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Solarmeter Design for High Solar Radiation Measurement and Experimental Validation

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Abstract: In this study, a solar meter was designed to measure high solar radiation. The solar meter uses the characteristic properties of a solar cell in order to measure solar radiation. In this way, measurements can be carried out without any limitations. The solar radiation equation was entered into the ARDUINO microcontroller in the solar meter, and the results were compared through another commercial solar meter. These results were entered into STATGRAPHIC software and three different functions with high regression values were obtained. These three functions were entered into the Arduino microcontroller and the experiments were repeated. According to the comparisons made using commercial device, R^2 values were determined as 0.944, 0.936, 0.938, and 0.986 for the first equation and for three different functions, respectively. Based on the values obtained, it has been determined that the solar meter can make highly accurate measurements and after the development of appropriate functions, it can be employed especially in high solar radiation concentrated systems.

Keywords: Solar meter, Solar Radiation, Arduino, Measurement.

Yüksek Güneş Işınımı Ölçümü için Solar Metre Tasarımı ve Deneysel Doğrulanması

Öz: Yapılan bu çalışmada, yüksek güneş ışınımını ölçmek için bir solar metre tasarlanmıştır. Solar metre bir solar hücrenin karakteristik özelliklerini kullanarak güneş ışınımı ölçebilmektedir. Bu sayede herhangi bir sınırlama olmadan ölçüm yapılabilmektedir. Güneş ışınımı eşitlikleri ARDUINO mikro kontrol kartı aracılığıyla tasarlanan solar metreye girilmiştir ve başka bir ticari solar metre ile karşılaştırılmıştır. Bu sonuçlar STATGRAPICH programına işlenerek yüksek regresyon oranına sahip 3 farklı fonksiyon elde edilmiştir. Bu 3 fonksiyon tekrar ARDUINO mikro kontrol kartına girilerek deneyler tekrarlanmıştır. Ticari cihaz ile karşılaştırıldığında elde edilen R^2 değerleri birinci eşitlik için 0.944 ve 3 farklı fonksiyon içinse sırasıyla 0.936, 0.939 ve 0.986 olarak tespit edilmiştir. Elde edilen değerlere dayanarak, tasarlanan solar metrenin oldukça hassas ölçümler yapabileceği ve uygun fonksiyonların geliştirilmesinden sonra, özellikle yüksek güneş radyasyonlu yoğunlaştırıcılı sistemlerde kullanılabileceği belirlenmiştir.

Keywords: Solar metre, Güneş ışınımı, Arduino, Ölçme.

1. Introduction

Solar energy is the most used renewable energy source. Solar radiation can be converted into energy through various methods in regions with sufficient solar radiation. Solar radiation is the most

