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Yearly, Seasonal and Monthly Daily Average Diffuse Sky Radiation Models

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ABSTRACT. A daily average diffuse sky radiation regression model based on daily global radiation was developed utilizing two year data taken near Blytheville, Arkansas (Lat. = 35.9°N, Long. = 89.9°W), U.S.A. The model has a determination coefficient of 0.91 and 0.092 standard error of estimate. The data were also analyzed for a seasonal dependence and four seasonal average daily models were developed for the spring, summer, fall and winter seasons. The coefficient of determination is 0.93, 0.81, 0.94 and 0.93, whereas the standard error of estimate is 0.08, 0.102, 0.042 and 0.075 for spring, summer, fall and winter, respectively. A monthly average daily diffuse sky radiation model was also developed. The coefficient of determination is 0.92 and the standard error of estimate is 0.083. A seasonal monthly average model was also developed which has 0.91 coefficient of determination and 0.085 standard error of estimate. The developed monthly daily average and daily models compare well with a selected number of previously developed models.

The future acceptance of solar energy as viable alternative to fossil fuel depends not only on design of efficient collection and storage systems, but also on knowledge of the solar energy available at the site under consideration. While total solar radiation on a horizontal surface is available in many locations, means of estimating the diffuse and direct normal components of this total is often desirable. These components are required for the sizing of solar collection systems such as flat plate collectors, concentrating collectors and photovoltaics.

There are quite large number of diffuse radiation models available in literature. In the models by Ruth and Chant (1976), Stanhill (1966), Collares-Pereira and Rabl (1979) and Liu and Jordan (1960), diffuse radiation is estimated from knowledge of global radiation on a horizontal surface. Nagaraja *et al.* (1983), Al-Riahi *et al.* (1992) and Coppolino (1992) developed models to estimate diffuse radiation from measured values of global radiation and percent of sunshine.

The diffuse solar radiation models may be hourly, daily or monthly models. In these models, the ratio of diffuse to total solar radiation on a horizontal surface (H_d/H) is related with the ratio of total radiation on a horizontal surface to that of the extraterrestrial radiation (H/H_o or K_t). The ratio K_t is often called clearness index.

A number of insolation models have been developed to predict the diffuse sky radiation from historical data of solar radiation. One of the first of these is the Liu and Jordan model that was developed in 1960. The Liu and Jordan model was based on data gathered from four stations in the United States and Europe. These stations were located in Nice, France (1931 - 1933); Helsingfors, Finlands (1928 - 1931); Kew Observatory in London (1947 - 1951) and Blue Hill, Massachusetts (1947 - 1956). This model was the pioneer attempt at devising a method for estimating the diffuse component of solar radiation using statistical averages. Their model remained as the standard model until nearly 1979 for all other models to compare with.

It had been noticed that many subsequent models generally deviated from the Liu and Jordan model by about 10%. The cause of this was attributed by Klein (1977), to the failure on Liu and Jordan's part to correct for the shadow band and the differing characteristics of the sky when taking diffuse radiation readings. The Kew Observatory data was the only data that had any correction factor for the shadow band used by Liu and Jordan in their model. The correction factor varies between 1 to 6 percent. The best fit equation for the Liu and Jordan model is:

$$\bar{H}_d / \bar{H} = 1.390 - 4.027\bar{K}_t + 5.531\bar{K}_t^2 - 3.108\bar{K}_t^3 \quad (1)$$

where:

$\bar{K}_t = \bar{H}/\bar{H}_o$

$\bar{H}_d$: Monthly average of daily diffuse radiation received on a horizontal surface.

$\bar{H}$: Monthly average of daily global radiation received on a horizontal surface.

$\bar{H}_o$: Monthly average of daily extraterrestrial radiation received on a horizontal surface.

Two other monthly models are the Choudhury (1963) and Page (1961) models both of which demonstrate linear relationships between K_t and H_d/H. The Choudhury model is based on data collected in New Delhi, India from 1957 to approximately 1961 (Choudhury 1963). This is the first model published after the Liu and Jordan model and in this case there was a correction factor used to account for error due to the shading ring on the diffuse readings. However, in the original paper, the opinion was that the Liu and Jordan model was more accurate and that the overestimation of diffuse radiation was probably due to intense pollution in the New Delhi sky. The

Page model was based on data gathered from ten different stations (Page 1961). Klein (1977) performed a comparison of Page, Liu and Jordan and Choudhury models and found that the Page model was in close agreement with the Choudhury model and the Liu and Jordan model underestimated the other two models, thus lending greater validity to that model. The Page model is expressed by the relationship:

$$\overline{H}_d/\overline{H} = 1.00 - 1.13\overline{K}_t \tag{2}$$

Since Page model was developed from a broader data base than the Choudhury, Page model will be considered for comparison with the model developed in the present work.

