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TECHNICAL NOTE

Calculation of the monthly-average transmittance–absorptance product

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1. INTRODUCTION

Simple design methods have been developed to estimate the monthly average thermal performance of many types of solar energy systems. Examples of design methods are the *f*-Chart method[1] for space and water heating systems, the solar load ratio method[2] for passive solar heating systems and the utilizability methods[3–5] for various types of industrial process and air conditioning systems.

These methods all require as input data, $\bar{S}$, the monthly average daily solar radiation per unit area absorbed on the collector plate surface. $\bar{S}$ is the product of $\bar{H}_T$, the monthly average daily radiation per unit area incident on a plane at the same orientation as the collector, and $(\overline{\tau\alpha})$, a monthly average transmittance-absorptance product. Methods are available to estimate $\bar{H}_T$ for surfaces of specified fixed orientation using commonly available radiation data on a horizontal surface[6]. Also, a value of the transmittance-absorptance product for radiation at normal incidence, $(\tau\alpha)_n$, can generally be obtained for experiment[7] or theory[8]. The concern of this paper is with a method of estimating the ratio of the monthly average to normal incidence transmittance–absorptance products, $(\overline{\tau\alpha})/(\tau\alpha)_n$, a factor which considers the variations in transmittance of the transparent collector cover system and absorptance of the collector plate with the solar position.

2. THE COLLECTOR TRANSMITTANCE–ABSORPTANCE PRODUCT

The transmittance of the transparent collector cover(s), τ, and the absorptance of the collector plate, α, are functions of the materials and the incidence angle of solar radiation. Ordinarily, the beam, diffuse and ground-reflected components of the solar radiation are incident on the collector surface at different angles. As a result, $(\tau\alpha)$, the transmittance–absorptance product at a given instant of time must be calculated as the radiation-weighted average of the beam, diffuse, and ground-reflected radiation components. Assuming diffuse radiation to be isotropic and a diffusively reflecting ground surface, $(\tau\alpha)$ is given by eqn (1).

$$(\tau\alpha) = \frac{G_b R_b (\tau\alpha)_b + G_d(1+\cos\beta)/2(\tau\alpha)_d + \rho G(1-\cos\beta)/2(\tau\alpha)_r}{G_T} \quad (1)$$

where G_T, is the solar flux on the tilted collector surface; G, is the solar flux on a horizontal surface; G_b, G_d, are respectively the solar fluxes of beam and diffuse radiation on a horizontal surface; R_b, is the ratio of beam radiation on the tilted surface to that on a horizontal surface; ρ, is the ground reflectance; β, is the angle between the plane of the collector and the horizontal; $(\tau\alpha)_b$, $(\tau\alpha)_d$ and $(\tau\alpha)_r$ are the transmittance–absorptance products for beam, diffuse and reflected solar radiation.

In the analysis which follows, it is convenient to divide eqn (1) by $(\tau\alpha)_n$, the transmittance–absorptance product for radiation at normal incidence, to obtain equation (2).

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{G_b R_b \dfrac{(\tau\alpha)_b}{(\tau\alpha)_n} + G_d \dfrac{(1+\cos\beta)}{2}\dfrac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho G \dfrac{(1-\cos\beta)}{2}\dfrac{(\tau\alpha)_r}{(\tau\alpha)_n}}{G_T}. \quad (2)$$

Methods for calculating G_T, G_b, G_d and R_b when G is known are given in Duffie and Beckman[8]. The transmittance-absorptance product ratios, $(\tau\alpha)_b/(\tau\alpha)_n$, $(\tau\alpha)_d/(\tau\alpha)_n$ and $(\tau\alpha)_r/(\tau\alpha)_n$, can be obtained by theory or experiment as described below.

3. THEORETICAL DETERMINATION OF THE COLLECTOR TRANSMITTANCE–ABSORPTANCE PRODUCT RATIOS

The transmittance of the transparent cover system to beam radiation at a known incidence angle can be determined by calculating the reflectance and absorptance of the covers using the Fresnel equation and Bouger's law as described in Duffie and Beckman. The collector plate absorptance for solar radiation at a particular incidence angle is difficult to assess in general since it is a function of both the material and the surface condition. Measurements of the absorptance of a non-selective blackened surface as a function of incidence angle were taken by Hottel and Woertz[9]. The limited data available suggests that the angular dependence of the absorptance of selective surfaces used in solar collectors is of similar form[10].

