CHAPTER II

LITERATURE REVIEW

2.1 Characteristics of Solar Radiation

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^6 km, and is, on the average, 1.5×10^8 km from the earth. As seen from the earth, the sun rotates on its axis about once every four weeks. However, it does not rotate as a solid body, the equator taking about 27 days and the polar regions about 30 days for each rotation.

The surface of the sun is at an effective temperature of about 5762^oK. The temperature in the central interior regions is variously estimated at 8×10^6 to 40×10^6 ^oK, and the density about 80 to 100 times that of water. The sun is in effect, a continuous fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. The fusion reactions which have been suggested to supply the energy radiated by the sun have been several; the one considered the most important is a process in which hydrogen (i.e., four protons) combines to form helium (i.e., one helium nucleus); the mass of the helium nucleus is less than that of the four protons, mass having been lost in the reaction and converted to energy.

This energy is produced in the interior of the solar sphere, at temperatures of many millions of degrees. It must transfer out to the surface and then be radiated into space. A succession of radiative and convective processes must occur, with successive emission, absorption, and reradiation; the radiation in the sun's core must be in the x-ray and gamma ray parts of the spectrum with the wavelengths of the radiation increasing as the temperature drops at larger radial distances.(1)

Figure 2.1 shows schematically the geometry of the sun-earth relationships. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by ± 3 %. At a distance of one astronomical unit, the mean earth-sun distance, the sun subtends an angle of 32'. The characteristics of the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside of the earth's atmosphere. The solar constant, I_{sc}, is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the radiation, in space, at the earth's mean distance from the sun.

A standard value of the solar constant proposed by Thekaekara and Drummond(2), is 1353 W/m^2 (1.940 cal/cm^2 min, 428 $Btu/ft^2 hr$, or 4871 kJ/m^2 hr).

Radiation at normal incidence received at the surface of the earth from the sun is subject to variations due to

a) variations in distance from earth to sun,

b) variations in atmospheric scattering by air molecules, water vapor, and dust, and

c) variations in atmospheric absorption by O_2, O_3, H_2O

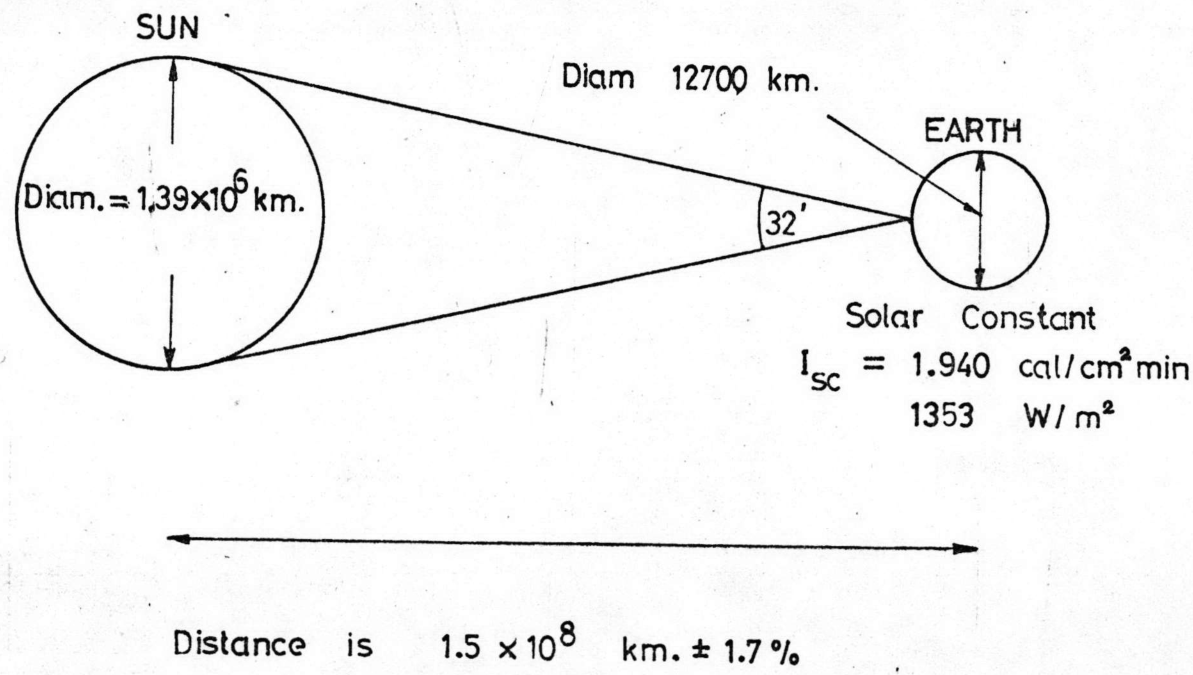

Figure 2.1 Schematic of sun-earth relationship

and CO_2.

