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Abstract

Solar energy is becoming a key player in manufacturing especially for off-grid applications such as community factories. Between the radiation emitted by the Sun and that absorbed on Earth, different phenomena take place. Many models were developed to tackle and explain these phenomena with varying levels of accuracy and complexity. Two commonly used models in most commercial simulation software such as ANSYS® Fluent® are the Fair Weather Condition and Theoretical Maximum Method. The aim of this paper is to investigate the accuracy of these models based on experimentally measured data. While these models assume a completely clear sky, the study is based on wet season. Global irradiance data acquired for different hours (9 o'clock, 12 o'clock and 15 o'clock) of the day was used. Results show good correlation between the average global irradiance for the Fair Weather Condition and the experimental values. The accuracy is more important for high solar elevation around 12 o'clock.

Keywords

Solar irradiation, experiment, models

1 INTRODUCTION

The sun is a star located 1.496 × 10^8 km from the Earth [1] and is the source of most of the energy on the Earth. The difference in energy emitted from the Sun and that received on the surface of the Earth is caused by a number modifying parameters. These range from reflection on the outer fringes of the atmosphere to absorption by atmospheric particles (dust, moisture). These factors have to be studied to understand how prediction models can be developed to estimate the component of the Sun's radiation that will reach the surface of the Earth and hence, allow modelling of the effect of radiation on the Earth. At the University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg South Africa, experimental data has been measured for global radiations over different periods of time. For this data to be applied to simulation, it is important to understand the accuracy of the solar calculators implemented in various computation fluid dynamics (CFD) packages. The main aim of this study is to compare these experimental results with two prediction models that are implemented in ANSYS® Fluent® release 16.0 [2]. The two models considered were the Fair Weather Conditions and the Theoretical Maximum Method. In addition, the quality of the data was evaluated in an attempt to establish a correlation between the experimental and model results. The results of this analysis would be used in the development of a solar dryer for drying biomass briquettes and agricultural produce such as fruits.

2 SOLAR RADIATION AND THEORETICAL BACKGROUND

The Sun, at a distance of 1.496 10^8 km from the Earth, emits electromagnetic waves due to the chemo-thermal agitation on its surface. The temperature on the surface of the Sun, also called photosphere, lies between 4000 and 6000 K, but can be assumed to be at 5777 K for purposes of black body radiation studies [1] [3]. These electromagnetic waves are characterized by their frequency, period and wavelength. The latter is commonly used to represent the distribution of the solar electromagnetic spectrum ranging from 0.001 nm (gamma γ) to about more than 1 km (radio wave). The integration of the light spectrum over the entire range of extra-terrestrial wavelengths gives the solar constant determined to be 1367 W/m² and depends of three parameters [4]: the temperature of Sun, the size of the Sun and the distance between the Sun and the Earth. In addition, this constant can change during the year due to the Earth's orbit around the Sun which is on an elliptical path. Thus, the solar constant can change by around ± 3.3% in a year.

When the extra-terrestrial solar radiation arrives on the Earth's atmosphere, a fraction is reflected back into space and the other part will pass through the atmosphere. Of the component that penetrates the atmosphere, two phenomena appear due to particles in the atmosphere. The radiation is either scattered or absorbed. The first is the deviation of electromagnetic waves when it meets an atmospheric particle and this depends mainly on the size of the particle. The principal consequence of this is the decomposition into direct and diffuse components. The second is the absorption

properties of molecules which absorb part of this radiation [1].
Then, there is also need to take into account the optical depth of the air mass which depends on two parameters: the geographical altitude and the zenith angle (θ_z). For the simple case, the latter parameter is taken into account through the simple Air Mass (AM) equation [3] i.e.:

$$AM = \frac{1}{\cos \theta_z} \quad (1)$$

After all the previously described phenomena that alter the incident radiation, around 52% of the radiation reaches the Earth [4, 1]. The irradiance (E) represents the flux density of incoming solar radiation on a unitary surface perpendicular to the rays on the Earth. From an energy point of view, 95% of solar energy is contained in the 0.3-2.4 microns band which contains the visible and infrared radiation [1].

3 EXPERIMENTAL AND MODELLING PROCEDURE

3.1 Aim of Experiments

The measurements were conducted as part of the development and performance monitoring of a biomass briquette dyer. The aim was therefore to quantify the amount of solar energy incident on the solar dryer flat plate collector.