Some of the radiation reflected from the collector absorber surface is reflected from the transparent cover system back onto the absorber. As a result, $(\tau\alpha)_b$, the transmittance–absorptance product for beam radiation, is given by eqn (3).

$$(\tau\alpha)_b = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \quad (3)$$

where ρ_d is the reflectance of the transparent cover system for diffuse radiation. Duffie and Beckman recommend that ρ_d be calculated from the Fresnel equation with an incidence angle of 60°.

Plots of $(\tau\alpha)_b/(\tau\alpha)_n$ vs beam radiation incidence angle for cover systems consisting of one to four indentical sheets of glass (refractive index = 1.526) are given in Fig. 1. *KL*, the extinction coefficient-path length product was set to 0.04 per plate to produce Fig. 1, although it was observed that the plots are nearly independent of the value of *KL* within the range 0.01–0.06. The

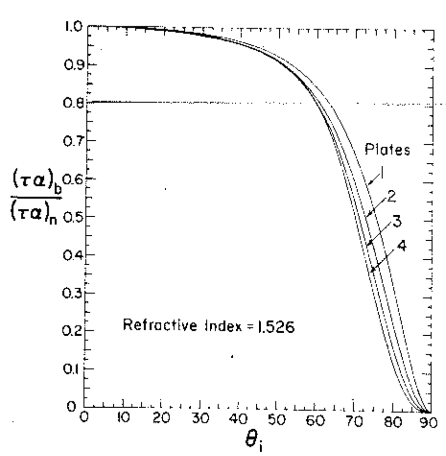

Fig. 1. $(\tau\alpha)_b/(\tau\alpha)_n$ vs incidence angle.

plots of $(\tau\alpha)_b/(\tau\alpha)_n$ are sensitive to the refractive index of the cover material, so Fig. 1 is applicable only for glass or other glazing materials such as Tedlar which have a refractive index similar to that of glass.

Assuming diffuse radiation to be isotropic, it has been shown that the transmittance-absorptance product ratio for diffuse radiation, $(\tau\alpha)_d/(\tau\alpha)_n$, has a value corresponding to that for beam radiation at an incidence angle of approx. 60°[9, 11, 12]. The transmittance–absorptance product ratio for ground-reflected radiation can be determined in a similar manner. The ground is assumed to be a diffusely reflecting surface having an average reflectance of ρ. Under these circumstances, Brandemuehl and Beckman[12] have calculated the mean incidence angle, $\bar{\theta}_r$, for which $(\tau\alpha)_b/(\tau\alpha)_n$ (from Fig. 1) is equal to $(\tau\alpha)_r/(\tau\alpha)_n$. $\bar{\theta}_r$ varies from 60° for vertical surfaces to 90° for horizontal surfaces and is given approx. by the relationship in eqn (4).

$$\bar{\theta}_r = 89.8 - 0.5788\beta + 0.002693\beta^2. \tag{4}$$

4. EXPERIMENTAL DETERMINATION OF $(\tau\alpha)_b/(\tau\alpha)_n$

The ASHRAE 93–77 solar collector testing standard[7] describes two methods of experimentally determining $K_{\tau\alpha}$, the incidence angle modifier which, in the nomenclature of this paper, is $(\tau\alpha)/(\tau\alpha)_n$. Ordinarily, collector thermal performance tests are performed on sunny days in which the diffuse radiation on the collector surface is small relative to the beam radiation. Assuming the ground-reflected radiation to be small also, the incidence angle modifier is approximately a measure of $(\tau\alpha)_b/(\tau\alpha)_n$. The ASHRAE testing standard recommends that the incidence angle modifier be plotted against $(1/\cos\theta_i - 1)$, a function which results in a linear relationship for incidence angles less than 60°. Experimental results in this form can be used in place of Fig. 1.