The Collares-Pereira and Rabl monthly model is one of the most recent developed models (Collares - Pereira and Rabl 1979). This was based on data gathered from five different stations located in Albuquerque, New Mexico, Forthood, Texas; Livermore, California; Raleigh, North Carolina and Maynard, Massachusetts; each having approximately two years worth of data, (Collares-Pereira and Rabl (1979)).

According to Duffie and Beckman (1980), the Collares-Pereira and Rabl model was considered one of the best models available and thus was recommended to be used for the calculation of diffuse radiation.

Duffie and Beckman (1980) indicated that there is a considerable disagreement among the various correlations mentioned above. Instrumental problems may contribute to the differences and atmospheric variables (air mass, season, or others) which may have to be taken into account. Nonetheless, there remain important questions of the best method for doing the estimations.

The objectives of this paper are to: (1) develop a statistical model to estimate the diffuse component of monthly and daily average radiation, and (2) to compare the developed models with Liu and Jordan, Page and Collares-Pereira and Rabl models.

Data Base for Solar Radiation

The models described in this paper were based on data taken near Blytheville, Arkansas (Lat. 35.9°N, Long. 89.9°W) over a two years period extending from April 1978 to April 1980. Total horizontal radiation was measured using an Eppley PSP pyranometer. Diffuse sky radiation was measured also using an Eppley pyranometer equipped with an Eppley shadow band. Although these two pyranometers were part of a comprehensive weather and solar radiation measuring station connected to a remote monitoring system, the shadow band was checked daily and adjustments was made as needed. The solar radiation measuring instruments were calibrated each year, which gives more confidence in the accuracy of the data collected. The pyranometers used are sensitive to solar radiation in the band of wavelength, $0.285 \leq \lambda \leq 2.8$ μm. The PSP pyranometers cosine response is ± 1% from normalization 0° - 70° zenith angle and ± 3% for 70 - 80° zenith angle. The temperature dependence is within ± 1% over the ambient temperature range - 20° to 40°C. The linearity is within ± 0.5% from 0 to 1400 W/m^2.

Data are recorded at one-minute intervals, hourly values are obtained from these values. The actually used data consist of hourly readings of the global radiation and the diffuse radiation on a horizontal surface.

This data base was collected by a sophisticated system and it was felt that it would be more reliable than any other available data base.

Results and Discussion

Daily Average Model

The daily sum of diffuse radiation (H_d) was obtained from the summation of the hourly values of diffuse radiation. Hourly values of diffuse radiation was calculated from hourly values of global and direct normal radiation. The clearness index (K_t) is defined as the ratio of the daily global radiation (H) to the daily extraterrestrial radiation (H_o). Experimental data of daily diffuse fraction (H_d/H) versus clearness index, K_t (H/H_o) is shown in Fig. 1. Statistical analysis of the data yielded the following empirical model for any day of the year.

$$H_d/H = 0.939 + 0.627K_t - 3.455K_t^2 + 1.721K_t^3 - 0.113K_t^4 \quad (3)$$

Where:

$K_t = H/H_o$
H_d : Daily diffuse radiation received on a horizontal surface.

H : Daily global radiation received on a horizontal surface.

H_o : Daily extraterrestrial radiation received on a horizontal surface.

The equation is shown graphically along with the data in Fig. 1.

The coefficient of determination (R^2) is 0.91 and the standard error of estimate is 0.092. This model is valid only for K_t values in the range from K_t = .11 to .74. For values of K_t ranging from 0 to .11 the curve can be considered constant at a value of H_d/H = .96 ± 0.016. For values of K_t greater than .74, H_d/H has a value of 0.17 ± 0.027.

