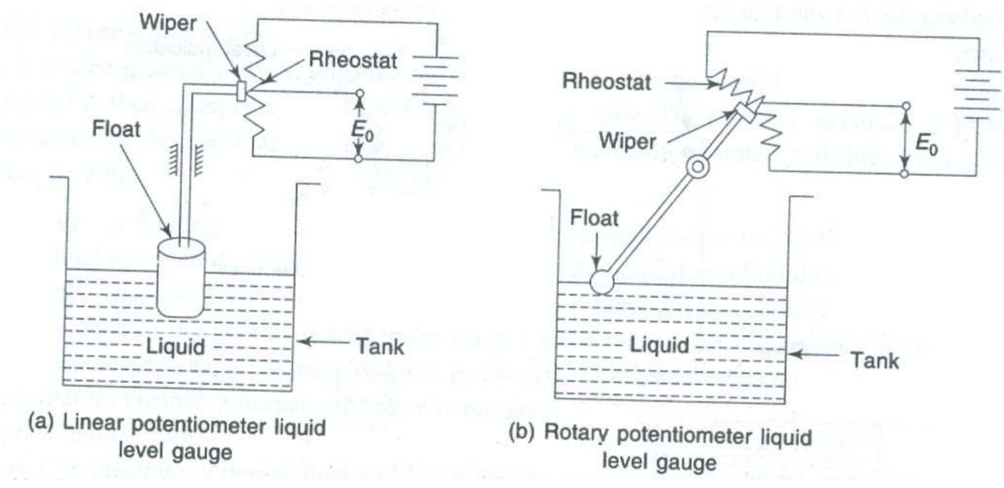


Fig.20.4 Typical float-operated rheostatic liquid level gauge

LECTURE NO.21

INDIRECT LIQUID LEVEL MEASUREMENTS - HYDROSTATIC PRESSURE LEVEL MEASUREMENT DEVICE - BUBBLER OR PURGE TECHNIQUE FOR LEVEL MEASUREMENT

INDIRECT LIQUID LEVEL MEASUREMENTS

Hydrostatic Pressure Level Measurement Device

The hydrostatic pressure created by a liquid is directly related to the height of the liquid column ($p = \rho g h$). Therefore, a pressure gauge is installed at the bottom or on the side of the tank containing the liquid (Fig. 21.1). The rise and fall of the liquid level causes a corresponding increase or decrease in the pressure p which is directly proportional to the liquid level h. The dial or scale of the pressure gauge is calibrated in the units of level measurement. These gauges function smoothly when the liquids are clean and non-corrosive. For corrosive liquids with solid suspensions, diaphragm seals between the fluid and the pressure gauge are generally employed.

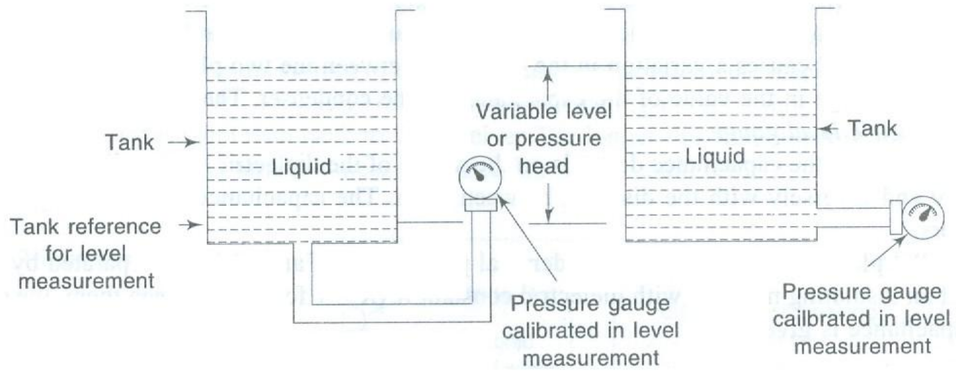


Fig.21.1 Typical arrangements of hydrostatic pressure type level measuring devices

Bubbler or Purge Technique for Level Measurement

In this method, the air pressure in a pneumatic pipeline is so regulated that the air pressure in the bubbler tube, shown in Fig. 21.2, is very slightly in excess over that of the hydrostatic pressure at the lowermost end of the bubbler tube. The bubbler tube is installed vertically in the tank with its lowermost open end at zero level. The other end of the tube is connected to a regulated air supply and a pressure gauge. The air supply in the bubbler tube is so adjusted that the pressure is just greater than the pressure exerted by the liquid column in the tank. This is achieved by adjusting the air pressure regulator until bubbles can be seen slowly leaving the open end of the tube. Sometimes a small air flow meter is fitted in the line to control / check the excessive flow of air. When the air flow is small and the density of the fluid is uniform, then gauge pressure is directly proportional to the height of the liquid level in the open tank. In practice, the gauge is directly calibrated in the units of liquid level and if the tank is uniformly shaped, then the calibration may be in the units of volume.

