Photovoltaic Generator Heating Model and Output Control

BY

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Dedication

To My Parents,
My Wife and Lovely Sons Ahmed & Mohammed

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LIST OF ABBREVIATIONS

A	:	Area (m^2)
a	:	Diode ideality factor
c_{pc}	:	Specific heat capacity of collector
c_{pg}	:	Specific heat capacity of glass
c_{pw}	:	Specific heat capacity of water
Eg	:	Band gap
FF	:	Fill factor
G	:	Irradiation
G_{aw}	:	Solar radiation that absorbed by the water
G_b	:	Direct (beam) radiation
G_{bt}	:	Direct radiation on surface with angle
G_d	:	Diffuse of irradiation
G_{dt}	:	Diffuse of irradiation on surface with angle
G_n	:	Nominal radiation
g	:	Acceleration , m/s^2
$h_{conv-gw}$	:	Convection between glass and water
$h_{conv-wa}$	:	Convection between water and air
h_{fg}	:	Heat of vaporization (kJ/kg)
I	:	Current (A)
I_d	:	A diode current
I_{pv}	:	Photovoltaic or photo-generated current

I_{sc}	:	Short circuit current (A)
K	:	Boltzmann factor
K_I	:	Temperature coefficient of current
k	:	Conduction coefficient of the glass, (W / mK)
k_a	:	Thermal conductivity
L	:	Thickness of glass (m)
L_c	:	length of panel
m_c	:	Cell mass (kg)
m_g	:	Glass mass (kg)
m_s	:	Mass of water in the storage tank (kg)
m_w	:	Mass of water on the front glass (kg)
$mdot_{in}$	:	The mass of water flow rate into the front glass (kg/s)
$mdot_{out}$	:	Mass of water flow rate out of the front glass (kg/s)
Nu	:	Nusselt
P_d	:	Dew point saturation vapor pressure (mm Hg)
P_T	:	Pressure of atmosphere (mm Hg)
P_w	:	Saturation vapor pressure of water (mm Hg)
$Q_{cond-cg}$	:	The conductive heat from cell to glass, in W/ m^2
$Q_{conv-gw}$	:	The convective heat from glass to water, in W/m^2
$Q_{conv-wa}$	:	The convective heat from water to the air, in W/m^2
Q_{evap}	:	Evaporative heat from water to the air, in W/m^2
$Q_{rad-sky}$	:	Heat of sky radiation in W/m^2
q	:	Electron charge

R_a	:	Rayleigh number
R_p	:	Parallel resistance
R_s	:	Series resistance
T	:	Temperature (°C)
T_a	:	Ambient temperature, (°C)
T_c	:	Temperature of the cell (°C)
T_g	:	Temperature of glass surface (°C)
T_s	:	Storage water temperature in the tank (°C)
T_{sky}	:	Sky temperature
T_w	:	Water temperature on the surface (°C)
t	:	Time
V	:	Voltage (V)
v	:	Kinematic viscosity (m^2/s)
w	:	Wind speed (m/s)

ABSTRACT

Full Name : Abdulraheem Mohammed Ahmed Baabbad
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A photovoltaic (PV) module is a nonlinear device that transforms the electrical energy from the sun. During the work of PV module, it has been observed that the amount of produced power goes dawn even with an increased radiation. That is because of increasing operating cell temperature. In this thesis, the operating cell temperature has been controlled to improve electrical efficiency of PV module using water cooling surface system. The electrical model and thermal model are analysed mathematically using MATLAB/ SIMULINK software. The behaviour and performance of cell temperature and output power are studied under environmental conditions such as ambient temperature and irradiation. In the simulation study; the proportional, integral and derivative (PID) controller is used for controlling the cell temperature and obtaining high output power efficiency. The effect of solar radiation and temperature on performance of PV module has been studied with I-V curves. Furthermore, in the experimental study the water cooling system has been designed and implemented. An operating cell temperature influence on output performance of PV panel with and without cooling cases is studied under Dhahran city, Saudi Arabia climate conditions. Similarly, the influence of cooling on I-V values is investigated. The experimental results show that the cooling using water control reduces the cell temperature and increases the output power

ملخص الرسالة

الاسم الكامل: عبدالرحيم محمد احمد باعباد

عنوان الرسالة: النموذج الحراري للمولد الضوئي والتحكم في المخرج

التخصص: هندسة كهربائيه

تاريخ الدرجة العلمية:

الوحدة الكهروضوئية عبارة عن جهاز غير خطي يقوم بتحويل الطاقة الشمسية الى طاقة كهربائية وقد لوحظ أثنا عمل جهاز الكهروضوئية بان كمية االقدرة الناتجة تقل حتى مع ارتفاع الاشعاع الشمسي بسبب ارتفاع درجة حرارة الخلية العاملة. في هذه الاطروحة تم التحكم بدرجة حرارة الخلية العاملة لتحسين الكفاءة الكهربائية من الوحدة الكهروضوئيهة باستخدام التبريد السطحي المائي. النموذج الكهربائي والحراري حُلل رياضياً باستخدام برنامج المحاكاة في الماتلاب لدراسة تصرف وأداء درجة حرارة الخلية وقدرة الخرج تحت الشروط البيئية مثل درجات الحرارة والاشعاع. في هذه الدراسة تم استخدام المتحكم بي اي دي للتحكم بدرجة حرارة الخلية والحصول على كفاءة قدرة خرج عالية. وقد تم دراسة تاثير الحرارة والاشعاع على أداء وحدة الكهروضوئية باستخدام منحنيات التيار –الجهد. وقد تم تصميم نظام التبريد السطحي باستخدام الماء وتنفيذه عمليا لدراسة تاثير درجة حرارة الخلية على ناتج اداء اللوحة الكهروضوئية في حالتي التبريد وبدون تبريد تحت الشروط المناخية لمدينة الظهران في المملكة العربية السعودية. ايضا اختبار منحنى التيار-الفولتية و القدرة– الجهد نفذا عمليا مع كلا الحالتين. النتائج التجريبيه بينت بان التبريد باستخدام الماء يقلل درجة حرارة الخليه ويزيد من قدرة الخرج.

CHAPTER 1

INTRODUCTION

1.1 Background

Photovoltaic (PV) cell is an important device in PV Systems. Such systems consist of multiple components based on electrical connections and mechanical components like mounting and different ways of regulating and modifying the electrical output.

With the advancement of technology and the use of multiple sources of energy, it becomes necessary to find other alternative sources that help reducing the current use of energy based on fossil fuel, especially in a large country. The renewable energy includes wind and solar energy as the main resources is suggested to become the answer for future's stable energy.

Solar energy is defined as a radiant energy produced from the sun. Two types of technologies can be used with solar energy, viz. solar thermal which is used for water heating and photovoltaic which is used to produce the electrical energy. Photovoltaic is a major source of the energy produced from converting the electromagnetic radiation. The use of PV has been increased in the last years with an increase of the demand of energy. The radiation is received by Photovoltaic cells that convert the sunlight energy to electrical energy. The amount of electricity depends on the amount of radiation and temperature received where more radiation means more electricity, while the efficiency of solar cell decreases when temperature increases. However, not all received energy from the sun is converted to electrical energy as some parts converted to heat and loosed. In addition, heat reduces the performance of the solar panel.

By studying the effect of high temperature on PV panel, it is observed that the efficiency of PV panel goes down during the day especially in the hot areas. For this reason many studies have been performed to enhance the solar panel efficiency. A small increase in the cell temperature decreases the solar cell output significantly. In order to increase the output from the solar panel, the solar cells need to be cooled. There are different methods of cooling used in latest researches by using active cooling, viz. air or water. This work proposes an automatic panel cooling system in which the water is automatically controlled to pass on the panel surface on demand to reduce the cell temperature and increase the power.

In Photovoltaic system the sunlight is converted to electricity by using solar panels. Solar radiation and temperature are the main factors that play an important part in the behaviour of the PV panel module. Solar radiation is defined as the electromagnetic waves that are sent by the Sun through the space to the Earth. Mathematically, solar radiation is defined as the amount of power density in unit of Watt per Meter-square (W/m^2) and it ranges from zero value to maximum value depending on time, local weather and location. Solar radiation consists of two main parts, viz. beam radiation and diffuse radiation. Beam radiation or direct radiation (Gb) is a radiation that comes from the sun without any alteration and received by the surface. On the other hand, diffuse radiation (Gd) is received by the surface after its direction has been changed. Total radiation is calculated by summing the two part of the radiation as follows:

$$Gtotal = Gb + Gd \tag{1.1}$$

Temperature is the other factor that affects PV performance. PV performance decreases with high temperature. So, the output power of the PV panel is gradually affected. As the irradiation increases during the day, the Photovoltaic current as well as the output power increases, causing a further increase in the temperature of the panel. Thus, an increase in the temperature causes a decrease in the voltage and lowers the PV module efficiency.

The kingdom of Saudi Arabia is a large country in which an increase in the electricity consumption is reported. In addition, it has a good place to use PV technology because it receives high radiation through the year and the sky usually clear. However, the temperature reaches high level during the summer causing reduction in PV module performance. To solve this problem and improve the PV module performance, an automatic cooling system has been proposed.

1.2 Photovoltaic Technology

According to the Standard Test Conditions (STC), the output power of Photovoltaic is measured with three conditions, viz. radiation, temperature and Standard light spectrum AM 1.5. This power is directly affected by the irradiance and is inversely to cell temperature. So, the increase in the amount of radiation resulted in an increase in the current and PV efficiency, but the increases in temperature causes a decrease in voltage and efficiency.

Solar panel has been built from a number of semiconductors solar cells that absorb the sun light and generate electrical energy. These solar cells that convert the light to power represent the fundamental power conversion unit of a photovoltaic system [44].

In order to understand PV cell work, Figure 1-1 was considered. When the Photovoltaic cell, that is a semiconductor diode, is connected to an external circuit, the current flowed. The photons in the sunlight have different frequencies and energies. Only the photons that have energy greater than the semiconductor band-gap energy can generate charge carriers in the cell.

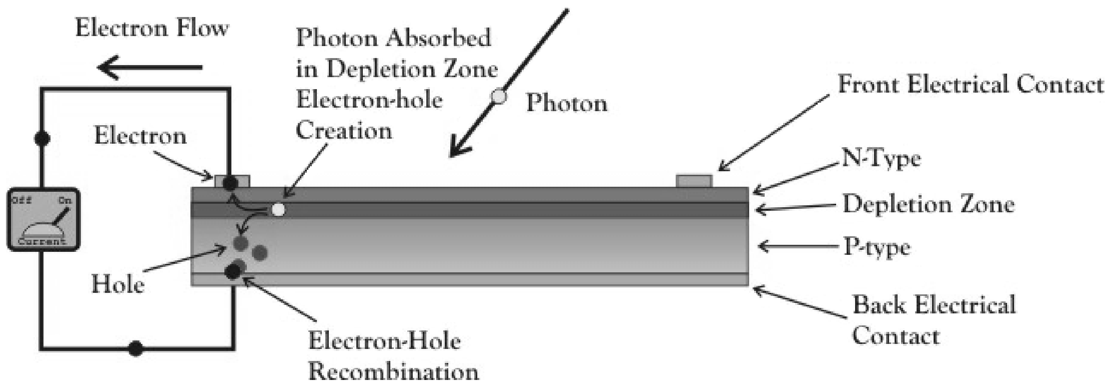


Figure 1-1: Photo electric effect of PV cell

1.3 PV Cell Materials and Types

Semiconducting materials such as silicon are used in making Photovoltaic cell to give electric current from solar radiation. There are four types of silicon photovoltaic cells:

1- Single crystal silicon

2- Polycrystalline silicon (or multicrystalline silicon)

3- Ribbon silicon

4- Amorphous silicon (or thin film silicon)

There are two main types of PV. These types are stand-alone system and grid connected system. When PV systems are used with other power sources like thermal generators, it is classified as hybrid systems.

1.4 PV Cells, Modules and Arrays

Cell is the main component of photovoltaic that is usually consists of silicon. In order to make a module of photovoltaic, many of PV cells are joined in series. PV modules in PV arrays design are joined in both parallel and series combinations. To add voltage or current, the PV solar cells are joined in series or parallel, respectively. Commercially, Photovoltaic modules available have 36 or more PV cells joined in series. See Figure 1-2.

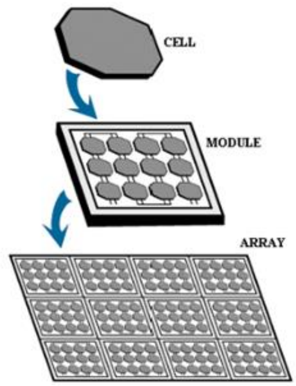


Figure 1-2: PV solar cells, modules and array

1.5 Advantages

- PV system provides renewable and green power. PV system could be used as alternative energy source.
- PV panel needs low cost for maintenance and operating.

- Reliability; the photovoltaic systems have been proven in different conditions their consistency.
- Durability; all modules that are used today show no degradation in the performance even after many years.
- Using PV system reduces the pollution that is produced from other sources.
- PV systems are safe.

1.6 Disadvantages

- PV system needs batteries to store the energy.
- Compared with other renewable power, PV system has relatively low efficiency
- PV system directly produces current that is converted to AC

1.7 PV Applications

Photovoltaic have many applications in our life. One of these applications is building integrated Photovoltaic (BIPV). In this application, the solar panels are used as the roof. This application decreases the amount of construction materials required while producing electricity. So, it provides a dual purpose. In addition, there are other applications such as satellites. The International space station uses multiple solar arrays to supply the power to all the equipment on board. Also, PV is used in agriculture such as pump water for plants or human. Moreover, the PV devises are used in the mobile stations to provide the electricity for these stations.

1.8 Thesis Overview

1.8.1 Motivation and Problems

Energy is an important part in the life. In recent years, there is an increasing demand for energy especially in the technological world. This demand rises with coming years. As a result, it becomes a necessary to find a new source of energy additional to the fossil fuel. The renewable energy such as solar energy is one of these sources. It provides a clean energy and reduces the damages that happen from using the oil in the environment and atmosphere of the earth.

Photovoltaic is a major source to produce the energy from the electromagnetic radiation. The use of PV increases in the last years with an increase in the energy demand. The amount of electricity depends on the amount of radiation where more radiation means more electricity and temperature.

Photovoltaic device is a good source of power. However, this power is not constant as it varies with time because of many factors like environmental conditions. Some of these conditions are irradiation, ambient temperature, cell temperature, and dust. Due to the uncertainty of these conditions that causes stability issues to power system, the PV panel output power and its efficiency would be effected. Temperature factor plays significant role in decreasing the power of PV.

Many research works observed that the efficiency of PV is decreased with the increase in the temperature, especially in the hot areas. In these areas, the amount of radiation is high. However, the temperature reaches a high level and causes drop in the power and efficiency especially during the summer. Saudi Arabia is one of these areas that have high radiation and temperature. As a result of high temperature, the efficiency of PV is degraded. This thesis proposes an automatic cooling system as a solution for this problem.

1.8.2 Objectives

The aim of this research is to develop a PV thermal model to be controlled for efficiency by using surface cooling water system. The objectives of thesis study are summarized below:

1. To study the electrical performance of PV panel under varying temperature and irradiation.

2. To develop a thermal model for PV panel based on water cooling system and to simulate it.

3. To design a thermal control system for PV module using PID controller. The system will then to be simulated.

4. To integrate the PV electrical model with the PV heat model and the control. The system performance will then tested by simulation.

5. To implement the whole PV generator with water cooling system and to automatically control its power output.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a detailed literature is presented with two parts. The first part is about the research study for electrical model and the second part is about the research study for thermal model.