Seasonal Daily Average Model

It is well known that solar radiation intensity is highly affected by variation of constituents of the atmosphere like dust, aerosols, smoke and clouds. Clouds, in particular, have a pronounced effect on the insolation. In areas where overcast skies

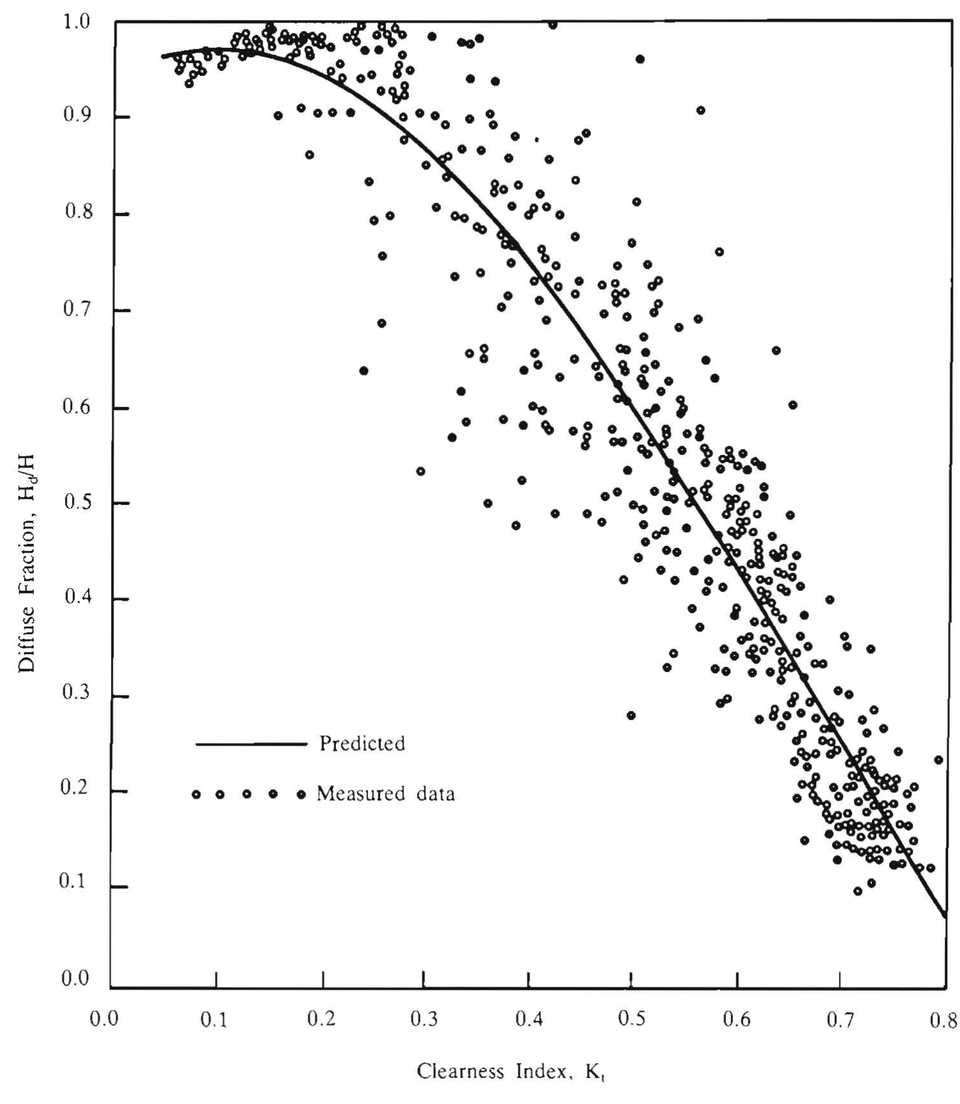

Fig. 1. The ratio of daily diffuse fraction as a function of clearness index, K_t.

are predominant in winter and under such conditions, the beam radiation is diffused by the water vapor particles. Thus, a greater proportion of the radiation reaching the earth surface is diffuse radiation. This is the case which is mostly encountered in winter and with a lesser extent in fall. The presence of clouds is minimum in spring and summer.

The data were also analyzed for a seasonal dependence. The data was grouped into the four seasons according to the spring. summer, fall and winter solstices of the sun. A regression correlation of the ratio of seasonal average daily diffuse to seasonal average daily total radiation with the ratio of seasonal average daily total radiation to seasonal average daily extraterrestrial radiation, ($K_t = H/H_o$) is developed and presented in the following regression equations:

Winter

$$H_d/H = 0.983 - 0.499K_t + 4.316K_t^2 - 13.289K_t^3 + 8.710K_t^4 \quad (4)$$

The coefficient of determination (R^2) is 0.93 and the standard error of estimate is 0.075.

