Adapting the Spencer model for diffuse solar radiation in Badajoz (Spain)

Adaptación del modelo de Spencer para radiación solar difusa en Badajoz (España)

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ABSTRACT:

Reliable estimations of solar global radiation and its partitioning direct-to-diffuse are demanded for the use of solar energy as renewable energy source. While solar global radiation is widely available at radiometric stations, measurements of the diffuse component are rather scarce. Therefore, sound models to obtain reliable estimations of the partitioning direct-to-diffuse are required. In this study, the Spencer's model is applied to original measurements performed at a radiometric station in Badajoz (Spain). This model proposes a linear relationship between the ratio diffuse to global solar radiation and the clearness index, defined as the ratio solar global irradiance at ground level to solar irradiance at the top of the atmosphere. Additionally, the regression coefficients were computed and compared to those proposed by Spencer for our latitude. Results indicate that Spencer's model reflects the general trend of the measurements. The calculated regression coefficients are similar to those proposed by Spencer, showing relative differences between 0.3% and 20%.

Keywords: Solar Radiation, Diffuse Radiation, Diffuse Radiation Model, Spencer's Model.

RESUMEN:

El desarrollo de la energía solar como una de las principales fuentes de energía renovable exige estimaciones fiables de la radiación solar global y su partición directa-difusa. Si bien la radiación solar global está disponible en un gran número de estaciones radiométricas, las mediciones de la componente difusa son más bien escasas. Por lo tanto, son necesarios modelos robustos para obtener estimaciones fiables de la partición directa-difusa. En este trabajo, se ha aplicado el modelo de Spencer a las medidas originales tomadas en una estación radiométrica en Badajoz (España). Este modelo propone una relación lineal entre el cociente de la radiación solar difusa y la radiación solar global y el índice de claridad, que se define como el cociente entre la radiación solar global a nivel del suelo y la radiación solar en el tope de la atmósfera. Además, se han calculado los coeficientes de regresión y se han comparado con los propuestos por Spencer para nuestra latitud. Los resultados indican que el modelo de Spencer refleja la tendencia general de las medidas. Los coeficientes de regresión calculados son similares a los propuestos por Spencer, mostrando diferencias relativas entre el 0.3% y el 20%.

Palabras clave: Radiación Solar, Radiación Difusa, Modelo de Radiación Difusa, Modelo de Spencer.

REFERENCIAS Y ENLACES / REFERENCES AND LINKS

- [1]. R. B. Benson, M. V. Paris, J. E. Sherry, C. G. Justus, "Estimation of daily and monthly direct, diffuse and global solar radiation from sunshine duration measurements", *Sol. Energy* **32**, 523-535. (1984).
- [2]. D. T. Reindl, W. A. Beckman, J. A. Duffie, "Diffuse fraction correlation", *Sol. Energy* **45**, 1-7 (1990).

- [3]. J. W. Spencer, "A comparison of methods for estimating hourly diffuse solar radiation from global solar radiation", *Sol. Energy* **29**, 19-32 (1982).
- [4]. A. J. Drummond, "On the measurement of sky radiation", *Arch. Meteorol. Geophys. Bioklim. Ser. B* **7**, 413-436. (1956).
- [5]. CM121 *Shadow Ring. Instruction Manual*. Kipp & Zonen (2004).

1. Introduction

There are numerous radiometric stations distributed around the globe to measure the different components of solar radiation and its different spectral subintervals. However, not all stations have instrumentation to measure all radiation components. When it is not possible to measure, radiometric quantities are indirectly estimated through physical or empirical models. One of the radiometric magnitudes often estimated from models is the diffuse irradiance. Knowledge of this magnitude is essential for the design of solar collectors for better use of solar energy. However, the instruments used for measuring this component require conditions that are not always possible, especially in isolated locations. For example, the use of trackers requires connection to the power supply while the use of shadow rings needs frequent adjustments according to the solar trajectory. For all these reasons, it is necessary the study and development of models for the estimation of diffuse solar irradiance.

Physical models require, in general, information from many different variables and are sometimes difficult to implement, thus the empirical models, that have the advantage of being less complex, have been widely developed in the different areas of atmospheric physics. Among these models are those built for estimating the diffuse component of solar radiation. Since the 60's until today, many empirical models have been proposed to calculate the proportion of diffuse radiation, k_d , from other radiometric and meteorological variables. Models have been developed for different time intervals (hourly, daily or monthly), and using different variables, such as maximum number of sunshine hours (R.B.Benson *et al.*, [1]), air temperature and humidity (Reindl *et al.* [2]), or with a combination of variables (Reindl *et al.* [2]). However, the most frequently used expressions relate diffuse fraction, k_d and the clearness index,

k_t . These models allow a good estimate of the diffuse component using only global solar radiation making its study particularly interesting. One of these models was propounded by Spencer [3].