5. CALCULATION OF THE MONTHLY-AVERAGE TRANSMITTANCE–ABSORPTANCE PRODUCT RATIO

Equation (2) provides a relationship for the transmittance–absorptance product ratio at a given instant of time. However, it is the monthly average value, $\overline{(\tau\alpha)}/(\tau\alpha)_n$, which is needed for solar energy system design methods. The monthly-average transmittance–absorptance product is found by integrating eqn (2) with respect to time over a month of N days.

$$\frac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} = \frac{\int^N \left[G_b R_b \frac{(\tau\alpha)_b}{(\tau\alpha)_n} + G_d(1+\cos\beta)/2\frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho G(1-\cos\beta)/2\frac{(\tau\alpha)_r}{(\tau\alpha)_n}\right] \mathrm{d}t}{\int^N G_T\,\mathrm{d}t}. \tag{5}$$

The integral in the denominator of eqn (5) is $\bar{H}_T N$ monthly average radiation (per unit area) on the collector surface. H_T is the product of $\bar{H}$, the monthly average daily radiation on a horizontal surface, and $\bar{R}$, the ratio of the monthly average radiation on a tilted surface to that on a horizontal surface. A method of calculating $\bar{R}$ is given in Ref. [6].

The second and third terms within the integral in the numerator of eqn (5) are easily evaluated since $(\tau\alpha)_d/(\tau\alpha)_n$ and $(\tau\alpha)_r/(\tau\alpha)_n$ are assumed to be constants corresponding to the values of $(\tau\alpha)_b/(\tau\alpha)_n$ for incidence angles of 60° and $\bar{\theta}_r$ respectively.

$$\int^N_{G_d} (1+\cos\beta)/2(\tau\alpha)_d/(\tau\alpha)_n\,\mathrm{d}t = \bar{H}_d(1+\cos\beta)/2(\tau\alpha)_d/(\tau\alpha)_n N \tag{6}$$

$$\int^N G_\rho(1-\cos\beta)/2(\tau\alpha)_r/(\tau\alpha)_n\,\mathrm{d}t = \bar{H}\rho(1-\cos\beta)/2(\tau\alpha)_r/(\tau\alpha)_n N \tag{7}$$

In eqn (6), $\bar{H}_d$ is the monthly average daily diffuse radiation, which can be estimated if $\bar{H}$ is known using one of several similar correlations proposed by Liu and Jordan[13], Page[14], Collares-Pereira and Rabl[15] and others. Liu and Jordan's correlation is used in the example calculation which follows.

The first term in the numerator of eqn (5) is evaluated by defining $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$, the monthly average transmittance–absorptance product for beam radiation, such that

$$\int^N G_b R_b (\tau\alpha)_b/(\tau\alpha)_n\,\mathrm{d}t = (\bar{H} - \bar{H}_d)\bar{R}_b\overline{(\tau\alpha)}_b/(\tau\alpha)_n N \tag{8}$$

where $\bar{R}_b$ is the ratio of the monthly average beam radiation on the tilted surface to that on a horizontal surface. $\bar{R}_b$ can be evaluated for surfaces of any orientation in the manner described in Ref. [6]. Substituting eqns (6)–(8) into eqn (5) results in the final relation for the monthly-average transmittance–absorptance product ratio.

$$\frac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} = 1 - \left(\frac{\bar{H}_d}{\bar{H}}\right)\frac{\bar{R}_b}{\bar{R}}\frac{\overline{(\tau\alpha)}_b}{(\tau\alpha)_n} + \frac{\bar{H}_d}{\bar{H}}\frac{(1+\cos\beta)}{2\bar{R}}\frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho\frac{(1-\cos\beta)}{2\bar{R}}\frac{(\tau\alpha)_r}{(\tau\alpha)_d}. \tag{9}$$

Values of $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ have been obtained by numerically evaluating the integral in eqn (8). For this integration, it is necessary to assume that G_b is distributed through the average day according to its long-term average. Thus,

$$G_b = (r_T\bar{H} - r_d\bar{H}_d) \tag{10}$$

where r_T and r_d are the long-term average hourly to daily ratios for total and diffuse radiation which are given graphically in Liu and Jordan[13] and analytically in Collares-Pereira and Rabl[15]. It has been observed that the computational effort involved in numerically integrating eqn (8) can be greatly reduced by using a single average day to represent each month. The recommended average days given in Table 1 of Ref. [6] were used for this purpose. Table 1 compares values of $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ calculated for a single average day and for the entire month for south facing surfaces at 40°N latitude having one cover plate. The differences between the average day and entire month results are quite small.

