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Simulation of Solar Radiation Incident on Horizontal and Inclined Surfaces

MA Basunia*[a], H Yoshio[b], and T Abe[c]

[a]*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*
[b]*Department of Biomechanical Systems, Ehime University, Matsuyama, 790-8566, Japan*
[c]*Department of Biomechanical Systems, Ehime University, Matsuyama, 790-8566, Japan*

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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^2 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*، ه.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 ١٤.٧ ميجا 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.

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*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 investigates 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.

$$Cos\,\theta = Cos\,\theta_z Cos\beta + Sin\,\theta_z Sin\beta Cos(\gamma_s - \gamma) \qquad (1)$$

where θ is the angle of incidence the angle between the beam radiation on a surface and the normal to that surface; θ_z is the angle of incidence; β is the angle between the plane of the surface considered and the horizontal, $0 \le \beta \le 180^o$, λ_s is the solar azimuth angle; λ 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, $-180^o \le \lambda \le 180^o$.

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

$$Cos\,\theta_z = Cos\phi Cos\delta Cos\,\omega + Sin\phi Sin\delta \qquad (2)$$

where ϕ is the latitude, the angular location north or south of the equator; δ is the angular position of the sun at solar noon, called declination; ω 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^o 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 β to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of (ϕ - β). Modifying Eqn. (2) yields

$$Cos\,\theta = Cos\delta Cos\,\omega Cos(\phi - \beta) + Sin\delta Sin(\phi - \beta) \qquad (3)$$

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

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

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, ω_s, when $\theta_z = 90^o$

$$Cos\,\omega_s = -\frac{Sin\phi Sin\delta}{Cos\phi Cos\delta} = -(Tan\phi Tan\delta) \qquad (5)$$

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

$$N = \frac{2}{15} Cos^{-1}(-Tan\phi Tan\delta) \qquad (6)$$

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:

$$R_b = \frac{Cos\,\theta}{Cos\,\theta_z} \qquad (7)$$

Cos θ_z and *Cos* θ 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^o in the Southern Hemisphere. In this case Eqs. (2) and (3) can be used to determine *Cos* θ_z and *Cos* θ, respectively, leading in the northern hemisphere, ($\lambda = 0$), to

$$R_b = \frac{Cos\delta Cos\,\omega Cos(\phi - \beta) + Sin\delta Sin(\phi - \beta)}{Cos\phi Cos\delta Cos\,\omega + Sin\phi Sin\delta} \qquad (8)$$

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	For average day of the month date	 *n*, Day of year	 δ, 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)

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

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

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

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:

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

$$\text{or } E = C\left(Cos\phi Cos\delta Cos\omega + Sin\phi Sin\delta\right) \tag{12}$$

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

The hourly extraterrestrial radiation strikes on a horizontal surface can be estimated from Eqn. (12) by integrating it between hour angles ω_1 and ω_2. The integration for an hour period results in the following equation, where I_o is the hourly extraterrestrial radition on horizontal surface, J/m^2.

$$I_0 = \frac{12\times 3600C}{\pi}\left[\begin{array}{c} Cos\phi\, Cos\delta\left(Sin\,\omega_2 - Sin\,\omega_1\right) \\ + \dfrac{\pi\left(\omega_2 - \omega 1\right)}{180} Sin\phi\, Sin\delta \end{array}\right] \tag{14}$$

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

$$I_0 = 3600C\ \left(Sin\phi\, Sin\delta + Cos\phi\, Cos\delta\, Cos\,\omega\right) \tag{15}$$

The daily theoretical solar radiation, H_0 striking on a horizontal surface is obtained by integrating Eqn. (12) over the period from sunrise to sunset. The integration yields where H_0 is the daily extraterrestrial radiation, J/m^2, and ω_s is the sun set hour angle in degrees.

$$H_o = \frac{24\times 3600C}{\pi}\left(Cos\phi Cos\delta Sin\omega_s + \frac{\pi\omega_s}{180} Sin\phi Sin\delta\right) \tag{16}$$