2.1 Electrical Model

Malik and M. Bin Haji Metali in [1] studied Influence temperature condition on photovoltaic module performance in climate of Bruneian. The authors studied the effect of work temperature on the parameters of PV panels. They found that the work temperature in different stages impact these parameters where the efficiency of PV panel decreases with an increase in the temperature.

Pradhan Arjyadhara, Ali S.M, Jena Chitralekha in [2] analyzed the solar PV performance with different irradiation and temperature factors .This work explains how the solar panel performance changes with change in the irradiation and temperature in addition to fill factor. The authors observed from a number of experiments using I-V & P-V curves that the performance varies with these factors.

Malik and S. Bin Haji Damit in [6] documented experimental work to investigate the effect of variation in sunlight radiation in PV performance. In this work, they found that the efficiency of output power is directly proportional to sunlight radiation. Also the output rating of a solar cell decreases when increasing the temperature of a cell. Many experiments were conducted in different months during one year and many results of effect radiation on output were considered. The efficiency values differ from month to other depending on the amount of irradiation and cell temperature. The averaged efficiency for six months was around 5.4%.

Takashi.M, Shingo.N and Hideyuki.T in [7] discussed the relationship between the performance of PV cell and the environmental factors such as distribution of solar spectrum and temperature. In addition, they studied how they effect the outdoor energy.

Carr and Pryor [10] studied the performance of five different PV module types in temperate climate of Perth, Western Australia. They measured maximum power and characteristics of I-V curves at STC for these types of module at orderly intervals. Also, the output energy in active operating conditions was calculated for these types. All values were compared to the manufacturers' values.

Gxasheka et al. [11] analyzed the influence of temperature and irradiance on the performance parameters. They reported that the dependence of efficiency on irradiance gives good information about performance at different irradiance levels and possible effects on the module cells.

De Soto et al. [13] evaluated the PV array performance model by using the values of short circuit current (Isc), the open circuit voltage (Voc) and the maximum power point voltage (Vmp) and current (Imp) at standard rating conditions (SRC). The light generated current (IL) was assumed to be linearly proportional to the solar irradiance. They assumed that series and parallel resistances constant.

Ishaque and Salam [14] used an improved modeling method to determine the photovoltaic (PV) module parameters by using differential evolution (DE) method. This technique enables the estimation of model parameters at different values of solar radiation and ambient temperature using the manufacturer's datasheet information. Compared with popular single diode module with series resistance, the performance of the model was evaluated. They stated that the proposed model produces better results for any irradiance and temperature variations. This method is useful for improving PV simulator in the future.

Sagor and Abido in [15] studied the influence of the variation of solar radiation and temperature on PV work in different locations in the Kingdom of Saudi Arabia. They observed from simulated results that the output power changes according to any change in the solar radiation and temperature. Also they stated that it is necessary to install Maximum Power Point Tracking to obtain good power result.

2.2 Thermal Model

Dubey and Tiwari in [25] developed the thermal modeling of a hybrid PV/T solar water heater. This model was considered and tested in the climate of New Delhi. They have developed a mathematical expression for combined PV/T flat plate collector. They have studied performance of water heating system. From the results, they noted that there is an increase in instantaneous thermal efficiency for different cases by covering the absorber by PV module fully and partially. It is concluded that the present system is self-sufficient one and can be built in distance areas for fulfillment of hot water requirements and electrical energy saved can be used for other goals. To enhance the PV performance, the PV/T collector technology has been developed using water cooling.

Saad and Masud in [27] found that the effective way to improve the PV module efficiency is by using water cooling surface to reduce the cell temperature. They noted from the experimental results that there is rise in output of the system by about 15% at maximum radiation conditions.

Kordzadeh in [28] made an analysis study about head of the system and array nominal power and its effects on the efficiency of PV modules using water film cooling. In the results it was noted that the output power was improved.

Abdolzadeh and Ameri in [29] used the cooling method by spraying the water on panel cell surface to study the effect of water on work temperature and obtain improved output power. They observed that temperature of the cell was decreased when the water was sprayed on the panel and its output power efficiency is more than that in traditional model without using water.

Tamayo Vera, Laukkanen, Siren in [30] studied Performance evaluation and multi-objective optimization of hybrid photovoltaic–thermal collectors. The collector's structure and performance using an elitist multi-objective evolutionary algorithm Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) were studied simultaneously with two water cooled PV/T models: one with a front glass cover and one without a glass cover. The output efficiency of the solar cells was increased against various conflicting objectives in Multi-objective optimization problems. The authors indicated that the problem of achieving high electrical power and reduced heat requires a multi-objective optimization approach.

Moharrm et al. in [33] studied the increase of performance of PV panel by using a less amount of water and electrical energy as cooling in hot areas in Egypt. In this study, a mathematical model was applied to determine the heating rate of the PV panels and when to start cooling. The effect of cooling system on PV panel in reducing the temperature and cleaning the panel was observed.

Gardas and Tendolkarin [34] developed a simulation model for single pass, single duct solar collector with fins to increase the electrical efficiency of PV by cooling. Seven gases are passed through the duct with the mass flow rate equals 0.00275kg/s that was required for this system.

Dorobantu et al. in [35] improved the electrical performance of PV panel by using free flow front water cooling solutions to enhance flat-type PV module. This work experimentally investigated on laboratory scale module operated outdoors under natural light luminance. As a result, the open voltage increases with reducing the temperature. They developed an equivalent electric circuit of the PV panel cooling system and proposed an appropriate algorithm for its parameters experimental determination.

Potuganti and Ponnapalli in [36] used the active cooling way by using water to improve the efficiency of solar PV panel. In this paper, the calculation was carried out and a net 7.75% improvement in efficiency of the model was made.

Kim et al. in [40] developed Cooling System for improving the efficiency of a Photovoltaic Module by using the water on surface of PV. They used a glass between the water and collector. The mathematical model of the cooling system was simulated and validated to get good predictions relative to the experiments. In their study, they used another PV panel as control system to compare the output power. The authors reported that the obtained improvements were 11.6% compared with a control module. In addition, the reported enhancement with prediction was 10%.

Abdelrahman, Eliwa and Abdellatif in [41] implemented the experimental test to study the effect of cooling on PV performance and improve the efficiency using three types of cooling methods; back surface, front surface film and both. They showed that the output with these different cooling methods increased because of the temperature of PV panel decreased with cooling. Also the research found that the value of this increase in the efficiency is different in these systems of cooling where a good result obtained from the third method when front and back systems of cooling were combined together.

Ali Tofighi in [42] evaluated the photovoltaic performance using thermal module simulation under two conditions of atmosphere; calm and non-calm conditions. During their work, they noted that the operating temperature is influenced by varying the environmental condition that is used as input data such as irradiation, wind speed and air temperature.

Bahaidarah et al. in [43] used the back surface water cooling method to improve the efficiency of PV module. The experimental study implemented under environmental condition of Dhahran city in Saudi Arabia. In this work, the electrical model and thermal model are developed to enhance the efficiency of solar panel. The authors noted that the efficiency of PV panel drops when the cell temperature increases. By using water cooling they noted that the temperature of panel decreased by 20% with increase in the output efficiency by 9%. Also they found that increasing flow rate mass play an important role in reducing the temperature. So keeping the flow rate constant with increasing irradiation causes reducing efficiency where the temperature increases.

Shahsavar and Ameri in [45] experimentally studied effect of change mass of air flow rate on output performance of PV/T using a directly coupled air cooled PV/T collector design. They noted that the increase in mass flow rate causes an increase in the efficiency of thermal model. The efficiency of power according to that change in flow rate also increases. However, this production power decreases because of the fans used in this work consumes this power. In addition, they made a study about influence of the glass as the cover on the performance of the model. They noted from this study that the thermal efficiency increased, but the electrical power efficiency decreased when the glass surface was removed from the model.

CHAPTER 3

MODELLING AND CONTROL

3.1 Electrical Model

A PV system is a nonlinear model that exhibits nonlinear P-V & I-V characteristics which vary with cell temperature and amount of solar radiation. Figure **3-1** below describes the equivalent circuit that includes a photo-generated current source, a diode, and parallel and series resistances.

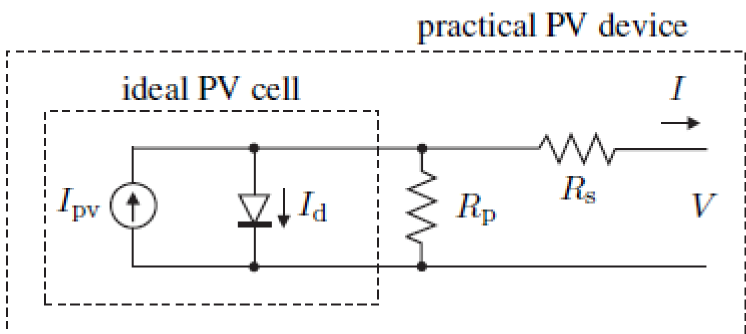


Figure 3-1: The equivalent circuit of PV cell module [20]

3.1.1 Mathematical Model

This section explains a set of equations that describe the mathematical model of PV module [19], [20]. These equations are formulated and used in MATLAB/ SIMULINK program in our simulation work. The output current of PV system is given in equation (3.1)

$$I = I_{PV} - I_d \tag{3.1}$$

Where, I_{PV} is a photovoltaic current and I_d is a diode current. I_d can be found by equation (3.2) where:

$$I_d = I_O \left[\exp\left(\frac{qV}{akT_c} \right) - 1 \right] \tag{3.2}$$

Where I_O is the reverse saturation current, T_c is a solar cell temperature, V is the diode voltage, k is the Boltzmann's constant and equal to 1.38*10$^{\wedge -32}$ J/K, q is charge an electron and equal to 1.6*10^{-19}, and a is the diode ideality factor. Using equation (3.1) and equation (3.2), the output current can be given as equation (3.3):

$$I = I_{PV} - I_O \left[\exp\left(\frac{qV}{aKT_c} \right) - 1 \right] \tag{3.3}$$

When series and parallel resistances - R_s and R_p - are included, the voltage-current equation is given as:

$$I = I_{PV} - I_O \left[\exp\left(\frac{V + R_S I}{aV_t} \right) - 1 \right] - \frac{V + R_S I}{R_P} \tag{3.4}$$

The equation (3.4) describes the equivalent circuit with five parameters. These parameters are photo generator current (Ipv), saturation current (Io), series resistance (R_s), parallel resistance (R_p) and the fifth parameter is diode ideality factor (a). Vt value can be calculated as shown in equation (3.5):

$$V_t = \frac{N_S k T_c}{q} \tag{3.5}$$

N_s refers to the number of the series connected cells in the module where it differs from a module to another. The photo-generated current in equation (3.6) depends on two factors; irradiation (G) and temperature:

$$I_{PV} = \left(I_{PV,n} + K_I \Delta_T\right)\frac{G}{G_n} \tag{3.6}$$

where Δ_T is given as:

$$\Delta_T = T_c - T_n \tag{3.7}$$

$I_{PV,n}$ is a photo-generated current at STC conditions and can be calculated as given in equation (3.8):

$$I_{PV,n} = \frac{R_P + R_S}{R_P} I_{sc,n} \tag{3.8}$$

The saturation current of the diode that depends on the temperature is governed in equation (3.9):

$$I_O = I_{O,n}\left(\frac{T_n}{T_c}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T_c}\right)\right] \tag{3.9}$$

The bandgap energy, (Eg) can be calculated mathematically. However, in this work it is assumed to be equal to 1.12. The saturation current in nominal condition can found as equation (3.10):

$$I_{O,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{aV_{t,n}}\right) - 1} \tag{3.10}$$

R_s and R_p are unknown resistance parameters and they are necessary to find I_{pv} value. Because of the R_p and R_s has high value and low value, respectively; the I_{pv} value approximately equal to I_{sc}.

3.1.2 PV Panel Characteristics

Given the electrical equations in the last section, it is obvious that PV depends on radiation and temperature. This can be observed by solving equation (3.4) given the values of irradiance and temperature. In addition, the plot of I-V and P-V curves can be obtained.

I-V curve of photovoltaic module depends on values of irradiance and temperature. If irradiance increases, the I-V curve will show an increase. In general, high irradiation gives better I-V curve, but high temperature gives a worse I-V curve and vice versa.

P-V characteristic curve obtained from I-V curve is calculated from multiplying the current and the voltage as shown in Figure 3-2. This curve shows how the output power is influenced by varying the current and the voltage that depend on the amount of irradiance and temperature. The output power is directly proportional to the amount of irradiation and is inversely to the cell temperature.

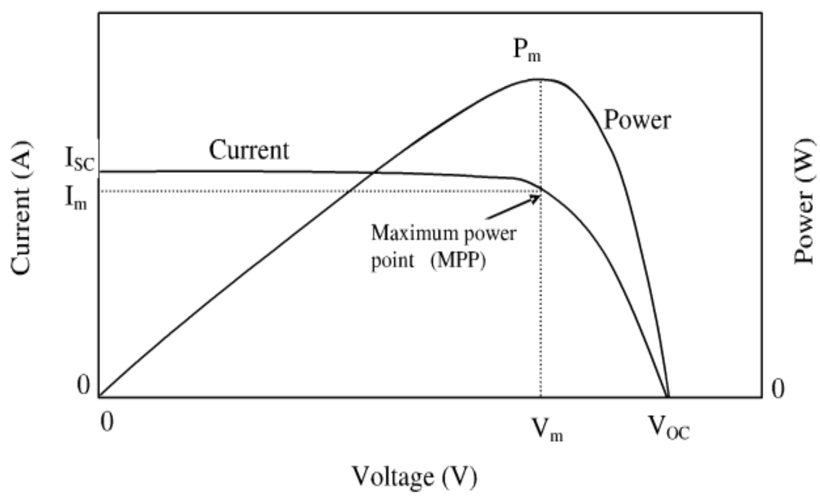


Figure 3-2 : I-V and P-V curves for a PV module

There are many parameters of photovoltaic can be obtained from I-V curve. The point on the bend in the I-V curve which obtained by multiplying the corresponding current (Im) and the corresponding voltage (Vm) is known as the maximum power point (MPP). The open circuit voltage value (Voc) occurs when the current equals zero, while the short circuit current (Isc) occurs when the voltage equals zero.

