CHAPTER 3

SOLAR RADIATION

3.1 SOURCE OF RADIATION

The source of solar radiation reaching the earth is a yellow star known as the Sun. It is a huge sphere of hot gaseous matter with a diameter of 1.39 x 10^9 m and is about 1.5 x 10^{11} m away from the Earth. The sun weights 2 x 10^{30} kgs and has luminosity of 3.8 x 10^{26} W. The basic structure of the sun is as shown in Fig. 3.1. About 90% of the total energy generated is from a region of 0 to 0.23 R (where R is the radius of Sun) which contains 40% of the total mass. The temperature inside this region is of the order of 8-40 x 10^6 degree C. This temperature drops down to around 5000 degree C at the surface of the sun, which is called the photosphere (upper layer of convective zone from 0.7 to 1.0 R) and is the source of most solar radiations[1].

The Sun is in effect a continuous fusion reactor with its constituent gases retained by the gravitational forces. Hydrogen (H_2) and Helium(He) appear to constitute in equal proportions. It is thus assumed that certain nuclear process involving these two gases may be the actual source of solar energy.

The basic fusion reaction is assumed to be the fusion of 4 protons (light nucleus) together to yield one helium (heavy nucleus) and 2 positrons alongwith the emission of about

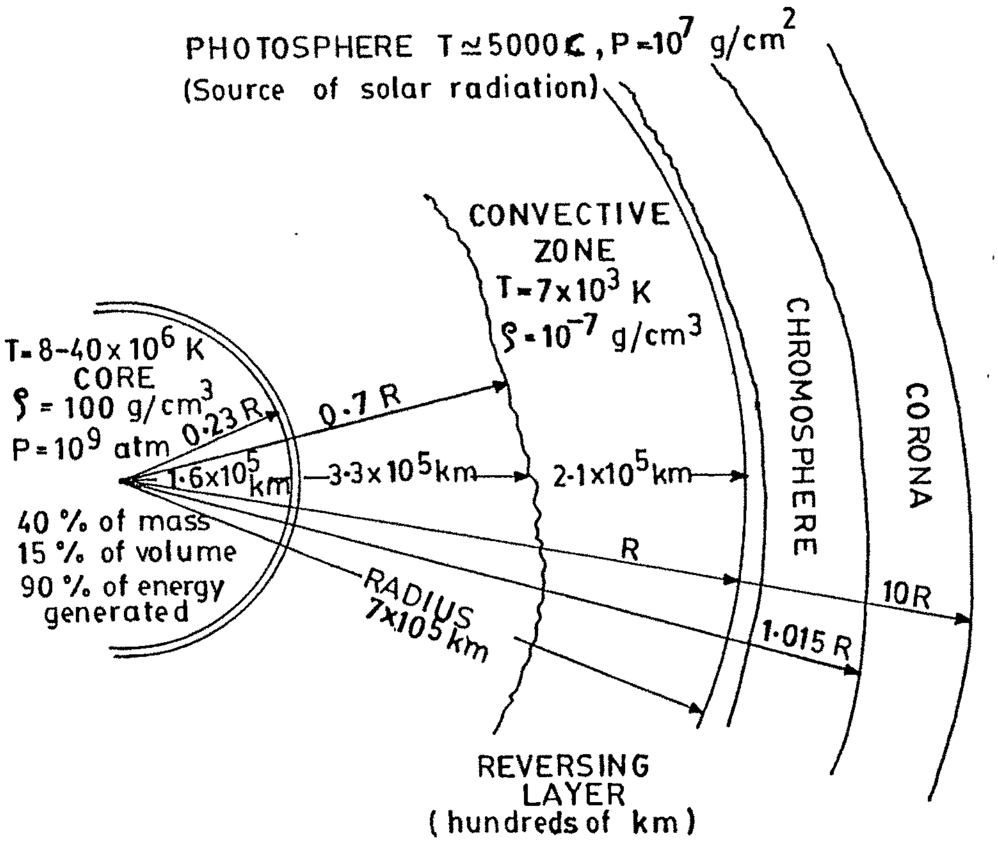

Fig. 3:1 Schematic drawing of the structure of the Sun.

26.7 MeV of energy as a result of mass reduction[2]. This means that when one gram of He is formed, an energy nearly equal to 4.4×10^{24} MeV is released which is equivalent to 1.5×10^5 kWh of electrical energy. Calculations based on the rate at which energy is generated from the Sun (ie. 3.9×10^{16} W) show that 2×10^{19} kg of H_2 is converted into He annually. The total mass of H_2 in the sun is estimated to be about 2×10^{30} kg. In order that it may loose 5% of the mass, it will continue to emit this energy for about five billion years. Thus the source of radiation may almost be considered as inexhaustible.

The brightness of the sun varies from its centre to the edge. However, for general calculations it is assumed that the brightness is uniform all over the solar disk. As viewed from the earth, the radiation coming from the Sun appears to be essentially equivalent to that coming from a black surface at 5487 degree C.