The main objective of this paper is to analyze the validity of the Spencer's model using data measured at the radiometric station installed in Badajoz (Spain). It consists in an hourly model that has been applied on numerous occasions and in different regions.

This study is performed in two ways, in a first step, the results obtained using the original coefficients propounded by Spencer for our latitude are analyzed and secondly, new values for the regression coefficients of Spencer model expressions were obtained and compared with the previous ones.

2. Experimental data

Data analyzed in this study were obtained from the radiometric station located on the terrace of the building of Physics Department at the University of Extremadura in Badajoz (Spain). The coordinates of the station are 38° 52' 58"N, 7° 0' 38"W and 199 m a.s.l. Measurements were recorded at one-minute basis for a period of study extending from November 23, 2009 until October 27, 2010. These have been the first measurements of diffuse radiation taken at this station.

Global irradiance was measured with a pyranometer CMP11. This instrument allows the measurement of global irradiance incident on a horizontal surface in an azimuth angle of 360° with wavelengths between 310 and 2800 nm. Diffuse irradiance was measured by other CMP11 pyranometer installed on a CM121 shadow ring that prevents direct radiation reaching the pyranometer sensor. All these instruments are manufactured by Kipp & Zonen.

Simultaneous data from all sensors were collected every ten seconds by a CR1000 data-logger (Campbell Sci.) and recorded as one-minute average.

In order to guarantee the quality of diffuse radiation data, the shadow ring has been adjusted every few days to ensure the complete shading of the pyranometer dome. On the other hand, it is necessary to correct measurements because the shadow ring itself obstructs not only direct radiation but a portion of diffuse radiation. For this purpose, diffuse measurements have been corrected by the method proposed by Drummond [4] and recommended by the manufacturer of the shadow ring. In this method, the portion of sky intercepted by the ring is given by the expression:

$$f = \left(\frac{2b}{\pi r}\right) \cos^3(\delta) (\omega_s \sin(\varphi) + \cos(\varphi) \cos(\delta) \sin(\omega_s)), \quad (1)$$

where ω_s is the hour angle at sunset, δ is the solar declination and φ is the latitude. The correction factor applied to the measurements is:

$$C_d = \frac{1}{1-f} \rightarrow D = C_d \cdot d, \quad (2)$$

where d is the diffuse irradiance given by the sensor with the shadow ring and D is the corrected measure.

Other important aspect related to the data quality control is the calibration of the instruments. Calibration consists of obtaining the function or constant factor, which transforms the voltage values obtained by the instrument into radiometric units. Periodic calibration of instruments is required to verify the stability of these factors, so the instruments used in this work have been calibrated by intercomparison with a reference pyranometer (CM11, #027771) in the Atmospheric Sounding Station (ESAt, INTA) located in El Arenosillo, Huelva, Spain (37.1°N, 07.06°W), which reference instrument has been previously calibrated at the World Radiation Center (WRC) in Davos, Switzerland. The calibration factor was obtained as the average of the ratios between the voltage signal of each radiometer and the

irradiance measured by the reference pyranometer.

In this paper, one-minute measurements of global solar radiation and diffuse solar radiation have been used. After a careful review of data, to detect possible anomalous values, only a 1.1 percent of data were discarded.

From the final data set, 75% of data have been randomly selected to analyze and adjust the model while the remaining 25% have been used for its validation.

3. Spencer's model and methodology

As indicated above, the empirical expressions most frequently used for calculating diffuse radiation include as variables the diffuse fraction of radiation, k_d , and the clearness index, k_t . This parameters are defined as:

$$k_t = \frac{I_g}{I_{TOA}}, \quad (3)$$

$$k_d = \frac{I_d}{I_g}, \quad (4)$$

where I_d is the diffuse irradiance, I_g is the solar global irradiance and I_{TOA} is the solar global irradiance at the top of the atmosphere.

In 1982, Spencer proposed a model to estimate k_d with the regression coefficients depending on the latitude. The model was developed using data from twelve stations distributed throughout Australia at latitudes between 20°S and 45°S. This model takes into account that the path of radiation in the atmosphere increases with latitude and the diffuse component also does. The model is summarized in the following expressions:

$$k_d = \begin{cases} a & k_t < 0.3, \\ b - ck_t & 0.3 \leq k_t \leq 0.75, \\ d & k_t > 0.75, \end{cases} \quad (5)$$

where the coefficients a , b , c and d depend on latitude and are obtained as:

$$a = b - 0.3c, \quad (6a)$$

$$b = 0.94 + 0.0118|\varphi|, \quad (6b)$$

$$c = 1.185 + 0.0135|\varphi|, \quad (6c)$$

$$d = b - 0.75c. \quad (6d)$$

Latitude in these expressions is given in degrees.

The model proposes a symmetric behavior with respect to Equator so the latitude dependence appears in absolute value.

