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COMPARATIVE STUDY OF DIFFERENT MODELS FOR CALCULATION OF DNI TO APPLICATION IN CSP TECHNOLOGIES

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Abstract. For prospecting or design of Concentrating Solar Power (CSP) systems it is necessary to know the distribution of the Direct Normal Irradiance (DNI) of the region. However, due to the recurring operational problems of measuring instruments, the use of mathematical models estimating the local DNI can be a very useful tool. The objective of this work is to construct a mathematical model that is used in the calculation of the DNI using experimental data provided by the Tropical Variable Variables Laboratory (INPE). This model will be compared with other mathematical models already present in the literature. The consideration of clean-sky was used, that is, the effects of cloudiness, among others, were neglected.

Keywords: Concentrating Solar Power, Direct Normal Irradiance, mathematical models, clear-sky

1. INTRODUCTION

The solar energy, unlike other renewable energy sources, can not be used on a permanent basis. It has a regular distribution, excluding the local climatic conditions, being characterized by being an intermittent source and possessing spatial variability related to meteorological and astronomical factors (Pereira *et al.*, 2017). According to Pereira *et al.* (2017), besides the potential of incidence of solar radiation, more specifically of Direct Normal Irradiance (DNI), it is necessary to know how the variation of distribution of this resource happens to be able to develop projects safe and able to take advantage of this source of energy properly.

The DNI is the main component of global irradiance used in solar concentrator projects (Blanc *et al.*, 2014). Solar power concentrating systems are usually used in power generation and can generate between a few kW and up to 50 MW (Desai *et al.*, 2014). According to Desai *et al.* (2014), the main CSP systems are the parabolic cylindrical collectors (PCC), the linear Fresnel reflectors (LFR), the parabolic disk (PD) and the solar power tower (SPT).

To evaluate the feasibility of implementing CSP systems, it is necessary to know the distribution of the local DNI. Mathematical models or experimental methods can be used to estimate this DNI. The problem of the use of experimental methods is that the equipment used can suffer failures, wear that prevent the constant measurement of the DNI, besides having no predictive character since the measurement has utility only at the time it is made due to the variability of the distribution of the incident solar radiation. The mathematical models, although they are only approximations and often do not take into account all the main parameters that interfere in the DNI distribution, can have a predictive character if validated by experimental data. This predictive power of the mathematical model can provide valuable information for study or design of CSP systems for a given region.

The objective of this work will be to compare the mathematical models constructed from experimental data with the mathematical models already present in the literature. For this work, the clean-sky model was considered (Behar *et al.*, 2015). Experimental data were extracted from the INPE (2017). The calculations are made to the city of Natal/Brazil.

2. METHODOLOGY

The parameters used in DNI models are well described by Duffie and Beckman (2013), being briefly presented by Behar *et al.* (2015). These parameters depend on the solar geometry, which in turn depends on the geographical location

and local weather conditions.

2.1 Mathematical models

2.1.1 HLJ model

The HLJ model is a combination of Hottel model for direct transmittance and Liu and Jordan model for diffuse transmittance (Duffie and Beckman, 2013). For this model the direct normal radiation is given by:

$$DNI_{HLJ} = \tau_{DNI} \cdot I_{so} \cdot \cos(\theta_z) \quad (1)$$

where I_{so} is the extraterrestrial radiation and θ_z the zenith angle. The term τ_{DNI} is called atmospheric attenuation. It is expressed by:

$$\tau_{DNI} = A_{HLJ} + B_{HLJ} \cdot \exp\left(\frac{-C_{HLJ}}{\cos(\theta_z)}\right) \quad (2)$$

whose parameters are given by the equations:

$$A_{HLJ} = a_0 \cdot (0,4237 - 0,00821(6 - A^2)) \quad (3)$$

$$B_{HLJ} = b_0 \cdot (0,5055 - 0,00595(6.5 - A^2)) \quad (4)$$

$$C_{HLJ} = c_0 \cdot (0,2711 - 0,01858(2.5 - A^2)) \quad (5)$$

in which A the altitude of the location in km . The values of a_0 , b_0 e c_0 are of 0,95, 0,98 e 1,02 respectively, considering a tropical climate (ref).