Values of $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ have been obtained for various collector types at latitudes between 20 and 50°N, slopes between 0° and 90° and azimuths between 0° (horizontal) and 90° (due east or west) for all months of the year. The results are most conveniently presented in terms of $\bar{\theta}_b$, the mean incidence angle for beam radiation. $\bar{\theta}_b$ is the incidence angle at which $(\tau\alpha)_b/(\tau\alpha)_n$ from Fig. 1 (or from experimental incidence angle modifier plots) is equal to $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$. Plots of $\bar{\theta}_b$ are given in Figs. 2–7.

An analytical correlation for the results in Figs. 2–7 was sought, but an acceptable relationship was not found. In previous studies[1, 6], this author has indicated that for surfaces facing directly towards the equator, $\bar{\theta}_b$ can be approximated as the incidence angle at 2.5 hr from solar noon on the average day of the month. This rule leads to acceptable results for solar heating systems, but inaccurate results are obtained for the summer months for collector slopes less than about 45°. In addition, the rule is not applicable for surfaces which do not face directly towards the equator.

EXAMPLE

Estimate $\bar{S}$ for a vertical south-facing mass wall for a passively solar heated building located in Madison, Wisconsin (43°N lat.). The mass wall is unshaded and double-glazed with $(\tau\alpha)_n$ equal to 0.76. Compare these values of $\bar{S}$ with those obtained if the mass wall is oriented 30° west of south.

Table 1. Comparison of values of $\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ calculated for an average day and for a month (40°N Lat. Azimuth = 0, 1 plate)

	Tilt = 0		Tilt = 45°		Tilt = 90°	
	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ (Average day)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ Month	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ (Average day)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ (Month)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ (Average day)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$ (Month)
Jan.	0.737	0.738	0.965	0.965	0.963	0.962
Feb.	0.822	0.819	0.961	0.960	0.931	0.932
Mar.	0.885	0.884	0.951	0.951	0.861	0.862
Apr.	0.919	0.919	0.941	0.940	0.746	0.746
May	0.932	0.932	0.926	0.926	0.583	0.586
June	0.935	0.935	0.917	0.917	0.476	0.477
July	0.934	0.934	0.921	0.921	0.526	0.531
Aug.	0.926	0.925	0.935	0.935	0.686	0.691
Sept.	0.901	0.900	0.948	0.948	0.823	0.826
Oct.	0.846	0.845	0.957	0.957	0.912	0.913
Nov.	0.762	0.761	0.963	0.964	0.955	0.956
Dec.	0.705	0.705	0.966	0.966	0.968	0.968

Table 2. Calculation of $\bar{S}$ for a south-facing vertical surface in Madison, Wisconsin

	$\bar{H}$ (MJ/m²)	$\bar{K}_T$	$\bar{R}_b$	$\bar{R}$	$\bar{H}_T$ (MJ/m²)	$\bar{\theta}_b$ (°)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$	$\overline{(\tau\alpha)}/(\tau\alpha)_n$	$\bar{S}$ (MJ/m²)
Jan.	6.41	0.49	2.64	1.93	12.37	39	0.96	0.94	8.86
Feb.	9.22	0.50	1.78	1.41	12.97	48	0.93	0.91	8.96
Mar.	13.99	0.54	1.06	0.97	13.59	58	0.85	0.85	8.72
Apr.	16.53	0.49	0.55	0.63	10.40	65	0.74	0.78	6.17
May	19.82	0.51	0.30	0.47	9.33	72	0.56	0.72	5.09
June	23.07	0.56	0.21	0.41	9.36	75	0.45	0.69	4.93
July	23.24	0.58	0.25	0.43	9.90	74	0.49	0.69	5.18
Aug.	19.76	0.56	0.43	0.55	10.88	68	0.67	0.75	6.17
Sept.	16.40	0.58	0.83	0.82	13.53	61	0.81	0.82	8.40
Oct.	11.28	0.55	1.52	1.28	14.44	51	0.92	0.90	9.82
Nov.	6.31	0.44	2.38	1.68	10.63	42	0.96	0.93	7.52
Dec.	5.63	0.48	2.96	2.11	11.85	37	0.97	0.95	8.54

