

# Simulation of Solar Radiation Incident on Horizontal and Inclined Surfaces

MA Basunia<sup>a</sup>, H Yoshio<sup>b</sup>, and T Abe<sup>c</sup>

<sup>a</sup>Department of Soils, Water & Agricultural Engineering, College of Agriculture and Marine Sciences, Sultan Qaboos University, P.O. Box 34, Al-Khod 123, Muscat, Sultanate of Oman

<sup>b</sup>Department of Biomechanical Systems, Ehime University, Matsuyama, 790-8566, Japan

<sup>c</sup>Department of Biomechanical Systems, Ehime University, Matsuyama, 790-8566, Japan

Received 2 January 2010; accepted 25 December 2011

**Abstract:** A computer model was developed to simulate the hourly, daily and monthly average of daily solar radiation on horizontal and inclined surfaces. The measured hourly and daily solar radiation was compared with simulated radiation, and favourable agreement was observed for the measured and predicted values on clear days. The measured and simulated monthly averages of total (diffuse and beam) daily solar radiation were compared and a reasonable agreement was observed for a number of stations in Japan. The simulation showed that during the rice harvesting season, September to October, there is a daily average of 14.7 MJ/m<sup>2</sup> of solar irradiation on a horizontal surface in Matsuyama, Japan. There is a similar amount of solar radiation on a horizontal surface during the major rice harvesting season, November to December, in Bangladesh. This radiation can be effectively utilized for drying rough rice and other farm crops.

**Keywords:** Solar energy, Simulation, Geometric factor, Daily and hourly solar radiation

## محاكاة الإشعاع الشمسي على الأسطح الأفقية والمائلة

مس. بسونيا<sup>ه</sup>، يوشي، ت أبي

**الملخص:** لقد تم تطوير نموذج حاسوبي لمحاكاة متوسط التغير في الإشعاع الشمسي حسب الساعة واليوم والشهر للأسطح الأفقية والمائلة. وتمت مقارنة الإشعاع الشمسي المقاس يومياً على حسب الساعة مع القيم المحسوبة بنظام المحاكاة. وقد وجد أنه هناك تناسق معقول بين القيم المحسوبة والمقاسة في الأيام ذات الطقس الصافي. كما تمت مقارنة المتوسط الكلي الشهري واليومي المقاس مع تلك المحاكاة ووجد أنه هناك موافقة معقولة بينهما لعدد من محطات الرصد باليابان. وأوضحت المحاكاة خلال فترة موسم حصاد الأرز (سبتمبر - أكتوبر) أنه هناك إشعاع شمسي يعادل 14.7 ميغا جول / متر مربع على الأسطح الأفقية في مدينة ماتسوياما اليابانية. وبالمقارنة مع بنجلاديش فقد أظهرت المحاكاة وجود تماثل في الإشعاع الحراري على الأسطح الأفقية خلال فترة حصاد الأرز (نوفمبر - ديسمبر). يمكن إستغلال هذه الإشعاعات على نحو فعال لتجفيف الأرز الخام والمحاصيل الأخرى.

**الكلمات المفتاحية:** الطاقة الشمسية، محاكاة، عامل هندسي، إشعاع شمسي على حسب اليوم والساعة

## 1. Introduction

The knowledge of the availability of solar radiation at any given location is important for the design and performance evaluation of solar drying equipment. The data on hourly, daily and monthly average solar radiation strike on horizontal and inclined surfaces are essential for designing solar drying equipment. Actual measurements of insolation are generally made in only a few places because of the cost of the instruments required, and the care needed for maintaining it. Simulations can be made on the basis of theoretical and statistical relationships developed for estimating

insolation from various weather observations, most of which are usually made at many locations. The temperature and relative humidity have great influence on the open air natural sun drying of farm crops as it is commonly practiced in Bangladesh and in other developing countries. In most tropical countries, including Bangladesh, the climate is characterized by hot and humid air during harvesting. This unfavorable climatic condition dictates the need for a more effective method of drying, grain. Because of the difficulties with open air sun drying particularly in wet weather, an alternative and efficient drying method is needed in tropical countries.

\*Corresponding author's e-mail: basunia@squ.edu.om

Bangladesh receives abundant solar radiation throughout the year, so a solar heated dryer can be used to solve the drying problem. Most of the farmers in Bangladesh operate on a small scale and cannot afford mechanically powered drying systems. An intermediate solution takes advantage of the ready availability of solar energy to utilize it for drying. It was reported (Bala and Zia-Uddin 1990) that solar dryers can be designed to enhance the effectiveness of solar drying in Bangladesh, and that there is potential for their adoption and application by small farmers. This would reduce grain loss and help to maintain the quality of dried grain. Solar drying systems must be properly designed in order to meet the particular drying requirements of specific crops and to give a satisfactory performance with respect to energy requirements (Steinfeld and Segal 1986). The designer should investigate both theoretically and practically, the physical needs of solar crop dryers and evaluate the performance of the solar dryers based on available solar energy. This paper deals with a simulation model to be used for the simulation of hourly, daily, and monthly average radiation incidents, both on horizontal and tilted surfaces.

