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Evaluation of solar constant using locally fabricated aluminium cylinder

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ABSTRACT

The solar constant is an important value for the studies of global energy balance and climate. The analysis of satellite data suggests a solar constant of 1366.10 Wm^{-2} with a measurement uncertainty of $\pm 3\ Wm^{-2}$ of the radiant energy emitted from the Sun. In this study, we used locally fabricated low cost devices of Aluminium cylinder to evaluate the solar constant and obtained an average value of 1381.26 Wm^{-2} from ground-based measurement of solar radiation, which turns out to be in close agreement with that suggested by satellite data measurement and those reported in many literatures. The observed slight deviation in our evaluated value is attributed to the fact that solar constant is not perfectly constant, but varies in relation to the solar activities and fluctuation in extraterrestrial radiation which is about 6.9 % during the year (from 1412.0 Wm^{-2} in January to 1321.0 Wm^{-2} in July) due to the Earth's varying distance from the Sun. The analysis further show that the coefficient of determination, $R^2 > 85\%$ for all the experimental days.

Keywords: solar constant, solar radiation, aluminium cylinder, satellite data measurement, ground-based measurement.

INTRODUCTION

The Sun is the source of energy that drives the cycle of life and death on earth. It is also the energy source that gives us warmth, evaporates water and melts snow. The sun is the primary source of energy for the earth's climate system and its five major components, the atmosphere, the biosphere, the cryosphere, the hydrosphere, and the land surface [1] Hence, solar radiation is a key parameter for our understanding of the climate system, and the processes and interactions taking place within it. The energy transferred from the sun in the form of radiant to the earth's surface is normally referred as the solar radiation. In any solar energy conversion system, the knowledge of global solar radiation is germane for the optimal design and prediction of the system performance [2].

The solar radiation is a major forcing function of physical and biological processes on our planet [3]. The spatial and temporal heterogeneity of incoming solar radiation determines the dynamic of the agricultural [4] ecologic [5] or hydrologic [6] processes. Therefore, knowledge of the spatial variability of radiation components is crucial in order to understand these processes. Additionally, this knowledge is a key tool in supporting policies of renewable and efficient energies.

The integration of the extraterrestrial spectrum over all wavelengths defines the solar constant GS_C. Thus, GS_C represents the flux density of incoming solar radiation on a unitary surface perpendicular to the rays at the mean Sun–Earth distance. Since the Sun radiance varies to some extent over short and long periods [7] the solar constant does not remain steady over time. There is a variation of about $\pm$ 1 Wm^{-2} around the mean solar constant during a typical Sun cycle of 11 years [8] Based on data collected over 25 years from terrestrial to space observations, the actual best estimate of the average solar constant is $GS_C = 1366.1\ Wm^{-2}$ [9].

The solar constant includes all types of solar radiation, not just the visible light. It is measured by satellite to be roughly 1.361 kilowatts per square meter (kW/m²) at solar minimum and approximately 0.1% greater (roughly 1.362 kW/m²) at solar maximum [10]. The actual direct solar irradiance at the top of the atmosphere fluctuates by about 6.9% during a year (from 1.412 kW/m² in early January to 1.321 kW/m² in early July) due to the Earth's varying distance from the Sun, and typically by much less than 0.1% from day to day.

In 1838, Claude Pouillet made the first estimate of the solar constant. Using a very simple pyrheliometer he developed, he obtained a value of 1228 W/m² [11] very close to the current estimate. In 1875, Jules Violle resumed the work of Pouillet and offered a somewhat larger estimate of 1.7 kW/m² based, in part, on a celebrated measurement that he made from Mont Blanc in France. In 1884, Samuel Pierpont Langley attempted to estimate the solar constant from Mount Whitney in California. By taking readings at different times of day, he tried to correct for effects due to atmospheric absorption. However, the final value he proposed, 2.903 kW/m², was much too large. Between 1902 and 1957, measurements by Charles Greeley Abbot and others at various high-altitude sites found values between 1.322 and 1.465 kW/m². Abbott showed that one of Langley's corrections was erroneously applied. His results varied between 1.89 and 2.22 calories (1.318 to 1.548 kW/m²), a variation that appeared to be due to the Sun and not the Earth's atmosphere. [12].

