11

Plant Instrumentation

11.1. GENERAL ASPECTS

In power plants the instruments are used for a number of reasons as to operate the power plant as efficiently as possible. Instruments provide accurate information for guidance to safe, continuous and proper plant operation.

The functions which the various instruments are required to perform are listed below :

1. **Operating guidance.** The instruments provide guidance to operate the power plant efficiently and economically.

2. **Performance calculations.** They render help in making performance calculations in respect of plant working.

3. **Maintenance and repair guidance.** As the instruments enable us to check the internal conditions of the equipment, thus they provide us maintenance and repair guidance.

4. **Economical supervision.** They enable us to supervise the plant economically.

5. **Cost allocation.** The instruments extend a helping hand in dealing with the problems concerning costs accounting and cost allocations.

11.2. CLASSIFICATION OF INSTRUMENTS

The two general classification of instruments are :

1. Those employing *purely mechanical methods.*
2. Those employing *electro-mechanical methods.*

With the increase in automation electronics is being used more widely in the field of instruments. Remote control has become an established practice in power plant engineering and specially in nuclear power station where the complete equipment is watched and controlled from a distance. Hence the importance of instrumentation in the power plant engineering has increased.

The instruments can also be classified as follows :

1. Indicating instruments
2. Recording instruments
3. Indicating and recording instruments
4. Indicating and integrating instruments
5. Indicating, recording and integrating instruments.

Commonly used instruments in a power plant

1. Pressure gauges
2. Thermometers
3. Liquid level gauges
4. Flow meters (Steam and gas)
5. pH measuring instruments
6. Gas analysers
7. Humidity measuring instruments
8. Impurity measuring instruments
9. Speed measuring instruments
10. Steam calorimeters and fuel calorimeters
11. Gong alarms
12. Electrical instruments.
    - (*i*) Ammeters
    - (*ii*) Voltmeters
    - (*iii*) Wattmeters
    - (*iv*) Power factor meters
    - (*v*) Reactive volt ampere meters
    - (*vi*) Ground detectors.

11.3. PRESSURE GAUGES

11.3.1. Pressure

Pressure is defined as a force per unit area. Pressures are exerted by gases, vapours and liquids. The instruments that we generally use, however, record pressure as the difference between two pressures. Thus, it is the *difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure.* Such devices indicate the pressure either above or below that of the atmosphere. When it is *above the atmospheric pressure,* it is termed *gauge pressure* and is *positive.* When it is *below* atmospheric, it is *negative* and is known as *vacuum.* Vacuum readings are given in millimetres of mercury or millimetres of water below the atmosphere.

It is necessary to establish an absolute pressure scale which is independent of the changes in atmospheric pressure. A pressure of absolute zero can exist only in complete vacuum. *Any pressure measured above the absolute zero of pressure* is termed an *'absolute pressure'.*

A schematic diagram showing the *gauge pressure, vacuum pressure* and the *absolute pressure* is given in Fig. 11.1.

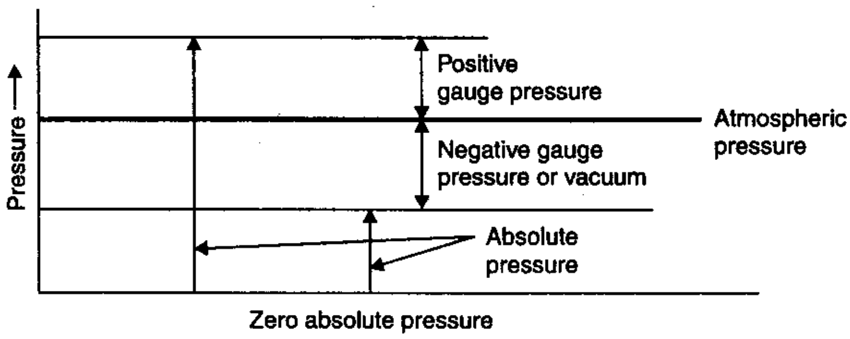

Fig. 11.1. Schematic diagram showing gauge, vacuum and absolute pressures.

Mathematically :

(*i*) Absolute pressure = atmospheric pressure + gauge pressure

$$p_{abs} = p_{atm.} + p_{gauge}$$

(*ii*) Vacuum pressure = atmospheric pressure – absolute pressure

Atmospheric pressure is measured with the help of barometer.

Unit for pressure

The fundamental SI unit of pressure is newton per square metre (N/m^2). This is also known as *Pascal*. In MKS it is usually expressed in kgf/cm^2.

Low pressures are often expressed in terms of mm of water or mm of mercury. This is an abbreviated way of saying that the pressure is such that which will support a liquid column of stated height.

11.3.2. Types of Pressure Measurement Devices

The pressure may be measured by means of indicating gauges or recorders. These instruments may be mechanical, electro-mechanical, electrical or electronic in operation.

1. **Mechanical instruments.** These instruments may be classified into following two groups :

— The *first group* includes those instruments in which the *pressure measurement is made by balancing an unknown force with a known force.*

— The *second group* includes those employing *quantitative deformation of an elastic member for pressure measurement.*

2. **Electro-mechanical instruments.** These instruments usually employ *mechanical means for detecting the pressure* and *electrical means for indicating or recording the detected pressure.*

3. **Electronic instruments.** Electronic pressure measuring instruments normally depend on some *physical change* that can be detected and indicated or recorded electronically.

11.3.3. Mechanical-type Instruments

Some of the above mentioned instruments are discussed below.

The *mechanical-type instruments* could be classified as follows :

(*i*) Manometer gauges

(*ii*) Limp diaphragm

(*iii*) Metal diaphragm and bellows

(*iv*) Bourdon tube type which may be spiral or helical.

11.3.3.1. Liquid manometers

Low pressures are generally determined by *manometers* which employ liquid columns. It is difficult and costly to construct manometers to measure high pressures, as otherwise the liquid column will become unwieldy and temperature corrections will also be difficult. Their use is, therefore, restricted to low pressures only, and for such purposes they are quite accurate.

The liquid commonly employed for manometers are mercury and water. Mercury is used for high and water for low pressures. For this purpose a liquid is suitable if it has a low viscosity, so that it can adjust itself quickly, and also a low co-efficient of thermal expansion, so that density changes with temperature are minimum.

The following manometers will be described :

1. U-tube manometer
2. Cistern manometer
3. Micro-manometer.

U-tube Manometer :

A U-tube manometer is in the form of U-tube and is made of glass. When no pressure is applied, the height of the liquid in the two legs is the same. The pressure is then applied to one leg, whilst the other is open to the atmosphere. Under this pressure the liquid will *sink* in this leg and will *rise* in the other. As the other leg is open to the air, therefore, the pressure on this side is known, and is barometric. Now the pressure applied to the first leg can be calculated. This is explained with reference to Fig. 11.2. This consists of a water manometer.

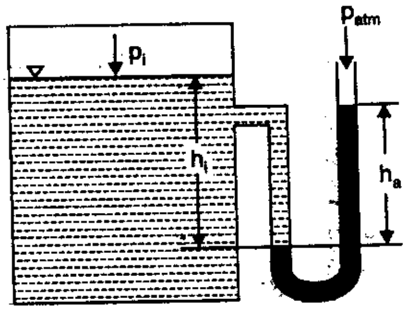

Fig. 11.2. Principle of U-tube manometer.

Considering equilibrium condition, we have :

$$p_{atm} + w_a h_a = p_i + w_i h_i$$

$$\therefore \quad p_i = p_{atm} - w_a h_a - w_i h_i$$

where, p_{atm} = Atmospheric pressure,

p_i = Pressure over water surface in the container,

h_a = Height of liquid in U-tube manometer,

h_i = Difference between water surface and lower surface of the liquid in manometer,

w_a = Specific weight of liquid, and

w_i = Specific weight of water.

The U-tube manometer shown in Fig. 11.3 is of the simplest form. However, readings have to be taken at *two different places*. Moreover, the *deflection of the two columns may not be the same*. To avoid this difficulty cistern or well type manometer is used.

Cistern manometer :

Fig. 11.4 shows a cistern manometer. The mercury reservoir A is made large enough so that change of level in the reservoir is negligible. This form of manometer is generally used for measuring pressures above atmospheric. In this case, *only one reading of the level in the column is required*. However, a zero-setting is necessary.

Micro-manometer :

The U-tube manometer (discussed above) is not very suitable for measuring very low pressures. Therefore, for such purposes, precision types are required. They are called *multiplying* or *micro-manometers*, because they multiply the movement of the level of the liquid. By far the most widely used type of multiplying manometer is the *inclined manometer*. If the tube is inclined as shown in Fig. 11.5 the sensitiveness of the U-tube manometer is increased. The inclined tube *causes a larger displacement of the liquid along the tube for a given pressure difference*.

The principle of the inclined manometer is explained in Fig. 11.6. If pressure $p_1 = p_2$, then the level of liquid is shown by LM. However, when p_1 is slightly greater than p_2, the level in the reservoir sinks by h_2, whilst level in the tube rises by a greater distance h_1, as shown in the diagram. If h is the vertical distance between the two surfaces due to difference of pressure, then also $$h = h_1 + h_2$$

$$h_1 = d \sin \theta$$

and $$h_2 \times A = d \times a$$

where, A = Area of cross-section of the reservoir, and
a = Area of cross-section of the inclined tube.

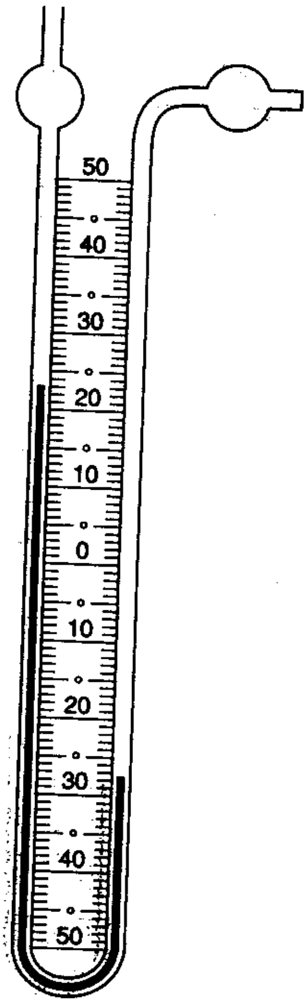

Fig. 11.3. U-tube manometer.

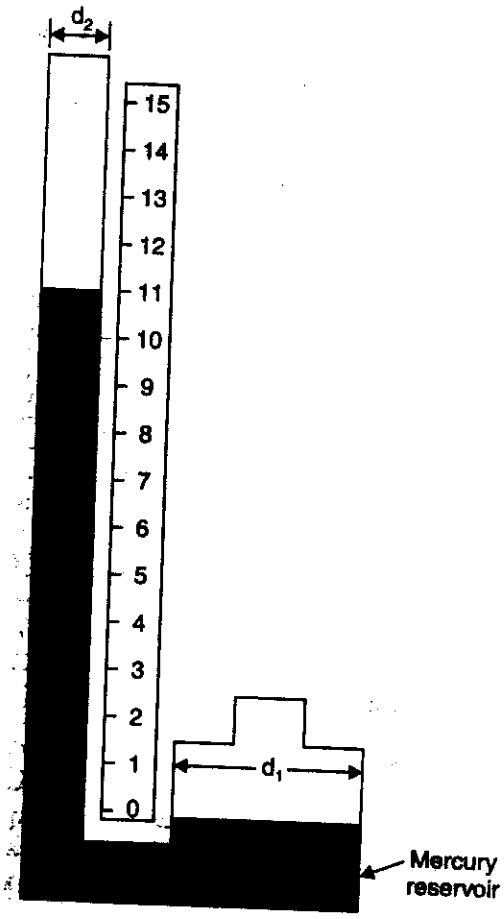

Fig. 11.4. Cistern manometer.

Also the pressure difference Δp *i.e.*, $(p_1 - p_2)$

$$= hw = \left(d \times \sin \theta + d \times \frac{a}{A}\right) w$$

$$= dw \left(\sin \theta + \frac{a}{A}\right)$$

where w is the specific weight of the liquid.

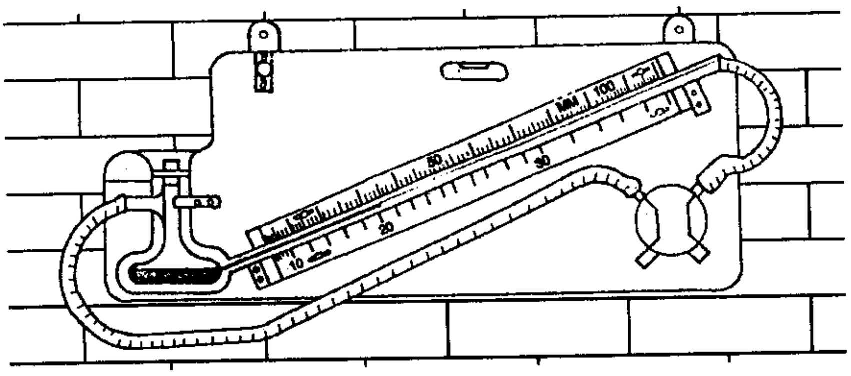

Fig. 11.5. Inclined manometer.