In addition, the fill factor (FF) and the Conversion efficiency (η) are another parameters of photovoltaic characteristics. These parameters can be defined as equation (3.11) and equation (3.12):

$$FF = \frac{P\max}{Voc \times Isc} \tag{3.11}$$

$$\eta = \frac{P\max}{G \times A_c} \tag{3.12}$$

The resistances Rs and Rp are the two parameters that remain unknown. Different ways have been proposed to find these resistances. One of these ways that had been used in [19], called the iterative method. This method gives the Rs value that is needed for a specific model, where Rs in this method starts from zero. Figure 3-3 explains another method to find these resistance values obtained from the I-V curve gradient with the short circuit and open circuit points. These resistances are described as equation (3.13) and equation (3.14):

$$R_S = \frac{\Delta V_S}{\Delta I_S} \tag{3.13}$$

$$R_P = \frac{\Delta V_P}{\Delta I_P} \tag{3.14}$$

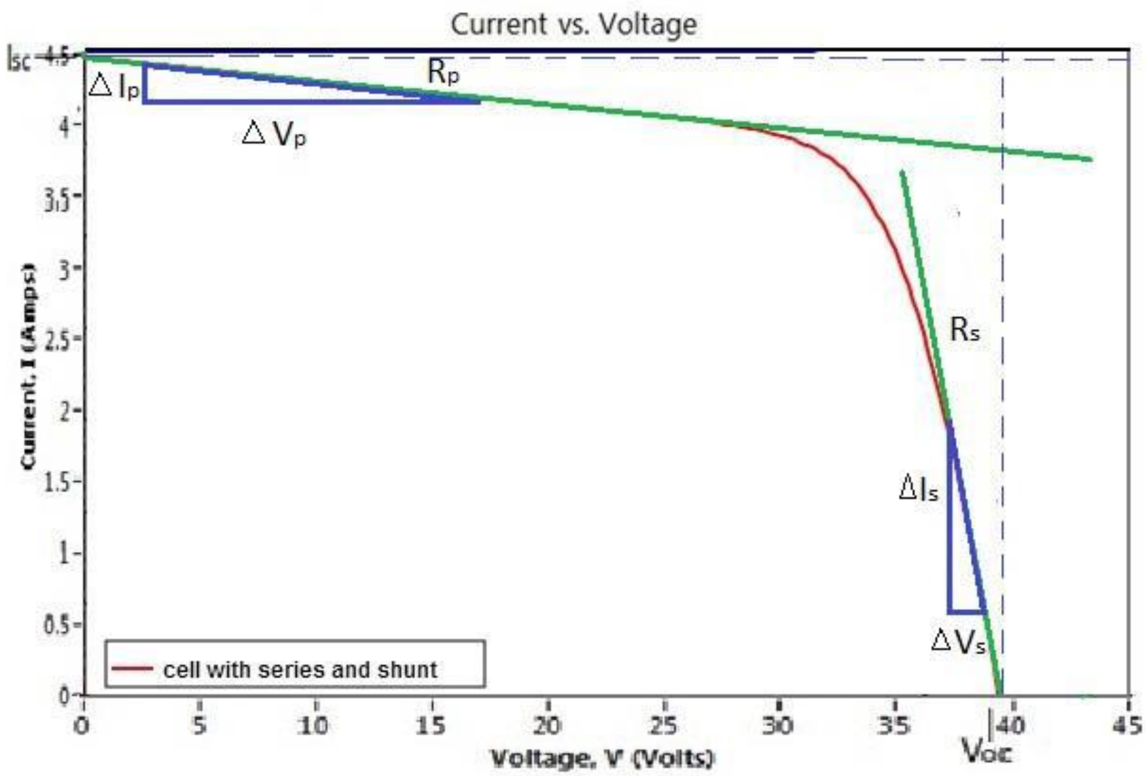


Figure 3-3 : Gradient method for determine series and shunt resistances values

The PV characteristics using I-V curve are included in this work to study the effect of the irradiation and the temperature on the performance of the PV panel using MATLAB application.

3.1.3 Nominal Operation Cell Temperature (NOCT) Condition

NOCT is a cell temperature that is reached with specific conditions. These conditions are an irradiation at 800W/m^2, a wind speed at 1m/s, an air temperature at 20 °C and a mounting of open surface.

The cell temperature of the module can be found by the following formula, [6], [16], and [31].

$$T_C = T_a + \left(\frac{NOCT - 20}{800} \right) \times G \tag{3.15}$$

Where Ta and NOCT are in degree Celsius (°C) and G in W/m^2.

3.2 Thermal Model

The block diagram in Figure 3.4 below describes the proposed PV cooling system that consists of two storage tanks, pump and PV panel with glass cover. Four temperature variables are considered as variable state. These temperatures are: water temperature, glass temperature, collector temperature and storage tank temperature. The main factors in this model are irradiation and temperature. Not all energy from the sun is converted to electrical energy, as part of this energy is lost as a heat. Because of the power efficiency of PV module decreases with an increase in the collector temperature, the voltage drops. An automatic cooling system using water is proposed to improve the output performance. When the temperature increases, the water in this model passes on the surface of the panel and absorbs the heat from the panel. As a result, the temperature of the panel is reduced and the efficiency of the output power increases.

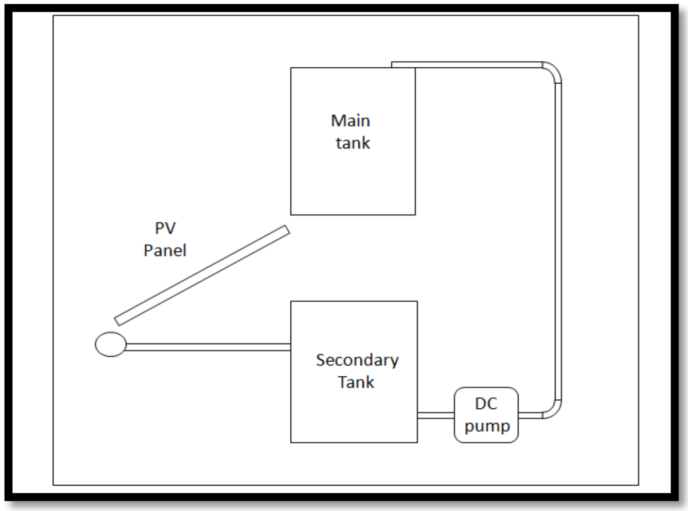


Figure 3-4: Block diagram of proposed PV cooling system

3.2.1 Mathematical Model

The mathematical model of thermal model is based on four equations (3.16, 3.29, 3.31 and 3.34) that describe four balances of energies [40]. The first equation is the water energy. This energy occurs on the front surface of PV panel where to be sandwiched between the air and the front glass of panel surface. The water absorbs energy from the sunlight and by convection between water and front glass. On the other hand, there is a loss in the energy from the water surface to the air through radiation, water-air convection and evaporation. The following Equation explains the balance of the energy of the water on the surface with inlet and outlet energy

$$m_w c_{pw} \frac{dT_W}{dt} = (G_{aw} - Q_{rad-sky} + Q_{conv-gw} - Q_{conv-wa} - Q_{evap})A_c + (\dot{m}_{in}\, c_{pw} T_s) - (\dot{m}_{out}\, c_{pw} T_w) \tag{3.16}$$

The above equation includes different components that affect the panel area. The first component is the solar radiation that defines as

$$G_{aw} = \alpha_b G_{bt} + \alpha_d G_{dt} \tag{3.17}$$

In this component two parts of radiation are needed; beam and diffuse radiation [40]. These types of radiation are described in the following equations:

$$G_{bt} = G_b \frac{\cos\theta}{\cos\theta_z} \tag{3.18}$$

$$G_{dt} = G_b \frac{1+\cos(a)}{2} \tag{3.19}$$

The second component is called the convection that is moved out from the water surface to the air. This process depends on the difference between air temperature, water temperature and wind speed as shown in the following equations:

$$Q_{conv-wa} = h_{conv-wa}(T_w - T_a) \tag{3.20}$$

$$h_{conv-wa} = 2.8 + 3.0V \tag{3.21}$$

The third component is the convection, but from the front of the glass to the water, and it is given as the following:

$$Q_{conv-gw} = h_{conv-gw}(T_g - T_w) \tag{3.22}$$

$$h_{conv-gw} = \frac{Nu.k_a}{L_c} \tag{3.23}$$

$$Nu = \left\{0.825 + \frac{0.387 R_a^{1/6}}{[1+(0.492/P_r)^{9/16}]^{8/27}}\right\}^2 \tag{3.24}$$

$$R_a = \frac{g\sin(a)\beta'(T_g - T_a)L_c^3}{\nu\alpha} \tag{3.25}$$

The last two energy components are Long wave radiation exchange between the water surface and the sky and Evaporation, respectively as given in the following equations:

$$T_{sky} = (T_a + 273.15)\left[\frac{T_d + 200}{250}\right] \tag{3.26}$$

$$Q_{rad-sky} = \varepsilon\sigma\left[\left(T_w + 273.15\right)^4 - \left(T_{sky} + 273.15^4\right)\right] \tag{3.27}$$

And

$$Q_{evap} = 26.639 \times 10^{-1} V^{\,0.5}(P_w - P_d)\frac{h_{fg}}{P_T} \tag{3.28}$$

All energy components of the water energy on PV module are shown in the figure below:

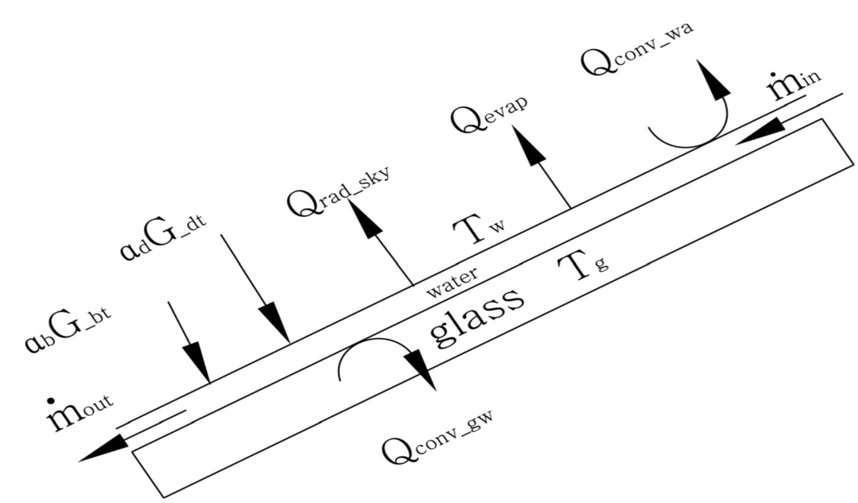


Figure 3-5: water energy balance on solar panel [40]

The second balance of energy equation that is given in (3.29) called front glass energy. This energy is obtained by the conduction from the collector and is lost by convection to the water:

$$m_g c_{pg} \frac{dT_g}{dt} = (Q_{cond-cg} - Q_{conv-gw})A_c \tag{3.29}$$

Where $Q_{cond-cg}$ is the conduction between the silicon and front glass, and calculated as the following:

$$Q_{cond-cg} = k \frac{(T_c + 273.15) - (T_g + 273.15)}{L} \tag{3.30}$$

The third equation of balance of energy is the collector energy:

$$m_c c_{pc} \frac{dT_c}{dt} = ((\tau\alpha)_b G_{bt} + (\tau\alpha)_d G_{dt} - Q_{cond-cg})A_c \tag{3.31}$$

The water stored in the tank is considered as the final energy balance. This can be explained as the following equation

$$m_s c_{pw} \frac{dT_s}{dt} = \dot{m}_{out}\, c_{pw} T_w + \left(\dot{m}_{in} - \dot{m}_{out}\right) c_{pw} T_s - \dot{m}_{in}\, c_{pw} T_s \tag{3.32}$$

The above equation includes two different masses, mass of inlet flow rate and mass of outlet flow rate. By solving above equation we obtain the following equation:

$$m_s c_{pw} \frac{dT_s}{dt} = \dot{m}_{out}\, c_{pw} T_w - \dot{m}_{out}\, c_{pw} T_s \tag{3.33}$$

Or

$$m_s c_{pw} \frac{dT_s}{dt} = \dot{m}_{out}\, c_{pw} (T_w - T_s) \tag{3.34}$$

The explained mathematical model shows that part of the radiation absorbed by the cell panel converted to electricity and the other part is converted to the heat. Also part of the heat is lost via radiation and convection from the top glass cover and the remainder part is removed by the cooling.

The thermal model and the electrical model are utilized together as hybrid system. The proposed cooling system using these models improves the performance of PV module.

3.2.2 Calculation of Solar Power Density

The formula below describes the solar power density during specific time such as a day:

$$\rho = \rho_{\max} \exp\left[\frac{-(t-t_0)^2}{2\sigma^2}\right] \tag{3.35}$$

t is the day hour in 24h, $\rho_{\max}$ is the maximum solar power density of t_0 and σ is the standard deviation. In this work the solar density was calculated by using the MATLAB application during a day:

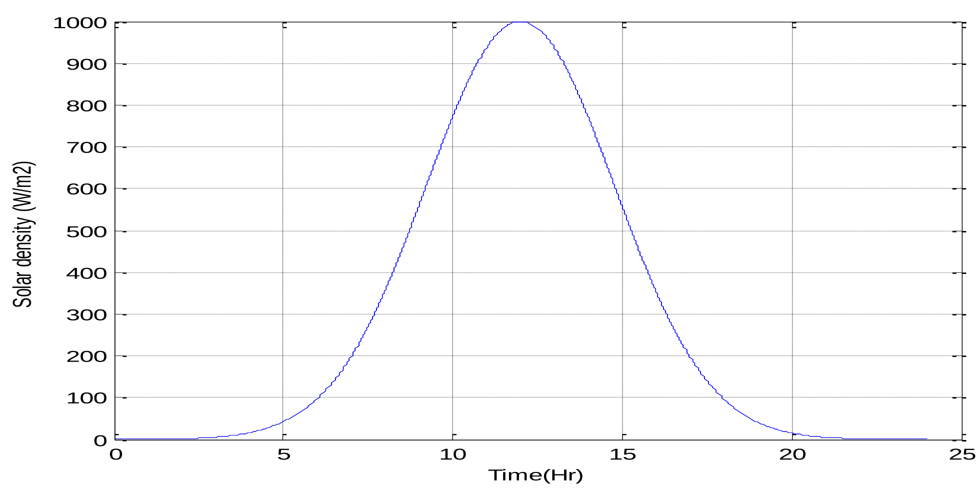


Figure 3-6: Solar power density calculated by MATLAB

3.3 Control Model

In order to keep the temperature of panel in certain level and to get better output power, the control of panel temperature is required. There are many types of control that could be used; such as PID control and MPC control; etc. In the PV thermal model, the panel temperature will be kept in a low value by controlling the flow rate of water. In this work we are going to use a control model that will be connected with PV thermal model to control the temperature of the panel using PID controller. Hence, the efficiency of output power will be improved.

3.3.1 PID Controller

PID controller is a famous controller and it is shortcut for three terms; proportional, integral and derivative. PID controller can be defined as "a feedback controller that is widely used in many control applications ", [51]. PID controller depends on the error value that is the difference between the set point value - as a desired value – and the measured value. The "error" value is minimized by PID controller. Trial and error, Ziegler-Nichols and Relay auto tuning are used to tune PID controller in order to get the PID parameters. The equation of PID calculation is given in equation (3.36). The control action was obtained by tuning the three gains parameters, Kp, Ki, and Kd that are combined together to find the output of this controller. It is not necessary to use all three terms of PID controller in all control application as some applications need only one or two terms and the others are neglected, i.e. equal zero. In this case, the PID is called P, PI, D or PD controller. PI is one of the most common types of PID controller because the action of D is more sensitive to noise. In this work, PI controller is used mostly as D is given zero or very small value.

$$u(t) = K_P e(t) + K_I \int_{t_0}^{t} e(t)dt + K_D \frac{de(t)}{dt} \tag{3.36}$$

3.3.2 PID Controller for Cell Temperature

Figure 3-7 displays a block diagram of PV/T model control using the closed loop PID controller to control the cell temperature.

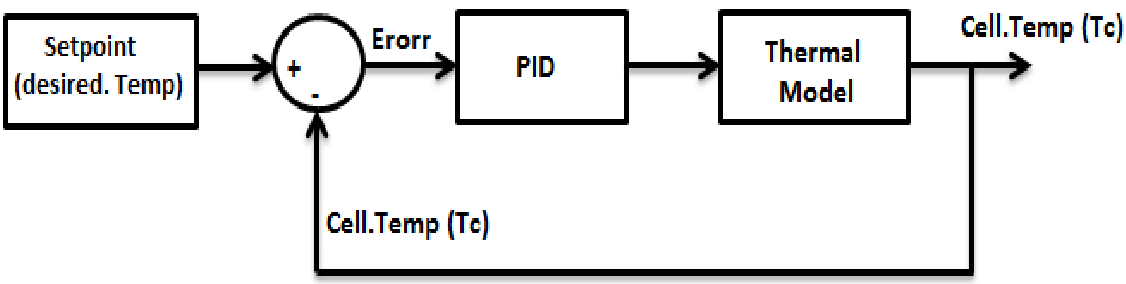


Figure 3-7: Block diagram of system control using PID control

PID controller is one of common control loop that gives a good result. By using this controller, the cell temperature was controlled. PID minimizes the error between the reference temperature in the set-point and the produced cell temperature from the thermal model. This takes place by adjusting the amount of flow rate mass of the water. PID sends control signal to the thermal model to get output temperature equals reference value in the set-point.