The normal solar radiation incident on the earth's atmosphere has a spectral distribution, indicated by Figure 2.2. The x-rays and other very short-wave radiations of the solar spectrum are absorbed high in the ionosphere by nitrogen, oxygen, and other atmospheric components; most of the ultraviolet is absorbed by ozone. At wavelengths longer than 2.5 μm, a combination of low extraterrestrial radiation and strong absorption by CO_2 and H_2O means that very little energy reaches the ground. Thus, from the viewpoint of terrestrial applications of solar energy, only radiation of wavelengths between 0.29 and 2.5 μm need be considered. This solar radiation is transmitted through the atmosphere, undergoing variations due to scattering and absorption.

Scattering, which results in attenuation of the beam radiation by air molecules, water vapor, and dust, has been the subject of a number of studies, and approximate methods have been developed to estimate the magnitude of the effect.

Absorption of radiation in the atmosphere in the solar energy spectrum is due largely to ozone in the ultraviolet, and water vapor in bands in the ultraviolet, and water vapor in bands in the infrared.

Solar radiation received from the sun is considered by the following definitions. Direct or beam solar radiation is the solar radiation coming from the solid angle of the sun's disk on a surface perpendicular to the solid angle. Diffuse solar

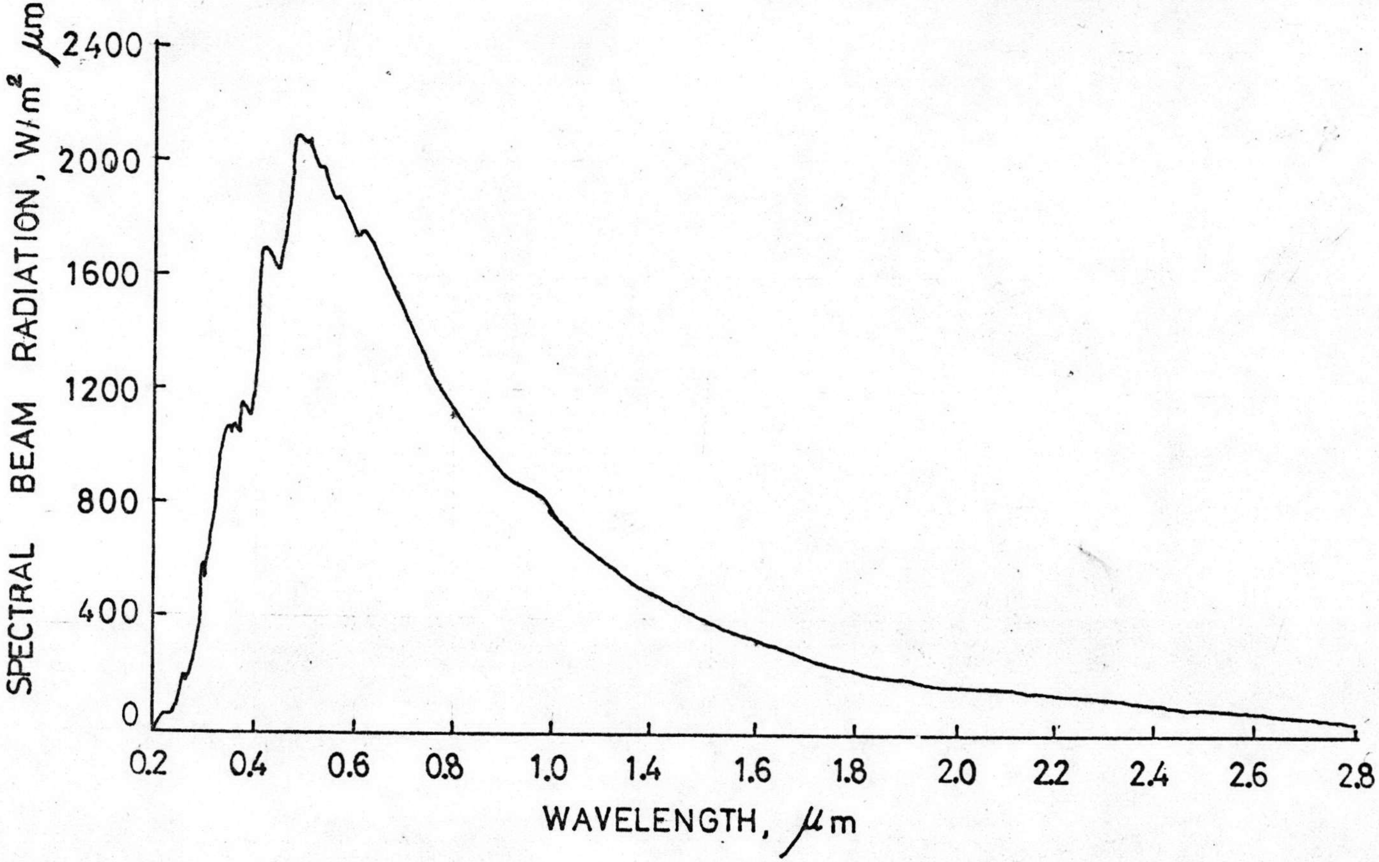

Figure 2.2 The NASA (1971) Standard spectral irradiance at the mean sun earth distance and a solar constant of 1353 W/m^2.

radiation or sky radiation is the solar radiation received on horizontal surface from a solid angle 2π with the exception of solid angle subtended by the sun's disk. Global or total solar radiation is the downward direct and diffuse solar radiation as received on a horizontal surface from a solid angle of 2π.

Radiation is considered in two wavelength ranges.

1. Solar, or short wave radiation: Radiation orginating from the sun, at a source temperature of about $6000^{o}K$, and in the wavelength range of 0.3 to 3.0 μm.

2. Heat, or long wave radiation: Radiation orginating from sources at temperature near ordinary ambient temperatures, and thus substantially all at wavelengths greater than 3 μm.

2.2 Instruments for Measuring Solar Radiation

The meteorological literature, in which radiation instruments and data are described and reported, uses several terms which are of interest to the solar process engineer:

1. Pyrheliometer: An instrument using a collimated detector for measuring solar radiation from a small portion of the sky including the sun (i.e., beam radiation) at normal incidence.