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important parameter that determines the methods of solar energy use. The measurement of solar radiation is used for applications such as confirming satellite measurements, analyzing the distribution and variation of radiation received, or estimating the energy efficiency of solar energy facilities [1]. Many studies have so far been conducted on the estimation and measurement of solar radiation. Abbasi and Qureshi [2] compared four experimental models with the satellite-based global and diffuse radiation values and proposed a new model that could estimate daily global and diffuse solar radiations in the city of Chhor in Pakistan. At the end of the study, 98.7% of NASA satellite data could be calculated by using Chhor's model. Shi et. al. [3] developed a new model for the estimation of daily solar radiation on an inclined topography in China. They tested the model they developed using the solar radiation observations in 98 stations located in China, and they found that the mean relative absolute error was 10.57%. Mghouchi et al. [4] proposed a new model capable of estimating the diffuse and global solar radiation in Tutouan, Northern Morocco and made a comparison between numerical simulation and this model. As a result, they found RMESE and MAPE values to be less than 15%. Bakirci [5] developed a model that estimates the solar radiation in the horizontal plane of 13 provinces in the Eastern Anatolia region of Turkey. As a result of the study, Van province had the highest value with 18.580 MJ / m^2-day, while Ağrı province had the lowest value with 13.644 MJ / m^2-day. Almorox [6] proposed a new model to estimate global solar radiation by calibrating the existing models and with the help of meteorological data such as precipitation, temperature etc. He stated that this new model gives accurate estimates for daily global solar radiation and has a high coefficient of determination (R^2 = 0.92). Studies have clearly shown that solar radiation is extremely important in the solar energy applications and many studies have been conducted to predict solar radiation [7-9]. Solar radiation is measured by a device called solar meter or pyranometer, and the accuracy and precision of this measurement are the most critical parameters in efficiency calculations. When the studies on the devices that measure solar radiation are examined, it is seen that many of these studies are aimed for increasing the measurement quality of pyranometers/solarmeters. Sartarelli et al. [10] calibrated a heat flux solar meter via the Hotell method in their study. The data obtained from this solar meter were compared to those obtained by a commercial solar meter, and they reached satisfactory results. The authors also stated that the heat flux solar meter is not affected by outdoor temperatures as it performs measurements by assessing the heat flow on a metal rod. Menyhar et al. [11] stated that the pyranometers must be leveled totally and continuously to obtain high-precision solar radiation data and in their study, they developed a new method that enables to detect even small declinations of a pyranometer. This method can detect annual, 10-min or hourly solar radiation even at values as small as 2 or 3 degrees. Baltazar and Haberl [12] used a Multi Pyranometer Array (MPA) and designed a method to calculate clear sky direct normal radiation being inspired by the anisotropic clear sky model. They presented an advanced model that calculated the normal direct solar radiation by grouping two expressions of a few MPA sensors in an analytically satisfactory manner. They found that the root mean square error (RMSE) decreased about 14-43% in comparison with the previous studies in the literature, indicating that this method is a promising approach for MPA. Singular standard polynomial functions depending on the angle of incidence were constructed in order to characterize the pyranometer sensitivity related to the standard uncertainties and upper estimation intervals in the study carried out by Boyd [13]. Free software which can calculate these functions using various algorithms was developed. Boyd stated that all the obtained data had a value higher than 0.98 R^2 by testing the uncertainties and sensitivities of 40 different pyranometers in 6 different models. Srikrishnan et al. [14] worked on an alternative approach that can detect direct normal solar radiation (DNI) of a multiple pyranometer by means of the ANN method and examined the results on various NN topologies. Lester and Myers [15] stated that pyranometers produced an electrical signal depending on global radiation and that the ratio of the signal to irradiance was the responsivity (RS) of the device. They stated that the RS value which is assumed to be constant in many engineering studies varied depending on the days in a year, the angle of zenith, and the net infrared radiation, and they proposed a RS function that can determine this RS value. They revealed that the function obtained for PSP pyranometers reduced the uncertainties in the radiation measurements. Martin et al. [16] proposed a new device that allows for the simultaneous measurement of diffuse solar radiation along the azimuthal and tilt angles. They pointed out that not many commercial instruments were designed for this purpose and offered a specific design based on a single multi-lobe shadow-ring that was capable of measuring diffuse solar radiation on normal surfaces at 60-90 ˚C and along various azimuthal angles by a few tilted pyranometers. Rahbar and Hasadi [17] aimed to design and produce an inexpensive pyranometer using a thermoelectric generator. Experiments in their study, in which equations related to the solar density, output voltage and ambient temperature were derived by employing mathematical and thermodynamically models, were conducted in Semman, Iran. After reviewing the existing studies on solar radiation measurement systems, a new device that would help the true measurement of solar radiation on horizontal surfaces and enable the user to read solar radiation in W/m^2, and that is easy to use and highly precise was designed and tested in a study conducted by Badran et al. [14]. The device can read the solar radiation instantaneously and also show the average radiation for a certain period of time. The device was programmed and designed by a programmable interfacing controller (PIC). The researchers also stated that the power supply circuit did not need any external power source as it was fed by the solar cell. When the existing studies in the literature are examined, it is seen that the measurement of solar radiation plays a vital role in solar energy systems and improving the quality of this measurement is extremely important. There are various solar energy applications. Today, one of the most current issues is to generate electricity from solar energy. The most effective way to generate electricity from solar energy is to use photovoltaic (PV) panels. The use of PV systems is increasing day by day. PV systems can be used directly or by being supported by concentrated systems [19-22]. The reason for using concentrators in PV systems is the low solar radiation in some regions or to obtain more energy by fewer PV panels. Solar radiation increases by means of concentrated systems and thus, higher power can be obtained inside a PV. However; the biggest problem encountered while working on concentrated systems is that the increased solar radiation cannot be measured in a reliable way. Many solar meters used in daily life can measure up to 2000 W/m^2 solar radiation. However, solar radiation in concentrated systems can exceed these values. Especially, in concentrated systems, it has been detected that reliable measurements cannot be done since hand-type equipment capable of measuring high amount of solar radiation does not exist. To address this problem, in this study we designed and produced a solar meter capable of performing measurements under high solar radiations. The most important difference between the designed solar meter and other solar meters is that the new solar meter does not include a photo diode; instead a small PV panel was used. Sensors used in solar meters are usually photodiodes and their measurement ranges are limited. Photodiode systems, especially in concentrated systems, cannot satisfy this need and cannot take accurate measurements. Failure in obtaining accurate measurements in a PV system means that it will not be possible to perform accurate thermodynamical analyses. Unlike other studies, a PV panel was employed as a measurement device for the first time in this study in order to resolve this problem. Solar radiation detected using the PV panel’s efficiency calculation yields correct results with no limitation on measurements. In order to test the accuracy and calibration of our device, the measurement intervals of the device were compared with a calibration-certified device.