The aim of this paper is to measure, evaluate and estimate the amount of solar energy per unit time of collected area at the mean distance of the earth's atmosphere (Solar constant) from a measurement of the Sun's radiation ground-based level using locally fabricated device of aluminium cylinder.

MATERIALS AND METHODS

The materials and equipment used in this study for the determination of solar constant consist of the following;

i. A glass plate to collect the sun's radiation into the cylinder
ii. A thermometer (Liquid in Glass thermometer).
iii. A retort stand clamp collar 5cm diameter, 0.5-1cm thick alluminium cylinder to collect the sun's energy with a hole drilled along one of its diameters.
iv. A polystyrene foam to prevent heat loss from the base to the outside environment.
v. A 5cm diameter PVC sleeve to prevent heat loss from the cylinder (the kind used in construction for down pipes).
vi. A short PVC piping, (the kind used by electricians).

The aluminium cylinder was weighed and painted dull black. The aluminium cylinder was then set inside the PVC sleeve and cylinder (the diameter of the hole should be the same as that of thermometer and making sure there is no airspace between the cylinder and the Sleeve).

The bottom of the device was then filled with polystyrene foam block to prevent heat loss from the base to the outside environment. The completed device was then placed on a retort stand clamp collar whereas the thermometer hole is-at 90°

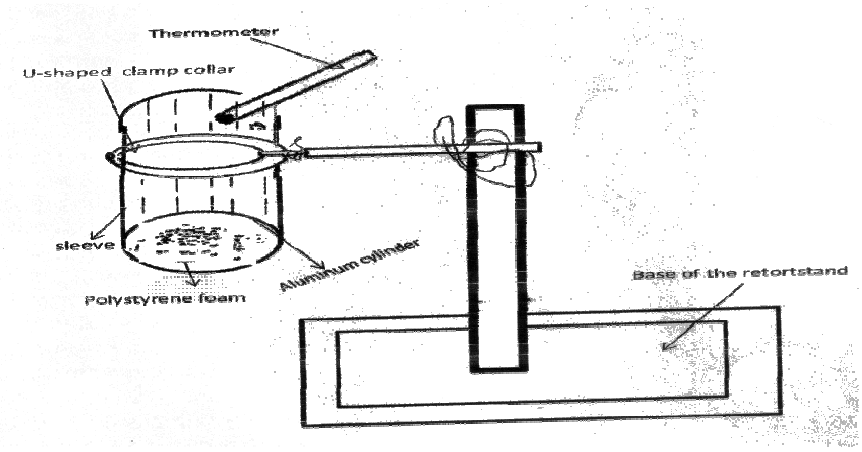

Figure 1: Mounting the Device on a Retort stand clamp collar

The experiment was carried out on the testing field of Sokoto Energy Research Center (S.E.R.C), Usmanu Danfodiyo University, Sokoto. The experiment was performed for five consecutive days from January 20, 2013 to January 24, 2013. The procedure in evaluating the extra terrestrial solar radiation or the solar constant using aluminium cylinder is as follows;

The device was first placed in a refrigerator for about 4 minutes to get a fairly constant (uniform) cooling device. The device was then mounted on a retort stand clamp collar. The device was adjusted so that the angle of incidence of light should be normal to the flat base of the cylinder. While the cylinder is being adjusted, it was ensured that the cylinder does not receive any light from the sun. For this purpose, it was marked with a polystyrene lid. This is allowed to reach equilibrium and the initial temperature (T_2) of the device is measured. The polystyrene mask was then removed and the cylinder exposed to sunlight for 5 minutes. Current measurement of the cylinder temperature as a function of time was then taken.

Mathematically, the solar constant, GS_C can be defined as:

$$GS_c = \frac{Q}{A \times t} \qquad (1)$$

where Q is the radiant energy received from the Sun in Joules (J). A, is the Area of Aluminium cylinder exposed to Sunlight in square metre (m^2) t, is the total time in carryout the experiment in seconds (s) and GS_c is the Solar constant in watts per square metre (Wm^{-2}).