## 2. Theoretical Considerations

### 2.1 Radiation Geometry

The geometric relationships between a plane of any particular orientation relative to the earth at any time and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles (Benford and Bock 1939). Simplification of the geometric relationships relating to the angle of incidence of beam radiation on a surface to the other angles leads to the following equation.

$$\cos \theta = \cos \theta_z \cos \beta + \sin \theta_z \sin \beta \cos(\gamma_s - \gamma) \quad (1)$$

where  $\theta$  is the angle of incidence the angle between the beam radiation on a surface and the normal to that surface;  $\theta_z$  is the angle of incidence;  $\beta$  is the angle between the plane of the surface considered and the horizontal,  $0 \leq \beta \leq 180^\circ$ ,  $\lambda_s$  is the solar azimuth angle;  $\lambda$  is the surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south,  $-180^\circ \leq \lambda \leq 180^\circ$ .

For the horizontal surface, the angle of incidence is the zenith angle of the sun  $\theta_z$ . For this condition,  $\beta = 0$ , and Eqn. (1) becomes

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (2)$$

where  $\phi$  is the latitude, the angular location north or south of the equator;  $\delta$  is the angular position of the sun at solar noon, called declination;  $\omega$  is the hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at  $15^\circ$  per hour, with morning negative and afternoon positive;.

The relationship for the angle of incidence of surfaces sloped due north or due south can be derived from the fact that surfaces with slope  $\beta$  to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of  $(\phi - \beta)$ . Modifying Eqn. (2) yields

$$\cos \theta = \cos \delta \cos \omega \cos(\phi - \beta) + \sin \delta \sin(\phi - \beta) \quad (3)$$

The declination  $\delta$  can be computed from the following equation (Duffie and Beckman 1991):

$$\delta = 23.45 \sin \left[ 360 \left( \frac{284 + n}{365} \right) \right] \quad (4)$$

where  $n$  is the day of the year. Recommended average days for months and values of  $n$  by month are given by Klein (1977) and are shown in Table 1. Equation (2) can be solved for the sunset hour angle,  $\omega_s$ , when  $\theta_z = 90^\circ$

$$\cos \omega_s = -\frac{\sin \phi \sin \delta}{\cos \phi \cos \delta} = -(\tan \phi \tan \delta) \quad (5)$$

The number of day light hours is given by following equation:

$$N = \frac{2}{15} \cos^{-1}(-\tan \phi \tan \delta) \quad (6)$$

### 2.2 Geometric Factor ( $R_b$ )

The ratio of direct (beam) radiation on the tilted surface to that on a horizontal surface is called geometric factor and it is usually expressed as:

$$R_b = \frac{\cos \theta}{\cos \theta_z} \quad (7)$$

$\cos \theta_z$  and  $\cos \theta$  are both determined from Eqns. (2) and (3). The optimum azimuth angle for the flat-plate collectors is usually zero in the Northern Hemisphere and  $180^\circ$  in the Southern Hemisphere. In this case Eqs. (2) and (3) can be used to determine  $\cos \theta_z$  and  $\cos \theta$ , respectively, leading in the northern hemisphere, ( $\lambda = 0$ ), to

$$R_b = \frac{\cos \delta \cos \omega \cos(\phi - \beta) + \sin \delta \sin(\phi - \beta)}{\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta} \quad (8)$$

### 2.3 The Theoretical (Extraterrestrial) Radiation on a Horizontal Surface

The amount of extraterrestrial radiation or radiation above Earth's atmosphere at any time of year is given by the following equation (Duffie and Beckman 1991).

**Table 1.** Recommended average days for months and value of n (the day of the year) by months

Month	n for ith Day of month	date	For average day of the month	
			n, Day of year	$\delta$ , Declination
January	i	17	17	- 20.9
February	31 + i	16	47	- 13.0
March	59 + i	16	75	- 2.4
April	90 + i	15	105	9.4
May	120 + i	15	135	18.8
June	151 + i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	- 9.6
November	304 + i	14	318	- 18.9
December	334 + i	10	344	-23.0

Source: Klein (1977)

$$E_n = S_c \left[ 1 + 0.033 \cos \left( \frac{360n}{365} \right) \right] \quad (9)$$

where  $E_n$  is the extraterrestrial radiation measured on the plane and normalized to the radiation on the nth day of the year,  $\text{W/m}^2$ ; and  $S_c$  is the solar constant ( $1367 \text{ W/m}^2$ ).