2. Materials and Method

A solar meter using a solar cell as a measurement sensor was designed and manufactured in this study. Inside the manufactured solar meter, solar radiation was calculated by taking advantage of the characteristics of the solar cells. Since the efficiency, area, and voltage produced by the solar cell were known, solar radiation was found using the following equation:

$$I = \frac{\mathrm{V} \times \mathrm{A}}{(\mathrm{PA}) \times (\eta)} \tag{1}$$

In this equation, I, V, A, PA, and η signify solar radiation, voltage produced by the solar cell, current, panel area, and the efficiency of the panel, respectively.
Equation 1 was entered into the Arduino microprocessor in the produced solar meter. After this step, solar radiation measurements were taken with a calibration-certified reference device and the produced solar meter (test device), and the results were compared. The structure of the solar meter and the final layout of the device are shown in Figure 1.

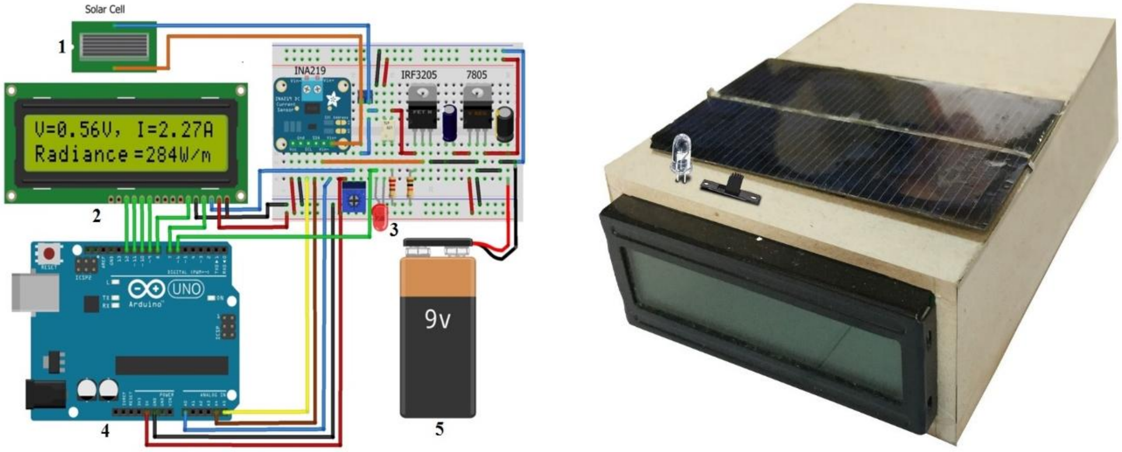

Figure 1. Solar Meter Design Elements (1. Photovoltaic Cell 2. LCD 3. Current Sensor, MOSFET and Supply Voltage 4. Arduino 5. 9 V Battery) and the final layout of the device.