For the case of Aluminium cylinder the radiant energy received from the Sun, Q can be express as [13]

$$Q = mc\Delta\theta \qquad (2)$$

m is the mass of the Aluminium cylinder in Kg, c, is the specific heat capacity in $JKg^{-1}K^{-1}$ and $\Delta\theta$ is the temperature change. Also, A can be express as

$$A = \pi r^2 \qquad (3)$$

where r is the radius of the Aluminium cylinder in metres (m). we used πr^2 because it is the circular part of the cylinder that was exposed to solar radiation.

RESULTS AND DISCUSSION

The following measurements were carried out during the experiment in order to compute for the solar constant, GS_c
Diameter of cylinder, d = 5cm = 0.05m

Radius of cylinder, $r = \frac{d}{2} = 0.025m$

Mass of cylinder, $m = 0.0195Kg$

Specific heat capacity of Aluminium = 900 $Jkg^{-1}K^{-1}$

The results obtained for the five consecutive days at different times of the day, period of exposure and their corresponding temperatures are given in the tables below.

Table 1: Cylinder temperature as a function of time on January 20, 2013

Time of the Day	Period of Exposure (min/sec)	Temperature (°C)
2:00 pm	5(300)	46
2:05 pm	10(600)	48
2:10 pm	15(900)	49
2:15 pm	20(1200)	49
2:20 pm	25(1500)	50
2:25 pm	30(1800)	51

T air, air temperature = 30^0C
Initial temperature of cylinder = 30^0C

Table 2: Cylinder temperature as a function of time on January 21, 2013

Time of the Day	Period of Exposure (min/sec)	Temperature (^{o}C)
2:00 pm	5(300)	45
2:05 pm	10(600)	46
2:10 pm	15(900)	48
2:15 pm	20(1200)	48
2:20 pm	25(1500)	50
2:25 pm	30(1800)	51

T air, air temperature = 30^0C
Initial temperature of cylinder = 30^0C

Table 3: Cylinder temperature as a function of time on January 22, 2013

Time of the Day	Period of Exposure (min/sec)	Temperature (^{o}C)
2:00 pm	5(300)	47
2:05 pm	10(600)	47
2:10 pm	15(900)	48
2:15 pm	20(1200)	48
2:20 pm	25(1500)	50
2:25 pm	30(1800)	52

T air, air temperature = 30^0C
Initial temperature of cylinder = 30^0C

Table 4: Cylinder temperature as a function of time on January 23, 2013

Time of the Day	Period of Exposure (min/sec)	Temperature (^{o}C)
2:00 pm	5(300)	47
2:05 pm	10(600)	48
2:10 pm	15(900)	50
2:15 pm	20(1200)	52
2:20 pm	25(1500)	53
2:25 pm	30(1800)	53

T air, air temperature = 30^0C
Initial temperature of cylinder = 32^0C

Table 5: cylinder temperature as a function of time on January 24, 2013

Time of the Day	Period of Exposure (min/sec)	Temperature (^{o}C)
2:00 pm	5(300)	48
2:05 pm	10(600)	48
2:10 pm	15(900)	49
2:15 pm	20(1200)	50
2:20 pm	25(1500)	51
2:25 pm	30(1800)	52

T air, air temperature = 30^0C
Initial temperature of cylinder = 30^0C

Figures (2-6) shows the graphs of temperature against time for the five consecutive days from the results of the data shown in Tables (1-5).