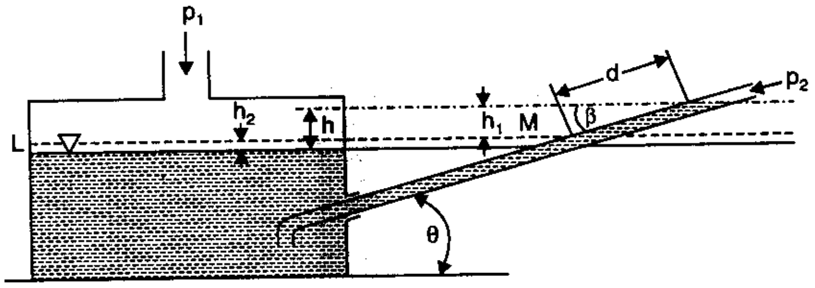

Fig. 11.6. Principle of inclined manometer.

The sensitiveness of the instrument can be varied by *changing the slope of the inclined tube*.

The position of the inclined tube is so arranged that $\left(\sin\theta + \frac{a}{A}\right)$ is round figure.

The multiplication factor of the gauge is :

$$\frac{l}{h} = \frac{1}{\sin\theta + \frac{a}{A}} .$$

Thus the multiplication factor depends on θ and $\frac{a}{A}$. *The smaller the valves of* θ *and* $\frac{a}{A}$, *the greater the multiplication factor*.

11.3.3.2. Important types of pressure gauges

The manometers and U-tubes (discussed earlier) are suitable for comparatively *low pressures*. For high pressures they become unnecessarily larger even when they are filled with heavy liquids. Therefore, for measuring medium and high pressures, we make use of elastic pressure gauges. They employ different forms of elastic systems such as tubes, diaphragms or bellows etc. to measure the pressure. The elastic deformation of these elements is used to show the effect of pressure. Since these elements are deformed within the elastic limit only, therefore these gauges are sometimes called *elastic gauges*. Sometimes they are also called secondary instruments, which implies that they must be calibrated by comparison with primary instruments such as manometers etc.

Some of the important types of these gauges are enumerated and discussed below :

1. Bourdon tube pressure gauge
2. Diaphragm gauge
3. Vacuum gauge.

Bourdon Tube Type Pressure Gauge

A Bourdon type tube pressure gauge is used for measuring *high as well as low pressures*. A simple form of this gauge is shown in Fig. 11.7. In this case the pressure element consists of a metal tube of approximately *elliptical cross-section*. This tube is bent in the form of a segment of a circle and responds to pressure changes. When one end of the tube which is attached to the gauge case, is connected to the source of pressure, the internal pressure causes the tube to expend, whereby circumferential stress *i.e.*, hoop tension is set up. The free end of the tube moves and is in turn connected by suitable levers to a rack, which engages with a small pinion mounted on the same spindle as the pointer. Thus the pressure applied to the tube causes the rack and pinion to move. The pressure is indicated by the pointer over a dial which can be graduated in a suitable scale.

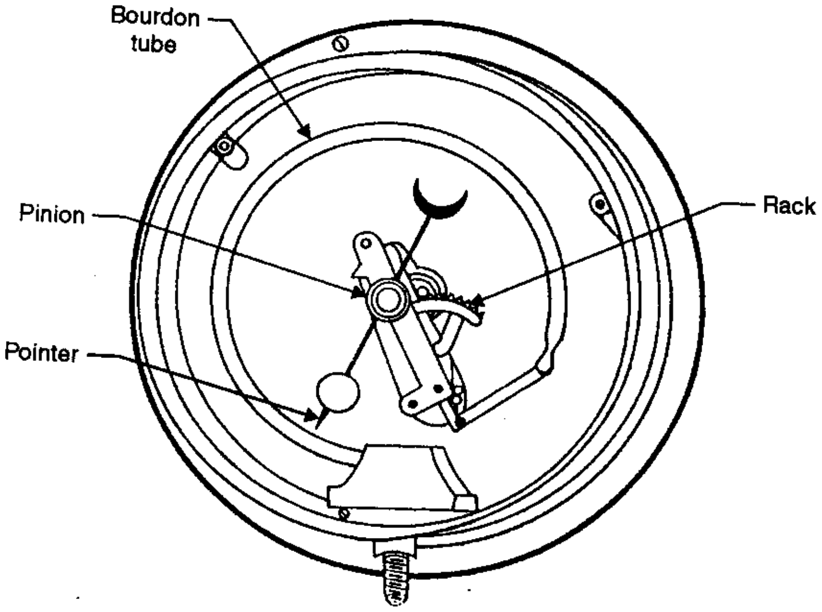

Fig. 11.7. Bourdon tube pressure gauge.

The Bourdon tubes are generally made of *bronze* or *nickel steel*. The former is generally used for low pressures and the latter for high pressures.

Depending upon the purpose for which they are required Bourdon tube gauges are made in different forms, some of them are :

(*i*) *Compound Bourdon tube*. These are used for measuring pressures both above and below atmospheric.

(*ii*) *Double Bourdon tube*. These are used where vibrations are encountered.

Diaphragm Gauge

This type of gauge employs a metallic disc or diaphragm instead of a bent tube. This disc or diaphragm is used for *actuating* the indicating device.

Refer Fig. 11.8. When pressure is applied on the lower side of the diaphragm, it is deflected upward. This movement of the diaphragm is transmitted to a rack and pinion. The latter is attached to the spindle of needle moving on a graduated dial. The dial can again be graduated in a suitable scale.

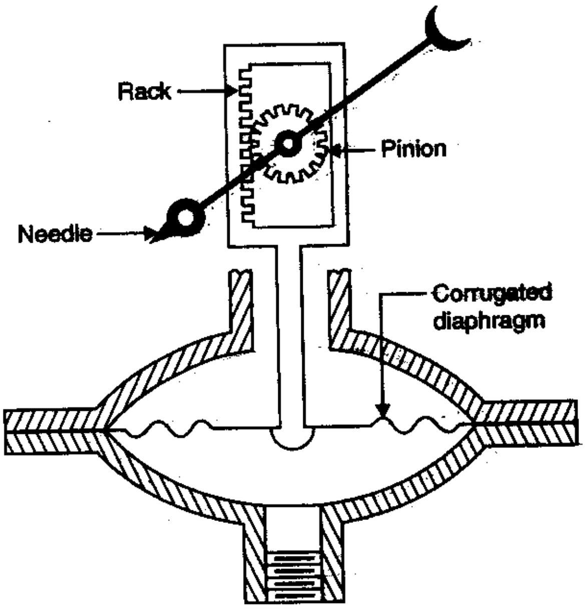

Fig. 11.8. Principle of diaphragm gauge.

Vacuum Gauge

Bourdon gauges discussed earlier can be used to measure vacuum instead of pressure. Slight changes in the design are required for this purpose. Thus, in this case, the tube be *bent inward instead of outward* as in pressure gauges. *Vacuum gauges* are graduated in millimeters of mercury below atmospheric pressure. In such cases, therefore, absolute pressure in millimeters of mercury is the difference between barometer reading and vacuum gauge reading.

Vacuum gauges are used to measure the vacuum in the *condensers* etc. If there is leakage, the vacuum will drop.

The pressure gauge installation require the following considerations :

(*i*) Flexible copper tubing and compression fittings are recommended for most installations.

(*ii*) The installation of a gauge cock and tee in the line close to the gauge is recommended because it permits the gauge to be removed for testing or replacement without having to shut down the system.

(*iii*) Pulsating pressures in the gauge line are not required.

(*iv*) The gauge and its connecting line is filled with an inert liquid and as such liquid seals are provided. Trapped air at any point of gauge lines way cause serious errors in pressure reading.

11.3.4. Electrical Transducers

A *transducer is a device for converting a signal of one sort into the other type*. In other words, a pressure gauge is a transducer for converting the distortion of a Bourdon spring into an indication through use of a calibrated dial and so on. In case of electrical transducers for measuring pressure, various transformations which are needed to convert pressure to some sort of usable electrical signal can be :

1. The change of resistance of an elastic material such as wire.
2. The change in capacitance when the distance between capacitor plates is varied or the dielectric is changed.
3. The conversion of a changing pressure into electrical voltage signals.

4. Creation of a voltage by the movement of a coil within a magnetic field.
5. Generation of a voltage or current through the use of photo-electric effects.
6. Torque-balance system (electromagnetic).

11.3.4.1. Potentiometer devices

One of the simplest of pressure or voltage transducer uses a potentiometer. The potentiometer is used to convert a pressure signal into an electrical voltage as shown in Fig. 11.9.

The potentiometer should have little friction. Levers may be used to match the required movement of the potentiometer with that of the bellows. The signal applied to the potentiometer may be relatively large of the order of several volts. By the use of potentiometric method the signal can be sent relatively long distance. In that case a remote reading systems may employ servomechanic system. In that case the galvanometer of the potentiometer is brought to the zero position.

11.3.4.2. Electromagnetic transducers

For many years a technique has been used which consists of a coil in the plate or grid circuit of an oscillating tube (one that is generating alternating current) to deliver current to some other circuit. The energy may be transferred into some other winding having a transformer action. The coil has to deliver more power to the secondary winding, the additional power must come from the winding in the plate. The increase in plate current causes relays to operate at some predetermined values of current. It can also be used to develop voltages across known resistors. It can cause electromagnets to establish forces used for measuring the force applied which is obtained by pressure belows.

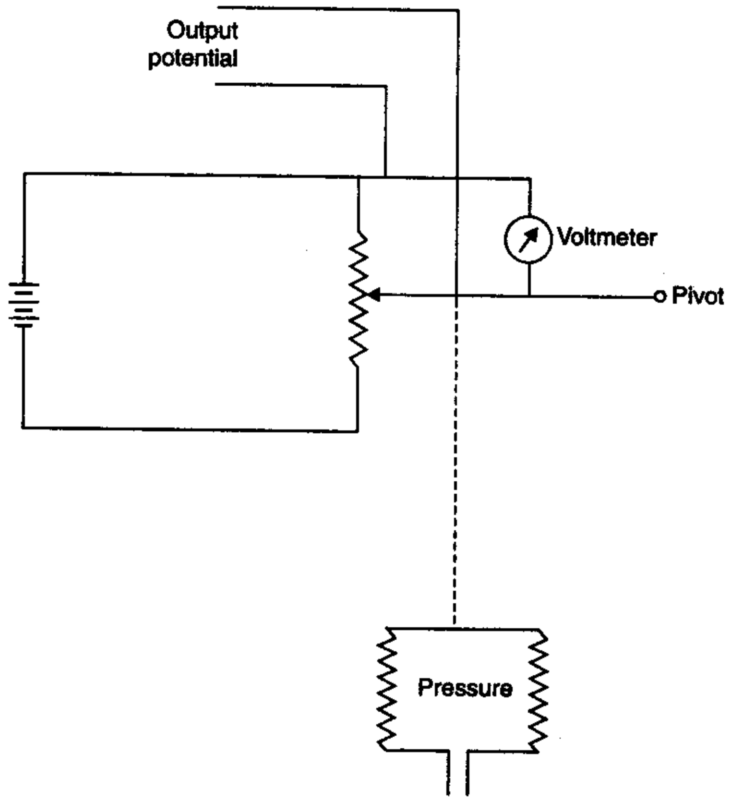

Fig. 11.9. Pressure-voltage transducer.

11.4. THERMOMETERS

11.4.1. Temperature

Temperature can be defined as a thermal state which depends upon the internal or molecular energy of the body. In practice, mean kinetic energy of molecules of a body changes, thus when body possessing high mean molecular kinetic energy is brought in contact with a body having low value, the energy will flow from the higher level to the lower level. This gives us an idea of the hot and cold bodies and the heat which is associated with them.

11.4.2. Temperature Measuring Instruments

Temperature measurements are among the most common and the most important measurement in a power plant. The precise control of temperature is essential in thermal power stations. Temperature measurements may be made in many ways. They can be classified in two broad categories :

1. **Non-electrical method**
   - (*i*) By using change in volume of a liquid when its temperature is changed.
   - (*ii*) By using change in pressure of a gas when its temperature is changed.
   - (*iii*) By using change in the vapour pressure when the temperature is changed.
2. **Electrical method**
   - (*i*) By thermocouples.
   - (*ii*) By change in resistance of material with change in temperature.
   - (*iii*) By comparing the colours of filament and the object whose temperature is to be found out.
   - (*iv*) By ascertaining the energy received by radiation.