The components used in the solar meter and their properties are given in Table 1.

Table 1. Components used in the produced solar meter and their properties

No	Device Name	Properties
1	Photovoltaic Cell	The photocell is used for the measurement in the device. It consists of a single cell and allows for the readout of voltage generated by the radiation falling on the surface.
2	LCD	The component that displays the readouts of the device.
3	Current Sensor (INA 209) Mosfet (IRF3205) Supply Voltage (7805)	------------------------------------
4	Ardunio	------------------------------------
5	9 V Battery	The power source of the device. It enables to take measurements for long durations.
6	Reference Solar meter Solar-meter Evomex TM 750	Measuring range -0….2000 W/m^2 Resolution- 1 W/m² Accuracy- ± 5%

The INA219 high side current sensor was used to measure the PV module short circuit current across the solar radiation measurement system. The reason for that was to eliminate the ground noise which negatively affects the precision of the measurements taken on the ground by the low side current measurement method which is preferred in power systems. Since many current measurement sensors are suitable for low side current measurements, they are placed between the ground side of the transmission and the target ground. This may negatively affect the current flow as it alters the ground reference of the circuit. Since the load is not directly grounded in the low side current sensor circuits, problems can be encountered during applications in which more than one load current are needed to be measured or all loads must be connected to a common ground [23, 24]. The INA219 current sensor is an electronic element capable of current measurement up to ± 3.2 A at a resolution of 0.8 mA, which eliminates these disadvantages [25].

The IRF3205 MOSFET was used inside the circuit as a switching element to prevent the solar battery from being permanently short circuited [26]. That made measurements of both the short circuit current and open circuit voltage of the solar cell possible without any alterations in the circuit. The IRF3205 is a linear circuit element with an internal resistance of 0.008 Ω during conduction. Thus, the influence of the switching element conduction resistance was minimized.

An Arduino Uno microcontroller card was used to control the electronic circuit inside the solar radiation measurement system. Arduino is an open source and a user-friendly electronic platform in terms of both hardware and software. It has 14 digital inputs/outputs, 6 analog inputs and an operating frequency of 16 MHz [27]. We selected this card because of its rich application library, high number of sample applications, price, and accessibility.

The INA219 current sensor, which was used to measure the short circuit current of the solar panel, is an electronic element that operates by a 5V DC supply and communicates with the Arduino board via I2C. The library built by Adafruit company for INA219 current sensor was defined to the Arduino software, and current measurements were taken using a built-in function. The ADC (Analog to Digital Converter) module of the Arduino board was used to measure the open circuit voltage of the solar panel. The ADC module is a 10-bit analog-to-digital converter unit based on the 5 V DC reference voltage supplied via Arduino. Accordingly,

since 10 bits = 1024 steps (0 to 1023), ADC unit reaches the 5 V reference voltage at 1023.

$5\,V = (1111111111)_2$

ADC precision 5V/(2^10-1)=0.00488 is found as V per bit. The corresponding voltage value of $(0001110011)_2$ read at the ADC unit is calculated as follows:

$$\frac{Resolution\ of\ ADC}{Reference\,Voltage} = \frac{Reading\ ADC}{Analog\,Voltage\ Measured} \tag{2}$$

$(0001110011)_2 = 115$

$$\frac{1023}{5} = \frac{115}{V_{oc}} \tag{3}$$

$115 \times 0.00488 = 0.56\,V$ Radiation was calculated via the formula $\frac{V_{oc} \times I_{sc}}{0.16 \times PA}$ and displayed on the LCD screen.