At any given time, the extraterrestrial radiation incident on a horizontal plane outside of the atmosphere is the normal incident of solar radiation as given by Eqn. (9) and divided by  $R_b$ .

$$E = S_c \left( 1 + 0.033 \cos \frac{360n}{365} \right) \cos \theta_z \quad (10)$$

Substituting the value of  $\cos \theta_z$  from Eqn. (2) in Eqn. (10) yields  $E$  for a horizontal surface at any time between sunrise and sunset as:

$$E = S_c \left[ 1 + 0.033 \cos \left( \frac{360n}{365} \right) \right] (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) \quad (11)$$

$$\text{or } E = C (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) \quad (12)$$

$$C = S_c \left[ 1 + 0.033 \cos \left( \frac{360n}{365} \right) \right] \quad (13)$$

The hourly extraterrestrial radiation strikes on a horizontal surface can be estimated from Eqn. (12) by integrating it between hour angles  $\omega_1$  and  $\omega_2$ . The integration for an hour period results in the following equation, where  $I_o$  is the hourly extraterrestrial radiation on horizontal surface,  $\text{J/m}^2$ .

$$I_o = \frac{12 \times 3600 C}{\pi} \left[ \cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + \frac{\pi (\omega_2 - \omega_1)}{180} \sin \phi \sin \delta \right] \quad (14)$$

The hourly extraterrestrial radiation can also be determined from the following approximate equation, evaluating at the mid point of the hour.

$$I_o = 3600 C (\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega) \quad (15)$$

The daily theoretical solar radiation,  $H_o$  striking on a horizontal surface is obtained by integrating Eqn. (12) over the period from sunrise to sunset. The integration yields where  $H_o$  is the daily extraterrestrial radiation,  $\text{J/m}^2$ , and  $\omega_s$  is the sun set hour angle in degrees.

$$H_o = \frac{24 \times 3600 C}{\pi} \left( \cos \phi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \phi \sin \delta \right) \quad (16)$$

#### 2.4 Estimation of Average Solar Radiation on a Horizontal Surface

The original Angstrom-type regression equation relates monthly average daily radiation to radiation on a clear day, at a given location. The average fraction of possible sunshine hours is given by

$$\frac{H_m}{H_c} = a + b \frac{n_d}{N_m} \quad (17)$$

where  $H_m$  is the monthly average daily radiation on a horizontal surface  $H_c$  is the average clear sky daily radiation for the location and month considered  $a$ , and  $b$  are empirical constants,  $n_d$  is the monthly average daily hours of bright sunshine  $N_m$  is the monthly average of the maximum possible daily hours of bright sunshine *i.e.*, the day length represented by  $N$  of the average day of the month in Eqn. (6).

Page (1964) and others have modified the method to base it on extraterrestrial radiation on a horizontal surface rather than on clear day radiation, using equation:

$$\frac{H_m}{H_{om}} = a_1 + b_1 \frac{n_d}{N_m} \quad (18)$$

where  $H_{om}$  is the extraterrestrial radiation for the given location, averaged over the period considered, and  $a_1$  and  $b_1$  are constants depending on location. Lof *et al.* (1966) developed sets of constants,  $a_1$  and  $b_1$  for various climate types and locations based on radiation data then available. For Poona, India,  $a_1 = 0.30$  and  $b_1 = 0.51$  through Eqn. (18). The ratio ( $H_m/H_{om}$ ) is termed as the monthly average clearness index.

### 2.5 Estimation of Hourly Solar Radiation on a Horizontal Surface from Daily Data

When hour-by-hour performance estimations for a solar system are needed, it is necessary to start with daily data and then to estimate hourly values from daily data. The ratio of hourly total radiation  $I$  to daily total radiation  $H$  on a horizontal surface is expressed as a function of day length. The ratio  $I/H$  is represented by the following equation of (Collares-Pereira, Rabl 1979):

$$\frac{I}{H} = \frac{\pi}{24} (c_1 + c_2 \cos \omega) \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \quad (19a)$$

where the parameters  $c_1$  and  $c_2$  are given by:

$$c_1 = 0.409 + 0.5016 \sin(\omega_s - 60) \quad (19b)$$

$$c_2 = 0.6609 - 0.4767 \sin(\omega_s - 60) \quad (19c)$$

The ratio of hourly diffuse radiation ( $I_d$ ) to the daily diffuse radiation ( $H_d$ ) on a horizontal surface is a function of time and day length. Liu and Jordan (1962) reported that  $I_d/H_d$  is the same as  $I_0/H_0$ , and is estimated from the following equation.

$$\frac{I_d}{H_d} = \frac{\pi}{24} \frac{(\cos \omega - \cos \omega_s)}{\left( \sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s \right)} \quad (20)$$

### 2.6 Beam and Diffuse Components of Hourly Global Radiation on a Horizontal Surface

An hourly clearness index ( $k_h$ ) can be defined as

$$k_h = \frac{I}{I_0} \quad (21)$$

where  $I$  is the hourly global radiation on a horizontal surface,  $J/m^2$ . The usual approach is to correlate  $I_d/I$ , which expresses the fraction of the hourly radiation on a horizontal plane which is diffuse, with  $k_h$ , the hourly clearness index.  $I_d$  is the hourly diffuse component of global radiation ( $I$ ). This correlation may not represent a particular hours very closely, but over a number of hour it adequately represents the diffuse fraction (Duffie and Beckman, 1991).