CHAPTER 4

MATLAB/SIMULINK SYSTEM MODELING

In this chapter, the PV system was modeled with MATLAB/SIMULINK program. The MATLAB code is carried out to study the effect of solar radiation and the temperature on PV system by studying I-V curve. In addition, the thermal model is studied to observe the behavior of temperatures that obtained using ODE code function.

The whole PV cooling model was built based on the mathematical model that was mention in chapter three for both models using SIMULINK program. The simulation with this model was carried out with two cases. The First case, the reproducing of the results for the Korean paper in [40] using our SIMULINK model and compare the simulation result with that results obtained by the author in [40]. The Second case , the adoption of that model on KFUPM area.

Finally, the PID controller is used to control the operating temperature of cell panel.

4.1 Photovoltaic /Thermal Model

This section describes the SIMULINK design for each model; electrical model and thermal model. Furthermore, the combination of the two models which gives the complete PV system.

4.1.1 PV Electrical Model

Based on the mathematical model that was given in chapter 3, the electrical model of PV system was built using MATLAB/SIMULINK program to study the electrical performance characteristic of PV and how the temperature and the solar radiation effect on the output power. The following figure shows the SIMULINK block diagram for the electrical model of PV system. This model depends on its parameters that differ according to type of the used model and the environmental conditions such as radiation, temperature, and wind speed, etc. The temperature and the radiation are used as required input data in the PV system. The output sources are the current, voltage and power that is obtained from multiplying the current and voltage. The load value depends on Rs and Rp value of the used module.

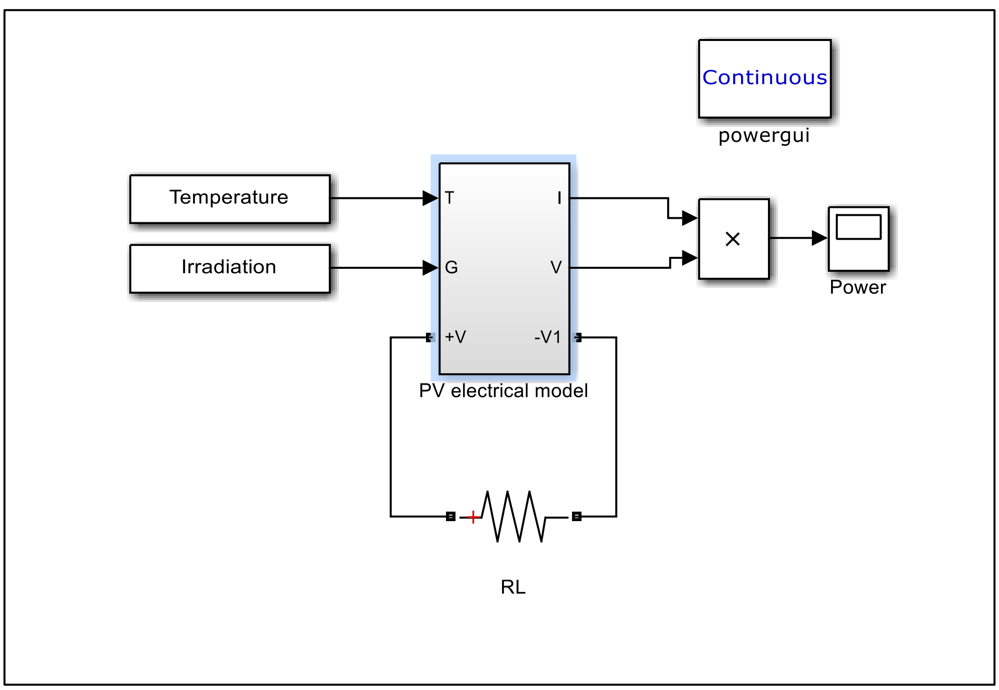


Figure 4-1 : PV electrical model SIMULINK

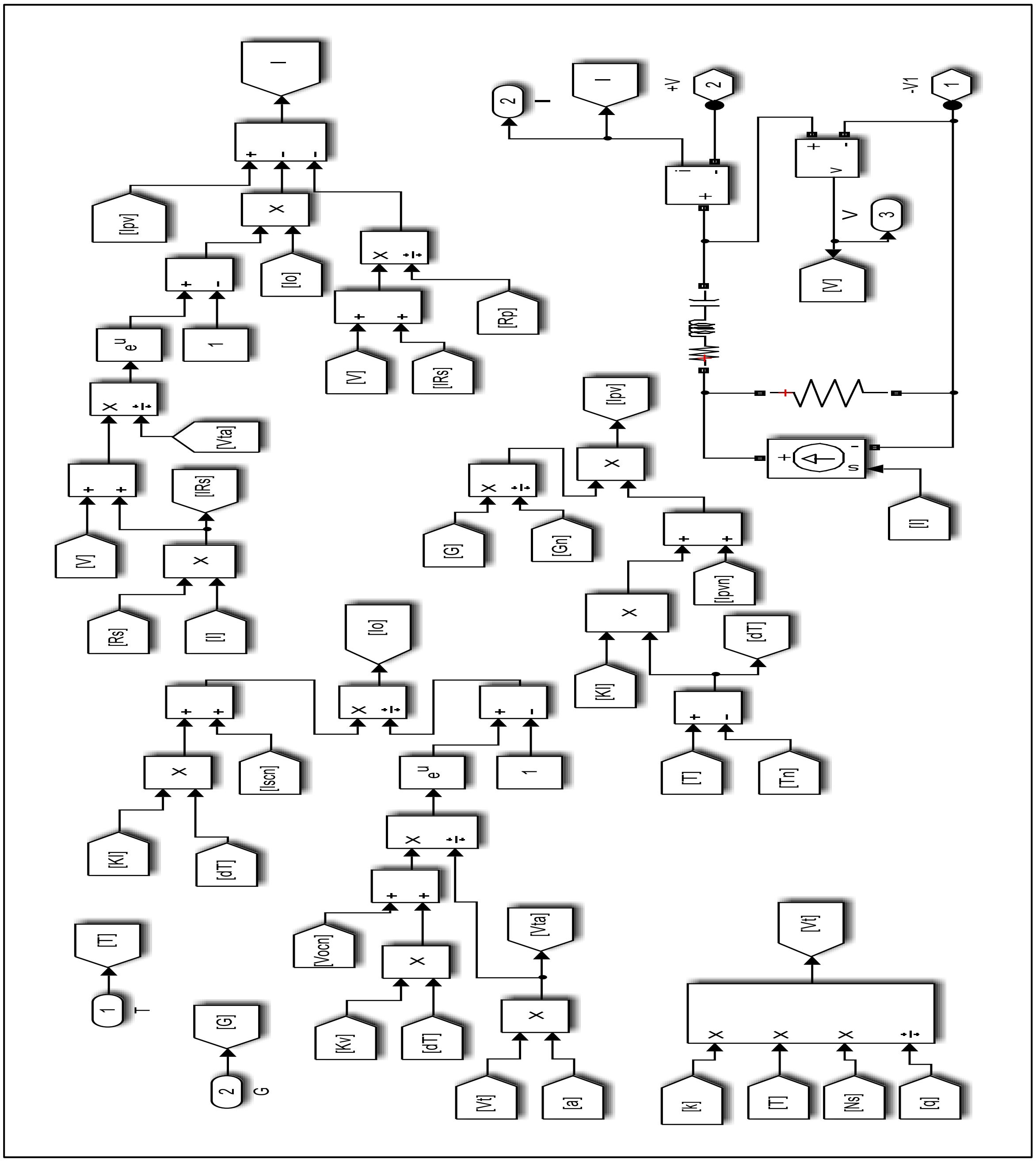


Figure 4-2 : Subsystem of PV electrical model SIMULINK

In addition, the PV model can be built as a MATLAB function as shown in the figure below. This function depends on MATLAB code for all equations and parameters of PV model.

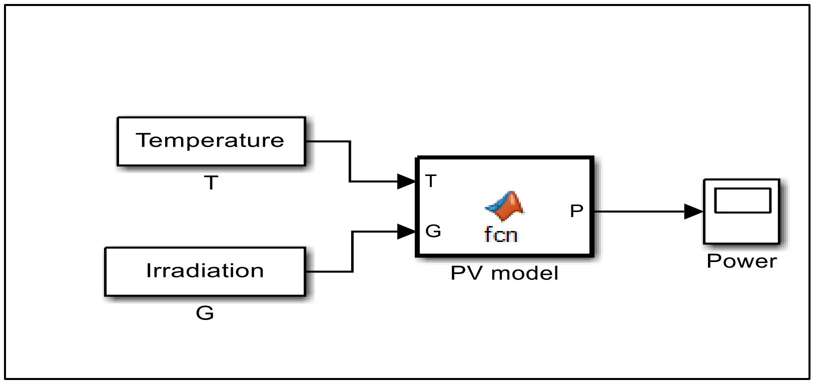


Figure 4-3: PV electrical model using Math function SIMULINK

4.1.2 Thermal Model

In SIMULINK program, the thermal model is designed as shown in Figure **4-4** . It is based on all energy balance equations of thermal model.

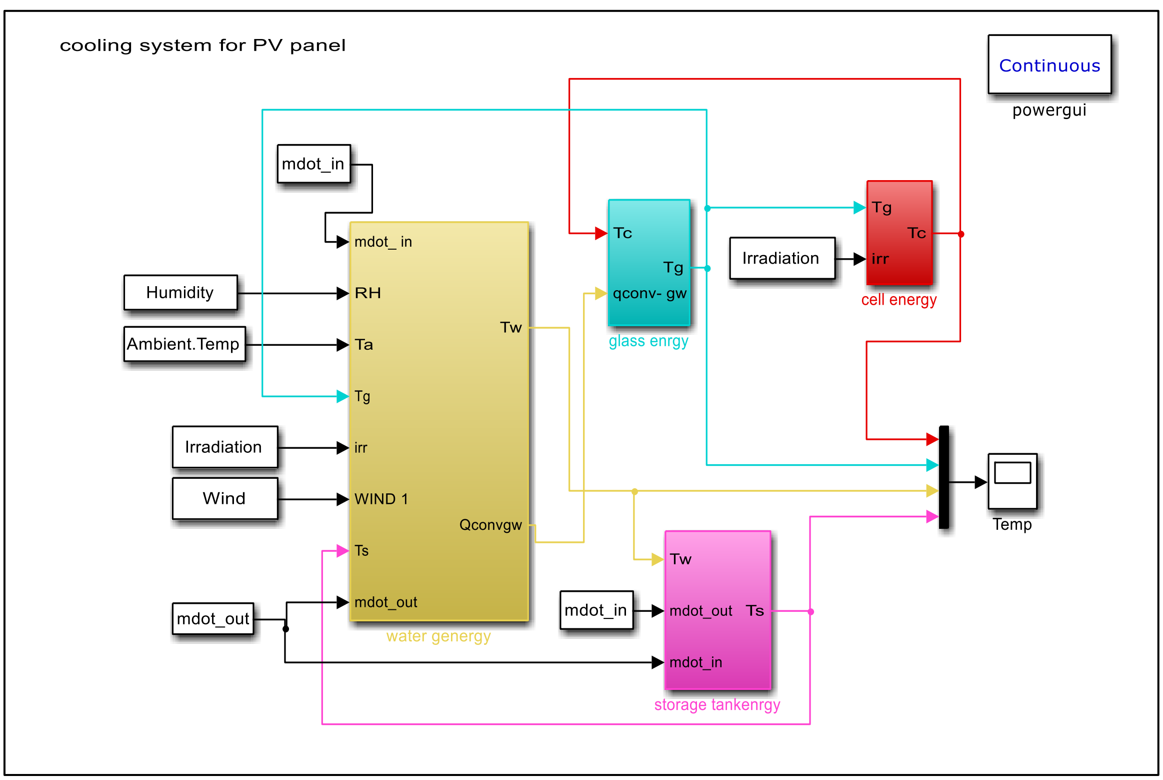


Figure 4-4 : Thermal model SIMULINK

The subsystem of each energy balance mask in the above figure is shown in the figures below. This energy is modeled using SIMULINK blocks according to the energy balance equations in chapter three.