3. Experimental Procedure

The designed device was tested through different functions inside a concentrated PV test apparatus as shown in Figure 2. First, equation 1 was entered into the Arduino microprocessor inside the produced device. In this equation, the area of the solar cell used as a sensor, the efficiency, and the voltage it produces are known. The values for these quantities are as shown in Table 2.

Figure 2. The experimental setup of the measurement

Table 2. Constant values for Eq. 1

Voltage (V)	0.56
Solar Cell Area (PA m^2)	0.004056
Panel Efficiency (η%)	16

In addition to the values that are assumed to be constant, the alternate current and solar radiation values are also present in Equation 1. Among these values, solar radiation can be determined based on alternate current. In this study, a current sensor was used to find the alternate current. 200 measurements were taken with the test and the reference device between 11th and 17th June, 2016 using Equation 1. These measurements were comparatively entered into Statgraphics software, and the equations of three functions with the highest regressions were obtained. The equations for the three obtained functions are shown below.

Function 1;

$$Reference\ device = {}^{1}/_{(0.000128743 + (1.27942/\text{Test device})} \tag{4}$$

Function 2;

$$Reference\ device = \mathrm{e}^{(-0.711554+(1.05461\ \mathrm{x}\ \ln(\text{Test device})))} \tag{5}$$

Function 3;

$$Reference\ device = (9.80345 + (0.0156715\ \mathrm{x}\ \text{test device}))^2 \tag{6}$$

The three equations were entered one by one into the Arduino microprocessor of the produced solar meter, and the experiments were conducted separately for each equation. The purpose of this process was to calibrate the device by means of another well-calibrated device. The closer the values measured by the test device are to each other within the measurement range of the reference device, the greater the accuracy of the radiation values that the test device can measure at high radiation. Since there is no other device to make comparisons for measurements taken by the test device at high solar radiation, this process and obtaining high regression values are quite crucial.

4. Results and Discussions

As a result of the experimental study, the measurements taken based on the initial equation of the test device (Equation 1) and the functions derived from this equation were analyzed in detail. The experimental study conducted by means of the initial equation was carried out with the data of 200 measurements taken between 11th-17th June 2016. The results obtained from this equation are shown graphically in Figure 3.

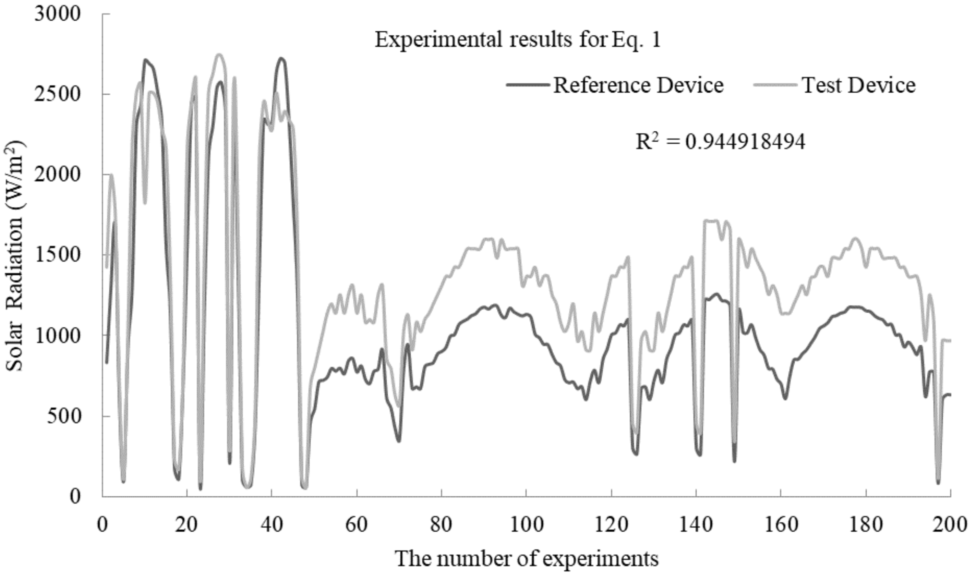

Figure 3. Experimental Results for Equation 1

The experimental study was conducted with the data obtained through 182 measurements between 20th and 21th June 2016 after the first function obtained from Statgraphics software was entered into the test device. Variations between the test and the reference devices according to this equation are shown in Figure 4.