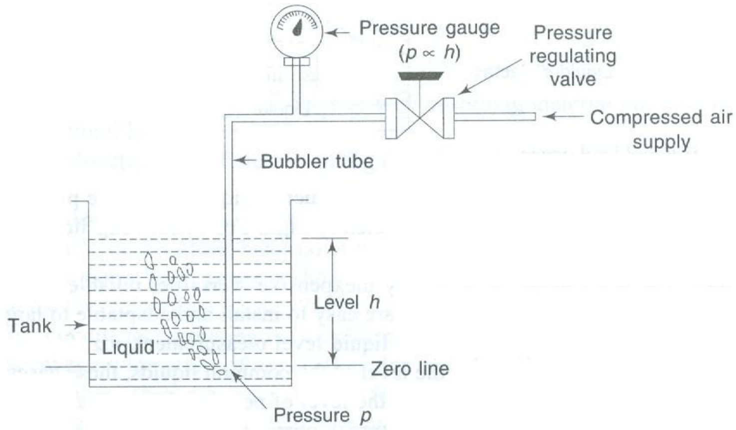


Fig.21.2 Bubbler or purge type of liquid level meter

LECTURE NO.22

CAPACITANCE LEVEL GAUGE - ULTRASONIC LEVEL GAUGE - NUCLEONIC GAUGE

Capacitance Level Gauge

A simple condenser / capacitor consist of two electrode plates separated by a small thickness of an insulator (which can be solid, liquid, gas or vacuum) called the dielectric. The change in liquid level causes a variation in the dielectric between the two plates, which in turn causes a corresponding change in the value of the capacitance of the condenser. Therefore, such a gauge is also termed a dielectric level gauge.

The magnitude of the capacitance depends on the nature of the dielectric, varies directly with the area of the plate and inversely with the distance between them. The capacitance can be changed by any of these factors.

In a parallel plate condenser which has identical plates each of area A (cm^2) separated by a distance d (cm) and an insulating medium with dielectric constant K (K = 1 for air) between them, the expression for the capacitance is given by

$$C(in\ \mu\mu F) = 0.0885\ \frac{A}{d} K$$

From the above equation it is observed that the **capacitance varies directly with the dielectric constant which in turn varies directly with the liquid level between the plates**. Figure 22.1 shows the schematic arrangement of a capacitance level gauge. The capacitance would be at a minimum when the tubes contain only air and at a maximum when the liquid fills the entire space between the electrodes. The change in capacitance can be measured by a suitable measuring unit such as a capacitive Wheatstone bridge by either manual null balancing or automatic null balancing using the null detecting circuit with a servo-motor that indicates the level reading.

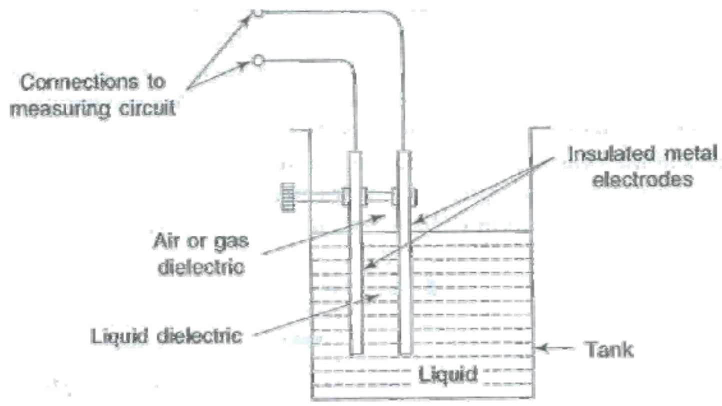


Fig. 22.1 Dielectric liquid level gauge

For the measurement of level in the case of non-conducting liquids, the bare probe arrangement may be satisfactory since the liquid resistance is sufficiently high. For conducting liquids, the probe plates are insulated using a thin coating of glass or plastic.