Spring

$$H_d/H = 0.845 + 2.239K_t^2 - 11.924K_t^2 + 17.339K_t^3 - 9.455K_t^4 \quad (5)$$

The coefficient of determination (R^2) is 0.93 and the standard error of estimate is 0.08.

Summer

$$H_d/H = 1.075 + 0.183K_t - 7.018K_t^2 + 14.820K_t^3 - 11.093K_t^4 \quad (6)$$

The coefficient of determination (R^2) is 0.81 and the standard error of estimate is 0.102.

Fall

$$H_d/H = 1.030 + 1.044K_t + 4.340K_t^2 - 11.200K_t^3 + 6.889K_t^4 \quad (7)$$

The coefficient of determination (R^2) is 0.94 and the standard error of estimate is 0.042.

Figure 2 shows the trend of variation of the diffuse radiation represented by the regression equation for each season. It is evident from the figure that winter has a higher diffuse component of radiation which is probably caused by the frequent cloud cover in winter. Fall follows next with slightly lower value.Spring and summer follow with approximately the same value for each. It can be concluded that a seasonal dependence does exist in the daily diffuse model.

Monthly Model

The daily summation of diffuse radiation for each month of the year were grouped. Statistical analysis was performed to determine the best fit for the correlation of the ratio of monthly average daily diffuse radiation to the monthly average daily total radiation with the corresponding clearness index $\bar{K}_{t+}= \bar{H}/\bar{H}_0)$

From the curve fit program, the coefficient up to the tenth order were obtained. However, the fourth order best fit equation was considered accurate enough to plot the model curve. The model has the following form:

$$(\bar{H}_d / \bar{H} = 1.7314 - 4.742\bar{K}_t + 2.45756\bar{K}_t^2 + 8.888\bar{K}_t^3 - 10.223\bar{K}_t^4 \qquad (8)$$

The coefficient of determination (R^2) is 0.92 and the standard error of estimate is 0.083.

Seasonal Monthly Average Model

For the monthly model a block of 26 days was defined as a "month" because this left one with a minimum of left over days to be discarded. In this particular model a seasonal dependence was noticed and three curves were established, one for winter, one for spring-fall and one for the summer time. These curves were distinguished from each other by the sunset hour angle (W_{ss}). The least squares fit yielded the following equation for diffuse fraction:

$$\bar{H}_d / \bar{H} = 0.775 + 0.247(W_{ss} - \pi/2) - 0.505 + 0.261\,(W_{ss} - \pi/2)\chi \cos 2(\bar{K}_t - 0.9) \qquad (9)$$

The various seasonal curves were distinguished from one another by the following boundary conditions following the procedure of Collares-Periera and Rabl (1979).

$W_{ss} \leq \pi/2 - 0.15$	For Winter
$W_{ss} \geq \pi/2 + 0.15$	For Summer
$\pi/2 - 0.15 < W_{ss} < \pi/2 + 0.15$	For Spring and Fall

The coefficient of determination (R^2) is 0.91 and the standard error of estimate is 0.085.

However, for the sake of comparison with other models only the middle or spring-fall curve will be used. This curve represents more or less an average for all seasons.

Comparison to Other Models

To check the validity of the developed regression models, a comparison was made with a number of previously developed models. The daily average diffuse model was compared with the Collares-Pereira and Rabl model (1979). This model was based on two years of data gathered from five locations. It is presently widely accepted model and will thus be compared with the developed daily model.

Figure 3 clearly shows the close agreement between the proposed daily model, equation (3) and that of Collares-pereira and Rabl model. As a more concrete comparison ten values of K_t, ranging from .2 to .7, were used to compute the values of