Orgill and Hollands (1977) used data from Canadian stations (Erbs *et al.* 1982) have used data from United States and one Australian station, and (Reindl *et al.* 1990) used independent data from the United States and Europe. The three correlations are essentially identical, although they were derived from three separate data sources. The correlation between hourly diffuse and global radiation developed by (Erbs *et al.* 1982) is as follows:

$$\frac{I_d}{I} = 1.0 - 0.9k_h \quad \text{for } k_h \leq 0.22 \quad (22a)$$

$$\frac{I_d}{I} = 0.951 - 0.164k_h + 4.388k_h^2 - 16.64k_h^3 + 12.34k_h^4 \quad (22b)$$

for  $0.22 < k_h \leq 0.80$

$$\frac{I_d}{I} = 0.165 \quad \text{for } k_h > 0.80 \quad (22c)$$

### 2.7 Beam and Diffuse Components of Daily Global Radiation on a Horizontal Surface

The daily clearness index,  $k_d$  is defined as the ratio of a particular day's radiation  $H$  on a horizontal surface, to the extraterrestrial radiation  $H_0$  for that day.  $H_d$  is the daily diffuse component of the total global radiation,  $H$  on that particular day,  $J/m^2$ . Mathematically it is expressed as

$$k_d = \frac{H}{H_0} \quad (23)$$

The following statistical relationship was given by Collares-Pereira and Rabl (1979):

$$\frac{H_d}{H} = 0.99 \quad \text{or } k_d \leq 0.17 \quad (24a)$$

$$\frac{H_d}{H} = 1.188 - 2.27k_d + 9.47k_d^2 - 21.87k_d^3 + 14.65k_d^4$$

for  $0.17 < k_d < 0.75$

(24b)

$$\frac{H_d}{H} = -0.54k_d + 0.632 \quad \text{for } 0.75 < k_d < 0.80$$
(24c)

$$\frac{H_d}{H} = 0.2 \quad \text{for } k_d \geq 0.8$$
(24d)

## 2.8 Beam and Diffuse Components of Monthly Global Radiation on a Horizontal Surface

The monthly average clearness index ( $K_m$ ) is defined as the ratio of monthly average daily radiation on a horizontal surface,  $H_m$  to the monthly average daily extraterrestrial radiation  $H_{0m}$ .  $H_{dm}$  is the diffuse component of the total global monthly average daily radiation  $H_m$ , J/m<sup>2</sup>. Mathematically it can be expressed as

$$K_m = \frac{H_m}{H_{0m}} \quad (25)$$

The (Erbs *et al.* 1982) correlation between the fraction of the monthly average daily radiation  $H_{dm}/H_m$  which is diffuse, and the monthly average clearness index  $K_m$  is represented by the following equations:

$$\frac{H_{dm}}{H_m} = 1.391 - 3.56K_m + 4.189K_m^2 - 2.14K_m^3$$

for  $\omega_s \leq 81.4^\circ$  and  $0.3 \leq K_m \leq 0.8$

(26a)

$$\frac{H_{dm}}{H_m} = 1.311 - 3.022K_m + 3.43K_m^2 - 1.82K_m^3$$

for  $\omega_s > 81.4^\circ$  and  $0.3 \leq K_m \leq 0.8$

(26b)

## 2.9 Hourly Radiation on a Tilted Surface

The radiation on the tilted surface includes three components: beam, isotropic diffuse, and solar radiation diffusely reflected from the ground (Reindl *et al.* 1990). Considering all diffusion is isotropic, the result is an equation that gives the hourly radiation on a tilted surface,  $I_t$ , in terms of parameters that can be determined either theoretically or empirically as is seen in Eqn. 27.

$$I_t = I_b R_b + I_d F_{vs} + I \rho_r F_{vg} \quad (27)$$

where  $I_b$  is the beam component of  $I$ ,  $R_b$  is the geometric factor,  $F_{vs}$  is the view factor to the sky for a surface sloped at an angle  $\beta$  from the horizontal,  $F_{vg}$  is the

view factor of the surface to the ground, and  $\rho_r$  is the surrounding diffuse reflectance for the total solar radiation. Equation (27) can be written as

$$I_t = I_b R_b + I_d \left( \frac{1 + \cos \beta}{2} \right) + I \rho_r \left( \frac{1 - \cos \beta}{2} \right) \quad (28)$$

where  $I_t$  is total hourly radiation incident on a tilted surface and  $\beta$  is the slope of the surface considered in degrees.

