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Modeling and Simulation of Energy Recovery from a Photovoltaic Solar cell

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Abstract.

Photovoltaic (PV) solar cell which converts solar energy directly into electrical energy is one of the feasible alternative sources to fossil fuel. This study aims at predicting the energy recovery from a typical photovoltaic solar cell, BP 3 series 235 W solar panel, by developing a reliable mathematical model of the solar panel which could represent the real systems. The model equation was solved using the 'solve block' tool in MathCAD 14 software and validated by physical data obtained from literature. Using the model developed the effects of temperature and solar irradiance on performance of PV solar panel was investigated using nominal conditions of 298 K and 1000 W/m^2 as basis. Temperature was varied between 273, 298, 323, 348 and 373 K at constant irradiance of 1000 W/m^2. Solar irradiance was also varied using 200, 400, 600, 800 and 1000 W/m^2 while maintaining temperature at 298 K. The energy recovery from the PV model was evaluated using the fill factor concept. From the analysis of results, there is some agreement between the simulation results and the reported experimental performance of the PV solar panel. The performance of the PV system increased with increase in temperature and solar irradiance. In purview of values of solar irradiation (200 – 1000 W/m^2) and temperature (273 - 373 K) that were studied, the energy recovery was maximum at 79.98% which agrees with values of between 75 and 85% obtained in practical solar cells.

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Introduction.

The quest for sustainable and clean energy for the ever growing human populace is probably the greatest global challenge of the 21st century (Clarke *et. al*., 2011; Dhahri and Omri, 2013). The world has depended majorly on fossil fuels as the source of energy for domestic and industrial uses. These fossil fuels have now been identified with environmental challenges and are non-renewable (Dhahri and Omri, 2013). This makes the conventional energy sources not to be sustainable along with their serious environmental problems such as global warming through the release of greenhouse gases to the atmosphere when the fuels are burnt. Recently, there has been increased concern about the effect of excessive amounts of greenhouse gases in the atmosphere (Ray, 2010). Carbon dioxide and methane are two major greenhouse gases. Carbon dioxide is produced whenever methane, coal or oil is burned to produce energy for utilization. Due to associated problems with fossils, there has been continuous research on renewable energy sources that are cleaner and can serve as good replacement from the normal fossil fuels. Some of these alternative sources include wind power (Sethi *et. al*., 2012), fuel cells, geothermal power, carbon sequestration and solar power. Harnessing these options can help reduce the output of carbon dioxide into the atmosphere (McKendry, 2002; Chu, 2011; Dhahri and Omri, 2013)

Among the options, solar power has gained attention of researchers because of the relative abundance of its source which is the sun (Gowtham *et. al*., 2012; Dhahri and Omri, 2013). Solar power comes to the Earth in the form of light or radiation. Having gained interest of researchers as energy derived from the sun, several methods of utilizing solar power have been found; one of these is the solar panels. In practice, series of about 36 or 72 solar cells make a solar panel or module, and a collection of modules make up an array. In a solar panel, light strikes a surface, excite an electron and electricity is produced. With the basic knowledge of physical sciences about the sun, the amount of power hitting the earth's surface per square meter can be calculated. If fully harnessed, solar power can provide more than enough power for human utilization in the present and in the future. So far, at laboratory-test scale, photovoltaic cells are typical solar cells types that give the highest energy conversion efficiency of 42.8 % as the best achievable efficiency of solar power conversion to electricity worldwide (Ray, 2010; Chu, 2011). The efficiencies are lower than this value for other solar collection methods. Solar power systems in application today have efficiency between 10 and 15% (Chu, 2011). Silicon is used in making solar cells because it is more efficient, abundant, and due to its application in the computer industry, methods of working with, and producing silicon wafers are well understood. But, from energy recovery standpoint, crystalline silicon has a band gap of 1.1 eV. This means that if a photon of light comes in with an energy of less than 1.1 eV, it fails to create an electron and hole pair across the band gap, and if it has an energy of more than 1.1 eV it does excite an electron and hole pair, but any extra energy is lost because the electron and hole settle at 1.1 eV quickly. This shows that the solar power conversion system experiences tangible loss of energy in the course of conversion, causing lack of high energy conversion efficiency. The cost of the solar power systems also hinders it from gaining full acceptance.