3.2 EXTRATERRESTRIAL RADIATION

The Earth revolves around the Sun and the eccentricity of its orbit is such that the distance between the Sun and the Earth varies by 1.7%. The energy from the Sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation at the Earth's mean distance from the Sun (i.e. 1.495×10^{11} m) outside the atmosphere is called the Solar Constant. The value of the Solar Constant has been the subject of extensive investigations and its standard value is estimated to be 1353 W/sq m[3]. This is also called the extraterrestrial solar radiation, i.e. the radiation in the absence of atmosphere. It may be noted that the maximum value of 2074 W/sq m occurs at a wavelength of 48A (Fig. 3.2) and most of the solar radiation is obtained within a wavelength of 20 and 260 A. The wave length region upto 40 A is called the ultraviolet range; 40 to 70 A the visible range and above 70 A the infrared range.

The spectral irradiance of a black body at 5487 degree C is also shown in Fig. 3.2. As can be seen, the solar spectrum is quite similar to the black body spectrum.

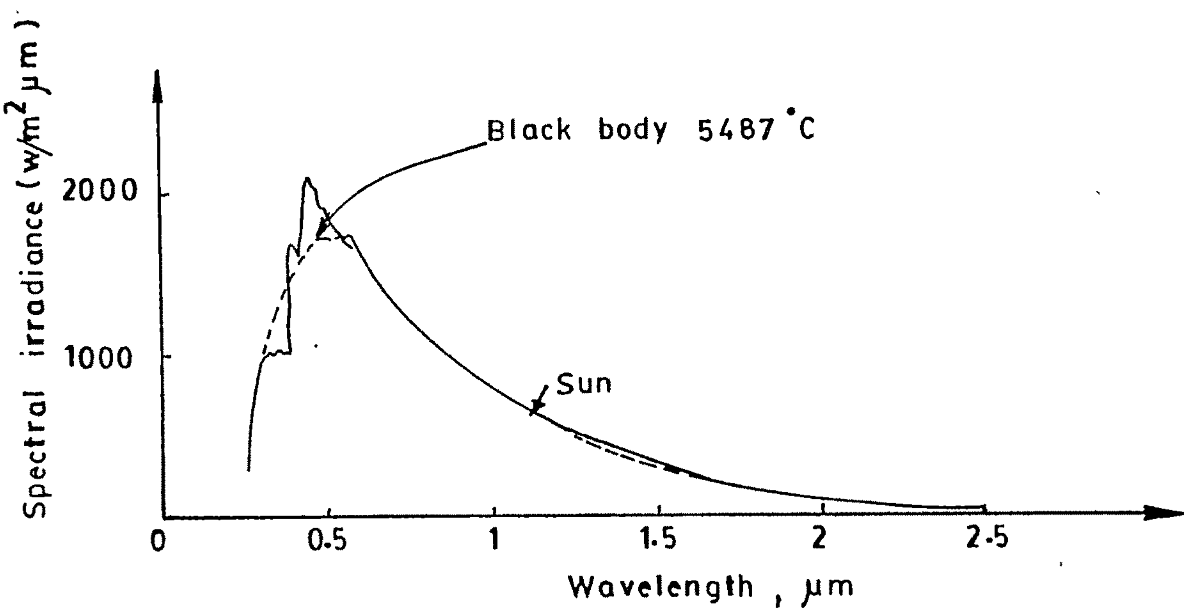

Fig. 3·2 Standard spectral irradiance of the Sun at a distance of $1{\cdot}495 \times 10^{11}$ m (average Sun-Earth distance)

3.3 RADIATION AT EARTH'S SURFACE

Solar radiation is received at the Earth's surface after being subjected to the mechanisms of attenuation, reflection, absorption and scattering in the Earth's atmosphere due to the presence of ozone layer, water vapour, carbon dioxide, dust and various gases. The radiation received without any change of direction is called the beam or direct radiation. The radiation received after scattering and reflection etc. is called the diffused or indirect radiation. The sum of the beam and diffused radiation is called the total or global radiation.

Since the global radiation reaches the Earth's surface after passing through the atmosphere, it's amount is reduced in comparison to the Solar Constant and is approximately about 1000 W/sq m in the plane perpendicular to solar radiation. As the Sun is very large and very far from the Earth, the solar energy reaches the earth in the form of collimated beam of electromagnetic radiation, with a total angular spread of about half a degree as shown in Fig. 3.3.

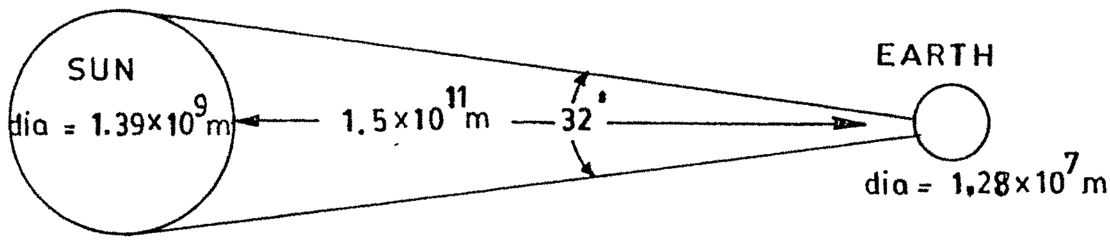

Fig.3·3 Schematic drawing (not to scale) of the Sun-Earth geometrical relationship.