Values of $\bar{H}$ and corresponding values of $\bar{K}_T$ (the ratio of monthly total to extraterrestrial radiation) can be found in Ref. [1]. For January, $\bar{H}$ is 6.41 MJ/m², K_T is 0.49 and thus $\bar{H}_d/\bar{H}$ is 0.38 from eqn 10(a), Ref. [6]. $\bar{R}_b$ is found from eqn (8), Ref. [6] (for south-facing surfaces) or eqn (11), Ref. [6] (for surfaces which do not face directly south). For January, $\bar{R}_b$ is 2.64 for the south facing surface which results in a value of $\bar{R}$ of 1.93 from eqn (7), Ref. [6] with $\rho = 0.2$. $\bar{H}_T$, the monthly average daily total radiation incident of the vertical south-facing surface, is the product of $\bar{H}$ and $\bar{R}$, equal to 12.37 MJ/m²-day. The monthly

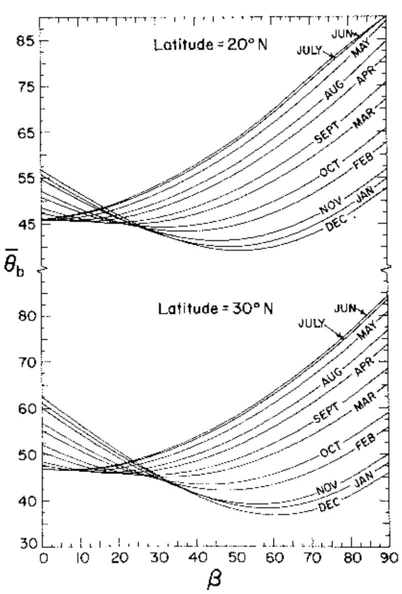

Fig. 2. $\bar{\theta}_b$ vs slope for south-facing surfaces at 20°N and 30°N.

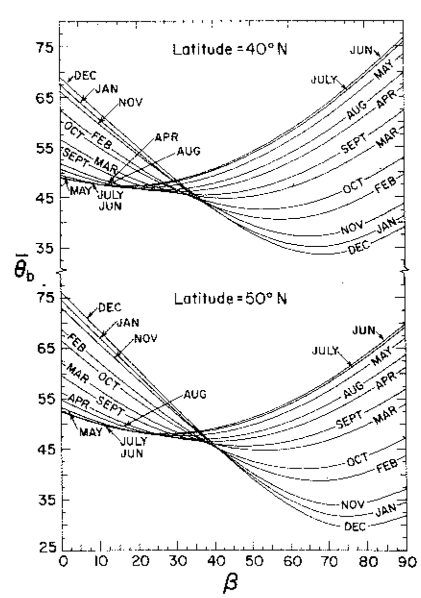

Fig. 3. $\bar{\theta}_b$ vs slope for south-facing surfaces at 40°N and 50°N.

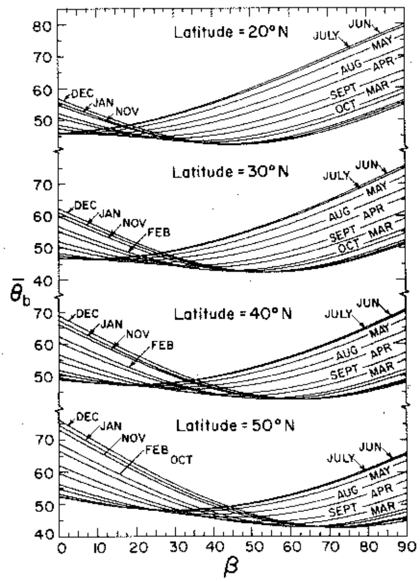

Fig. 4. $\bar{\theta}_b$ vs slope for surfaces facing 30° east or west of south.