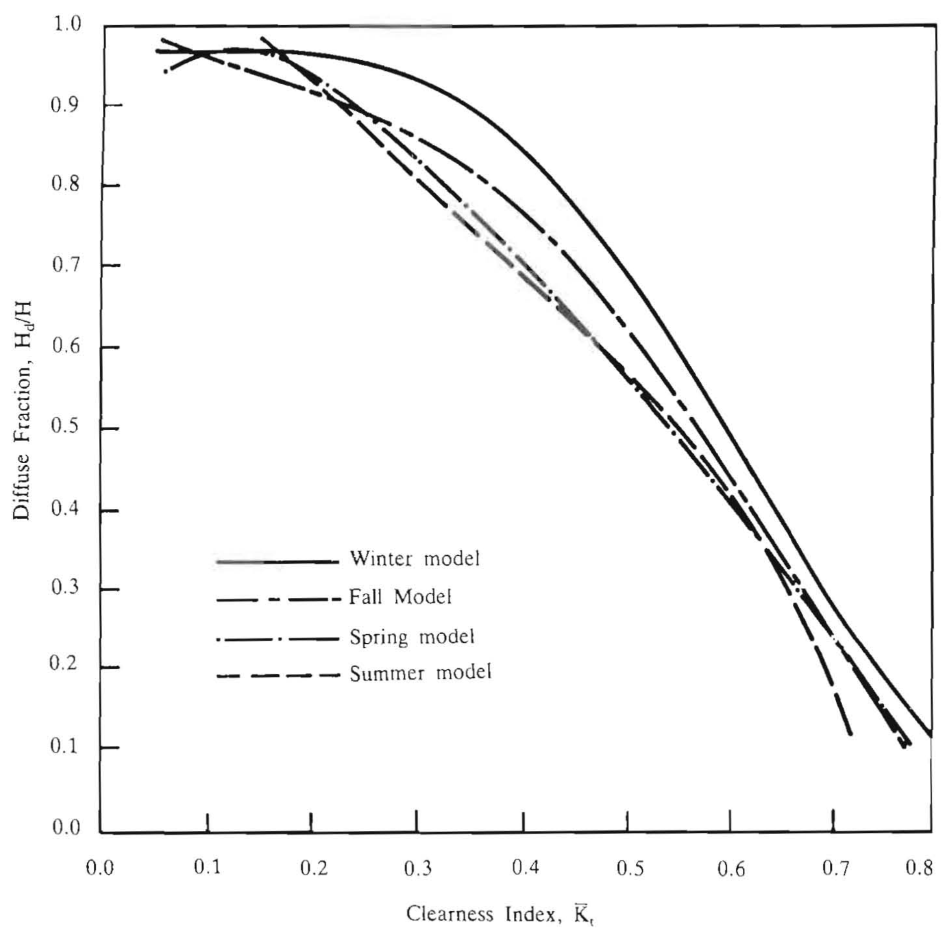

Fig. 2. Seasonal models for daily diffuse fraction as a function of clearness index, K_t.

H_d/H using the two models. Using the Collares-Pereira and Rabl daily model as a base, the developed daily model differs by an average of 2.74% ranging from + 3.5% to − 4.6%. These minor differences can be attributed to the differences between atmospheric conditions of localities where data was taken.

The proposed monthly average daily diffuse radiation model is compared with three similar models. These models are Liu and Jordan model (1960), Page model (1961) and the Collares-Pereira and Rabl model (1979).