## 2.10 Daily Total Radiation on a Tilted Surface

If the diffuse and ground reflected radiations are each assumed to be isotropic, then in a manner similar in Eqn. (27), for a given day, the radiation on tilted surface can be written as

$$H_T = (H - H_d) R_{bm} + H_d \left( \frac{1 + \cos \beta}{2} \right) + H \rho_r \left( \frac{1 - \cos \beta}{2} \right) \quad (29)$$

where  $R_{bm}$  is the monthly average daily geometric factor, or the ratio between the monthly average daily beam radiation on the tilted surface and that on a horizontal surface. For a surfaces with  $\gamma = 0$ ,  $R_{bm}$  is expressed as

$$R_{bm} = \frac{\cos(\phi - \beta) \cos \delta \sin \omega_m + (\pi/180) \omega_m \sin(\phi - \beta) \sin \delta}{\cos \phi \cos \delta \sin \omega_s + (\pi/180) \omega_s \sin \phi \sin \delta} \quad (30)$$

where  $\omega_m$  is the sunset hour angle for the sloped surface for the mean day of the month, which is given by

$$\omega_m = \min \left[ \begin{array}{l} \cos^{-1}(-\tan \phi \tan \delta); \\ \cos^{-1}\{-\tan(\phi - \beta) \tan \delta\} \end{array} \right] \quad (31)$$

where "min" means the smaller value of the two items in the brackets. If we divide by the monthly average daily extraterrestrial radiation  $H_{0m}$  and substitute  $K = H/H_{0m}$ , then Eqn. (30) becomes

$$\frac{H_T}{H_{0m}} = K \left[ \begin{array}{l} \left( 1 - \frac{H_d}{H} \right) R_{bm} + \frac{H_d}{H} \left( \frac{1 + \cos \beta}{2} \right) \\ + \rho_r \left( \frac{1 - \cos \beta}{2} \right) \end{array} \right] \quad (32)$$

The ratio  $H_d/H$  is the daily fraction of the diffuse radiation and can be found from Eqn. (24) as a function of  $k_d$ . Therefore Eqn. (32) can be used to calculate the daily total radiation on a tilted surface.

### 2.11 Monthly Average Daily Radiation on a Tilted Surface

For use in solar process design, the monthly average daily radiation on a tilted surface is needed. The method described by Liu and Jordan (1963) which is extended by Klein (1977) has been widely used. If the diffuse and ground reflected radiations are each assumed to be isotropic, then in a manner similar to Eqn. (28), the monthly mean solar radiation on an unshaded tilted surface can be expressed as

$$H_{tm} = H_m \left( 1 - \frac{H_{dm}}{H_m} \right) R_{bm} + H_{dm} \left( \frac{1 + \cos\beta}{2} \right) + H_m \rho_r \left( \frac{1 - \cos\beta}{2} \right) \quad (33)$$

where  $H_{tm}$  is the monthly average daily total radiation on a sloped surface and  $H_{dm}/H_m$  is a function of  $K_m$ .

### 3. Simulation Procedure for Hourly and Daily Radiation on Horizontal and Tilted Surfaces

The basic equations to be used are Eqs. (28) and (29). The first steps are to obtain  $I_d/I$ ,  $R_b$ ,  $H_d/H$  and  $R_{bm}$ . The ratios  $I_d/I$  and  $H_d/H$  are functions of  $k_h$  and  $k_d$ , and can be obtained from Eqs. (22) and (24), respectively. For a particular day of the year and location where  $n$  and  $\phi$  are known,  $\delta$  can be calculated from Eqn. (4). For known values of  $\phi$  and  $\delta$ , sunset hour angle  $\omega_s$  and day light hours  $N_m$  or  $N$  are calculated from Eqs. (5) and (6), respectively. For the calculation of hourly radiation on a tilted surface,  $R_b$  is needed and can be computed from Eqn. (8). The calculation of  $R_{bm}$  requires sunset hour angle of the sloped collector. Equation (31) is used to calculate the sunset hour angle  $\omega_m$ . With known  $n$  and  $\omega_s$ , from Eqs. (15) and (16), the hourly extraterrestrial (theoretical) radiation  $I_0$  and daily extraterrestrial (theoretical) radiation,  $H_o$ , can be estimated. Then with assumed daily hours of bright sunshine ( $n_d$ ), the  $n_d/N_m$  ratio is calculated to be used in Eqs. (18) and to find the value of daily radiation  $H$  on a horizontal surface. From the known value of  $H$ , the value of hourly radiation  $I$  on a horizontal surface is determined from Eqn. (19). So both  $k_h$  and  $k_d$  are known from Eqs. (21) and (23), respectively. From known  $k_h$  and  $k_d$  ratios,  $I_d/I$  and  $H_d/H$  ratios can be calculated from Eqs. (22) and (24), respectively.  $I_d$  value also can be calculated from a known  $H_d$  using Eqn. (20).  $I_b$  is the difference between  $I$  and  $I_d$ .  $\phi$  is considered equal to  $\beta$ . Then

Eqs. (28) and (29) are used to calculate the hourly and daily radiation incident on a tilted surface.