3.2 Experimental procedure

Global radiation was measured using a pyranometer in which the radiant energy is absorbed by a blackened surface in which temperature rise is captured using a thermopile. The resultant temperature change is measured as a potential difference (PD). The PD generated due to temperature change was recorded with the use of multi-meter and was then converted to radiation.
The experimental data for a site in Johannesburg, South Africa was collected by Bloem [5] and Ragalavhanda [6] at the University of Johannesburg, Auckland Park Kingsway Campus in Johannesburg, South Africa. The location has the following global position (GP) coordinates:

- Latitude : -26°,11' S
- Longitude : 28°,00' E
- Time zone : GMT + 2 hours

The pyranometer "Second class" (16103.3) from Lambrecht used was calibrated in accordance to ISO 9847 [7] standard. The settings of the pyranometer have a sensitivity of 7-25μV/ (W/m²), a directional error of ± 25 W/m² and a measuring wavelength range of 285-3000 nm. The measurements were made every 15 minutes on a horizontal surface.

The data from Reunion Island was recorded automatically every minute to provide data for a different location and parameters i.e. wind speed, relative humidity, sky temperature, rainfall etc. The localisation was at Saint-Pierre IUT on the Reunion Island, France with GP coordinates:

- Latitude : -21°,20' S
- Longitude : 55°,29'' E
- Time zone : GMT + 4 hours

The pyranometer "Second class" (16103.3) from Lambrecht was also used and was calibrated in accordance to ISO 9060 [8] standard. The settings of the pyranometer have a sensitivity of 7-14μV/ (W/m²), a directional response error of 10 W/m² and a measuring wavelength range of 285-2800 nm. The measurements were made at an interval of one minute on a horizontal surface.

3.3 MODELLING DATA

3.3.1 Solar calculator

For the modelling data, ANSYS® Fluent® software release 16.0 [2] was used to calculate solar irradiance for clear sky with two methods i.e. Fair Weather Conditions and Theoretical Maximum Method. The first is based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) method [8]. The second is from the National Renewable Energy Laboratory (NREL) method. Note that cloud cover is modelled through a cloudiness coefficient between 0 and 1 defined by the user (for most simulations, it is set to 1). The inputs for both models are common to experimental localisation, namely global position (longitude, latitude and time zone), simulation time (start and duration if transient), the mesh orientation, solar irradiation method and the sunshine factor [2]. The main outputs that are calculated (eq. 2) are: the beam solar flux (E_b), the diffuse component (E_d) and the reflected component from the ground (E_r). The latter will not be considered here since the measurements are based on a horizontal surface. To understand the differences of these models, the authors will present the parameters to understand their limitations. The direct component (beam) of the radiation is calculated according to the method chosen while the diffuse component is obtained from the ASHRAE method in both cases. Finally the global radiation reaching a unit surface is given by:

$$E = E_b + E_d + E_r \quad (2)$$

The ASHRAE direct method (eq.3) uses empirical coefficients (A, B), calculated in 1964 on the basis of atmospheric conditions defined by: 0.25cm NTP ozone, dust 200 particles /cm^3, water vapor content is between 0.795 to 2.8 cm for winter and summer respectively. According to [9], A is the apparent solar irradiation at air mass = 0, B is the atmospheric extinction coefficient which is the slope of direct normal irradiance as a function of air mass.

$$E_b = \frac{A}{e^{B.AM}} \quad (3)$$

The NREL direct method (eq.4) uses a Solar Position and Intensity Code (Solspos) algorithm. S_{etrn} is the top of the atmosphere direct normal solar irradiance, corresponding to solar constant taking into account the Earth-Sun distance. $S_{unprime}$ is coefficient corresponding to a clearness index and is defined by [10] as the ratio of Earth's overall surface area over extra-terrestrial global irradiance.

$$E_b = S_{etrn}.S_{unprime} \quad (4)$$

The diffuse component is calculated according to the ASHRAE method for both methods (eq.5). An empirical coefficient C is used to connect the direct and diffuse components. The coefficient α correspond to the tilt angle of the surface. It corresponds to a linear coefficient which is defined as the ratio of the total irradiance over the direct irradiation for a horizontal earth surface.

vector. In practice, the latter is not used because it overestimated values of the actual conditions of sunshine [2]. Although, the ASHRAE method is used, the coefficients used are empirical as determined in 1964 in the United States (Mount Wilson and Washington) [1]. Thus, they don't consider the variation of local conditions (altitude, ozone concentration, water vapor concentration etc.) and time of the atmosphere (changes in industrial discharges, decreased ozone layer, aerosol concentration etc.). It follows that the coefficients are global and do not differentiate the respective influence of other phenomena.
Thus, for direct component ASHRAE method specifies that an error can occur for specific conditions (clear weather and high humidity) that can result in errors up to 15% [8]. It recommends the use of a Clarity Index (C_n), equivalent to Sunprime, but which is not included in Ansys FLUENT software. The Fair Weather method is presented in the literature as simple, including only few parameters. To overcome these problems some authors have redefined the empirical coefficients for their locality [11, 12, 13]. Finally, some studies have compared different models for the global, diffuse and global radiation. These studies do not arrive at the same conclusion. Some of them find a good

