COMPARATIVE STUDY OF DIFFERENT MODELS FOR CALCULATION OF DNI ON NATAL CITY

Gabriel da Silva Lima, limagabriel@bct.ect.ufrn.br[1]
Gabriel Ivan Medina Tapia, gmedinat@ct.ufrn.br[1]
Adeilson de Olveira Souza, adeilson_souza@live.com[1]

[1]Universidade Federal do Rio Grande do Norte, Mechanical Engineering Department, Campus Universitário, 3000, Lagoa Nova, Natal, 59072-970, Brazil

Abstract: *The development of technologies for the benefit of solar energy has been highlighted in recent years due to its huge potential use for generating electricity. Among these technologies highlights the Concentrated Solar Power (CSP) that reflect the solar radiation to a specific point. Because these concentrators are subject to seasonal variation of solar irradiation is of great importance to measurement of such energy over a specific period. This paper presents the use of mathematical models to calculate the Direct Normal Irradiance (DNI) allowing of this way to quantify the availability of this energy in regions where there is not availability of measurement instruments. The calculation models take into account climatic and geographical characteristics of the analyzed region. The approach of sky-clean is used in all study models to calculate the solar irradiance. The mathematical models used are: HLJ (combination of models Hottel, Liu and Jordan), Kumar, Fu and Rich, Daneshyar-Paltridge-Proctor (DPP) and Meinel. It was performed a comparative study with experimental data obtained by CTGAS-ER. A high correlation and low error was detected with the Meinel and HLJ models and the experimental data to the city of Natal/Brazil.*
Keywords: *Direct Normal Irradiance, Concentrated Solar Power, mathematical models, comparative study*

1. INTRODUCTION

Among the sources of electricity solar energy is the most abundant, especially in Brazil due to the high incidence of solar radiation (Porfirio and Ceballos, 2013). This type of energy can be used directly for residential (small projects), and (in the case of large complex) for industrial use.

Solar energy can be harnessed in two ways: photovoltaic panels and concentrators (Concentrated Solar Power - CSP). In the case of photovoltaic solar energy is converted directly into electricity through photovoltaic cells (Seguel, 2009). In the case of concentrators the conversion of solar energy into electricity is not direct. Mirrors are used to redirect the incident solar radiation to heat a working fluid (steam, usually) that, in turn, you can move a turbine thus obtaining mechanical energy and generate electricity by coupling a generator to the system (ANEEL, 2005).

The construction of CSP systems requires knowledge of only part of the solar radiation that can be measured directly: the Direct Normal Irradiance (DNI). To know this factor is required for project design and operation of these systems using CSP technology (Porfirio and Ceballos, 2013).

To calculate the DNI it is necessary the use of specialized and/or mathematical modeling tools. In this work due to lack of equipment, mathematical models are used to estimate the time variation of the DNI throughout the day. The calculations are made to the city of Natal/Brazil. The results will be validated by experimental data obtained in CTGAS-ER.

2. PARAMETERS

Several parameters were used to express the mathematical models used. These parameters depend on the solar geometry, which in turn depends on the geographical location and local weather conditions.

2.1 Solar geometry and radiation

2.1.1 Declination angle

The declination angle is defined as the angular position of the sun at noon on the equator plane. It ranges between -23,45 ° and 23,45 °, that is, the winter solstice to the summer solstice respectively ((Duffie and Beckman, 1991) and (Behar *et al.*, 2015)). Mathematically it can be expressed as (Duffie and Beckman, 1991):

$$\delta = \frac{180}{\pi}(0,006918 - 0,399912\cos(\Gamma) + 0,070257\sin(\Gamma) - 0,006758\cos(2\Gamma) + 0,000907\sin(2\Gamma) - 0,002697\cos(3\Gamma) + 0,00148\sin(3\Gamma)) \quad (1)$$

in which Γ is given by:

$$\Gamma = 360\frac{n-1}{365} \quad (2)$$

to the nth day of the year.