The capacitance type level gauge is relatively inexpensive, versatile, reliable and requires minimal maintenance. These units have no moving parts, are easy to install and adaptable to large and small vessels. Further, such devices have a good range of liquid level measurement, viz. from a few cm to more than 100 m. In addition, apart from sensing the level of the common liquids, these gases find wide use in other important applications such as determining the level of powdered or granular solids, liquid metals (high temperatures), liquefied gases (low temperatures), corrosive materials (like hydrofluoric acid) and in very high pressure industrial processes.

Ultrasonic Level Gauge

A schematic diagram of the ultrasonic level gauge is shown in Fig. 22.2. Sound waves are directed towards the free surface of the liquid under test from an ultrasound transmitter. These waves get reflected from the surface of the liquid and are received by the receiver. In this technique, liquid level variations are quite accurately determined by detecting the total time taken by the wave to travel to the liquid surface and then back to the receiver. The longer this time interval, the farther away is the liquid surface, which in turn is a measure / indication of the liquid level.

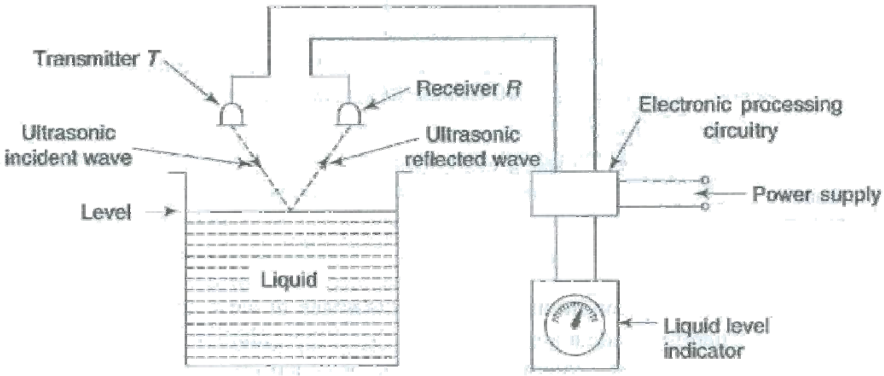


Fig. 22.2 Schematic of ultrasonic liquid level gauge

It may be noted that the operating principle of this instrument is quite simple. But the actual instrument is expensive and requires a high degree of experience and skill in operation. However, its main advantage is a wide range of applications in level measurement for different types of liquid and solid substances.

Nucleonic Gauge

The working principle of the nucleonic gauge or gamma ray liquid level sensor is that the absorption of gamma rays varies with the thickness of the absorbing material (i.e. height of liquid column) between the source and the detector. The higher the height of the liquid column, greater is the absorption of gamma rays and consequently lower is the detector output. The output is measured and correlated with the level of liquid in the tank using the following exponential type of expression applicable in such an arrangement:

$$I = I_o \, e^{-\mu\rho x}$$

where

I is the intensity of radiation falling on the detector

I_o is the intensity of radiation at the detector with absorbing material not present

e is base of natural logarithm = 2.71

μ is the mass absorption coefficient in m^3/kg (constant for a given source and absorbing material)

ρ is the mass density of the test material in kg/m^3

x is the thickness of absorbing material in m (i.e. height of liquid column in the present case).

The schematic of the liquid level gauge is shown in Fig. 29.3. The instrument consists of a radioactive source (which may be either Ce-137, Am-241 or Co-60), a radiation detector (of ion is at ion chamber type) and electronic circuits incorporating the amplifiers and read-out instrument or recorder-controller.