### 4. Simulation Procedure for Monthly Average Daily Radiation on Horizontal and Tilted Surfaces

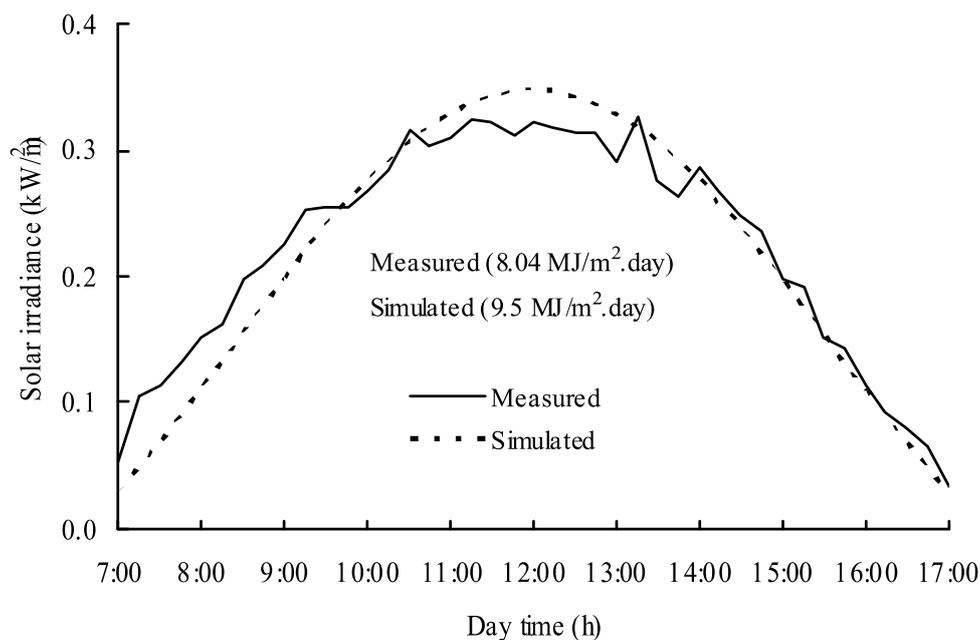
The basic equation to be used is Eqn. (33). The first steps are to obtain  $H_{dm}/H_m$  and  $R_{bm}$ . The ratio  $H_{dm}/H_m$  is a function of  $K_m$  and it can be obtained from Eqn. (26). For the mean day of any month  $n$  is known (Table 1) and  $\delta$  can be calculated from Eqn. (4). For known values  $\phi$  and  $\delta$ , sunset hour angle  $\omega_s$  and monthly average of the maximum possible daily hours  $N_m$  or  $N$  are calculated from Eqs. (5) and (6), respectively. Then with assumed monthly average daily hours of bright sunshine ( $n_d$ ), the  $n_d/N_m$  ratio is calculated to be used in Eqn. (18). With known  $n$  and  $\omega_s$ , the extraterrestrial (theoretical) radiation  $H_{om}$  is calculated from Eqn. (16). The monthly average daily radiation  $H_m$  on a horizontal surface is calculated from Eqn. (18). Then  $K_m$  is obtained from Eqn. (25). Equation (26) is used to calculate the  $H_{dm}/H_m$  ratio from  $K_m$ . The calculation of  $R_{bm}$  requires sunset hour angle  $\omega_m$ . Equation (31) is used to calculate sunset hour angle  $\omega_s$ . Finally, global radiation on an inclined surface is calculated using Eqn. (33). In this way monthly average daily radiation incidences on horizontal and tilted surfaces are calculated for the 12 months of the year. A computer program was written in BASIC programming language.

### 5. Measured and Simulated Solar Radiation Data

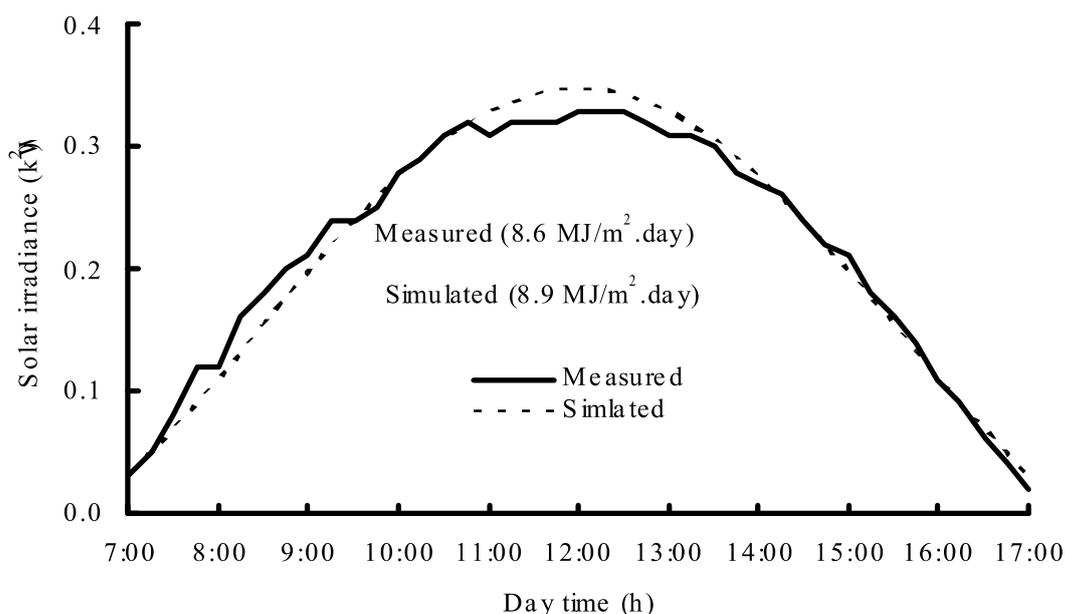
A pyranometer we used to measure the solar radiation incident on a horizontal surface for several days in October 2004 from morning to evening. The pyranometer was connected to a personal computer via a data logger (Green klt 77) to collect the radiation data at one minute intervals using BASIC programming language. Sensitivity of the pyranometer was 10.5 mV/(cal.cm<sup>2</sup>.min) (Moll-Goregiatic type MS-61). The model described was applied to generate total global hourly, daily, and monthly average radiation on a horizontal and tilted surfaces. The comparison between the measured total (beam and diffuse) and the simulated total (beam and diffuse) solar radiation on a horizontal surface versus time for clear days are shown in Figures 1 and 2. There was favourable agreement between the measured and predicted values on a day with clear skies.