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 verage fraction of possible sunshine hours is given by

$$\frac{H_m}{H_c} = a + b\frac{n_d}{N_m} \tag{17}$$

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:

$$\frac{H_m}{H_{om}} = a_1 + b_1 \frac{n_d}{N_m} \tag{18}$$

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):

$$\frac{I}{H} = \frac{\pi}{24}\left(c_1 + c_2\, Cos\,\omega\right)\frac{Cos\,\omega - Cos\,\omega_s}{Sin\,\omega_s - \frac{\pi\omega_s}{180} Cos\,\omega_s} \tag{19a}$$

where the parameters c_1 and c_2 are given by:

$$c_1 = 0.409 + 0.5016 Sin\left(\omega_s - 60\right) \tag{19b}$$

$$c_2 = 0.6609 - 0.4767 Sin\left(\omega_s - 60\right) \tag{19c}$$

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.

$$\frac{I_d}{H_d} = \frac{\pi}{24}\frac{\left(Cos\,\omega - Cos\,\omega_s\right)}{\left(Sin\,\omega_s - \frac{\pi\,\omega_s}{180} Cos\,\omega_s\right)} \tag{20}$$

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

An hourly clearness index (k_h) can be defined as

$$k_h = \frac{I}{I_o} \tag{21}$$

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:

$$\frac{I_d}{I} = 1.0 - 0.9k_h \quad \text{for} \quad k_h \le 0.22 \tag{22a}$$

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

$$\text{for} \quad 0.22 < k_h \le 0.80 \tag{22b}$$

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

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

$$k_d = \frac{H}{H_o} \tag{23}$$

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

$$\frac{H_d}{H} = 0.99 \quad \text{or} \quad k_d \le 0.17 \tag{24a}$$

$$\frac{H_d}{H} = 1.188 - 2.27k_d + 9.47k_d^2 - 21.87k_d^3 + 14.65k_d^4 \quad \text{for } 0.17\ k_d < 0.75 \tag{24b}$$

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

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

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^2. Mathematically it can be expressed as

$$K_m = \frac{H_m}{H_{om}} \tag{25}$$

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:

$$\frac{H_{dm}}{H_m} = 1.391 - 3.56K_m + 4.189K_m^2 - 2.14K_m^3 \quad \text{for } \omega_s \leq 81.4^0 \text{ and } 0.3 \leq K_m \leq 0.8 \tag{26a}$$

$$\frac{H_{dm}}{H_m} = 1.311 - 3.022K_m + 3.43K_m^2 - 1.82K_m^3 \quad \text{for } \omega_s > 81.4^0 \text{ and } 0.3 \leq K_m \leq 0.8 \tag{26b}$$

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.

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

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 β from the horizontal, F_{vg} is the view factor of the surface to the ground, and ρ_r is the surrounding diffuse reflectance for the total solar radiation. Equation (27) can be written as

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

where I_t is total hourly radiation incident on a tilted surface and β 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

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

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

$$R_{bm} = \frac{Cos(\phi - \beta) Cos\delta Sin\omega_m + (\pi / 180)\omega_m Sin(\phi - \beta) Sin\delta}{Cos\phi Cos\delta Sin\omega_s + (\pi / 180)\omega_s Sin\phi Sin\delta} \tag{30}$$

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

$$\omega_m = \min \begin{bmatrix} Cos^{-1}(-Tan\phi Tan\delta); \\ Cos^{-1}\{-Tan(\phi - \beta) Tan\delta\} \end{bmatrix} \tag{31}$$

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

$$\frac{H_T}{H_{0m}} = K \begin{bmatrix} \left(1 - \frac{H_d}{H}\right) R_{bm} + \frac{H_d}{H}\left(\frac{1 + Cos\beta}{2} \right) \\ + \rho_r \left(\frac{1 - Cos\beta}{2} \right) \end{bmatrix} \tag{32}$$

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

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

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 Eqns. (22) and (24), respectively. For a particular day of the year and location where n and φ are known, δ can be calculated from Eqn. (4). For known values of φ and δ, sunset hour angle ω_s and day light hours N_m or N are calculated from Eqns. (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 ω_m. With known n and ω_s, from Eqns. (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 Eqns. (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 Eqns. (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. φ is considered equal to β. Then Eqns. (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 δ can be calculated from Eqn. (4). For known values ϕ and δ, sunset hour angle ω_s and monthly average of the maximum possible daily hours N_m or N are calculated from Eqns. (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 ω_s, the extraterrestrial (theoretical) radiation H_{0m} 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 ω_m. Equation (31) is used to calculate sunset hour angle ω_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^2.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 insulation on a horizontal surface was 8.04