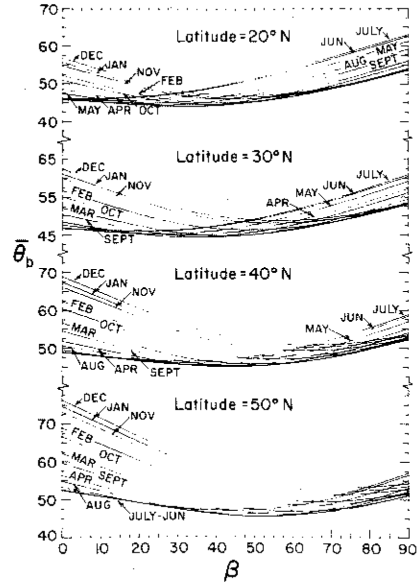

Fig. 6. $\bar{\theta}_b$ vs slope for surfaces facing 60° east or west of south.

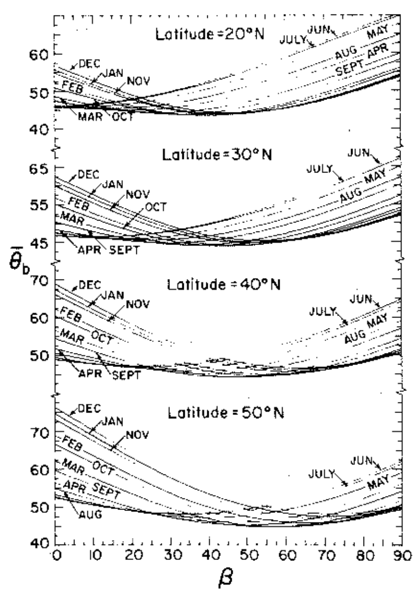

Fig. 5. $\bar{\theta}_b$ vs slope for surface facing 45° east or west of south.

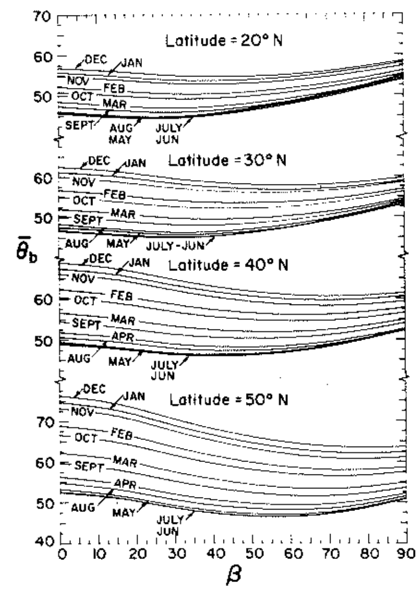

Fig. 7. $\bar{\theta}_b$ vs slope for surfaces facing 90° east or west of south.

Table 3. Calculation of $\bar{S}$ for a vertical surface facing 30° west of south in Madison, Wisconsin

	$\bar{H}$ (MJ/m²)	$\bar{K}_T$	$\bar{R}_b$	$\bar{R}$	$\bar{H}_T$ (MJ/m²)	$\bar{\theta}_b$ (°)	$\overline{(\tau\alpha)}_b/(\tau\alpha)_n$	$\overline{(\tau\alpha)}/(\tau\alpha)_n$	$\bar{S}$ (MJ/m²)
Jan.	6.41	0.49	2.29	1.71	10.96	48	0.93	0.91	7.60
Feb.	9.22	0.50	1.58	1.28	11.77	50	0.92	0.90	8.04
Mar.	13.99	0.54	1.03	0.95	13.26	54	0.89	0.88	8.79
Apr.	16.53	0.49	0.64	0.69	11.32	60	0.83	0.83	7.12
May	19.82	0.51	0.41	0.54	10.75	67	0.70	0.77	6.24
June	23.07	0.56	0.32	0.48	11.01	69	0.65	0.75	6.23
July	23.24	0.58	0.36	0.50	11.66	69	0.65	0.74	6.53
Aug.	19.76	0.56	0.53	0.62	12.30	63	0.78	0.80	7.47
Sept.	16.40	0.58	0.85	0.85	13.86	56	0.88	0.86	9.05
Oct.	11.28	0.55	1.37	1.18	13.31	51	0.92	0.90	9.04
Nov.	6.31	0.44	2.07	1.50	9.49	48	0.93	0.91	6.55
Dec.	5.63	0.48	2.56	1.86	10.49	47	0.94	0.92	7.31