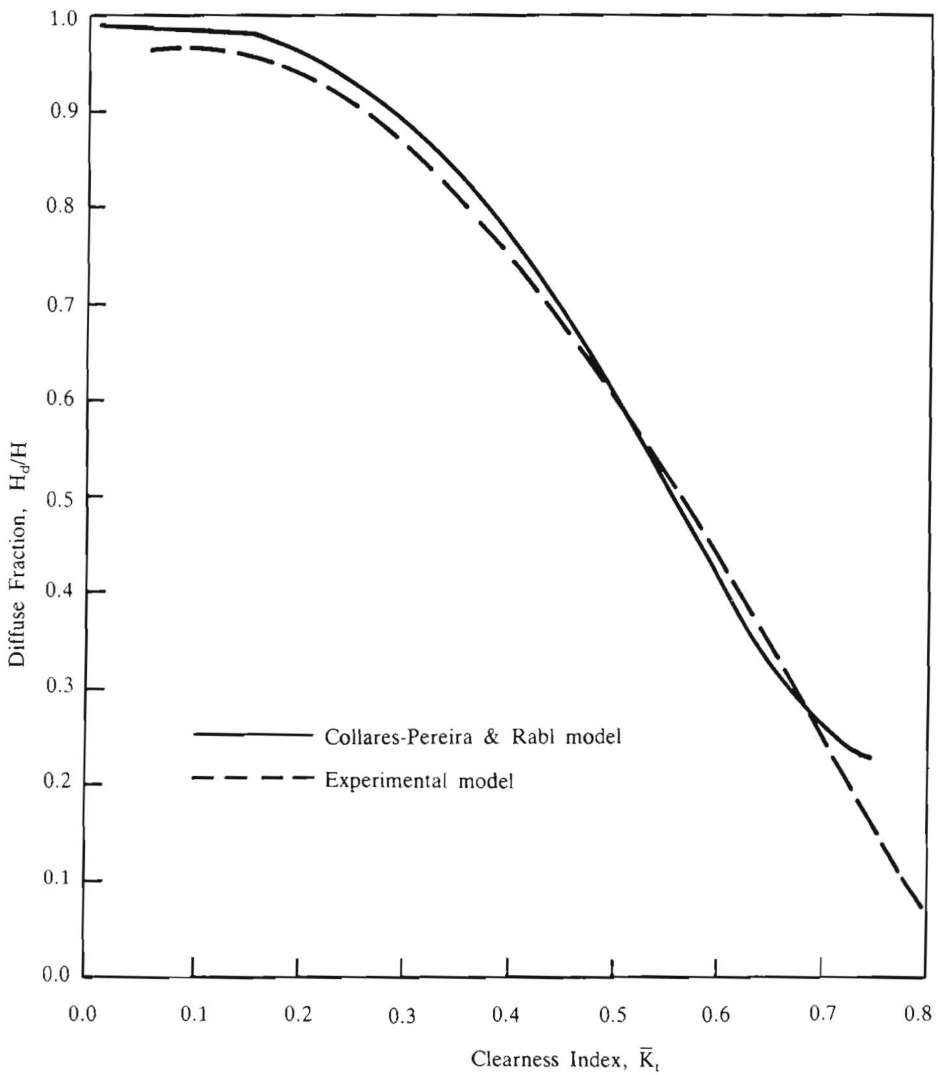

Fig. 3. Comparison between the developed daily model and Collares-Pereira & Rabl model.

These models were developed in sequence of time and it was felt that they would be a good representation of the monthly model research to date. The Liu and Jordan model was selected mainly because it was the first one. The Page model is a good intermediate model whereas the Collares-Pereira and the Collares-Pereira and Rabl model is one of the most recent one and is currently one of the more commonly recommended models. When comparing the models fourteen values of $\bar{K}_t$ ranging from 0.3 to 0.625, in increments of 0.025 were used to compute $\bar{H}_d/\bar{H}$ for all four models including the proposed model (Table 1). It is found that the Liu and Jordan model underpredicts the proposed monthly daily average diffuse model by an average of 15%. The Page model underpredicts the proposed model by about 3.5%. The Collares-Pereira and Rabl model also underpredicts the proposed model by about

Table (1). Comparison Between (H_d/H) values predicted by the proposed monthly model and other models

$\bar{K}$	$\bar{H}_d \bar{H}$			
	L&J*	**Page**	**C-P and R**	**Proposed**
0.3	0.5958	0.661	0.5899	0.6869
0.325	0.5587	0.63275	0.5666	0.64056
0.35	0.5248	0.6045	0.5438	0.6000
0.375	0.4938	0.57625	0.52155	0.5648
0.4	0.4652	0.548	0.500	0.5344
0.425	0.4390	0.45198	0.4791	0.5080
0.45	0.4147	0.4915	0.4589	0.4851
0.475	0.39202	0.46325	0.43955	0.4646
0.5	0.37075	0.435	0.4210	0.4458
0.525	0.35057	0.40675	0.40342	0.4275
0.55	0.33118	0.3785	0.38673	0.4086
0.575	0.3123	0.35025	0.371021	0.3879
0.6	0.29363	0.322	0.35634	0.3640
0.625	0.275	0.2938	0.3427	0.3356

*L&J : Model by Liu and Jordan model (1960)
Page: Model by Page (1961).
C-P and R: Model by Collares-Pereira and Rabl (1979).

6.5%. This trend can be seen clearly in Figure 4, where the proposed model is shown together with the other three models discussed above. Although Liu-Jordan work is considered to be a pioneer, it is well understood that their measurements of diffuse radiation was not corrected for the reduction of diffuse radiation due to the presence of the shadow band. Figure 4 shows that the Liu-Jordan model of the monthly average daily diffuse radiation underpredicts that of the present work. Page model presented in Fig. 4 is a linear model which is a rough approximation of the actual non linear variation of $\bar{H}_d/\bar{H}$ versus $\bar{K}_t$. Collares-Pereira and Rabl underpredicts the model proposed in this work in equation (8) and presented in Fig. 4.