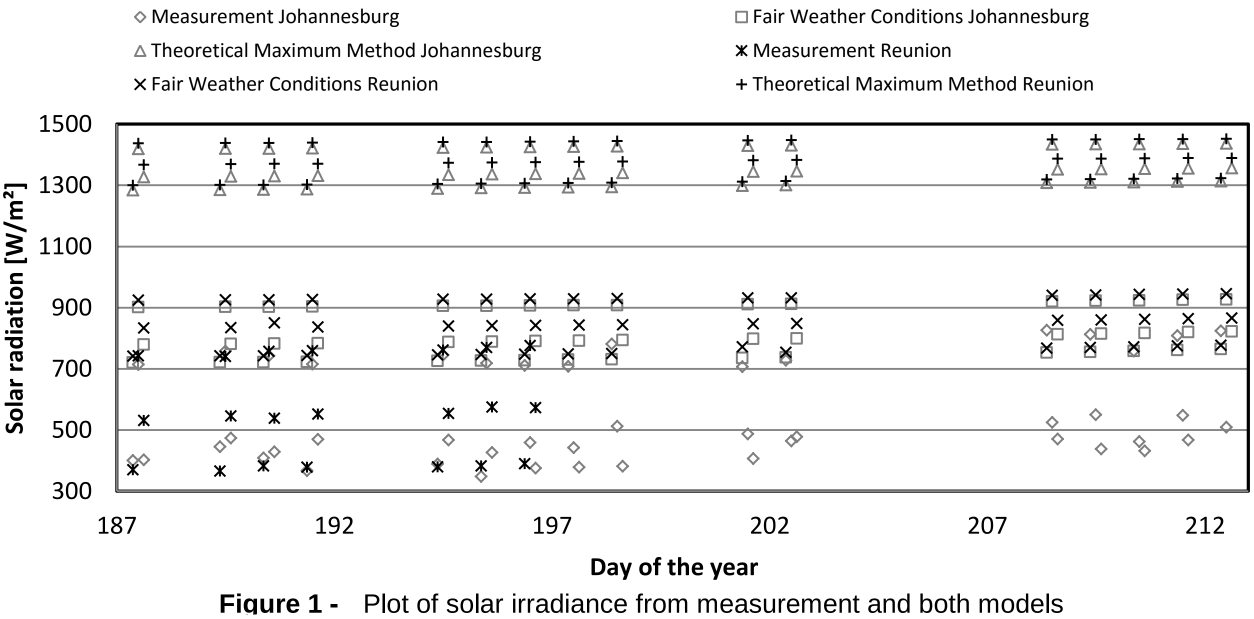

Figure 1 - Plot of solar irradiance from measurement and both models

$$E_d = C.E_{bn}\frac{1+\cos\alpha}{2} \quad (5)$$

The different methods to calculate the direct component and diffuse radiation incident on a unit area have been presented. The difference between the two methods for direct component is based on extra-terrestrial radiation, A and S_{etrn} on ASHRAE and NREL method respectively. The first uses apparent solar constant which is calculated from empirical data while Theoretical Maximum Method uses the solar constant corrected by Earth radius

correlation with ASHRAE [(1)] and others conclude the diffuse component [(2)] can produce errors dues to the simplicity of the method.

3.4 Experimental and modelling data

For the experimental data collected in the month of July 2015, three hours (legal time) were recorded each day and special not made for: 9 o'clock, 12 o'clock and 15 o'clock. However, due to weather changes (cloudy day) and data logging procedure followed (not automatically saving for

Johannesburg), 15 and 7 days are available for the Johannesburg and Reunion Island respectively. The lower value of Reunion Island is essentially due to the presence of more cloudy days.
The modelling data, using the solar calculator, was obtained by the addition of the direct and diffuse components based on the assumption of a completely clear sky, i.e. sunshine factor of 1. Moreover, it's assumed that the ground reflexion component and the influence of neighbouring buildings and structures i.e. microclimate are negligible.
The data are presented together (see Figure 1) bringing together for each site and time: the experimental data, The Fair Weather Condition and the Theoretical Maximum Method. Some outlier data are deleted due to error of acquisition or failure to meet clear sky model requirements. Thus 15 and 7 days are available for Johannesburg and Reunion Island respectively.