3.4 THE EARTH

For all practical purpose the earth is considered to be a sphere of diameter nearly 12,800 kms but in reality it is a sphere flattened at the poles and bulging in the plane normal to the poles. The earth rotates once on its axis in

24 hrs and completes a revolution around the sun in 365.25 days (3). The earth makes an ellipse around the sun, with the sun being at one of the foci. About 1st January, the earth is closest to the Sun and on 1st July it is most remote, being about 3.3% further away.

The earth's axis of rotation is tilted at 23.5 degree with respect to the orbit around the Sun. During the yearly revolution, the earth's axis of rotation remains in the same direction as shown in Fig. 3.4. This tilted position of the earth alongwith its daily rotation and yearly revolution effect the day and night conditions, changing duration of day and night and the changing seasons. Fig. 3.4 also shows the effect of the earth's titled axis at various times of the year and Fig. 3.5 shows the position of the earth, relative to Sun's rays at the time of winter solstice and summer solstice.

3.5 BASIC EARTH SUN ANGLES

As explained earlier, the earth is continuously rotating and revolving which result in the apparent movement of the sun across the sky. Due to this, an understanding of the relative position of the sun at a given time is of paramount importance to the solar scientist. For a complete specification of the sun's position in the sky at a particular time, two angles are defind, namely the solar

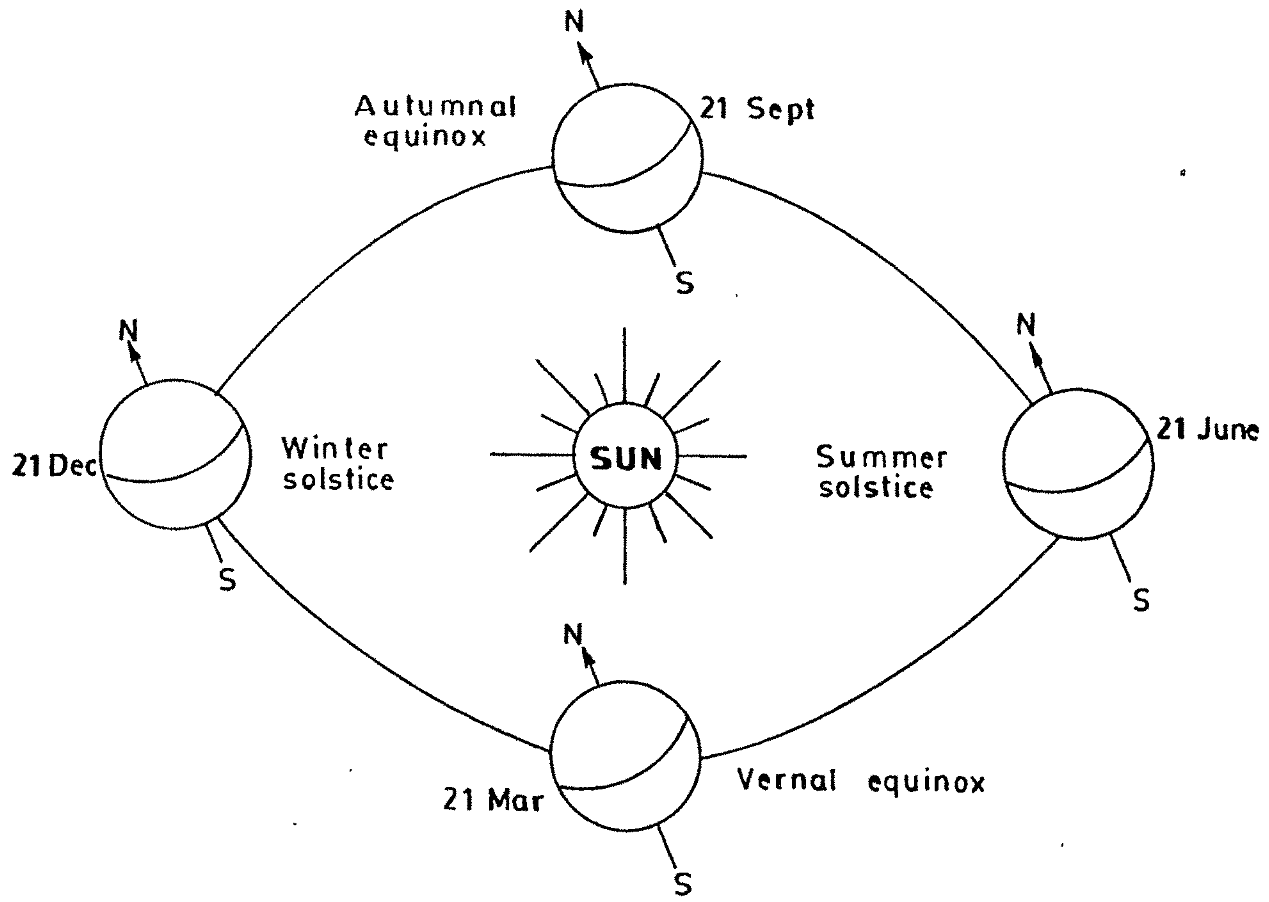

Fig. 3·4 Positions of the earth with respect to the sun at solstices and equinoxes.