For validating the model, measurements of solar global and diffuse irradiance at a one-minute basis in Badajoz (Spain) were performed. Hourly averages of these measurements were calculated and the Spencer's model was applied to those data. Additionally, the regression coefficients were calculated and compared to those proposed by Spencer for our latitude. Finally, the new approach has been validated with an independent data set from the same radiometric station.

Statistical parameters such as root mean square error (*RMSE*), mean percentage error (*MPE*) and mean absolute bias error (*MABE*) have been used in order to analyze the goodness of model results. These statistics are defined as:

$$RMSE = 100 \sqrt{\frac{1}{N} (x_{i,mod} - x_{i,exp})^2}, \quad (7)$$

$$MPE = \frac{100}{N} \sum_{i=1}^N \left(\frac{x_{i,mod} - x_{i,exp}}{x_{i,exp}} \right), \quad (8)$$

$$MABE = \frac{100}{N} \sum_{i=1}^N \left| \frac{x_{i,mod} - x_{i,exp}}{x_{i,exp}} \right|, \quad (9)$$

where N is the total number of measurements, $x_{i,mod}$ is the i th-estimate and $x_{i,exp}$ is the i th-measurement.

The statistic *RMSE* is a measure of the differences between the model and experimental measurements, *MPE* gives an estimate of the percentage by which a model underestimates or overestimates the experimental results, a positive value indicates that the model overestimates the experimental data while a negative value indicates underestimation. *MABE* is a measure of the goodness of the fit. Small values of these statistics represent a better fit of the model.

4. Results

In this section we will discuss the results obtained applying Spencer's model to the data obtained in our station. Analysis is performed in two ways: (a) analysing the results obtained

using the original coefficients propounded by Spencer for our latitude and (b) obtaining new values for the regression coefficients of Spencer model expressions and comparing with the previous ones.

In the first step, the parameters a , b , c and d have been calculated for our latitude by the expressions (6) and then, k_d values have been estimated by expression (5). In Fig. 1 it can be observed how the original model (orange line) reflects the general trend of the data but tends to be overestimated with respect to experimental data, especially for low values of k_t .

Fig. 1. Original model and new approach.

This is confirmed by the positive value of the statistic *MPE*, 17.3%, while for *MABE* and *RMSE* were obtained 32.1% and 12.6% respectively. The high value of statistical *MABE* highlights the wide dispersion of experimental data on the model. This dispersion is mainly due to the great diversity of possible situations that may lead to the same value of k_t . The clearness index is a measure of the attenuation of radiation by the atmosphere. However, such attenuation may be due to different causes such as cloud cover or the action of the aerosols and gases on the radiation. These factors have different influence on the radiation dispersion so that the proportion of diffuse can take very different values for the same radiation attenuation.

In a second step values for a , b , c and d coefficients of Spencer model were obtained by

regression analysis. These results are shown in Table I with those propounded in the original model calculated with Eq. (6). The relative differences between them are also shown.

These coefficients correspond to the functional form of the model in the range of k_t values below 0.7, where the data dispersion is higher. Other possible causes of the differences between the coefficients given by the model and those obtained by the new approach could be the wide range of latitudes in which data were taken for the original model development or the different instruments used in the measurement stations.

The estimates with the new coefficients (red line) have been represented in Fig. 1. This graph shows the improvement of this model compared to the original. The differences between them are smaller when the value of clearness index, k_t , increases.

A quantitative comparison of both models can be done with the statistics *RMSE*, *MPE* and *MABE*, listed in Table II. In this table it is observed as statistical values for the new approach are slightly better than those obtained for the original model, but the new approach overestimates de experimental data.

Table I
Spencer model coefficients.

Coefficient	Original model	New approach	Relative difference
<i>a</i>	0.89	0.78	12%
<i>b</i>	1.40	1.23	16%
<i>c</i>	1.71	1.43	20%
<i>d</i>	0.12	0.13	0.3%

Table II
Statistics for original and approach models.

	<i>RMSE</i> (%)	<i>MPE</i> (%)	<i>MABE</i> (%)
Original model	12.6	17.3	32.1
New approach	11.6	14.2	31.1

This new approach has been validated with an independent data set as described in section 2. In this validation the values obtained for the statistical *RMSE*, *MPE* and *MABE* were 12.4%, 15.8% and 31.8% respectively. These values are similar to those obtained for the approach.

5. Conclusions

The model proposed by Spencer for the estimation of hourly portion of diffuse solar irradiance from clearness index has been implemented and tested. In addition, a new approach of this model has been obtained, by fitting the functional form given by the model. This functional form reflects the general behavior of the data. Both, the original model and the new approach overestimate the experimental data although the latter does to a lesser extent. The coefficients *a*, *b*, *c* and *d* estimated from the original model for our station and the new ones calculated by regression analysis, have relative differences of 12%, 16%, 20% and 0.3% respectively. The statistics *RMSE*, *MPE* and *MABE*, obtained with the new approach are lower than those found using the original model.

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