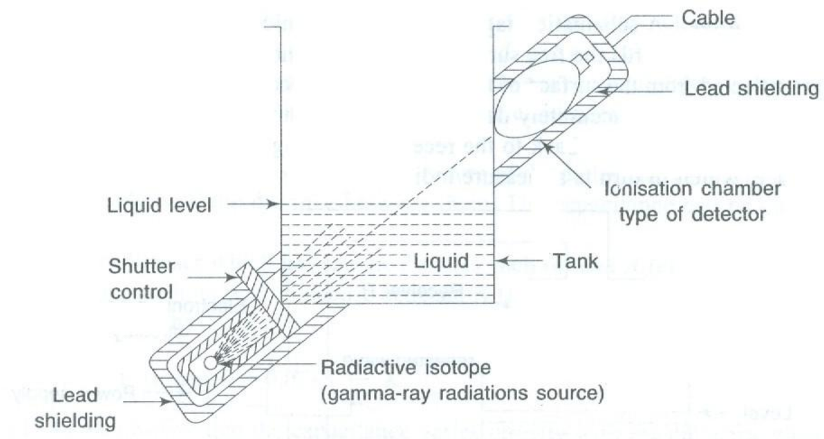


Fig.22.3 Schematic of gamma ray liquid level gauge

Nuclear gauges cover a wide range of applications for recording the level of a wide variety of liquid as well as solid substances. They are quite suitable for large reservoirs of 30-40 m diameter and can give continuous measurements of heights of 20 m or more with repeatability of ± 1%. Like the ultrasonic gauge, this is also a non-contact device and the level measurement is not affected by conditions of high or low temperatures, pressure, viscosity, corrosion, abrasion, etc. Further, these gauges are quite rugged and can withstand severe operating conditions. The main drawback in these gauges is the risks involved due to radiation effects. Therefore, adequate shielding to limit the radiation field intensity well below the Atomic Energy Commission (AEC) tolerances has to be provided for.

LECTURE NO.23

CONTROL SYSTEMS- INTRODUCTION- *BASIC COMPONENTS OF THE CONTROL SYSTEM-* CLASSIFICATION OF CONTROL SYSTEMS – OPEN LOOP SYSTEM - CLOSED LOOP SYSTEM - SERVO MECHANISMS

CONTROL SYSTEMS

Introduction

Automatic control is the maintenance of a desired value of quantity or condition by measuring the existing value, compare it with the desired value and employing the difference to initiate action for reducing this difference.

Automatic control systems are used in practically every field of our life. Since, nowadays it has become a tendency to complete the required work or a task automatically by reducing the physical and mental effort. The different applications of automatic control systems are:

1. Domestically they are used in heating and air conditioning.

2. Industrial applications of automatic control system includes:

   (i) Automatic control of machine tool operations.

   (ii) Automatic assembly lines.

   (iii) Quality control, inventory control.

   (iv)In process industries such as food, petroleum, chemical, steel, power etc. for the control of temperature, pressure, flow etc.

   (v) Transportation systems, robotics, power systems also uses automatic control for their operation and control.

   (vi) Compressors, pumps, refrigerators.

   (vii) Automatic control systems are also used in space technology and defence applications such as nuclear power weapons, guided missiles etc.

(viii) Even the control of social and economic systems may be approached from theory of automatic control.

The term control means to regulate, direct or command. A control system may thus be defined as: "An assemblage of devices and components connected or related so as to command, direct or regulate itself or another system".

In general the objectives of control system are to control or regulate the output in some prescribed manner by the inputs through the **elements of the control system**.

Basic components of the control system *are*:

(i) Input i.e. objectives of control. It is the excitation applied to a control system from external source in order to produce output.

(ii) Control System Components. Devices or components to regulate direct or command a system that the desired objective is achieved.

(iii) Results or Outputs. The actual response obtained from a system.

Fig. 23.1 Block diagram of control system.

Classification of Control Systems:

There are two basic types of control Systems:

1. Open Loop System (Non-feed Back)
2. Closed Loop System (Feed Back)

Open Loop System (Non-feed Back)

The elements of an open loop system can usually be divided into two parts : the Controller and the Controlled process as shown in Fig.23.2.

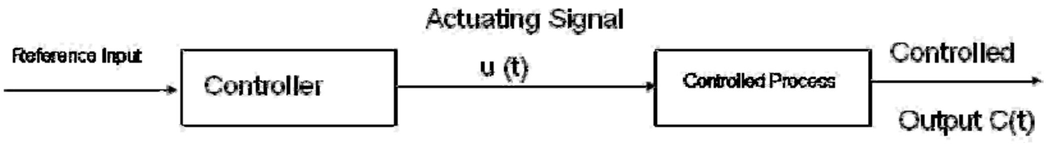


Fig.23.2 Open loop system

- An input signal or command r (t) is applied to the controller which generates the actuating signal u(t).
- Actuating signal u(t) then controls (activates) the process to give controlled output c(t). In simple cases, the controller can be an amplifier, mechanical linkage, filter, or other control element, depending on the nature of the system. In more sophisticated cases the controller can be a computer such as microprocessor.
- The control action has nothing to do with output c (t) i.e. there is no any relation between input and output.
- There is no feed back hence it is known as non-feedback

system. Examples of open loop System:

1. Traffic control signals at roadway intersections are the open loop systems. The glowing of red and green lamps represents the input. When the red lamp grows the traffic stops. When green lamp glows, it directs the traffic to start.

The red and green light travels are predetermined by a calibrated timing mechanism and are in no way influenced by the volume of traffic (output).