2.1.2 Kumar model

This model is described by the equation below (Behar *et al.*, 2015):

$$DNI_{Ku} = 0,56I_{so}(\exp(-0,65m_{Ku}) + \exp(-0,095m_{Ku})) \cdot \cos(\theta_z) \quad (6)$$

The air mass used in the equation is given by:

$$m_{Ku} = \frac{Pa}{Pa_0} \cdot ((1229 + (614 \cos(\theta_z))^{0,5}) - 614 \cos(\theta_z)) \quad (7)$$

where Pa is the local atmospheric pressure and Pa_0 is the pressure at sea level (101.3 kPa).

2.1.3 Fu and Rich model

This model depends only on the zenith angle and altitude of the spot (Behar *et al.*, 2015):

$$DNI_{FR} = I_{so} \tau_{bulk}^{m_f} \cos(\theta_z) \quad (8)$$

The term τ_{bulk} is the volume of atmospheric transmittance, adopted as 0,5 per (Behar *et al.*, 2015), and m_f is the correction of the air mass given by:

$$m_f = \frac{\exp(-0,000118A - 1,638 \times 10^{-9}A^2)}{\cos(\theta_z)} \quad (9)$$

2.1.4 DaneshyarPaltridgeProctor model (DPP)

This model depends only on the angle of zenith (Badescu, 1998):

$$DNI_{DPP} = 950,2 \cos(\theta_z)(1 - \exp(-0,075(90^\circ - \theta_z))) \quad (10)$$

2.1.5 Meinel model

This model depends on the air mass and the angle of zenith (Behar *et al.*, 2015):

$$DNI_{Mei} = I_{so}0,7^{m_{ar}^{0,678}} \cos(\theta_z) \quad (11)$$

in which the mass of air in this case is calculated by:

$$m_{ar} = \frac{1}{\cos(\theta_z)} \quad (12)$$

2.2 Adjusting curves for local experimental data

Using the data provided by INPE (2017) the Origin8 software was used to perform a curve fit of a set of DNI distributions separated by season. The separation was made by season due to the impact on the distribution of solar radiation on the earth face caused by the change of the Earth's inclination along the movement of translation around the Sun.

3. RESULTS AND DISCUSSION

3.1 Experimental Model

A model based on the experimental data was proposed. This model has five parameters that are modified based on the season. The proposed model is shown in Eq. (13):

$$DNI = (A + Bt + Ct^2) \cdot e^{Dt+Et^2} \quad (13)$$

where t is the hours of day.

The parameters for each season of the year are shown in Tab. 1.

Table 1. Parameters of the experimental model

Day	A	B	C	D	E
16/01	-121.6456	29.19951	-1.27294	0.4999	-0.02137
19/04	-9.66147	2.17171	-0.0927	0.99998	-0.04432
01/07	-8.51215	1.83153	-0.07709	1.0161	-0.04443
20/10	-27.50493	7.1261	-0.32499	0.77337	-0.03451

The model proposed together with the models found in the literature are shown in Figs. 1, 2, 3 and 4.

3.2 Statistical Analysis

To measure the relation between the experimental data and the data obtained by mathematical models in this paper, was used the Pearson correlation coefficient (Eq. (14)). The variables used were the irradiance obtained for experimentally model and obtained from mathematical models. A unit value of the coefficient implies a perfect linear relation between experimental and theoretical. It is expected then a value closer to 1 as possible.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum(x_i - \bar{x})^2)(\sum(y_i - \bar{y})^2)}} \quad (14)$$

where x_i are the i-th irradiance calculated by mathematical models and y_i are the i-th experimental irradiance. The \bar{x} and \bar{y} are the averages. The results are showed in the Tab. 2.