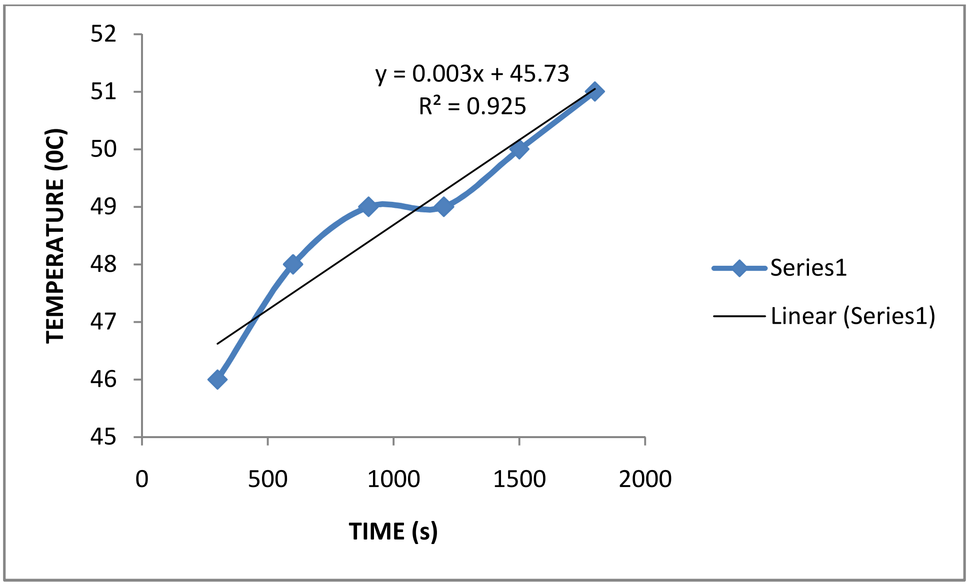

Figure 2: graph of temperature against time on January 20, 2013

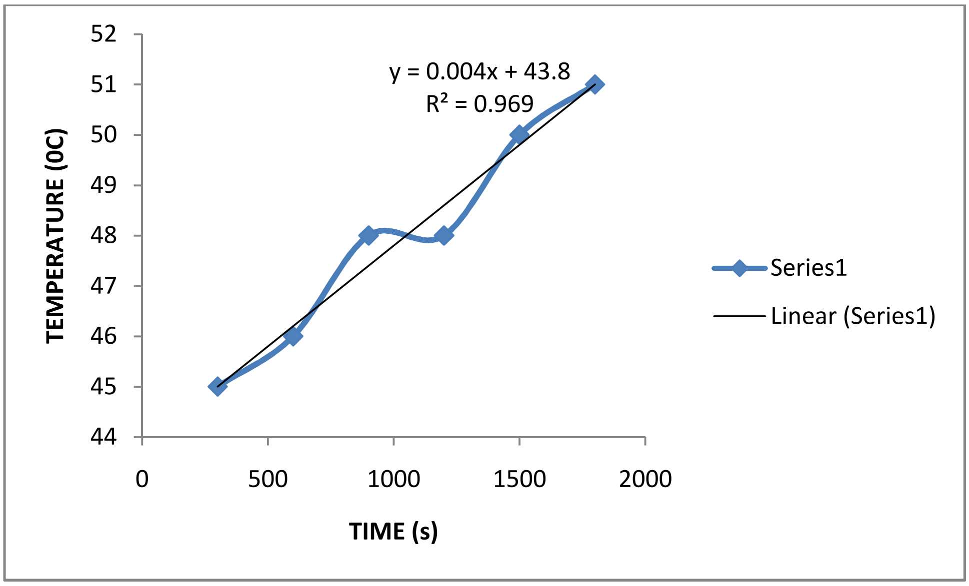

Figure 3: graph of temperature against time on January 21, 2013

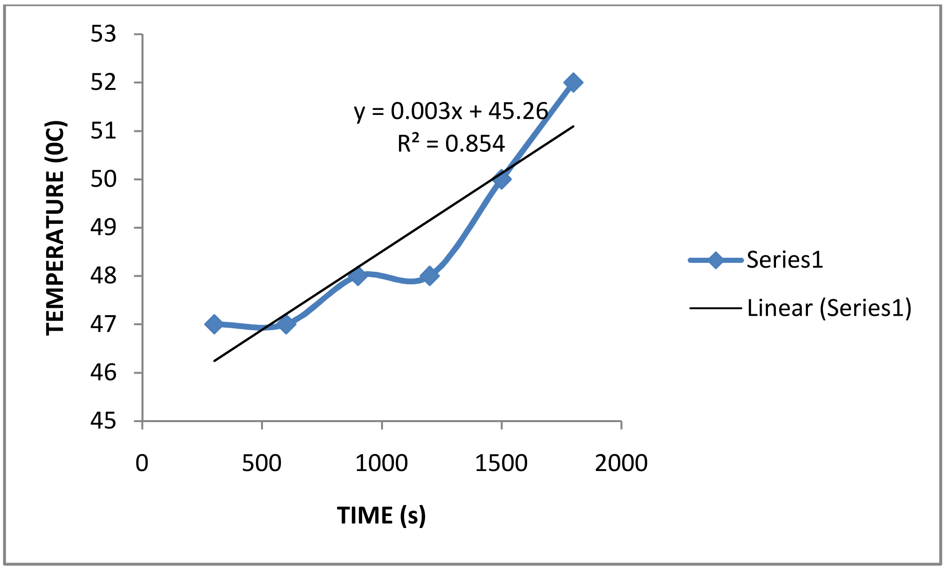

Figure 4: graph of temperature against time on January 22, 2013

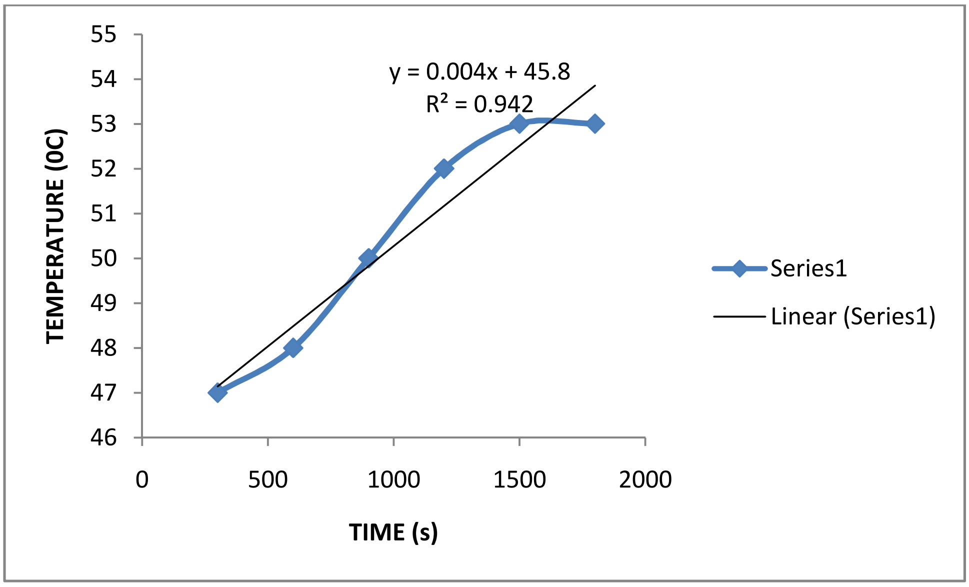

Figure 5: graph of temperature against time on January 23, 2013

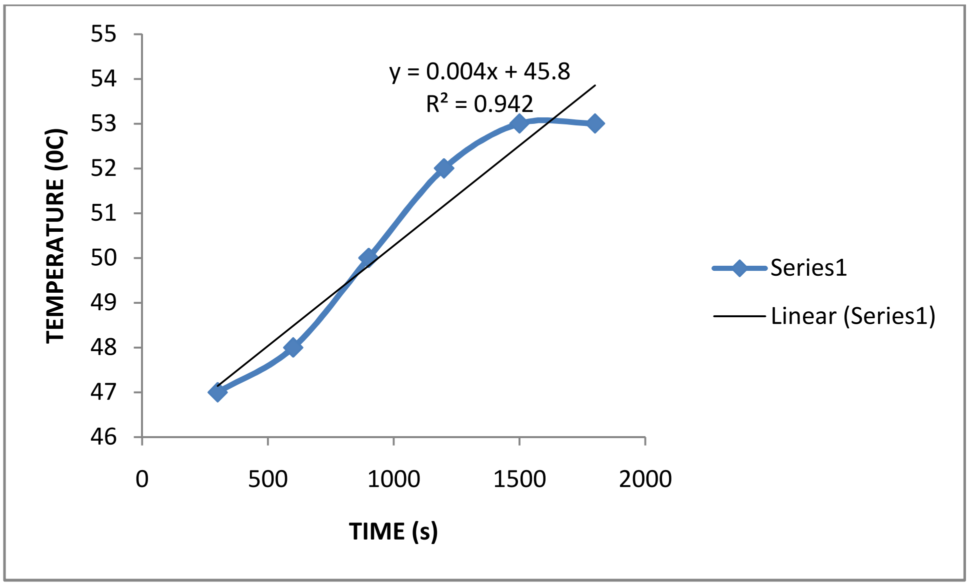

Figure 6: graph of temperature against time on January 24, 2013

Table 6: Summary of the computed solar constant at different time of the days

Date	m(kg)	c(JKg^{-1}K^{-1})	T(K)	π	r^2	A(m^2)	Q(J)	t(s)	A×t	GSc
20/01/2013	0.0195	900	278	3.142	0.000625	0.001964	4878.9	1800	3.53475	1380.267
21/01/2013	0.0195	900	279	3.142	0.000625	0.001964	4896.45	1800	3.53475	1385.232
22/01/2013	0.0195	900	278	3.142	0.000625	0.001964	4878.9	1800	3.53475	1380.267
23/01/2013	0.0195	900	279	3.142	0.000625	0.001964	4896.45	1800	3.53475	1385.232
24/01/2013	0.0195	900	277	3.142	0.000625	0.001964	4861.35	1800	3.53475	1375.302

The solar constant, GS_c is obtained as the average computed solar constant from table 6 as

$$GS_c = \frac{1380.267 + 1385.232 + 1380.267 + 1385.232 + 1375.302}{5} = 1381.260Wm^{-2}$$