2. **Automatic washing machine**: In washing machine, input is dirty clothes, water, soap and output is clean cloths. Soaking, washing and rinsing operations are carried out on a time basis. However, the machine does not measure the output signal, namely the cleanliness of the clothes.

Advantages of Open Loop System:

1. Simple in construction.

2. Economic.

3. More stable.

4. Easy maintenance.

Disadvantages of Open Loop System:

1. Inaccurate and unreliable.

2. It is affected by internal and external disturbances, the output may differ from the desired value.

3. It needs frequent and careful calibrations for accurate results.

4. Open loop systems are slow because they are manually controlled.

5. There is no feed back control. The control systems are rather unsophisticated.

<u>Closed Loop System</u>

A closed loop control system measures the system output compares it with the input and determines the error, which is then used in controlling the system output to get the desired value.

In closed loop system for more accurate and more adaptive control a link or feedback from the output to the input of the system is provided. The controlled signal c(t) is fed back and compared with the reference input r(t), an actuating signal e(t) proportional to the difference of the input and the output is send through the system to correct the error and bring the system output to the desired value. The system operation is continually correcting any error that may exit. As long as the output does not coincide with the desired value, there is likely to some kind of actuating signal.

Thus, the closed loop systems correct the drifts of the output which may be present due to external disturbance or due to deterioration of the system itself.

The closed loop system may have one or more feedback paths. Fig.23.3 shows the general block diagram of closed loop system.

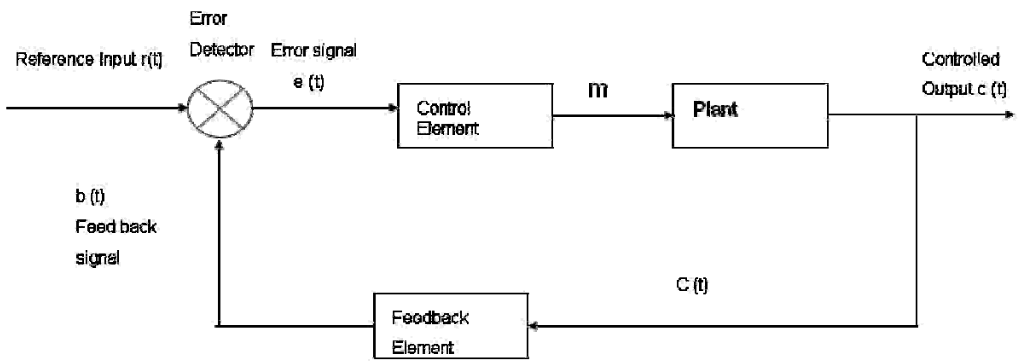


Fig. 23.3 Closed loop system

r(t) = reference input

e(t) = error or actuating signal

b(t) = feedback signal

m = manipulation

Advantages of Closed Loop System:

- These systems can be used in hazardous or remote areas, such as chemical plants, fertilizer plants, areas with high nuclear radiations, and places at very high or very low temperatures.
- Increased productivity
- Relief of human beings from hard physical work and economy in operating cost.
- Improvement in the quality and quantity of the products.
- They are more reliable than human operators.
- A number of variables can be handled simultaneously by closed loop control systems.
- In such systems there is reduced effect of non-linearities and distortions.
- Closed loop systems can be adjusted to optimum control performance.
- Such systems senses environmental changes, as well as internal disturbances and accordingly modifies the error.
- Satisfactory response over a wide range of input frequencies.

Disadvantages of Closed Loop Control System:

- It is more complex and expensive.

- Installation and adjustment is intricate.
- Maintenance is difficult as it involves complicated electronics. Moreover trained persons are required for maintenance.
- Due to feed back, system tries to correct the error time to time. Tendency to over correct the error may cause oscillations without bound in the system.
- It is less stable as compared to open loop system.

Table 23.1 Comparison between open loop and closed loop systems

	Open Loop System		Closed Loop System
1	No feed back	1	Feed back is present
2	No error detector	2	Error detector is included
3	Simple in construction, easy to built	3	Complex design, difficult to built
4	Disturbances occurring in the process are not controllable	4	Disturbance do not affect the process, they can be controlled automatically
5	It is more stable	5	It is less stable
6	Economical	6	Expensive
7	Less accuracy	7	Accurate
8	Response is slow	8	Response is fast
9	Examples: Two way traffic control, automatic toaster, coffee maker, hand drier	9	Examples: Human being, automatic electric irons, automatic speed control system, centrifugal watt governor etc

Servo Mechanisms

A servo mechanism is an automatic control system (closed loop system) in which the controlled variable is a mechanical position (displacement), or a time derivative of displacement such as velocity and acceleration. **The name servo mechanism or regulator may describe a complete system that provides automatic control of an object or quantity as desired**. Such a system may include many electrical, mechanical or hydraulic devices, by their use a person can control large power with greater speed and accuracy than that person alone can provide.