In order to meet human demand for energy, more efficient power collection mechanisms need to emerge. This is because viability and commercialization of solar power as an alternative, sustainable and renewable energy source would be limited by the restricted efficiency (Chu, 2011). Furthermore, since energy lost is mainly through the solar panel itself when heated by the sun, another way of improving the performance and efficiency of the solar panel would be by developing effective cooling systems.

Temperature and irradiation are two main physical factors that affect performance of a solar cell, module or array. Other parameters include open-circuit voltage and short-circuit current. Well modelled computer simulation of a solar power system would be a reliable tool that can represent governing parameters in working a solar power system. This present work aims at carrying out a computer simulation of energy recovery from a typical photovoltaic cell.

Materials and method

A single-diode model (also called the five parameters model) was used in developing the model equations of a PV system. In the single-diode model the current source is used to model the incident solar irradiance, a diode for the polarization phenomena, a series resistance and a parallel resistance to represent the power losses **(**El Tayyan, 2013).

For a single PV solar cell, the cell terminal or output current can be written by applying Kirchhoff's law (Gowtham *et al.*, 2012; El Tayyan, 2013; Salmi *et al.*, 2012);

$$I = I_{Ph} - I_{Dio} - I_{Sh} \quad (1)$$

Where I is the output current of the cell, I_{Ph} is the irradiance current or photocurrent at nominal condition of 298 K temperature and irradiation of G = 1000 W/m^2; I_{Dio} is the parallel current across the diode, and I_{Sh} is the shunt current due to shunt resistor R_{Sh}. The diode current I_{Dio} and the shunt current I_{Sh} are given respectively, by the following relationships (Tian *et al*., 2012):

$$I_{Dio} = I_o\left[e^{\left(\frac{q(V+IR_s)}{nkT}\right)} - 1\right] \quad (2)$$

$$I_{Sh} = \frac{V+IR_s}{R_{Sh}} \quad (3)$$

In Equations (2) and (3), I_o is the diode saturation current or cell reverse saturation current, q is the electronic charge (= 1.602 x 10^{-19} C), V is the solar cell output voltage, R_s is series resistance, n is called ideality factor or ideal constant of diode, k is Boltzmann constant (= 1.3806503 x 10^{-23} J/K), and T is cell temperature. Substituting Equations (2) and (3) into (1) gives a non-linear Current-Voltage (I-V) relationship for a single solar cell as:

$$I = I_{Ph} - I_o\left[e^{\left(\frac{q(V+IR_s)}{nkT}\right)} - 1\right] - \left(\frac{V+IR_s}{R_{Sh}}\right) \quad (4)$$

Since (kT/q) is the temperature or thermal voltage, V_T, measured in volts (Sethi *et. al*., 2012), Equation (4) can be written as;

$$I = I_{Ph} - I_o\left[e^{\left(\frac{(V+IR_s)}{nV_T}\right)} - 1\right] - \left(\frac{V+IR_s}{R_{Sh}}\right) \quad (5)$$

If the factor ($1/nV_T$) is replaced by a single term C_{ekT}, representing the reciprocal of thermal voltage of the PV system, then Equation (5) becomes;

$$I = I_{Ph} - I_o\left[e^{\left(C_{ekT}(V+IR_s)\right)} - 1\right] - \left(\frac{V+IR_s}{R_{Sh}}\right) \quad (6)$$

At open circuit conditions, the output current, I, is zero. The diode saturation current I_o is obtained by evaluating Equation (5) for the open circuit conditions as follows (El Tayyan, 2013):

$$I = I_{Ph} - I_o\left[e^{\left(\frac{(V_{OC})}{nV_T}\right)} - 1\right] - \left(\frac{V_{OC}}{R_{Sh}}\right) \quad (7)$$

Equation (7) can then be arranged to give:

$$I_o = \frac{I_{Ph} - \left(\frac{V_{OC}}{R_{Sh}}\right)}{e^{\left(\frac{(V_{OC})}{nV_T}\right)} - 1} \qquad (8)$$

Also, upon substitution of C_{ekT} for $(1/nV_T)$ in Equation (8), the diode saturation current is obtained as:

$$I_o = \frac{I_{Ph} - \left(\frac{V_{OC}}{R_{Sh}}\right)}{e^{(C_{ekT} V_{OC})} - 1} \qquad (9)$$