The thermometers may also be classified as follows :

1. **Expansion thermometers**
   - (*i*) Liquid-in-glass thermometers
   - (*ii*) Bimetallic thermometers
2. **Pressure thermometers**
   - (*i*) Vapour pressure thermometers
   - (*ii*) Liquid-filled thermometers
   - (*iii*) Gas-filled thermometers
3. Thermocouple thermometers
4. Resistance thermometers
5. Radiation pyrometers
6. Optical pyrometers.

11.4.2.1. Expansion thermometers

The expansion thermometers make use of the differential expansion of two different substances. Thus in liquid-in-glass thermometers, it is the difference in expansion of liquid and the containing glass. And in bimetallic thermometers, the indication is due to the difference in expansion of the two solids. These thermometers are discussed below :

(*i*) **Liquid-in-glass thermometer.** This is a very familiar type of thermometer. The mercury or other liquid fills the glass bulb and extends into the bore of the glass stem. Mercury is the most suitable liquid and is used from – 38.9°C (melting point) to about 600°C. The thermometers employed in the laboratory have the scale engraved directly on the glass stem. A usual type of mercury-in-glass thermometer is shown in Fig. 11.10. An expansion bulb is usually provided at the top of the stem to allow room for expansion of mercury, in case the thermometer is subjected to temperatures above its range. The upper limit for Mercury-in-glass thermometers is about 600°C. As the upper limit is far above the boiling point of mercury, some inert gas *i.e.*, nitrogen is introduced above the mercury to prevent boiling.

Pentane, Ethyl alcohol and Toluene are the other liquids which can be used for liquid-in-glass thermometers. Since these liquids are normally colourless a dye is added to facilitate reading. These liquids have a low freezing point as shown below and are suitable for low temperature thermometers.

Liquid	*Boiling point*	*Freezing point*
Pentane	36°C	– 130°C
Ethyl alcohol	78°C	– 100°C
Toluene	110°C	– 92°C

(*ii*) **Bimetallic thermometers.** In a bimetallic thermometer differential expansion of bimetallic strips is used to indicate the temperature. It has the advantage over the liquid-in-glass thermometer, that it *is less fragile* and is *easier to read.* In this type of thermometer two flat strips of different metals are placed side by side and are welded together. Many different metals can be used for this purpose. Generally one is a *low expanding metal* and the other is *high expanding metal.* The bimetal strip is coiled in the form of spiral or helix. *Due to rise in temperature, the curvature of the strip changes. The differential expansion of a strip causes the pointer to move on the dial of the thermometer.*

11.4.2.2. Pressure thermometers

In pressure thermometers liquids, gases and vapours can all be used. The principle on which they work is quite simple. The fluid is confined in a closed system. In this case the *pressure is a function of the temperature*, so that when the fluid is heated, the pressure will rise. And the temperature can be indicated by Bourdon type pressure gauge. In general, the thermometer consists of a bulb which contains bulk of the fluid. The bulb is placed in the region whose temperature is required. A capillary tube connects the bulb to a Bourdon tube, which is graduated with a temperature scale.

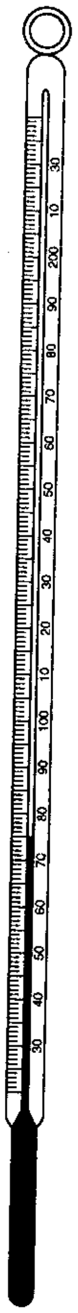

Fig. 11.10. Mercury-in-glass thermometer.

Pressure thermometers are discussed below :

(*i*) **Vapour pressure thermometer.** A schematic diagram of a vapour pressure thermometer is shown in Fig. 11.11. When the bulb containing the fluid is installed in the region whose temperature is required, some of the fluid vapourizes, and increases the vapour pressure. This change of pressure is indicated on the Bourdon tube. The relation between temperature and vapour pressure of a volatile liquid is of the *exponential form*. Therefore, the scale of a vapour pressure thermometer will not be linear.

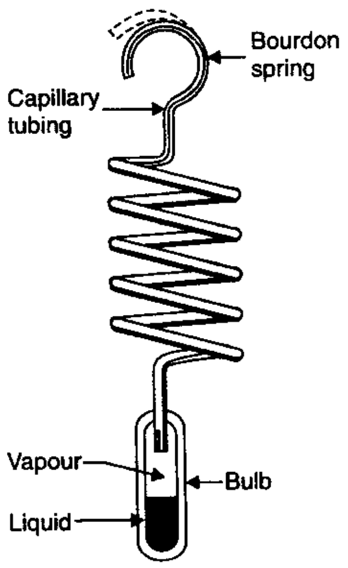

Fig. 11.11. Vapour pressure thermometer.

(*ii*) **Liquid-filled thermometer.** A liquid-filled thermometer is shown in Fig. 11.12. In this case, the *expansion of the liquid causes the pointer to move on the dial.* Therefore liquids having high co-efficient of expansion should be used. In practice, many liquids *e.g.* mercury, alcohol, toluene, and glycerine have been successfully used. The operating pressure varies from about 3 to 100 kgf/cm^2. These type of thermometers could be used for a temperature upto 650°C in which mercury could be used as the liquid.

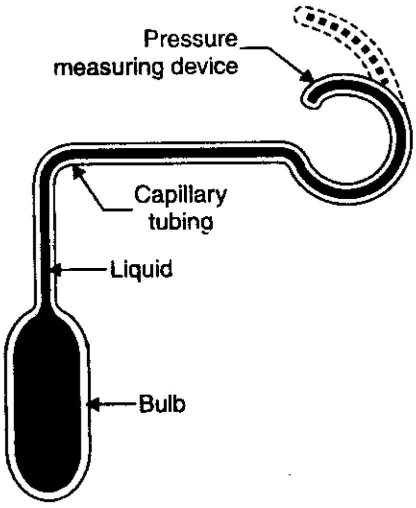

Fig. 11.12. Liquid-filled thermometer.

In actual design, the internal diameter of the capillary tube and Bourdon tube is made much smaller than that of the bulb. This is because the capillary tube is subjected to a temperature which is quite different from that of the bulb. Therefore, to minimise the effect of variation in temperature to which the capillary tube is subjected, the *volume of the bulb is made as large as possible as compared with the volume of the capillary*. However, large volume of bulb tends to increase time lag, therefore, a *compensating device is usually built into the recording or indicating mechanism, which compensates the variations in temperature of the capillary and Bourdon tubes.*

(*iii*) **Gas-filled thermometers.** The temperature range for gas thermometer is practically the same as that of liquid filled thermometer. The gases used in the gas thermometers are *nitrogen* and *helium*. Both these gases are chemically inert, have good values for their co-efficient of expansion and have low specific heats. The construction of this type of thermometer is more or less the same as mercury-thermometer in which Bourdon spring is used. The errors are also compensated likewise. The only difference in this case is that bulb is made much larger than used in liquid-filled thermometers. For good performance the volume of the bulb should be made at least 8 times than that of the rest of the system.

These thermometers are generally used for pressures below 35 kgf/cm^2.

11.4.2.3. Thermocouple thermometers

For higher range of temperature *i.e.*, above 650°C, filled thermometers are unsuitable. For higher range of temperature, thermocouples and pyrometers are used.

In its simplest form a thermocouple consists of *two dissimilar metals or alloys which develop e.m.f. when the reference and measuring junctions are at different temperatures*. The reference junction or cold junction is usually maintained at some constant temperature, such as 0°C and the device used for measuring the temperatures. Fig. 11.13 shows a simple circuit of a thermocouple and the temperature measuring device. In many industrial installations the instruments are equipped with automatic compensating devices for tempearture changes of the reference junction, thus eliminating the necessity of maintaining this junction at constant temperature.

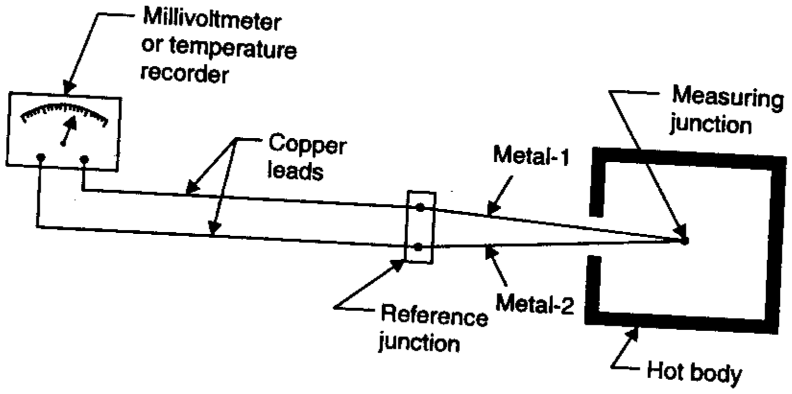

Fig. 11.13. Thermocouple.

Table 11.1 gives the composition, useful temperatures range and temperature versus e.m.f. relationship for some commercial thermocouples.

Table 11.1. Composition, Useful Temperature Range and E.m.f. Produced for Some Thermocouples

S. No.	*Thermocouple*	*Composition*	*Temperature (°C)*		*Thermo-electric power*		*Remarks*
			Useful-range	*Max.*	*°C*	*Milli-volt*	
1.	*Platinum vs Platinum-rhodium*	Pure platinum vs Pt + 10 or 13% Rh	400 to 1450	1700	0 500 1000 1500	0.0 4.219 9.569 15.498	Used for high temperature measurements
2.	*Chromel vs Alumel*	90% Ni + 10% Cr vs 95 Ni + 5% (Al + Sn) Mn	– 200 to 1200	1450	– 200 0 300 600 900 1200	– 5.75 0.0 12.21 24.90 37.36 48.85	High resistance to oxidation
3.	*Iron vs Constantan*	Pure iron vs 45-60% Cu + 55-40% Ni	– 200 to 750	1000	– 200 0 300 600 900	– 8.27 0.0 16.59 33.27 52.29	—
4.	*Copper vs Constantan*	Pure copper vs Cu-Ni constantan	– 200 to 350	600	– 200 0 200 400	– 5.539 0.0 9.285 20.865	Not suitable in air due to excessive oxidation.

11.4.2.4. Resistance thermometers

The fact that the electrical resistance of the metals increases with temperature is made use of in resistance thermometers which are purely electrical in nature. A *resistance thermometer is used for precision measurements below 150°C.*

A simple resistance thermometer consists of a *resistance element or bulb, electrical loads, and a resistance measuring or recording instrument.* The resistance element (temperature sensitive element) is usually supplied by the manufacturers with its protecting tube and is ready for electrical connections. The resistance of the metal used as resistance element should be reproducible at any given temperature. *The resistance is reproducible if the composition or physical properties of the metal do not change with temperature. For this purpose platinum is preferred.* A *platinum resistance thermometer* can measure temperatures to within ± 0.01°C. However, because of high cost of platinum, nickel and copper are used as resistance elements for industrial purposes for low temperatures. The fine resistance wire is wound in a spiral form on a mica frame. The delicate coil is then enclosed in a porcelain or quartz tube. The change of resistance of this unit can be measured by instruments such as wheatstone bridge, potentiometer or galvanometer.

Advantages

The resistance thermometers possess the following *advantages* over other devices :

1. A resistance thermometer is very accurate for low ranges below 150°C.
2. It requires no reference junction like thermocouples and as such is more effective at room temperature.
3. The distance between the resistance element and the recording element can be made much larger than is possible with pressure thermometers.
4. It resists corrosion and is physically stable.

Disadvantages

1. The resistance thermometers cost more.
2. They suffer from time lag.

11.4.2.5. Radiation pyrometer

A device which measures the total intensity of radiation emitted from a body is called *radiation pyrometer.*

The elements of a total radiation pyrometer are illustrated in Fig. 11.14. It collects the radiation from an object (hot body) whose temperature is required. A mirror is used to focus this radiation on a thermocouple. This energy which is concentrated on the thermocouple raises its temperature, and in turn generates an e.m.f. This e.m.f. is then measured either by the galvanometer or potentiometer method. Thus rise of temperature is a function of the amount of radiation emitted from the object.

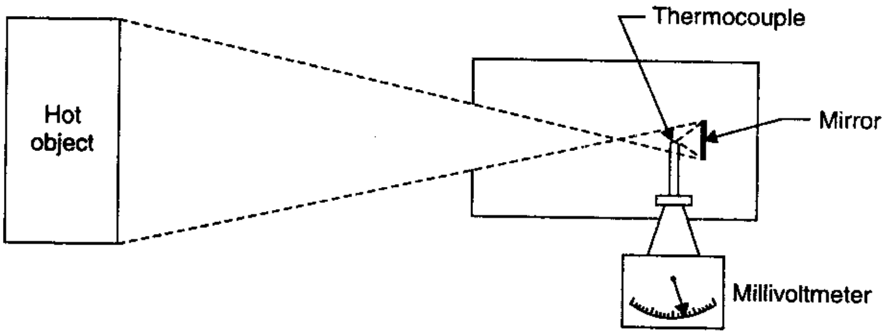

Fig. 11.14. A schematic diagram of radiation pyrometer.