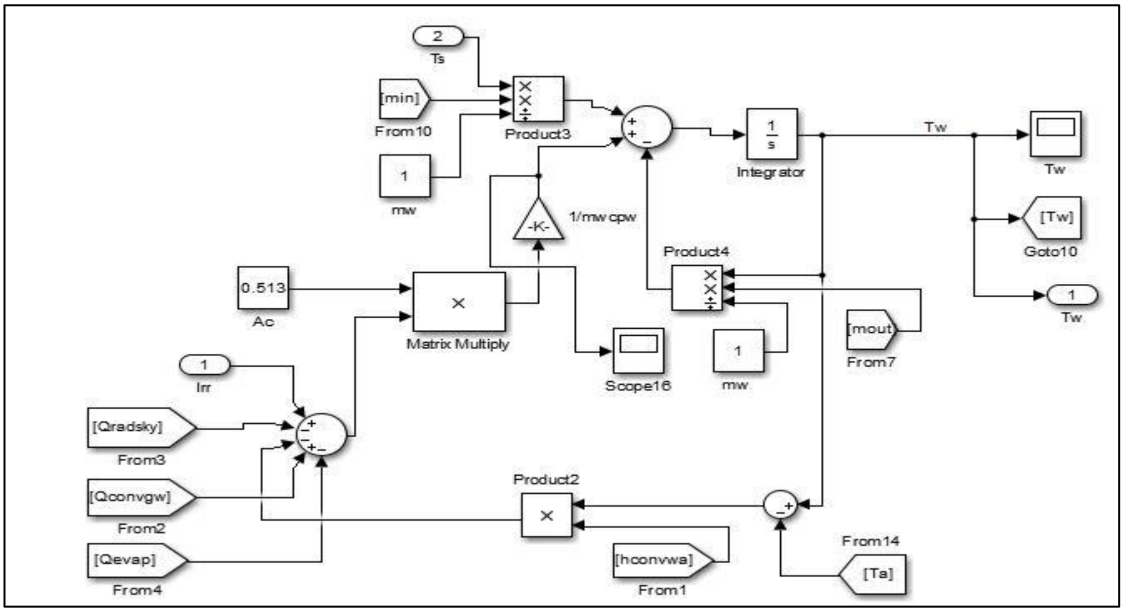


Figure 4-5 : Subsystem of energy balance of water

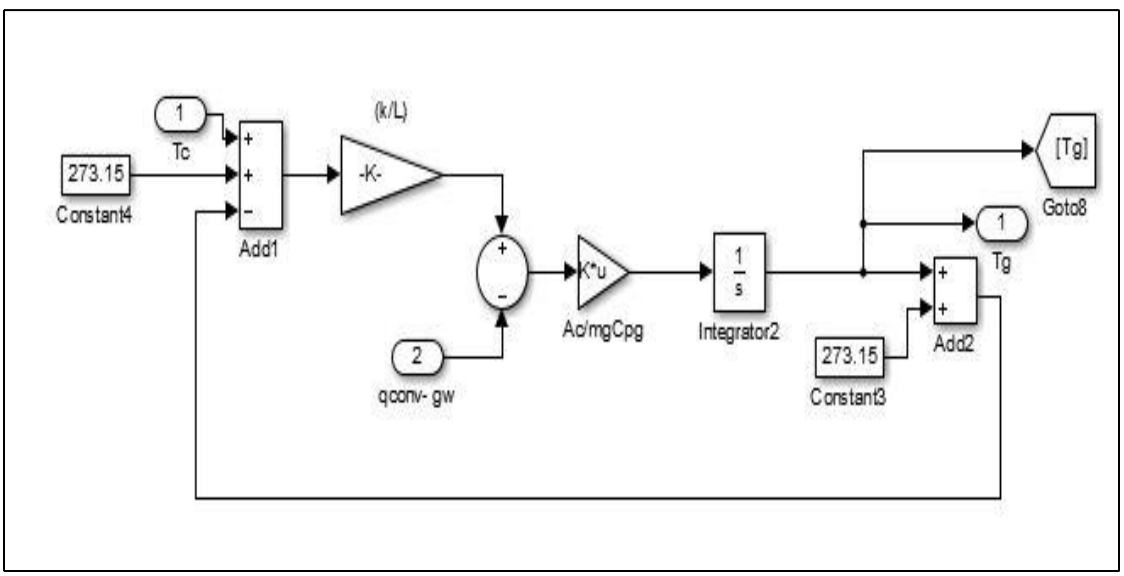


Figure 4-6: Subsystem of energy balance of glass

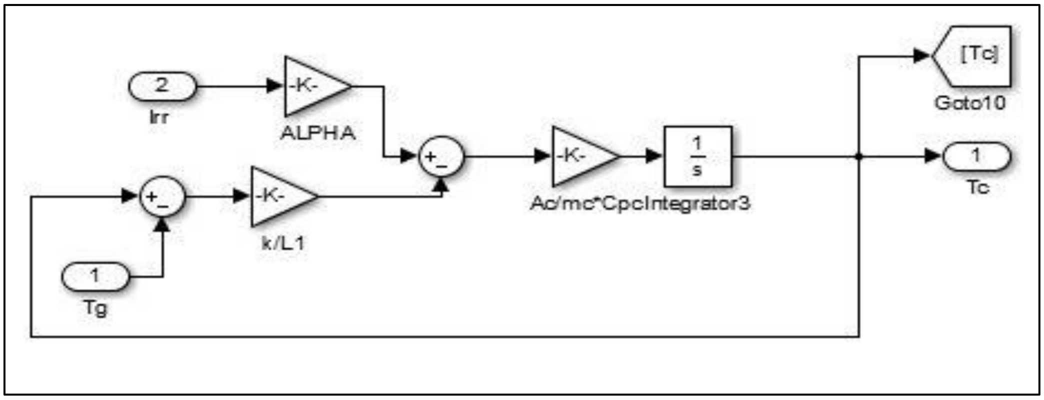


Figure 4-7 : Subsystem of energy balance of cell

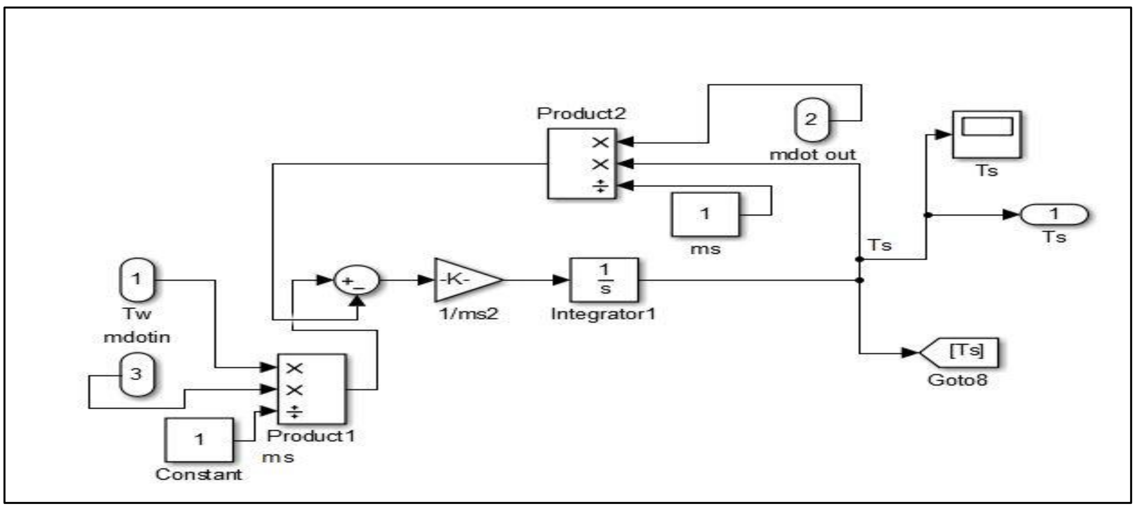


Figure 4-8 : subsystem of energy balance of tank storage

4.1.3 PV/T Cooling System Model

As the whole system the PV/T model is built. Figure **4-9** describes the SIMULINK block diagram of PV/T cooling system. The input data is connected to the heat model and the cell temperature as the output of heat model is connected to the PV electrical model as the input temperature. The input radiation is used for both models. Ambient temperature, wind speed, irradiation and humidity are taken as input signals for three days. The four balanced energy are modeled in SIMULINK block to get the four output temperatures (Tw, Tg, Tc, Ts).

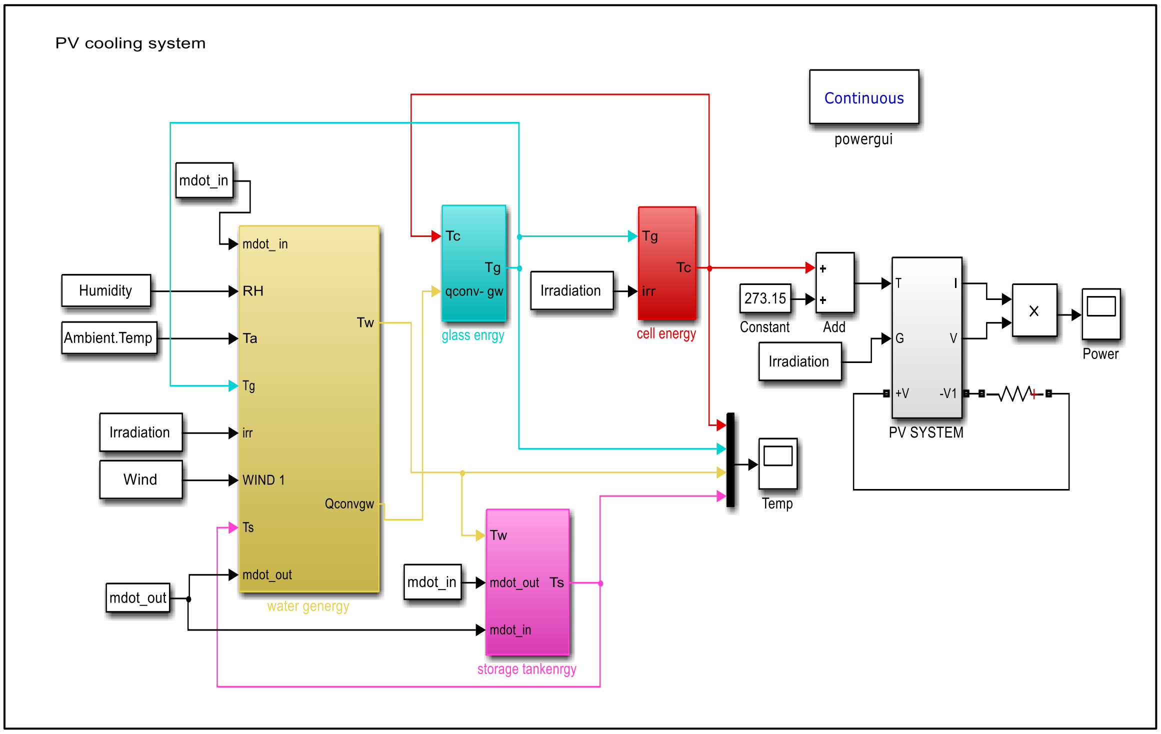


Figure 4-9: PV/T cooling system SIMULINK

4.2 The Model Control Using PID Controller

Before the use of the PID control with the whole system, two tests with this controller are implemented. The First test is with the PV model while the second test is with the thermal model.

4.2.1 PV Electrical Model Control

Figure **4-10** explains the electrical model control using PID controller. The PID controller is connected with PV electrical model for controlling the output. The output in this model is the power. Through this model the output power will control feedback for obtaining the desired power. This occurs by controlling input cell temperature. The PID controller minimizes the error that is the different between the set point value as the desired value and the output signal. Then the PID controller will send a signal to the electrical model to make the output signal equals to the set point. This model is helpful to determine the value of the cell temperature required to obtain a desired output power under specific radiation condition.

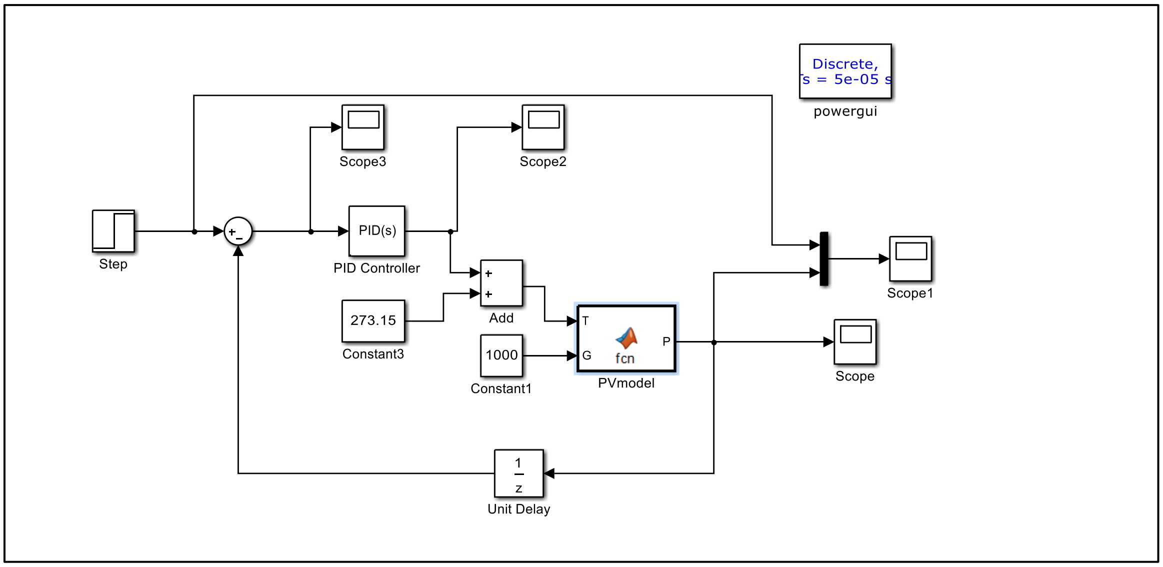


Figure 4-10 : Electrical PV model with PID controller

4.2.2 Thermal Model Control

In thermal model, the PID controller was used to control the output temperature by controlling inlet mass of flow rate. In this model, the PID controller is connected to the input flow rate of the water as is shown in Figure **4-11**. This model is an important to understand and study the behavior of the heat model using the PID controller that is used through this model to control the output from the thermal model and to obtain the desired value to improve the output efficiency of PV module in the whole system.

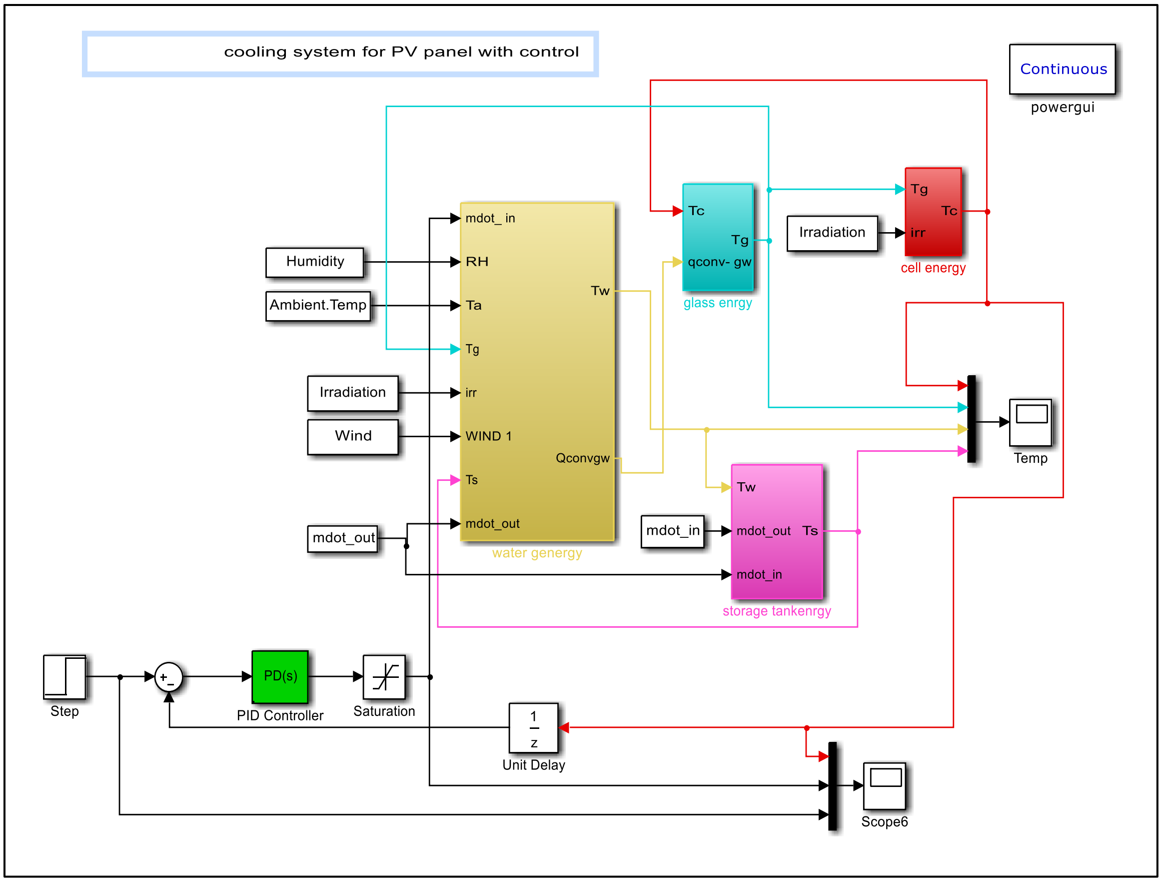


Figure 4-11 : Thermal model with PID controller

SIMULINK control module is tested for our modules that are used in this work, which has been mentioned previously. The cell temperature signal from thermal model is controlled to compare it with a set point value that is adjusted to be a desired value as the condition to get a better output. The difference between the set point value and the feedback signal that is entered to the PID controller is called the error. Then the PID controls the cell temperature to get the desired value at the output by controlling the water flow rate.