Substituting Equation (9) into Equation (6) gives the model Equation (10) which is solved in MathCAD. This is for a single PV solar cell.

$$I = I_{Ph} - \left(\frac{I_{Ph} - \left(\frac{V_{OC}}{R_{Sh}}\right)}{e^{(C_{ekT} V_{OC})} - 1}\right)\left[e^{(C_{ekT}(V + IR_s))} - 1\right] - \left(\frac{V + IR_s}{R_{Sh}}\right) \qquad (10)$$

The solve block non-linear solver in MathCAD is invoked to simulate Equation (10) for a PV solar cell using necessary input data and values of constants. For the PV solar panel, the model equation is developed based on standard reference conditions. The model also considers variation in temperature and solar irradiance. Hence, reference conditions for photocurrent I_{Ph}, shunt resistance R_{Sh}, series resistance R_s, temperature T_{ref}, and solar irradiance G_{ref} are specified. The open-circuit voltage V_{OC} and the constant C_{ekt} are also given. To obtain this model equation for the solar panel, fundamental modifications to Equation (10) include the number of solar cells, and its temperature and irradiance dependence.

First, set of linear equations are written to represent photocurrent, shunt resistance and series resistance at given temperature and irradiance other than reference values (Tian *et al.*, 2012). The photocurrent relationship is given by Equation (11),

$$I_{Ph} = I_{Ph,ref}\left(\frac{G}{G_{ref}}\right)\left[1 + \frac{\alpha_T}{I_{Ph,ref}}\left(T - T_{ref}\right)\right] \qquad (11)$$

Where I_{Ph} is photocurrent at a given temperature T and irradiance G, α_T is a current-temperature factor (amp/K). $I_{Ph,ref}$, G_{ref} and T_{ref} are reference values of photocurrent, solar irradiance and temperature. The shunt resistance is given by Equation (12),

$$R_{Sh} = \left(\frac{G}{G_{ref}}\right) R_{Sh,ref} \qquad (12)$$

Where R_{Sh} is shunt resistance at a given temperature and solar irradiance; $R_{Sh,ref}$ is reference value of shunt resistance at standard reference conditions. The series resistance at other conditions is related to its value at reference conditions as:

$$R_s = R_{s,ref} \qquad (13)$$

Now, from Equation (10), in order to develop this equation for a PV Solar module where a number of solar cells are normally arranged in series, the model equation is obtained as follows (Tian *et. al.*, 2012):

$$I = I_{Ph} - \left(\frac{I_{Ph} - \left(\frac{V_{OC}}{N_s R_{Sh}}\right)}{e^{\left(\frac{C_{ekT} V_{OC}}{N_s}\right)} - 1}\right)\left[e^{\left(\frac{C_{ekT}(V + IR_s)}{N_s}\right)} - 1\right] - \left(\frac{V + IR_s}{N_s R_{Sh}}\right) \qquad (14)$$

But, here values of I_{Ph}, R_{Sh} and R_s are determined by expressions in Equations (11), (12) and (13) respectively. Upon substitution of these three equations into Equation (14), an integrated equation for the PV solar panel is obtained as given in the following Equation (15),

$$I = I_{Ph,ref}\left(\frac{G}{G_{ref}}\right)\left[1 + \frac{\alpha_T}{I_{Ph,ref}}\left(T - T_{ref}\right)\right] - \left(\frac{\left[I_{Ph,ref}\left(\frac{G}{G_{ref}}\right)\left[1 + \frac{\alpha_T}{I_{Ph,ref}}\left(T - T_{ref}\right)\right]\right] - \left(\frac{V_{OC}}{N_s\left(\frac{G}{G_{ref}}\right)R_{Sh,ref}}\right)}{e^{\left(\frac{C_{ekT} V_{OC}}{N_s}\right)} - 1}\right)\left[e^{\left(\frac{C_{ekT}(V + IR_s)}{N_s}\right)} - 1\right] - \left(\frac{V + IR_s}{N_s\left(\frac{G}{G_{ref}}\right)R_{Sh,ref}}\right) \qquad (15)$$