Advantages of the pyrometers

1. The temperature of moving objects can be measured.
2. A higher temperature measurement is possible than that possible by thermocouples etc.
3. The average temperatures of the extended surface can be measured.
4. The temperatures of the objects which are not easily accessible can be measured.

11.4.2.6. Optical pyrometer

An optical pyrometer works on the *principle that matters glow above 480°C and the colour of visible radiation is proportional to the temperature of the glowing matter.* The amount of light radiated from the glowing matter (solid or liquid) is measured and employed to determine the temperature.

Fig. 11.15 shows a *disappearing filament pyrometer.*

Operation

- The optical pyrometer is sighted at the hot body and focused.
- In the beginning filament will appear dark as compared to the background which is bright (being hot).
- By varying the resistance in the filament circuit, more and more current is fed into it, till filament becomes equally bright as the background and hence disappears.
- The current flowing in the filament at this stage is measured with the help of an ammeter which is calibrated directly in terms of temperature.
- If the filament current is further increased, the filament appears brighter as compared to the background which then looks dark.

An optical pyrometer can measure temperatures ranging from 700 to 4000°C.

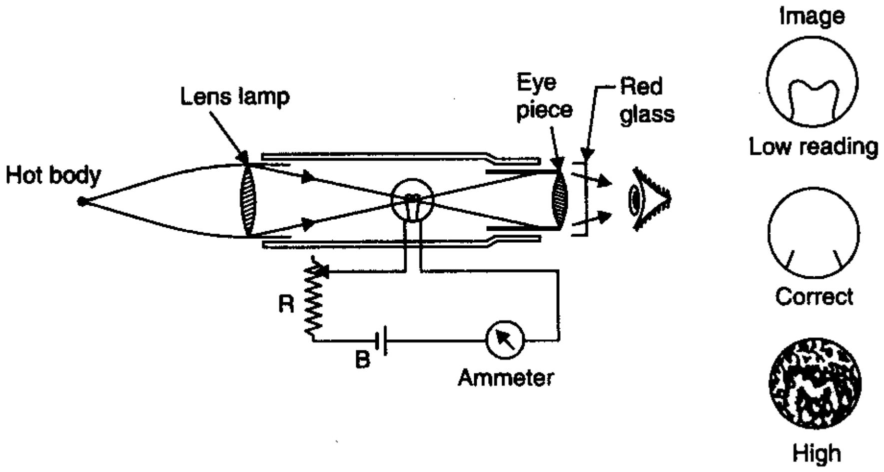

Fig. 11.15. Optical pyrometer.

Table 11.2 gives the summary of temperature range of different instruments.

Table 11.2. Summary of Temperature Range of Different Instruments

Type of Instruments	*Liquid-in-Glass Thermometer*	*Bimetallic Thermometer*	*Pressure thermometers*			*Thermocouples*			*Resistance thermometers*				*Radiation Pyrometers*	*Optical Pyrometers*
	Mercury		Vapour Pressure	Liquid-filled	Gas-filled	Iron-Constantan	Copper-Constantan	Chromel Alumel	Platinum Platinum-Rhodium	Copper	Nickel	Platinum	—	—
Low temperature limit	– 39°C	– 75°C	– 250°C	– 87°C	– 269°C	– 196°C	– 250°C	– 184°C	0°C	– 140°C	– 184°C	– 184°C	About room temp.	760°C
High temperature limit	600°C	540°C	316°C	650°C	540°C	760°C	350°C	1260°C	1540°C	120°C	316°C	760°C	As high as desired	As high as desired
Remarks	Low price; Fairly accurate; Easily broken.	Easier to read than Liquid-in-glass thermometers.	Normally scale non-linear.	To be compensated for variation in ambient temperatures.	Requires large bulb; Linear scale.	Widely used in Industry.	Constantan is 60% Cu, 40% Ni.	Chromel is 20% Cr, 80% Ni. Alumel is 2% Al, 98% Ni.	Expensive.	Very sensitive. Suitable for narrow range instruments.			—	—

11.5. LIQUID LEVEL GAUGES

In a boiler house one of the important readings is the *level of water*. The water level should be measured in all boilers all the times. Out of several methods available for determining the levels, some of them are as follows :

1. By sight glass
2. Cable and float
3. By hydrostatic pressure
4. By float and hydraulic pressure
5. By strain gauges
6. By radiation absorption gauges.

11.5.1. Gauge Glass

In case of high pressure boilers (350 kgf/cm^2, 650°C) special attention is given to the sufficient strength of the glass. One of the drawbacks of the gauge glass is when liquid stains or discolours the tube to such a degree that the level cannot be read and the tube cleaning is required. A special device uses a special guide float carrying a permanent magnet within a stainless-steel chamber and a scale consisting of a series of magnetised elements mounted on the outside of the chamber. They are attracted to each other thus forming a continuous scale, one face being painted and the other silver. The liquid level in modern thermal power station is indicated on a liquid level recorder which is generally located at a distance from the actual boiler tank.

11.5.2. Electrical Level Gauges

A simpler way of measuring the level using electrical circuit is the use of triode tube. Fig. 11.16 shows the principle of electrical transducers. If the level in the tank is below the required level

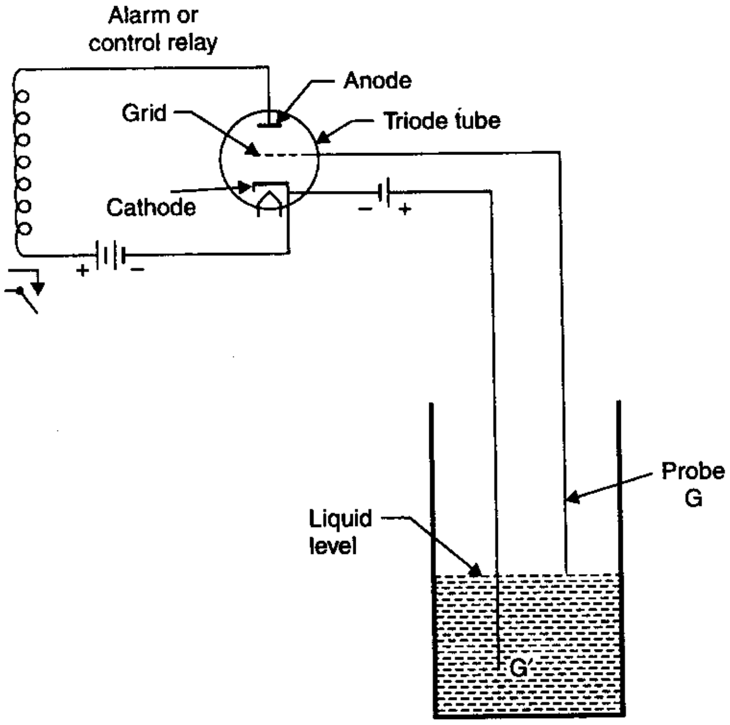

Fig. 11.16. Electrical level gauge principle.

G, there is no complete circuit to the grid of the tube, which then accumulates a charge of electrons. This makes it very negative in effect and reduces the tube plate current to a very small amount. Under these circumstances, very little current in the relay coil completes the alarm circuit. The alarm thus indicates the dangerously low level in the boiler tank. A red light signal also serves the same purpose. On the other hand if the level of water rises, it completes the circuit between G and other terminals G'. The electrons can then be removed from the grid circuit. As the grid is made less negative, the plate current will continue to rise until sufficient current flows in the relay coil to operate it. The triode tube can well be replaced by transistors.

11.6. FLOW METERS

The various flow meters employed for measuring flow rates are as follows :

1. *Steam flow meters*—measure steam output of boilers and turbine supply etc.
2. *Air flow meters*—measure air flow rate in gas turbines etc.
3. *Water flow meters*—measure feed water condensate and pump discharge.

Rate of flow of water is generally measured by a venturimeter Fig. 11.17. It consists of three parts :

(*i*) A short converging part.
(*ii*) Throat
(*iii*) Diverging part

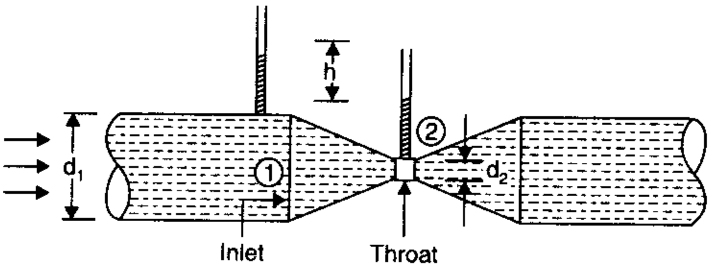

Fig. 11.17. Venturimeter.

A venturimeter works on Bernoulli's principle. As the water flows from end 1 to end 2 a difference between water levels (h) in the piezometers is obtained.

The rate of water discharge (Q) is given by

$$Q = C_d \times \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}} \times \sqrt{2gh}$$

where a_1 = Area at section 1 = $\frac{\pi}{4} d_1^2$,

a_2 = Area at section 2 = $\frac{\pi}{4} d_2^2$,

h = Difference in water levels in the piezometers, and

C_d = Co-efficient of discharge.

11.7. pH MEASURING INSTRUMENTS

The pH is a number denoting the degree of acidity or alkalinity of a substance. It does not indicate the quantity of acid or alkaline in a solution as found by titration method. It is derived by measuring the amount of hydrogen ion (H^+) in grams per litre of solution. For example, pure water ionizes to produce 10^{-7} grams of H_2 ions per litre. Therefore, any substance producing 10^{-7} grams of hydrogen ions per litre is considered to be a neutral solution. The greater the amount of hydrogen ions present in solution its acid reaction becomes stronger. Therefore, pure water being neutral solution, any solution producing more hydrogen ion than pure water will be acidic and degree is governed by the difference. Other solution producing less hydrogen ions than pure water will be alkaline and the degree is also governed by the difference.

The p-H value of all solutions is accommodated between 0 and 14. The selection of the numbers 0 to 14 is not arbitrary but is actually the number of decimal places required to record the measure of weight of H_2 ions per litre of solution having ascending or descending values of acid and alkaline. Thus a solution having no decimal place is represented by 1 or 1 gram of H_2 ions per litre. This solution would be highly acidic as compared with water. Such value on pH scale is represented as zero. Acid or alkaline nature of a solution depends on whether hydrogen or hydroxyl (OH) ions predominate. The pure water contains H^+ and OH^- ions. The extent to which this dissociation is present in a given sample depends upon temperature. At 20°C, the concentration of these ions is of the order of 10^{-14}. Due to this, pH scale has been spread to 14.

Earlier pH number was measured by observing the *change in colour or turbidity by comparing it with a standard sample*. The mostly used *now a days is to find pH numbers by measuring the potential created by a special battery*. The hydrogen ion reacts with a special glass electrode and produces a potential whose value can be measured. It has been seen that the current flow in the ionisation cell is extremely small, being of the order of a billionth of an ampere. This can be detected by passing it through a resistor of extremely high value. The potential developed under these conditions is then read by noting the response of a meter in the plate circuit of a special vacuum tube. The circuit has two cells, one the *active cell which produces an e.m.f. proportional to the hydrogen ion concentration. The second cell is used for reference purposes*. This reference cell is made with calomel, which is a compound of mercury or with silver-silver chloride. One of the methods of measuring hydrogen ion concentrations is based on the fact that when a piece of metal is placed in an ionic solution of the same metal, there will be a potential developed between the metal and the solution. *The value of this e.m.f. is proportional to the concentration of ions.*

11.8. GAS ANALYSERS

The gas analysis is carried out to determine the concentration of one or more components of a gas mixture. In *steam power plants*, the object of gas analysis is to keep the concentration of carbondioxide (CO_2) and oxygen (O_2) as *minimum as possible* therefore constant recording of these components in exhaust gases is necessary. The recording of these components helps to improve the efficiency of steam generation. The common types of analysers used for the measurement of CO_2 and O_2 are described below.

Measurement of Carbondioxide (CO_2) :

Since the gases differ in their ability to conduct the heat, therefore, the *proportion of various constituents of flue gases* can be determined by *measuring their thermal conductivity*. If the thermal conductivity of air is considered as *unity* at 0°C, the thermal conductivity of $CO_2 = 0.585$; $H_2 = 7.35$, $N_2 = 1.015$; $O_2 = 1.007$ respectively.

Fig. 11.18 shows the commonly used method for measuring CO_2 content is flue gases.

- It consists of hot wire thermal conductivity gas analysis cell which comprises of *two chambers*, each containing a *wire filament* as shown in Fig. 11.18.
- The gas is passed through one chamber whose conductivity is to be measured and other chamber is filled with a reference gas like air and scaled.