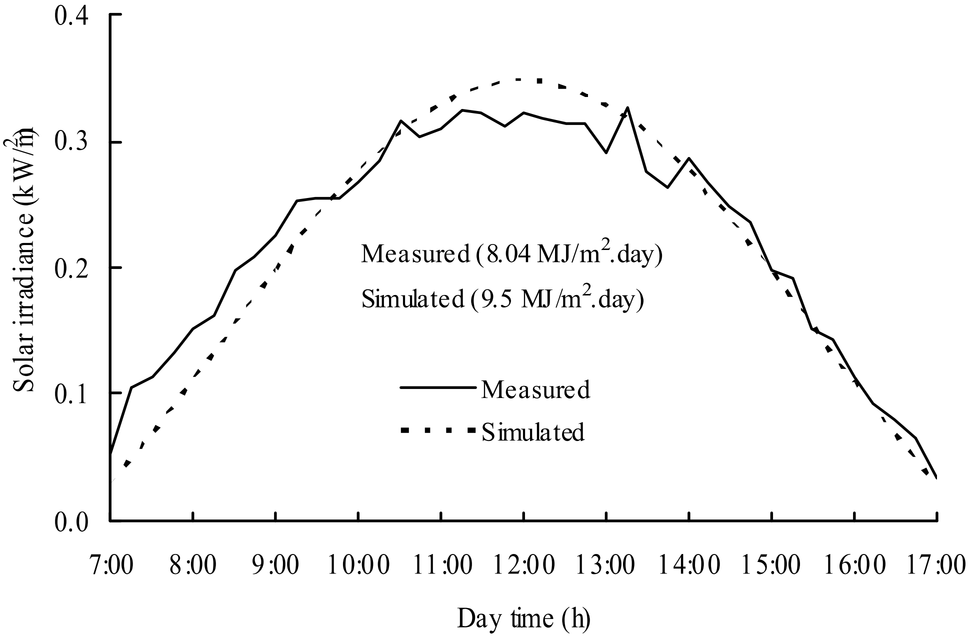

Figure 1. Total (beam and diffuse) measured and simulated solar radiation a horizontal surface versus time for a clear day on October 5, 2004

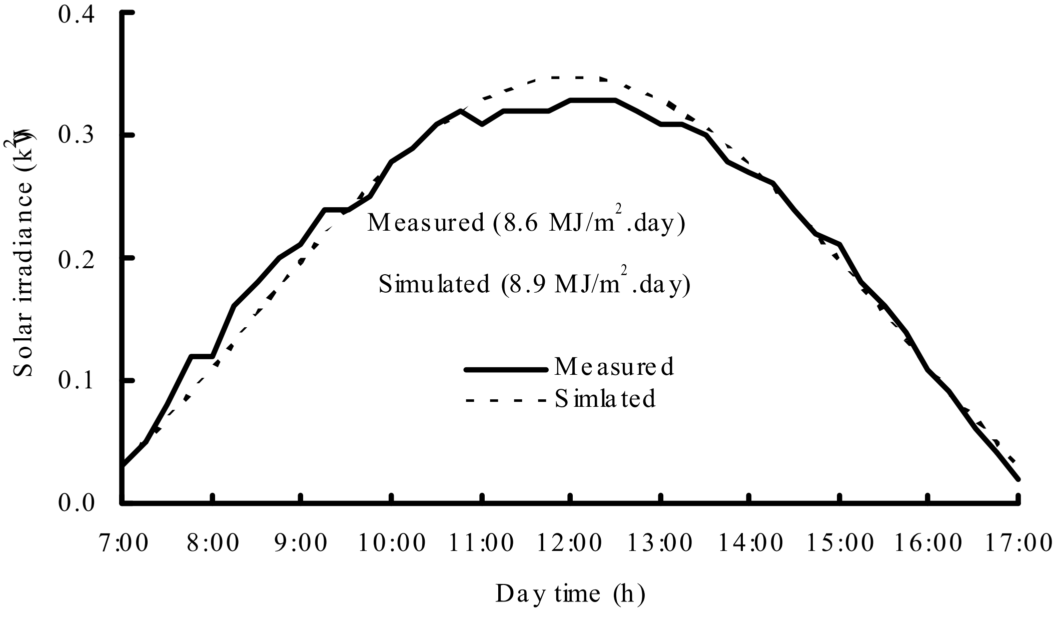

Figure 2. Total (beam and diffuse) measured and simulated solar radiation on a horizontal surface versus time for a clear day on October 24, 2004