For example in October 5, 2004 day, actual measured insolation on a horizontal surface was 8.04

Simulation of Solar Radiation Incident on Horizontal and Inclined Surfaces



**Figure 1.** Total (beam and diffuse) measured and simulated solar radiation a horizontal surface versus time for a clear day on October 5, 2004



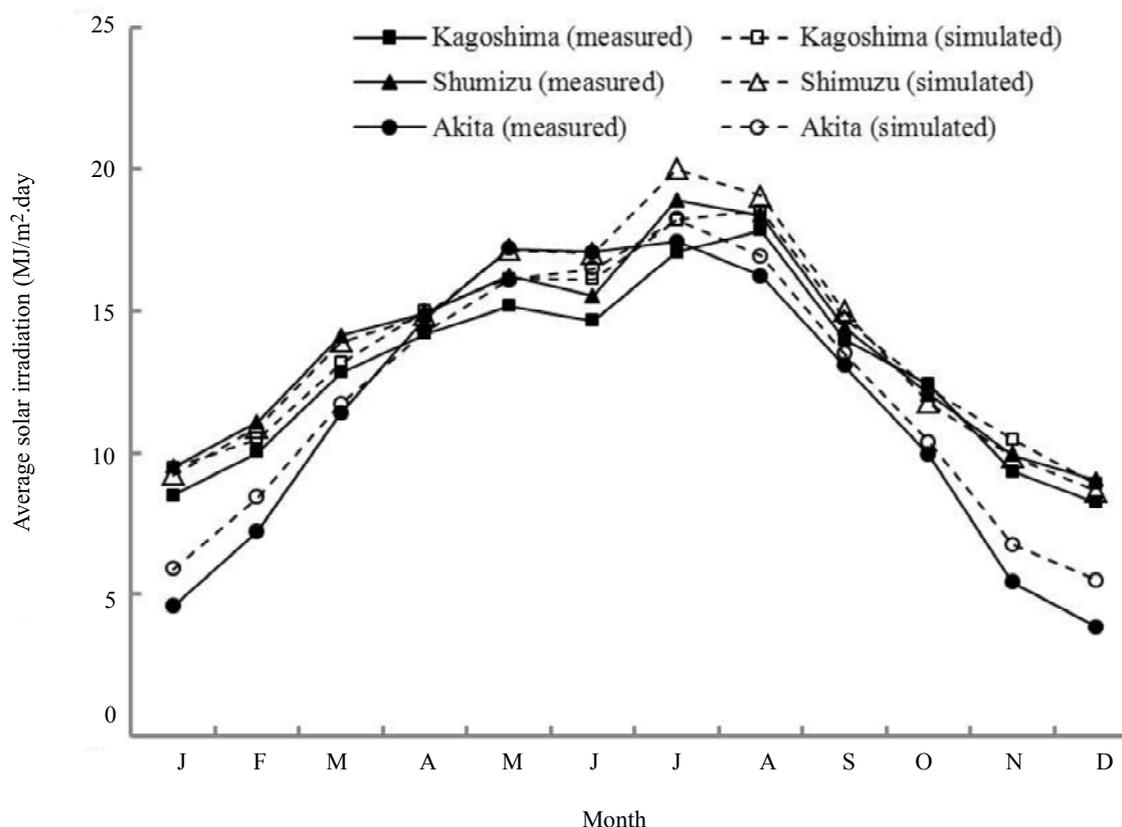
**Figure 2.** Total (beam and diffuse) measured and simulated solar radiation on a horizontal surface versus time for a clear day on October 24, 2004

$\text{MJ/m}^2$  and simulated one was  $9.5 \text{ MJ/m}^2$ . Similarly in October 24, 2004 day, actual measured insolation was  $8.6 \text{ MJ/m}^2$  and simulated one was  $8.9 \text{ MJ/m}^2$ . So the hourly and daily radiations incident on horizontal surfaces can be simulated from the theoretical relationships.