In Equations (14) and (15), N_s is the number of cells arranged in series to form the PV module, I is output current and V is output voltage of the module. If more than one PV module is considered, where each module has N_c cells in series, and there are N_m modules, then:

$$N_s = N_m \times N_c \qquad (16)$$

Equation (15) is the final model equation for the PV solar module. Output current and voltage of the PV module can now be obtained from this equation. To evaluate the efficiency of the PV module, the fill factor (FF) can be used (Petkov *et. al.*, 2011). This is a factor which shows to what extent the real effectiveness of the cell, $(V_{mp} \times I_{mp})$ approximates the idealized $(V_{oc} \times I_{sc})$:

$$Fill\ factor\ (FF) = \frac{V_{mp} \times I_{mp}}{V_{OC} \times I_{SC}} \qquad (17)$$

Where V_{mp} and I_{mp} are respectively the voltage and current at the maximum power point; V_{OC} is the open-circuit voltage; I_{SC} is the short-circuit current. For the real PV cells the fill factor ranges from 0.75 to 0.85 (Petkov *et al.*, 2011). The available theoretical power is therefore calculated as V_{OC} x I_{SC} = 37.2 V x 8.48 A = 315.456 watt or 0.315 kW.

Simulation

The developed mathematical model was simulated using the 'solve block' in MathCAD 14 software. It is a datasheet based parameter determination model which uses data provided by the manufacturer. With the operational data provided by the manufacturer, the BP 3 Series 235 W PV panel was the solar power system considered in this study (Tian *et al.*, 2012). The values of the following parameters were defined as: T_{ref}= 298 K, G_{ref} = 1000 W/m^2, q =1.602 x 10^{-19} C, k = 1.38065 x 10^{-23} J/K, N_s = 36 cells, α_T = 0.00515 A/K, β'_T = 0.28 V/^{o}C, $V_{OC,\ ref}$ = 37.2 V, $I_{SC,\ ref}$ = 8.48 A, and $E_{g,ref}$ = 1.237 eV, where 1 eV = 1.6 x 10^{-19} joule. Also, the parameters at reference or nominal conditions are defined as: I_{Phref} = 8.48 A, R_{Shref} = 5 ohm, R_{Sref} = 0.005 ohm, n_{ref} = 1.1. The Photovoltaic system-related parameters are as provided by Tian *et al.* (2012) for BP 3 series 235 W PV system, while other physical constants such as T_{ref}, G_{ref}, q and k have their known standard values.

Simulation Algorithm

The following algorithm was used in simulation of the PV mathematical model in MathCAD 14 software;

(i) The following were specified; T = 273, 298, 323, 348, 373 K; and G = 1000, 800, 600, 400, 200 W/m^2.

(ii) Calculations were done using appropriate formula for I_{Ph}, R_{Sh}, and R_s using their corresponding reference values earlier specified.

(iii) Substitution was carried out for I_{Ph}, I_o, and $V_{OC}(T)$ into Equation (15) to obtain $I(T)$.

(iv) Values of $I(T)$ were plotted against $V_{OC}(T)$ to obtain I-V characteristics curve.

(v) Also, power, P was plotted against $V_{OC}(T)$, where P = $I(T)$ x $V_{OC}(T)$.

(vi) Evaluation of energy efficiency/recovery of the PV module using Equation (17) was carried out.

Results

In order to verify the reliability of the mathematical model developed, the simulation results were compared with experimental data for a BP 3 Series 235 W solar cell. The model validation was systematically done by evaluating the results of temperature effects and effects of solar irradiation using the experimental data of Tian *et al.* (2012). These are presented in Figures (1) to (4) for effect of solar irradiation, and Figures (5) to (8) for effects of temperature on performance of the PV module. Figure 5 gives the effect of temperature and solar irradiance on energy recovery and efficiencies of PV solar power.