The output is designed to follow a continuously changing input or desired variable. The servo mechanisms are inherently fast acting (small time lag with response time in the order to milliseconds) as usually employ electric or hydraulic actuations. These systems are essentially used to control the position or speed of a mechanism which is either too heavy or too remote to be controlled manually. e.g. power assisted steering and control in large cars, air crafts, ships etc. The complete automation of machine tools together with programmed instructions is another notable example of servo mechanism.

Servos are used in defence, navigation as well as in industry. They are used in industry in the automatic follow-up control of precision machine tools, the remote handling of dangerous materials, the automation of production lines etc.

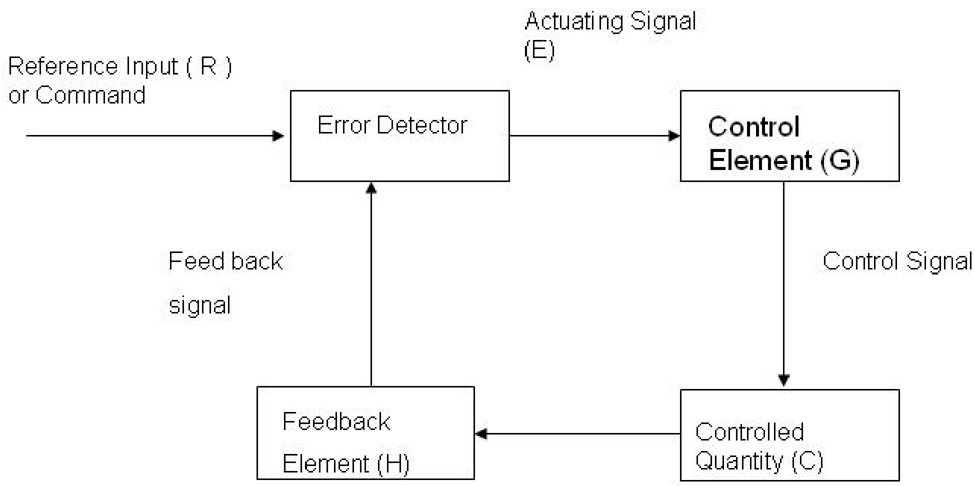


Fig.23.4 A block diagram of servo showing its basic parts.

LECTURE NO.24

CONTROLLERS AND CONTROL ACTION - PNEUMATIC CONTROLLER - HYDRAULIC CONTROLLERS - ELECTRIC CONTROLLERS

CONTROLLERS AND CONTRL ACTION

An automatic controller compares the actual value of the plant output with the desired value of output, determines the deviation and produces a signal which will reduce the deviation to zero or to a small value.

The manner in which the automatic controller produces the control signal is called control action. The control action may operate through mechanical, pneumatic, hydraulic or electrical means.

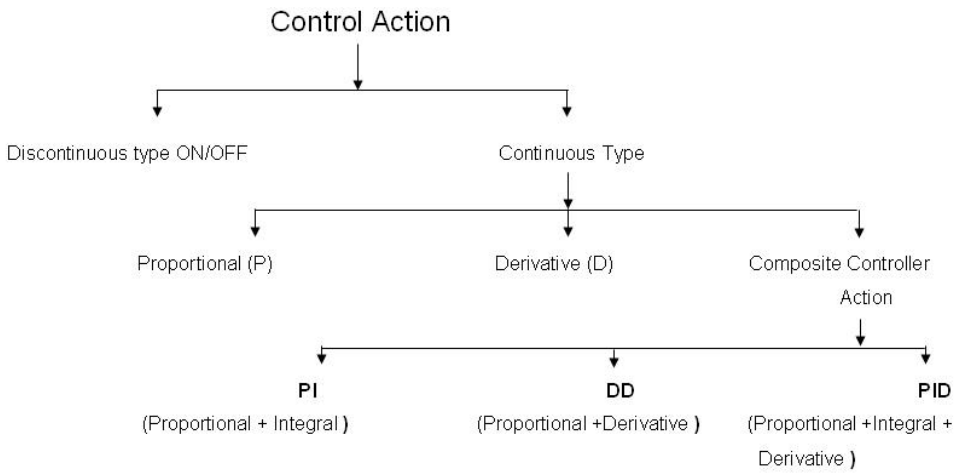


Fig. 24.1 Classification of control actions

Controllers can be in the form of (i) Pneumatic (ii) Hydraulic (iii) Analog or digital

The choice of the control action for a particular operation depends upon:

- The nature of the plant
- Operating conditions
- Size and weight
- Availability and cost
- Accuracy and reliability and
- Safety etc

Control Actions

ON-OFF or two position control action

The controller is ON when the measured value is below set point and the output is at maximum level. When the measured value is above the set point the controller is OFF and the output is minimum i.e. zero.