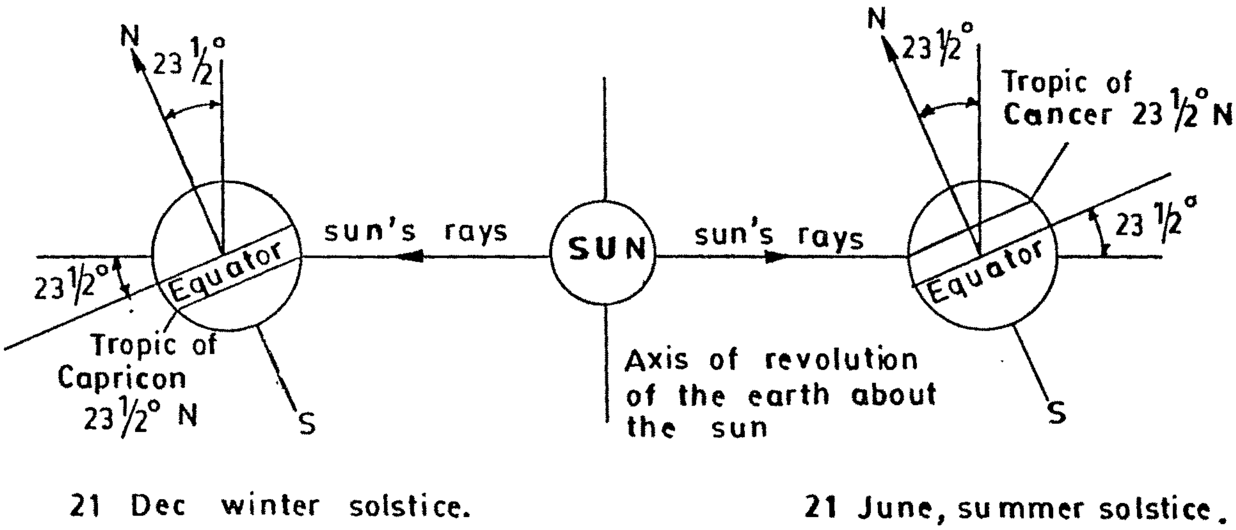

Fig. 3·5 Summer and winter solstice

altitude and solar azimuth. Daily the sun appears to be moving across the sky from east to west following the path of a circular arc, which is longer in summer than in winter. Fig. 3.6 shows the solar path for one day. The solar

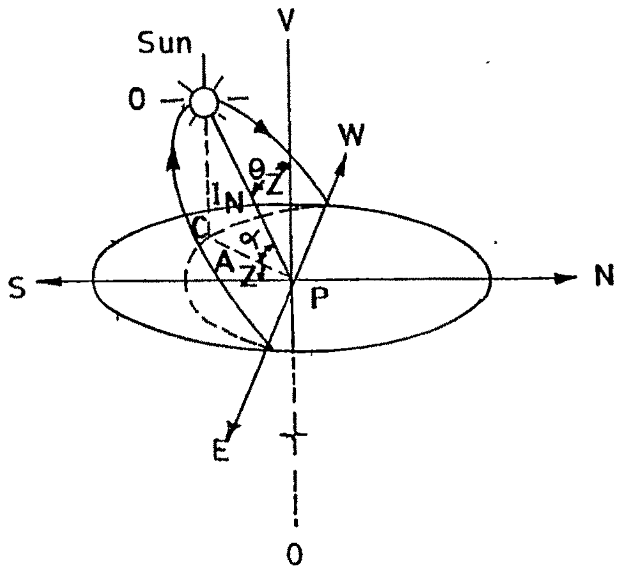

Fig. 3·6 Solar path for one day

altitude angle (α) is defined as the angle in a vertical plane between the sun's rays and the horizontal projection of the sun's rays. The azimuth angle (Az) is the angle in the horizontal plane measured from south to the horizontal projection of the sun's rays. A third angle called Zenith angle (θ_z) is the angle between the sun's rays and a line perpendicular to the horizontal plane. It can be seen from Fig. 3.6 that the sum of solar altitude angle and zenith angle is equal to 90 degrees. To specify a location on the surface of the earth, one needs to know the Latitude 'La' and Longitude ' ϕ ' of the place. The Latitude of a place is the angle between the line joining the place with the centre of the earth and the equator plane. It is designated as north positive and south negative. The longitude angle is the angle between the meridian of a place and the prime meridian passing through the observatory at Greenwich, United Kingdom. Longitudes are measured 0 to 180 degree east of Greenwich or 0 to 180 degree west of Greenwich.

The angular displacement of the sun from the plane of the earth's equator is called the Declination of the sun . This angle varies between + 23.5 degrees and - 23.5 degrees as the earth revolves around the sun. The latitude at $\pm$ 23.5 degree, the Tropics of Cancer and Capricorn (Fig.3.5) enclose the only region on earth where the sun's rays strike normal to its surface sometime during the year. The declination angle can be approximately determined from the Cooper equation in Duffie & Backman[1].

$$\delta = 23.45 \text{ Sin } \left(360 \frac{284 + n}{365}\right) \qquad \ldots\ldots\ldots\ldots(3.1)$$

where n is the day of the year, $1 \leqslant n \leqslant 365$.

Hour angle ω is the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15 degrees per hour; solar noon being zero, morning positive and afternoon negative.