Tables (1-5) shows the results of temperature and period of exposure of the Aluminium cylinder at different time of the day, it was observed that the temperature readings varies slightly, this can be trace to the variability of solar radiation due to absorption and scattering of solar radiation by atmospheric gases, aerosols, clouds and Earth's surface entering the Earth's atmosphere.
Figures (2-6) shows the graphs of variation of temperature at different time of the day. The coefficient of determination, R^2 was observed to be highest with 96.9 % in Figure 3 and lowest with 85.4 % in Figure 4. The variation apart from the above reason may be attributed to high and low relative sunshine duration and clearness index which is a function of solar radiation.

Table 6 gives the summary of the computed solar constant at different time of the days from which the average solar constant, GS_c was obtained to be $1381.260Wm^{-2}$ this value is in close agreement with that of satellite data measurement of 1366.10 Wm^{-2}. However, the variation is due to the fact that solar constant is in fact, not constant, but varies due to solar activities and solar radiation due to atmospheric effects (absorption and scattering); local variations in the atmosphere such as water vapour, clouds and pollution; latitude of the location; season of the year and time of the day.

CONCLUSION

At any given moment, the amount of solar radiation received at a location on the Earth's surface depends on the state of the atmosphere, the location's latitude, and the time of day. This present research work was carried out at Sokoto Energy Research Centre, Sokoto, North Western Nigeria (Latitude 13.01^{0}N, Longitude 05.15^{0}E, Altitude 305.8m above the sea level) for five consecutive days from January 20, 2013 - January 24, 2013 this is one of the months of the period of dry season in this region, as such, appreciable high sunshine duration and clearness index due to solar radiation are recorded. In this study, we used locally fabricated low cost devices of aluminium cylinder to evaluate the solar constant and obtained an average value of 1381.26 Wm^{-2} from ground-based measurement of solar radiation, which compares favorably well with that suggested by satellite data measurement as 1366.10 Wm^{-2} and those reported in many literatures. The observed variation in our evaluated value is attributed to the fact that solar constant is not perfectly constant, but varies in relation to the solar activities.

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