These are relatively simple and economical. ON -OFF controllers are widely used in both industrial and domestic control systems. These controllers are not suitable for complex systems. The examples of their applications are: Room heaters, Refrigerators, mixers or food processors, level control of water tanks etc.

Proportional Control Action (P)

Proportional control action is a continuous mode of operation. In proportional control, the output changes with proportional change of input. It is widely used control action where the output of controller is a linear function of error signal.

The proportional control follows the law :

$$m(t) = kp\, e(t) + P_0$$

where,

$m(t) =$ controller output

$e(t) =$ error signal

$kp =$ gain of controller

$P_0 =$ output of controller when error is zero

The proportional controller may be thought of as an amplifier with high and adjustable gain.

Composite Control Action

Composite control action means combination of two continuous control action:

1. Proportional Plus Integral Control Action (P + I)

The proportional control action produces off set in the system whenever load change occurs. This offset can be eliminated by adding integral action to the proportional control action. The output is

$$m(t) = kp\, e(t) + \frac{kp}{Ti} \int_0^T e(t)\, .dt + P_0$$

2. Proportional Plus Derivative (PD) Control Action

In a derivative control mode, the magnitude of the controller output is proportional to the rate of change of the actuating error signal. The control action in which derivative control action is added to the proportional control action is called PD control action.

The governing equation of PD control action is

$$m(t) = kp\, e(t) + kp\, .Td \frac{d\, e(t)}{dt} + P_0$$

Advantages: Improves damping ratio and reduces maximum overshoot.

3. PID Control Action: It is powerful but complex control action. In a **PID** control action, the output m(t) is a linear combination of input e(t), the time rate of change of input and the time integral of input. The control is thus an additive combination of proportional action, derivative action, and integral action.

The equation of PID control action is given by

$$m(t) = kp\, e + kp.Td \frac{d\, e}{dt} + \frac{kp}{Td} \int e\, dt + P_0$$

PNEUMATIC CONTROLLER

Pneumatic controllers use air medium (or other gases in special situations) to provide an output signal which is a function of an input error signal. Regulated pressurized air supply at about 20 psg is used as a input signal. Air medium has the advantage of being non-inflammable and having almost negligible viscosity compared to the high viscosity of hydraulic fluids. The danger of explosion existed due to electrical equipment is avoided by pneumatic controller.

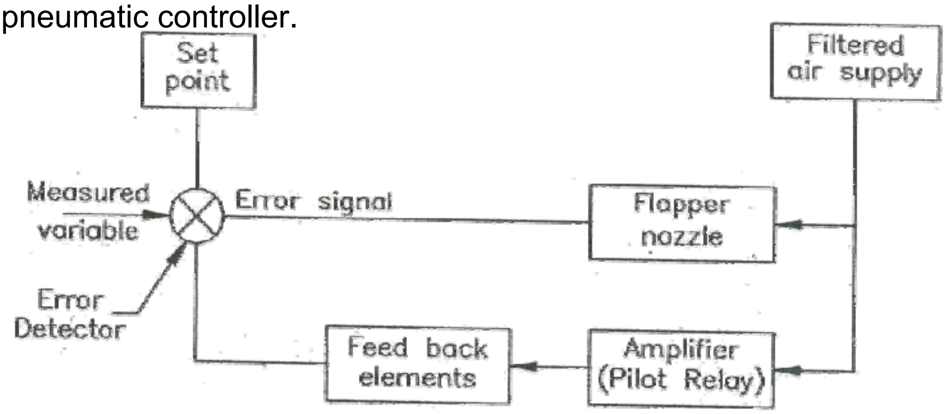


Fig.24.2 Schematic of a pneumatic control system

Advantages and Limitations of Pneumatic Controllers:

Advantages

- The danger of explosion is avoided.
- For operating the final control elements relatively high power amplification is obtained.
- Due to availability of free supply of air it is relatively inexpensive.
- Comparatively simple and easy to maintain.