4.2.3 PV/T Cooling System Control

Figure **4-12** explains block diagram of PV/T cooling system with PID controller. In this model, the output temperature from the thermal model is controlled by controlling the mass of the water flow rate - in the experimental study the part of control is the water using control valves. Then the controlled temperature is used as an input temperature of the PV model to determine the output power in high temperature. The control system can be used with any type of PV module with some necessary variation in parameters setting for the used module in SIMULINK model. In this system, the PID controller does the control for the cell temperature (Tc) until it is agreement with the set point where the error is equal to zero. Then this temperature uses for PV module to calculate the output power

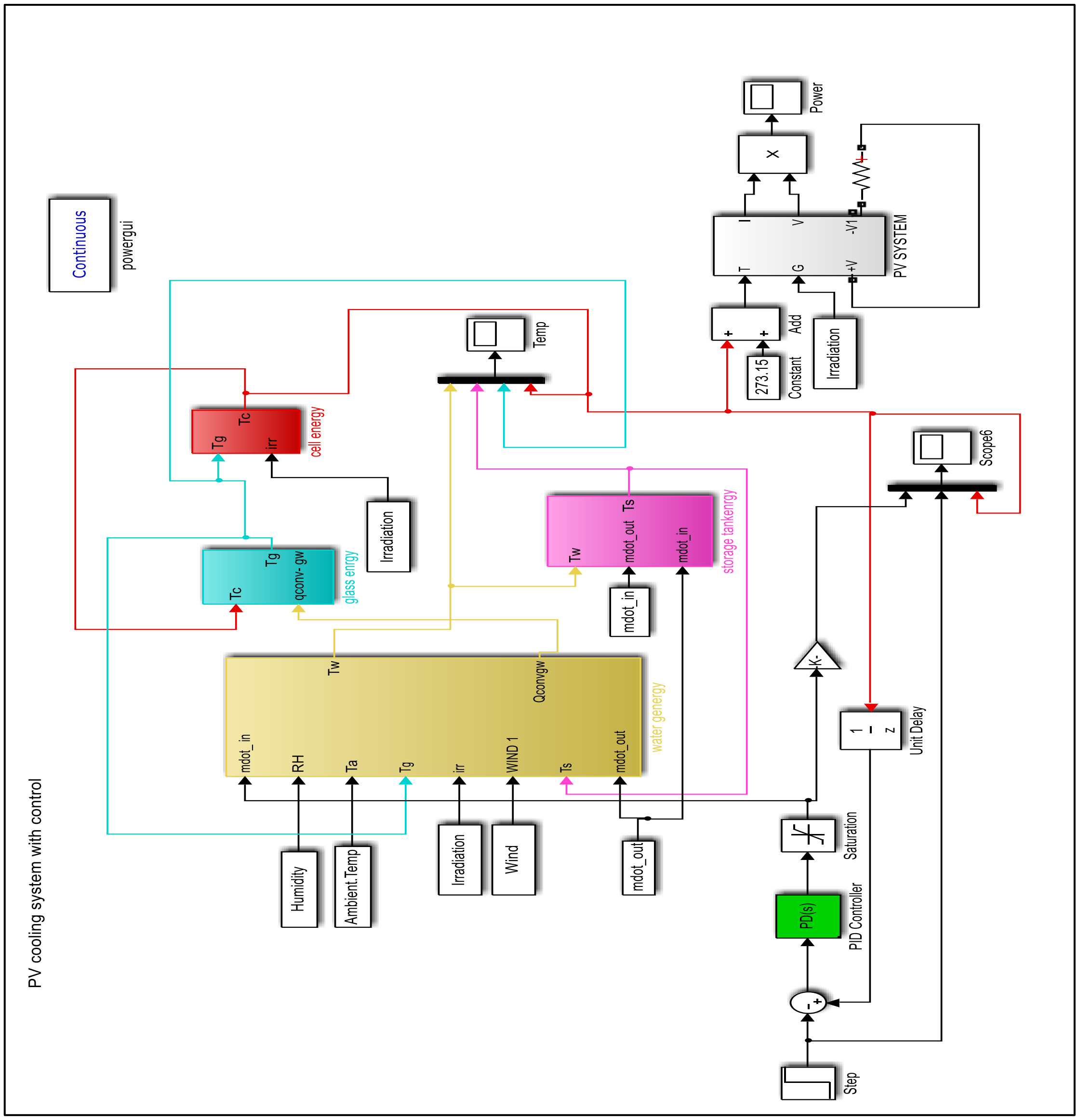


Figure 4-12 : SIMULINK of PV cooling system control

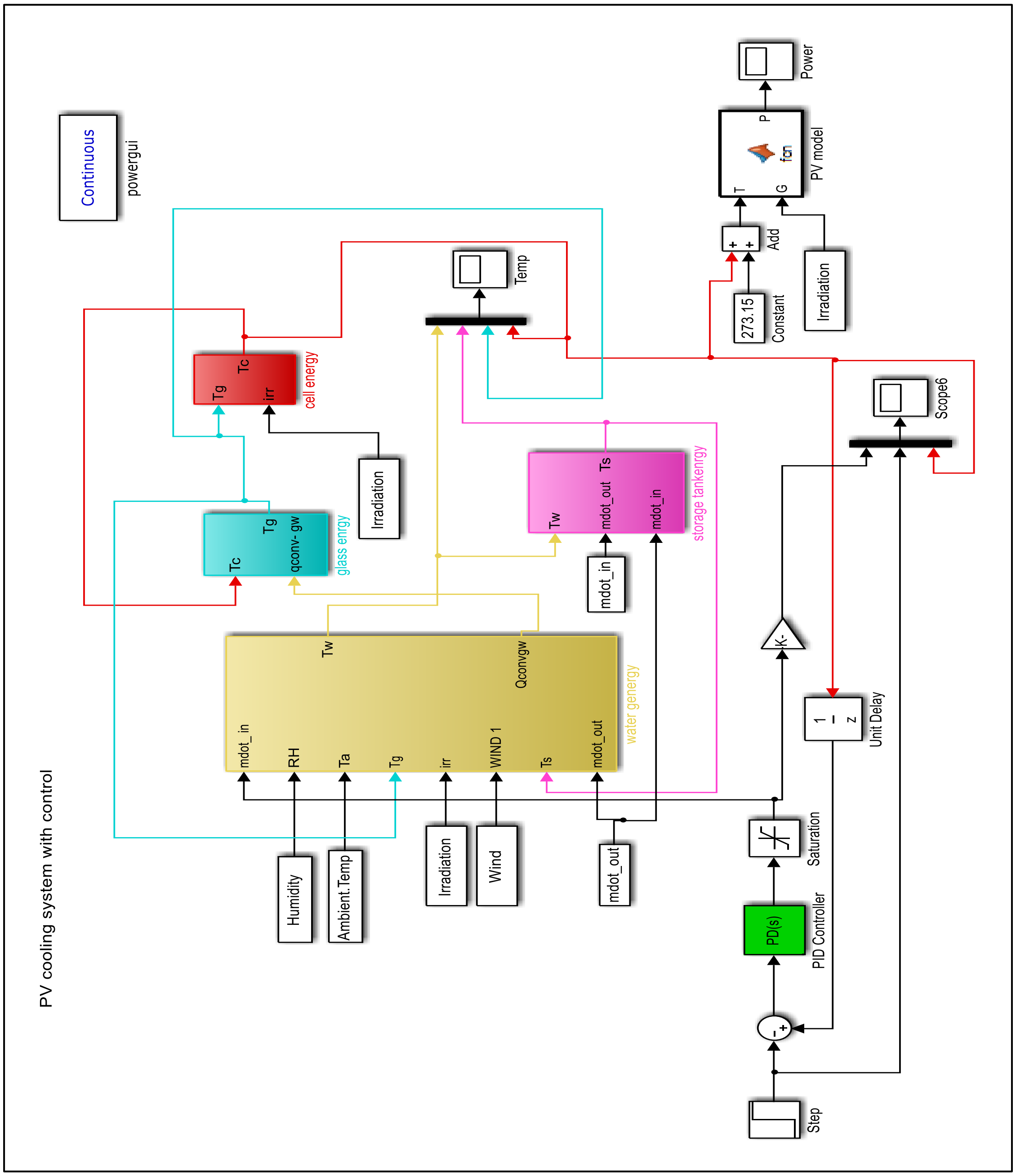


Figure 4-13: SIMULINK of PV cooling system control with Math function

CHAPTER 5

EXPERIMENT SETUP

The experimental evaluation of PV module efficiency has been reported in different researches in the previous literature. There are many ways of cooling were used to improve the PV module performance, such as front PV surface cooling and back PV surface cooling by using water or air.

In this chapter an experimental test for PV module performance with and without cooling is carried out using two parts. The first part is a cooling system by using manual valves and the second part is by using control valves. Furthermore, the I-V & P-V curves characteristics of PV system are taken.

5.1 System Setup

In this section, the components of the experimental setup are discussed. The system that is used in this work consists of two main parts connected together as a PV cooling system. These parts are the PV system and the cooling system. The experiment is performed in a natural sunlight surface in King Fahd University of Petroleum and Minerals (KFUPM) area, Dhahran, Saudi Arabia.

5.1.1 PV System

In PV system, different components are required to find the output performance. This part explains the details of these components that are going to be used in this work

PV Panel Module:

The solar panel used in this project consists of 72 monocrystalline silicon type solar cells with a total rated power of 230 W and an efficiency of 18.5%. The other specifications that were given by the manufacturer can be shown in Table 5-1

Table 5-1: Specifications of the PV module

MODEL	SPR-230-WHT-U
Maximum power (Pmp)	230 W
Maximum power voltage (Vmp)	41.0 V
Maximum power current (Imp)	5.61 A
Open circuit voltage (Voc)	48.7 V
Short circuit current (Isc)	5.99A
Temperature coefficient of current (KI)	3.4 mA/K
Temperature coefficient of voltage(KV)	-132.5 Mv/K
Temperature coefficient of power	-0.38%/K
Cell Number	72
Length	1559 mm
Width	798 mm
Area	1.24 m^2

Thermocouples:

Thermocouples are widely used devices for temperature measurement, especially in the industry as it can withstand high temperatures up to 2500°C [52]. The thermocouple is a differential device, which measures the potential difference between two junctions, hot and cold junction [52] as shown in Figure **5-1**. In a PV system, two thermocouples are connected directly with the panel on a surface to measure the glass temperature and back to measure the cell temperature. Another thermocouple is placed in free to ambient temperature measurement.

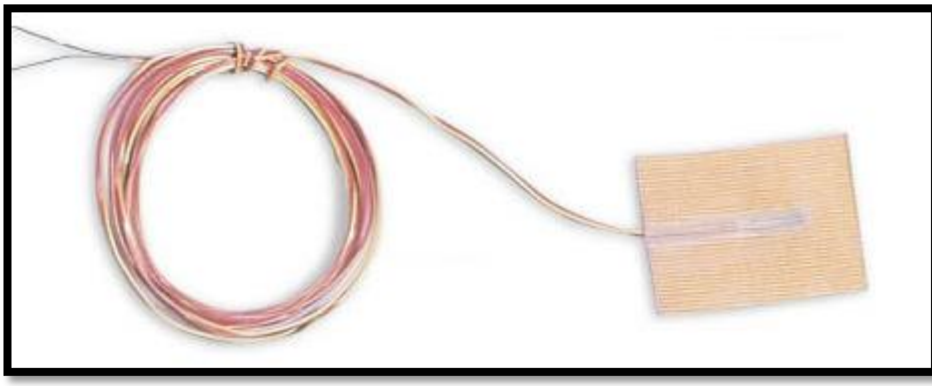


Figure 5-1: Thermocouple type

Pyranometer:

Pyranometer is a measurement device used to measure sun and sky irradiations. It gives the output results as a voltage in relation to the solar radiation density. To measure radiation values in (W/m^2), the output result of this device can be converted using the following formula:

$$\mathrm{Irr} = \frac{\mathrm{Vpyr}}{8.22 * 10^{-6}} \tag{5.1}$$

Where "$8.22 * 10^{-6}$" is the conversion constant for the used pyranometer, Irr is Solar Irradiations, and Vpyr is Pyranometer output.

Figure 5-2: Pyranometer

Current and Voltage Measurements:

An ammeter and a voltmeter device are used for finding the values of the voltage and the current of PV panel.

5.1.2 PV Cooling System

Tank Storage:

The water that is used to cooling PV panel is stored in the insulated tank. In this work, two insulated tanks are used. The upper tank stores the water that's used in the cooling and the lower tank is used to collect the outlet of water after cooling from the collected pipe and then circulate again to the upper tank by using a DC pump.

Pump:

For delivering the water from the lower tank to the upper tank, the DC pump is used as shown in Figure 5-3. The specifications of the pump are listed in Table **5-2**. In addition, 12V solar battery is used to run the DC pump.

Figure 5-3: DC Pump

Table 5-2: Pump specification

Parameter	Value
Voltage	12 V DC
Maximum Current	7.5 A
Flow rate	3 litters per minute (LPM)
Shut-off Pressure	3.7 Bar

Filter:

The outlet water from the panel could contain dust. Hence, the filter as shown in Figure 5-4 is used between the outlet and the lower tank to remove the dust.

Figure 5-4: Filter

Pipe and Hose:

For connecting the cooling system, a set of pipes of different sizes and hoses are used.

Regulator and automatic valve:

Two manual valves are installed to control the flow rate of water. Then, these valves are replaced by automatic control valves.

Cooling Thermocouples:

Two thermocouples are used to measure the temperature of the water and the storage tank.

5.1.3 Others Devices:

For experimental measurement and integral system, other devices and circuits are employed.

Resistive Load:

It consists of three resistors of 1000 ohm. Each of those resistors are connected in parallel as shown in Figure **5-9**. The load resistance can be controlled in order to generate IV-Curve and generate maximum number of power.

AD595 Thermocouple Amplifier:

In order to get a better and more accurate result, an AD595 thermocouple amplifier is used to work for type K thermocouple. Figure **5-5** shows the AD595 circuit.

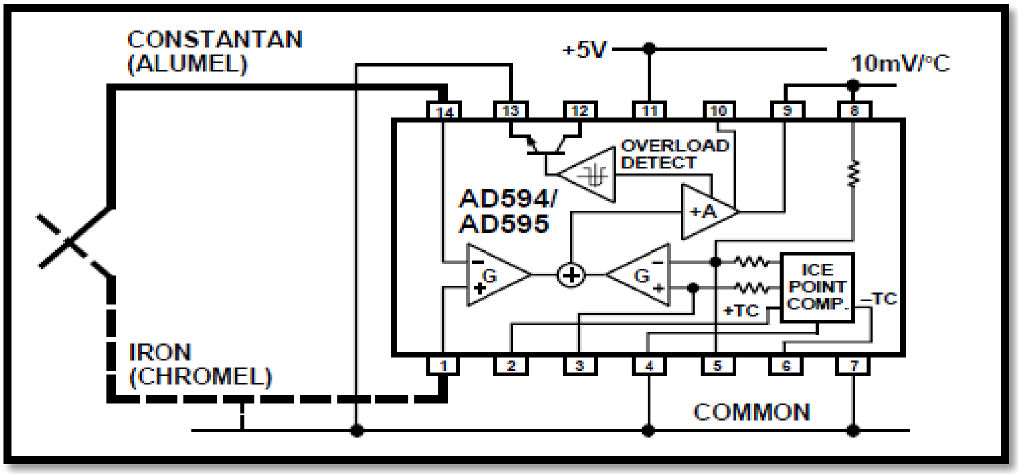


Figure 5-5:AD595 basic connection, single supply operation [53]

Isolation Amplifier:

In this work, an LD 735 261 is used to step down the voltage as well as to convert/step down the current signal into an acceptable voltage signal so that the Arduino microprocessor can read the solar panel output current and voltage.

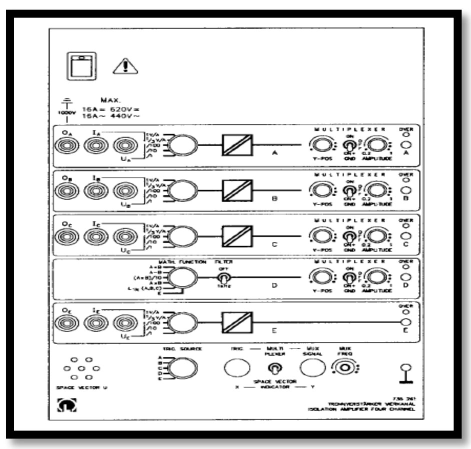


Figure 5-6: Isolation Amplifier

Arduino:

In order to acquire the data and control the project, the Arduino microprocessor is used. The Arduino receives four amplified thermocouple signals, an amplified pyranometer signal, and current and voltage readings from the isolation amplifier. In addition, the

Arduino requires an external circuit to convert all the sensor signals into a desirable signal. The Arduino receives all the signals from its analog pins and read them using its built in analog to digital converter. The Arduino can also store the received data in an excel file using a special macro. From the received readings, it opens/closes the water valve to start/stop the cooling.