2.1.2 Eccentricity correction factor

The Earth's orbit eccentricity is due to the distance between the Sun and the Earth and can range up 1,7$\%$. This correction is given by (Behar *et al.*, 2015):

$$E_0 = 1,00011 + 0,034221\cos(\Gamma) + 0,00128\sin(\Gamma) + 0,000719\cos(2\Gamma) + 0,000077\sin(2\Gamma) \tag{3}$$

2.1.3 Hour-angle sunset

The hour-angle sunset can be estimated by (Behar *et al.*, 2015):

$$\omega_s = \arccos(-\tan\phi\tan\delta) \tag{4}$$

in which ϕ is the latitude of the place.

From Equation 4 can calculate the hours of sunrise and sunset, respectively:

$$Sr = 12 - \frac{\omega_s}{15} \tag{5}$$

$$Ss = 12 + \frac{\omega_s}{15} \tag{6}$$

The number of hours of sunshine is based on Eq. 4:

$$L_d = \frac{2}{15\,^\circ}\arccos(\tan\phi\tan\delta) \tag{7}$$

2.1.4 Solar time and hour-angle

The solar time is given by a relation between the local time (SDT), geographic location (longitude, L_{loc}) and meridian time zone (L_{st}):

$$ST = SDT + \frac{4(L_{st} - L_{loc}) + E}{60} \tag{8}$$

The term E is given by the equation of time (Duffie and Beckman, 1991):

$$E = 229,2(0,000075 + 0,001868\cos(\Gamma) - 0,032077\sin(\Gamma) - 0,014615\cos(2\Gamma) - 0,04089\sin(2\Gamma)) \tag{9}$$

The hour-angle is the angular displacement of the sun of the local meridian due to the earth's rotation axis in 15 $^\circ$ per hour:

$$\omega = 15\,^\circ(ST - 12) \tag{10}$$

2.1.5 Zenith angle

The zenith angle is the angle between the vertical and the line of the sun, that is, the angle of incidence of the direct radiation on the horizontal surface (Duffie and Beckman, 1991). It is written as (Duffie and Beckman, 1991):

$$\theta_z = \arccos(\cos(\delta)\cos(\phi)\cos(\omega) + \sin(\delta)\sin(\phi)) \tag{11}$$

2.1.6 Extraterrestrial radiation

According Behar *et al.* (2015) extraterrestrial radiation can be found by the equation:

$$I_{so} = I_{sc}E_0 \tag{12}$$

in which I_{sc} is the solar constant. Behar *et al.* (2015) expressed this constant as 1366,1 W/m^2.

2.2 Atmospheric parameters

2.2.1 Atmospheric pressure

The local atmospheric pressure is given by (Behar *et al.*, 2015):

$$Pa = Pa_0\left(\frac{Am \cdot LR}{T_{0k}} + 1\right)^{\frac{-g}{LR \cdot R_{gas}}} \tag{13}$$

in which Pa_0 is the pressure at sea level (101.325 Pa), LR is the reason of temperature due to altitude (-6,3$\cdot$10$^{-3}K/m$), Am is the altitude of the location in meters, T_{0k} is the average temperature at sea level (288,15 K), g is the acceleration of gravity (9,80665 m/s^2) e R_{gas} is the gas constant for air (287,053 J/kgK).

2.2.2 Air mass

Air mass is the mass ratio of the atmosphere of the optical path in which the radiation is scattered and absorbed ((Behar *et al.*, 2015) and (Duffie and Beckman, 1991)). Behar *et al.* (2015) describes how:

$$m_r = \frac{1}{\cos(\theta_z) + 0,15(93,885 - \theta_z)^{-1,253}} \tag{14}$$

The air mass to a local atmospheric pressure is related to the air mass at atmospheric pressure at sea level:

$$m_{ar} = m_r \frac{Pa}{Pa_0} \tag{15}$$

2.3 Mathematical models

2.3.1 HLJ model

The HLJ model is a combination of Hottel model for direct transmittance and Liu and Jordan model for diffuse transmittance. It is applied to a case of clear sky. For this model the direct normal radiation is given by:

$$DNI_{HLJ} = \tau_{DNI} \cdot I_{so} \cdot \cos(\theta_z) \tag{16}$$

The term τ_{DNI} is called atmospheric attenuation. It is expressed by:

$$\tau_{DNI} = A_{HLJ} + B_{HLJ} \cdot exp\left(\frac{-C_{HLJ}}{\cos(\theta_z)}\right) \tag{17}$$

whose parameters are given by the equations:

$$A_{HLJ} = a_0 \cdot (0,4237 - 0,00821(6 - A^2)) \tag{18}$$

$$B_{HLJ} = b_0 \cdot (0,5055 - 0,00595(6.5 - A^2)) \tag{19}$$

$$C_{HLJ} = c_0 \cdot (0,2711 - 0,01858(2.5 - A^2)) \tag{20}$$

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).