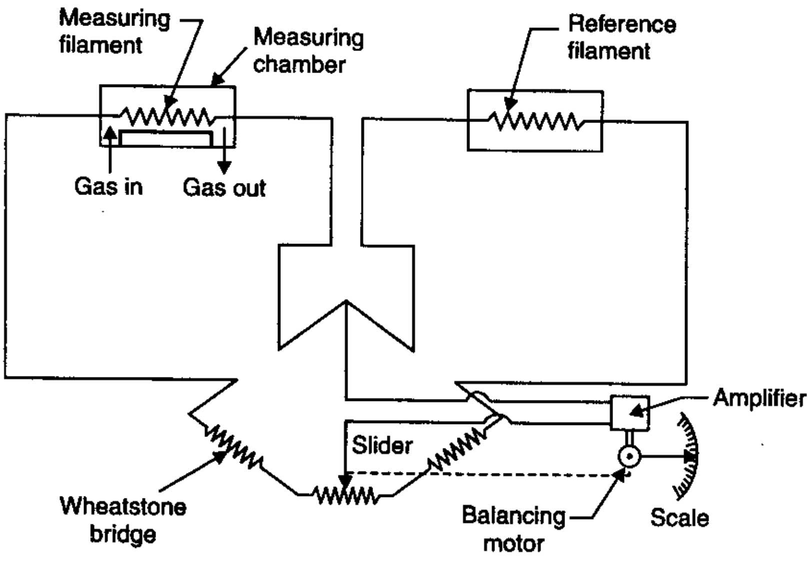

Fig. 11.18. Electrical circuit for the measurement of CO_2 content in the gases.

- The platinum wire elements are passed through the cells (as shown in Fig. 11.18) and form a Wheatstone bridge circuit. Under normal working conditions, these elements are heated by the bridge current.
- The temperature of the filament in the measuring chamber rises as the conductivity of the gases passing around it decreases, as the heat of the filament cannot be carried by the gases. Thus the temperature, and hence the resistance of the two platinum wire elements changes, and unbalances the bridge and provides an *unbalanced voltage which is proportional to the percentage of* CO_2. This unbalanced voltage can be used for measuring the percentage of CO_2 in flue gases.
- To compensate the error which would arise from variation in temperature of the gas, another resistance is inserted in the circuit (not shown).

This type of instrument gives accurate values if *the proportion of* H_2 *present is small and constant.*

Measurement of Oxygen (O_2)

Although there are other methods to measure O_2, we shall discuss have only *"paramagnetic oxygen analyser"*. This analyser works on the principle of *paramagnetic properties of* O_2. Oxygen is the only paramagnetic component in the flue gases. It has very high magnetic permanence compared with other gases. The magnetic permanence of paramagnetic gases *decreases with an increase in temperature*. The gas molecules near the heated body in the magnetic field lose part of their magnetic properties and are pushed out of the magnetic field by cooler molecules. The temperature of the cooler molecules entered in the magnetic field where heated body is situated is increased and in turn they are also pushed out of magnetic field by other molecules. In this way, a convection flow known as *'Magnetic Wind'* is created which cools the heated body. The magnetic wind increases with an increase in O_2 content in the flue gases and cooling of the heated body is intensified. *The temperature change of heated body alters its electric resistance which indicates the concentration of* O_2 *in the gas mixture*. Therefore, the O_2 content can be measured by measuring an electric resistance of the heated body which can be one of the arms of Wheatstone bridge.

Fig. 11.19 shows the electric circuit used for O_2 measurement using the magnetic wind type principle.

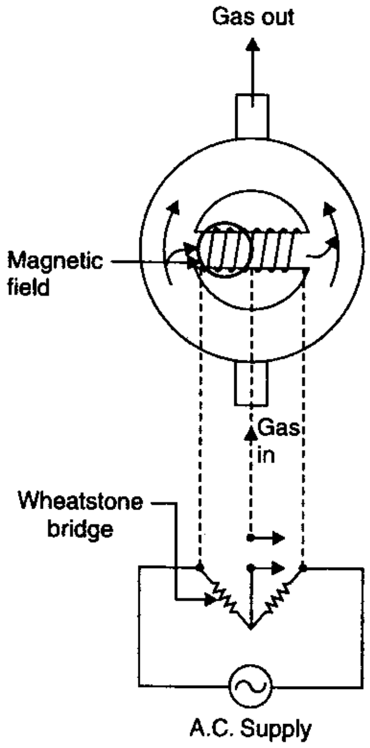

Fig. 11.19. Paramagnetic oxygen analyser.

- The gas is aspirated into the measuring cell through an annulus with an horizontal by-pass tube (as shown in Fig. 11.19). This by-pass tube has two identical adjacent platinum windings on the outside which are connected into a Wheatstone bridge circuit and become heated by the application of voltage across the bridge. One of these windings is cut by an intense magnetic field produced by a large permanent magnet.
- When the sample of flue gas enters into the cell, O_2 is drawn into the bypass by virtue of its paramagnetic properties. It is heated by the winding which reduces the magnetic susceptibility of the gas. Cool O_2 from the gas of higher susceptibility is drawn in the tube displacing the hot gas which passes along the tube back into the annulus. This *'magnetic wind' causes differential cooling of the two windings and by the change of resistance with temperature unbalances the bridge. The resulting unbalanced e.m.f. is measured by a standard potentiometer recorder and is proportional to the oxygen content of the sample.*

Measurement of Carbon-monoxide (CO) :

A carbon-monoxide analyser words on the principle of non-dispersive infra-red absorption and is suitable for all biatomic molecules. The principle of the apparatus is based on *molecular specific absorption of bands of infra-red radiation. The different radiation intensities, depending on the gas concentration, are first converted in the receiver chamber into flow pulses and then into electrical signals.* The system first shoots beams of infra-red and visible light through the gases in the smoke stack. A molecule of a particular gas hungrily absorbs light energy at particular wavelength. By comparing the original intensities of the beam (I_0) with the amount of light that reaches the detector (I), the analyser determines the relative amounts of CO in the gases. The resulting signal is *amplified* and transmitted to the control room. The concentration of the gas is measured in terms of the ratio as log (I/I_0). Therefore, any light level change, darking of the window, scattering of particulates or water droplets in the gas steam, effects both I and I_0 equally, and maintains the ratio unchanged.

Orsat Apparatus

The flue gas analysis can be carried out by **Orsat's apparatus.** Fig 11.20 shows a typical Orsat's apparatus.

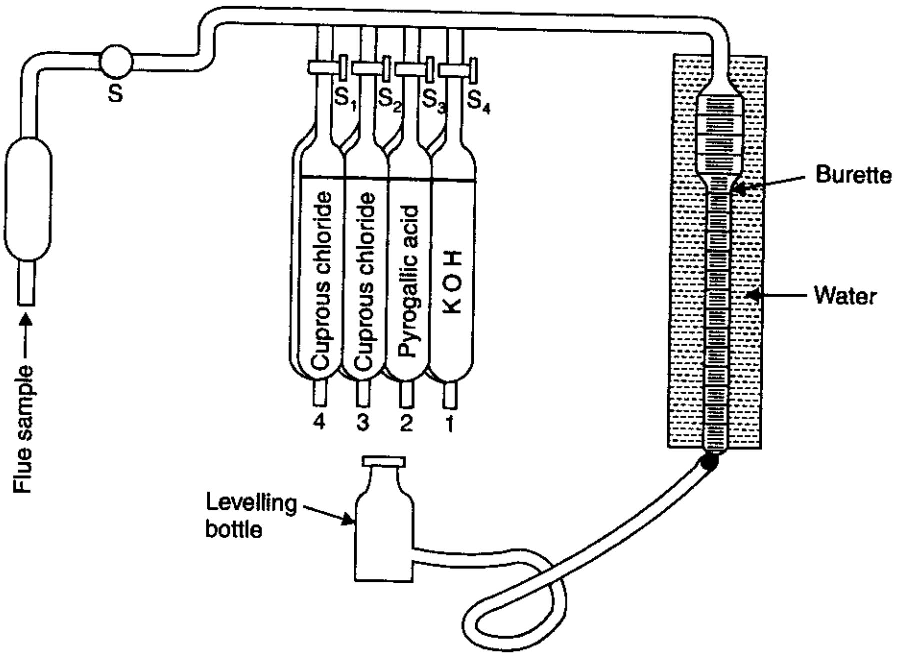

Fig. 11.20. Orsat's apparaturs.

Construction. It consists of a burette, gas cleaner and four absorption pipettes 1, 2, 3, 4. The pipettes are interconnected by means of a manifold fitted with cocks S_1, S_2, S_3, and S_4 and contain different chemicals to absorb *carbondioxide (CO_2), carbon monoxide (CO)* and *oxygen (O_2)*. Each pipette is also fitted with a number of small glass tubes which provide a greater amount of surface. These tubes are wetted by the absorbing agents and are exposed to the gas under analysis. The measuring burette is surrounded by a water jacket to prevent changes in temperature and density of the gas. Pipette 1 contains *caustic soda (KOH)* which ***absorbs carbondioxide***, pipette 2 is filled with an *alkaline solution of pyrogallic acid* which ***absorbs oxygen content of the gas*** while pipettes 3 and 4 are provided with an acid solution of ***cuprous chloride to absorb carbon monoxide***. Furthermore the apparatus has a levelling bottle and a three way cocks to connect the apparatus either to gases or to atmosphere.

Procedure. A 100 cm^3 of gas whose analysis is to be made is drawn into the bottle by lowering the levelling bottle. The stop cock S_1 is then opened and the whole flue gas is forced to pipette 1. The gas remains in this pipette for sometime and most of the carbondioxide is absorbed. The levelling bottle is then lowered to allow the chemical to come to its original level. The volume of gas thus absorbed is read on the scale of the measuring burette. The flue gas is forced through the pipette 1 for number of times to ensure the whole of the carbondioxide is absorbed. Further, the remaining flue gas is then forced to the pipette 2 which contains pyrogallic acid to absorb whole of oxygen. The reading on the measuring burette will be the sum of volume of CO_2 and O_2. The oxygen content can then be found out by subtraction. Finally, as before, the sample of gas is forced through the pipettes 3 and 4 to absorb carbonmonoxide completely.

The amount of nitrogen in the sample can be determined by subtracting from total volume of gas the sum of carbondioxide, carbonmonoxide and oxygen contents.

Note. *Orsat apparatus provides the percentage of dry flue gases because steam if present will be condensed and sulphur dioxide absorbed.*

11.9. HUMIDITY MEASURING INSTRUMENTS

Definitions

Humidity. It is the measure of water vapour present in a gas. It is usually measured as absolute humidity, relative humidity or dew point temperature.

Absolute humidity. It is the mass of water vapour present per unit volume.

Specific humidity. It is the ratio of mass of water vapour present in a sample of a moist gas to the mass of the entire sample.

Relative humidity. It is the ratio of water vapour pressure actually present to water vapour pressure required for saturation at a given temperature. The ratio is expressed in per cent. Relative humidity (RH) is always dependent upon temperature.

Moisture. It refers to the amount of liquid absorbed by a solid. It has also been used to refer to the water chemically bound, adsorbed, or absorbed in a liquid.

Dew point. It is the temperature at which saturation of water vapour pressure is equal to the partial pressure of water vapour in the atmosphere. The relative humidity at dew point is 100%. The dew point has also been defined as the temperature at which the actual quantity of water vapour in the atmosphere is sufficient to saturate this atmosphere with water vapour.

Measuring Instruments

Hygrometers

The hygrometer is an instrument which measures humidity directly. It can be calibrated in terms of absolute humidity. More frequently its output is used to indicate relative humidity.

The various types of hygrometers used are :

1. Resistive hygrometer
2. Capacitive hygrometer
3. Microwave hygrometer
4. Aluminium oxide hygrometer
5. Crystal hygrometer.

The *resistive hygrometer* is described below.

Resistive hygrometer. Some hygroscopic salts exhibit a change in resistivity with humidity. The most common is *lithium chloride.* This, with a binder, may be coated on a wire or on electrodes. Resulting resistance changes cover a wide range, *e.g.* 10^4 to 10^9 Ω as the humidity changes from 100 to 0 per cent. This makes it impractical to design a single element to operate from 1 to 100 per cent relative humidity. Instead *several elements* are used, each in a narrow range, with provision for switching elements. Resistance is measured either with a Wheatstone bridge or by a combination of current and voltage measurements.

Most of these must not be exposed to conditions of 100 per cent humidity as the resulting condensation may damage the device. Either they must be operated in a constant temperature environment or temperature corrections must be made. These are accurate to within ± 2.5 per cent or ± 1.5 per cent in some cases. Response times are typically of the order of a few seconds. These are currently the most common electronic hygrometers.

A typical resistance hygrometer is shown in Fig. 11.21. Two metal grids are bonded to a sheet of plastic.

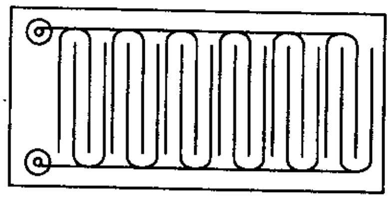

Fig. 11.21. Resistive hygrometer.

The whole is coated with a layer of moisture sensitive chemical such as lithium chloride. The resistance changes when this chemical is exposed to variations in humidity. The higher the relative humidity, the more moisture the lithium chloride will absorb, and the lower will be its resistance.