3.6 SOLAR TIME AND THE EQUATION OF TIME

In any time zone, the standard time is measured with respect to a standard meridian, and all watches in that time zone are tuned to show the same time. Indian Standard Time (IST) is measured for the meridian 82.5 degree E passing through Allahabad. Hence to find out the local solar time, a correction needs to be applied to the standard time. Besides this a second correction called the equation of time is needed which takes into consideration the perturbations in the rate of rotation. This correction is based on experimental observations and is plotted in Fig. 3.7.

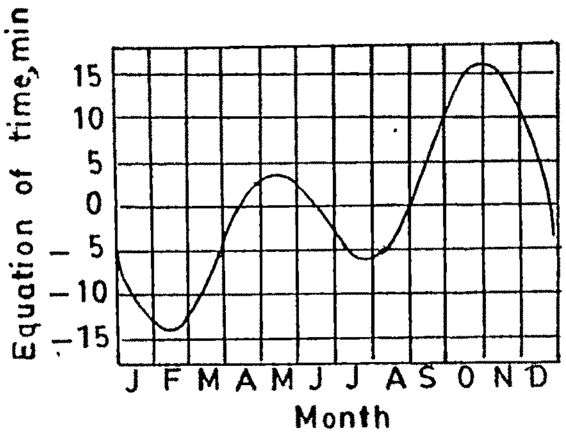

Fig.3·7 The equation of time

Thus,

$$\text{Local Solar Time} = \text{Standard time} + 4\ (\text{La st} - \text{La loc}) + \text{Et} \quad \ldots.(3.2)$$

Where,

La st = Standard meridian

La loc = Longitude of the location in degrees west

Et = Equation of time

Equation of time can also be calculated as follows :

$$Et = 9.87 \text{ Sin } 2B - 7.53 \text{ Cos } B - 1.5 \text{ Sin } B \quad \ldots\ldots(3.3)$$

Where

$$B = \frac{360\ (n - 81)}{364}$$

n = day of the year, $1 \leqslant n \leqslant 365$

Since the earth rotates anti-clockwise, local time of the east leads the local time of the west.

3.7 COMPUTATION OF SOLAR RADIATION

Various agencies collect meteorological data which include solar radiation on a regular basis at many locations in the world. In India this is mainly done by the Indian Meteorological Department (IMD) and the information is published in various forms (6,7,8). By being careful in selecting the correct information from this publications, one can get reasonally accurate information to help in designing solar energy systems or for evaluating the expected performance of an established device.

Such published information may not be sufficient for actually developing a product or for experimentally evaluating the performance of an existing product. In such situations, one needs to measure the required data using the right instruments.

Pyranometer is a highly sensitive instrument which measures the intensity of the total solar radiation. The instrument has a hemispherical field of view. An integrator, recorder, datalogger or a simple milli-voltmeter can be connected to the pyranometer as the output device. Usually pyranometers are installed on horizontal surfaces, but these can also be used on tilted surfaces. Pyranometer can be employed to measure only the diffused radiation by installing a shading ring over it. By adjusting the shading ring, the direct radiation can be shaded from falling on the sensor of the instrument. Fig. 3.8 shows a pyranometer installed with a shading ring. By employing two pyranometers one with shading ring and the other without, diffused, direct and total solar radiation can be estimated.

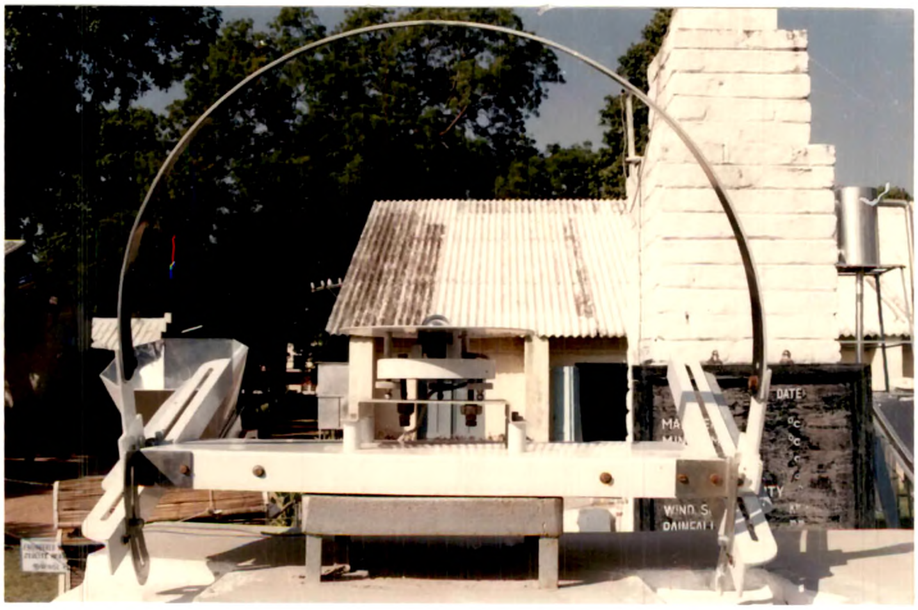

Fig. 3.8 : Pyranometer with shading ring

In order to actually measure direct solar radiation, an instrument called pyrheliometer shown in Fig. 3.9 is used.