2. Pyranometer: An instrument for measuring total hemispherical solar (direct + diffuse) radiation, usually on a horizontal surface. If shaded from the beam radiation by a shade ring, it measures diffuse radiation.

3. International Pyrheliometric Scale (1956): Two standard

reference pyrheliometers have been in use for many years (the Abbot, or Smithsonian instrument, and the Angstrom instrument). The scales defined by these instruments did not agree, and in 1956 a new "International Pyrheliometric Scale 1956" was established which applied corrections to previously obtained measurements for each of these (-2.0 % to Smithsonian scale, + 1.5 % to the Angstrom scale). All instruments manufactured and calibrated since 1956 use the new scale.

In addition, the term solarimeter, solar radiometer, radiometer and actinometer are encountered; they can generally be interpreted to be the same as pyranometer.

Solar radiation measurements are most often made of total radiation, in energy per unit time per unit area, on a horizontal surface, by pyranometer. Measurements are also made of beam radiation, by pyrheliometer, which respond to solar radiation received from a very small portion of the circum solar sky. Instruments for these measurements convert radiation to some other form of energy and provide a measure of the energy flux produced by the radiation.[1] The most common pyranometers in use today are based on detection of the difference between the temperature of black surfaces (which absorb most solar radiation), and white surfaces (which reflect most solar radiation) by thermopiles. Properly protected from wind, and compensated for changes in ambient temperature, the thermopilies give millivolt signals that can be readily detected, recorded, and integrated over time.

The Eppley Pyranometer is based on the above principle and has become the most common instrument in use by weather bureau stations. It uses concentric silver rings, 0.25 mm thick, appropriately coated black and white, with either 10 or 50 thermocouple junctions to detect temperature differences between the coated rings. Later models use wedges arranged in a circular pattern, with alternate black and white coatings. The disks or wedges are enclosed in a hemispherical glass cover. Its performance has been carefully studied by MacDonald.[3] Similar instruments are manufactured in Europe under the name Kipp. The Eppley pyranometers, and similar instruments, are calibrated in a horizontal position. In general use, without frequent calibration the data from them are probably no better than ± 5 %. With frequent calibration against standard instrument, the data may be as good as ± 2 %. Calibrations of these instruments will vary to some degree if the instrument is inclined to measure radiation on other than a horizontal surface.