The resistance of the sensing unit is a measure of the relative humidity. Resistance should be measured by applying A.C. to the Wheatstone bridge. D.C. voltage is not applied because it tends to breakdown the lithium chloride to its lithium and chlorine atoms. The current flow is a measure of the resistance and hence of the relative humidity.

Psychrometers

The psychrometer is a humidity measuring instrument which utilizes one wet bulb thermometer and one dry bulb thermometer. The dry bulb thermometer measures the ambient temperature and the wet bulb thermometer measures temperature reduction due to evaporative cooling. A wick, a porous ceramic sleeve, or a similar device saturated with water is in close physical contact with the "bulb" (sensing portion) of the wet bulb thermometer to keep it moist. Relative humidity is determined from the two temperature readings and a reading of the barometric pressure usually with the help of a **Psychrometric Chart.** At any given ambient temperature, the relative humidity decreases as the difference between dry bulb and wet bulb readings increases.

Some of the psychrometers are described below :

1. Sling psychrometer :

This device consists of two similar thermometers mounted side by side as shown in Fig. 11.22. The bulb of one of the thermometers is covered by a wet cloth.

When a thin film of water is brought into close contact with air, a portion of it evaporates, and the temperature of the remaining water is lowered due to heat required by the evaporation process. The amount of evaporation and consequent lowering of the temperature depends upon the capability of the air to absorb the moisture. Thus if the relative humidity is lower, air has small moisture and can therefore absorb more. Hence the evaporation is faster and the temperature of the remaining water will be lower.

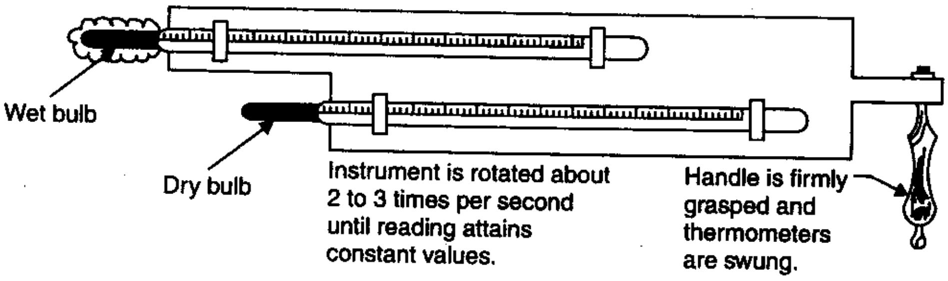

Fig. 11.22. Sling psychrometer.

In the sling psychrometer, a handle is provided whereby the thermometer may be whirled, so that the bulbs continuously come in contact with fresh air. If this is not done the stagnant mositure-laden air will engulf the thermometer thereby causing errors.

The dry bulb thermometer is unaffected by the moving air and registers the ambient temperature. The wet bulb thermometer shows a lower temperature due to evaporation. Since the cooling effect is a function of the relative humidity of air, the relative humidity may be determined by comparing the readings of the two thermometers. Relative humidity can directly be read off from psychrometric charts.

Psychrometric charts graphically describe the relationship between the properties of moist air *i.e.*, the dry bulb, the wet bulb and dew point temperatures of the mixture and humidity.

2. Commercial type psychrometer :

A commercial type psychrometer is shown in Fig. 11.23. The filled system thermometer bulbs are placed adjacent to each other and air is blown across the assembly or they may be placed where there is strong current of air (nearly 5 m/s). One of the bulbs is coated with a knitted or woven cotton which is suspended into a water reservoir whose level is controlled so that the required conditions are satisfied. The temperatures are recorded by suitable recorders.

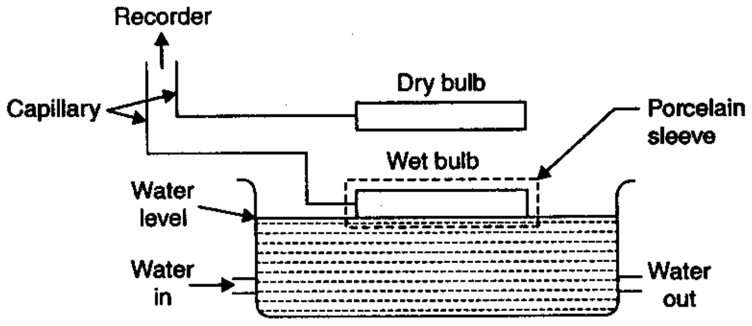

Fig. 11.23. Commercial type psychrometer.

The two thermometers are connected to a recorder through capillary tubes. In order to avoid errors arising on account of contamination of the wick the bulb may be enclosed in a porcelain sleeve and water is pumped into the annular space at a constant rate. These instruments are not suited for instantaneous monitoring and control of humidity.

A variation in the indication and recording arrangement is also possible if the filled in thermometers are replaced by resistance thermometers or thermocouples.

Dew Point Measurements

The dew point is a discrete temperature. Specially, it is that temperature at which liquid water and water vapour, or ice and water vapour are in equilibrium. At this temperature only one value of saturation vapour pressure (of water vapour) exists. Hence, the absolute humidity can be determined from this temperature if the pressure is known.

Two methods used for measuring dew point temperatures are given below :

First Method

Refer Fig. 11.24. This method uses the resistive hygrometer described previously. The arrangement consists of a thin metal tube covered with a glass cloth saturated with lithium chloride. A double winding of silver is made over the glass cloth.

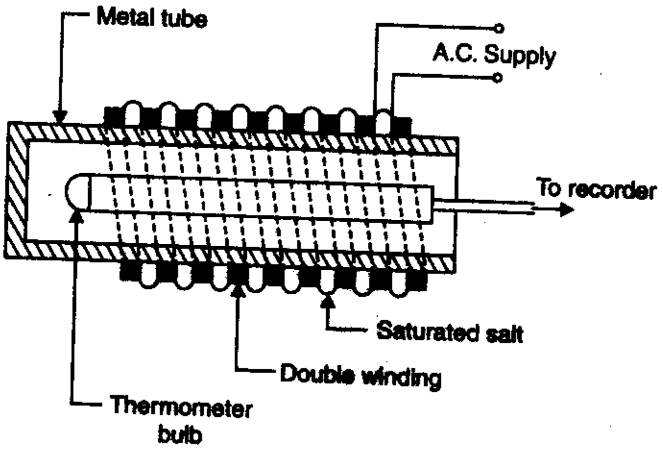

Fig. 11.24. Dew point recorder.

A low voltage A.C. supply is connected to the winding. The electric conductivity between the wires is proportional to the moisture in the salt absorbed from surrounding gas. When the humidity is low, there is small current flow, and the temperature rise of the winding is small. When the humidity is high, a high current flows through the winding causing large heat to be generated and the temperature of the cell is high. The thermometer placed inside the metal tube measures the cell temperature, and therefore absolute humidity or dew point.

This instrument can be used for measuring dew point with an accuracy of ± 2%. The main advantage of this dew point instrument are its *simplicity* and *fast response*.

Second Method

This method determines the temperature at which moisture condenses by impinging a jet of the gas (whose dew point is to be measured) on a mirror and finding the exact temperature at which the surface becomes cloudy. This method is shown in Fig. 11.25. Automatic control can be used by having feedback.

The gas is supplied continuously. This dew point recorder is provided with arrangements for both cooling and heating of the mirror. Light falling on the mirror from a standard light source is reflected on a photo-tube. Another photo-tube receives light straight from the source. The outputs of tubes are then compared by a comparator. If the mirror is foggy due to condensation an error signal is sent and the heater starts functioning and the refrigerator is turned off. If the condensation has not started, the heater is shut off and the refrigerator turned is on. The cycle continues. Thus, the temperature of the mirror tells about the temperature necessary to condense the gas. The temperature is sensed by a thermocouple. The temperature is measured and recorded by a suitable device.

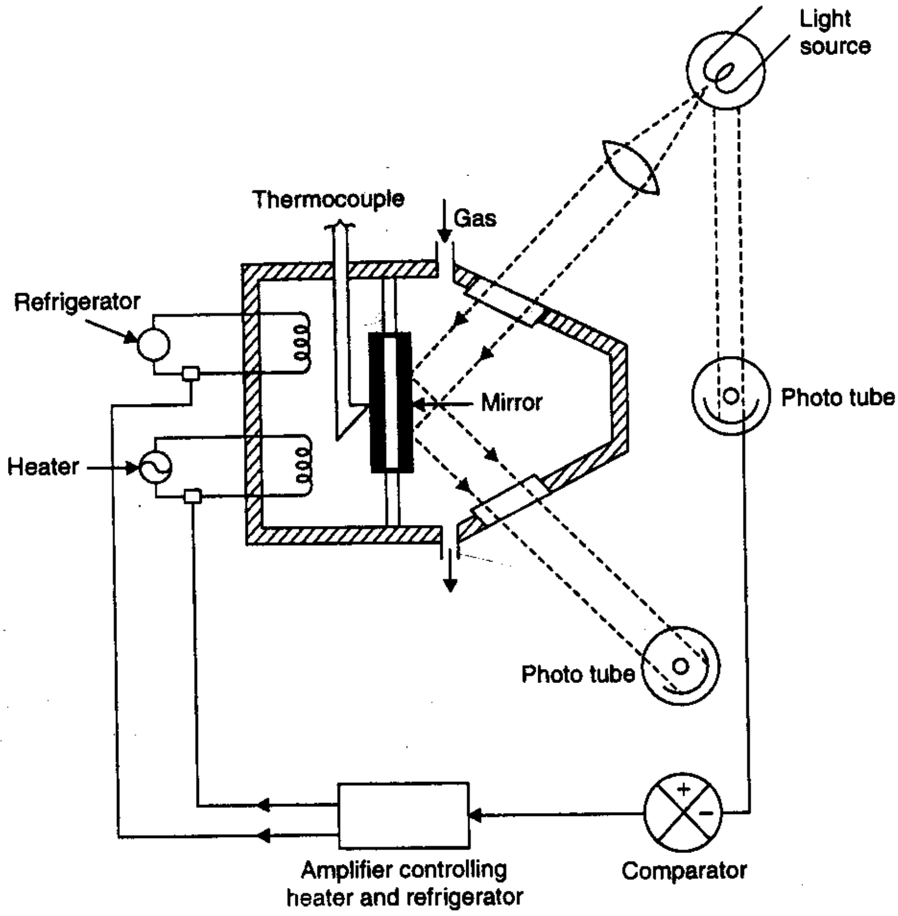

Fig. 11.25. Schematic diagram of dew point recorder.

11.10. IMPURITY MEASURING INSTRUMENTS

The following impurities may be present in the *feed water* used in a boiler to generate steam :

1. Sodium chlorides and other chlorides
2. Calcium sulphate and other sulphates
3. CO_2 from evaporators
4. Silica from dust etc.
5. Oxygen from air in condenser etc.
6. Metallic pieces picked up by steam while passing through pipes.

The above mentioned impurities should be kept to the *minimum.*

Fig. 11.26 shows *dionic water purity meter.*

— *It works on the principle that the electrical conductivity of an electrolyte dissolved in water depends on the amount of salt in solution i.e., the extent of impurity.*

The resistance between the opposite faces of a cube of standard water in the instrument is *compared* with the resistance when the water contains more impurities.

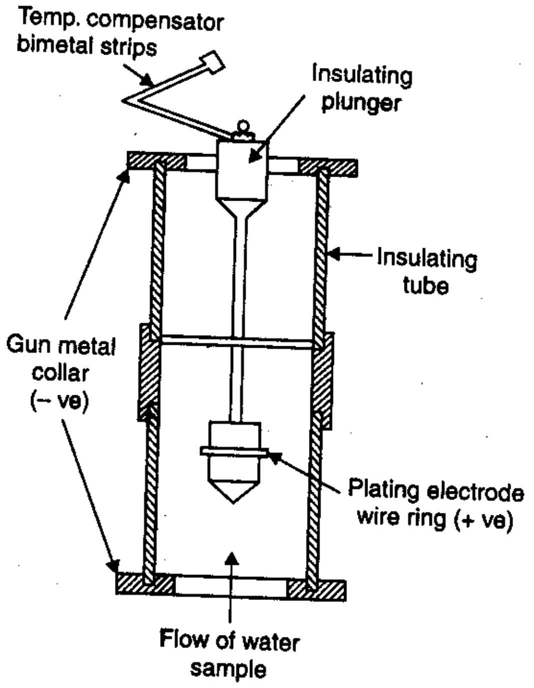

Fig. 11.26. Dionic water purity meter.

- A sample of water, in this water, is allowed to flow through it. The automatic correction for temperature variation is effected by the plunger. The insulating plunger varies water cross-section automatically by temperature compensator to give correction to 20°C.
- Conductivity is measured of two water columns in between rings and gunmetal collars. *The conductivity per cm^3 indicated is the reciprocal of the resistance measured.* The standard of reference is the resistance of one megaohm between opposite faces of a cm^3 of solution.
- Dionic readings of condensate and feed water at various points of flow are brought to one control point, connections to the meter being provided by special piping. By this arrangement the source of contamination can be speedily located.