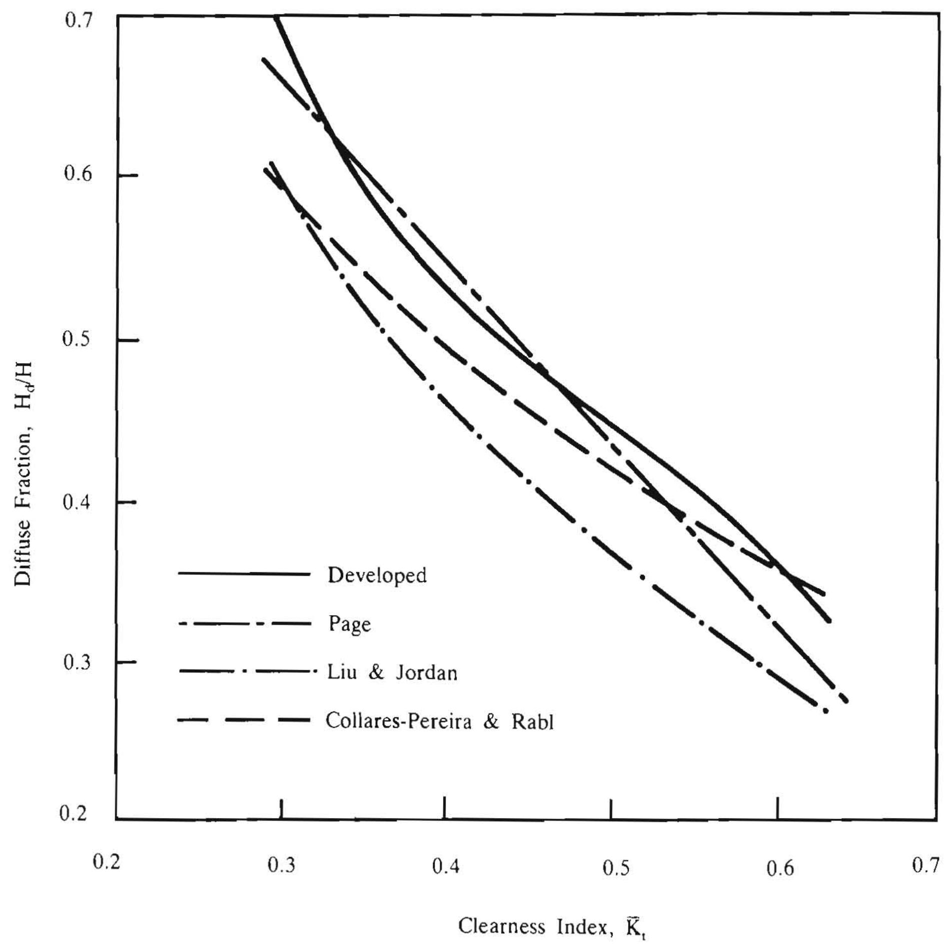

Fig. 4. The monthly average daily diffuse radiation as a function of the clearness index.

Conclusion

1. A model to compute the yearly daily average diffuse radiation was developed on the basis of data measured near Blytheville, Arkansas, U.S.A. and compared with another model by Collares-Pereira and Rabl (1979). A close agreement between these two models was found.

2. Four seasonal models were also developed with the same data set. It was found that winter has a higher daily diffuse radiation which is probably caused by the more frequent cloud cover, fall follows next, whereas spring and summer have the lowest diffuse radiation.

3. A monthly daily average diffuse model was also developed and compared with that of Liu and Jordan, Page and the Collares-Pereira and Rabl model. The Page model seemed to be most closely compared with the developed model.

References

Al-Riahi, M., **Al-Hamadani, N.** and **Tahir, K.** (1992) An Empirical Method for Estimation of Hourly Diffuse Fraction of Global Radiation, *Renewable Energy*, **2**(4/5): 451.

Choudhury, N.K.D. (1963) Solar Radiation At New Delhi, *Solar Energy*, **7**: 44.

Collares-Pereira and **Rabl,** (1979) The Average Distribution of Solar Radiation - Correlations Between Diffuse and Hemispherical and Between Daily and Hourly Insolation Values, *Solar Energy*, **22**: 155.