MJ/m^2 and simulated one was 9.5 MJ/m^2. Similarly in October 24, 2004 day, actual measured insulation was 8.6 MJ/m^2 and simulated one was 8.9 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 MJ/(m^2.day) of solar energy is available on

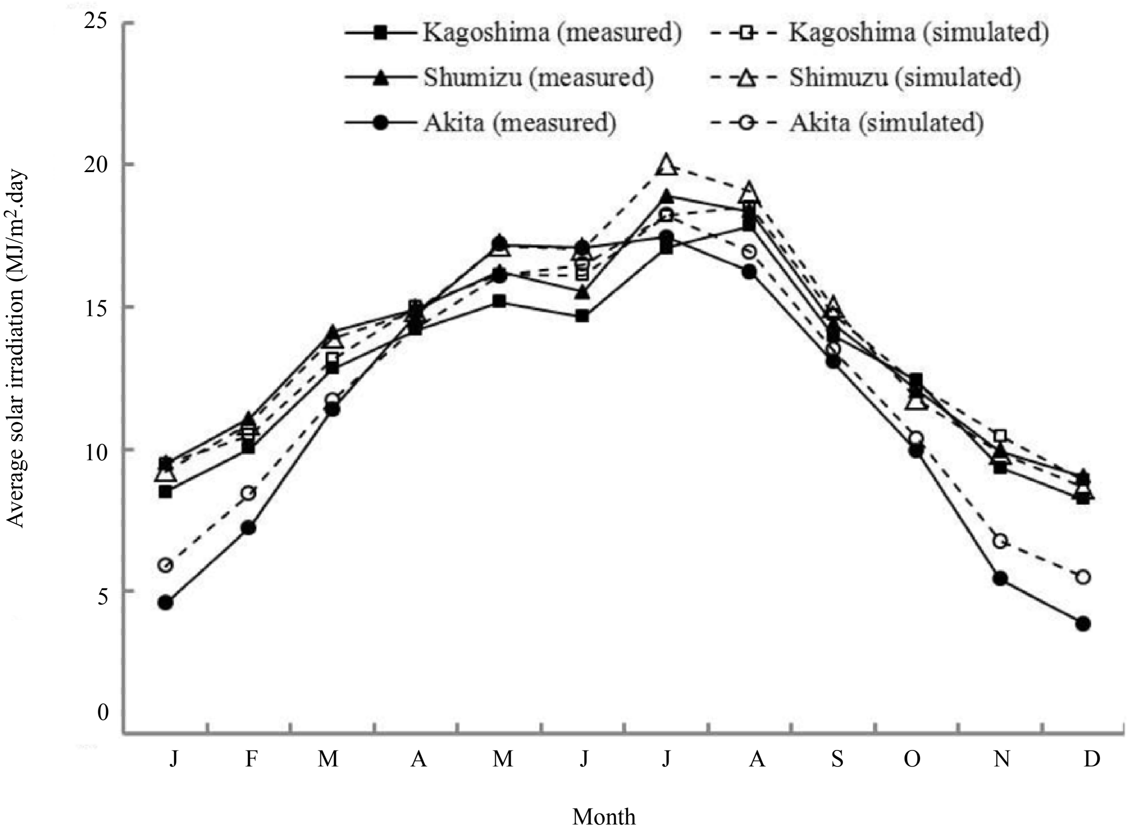

Figure 3. Variations of measured and simulated monthly average daily global solar radiation with time of the year at three stations of Japan

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

	Matsuyama (Japan)		Bangladesh	
Month	Horizontal surface (MJ/m^2)	Inclined surface (MJ/m^2)	Horizontal surface (MJ/m^2)	Inclined surface (MJ/m^2)
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 $MJ/(m^2.day)$) 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 surfaces. Bangladesh lies in a narrow range of latitude (20º - 26º 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.

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