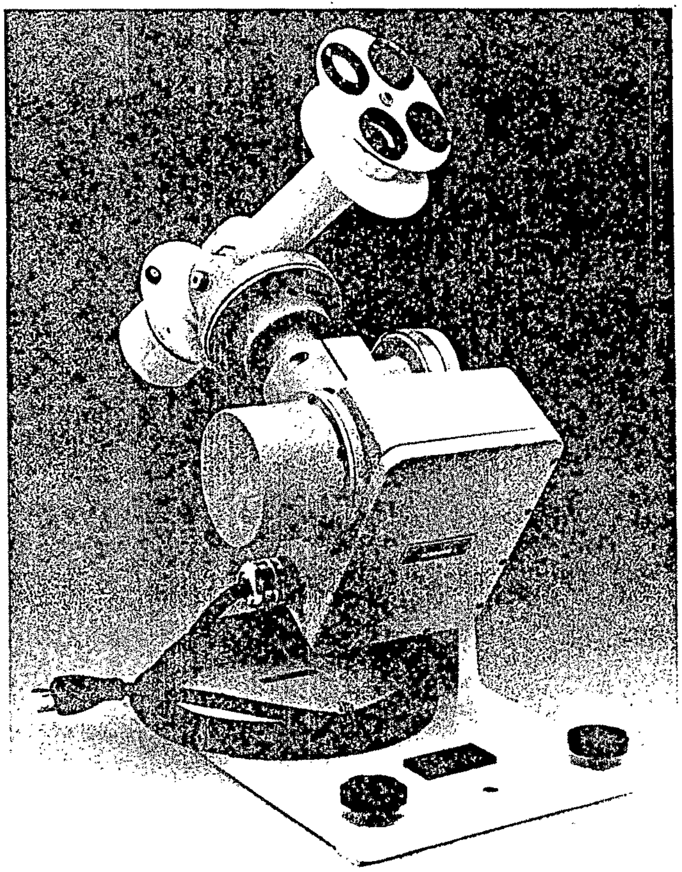

Fig. 3.9 : Pyrheliometer with auto tracking arrangement

The instrument has a telescopic arrangement to house the sensor. The teliscope needs to be directed towards the sun for measurement. If continuous measurement is required, the pyrheliometer can be mounted on a tracking arrangement. A separate readout system is essential for data collection. Optical filters are used with a pyrheliometer to obtain solar radiation in different wave length regions.

To measure the duration of sun shine in a day, an instrument called Sun Shine Recorder is used. The instrument consists of a high quality glass sphere mounted in a section of a spherical bowl. A special chart needs to be placed daily in the bowl. Solar radiation falling on the sphere is focused on the chart. During bright sun shine, it burns a path on the chart. From the chart one can find out the total number of hours with bright sun shine. Fig. 3.10 shows the sun shine recorder.

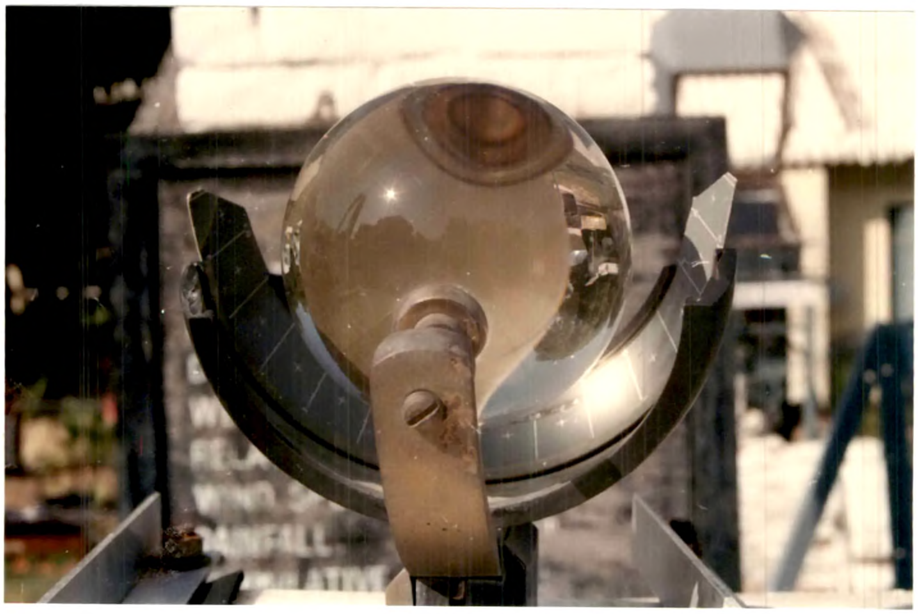

Fig. 3.10 : Sunshine recorder

3.8 UTILIZATION OF SOLAR ENERGY

The solar radiation reaching the earth's surface can be utilized for practical purposes through various modes. It can be converted directly to electricity using solar cells. Solar cells are semiconductor devices that produce electrical energy when exposed to sun light. A number of solar cells can be connected in a Series-Parallel configuration to yield the required power for various applications like lighting, water pumping, and operation of electronic devices like radio resevers, television, etc. Solar cells can also to used for operating conventional refrigerators. The major disadvantage of solar cells is their high cost. Currently solar cells cost about Rs. 300/- per Watt of installed capacity.