2.3.2 Kumar model

This model is described by the equation below:

$$DNI_{Ku} = 0,56I_{so}(exp(-0,65m_{Ku}) + exp(-0095m_{Ku})) \cdot \cos(\theta_z) \tag{21}$$

The air mass used in the equation is given by:

$$m_{Ku} = \frac{Pa}{Pa_0} \cdot ((1229 + (614\cos(\theta_z))^{0,5}) - 614\cos(\theta_z)) \tag{22}$$

2.3.3 Fu and Rich model

This model depends only on the zenith angle and altitude of the spot:

$$DNI_{FR} = I_{so}\tau_{bulk}^{m_f}\cos(\theta_z) \tag{23}$$

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:

$$m_f = \frac{exp(-0,000118A - 1,638 \times 10^{-9}A^2)}{\cos(\theta_z)} \tag{24}$$

2.3.4 Daneshyar–Paltridge–Proctor model (DPP)

This model depends only on the angle of zenith:

$$DNI_{DPP} = 950,2\cos(\theta_z)(1 - exp(-0,075(90^\circ - \theta_z))) \tag{25}$$

2.3.5 Meinel model

This model depends on the air mass and the angle of zenith:

$$DNI_{Mei} = I_{so} 0,7^{m_{ar}^{0,678}} \cos(\theta_z) \tag{26}$$

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

$$m_{ar} = \frac{1}{\cos(\theta_z)} \tag{27}$$

3. RESULTS AND DISCUSSION

Natal/Brazil (5 °50'S, 35 °12'W, 58 m of altitude) is at ambient temperature 26 $°C$ and relative humidity 60%, according to data obtained by CTGAS-ER. Also, experimental data were obtained from CTGAS-ER of DNI for days 02/06, 18/07 e 13/08, year of 2015. For these days the models described above were used to generate graphics of DNI (n =153, n =199 e n =225):