11.11. SPEED MEASURING INSTRUMENTS

The following instruments are used for measuring speed :

1. Vibrating reed tachometer
2. Clock type tachometer
3. Stroboscope
4. Revolutions counter.

11.12. STEAM CALORIMETERS AND FUEL CALORIMETERS

11.12.1. Steam Calorimeters

The *dryness fraction of steam* can be measured by using following calorimeters :

1. Tank or bucket calorimeter.

2. **Throttling calorimeter.**
3. **Separating and throttling calorimeter.**

11.12.1.1. Tank or bucket calorimeter

The dryness fraction of steam can be found with the help of tank calorimeter as follows :

A known mass of steam is passed through a known mass of water and steam is completely condensed. The heat lost by steam is equated to heat gained by the water.

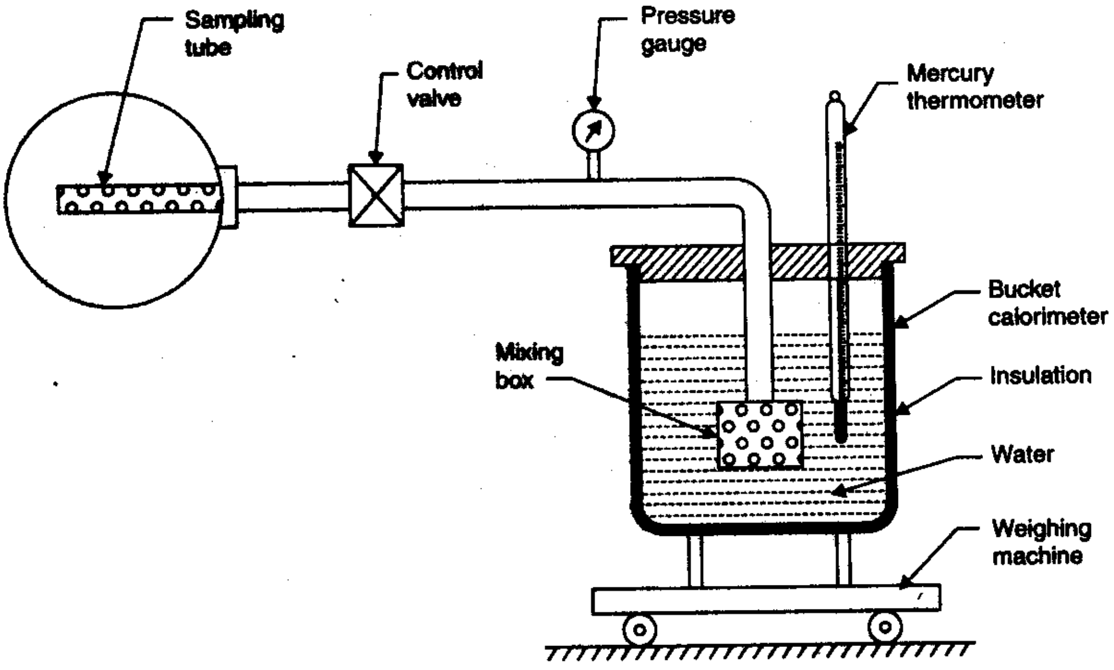

Fig. 11.27. Tank or bucket calorimeter.

Fig 11.27 shows the arrangement of this calorimeter.

The steam is passed through the sampling tube into the bucket calorimeter containing *a known* mass of water.

The weight of calorimeter with water before mixing with steam and after mixing the steam are obtained by weighing.

The temperature of water before and after mixing the steam are measured by *mercury thermometer*.

The pressure of steam passed through the sampling tube is measured with the help of *pressure gauge*.

Let p_s **= Gauge pressure of steam (bar),**

p_a **= Atmospheric pressure (bar),**

t_s **= Saturation temperature of steam known from steam table at pressure** $(p_s + p_a)$**,**

h_{fg} **= Latent heat of steam,**

x **= Dryness fraction of steam,**

c_{pw} **= Specific heat of water,**

c_{pc} **= Specific heat of calorimeter,**

m_c = Mass of calorimeter, kg,

m_{cw} = Mass of calorimeter and water, kg,

$m_w = (m_{cw} - m_c)$ = Mass of water in calorimeter, kg,

m_{cws} = Mass of calorimeter, water and condensed steam, kg,

$m_s = (m_{cws} - m_{cw})$ = Mass of steam condensed in calorimeter, kg,

t_{cw} = Temperature of water and calorimeter before mixing the steam, °C, and

t_{cws} = Temperature of water and calorimeter after mixing the steam, °C.

Neglecting the losses and *assuming* that the ***heat lost by steam is gained by water and calorimeter***, we have

$$(m_{cws} - m_{cw})\,[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$

$$= (m_{cw} - m_c)\,c_{pw}\,(t_{cws} - t_{cw}) + m_c\,c_{pc}\,(t_{cws} - t_{cw})$$

$$\therefore \quad m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})\,[m_{cw} - m_c)(c_{pw} + m_c\,c_{pc}]$$

or

$$m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})(m_w c_{pw} + m_c c_{pc}) \quad \text{...(11.1)}$$

The $m_c c_{pc}$ is known as *water equivalent of calorimeter*.

The value of dryness fraction 'x' can be found by solving the above equation.

The value of dryness fraction found by this method involves some *inaccuracy* since losses due to convection and radiation are not taken into account.

The calculated value of dryness fraction neglecting losses is always less than the actual value of the dryness.

11.12.1.2. Throttling calorimeter

The dryness fraction of wet steam can be determined by using a throttling calorimeter which is illustrated diagrammatically in Fig. 11.28.

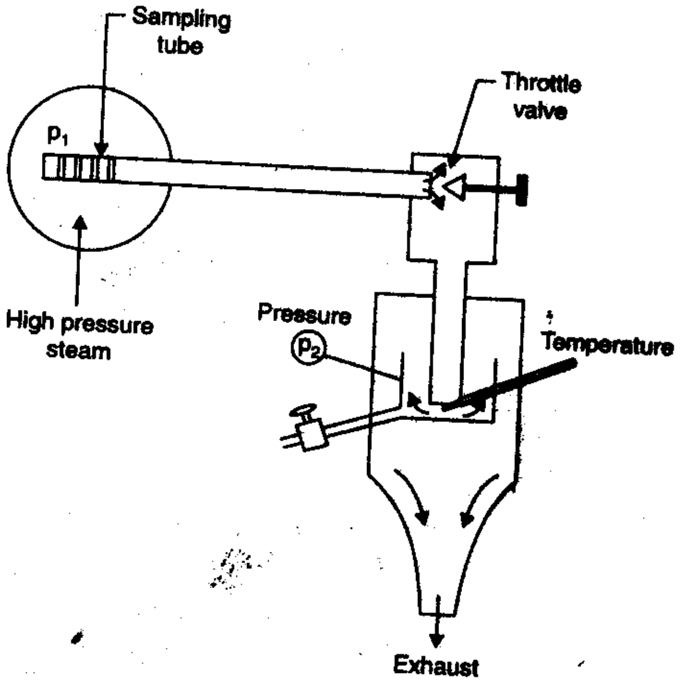

Fig. 11.28. Throttling calorimeter.

The steam to be sampled is taken from the pipe by means of suitably positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. Here the temperature is taken and the steam ideally should have about 5.5 K of superheat.

The throttling process is shown on *h-s* diagram in Fig. 11.29 by the line 1-2. If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will become superheated. State 2 can then be defined by the *measured pressure and temperature*. The enthalpy, h_2 can then be found and hence

$$h_2 = h_1 = (h_{f_1} + x_1 h_{fg_1}) \text{ at } p_1$$

[where $h_2 = h_{f_2} + h_{fg_2} + c_p(T_2 - T_{s_2})$]

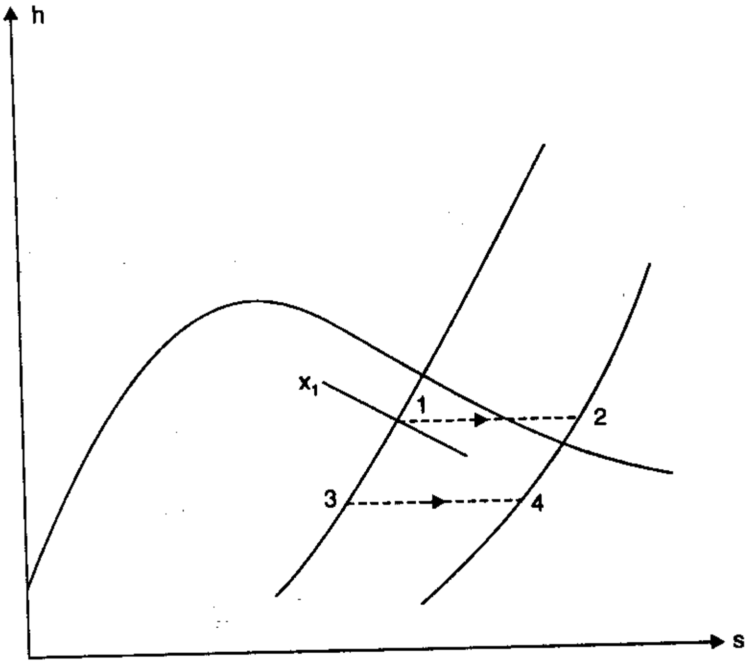

Fig. 11.29. Throttling process.

$$\therefore \qquad x_1 = \frac{h_2 - h_{f_1}}{h_{fg_1}} \qquad \text{...(11.2)}$$

Hence the dryness fraction is determined and state 1 is defined.

11.12.1.3. Separating and throttling calorimeter

If the steam whose dryness fraction is to be determined is *very wet* then throttling to atmospheric pressure *may not be sufficient to ensure superheated steam at exit*. In this case it is *necessary to dry the steam partially, before throttling*. This is done by *passing the steam sample from the main through a separating calorimeter* as shown in Fig. 11.30. The steam is made to change direction suddenly, and the water, being denser than the dry steam is separated out. The quantity of water which is separated out (m_w) is measured at the separator, the steam remaining, which *now has a higher dryness fraction*, is passed through the *throttling calorimeter*. With the combined separating and throttling calorimeter it is *necessary* to condense the steam after throttling and measure the amount of condensate (m_s). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient.

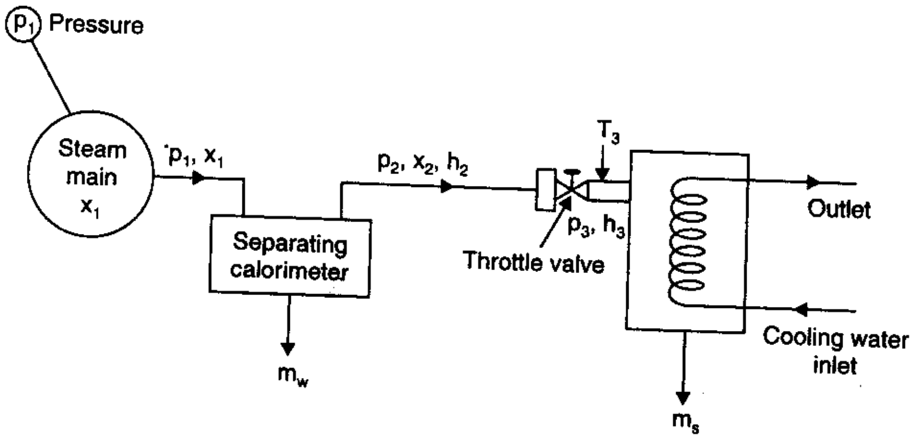

Fig. 11.30. Separating and throttling calorimeter.

Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the separating calorimeter is equal to $x_2 m_s$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

$$\text{Hence fraction in main, } x_1 = \frac{\text{Mass of dry vapour}}{\text{Total mass}} = \frac{x_2 m_s}{m_w + m_s}.$$

The dryness fraction, x_2, can be determined as follows :

$$^*h_3 = h_2 = h_{f_2} + x_2 h_{fg_2} \text{ at } p_2 \; [^*h_3 = h_{f_3} + h_{fg_3} + c_p(T_{sup} - T_{s_3}) \text{ a pressure } p_3]$$

or $$x_2 = \frac{h_3 - h_{f_2}}{h_{fg_2}}$$

The values h_{f_2} and h_{fg_2} are read from tables at pressure p_2. The pressure in the separator is small so that p_1 is approximately equal p_2.

11.12.2. Fuel Calorimeters

11.12.2.1. Bomb calorimeter

The calorific value of solid and liquid fuels is determined in the laboratory by *'Bomb Calorimeter'*. It is so named because its shape resembles that of a bomb. Fig. 11.31 shows the schematic sketch of a bomb calorimeter.