There are many useful applications of solar energy in the form of heat which works out to be more economical. The flat plate collector is the most economical method of collecting solar energy for medium temperature applications. Water or air can be heated upto about 70 degree C with the help of flat plate collectors. For high temperature applications, various types of solar concentrators can be used.

3.8.1 Solar Concentrators :

Solar collection devices that increase the receiver surface flux intensity over that incident on the collector aperture are called concentrators. Concentration is achieved by the use of reflecting or refracting element, positioned to concentrate the incident flux onto a receiver. Solar concentrators use only direct radiation. Various types of solar concentrators have been developed. A few of the popular ones are explained here.

Compound Parabolic Concentrators (CPC) :

This is a non imaging concentrator that works with only seasonal tracking[9]. This was first developed independently by Winston[10] and Baranov[11]. It consists of two parabolic segments, oriented such that focus of one is located at the bottom end point of the other and vice versa. The CPC can be used in a nontracking mode for concentration ratios upto 6. These are normally used for water heating or low pressure steam generation.

Cylindrical Parabolic Concentrator :

This consists of a cylindrical parabolic reflector and a metal tube receiver at its focal plane. The heat transfer fluid flows through the receiver tube and gets heated. This concentrator can be installed in the East-West, North-South or Polar axis[12]. Continuous single axis tracking is essential when the concentrator is installed in the North-South or Polar axis. This concentrator is used for water heating as well as steam generation.

Paraboloidal Dish Concentrator :

A parabola when rotated about its optical axis produces a surface known as paraboloid[13]. When a concentrator of this type is used to concentrate solar energy, high concentration ratios can be achieved[14]. This can be used for cooking food and sterilizing medical equipment. If made in very large size, it can be used for steam generation or melting metals. These concentrators need continuous two axis tracking.

3.8.2 Flat Plate Collectors :

As the name suggests, flat plate collector uses a black flat absorber to absorb solar radiation falling on it. These are mainly used for heating water or air upto about 70 degree C temperature. The absorber is installed in an outer box with thermal insulation at the back and sides. Fig. 3.11 shows a flat plate collector used for heating water. On the top on the absorber, a transparent glazing is fitted to reduce convective heat losses. The collector is sealed air tight to prevent rain water and dust from entering the collector and also prevent hot air from leaking outside.

Flat plate collectors use both beam and diffused solar radiation, do not require tracking of the sun and require very little maintenance. These are almost always mounted in a stationary position with an orientation optimized for the particular location and the time of the year the collector is intended to provide maximum output.

Under steady state condition, the performance of a solar collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal losses and optical losses.