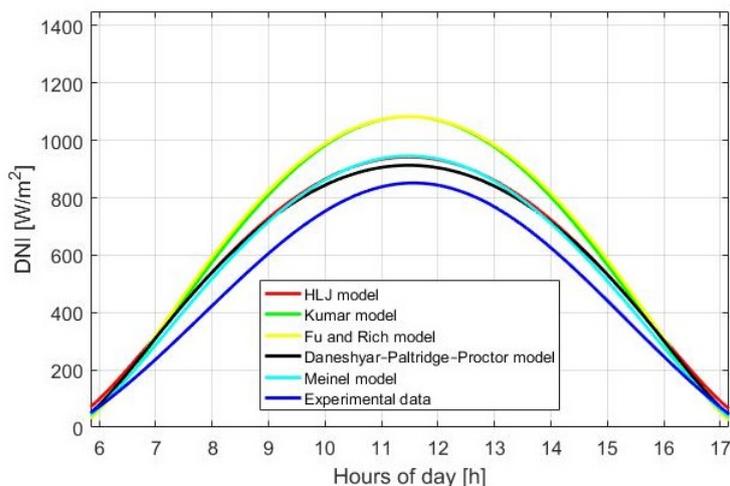


Figure 1. DNI along the day 16/01

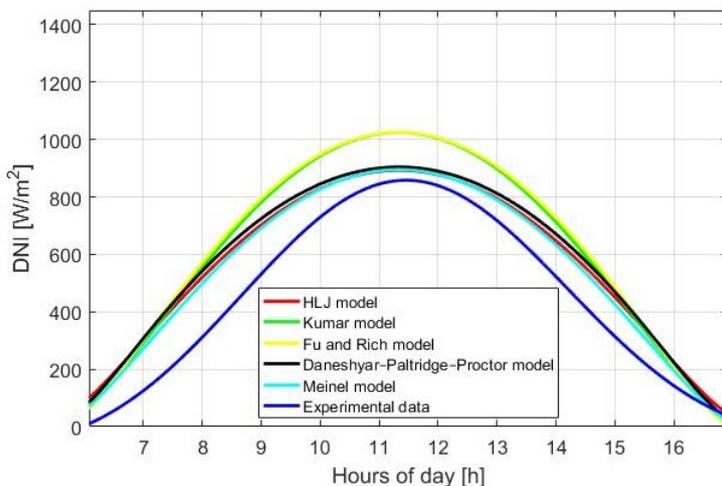


Figure 2. DNI along the day 19/04

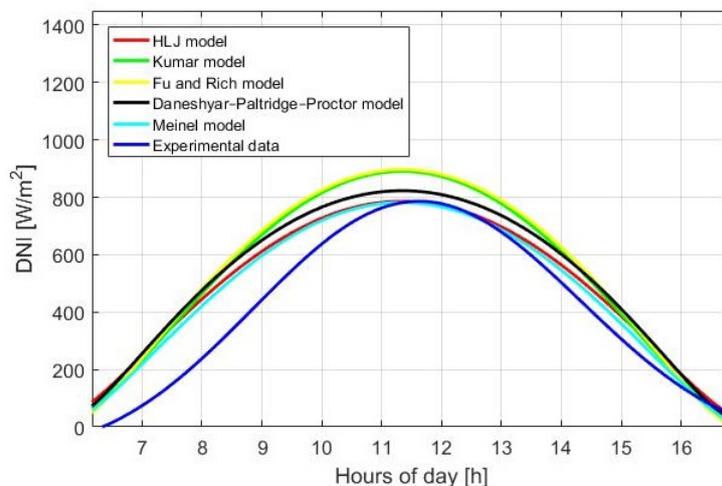


Figure 3. DNI along the day 01/07

The Mean Squared Error (MSE) is a mathematical artifact used to measure the difference between predicted values of models and real values. The lower its value, the better the model adjustment to the real data. It is used as optimization