The Moll-Gorczynski solarimeter is a pyranometer based on thermopiles having hot junctions exposed to solar radiation and cold junctions shaded from the radiation.

Another type of pyranometer, the Robitsch, is based on differential expansion of bimetal elements exposed to solar radiation; this has the advantage, where no power is available, of the possibility of direct mechanical linkage to a spring-driven recording drum. Thermal expansion radiometer are widely used in isolated stations, and while they are not precise, they are a major source of the solar radiation data that are available.

Pyranometers have also been based on photovoltaic (solar cell) detectors, (e.g., the Yellott solarimeter). Silicon cells are the most common for solar energy, although cadmium sulfide and selenium cells have been used, for example, for measurements of visible light in photography. Silicon solar cells have the property that their light current (approximately equal to the short-circuit current at normal radiation levels) is a linear function of the incident solar radiation. They have the disadvantage that the spectral response is not linear, so instrument calibration is a function of the incident radiation. Also, the calibration varies with the angle of incidence of the radiation.

The Bellani distillation pyranometer uses flat or spherical containers of alcohol which are connected to calibrated condenser-receiving tubes. The quantity of alcohol condensed is a measure of the integrated solar energy on the spherical or flat receiver.

Three pyrheliometer have been in widespread use to measure normal incidence beam radiation: the Angstrom pyrheliometer, the Abbot water flow pyrheliometer, and the Abbot silver disc pyrheliometer. These instruments provide primary and secondary standards of solar radiation measurements.

In addition to radiation measurements, there are in wide-spread use instruments for recording the duration of "bright sunshine." The standard U.S. Weather Bureau instrument uses a pair of photocells, one of which is shaded from beam radiation. When radiation is all diffuse, the cells indicate nearly equal radiation levels; when beam radiation is incident on the instrument, the cell exposed to that beam radiation indicates higher intensity than the shaded cell. The duration of a critical intensity difference detected by the two cells is a measure of duration of "bright sunshine." An older instrument, the Campbell-Stokes recorder uses a spherical lens that produces an image of the sun on a treated paper. The paper is burned whenever the beam radiation is above a critical level. The lengths of the burned portions of the paper provide an index of the duration of sunshine.

2.3 Solar Radiation Data

For the purpose of planning equipment and installations for utilizing solar energy, solar radiation data must be known. Measurements of solar radiation are usually made by meteorological stations. Several types of instruments are known for measuring and recording solar characteristics.

In Thailand, there used to be a few meteorological stations for measuring solar radiation but now only one station exists in Bangkok. There are 20 stations for measuring duration of sunshine with Cambell-Stokes sunshine recorders.

The analysis of the meteorological data had been used to produce a comprehensive survey of the solar energy available in Thailand.[4] The results has been presented in a form suitable for use in designing and predicting the performance of solar energy equipment. Geographical, seasonal, and diurnal variations of global solar radiation were surveyed. Detailed maps were given of the geographical distribution of solar radiation prepared from data on cloudiness at 44 stations, duration of sunshine at 18 stations, and linear regressions relating radiation to sunshine at Chiang Mai and Bangkok. The highest mean values were above 470 cal cm^{-2} d^{-1} and were widespread in spring. The lowest values were below 350 cal cm^{-2} d^{-1} in restricted localities with heavy rainfall in autumn. Rough estimates of diffuse solar radiation and atmospheric turbidity were made from the radiation--sunshine regression parameters. Fluctuation in the daily solar radiation were examined in an unbroken five-year sequence of measurements at Bangkok, and were also estimated from daily sunshine measurements at Bangkok and three other stations in Thailand. The time series of daily totals of global solar radiation at Bangkok was analysed as a second order random process. The observed annual frequencies of runs of consecutive days with low radiation were given. Finally, the diurnal variation of global solar radiation determined from hourly measurements at Chiang Mai and Bangkok was analysed.

2.4 Low Cost Radiometers

Reliable, quantitative data on solar radiation are essential in meteorological and climatological studies, for proper utilization of solar energy, for studying its biophysical aspects particularly in relation to design of equipment, and for prediction of environmental hazards in various operations.

Development of simple, rugged, and relatively inexpensive radiometer for measuring solar radiation is of great importance particularly for countries with limited resources.

Various specialists have been considering to design the radiometers for measuring solar energy that are inexpensive and easy to make which should be fulfilled by simple low cost radiometer are stated below.(5)

1. Minimum cost, hence, the use of a chart recorder is inadmissible.

2. Simplicity of construction containing no fragile parts which cannot be replaced easily.

3. No electrical supply required.

4. Minimum attention required for operation.

5. No scientific training or knowledge required by the operator.

The interesting results of the previous investigations are stated below.