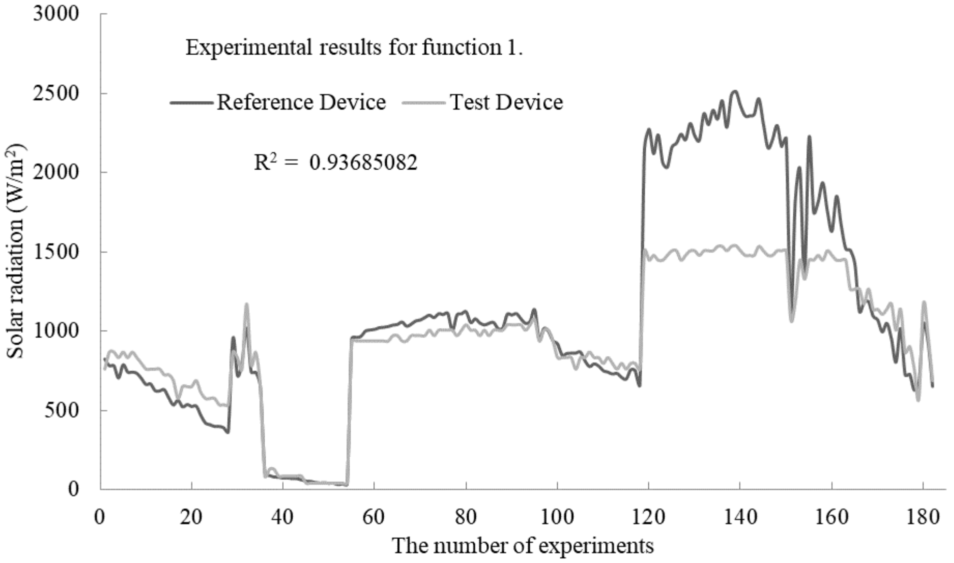

Figure 4. Experimental results for function 1.

According to the first equation, regression declined. At this stage, variables such as efficiency and temperature were examined. According to the comparative table of the current value read by the current sensor, the radiation value of the device, and the theoretical radiation values with respect to current, the efficiency was found to be 16% on average and was added to the equation.

After this improvement, the experimental study continued with 295 measurements for function 2 between 4-7 November 2016. The graph for the second function is shown in Figure 5.

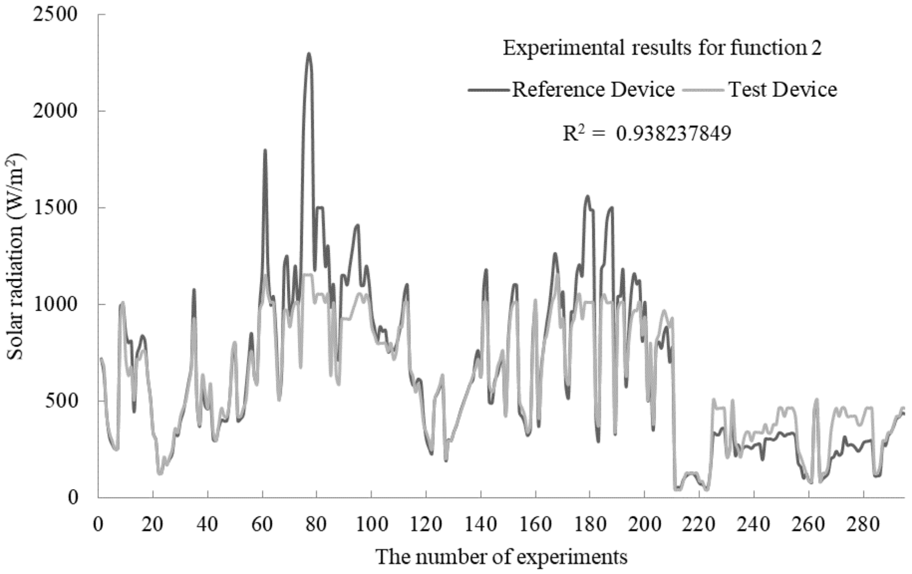

Figure 5. Experimental Results for Function 2.