average transmittance-absorptance product ratio is found from eqn (9). From Fig. 1 at an incidence angle of 60°, $(\tau\alpha)_d/(\tau\alpha)_n$ is 0.83. From eqn (4), $\bar{\theta}_r$ is approx. 60°, so $(\tau\alpha)_r/(\tau\alpha)_n$ is also 0.83. The mean incidence angle for beam radiation, $\bar{\theta}_b$, at a 43°N latitude is found to be 39° by linearly interpolating the January values for latitudes of 40° and 50° in Fig. 3. Thus $(\overline{\tau\alpha})_b/(\tau\alpha)_n$, from Fig. 1, is 0.96. Substitution of these values into eqn (9) results in $(\overline{\tau\alpha})/(\tau\alpha)_n$, equal to 0.94. $\bar{S}$, the product of $\bar{H}_T$, $(\tau\alpha)_n$ and $(\overline{\tau\alpha})/(\tau\alpha)_n$, is then 8.86 MJ/m^2. The calculations are summarized in Table 2 (for the south-facing surface) and Table 3 (for the vertical surface facing 30° west of south).

NOMENCLATURE

- G total solar flux on a horizontal surface, W/m^2
- G_b beam solar flux on a horizontal surface, W/m^2
- G_d diffuse solar flux on a horizontal surface, W/m^2
- G_T total solar flux on an inclined surface, W/m^2
- $\bar{H}$ monthly-average daily total radiation incident on a horizontal surface, J/m^2
- $\bar{H}_d$ monthly-average daily diffuse radiation incident on a horizontal surface, J/m^2
- $\bar{H}_T$ monthly-average daily total radiation incident on an inclined surface J/m^2
- KL extinction coefficient—path length product for a transparent cover
- $\bar{K}_T$ ratio of monthly total to extraterrestrial radiation on a horizontal surface
- $K_{\tau\alpha}$ incidence angle modifier $((\tau\alpha)/(\tau\alpha)_n)$
- N number of days in a month
- $\bar{R}$ ratio of monthly-average radiation on an inclined surface to that on a horizontal surface
- R_b ratio of the beam radiation on an inclined surface to that on a horizontal surface
- $\bar{R}_b$ ratio of monthly-average beam radiation on a tilted surface to that on a horizontal surface
- $\bar{S}$ monthly-average daily total radiation absorbed on an inclined surface, J/m^2
- t time, sec

Greek characters

- α absorptance for solar radiation
- β surface inclination (°)
- θ_i incidence angle of solar radiation (°)
- $\bar{\theta}_b$ mean incidence angle for beam radiation (°)
- $\bar{\theta}_r$ mean incidence angle for ground-reflected radiation (°)
- ρ ground reflectance
- ρ_d reflectance of the transparent cover system for diffuse radiation
- $(\tau\alpha)$ collector transmittance–absorptance product
- $(\tau\alpha)_b$ collector transmittance–absorptance product for beam radiation
- $(\tau\alpha)_d$ collector transmittance–absorptance product for diffuse radiation
- $(\tau\alpha)_n$ collector transmittance–absorptance product for diffuse at normal incidence
- $(\overline{\tau\alpha})$ monthly-average collector transmittance–absorptance product
- $(\overline{\tau\alpha})_b$ monthly-average collector transmittance–absorptance product for beam radiation

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