In 1957, Schoffer, Kuhn and Sapsford(6) produced an economical radiometer which can be used for measurement of incoming and reflected shortwave (solar) radiation and incoming and outgoing long-wave (thermal) radiation. With modifications, pairs of the radiometers can serve as a pyrheliometer for solar radiation measurement. The basic radiometer consisted of two blackened sensing surfaces, one facing upwards and one downwards, shielded from ventilation effects by pairs of spectrally transparent polyethylene film, and separated from one another by an insulating medium such as expanded polystyrene. Radiation is determined from air temperature and from the temperatures of the two blackened surfaces, which may be measured with any convenient temperature detectors. For pyrheliometer use, a pair of radiometers, one with "black" and one with "white" sensing surfaces, are used over an opaque shield. They constitute an "economical pyrheliometer". Measurements are made of the temperatures of four surfaces and ambient air temperatures. From the energy balances for the surfaces, an equation can be derived relating the incident solar radiation to the measured temperatures.

Such radiometers are commercially available, and the estimated cost of a pyrheliometer assembly is under $ 50, depending on what temperature detectors are used. Comparisons of the output of an Eppley pyrheliometer, a silicon solar cell, and the economical pyrheliometer have been made, and show good agreement when the top layer of polyethylene is near ambient temperature.

In 1961, Heywood[5] constructed a simple low cost radiometer which measured the radiation received daily on a flat surface, primarily with the object of predicting performance of flatplate types of solar water heaters. Instead of a pyrheliometer, a capacity instrument is advocated. The heat gained during a period which may vary from a few minutes to the whole day is measured by the rise in temperature of a suitable mass of water on metal. After testing several models, the one finally adopted consists of a standard "thermos" flask with a capacity of one pint (570 ml). The radiation absorbing surface is a blackened copper disk fitted to the flask by means of a copper tube which conducts the heat to the water in the flask. Provisions are made against heat flow from or to the atmosphere. The cost for producing the instrument is estimated to be about twenty dollars. The temperature rise of the water, measured by means of a specially designed maximum and minimum thermometer is a measure of the radiation received during a day.

Whillier and Tout[7] developed a simple, accurate, cheap integrating instrument for measuring daily solar radiation in 1964. The complete instrument comprises two components, namely the solar transducer of pyranometer (which is mounted outdoors in the same way as the conventional Eppley or Kipp pyranometer), and a conventional household style d.c. ampere-hour meter. The solar transducer is connected directly to the ampere-hour meter in a circuit with a total electrical resistance less than 0.01 ohm, so that the ampere-hour meter continuously integrates the short-circuit current, displaying the total on the indicating dials. The dials of the ampere-hour meter are read every evening to give the daily ampere-hours, which will be directly proportional to the daily solar radiation. The instrument cost about $ 100.

In 1965, Brodie[8] produced a simple mechanical device, the "wig-wag", for the measurement of solar radiation. It is based on the expansion of the gaseous phase of a volatile liquid as a result of the conversion of radiant energy to sensible heat. The receiving surface of the wig-wag is spherical. Incident radiation can be expressed in terms of that received by a horizontal surface through the application of Lambert's Cosine Law; in applying this law, consideration must be changed twice each year but a suggested modification of the housing eliminate the need for change of direction. This instrument satisfies the criteria set up by the Hawiian sugar industry for an acceptable field instrument: low cost, high accuracy, dependable field performance, low maintenance, and simple measurements.

An inexpensive instrument has been designed for measuring the net solar radiation flux through a plane by Darkow and Alberty[9] in 1972. Sensing surface coating modifications will permit the determination of net radiation flux within preselected broad bands within the solar spectrum. The basic instrument consists of two-thin, disk-like sensors mounted in a common plane. Solar and infrared radiation impings on both sides of the sensors. Opposite sides of the sensors are coated with materials such as black and white paints having essentially equal infrared (4-μm to 50-μm) absorptivities but with markedly different absorptivities in that portion of the spectrum containing the bulk of the solar energy (0.3μm to 15μm). The sensors are identical except that one is mounted with its "white" side up and "black" side down while the other is mounted in the reverse position. The simultaneous solution of the energy flux equations for both sensors shows that the net solar flux density passing through the plane of the sensors is directly determinable to simply monitoring the temperatures of the two sensor disks.