Limitations:

- Slow response and longer time delays.
- The lubrication of mating parts create difficulty.
- Compressed air pipe is necessary throughout the system.
- In pneumatic system there is a considerable amount of compressibility flow so that the systems are characterized by longer time delays

Hydraulic Controllers

In hydraulic controllers power is transmitted through the action of fluid flow under pressure. The fluid used is relatively incompressible such as petroleum base oils or certain non-inflammable synthetic fluids. Fig. 24.3 shows a schematics of a hydraulic control system.

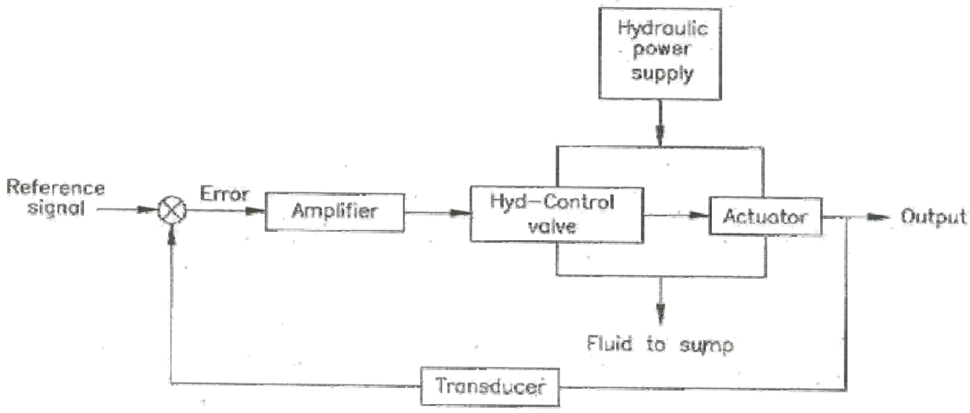


Fig.24.3 Schematic of a hydraulic controller

The major components of a hydraulic controller are:

an error detector

an amplifier

a hydraulic control valve, and

an actuator.

Advantages of hydraulic controllers

- High speed response.
- High power gain.
- Long life due to self lubricating properties of fluid.
- Simplicity of actuator system
- Easy maintenance.

Limitations of hydraulic controllers

- Hydraulic fluids require careful maintenance to remove impurities, corrosive effects etc.
- Seals should be properly maintained to prevent leakage of hydraulic fluids.

Electric controllers

Electrical control devices are most widely used because of their accuracy and fast response with easy handling techniques. Electric controller for proportional, proportional plus integral and proportional + integral +

derivative actions may be divided into two types: (1) The null balance type in which an electrical feedback signal is given to the controller from the final elements.

(2) The direct type in which there is no such feedback signal.

As with the pneumatic controller, the various control actions are accomplished by modifying the feed back signal. This is done by adding properly combined electrical resistances and capacitances to feedback circuit just as restrictions and bellows were added in the pneumatic circuit.

A very simple form of two step controller is the room-temperature thermostat. Fig.24.4 show simple type of electrical two position control. The U shaped bimetal strip fixed at one end of the thermostat frame deflects when heated, its free and moving in such a direction as to separate the fixed and moving contacts. When the bimetal strip cools the two contacts are once more brought in contact. The small permanent magnet ensures the opening and closing of the contacts with a snap action to minimize the damage caused by arcing. The adjusting screw varies the small range of temperature, sometimes called the differential gap between contacts opening on rising temperature and closing on falling temperature.

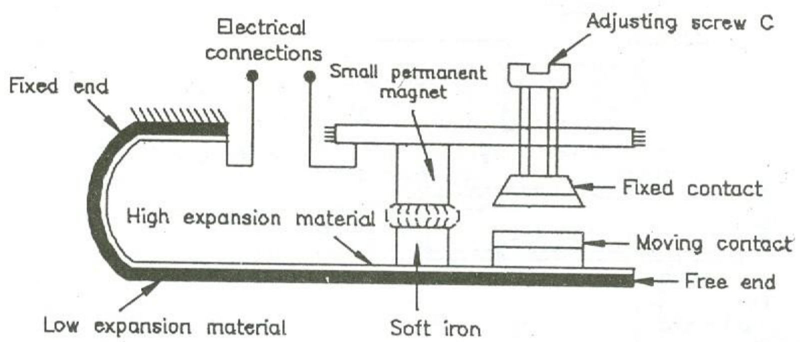


Fig. 24.4 Electrical two position control