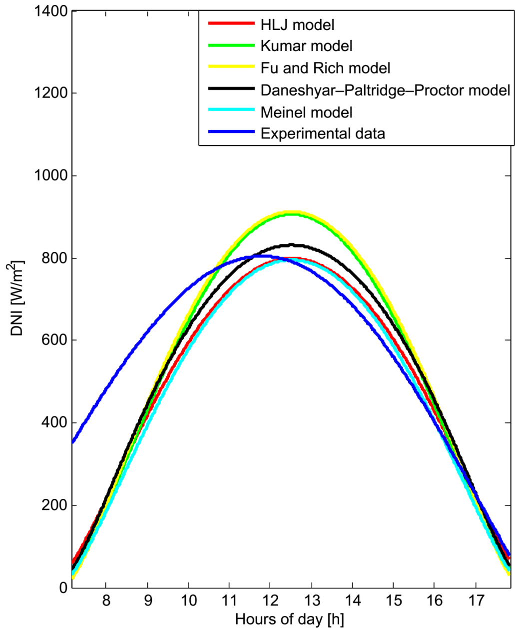

Figura 1: **DNI along the day 02/06, n=153**

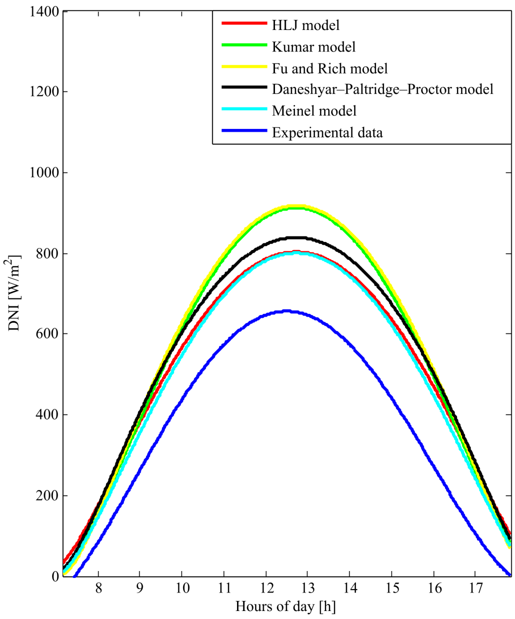

Figura 2: **DNI along the day 18/07, n=199**

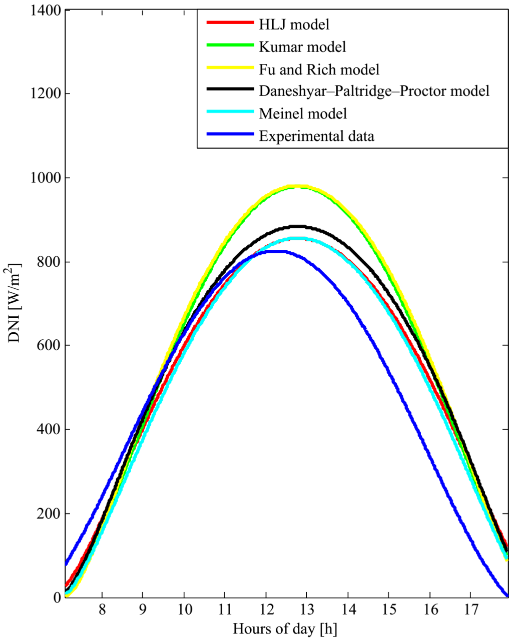

Figura 3: **DNI along the day 13/08, n=225**

The curve of experimental data is a curve fitted to the data obtained by CTGAS-ER.

3.1 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. 28). The variables used were the irradiance collected experimentally 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.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left(\sum(x_i - \bar{x})^2\right)\left(\sum(y_i - \bar{y})^2\right)}} \tag{28}$$

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. 1.

Tabela 1: **Pearson correlation coefficient**

Day	HLJ model	Kumar model	Fu and Rich model	DPP model	Meinel model
02/06	0,557939	0,575180	0,564964	0,546932	0,565096
18/07	0,924587	0,931067	0,929958	0,923031	0,928434
13/08	0,902051	0,910211	0,905928	0,897194	0,906152

The Mean Squared Error (MSE) is a mathematical artifice 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 criterion in the selection of parameters and selection of models. The MSE is defined by:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 \tag{29}$$

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 data. The results are showed in the Tab. 2.

Tabela 2: **Mean Squared Error**

Day	HLJ model	Kumar model	Fu and Rich model	DPP model	Meinel model
02/06	63.446,94	66.885,71	69.174,44	65.001,23	67.744,50
18/07	31.871,11	48.927,93	52.850,37	40.756,13	27.076,40
13/08	16.959,78	27.305,26	29.906,02	20.876,70	15.561,77

3.2 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 of the correlation coefficient and mean square errors, it is noted that the Meinel and HLJ models best describes the experimental data, showing strong correlation with them and low error. The strong correlation is observed in the Tab. 1 on days 18/07 and 13/08 on all models, but the low error is observed in these models (Meinel and HLJ) on these days also (Tab. 2). The strong correlation shows that the curves were able to adjust well on these days.

On day 02/06 the correlation was weak and the errors were higher on all models. This event can be explained by the cloudiness that could have happened on this day.

4. CONCLUSIONS

In this work were described mathematical models to assess the DNI throughout the day. These models rely on geographical parameters and characteristics local climatic.

From the equations described DNI curves were plotted and placed in comparison with data obtained experimentally on CTGAS-ER. A curve was fitted for this data. The fact that these equations do not take into account the cloud cover, and other factors, led to the experimental DNI stay, often, below the DNI obtained by mathematical models. Nevertheless, the curves generated by these models adjusted well to the experimental data.

Taking into account the statistical analysis it can be seen that the Meinel and HLJ models reproduced the strongest correlation and lowest error by MSE to the city Natal/Brazil. Based on this, now it is possible design systems that generates power with CSP technology.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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