The measured monthly average daily radiation incidents on a horizontal surface of a flat plate collector

were compared for a number of stations in Japan. There was favorable agreement between the measured and simulated values (Figure 3).

It is expected that simulated values will show the same level of accuracy with the measured data of other places. Simulations show that during the paddy harvesting period from mid-September to mid-October, about  $14.7 \text{ MJ/(m}^2 \cdot \text{day)}$  of solar energy is available on



**Figure 3.** Variations of measured and simulated monthly average daily global solar radiation with time of the year at three stations of Japan

**Table 2.** Simulated monthly average daily global solar radiation incident on horizontal and inclined surfaces at Matsuyama, Japan and Bangladesh

Month	Matsuyama (Japan)		Bangladesh	
	Horizontal surface (MJ/m <sup>2</sup> )	Inclined surface (MJ/m <sup>2</sup> )	Horizontal surface (MJ/m <sup>2</sup> )	Inclined surface (MJ/m <sup>2</sup> )
January	8.88	13.09	11.26	14.06
February	10.01	12.89	11.92	13.76
March	12.80	14.32	14.22	15.08
April	14.84	14.74	15.41	15.16
May	16.16	15.20	15.93	15.17
June	16.20	14.98	15.58	14.70
July	18.27	17.01	17.77	16.80
August	18.42	17.91	18.70	18.11
September	14.42	15.29	15.59	15.97
October	11.75	14.17	13.66	15.19
November	9.86	13.67	12.29	14.80
December	8.30	12.27	10.72	13.38

Note: Tilted angle is considered as equal to the latitude of respective places

a tilted surface at Matsuyama, Japan, and that an almost similar amount (14.1 MJ/(m<sup>2</sup>.day)) of solar energy is also available during the major rice harvesting season in Bangladesh from November-December.

This energy can be utilized for drying rough rice and other farm crops. The model has been developed on the basis of available relations for hourly, daily, and monthly average radiation on horizontal and tilted sur-

faces. Bangladesh lies in a narrow range of latitude ( $20^{\circ}$  -  $26^{\circ}$  N) and, therefore, the same level of solar radiation is expected to be incident throughout the country.

## 6. Conclusions

A simulation model was developed on the basis of best available relations for daily, hourly and monthly average radiation on horizontal and tilted surfaces. The simulated hourly and daily solar radiation values were compared with the measured values and a favourable agreement was observed between them. The measured monthly average daily solar radiation was compared with the simulated values and a reasonable agreement was observed for a number of stations in Japan. Considering the narrow range of latitude and similar terrain and weather conditions, the same level of solar radiation is expected throughout Bangladesh. The amount of solar energy available during major rice harvesting season in Matsuyama, Japan, and Bangladesh are almost the same and can be used for drying rough rice and other farm crops.

## References

- Bala, BK, Zia-Uddin ATM (1990), Simulation of solar drying of rough rice. Proclamation of the 1<sup>st</sup> World Renewable Energy Congress, Reading, UK 938-942.
- Benford F, Bock JE (1939), Transaction of the Illumination Engineering Society 34:200-203.
- Collares-Pereira M, Rabl A (1979), The average distribution of solar radiation-correlation between diffuse and Hemispherical and between day and hourly insolation values. *J. of Solar Energy* 22:155-162.
- Duffie JA, Beckman WA (1991), Solar engineering of thermal process. A Wiley-International Publication. John Wiley and Sons, New York.
- Erbs DG, Klein SA, Duffie JA (1982), Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *J. of Solar Energy* 28:293-300.
- Klein SA (1977), Calculation of monthly average insolation on tilted surfaces. *J. of Solar Energy* 19: 325-330.
- Liu, BYH, Jordan RC (1962), Daily insolation on surfaces tilted toward the equator. *ASHRAE Journal* 3(10):53-58.
- Liu, BYH, Jordan RC (1963), The long-term average performance of flat-plate solar energy collectors. *J. of Solar Energy* 7:53-59.
- Lof GOG, Duffie JA, Smith CO (1966), World distribution of solar radiation. Engineering experimentation station report 21, University of Wisconsin, Madison.
- Orgill JF, Hollands KGT (1977), Correlation equation for hourly diffuse radiation on a horizontal surface. *J. of Solar Energy* 19:357-363.
- Page JK (1964), The estimations of monthly mean values of daily total short-wave radiation of vertical and inclined surfaces from sunshine records for latitudes 400N-400S. Proc. of the UN conference on new sources of Energy 4:378-385.
- Reindl DT, Beckman WA, Duffie JA (1990), Diffuse fraction correlation. *J. of Solar Energy* 45:1-6.
- Steinfeld A, Segal I (1986), A simulation model for solar thin layer drying process. *J. of Drying Technology* 4:536-554.