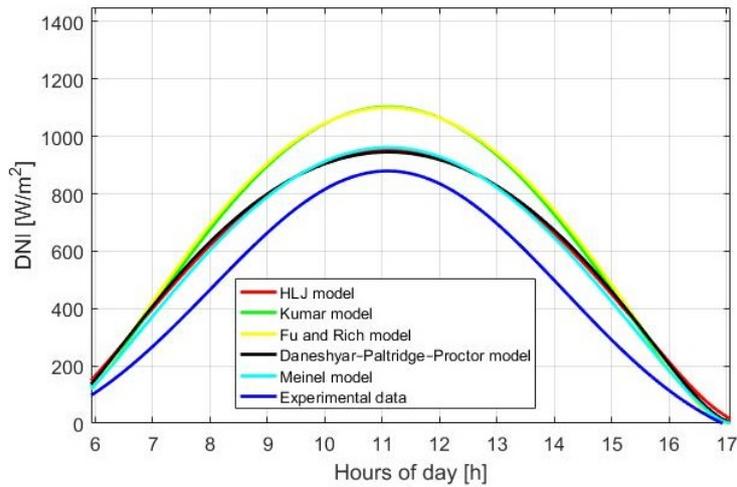


Figure 4. DNI along the day 20/10

Table 2. Pearson correlation coefficient

Day	HLJ model	Kumar model	Fu and Rich model	DDP model	Meinel model
16/01	0.997386	0.998715	0.997535	0.995	0.998047
19/04	0.980879	0.985414	0.981473	0.975356	0.982839
01/07	0.967078	0.971695	0.967873	0.962428	0.968953
20/10	0.992142	0.995457	0.992854	0.987783	0.993748

criterion in the selection of parameters and selection of models. The MSE is defined by:

$$MSE = \frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2 \quad (15)$$

in which the x_i takes the role of predict values and y_i of real or observed values. In this paper was used the MSE to select the mathematical model that best fits the experimental model. The results are showed in the Tab. 3.

Table 3. Mean Squared Error

Day	HLJ model	Kumar model	Fu and Rich model	DDP model	Meinel model
16/01	8481.348	28475.94	31076.87	6478.049	6591.198
19/04	15438.89	32338.45	35578.62	19103.35	11925.27
01/07	11774.64	20159.13	23112.1	16989.66	8617.16
20/10	14653.33	37837.62	331949.4	331947.9	331949.4

The mean absolute percentage error (MAPE) is a measure of prediction accuracy of a forecasting method in statistics. It usually expresses accuracy as a percentage, and is defined by the equation:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{x_i - y_i}{y_i} \right| \quad (16)$$

in which the x_i takes the role of predict values and y_i of real or observed values. In this paper was used the MAPE to select the mathematical model that best fits the experimental model. In the Table 4 is shown the results.

3.3 Discussion

All mathematical models presented are based on geographical parameters. Cloudiness in place is not considered, i.e., all the models are valid for clear-sky.

From the values the mean square error, it is noted that for each season of the year there is a distant model that is better suited to the experimental model. But analyzing the value of MAPE, it was observed that the Meinel model better fit the experimental model. The strong correlation between the data obtained from the experimental model and the mathematical

Table 4. Mean Absolute Percentage Error

Day	HLJ model	Kumar model	Fu and Rich model	DDP model	Meinel model
16/01	20.67%	26.45%	29.19%	16.36%	14.25%
19/04	55.33%	58.73%	59.9%	55.48%	43.67%
01/07	26.17%	35.04%	42.1%	35.34%	23.88%
20/10	33%	40.8%	40.67%	32.78%	26.29%

model is observed for all models. For the summer the models Meinel and DDP presented the lowest MSE values. For fall and winter Meinel showed lower value. As for spring, HLJ presented lower MSE value.

Analyzing the value of MAPE, it is observed that the models present a large discrepancy in the average in relation to the observed values. Not fitting well to the experimental model in the average.

4. CONCLUSIONS

In this work, a DNI calculation model was developed for the experimental data obtained by INPE (2017). A general model of equation was put with the parameters varying according to the seasons of the year.

The model obtained with the experimental data was compared with the calculation models present in the literature. The fact that this experimental model did not take into account the cloudiness, among other factors, influenced the appearance of a lower DNI curve than the mathematical models put in this work.

Taking into account the statistical analysis made was observed a strong correlation between the model obtained with the experimental data and with the mathematical models of the literature used. But, by analyzing the MSE and MAPE values, some distinct facts were found: the Meinel model better fit the experimental model in terms of comparison using the MAPE, but using the MSE as a comparison it was observed that different mathematical models adjusted for different seasons. However, in general and observing the MAPE results, it was observed that the models tested in this work did not present good agreement with the proposed model obtained with the results of INPE (2017), even taking into account the sky-clean condition.

Further study with the variation of the parameters of the proposed model during the year, besides the analysis with other models used in the literature, should be done to better estimate a more robust model for calculating DNI.

It should be noted, however, that the proposed model, despite the discrepancy with the models in the literature, fits well with the experimental data in each season, thus serving as a utility for CSP systems projects.

5. ACKNOWLEDGEMENTS

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