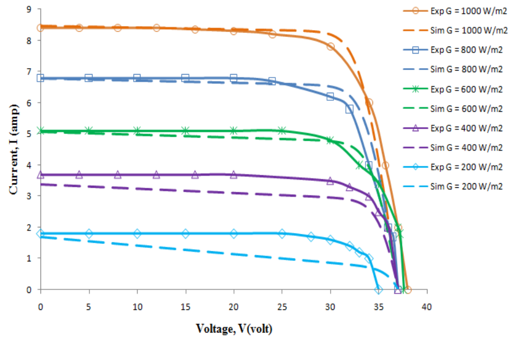

Figure 1: Comparison of simulated I-V characteristic curve with the reference experimental I-V characteristic curve for different solar irradiance at room temperature (298 K)

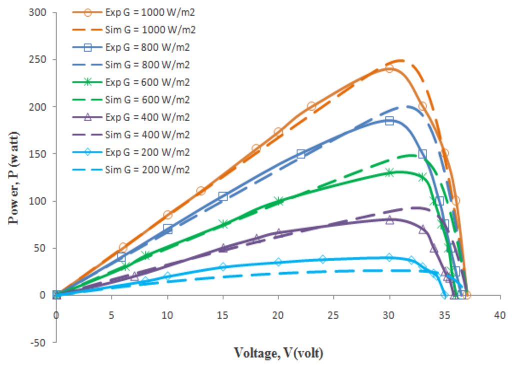

Figure 2: Comparison of simulated P-V characteristic curve with the reference experimental P-V characteristic curve for different solar irradiance at room temperature (298 K)

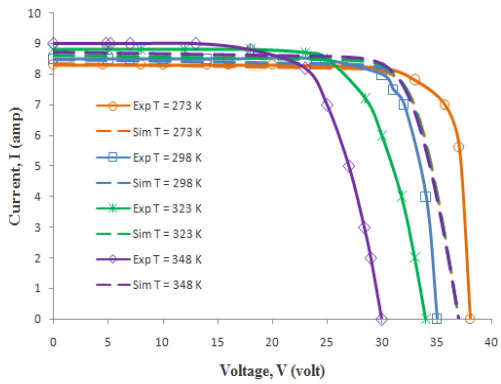

Figure 3: Comparison of simulated I-V characteristic curve with the reference experimental I-V characteristic curve for different temperature at solar irradiance of 1000 W/m^2

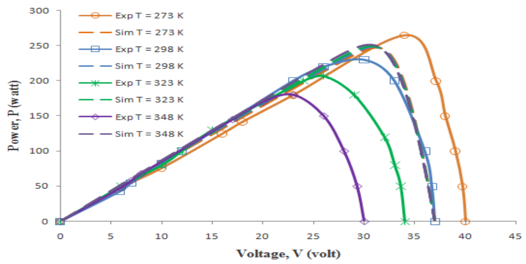

Figure 4: Simulated P-V characteristic curve for different temperatures at solar irradiance of 1000 W/m^2

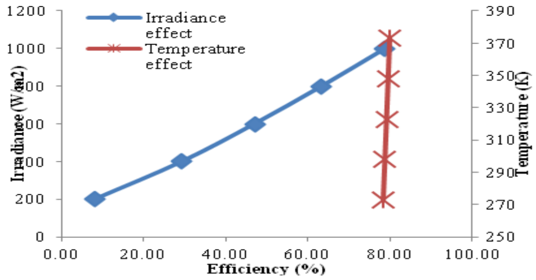

Figure 5: Effect of temperature and solar irradiance on energy recovery and efficiencies of PV solar power

With the use the concept of the Fill factor, the efficiencies of the PV module at different operating conditions are presented in Tables 1 and 2.

Table 1: Energy recovery from the PV panel at different irradiation and temperature of 298 K

G (W/m^2)	P_{max} (W)	FF	Efficiency (%)
1000	248.547	0.7879	78.79
800	199.757	0.63323	63.32
600	148.248	0.46995	46.99
400	92.512	0.29326	29.33
200	25.667	0.08136	8.14

Table 2: Energy recovery from the PV panel at different temperatures, irradiance of 1000 W/m^2

Temp	P_{max} (W)	FF	Efficiency (%)
273	247.275	0.78387	78.39
298	248.547	0.7879	78.79
323	249.808	0.79189	79.19
348	251.055	0.79585	79.58
373	252.287	0.79975	79.98

Discussion

Current-voltage (I-V) and power-voltage (P-V) characteristic curves show the effect of varying solar irradiance at room temperature on current and power output of the PV solar module. Between the voltages of 0-32 V, the maximum current generated from the PV solar module remain constant (8.5 A for 1000 w/m^2 solar irradiance). Similar trends were observed for lower irradiations (Ray, 2010; Chu, 2011; Tian *et al.*, 2012). Higher voltages (greater than 33 V) brought about a decrease in the current obtainable from the PV system. This inferred that for optimal current performance, voltage range should operate between 0 to 30 V. Power generations from the P-V plots, showed increases with increase in voltages. Peak power generation was observed at voltage of 32V. The higher the solar irradiance, the greater the power generated. Peak power of 250 W (for 1000 w/m^2 solar irradiance) observed had similar trends for lower irradiations. Comparisons of the observations in this study with those of Tian *et al.* (2012) show some agreement between the model results and experimental data.