Coppolino, S. (1992) Applicability of a Simple Model for Computing diffuse Solar Radiation to Locations of the European, Asian and North American Areas, *Renewable Energy*, **2**(4/5): 469.

Duffie, J.A. and **Beckman, W.A.** (1980) *Solar Engineering of Thermal Processes*, John Wiley and Sons, New York.

Klein, S.A. (1977) Calculation of monthly average insolation on titled surfaces, *Solar Energy*, **19**: 325.

Liu, B.Y.U. and **Jordan, R.C.** (1960) The Interrelationship and Characteristics Distribution of Direct, Diffuse and Solar Radiation, *Solar Energy*, **4**(1).

Nagaraja, Rav C.R. and **Bradley, A.** (1983) Estimation of the Daily Global Solar Irradiation at Corvalis, Oregon, U.S.A. from the Hours of Bright sunshine, the daily Temperate Range and Relative Humidity, *Journal of Climatology*, **3**: 197.

Page, J.K. (1961) The estimation of monthly mean values of daily total shortwave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N - 40°S, Proc. U.N. Conf. on New Sources of Energy, Paper No. 35/5/98.

Ruth, D.W. and **Chant, R.W.** (1976) The Relationship of Diffuse Radiation to Total Radiation in Canada, *Solar Energy*, **18**: 153.

Stanhill, G. (1966) Diffuse Sky and Cloud Radiation in Israel, *Solar Energy*, **10**: 96.

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المعدل السنوي والفصلي والشهري لشدة الأشعة المشتتة خلال يوم

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يعتمد مستقبل إستخدام الطاقة الشمسية كمصدر بديل وهام للطاقة ليس فقط على تطوير كفاءة المجمعات الشمسية وأنظمة تخزين الطاقة وإنما أيضاً على معرفة شدة الإشعاع الشمسي الساقط على سطح الأرض في منطقة معينه. بينما تتوفر في كثير من المناطق في العالم معلومات وفيرة عن شدة الإشعاع الشمسي الكلي (المباشرة والمشتتة) التي تم قياسها لفترات زمنية طويلة نسبياً. إلا أن معرفة شدة الإشعاع الشمسي المباشر ضروري لبعض تطبيقات إستخدام الطاقة الشمسية مثل إستخدام المجمعات الشمسية التي تعتمد على مبدأ تركيز الأشعة الشمسية في بؤرة محددة؛ كما أن معرفة شدة الأشعة الشمسية المشتتة ضرورية أيضاً لكثير من التطبيقات الهندسية مثل الأشعة الساقطة على جدران المباني أو الأشعة المشتتة التي تصل من خلال النوافذ الى داخل المباني أو الصوبات الزجاجية.

يوجد الآن عدد كبير من النماذج الرياضية لحساب الأشعة المشتتة بناء على معرفة شدة الأشعة الكلية الساقطة على سطح أفقي. بعض هذه النماذج تستخدم لحساب الأشعة المشتتة الساقطة على سطح أفقي خلال ساعة وبعضها يستخدم لحساب الأشعة خلال يوم كما توجد نماذج رياضية لحساب الأشعة خلال شهر. هذه النماذج الرياضية مبنية على علاقة بين نسبة الأشعة المشتتة إلى الأشعة الكلية ونسبة الأشعة الكلية إلى الأشعة الشمسية الكلية خارج الغلاف الجوي (تسمى هذه النسبة معامل النقاء).

في هذا البحث تم تطوير إنموذج رياضي لحساب الأشعة الشمسية المشتتة خلال يوم وذلك بإستخدام بيانات تجريبية عن شدة الأشعة الشمسية التي تم قياسها خلال عامين في مدينة بلايثفيل، اركنساس في أمريكا (خط العرض = ٣٥,٩، خط الطول = ٨٩,٩). في هذا البحث تمت أيضاً دراسة تغير شدة الأشعة الشمسية المشتتة الساقطة على سطح أفقي مع تغير الفصل وتبعاً لذلك تم تطوير إنموذج رياضي لحساب المعدل الفصلي لشدة الأشعة الشمسية المشتتة خلال يوم لكل فصل، كما تم تطوير إنموذج ثالث لحساب المعدل الشهري لشدة الأشعة الشمسية المشتتة خلال يوم. جرى مقارنة النماذج الرياضية المطورة في هذا البحث مع النماذج الأخرى المشابهة.