The calorimeter is made of austenitic steel which provides considerable resistance to corrosion and enables it to withstand high pressure. In the calorimeter is a strong cylindrical bomb in which combustion occurs. The bomb has two valves at the top. One supplies oxygen to the bomb and other releases the exhaust gases. A crucible in which a weighed quantity of fuel sample is burnt is arranged between the two electrodes as shown in the Fig. 11.31. The calorimeter is fitted with water jacket which surrounds the bomb. To reduce the losses due to radiation, calorimeter is further provided with a jacket of water and air. A stirrer for keeping the temperature of water uniform and a thermometer to measure the temperature up to an accuracy of 0.001°C are fitted through the lid of the calorimeter.

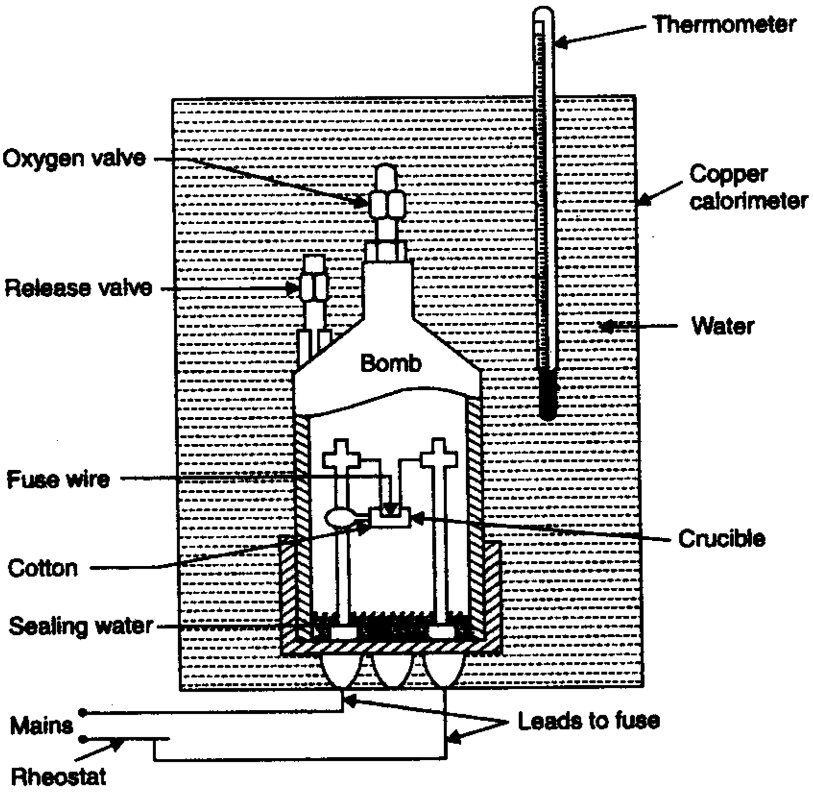

Fig. 11.31. Bomb calorimeter.

Procedure. To start with, about 1 gm of fuel sample is accurately weighed into the crucible and a fuse wire (whose weight is known) is stretched between the electrodes. It should be ensured that wire is in close contact with the fuel. To absorb the combustion products of sulphur and nitrogen 2 ml of water is poured in the bomb. Bomb is then supplied with pure oxygen through the valve to an amount of 25 atmosphere. The bomb is then placed in the weighed quantity of water, in the calorimeter. The stirring is started after making necessary electrical connections, and when the thermometer indicates a steady temperature fuel is fired and temperature readings are recorded after 1/2 minute intervals until maximum temperature is attained. The bomb is then removed ; the pressure slowly released through the exhaust valve and the contents of the bomb are carefully weighed for further analysis.

The heat released by the fuel on combustion is absorbed by the surrounding water and the calorimeter.

From the above data the calorific value of the fuel can be found in the following way :

Let w_f = weight of fuel sample (kg)

w = weight of water (kg)

C = calorific value (higher) of the fuel (kJ/kg)

w_e = water equivalent of calorimeter (kg)

t_1 = internal temperature of water and calorimeter

t_2 = final temperature of water and calorimeter

t_c = radiation corrections.

Heat released by the fuel sample = $w_f \times C$.

Heat received by water and calorimeter

$$= (w + w_e)\,[(t_2 - t_1) + t_c]$$

Heat lost = heat gained

$$w_f \times C = (w + w_e)[(t_2 - t_1) + t_c]$$

$$C = \frac{(w + w_e)(t_2 - t_1) + t_c}{w_f} \text{ kJ/kg} \qquad ...(11.3)$$

Note 1. Corrections pertain to the heat of oxidation of fuse wire, heat liberated as a result of formation of sulphuric and nitric acids in the bomb itself.

2. It should be noted that *bomb calorimeter measures the higher or gross calorific value because the fuel sample is burnt at a constant volume in the bomb.* Further the bomb calorimeter will measure the H.C.V. directly if the bomb contains adequate amount of water before firing to saturate the oxygen. Any water formed from combustion of hydrogen will, therefore, be condensed.

The procedure of determining calorific values of liquid fuels is similar to that described above. However, if the liquid fuel sample is volatile, it is weighed in a glass bulb and broken in a tray just before the bomb is closed. In this way the loss of volatile constituents of fuels during weighing operation is prevented.

11.12.2.2. Junker's gas calorimeter

The calorific value of gaseous fuels can be determined by junker's gas calorimeter.

Fig. 11.32. illustrates Junker's gas calorimeter. Its principle is somewhat similar to Bomb calorimeter ; in respect that heat evolved by burning the gas is taken away by the water. In its simplest construction it consists of a combustion chamber in which the gas is burnt (in a gas burner). A water jacket through which a set of tubes called flues pass surrounds this chamber. Thermometers are incorporated at different places (as shown in Fig. 11.32) to measure the temperatures.

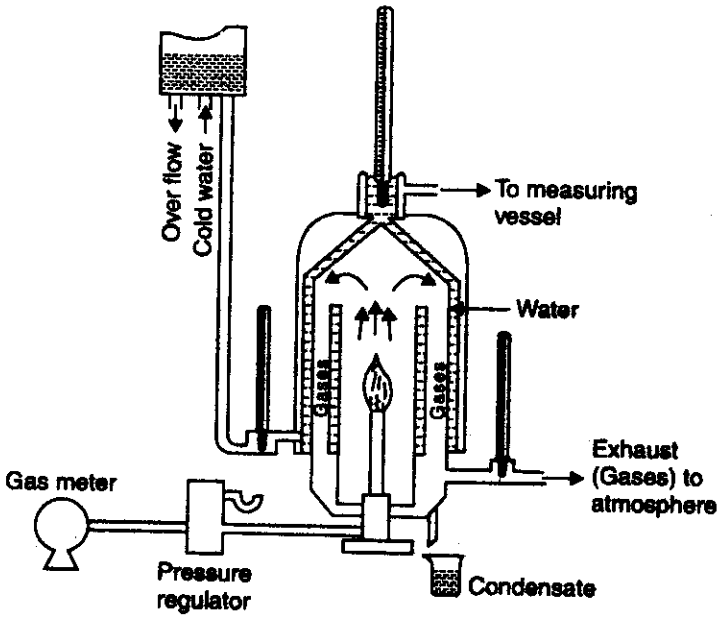

Fig. 11.32. Junker's gas calorimeter.

Procedure. A metered quantity of gas whose calorific value is to be determined is supplied to the gas burner *via* a gas meter which records its volume and a gas pressure regulator which measures the pressure of the gas by means of a manometer. When the gas burns the hot product of combustion travels upwards in the chamber and then downwards through the flues and finally escape to the atmosphere through the outlet. The temperature of the escaping gas is recorded by the thermometer fitted at the exit and this temperature should be as close to room temperature as possible so that entire heat of combustion is absorbed by water. The cold water enters the calorimeter near the bottom and leaves near the top. Water which is formed by condensation of steam is collected in a pot.

The quantity of gas used during the experiment is accurately measured by the meter and temperature of ingoing and outgoing water are indicated by the thermometers. From the above data the calorific value of the gas can be calculated.

Note 1. The volume of gas used during the experiment should be converted to volume at S.T.P. (standard temperature and pressure) *i.e.*, 15°C, 760 mm respectively.

2. The gross calorific value is obtained by dividing the heat given out by corrected volume of gas. The net or lower calorific value of the gas is obtained by subtracting from total heat the heat associated with condensed water (which is obtained by multiplying the weighed condensate by latent heat of vapourisation of water).

HIGHLIGHTS

1. Commonly used instruments in a power plant are :
   (*i*) Pressure gauges (*ii*) Thermometers (*iii*) Liquid level gauges (*iv*) Flow meters (*v*) pH measuring instruments (*vi*) Gas analysers (*vii*) Humidity measuring instruments (*viii*) Impurity measuring instruments (*ix*) Speed measuring instruments (*x*) Steam calorimeters and fuel calorimeters (*xi*) Gong alarms.
2. Low pressures are generally determined by *manometers* which employ liquid columns.
3. A Bourbon type tube pressure gauge is used for measuring high as well as low pressures.
4. A transducer is device for converting a signal of one sort into the other type.
5. Temperature can be defined as a thermal state which depends upon the internal or molecular energy of the body.
6. A resistance thermometer is used for precision measurements below 150°C.
7. An optical pyrometer works on the principle that matters glow above 480°C and the colour of visible radiation is proportional to the temperature of the glowing matter.
8. The hygrometer is an instrument which measures humidity directly.
9. The psychrometer is a humidity measuring instrument which utilizes one wet bulb thermometer and other dry bulb thermometer.
10. Dionic water purity meter works on the principle that the electrical conductivity of an electrolyte dissolved in water depends on the amount of salt in solution *i.e.*, the extent of impurity.
11. The dryness fraction of steam can be measured by using the following calorimeters :
    (*i*) Tank or bucket calorimeter
    (*ii*) Throttling calorimeter
    (*iii*) Separating and throttling calorimeter.

THEORETICAL QUESTIONS

1. List the functions which the various types of instruments in a power plant have to perform.
2. How are instruments classified ?
3. What is the difference between gauge pressure and absolute pressure ?
4. Enumerate various types of pressure measurement devices.

5. Explain briefly the following :
   (*i*) U-tube manometer
   (*ii*) Micro-manometer.
6. Describe briefly the following pressure gauges :
   (*i*) Bourdon tube pressure gauge
   (*ii*) Diaphragm gauge.
7. Explain briefly the following :
   (*i*) Electrical transducers
   (*ii*) Electromagnetic transducers.
8. How is temperature defined ?
9. How are temperature measurements made ?
10. How are thermometers classified ?
11. Explain briefly the following :
    (*i*) Bimetallic thermometers
    (*ii*) Liquid filled thermometers
    (*iii*) Gas-filled thermometers.
12. Write a short note on resistance thermometers.
13. Explain with a help of a neat sketch the construction and working of a radiation pyrometer.
14. What are the advantages of pyrometers ?
15. State the principle on which an optical pyrometer works.
16. Describe with the help of a neat sketch an optical pyrometer.
17. Explain briefly the following liquid level gauges :
    (*i*) Gauge glass
    (*ii*) Electrical level gauges.
18. Write a short note on 'Flow meters'.
19. Explain the procedure for measuring CO_2 content in the gases.
20. What is humidity ? How can it be measured ?
21. Give the description of resistive hygrometer.
22. How can the dryness fraction of steam determined by the following ?
    (*i*) Tank or bucket calorimeter
    (*ii*) Separating and throttling calorimeter.

12

Major Electrical Equipment in Power Plants

12.1. Introduction. 12.2. Generating equipment—Classification—Two-wire direct current generators—Alternator-current generators. 12.3. Transformers—General aspects—Basic definitions—Working principle of a transformer—Transformer ratings—Kinds of transformers—Transformer construction—Transformer windings, terminals, tappings and bushings—Transformer Cooling—Three phase transformer—Instrument transformers—Constant-current transformers. 12.4. Switchgear—Functions of a switchgear—Switches—Fuses—Circuit breakers—Types of switchgear 12.5. Protection of electrical systems—General aspects— Different types of relays—Alternator protection—Transformer protection—Bus protection—Protection of transmission lines. 12.6. Short circuits in electrical installations and limiting methods. 12.7. Control room. 12.8. Earthing of a power system. 12.9. Electrical equipment-layout. 12.10. Voltage regulation. 12.11. Transmission of electric power—Systems of transmission—Line supports—Conductor material—Line insulators—Distribution systems—Underground cables. 12.12. Substations—Classification of substations. 12.13. Indian Electricity Act—Highlights—Theoretical Questions—Competitive Examinations Questions.

12.1. INTRODUCTION

In different types of power plants such as thermal power plant, hydro-power plant, nuclear power plant etc. the electricity is generated. A number of electrical equipments which are available in a power plant are listed below :

1. Generators
2. Excitors
3. Transformers
4. Reactors
5. Circuit breakers
6. Switchgear and protective equipment
7. Control board equipment
8. Busbars
9. Standby generators etc.