Current-voltage (I-V) and power-voltage (P-V) characteristic curves show the effect of varying temperature at standard value of solar irradiation on current and power output of the PV solar module. The higher the temperature of the PV solar system, the greater the current generated. At a temperature of 273 K (0^{o}C), the obtained current generated was about 8.1 A, this current increased to about 9.0 A when the temperature was increased to 348 K (75^{o}C). Temperature also has positive effects on the voltage generated from the system. The voltage increased between 0-30 V before gradually dropping. The drop in voltage was evident at higher temperature (25 V for 348K). The higher climatic temperatures experienced in Nigeria and Africa is a key factor to tap into when applying solar PV system for power generation. From the PV curve, the peak power generated was lower at higher temperature (180 W at 348 K and 250 W at 273 K). Higher power was obtained at higher voltages.

Using the concept of the Fill factor, efficiencies of the PV module at different operating conditions were investigated. The fill factor was calculated using the data provided by manufacturer for BP 235 W series of the PV power system; Open-circuit voltage, V_{OC} of 37.2 V and short-circuit current, I_{SC} of 8.48 A, and G is the solar irradiance (W/m^2) (Ray, 2010; Chu, 2011; Tian *et. al.*, 2012). A maximum efficiency of 78.79% was attained at temperature of 298 K and irradiance of 1000 W/m^2. The performance of the solar panel increases with increase in temperature. The energy recovery is maximum (79.98%) at temperature of 373 K and solar irradiation of 1000 W/m^2. However, for efficient operation of the PV solar system, careful selection of the operating temperature is required in the design of the solar panel. This is because higher temperatures may pose some challenges to the design materials, and may also have other effects on the panel. Efficiency values represent true efficiencies of practical PV cells which fill factor ranges from 0.75 to 0.85 (Petkov *et. al.*, 2011). For instance, commercial solar modules sold have a fill factor of 0.75. Also, the closer the fill factor is to 1 the better the solar cell is. While irradiance has pronounced influence on the performance of the PV system, temperature has little effect. The mathematical model of the PV module in this work is therefore good representation of the solar power system, with energy recovery of about 78.79% at irradiation of 1000 W/m^2 and ambient temperature of 298 K (25^{o}C). Our investigation shows the effect of temperature and solar irradiance on the efficiencies and energy recovery of the photovoltaic solar power. Given the theoretical power available in the BP 3 series 235W photovoltaic power as 0.315 kW, the energy recovery from the system based on the efficiency of 79.98% will be 0.252 kW.

Conclusion

Mathematical model of a photovoltaic solar panel is developed in order to predict the performance and energy recovery of the solar power system at different operating conditions. The PV mathematical model developed was simulated and validated for a BP 3 Series 235 W photovoltaic solar power system. A comparison between the simulation results and the physical data showed that there is a good agreement between the model and the real PV system at various operating conditions considered. Effects of solar irradiation and temperature on the performance of the PV system were studied. Both were found to have direct relationship with power output of the solar panel; an increase in either parameter increased the power output. The energy recovery and efficiency of the PV power system was evaluated using the concept of Fill factor. An efficiency of 78.79% was attained at room temperature of 298 K and irradiance of 1000 W/m^2, while the energy recovery is maximum (79.98%) at temperature of 373 K and solar irradiation of 1000 W/m^2. Based on the maximum efficiency of 79.98%, the energy recovery was found to be 0.252 kW. The efficiency values conform with efficiencies of practical PV solar systems, ranging from 0.75 to 0.85. The mathematical model of the PV module in this work is therefore a good representation of the solar power system, having maximum energy recovery of about 79.98 % at irradiation of 1000 W/m^2 and temperature of 373 K.

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