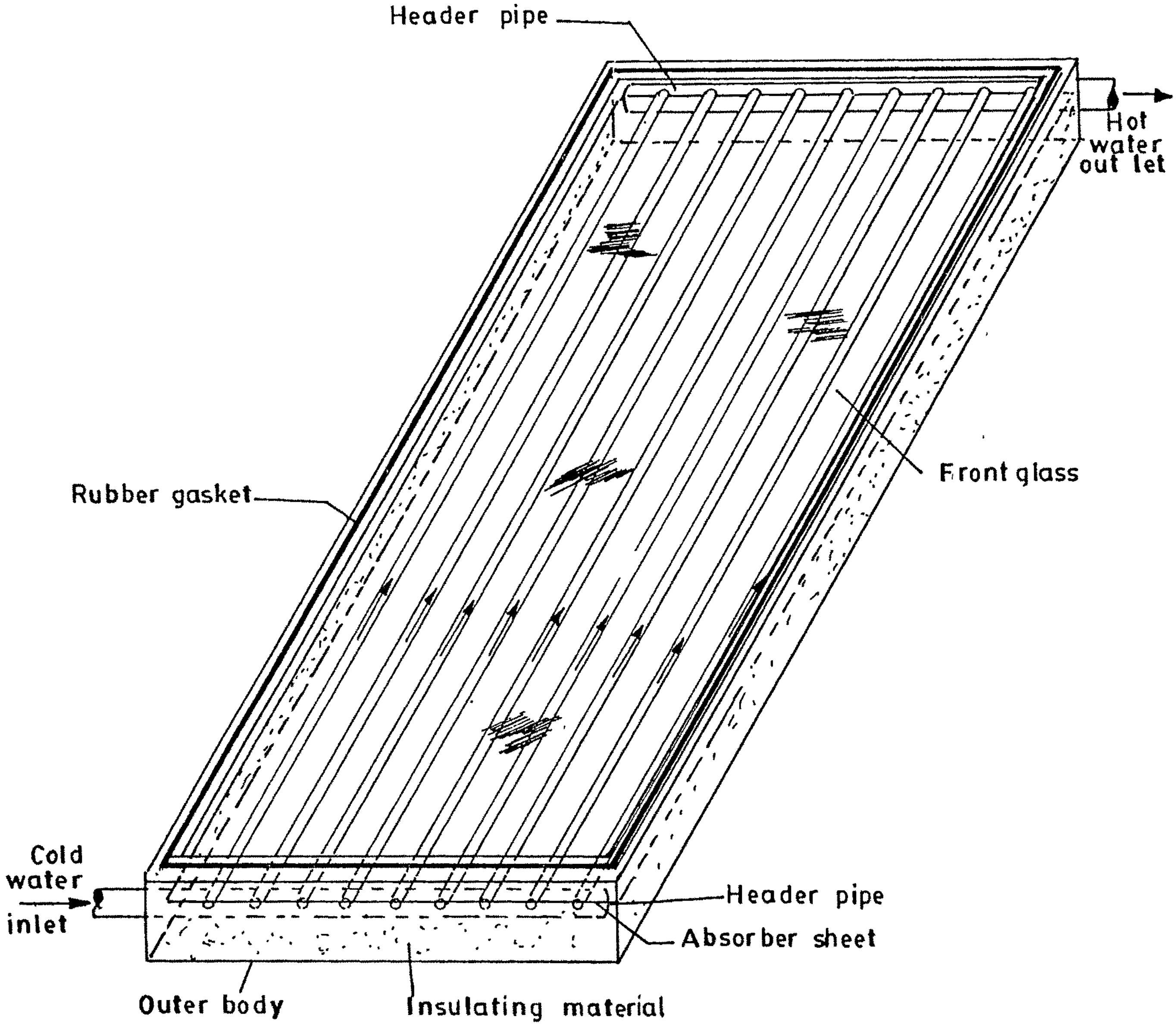

Fig. 3·11 Flat plate collector

$$Q_u = A_c [S - U_l (T_{p,m} - T_a)] \quad \text{.............(3.4)}$$

Where,

Q_u = Useful energy output of a collector, W

A_c = Area of collector, sq m

S = Solar radiation absorbed by the collector, W/sq m

U_l = Overall heat loss coefficient, W/sq m degree C

$T_{p,m}$ = Mean absorber temperature, degree C

T_a = Ambient temperature, degree C

The collector efficiency over some specified time period is expressed as follows :

$$\eta = \frac{Q_u \; dt}{A_c \; G \; dt} \quad \text{..................(3.5)}$$

Where

η = Efficiency, dimensionless

G = Total solar radiation incident on the collector, W/sq m

dt = Time interval, sec. or hour

Collector Orientation :

For maximum annual energy availability, a surface slope equal to latitude is best. For maximum summer utility, slope should be approximately 10 to 15 degree less than latitude. For maximum winter energy utility, slope should be approximately 10 to 15 degree more than latitude. The best surface azimuth angles for maximum incident radiation are 0 degree in the northern hemisphere and 180 degree in the southern hemisphere. That is, the surface should face the equator.

Radiation Augmentation :

To increase the temperature of a flat plate collector, certain improvements can be incorporated. These are selectively coating the absorber, double glazing and booster mirrors.

Selective coating is a surface preparation, black in appearance which combines low thermal emissivity with high absorptance. Such a surface can be developed through electrodeposition of Black Nickel or Black Chrome or by pasting a commercially available selective foil to the absorber. Double glazing reduces the convective heat loss that take place from the glazing to the ambient by lowering the exposed glass temperature. Double glazing is reported to increase the collector temperature by about 10 degree C. As each additional glazing will also reduce the incoming solar energy, more than two glazing is usually not employed.

Additional reflectors as shown in Fig. 3.12 can be used to increase the radiation falling into the receiver. The concentration ratios of this type of collectors will be less than four. As the solar angle of incidence increase, the mirrors become less effective. For a single collector booster mirrors can be used on all the sides. But when the sun angle exceeds the semiangle of the booster mirrors, the mirrors actually starts casting shadow on the absorber.

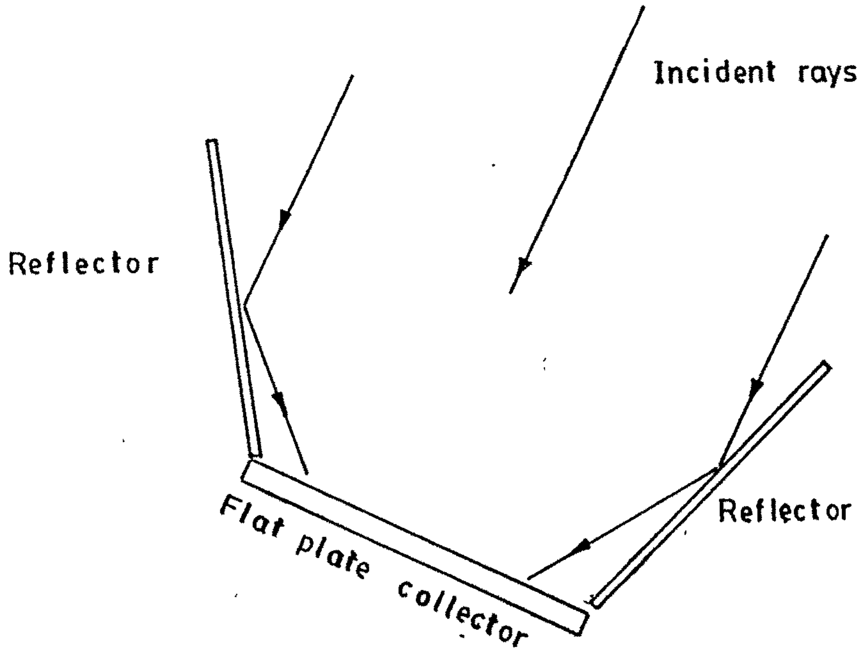

Fig. 3.12 Booster arrangement to increase incident radiation.

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