In the whole system, all components are connected. The control circuit using Arduino is implemented to control the valves operation of the water based on the temperature. In order to monitor the amount of radiation the pyranomater device is used. The solar radiation that is coming from the sun causes an increase in the temperature. So, four thermocouples are used to measure the four temperatures. These temperatures are ambient temperature, glass temperature, cell temperature and water temperature. Figure **5-7** and Figure **5-8** explain thermocouple place on the panel. End of those thermocouples are connected to amplifiers circuit, then to Arduino to store data in the computer.

Figure 5-7: Thermocouple attached to the glass of the PV panel

Figure 5-8: Thermocouple attached to the back of one of the solar cells

The Solar panel supplies the resistive load with power. Ammeter connected in series with the current load and Voltmeter connected in parallel with the load voltage for calibration. In Isolation amplifier, two channels are used. The first channel measures the load voltage and step it down by a factor of 1V/100V, and the second channel measures the load current and convert it into a voltage signal while stepping it down by a factor of 1V/3A. The data is collected using Arduino and saved in an excel file in the computer. For the cooling, the water moves in circular circuit from the upper tank through the valves to the lower tank after passing through the filter then to the upper tank using the DC pump. During this circle, the water passes on the surface of the panel to reduce the temperature on the panel and hence an increase in the efficiency is achieved.

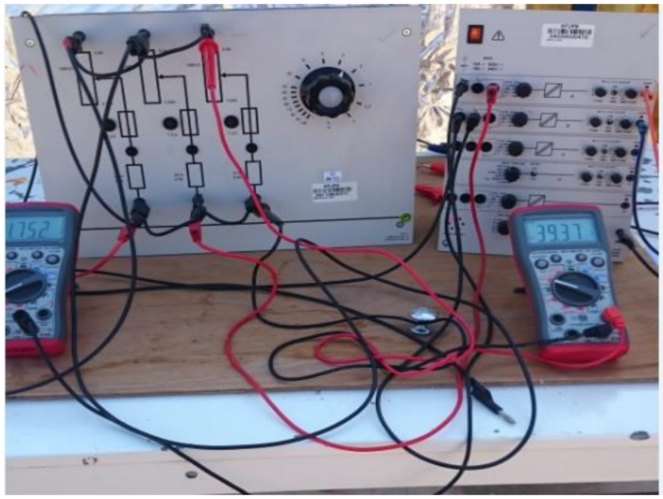


Figure 5-9: Measurement devices and load bank

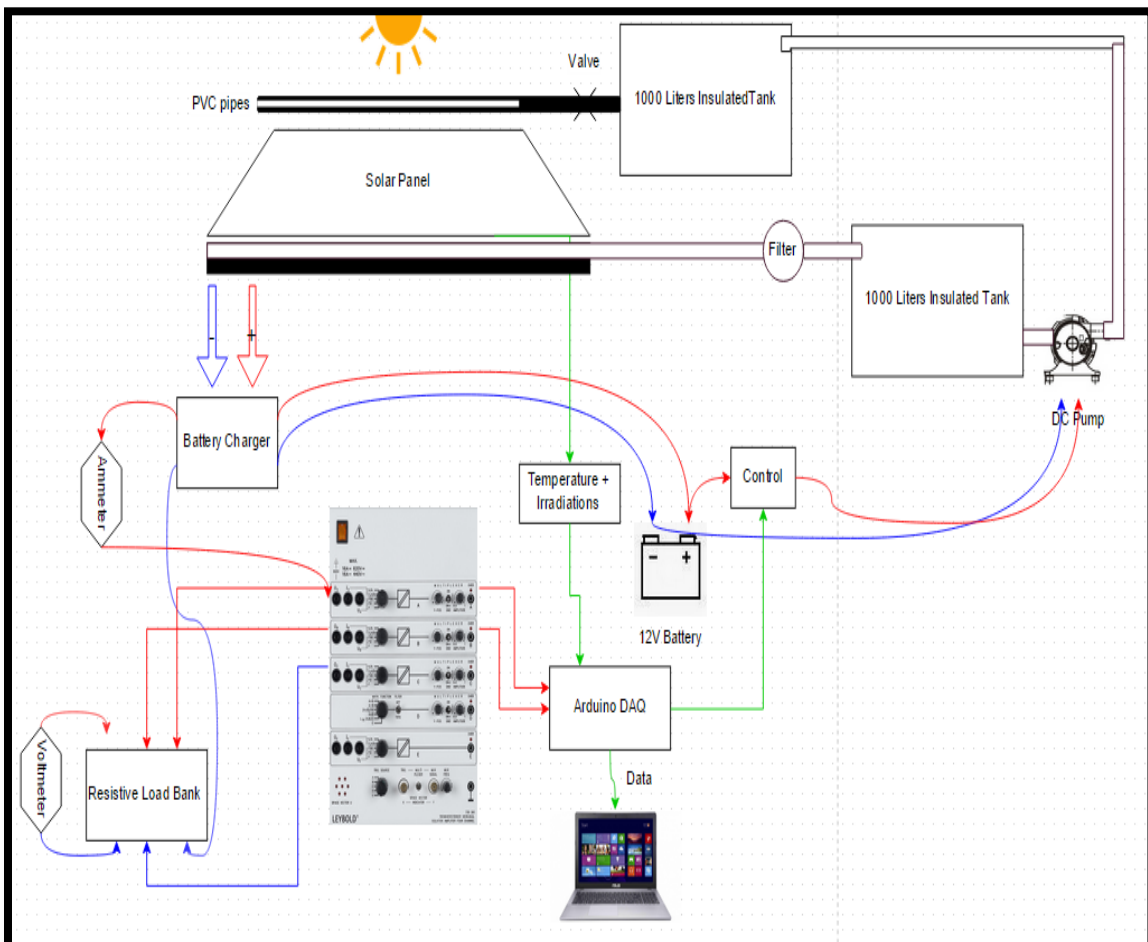


Figure 5-10: Data Acquisition setup

5.1.4 System Installation

This section explains the process of building the cooling system for this work. The pictures below describe the building stages of the system. The solar panel is fixed on a stand with four wheels to easy move it at necessary. There are two tanks used in this work, upper tank and lower tank, with a DC pump in between to push the water to the upper tank. Two tubes are fixed at the top edge of the solar to collect the water from upper tank and at the bottom edge of solar to collect the water that pass on the PV surface to the lower tank. Before the lower tank, the filter is used for filtering the dust from water. Different sizes of pipes system are used to connect all parts of the whole system.

Figure 5-11 : Upper and bottom tube setup to collect water


Figure 5-12 : Right side of panel with up and down tubes


Figure 5-13 : front side of the system setup with 2-tank


Figure 5-14 : Connect bottom tube with filter and bottom thank


Figure 5-15 : Front view of manually PV cooling system

The figure above explains the cooling system using manual valves connected in right and lift of the upper tube. Then, some changing conducted in the system where the manual valves replaced by the control valves and fixed above the upper tube as shown in Figure **5-16**. These control valves operating as on-off using Arduino under specific condition as shown in flowchart in Figure **5-19**.

Figure 5-16 : Front view of PV cooling system control using ON-OFF valve

5.1.5 Water Flow Adjusting on Panel Surface

For passing water on surface during the cooling, two ways are considered. The first way is by using aluminium boards. This way played a good role to cover the panel by about 90% of the water, but it needs an adjustment before the starting of the experiment. The second way is the best way especially with the flow control. This way developed by using the isolation material which absorbs the water from the upper tube to the out on the surface of panel as shown in below

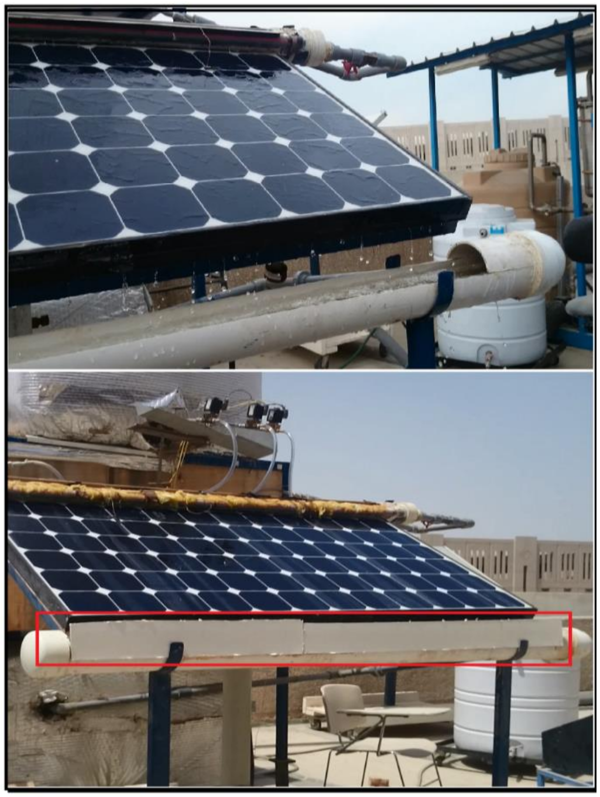


Figure 5-17 : Pass water control

5.2 PV Characteristics Measuring

The block diagram in Figure **5-18** describes the electrical circuit that is used to study the electrical characteristics of PV panel such as I-V curve, short circuit current and open circuit voltage. In this circuit, the resistive load is joined in series with solar panel. Also, two multimeters are connected with PV panel, the first one is for voltage measuring that is connected in parallel and the other one is for current measuring which is connected in series.

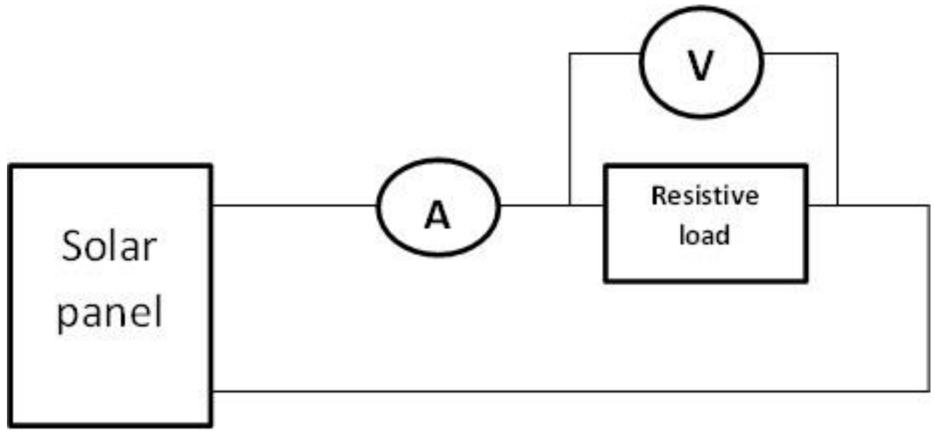


Figure 5-18 : Block diagram of PV model measurement

The measuring of all electrical characteristics in this work obtained in two cases, (i) without cooling and (ii) with cooling. Initially, the short circuit current and the open circuit voltage parameters are measured with those two cases. For the open circuit voltage, the multimeter is connected in parallel with the PV panel and in series for the short circuit current. Then the resistive load connected as shown in the above circuit to obtain the I-V curve. The readings of voltage and current in the two cases started with the minimum value of resistive load. The resistive load value is increased through many steps until reaching the maximum resistance value. Each step produces a new reading of voltage and current. During the changing of the resistance value from the minimum to the maximum, the voltage changes from the minimum voltage to the maximum voltage. In the same time, the current also changes but from the maximum to the minimum value. The power can be calculated by multiplying the corresponding values of the voltage and the current. Under radiation and temperature conditions, the test is conducted through two cases. In the first case without cooling, the resistive load is put in minimum value and the voltage and the current readings are recorded. Then, we increase this value by varying the resistive load to the maximum value during many steps and in each step we record the new value of voltage and current. In the second case with cooling, the similar procedure is followed using water on the front surface of the panel.

5.3 Valves Control Algorithmic State Machine

The flow chart in the following figure explains the mechanism of the proposed cooling system using valves control under three conditions. These conditions are irradiation, efficiency and the different operating temperature (TD) between the desired value and the measured value. In the control system, the measured temperature is compared with the desired temperature. If TD is a positive, the control valve will be opened and the water will flow on the surface for cooling. In this work, three control valves are used. They operate depending on the value of the different temperature as explained in the flowchart. If this value need small flow rate then one valve will open. If that is not enough, then the second valve will open and so on for the third one. This variation in flow rate will give better cooling result.

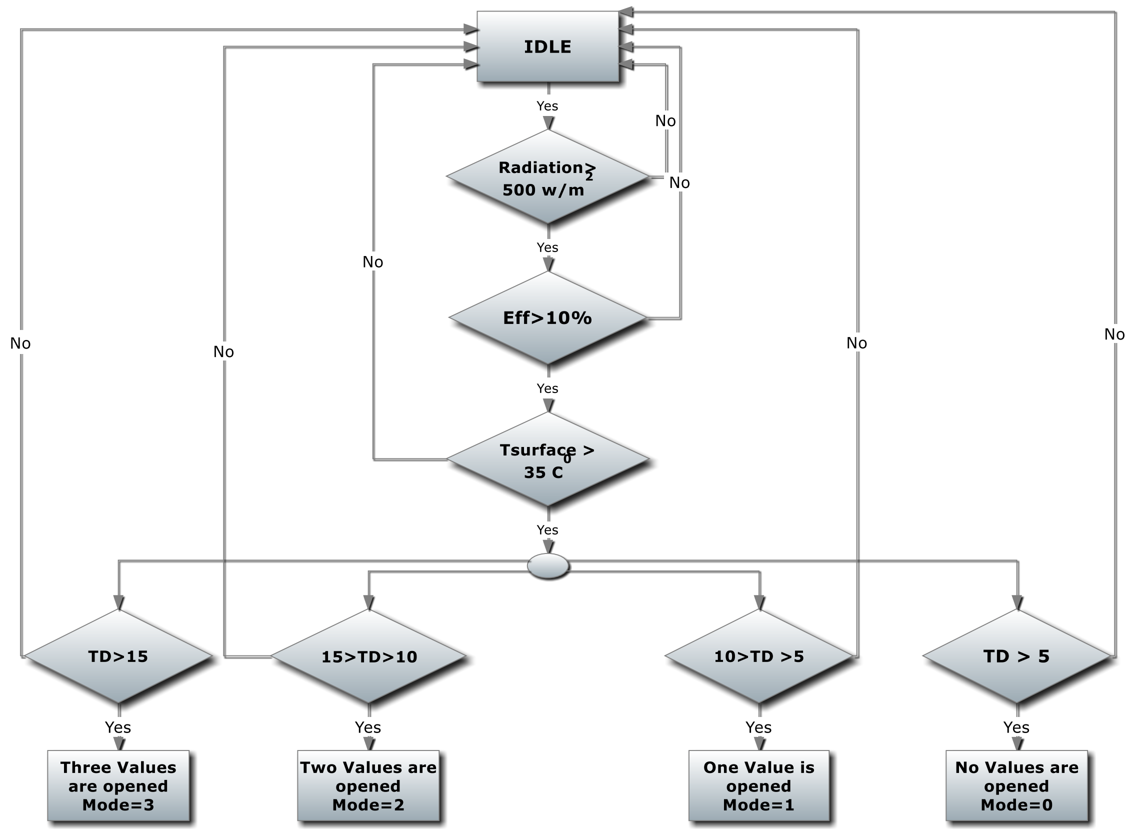


Figure 5-19: Valves control algorithm

CHAPTER 6

SIMULATION AND EXPERIMENTAL RESULTS

This chapter discusses the obtained results of the simulation model. In addition, it discusses the achieved experimental results.