Finally, the third function was loaded into the device and the experimental study was completed on 11th November 2016 with 220 measurements. The graph obtained for the third equation is shown in Figure 6.

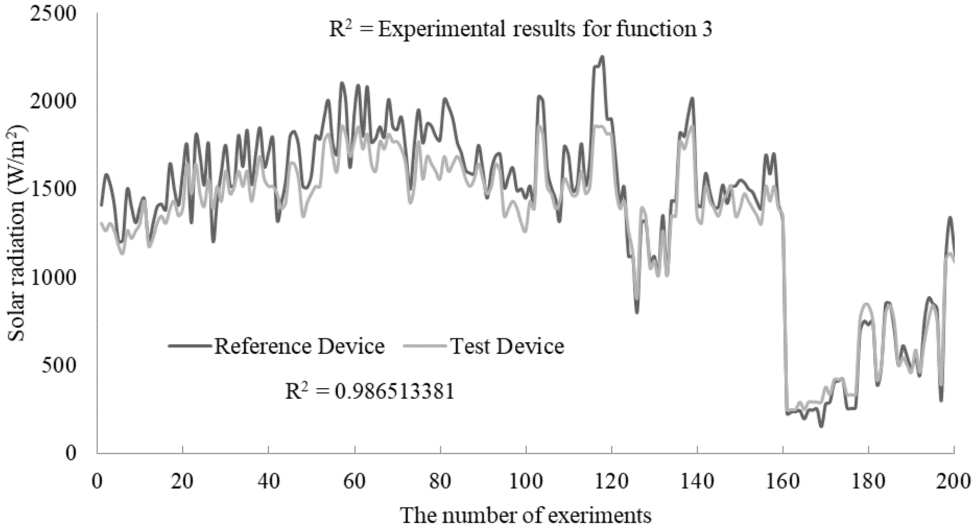

Figure 6. Experimental Results for function 3.

The regression results obtained for all the functions are shown in Table 3. The regression results given in this table are both experimental and theoretical. Since the experimental study started using the first main equation, only the experimental regression for the main equation is given in Table 3. Other functions were obtained according to this regression result.

Table 3. Function-regression table

Explanation	Equations	Theoretical Regressions	Experimental Regressions
Main Equation	$I = \frac{\mathrm{V} \times \mathrm{A}}{(\mathrm{PA}) \times (\eta)}$	------	0.9449
Function 1	$Reference\ device = {}^{1}/_{(0.000128743 + (1.27942/\text{Test device})}$	0.9266	0.9368
Function 2	$Reference\ device = \mathrm{e}^{(-0.711554+(1.05461 \text{ x } \ln(\text{Test device})))}$	0.9489	0.9382
Function 3	$Reference\ device = (9.80345 + (0.0156715 \text{ x test device}))^2$	0.9640	0.9865

5. Conclusions

As a result of the experiments conducted with the designed solar radiation measurement device, the following results were obtained:

1. The use of a solar cell instead of a photo diode inside the experimentally tested device does not impose a limitation for the measurements taken by the device due to the solar radiation and the increasing current.
2. Since the increase in current due to the increasing solar radiation damages the photodiode, there must be a measurement range in these devices. Since solar meters cannot measure high solar radiation particularly in concentrated solar radiation measurements, these radiation values can be estimated through calculation.
3. The device designed and experimentally tested was experimentally analyzed in a system with a concentration of radiation up to 2500 W/m^2. A function was derived via the Statgraphic 14.1 software by making comparisons within the reference device measurement range.
4. In the measurements taken up to 2500 W/m^2, accuracy was ensured through the experiments conducted with Function 3 at the rate of R^2=0.98.
5. The lack of a measurement limitation for the usage of solar cells as radiation sensors revealed that this kind of a solar meter can measure high intensity concentrated solar radiation through appropriate functions.

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