4 RESULTS

4.1 Method and indicators

To evaluate the data and their quality the average and the standard deviation will be introduced.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (6)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}} \qquad (7)$$

Then in order to compare the experimental data and the predictions of the models, the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) which are statistical standards for assessing performance of solar radiation are used [15, 16]. In this case the error (e_i) will be considered as the difference between the model prediction and the experimental measurement for a given day. Finally the two indicators are divided by the average of the reference i.e. measure to have the final result in percent:

$$MBE = \frac{1}{n\bar{m}}\sum_{i=1}^{n} e_i \qquad (8)$$

$$RMSE = \frac{1}{\bar{m}}\sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \qquad (9)$$

4.2 Results

The full results presented in figure 1 are compared for each hours and both model and experiments. The global results are given in table 1 and the others results are incorporated in the analysis.

	Johannesburg		
Indicator	Experiment	Fair weather	Maximum Theoretical
Average	548.714	815.7	1355.9
σ	156.615	74.3	54.2
R²		0.938	0.937
MBE		48.7	147.1
RMSE		51.1	99.8
	Reunion Island		
Indicator	Experiment	Fair weather	Maximum Theoretical
Average	562.952	846.4	1378.8
σ	159.512	74.0	56.4
R²		0.987	0.997
MBE		50.3	144.9
RMSE		52.5	97.1

Table 1 - Statistical performance of the two models

The results show a relative good correlation between the two models and the experimental data with a better coefficient of correlation for the Reunion Island data. This is explained by the higher source of error in the South African site due to manual recording of data and reflective surfaces i.e. building close by. However, the MBE and RMSE show an important difference of value between the measurement and the models for the two places and especially for the Maximum Theoretical Method.

Globally, the difference between experiment value for the site, and the Maximum theoretical model are important. The errors committed for Johannesburg are between 67% and 78% for Fair weather condition. The errors committed for Johannesburg and using Maximum Theoretical are more than 100% and thus reject the utilisation of this model for engineering application.

At Johannesburg the average for solar radiation at 9 o'clock, 12 o'clock and 15 o'clock is found experimentally to be 412.21 W/m², 756.4 W/m² and 477.57 W/m² respectively. For the Reunion Island the experimental solar radiation average are 378.27 W/m², 758.0 W/m² and 552.57 W/m² for corresponding times respectively.

By looking per hours of measurement i.e. 9 o'clock 12 o'clock and 15 o'clock, the standard deviations of the experimental data are both 40.57 W/m² and 44.05 W/m² for the site of Johannesburg. For the Reunion Island the standard deviation of the data are between 5.95 W/m² and 12.45 W/m² for 9 o'clock and 12 o'clock respectively. The higher standard deviation for Johannesburg can be explained by the human error during the recording while in Reunion Island the recording is done automatically.

The coefficient R^2 has the objective to show the correlation between the experimental data and the model predictions. The results in Table 1 show a value of 0.938 and 0.937 for Johannesburg and

0.987 and 0.997 for Reunion Island. It means the experimental value agrees with the two models for global data. The results per hours are less impressive with a coefficient between 0.412 and 0.535 for Johannesburg and between 0.597 and 0.923 for Reunion Island.

The errors between each model and the experimental data are taking into account by the MBE and RMSE. The better accuracy for the different hours is for 12 o'clock were the MBE and RMSE is equal to 20.5 % and 23.12 % for Johannesburg and Reunion Island respectively by comparing experimental and Fair Weather condition. The difference between the data and the Maximum Theoretical Method are too large to be considered for engineering applications.

The results per hours i.e. 9, 12 and 15 o'clock show better accuracy for high solar elevation meaning 12 o'clock. This is due to the increasing scattering with the longer transmission path of the solar radiation in the atmosphere during the off noon times.

5 CONCLUSION

The objective of this study is to demonstrate the accuracy of solar radiation models in modelling performance of solar dryers to be implemented in community factories. Indeed between the radiation emmitted by the Sun and the radiaiton reaching the Earth different phenomena occurs. Different models are availble which differ by the number of input parameters required and their complexity. The simplicity of these models can be accepted if the accuracy is acceptable. If this is achievable, significant amount of time will be spent in developing the model to study and optimise the performance of these solar dryers.

This study has compared the accuracy of two models i.e. Fair Weather Condition and Theoretical Maximum Method in predicting experimentally measured solar irradiance acquired at University of Johannesburg and at Reunion Island University. The results show a similar behaviour for both models and the experiment data. However, the accuracy of both models is compromised for example around 9 o'clock and 15 o'clock. For higher elevation, the accuracy for Fair Weather condition increases and is found to be around 20.5 % and 23.12 % for Johannesburg and Reunion Island respectively.

The Theoretical Maximum Method shows significant difference with experiment data for the two sites and hence, must be avoided for manufacturing/engineering study.

It is recommended that further studies be conducted by increasing the amount of data by conducting more measurements during the year. The summer studies can also be interesting to see the importance of the solar elevation to these results. Finally, the Fair Weather Condition possesses empirical coefficient calculated in America, and could be calculated for Johannesburg using experimental data.

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7 BIOGRAPHY

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