6.1 Simulation Results

This section provides all simulated results of the PV/T model with three parts. The first part is to study the temperature and solar radiation effect on the PV model electrical operation using I-V curves characteristics. The second part is to validate the proposed PV cooling model under the environmental conditions given in [40]. The last applies the proposed PV cooling model under environmental conditions of Saudi Arabia.

In this work, three PV modules are used with different output power. These modules are:

1- STP060-12/Sb Module

2-NSS-24 150M Module

3- SPR-230-WHT-U Module

Table 6-1 describes model parameters values for the selected modules in the Standard Test Condition.

Table 6-1 : Model parameters values

MODEL	SPR-230-WHT-U	STP060-12/Sb	NSS-24 150M
Maximum power	230W	60W	150W
Maximum power voltage (Vmp)	41.0V	17.4V	36V

Maximum power current (Imp)	5.61 A	3.45 A	4.16 A
Open circuit voltage (Voc)	48.7 V	21.6 V	43.2 V
Short circuit current (Isc)	5.99 A	3.9 A	4.49 A
Temp. coefficient of current (KI)	3.4 mA/K	0.055%/K	2.12 mA/K
Temp. coefficient of voltage (KV)	-132.5 mv/K	-0.075 V/K	-99.1 mV/K
Cell Number	72	36	72
Length	1559 mm	771 mm	1580 mm
Width	798 mm	665 mm	808 mm
Area	1.24 m^2	0.513 m^2	1.3 m^2

6.1.1 Temperature and Solar Radiation Influence on PV Performance

In this thesis, a MATLAB/SIMULINK model is used to study the electrical performance characteristics of PV model. In addition, it studies the effect of the temperature and the solar radiation on the output power. The simulation is based on the three selected modules.

The behavior of I-V and P-V curves depend on the amount of received irradiation and temperature. The increase in solar irradiation causes an increase in the current that is produced from the solar cell. Hence, output power will increase without any change in the voltage. On the other hand, the output power decreases when the temperature increases. In this case, the voltage of the solar cell will decrease while the current will not be affected. Different experiments are carried out using MATLAB program to study these facts. All facts are achieved for each of the three selected modules.

Influence of Solar Radiation:

The I-V & P-V curves in the figures below describe the effect of irradiation on PV performance. The selected three modules are studied using three different values of irradiation. These values are 1000W/m^2, 800 W/m^2 and 600 W/m^2. The temperature is taken to be constant in nominal value (T=25°C).

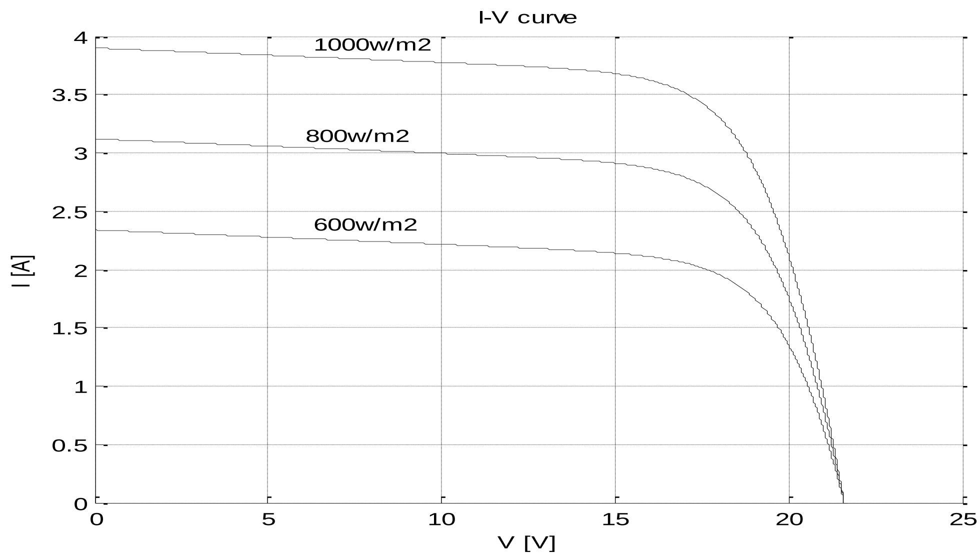


Figure 6-1: I-V curve of STP060-12/Sb module with different irradiation

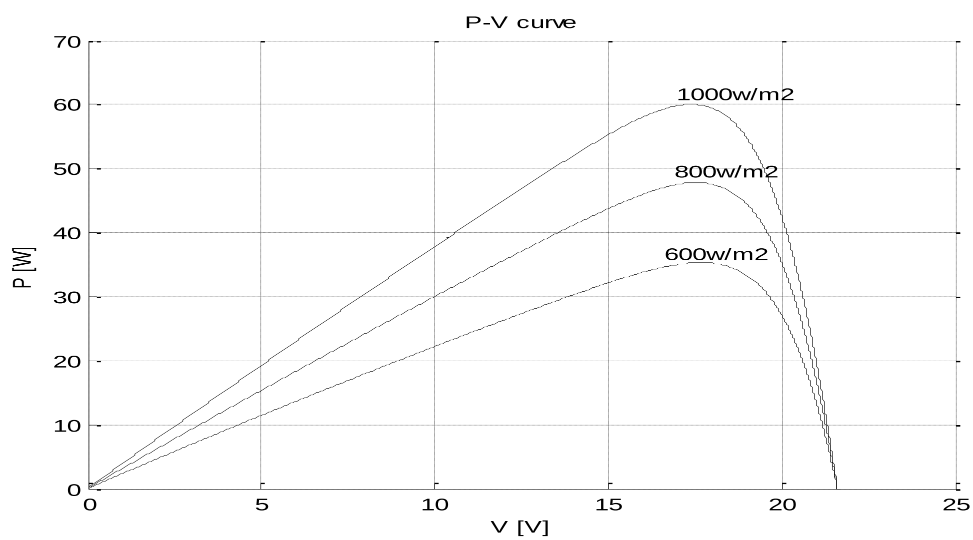


Figure 6-2 : P-V curve of STP060-12/Sb module with different irradiation

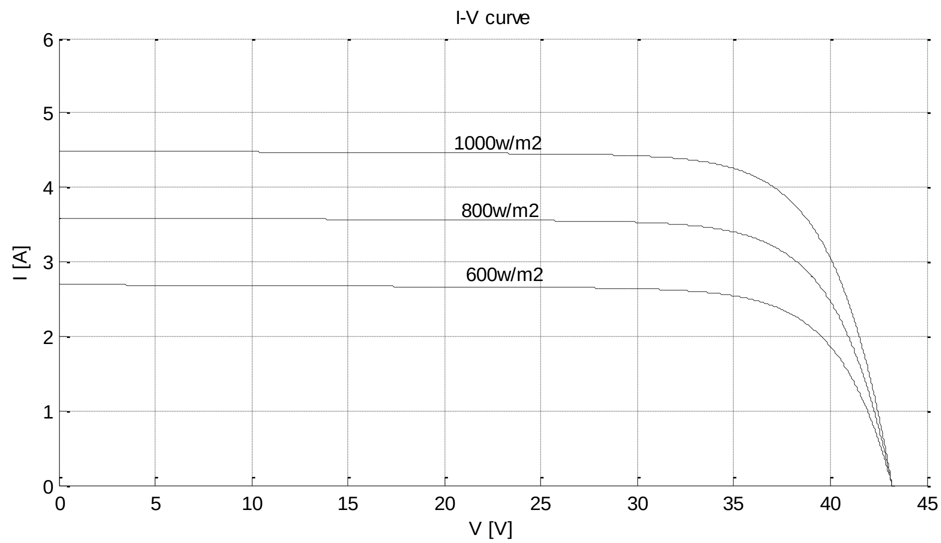


Figure 6-3 : I-V curve of NSS-24 150M Module with different irradiation

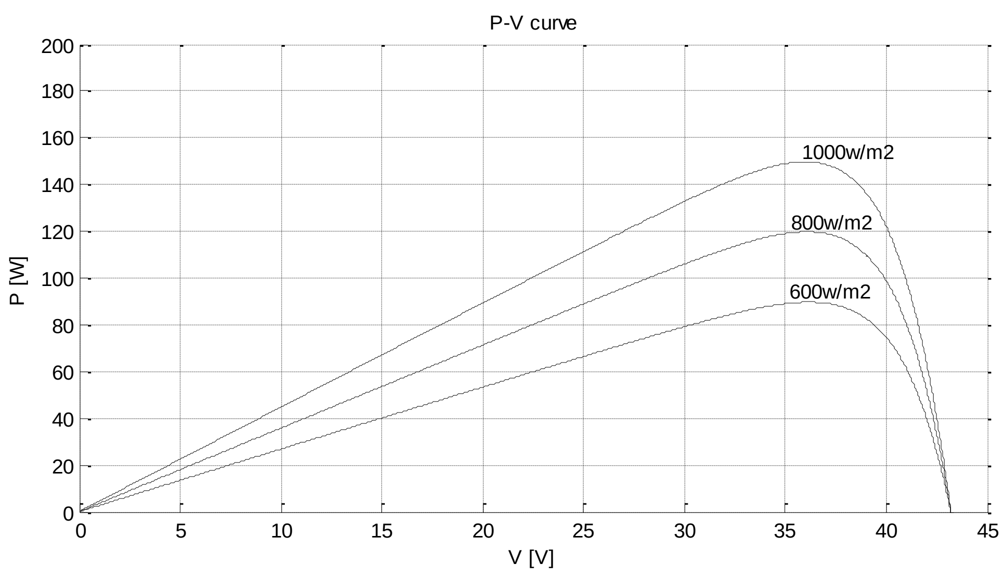


Figure 6-4 : P-V curve of NSS-24 150M Module with different irradiation

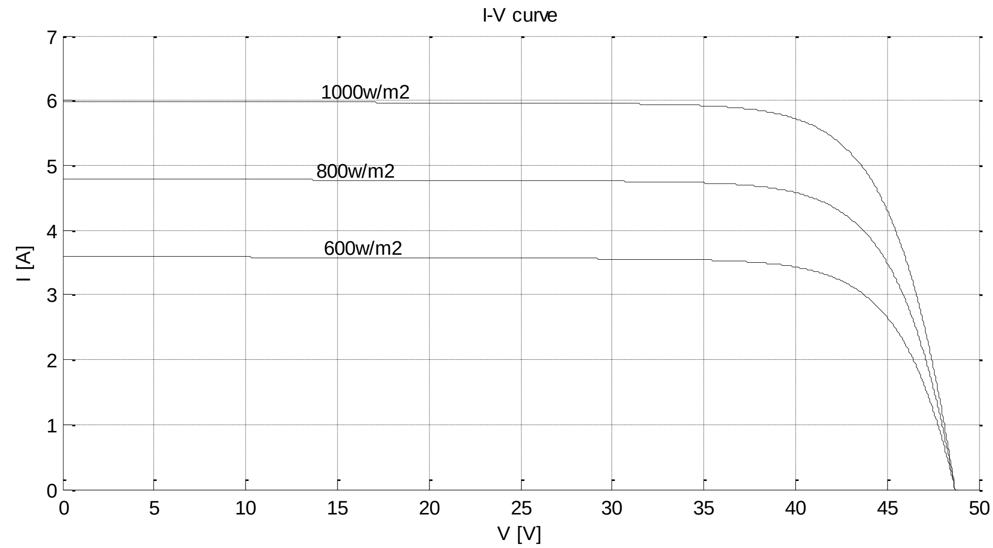


Figure 6-5 : I-V curve of SPR-230-WHT-U module with different irradiation

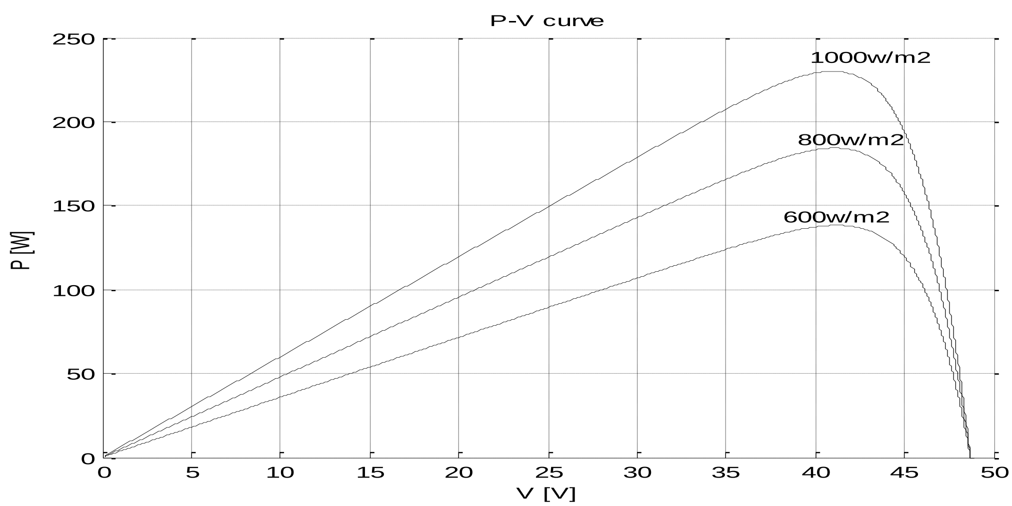


Figure 6-6 : P-V curve of SPR-230-WHT-U module with different irradiation

From the figure 6.1 – 6.6, it can be observed that the Voc remains constant regardless of the value of current and radiation. In addition, the increase in the current causes an increase in the output power as is shown in the given P-V curves.

Influence of Temperature:

Temperature is one of environmental condition that influences the PV output performance. The following figures (6.7 – 6.12) describe both I-V and P-V curves of the three modules using three different values of temperature, viz. 25, 50, and 75°C. The irradiation is fixed as a nominal value (1000W/m^2). From the given figures, it can be noted that the temperature is inversely proportional with the voltage of the panel. The voltage is reduced when the temperature of the panel increases and therefore the output decreases.

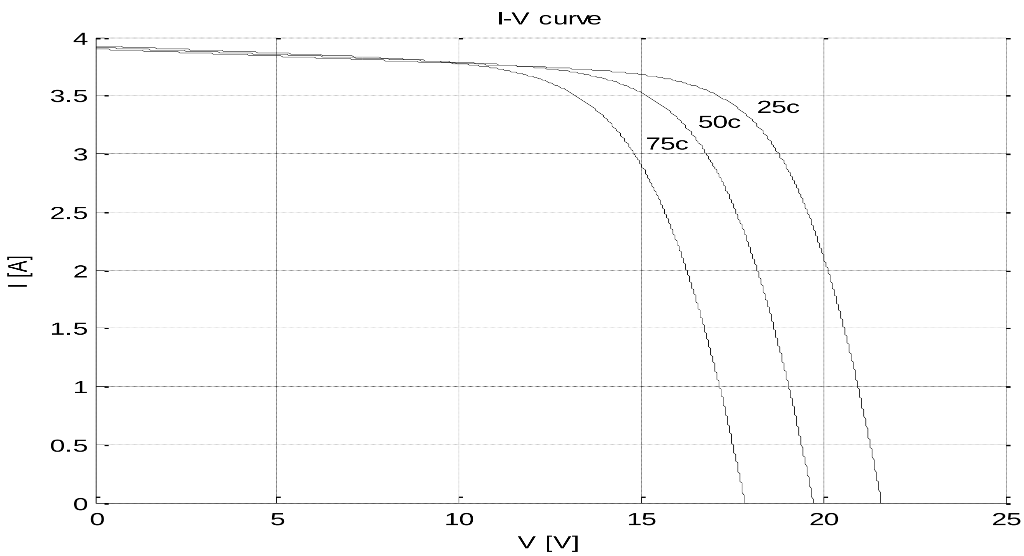


Figure 6-7 : I-V curve of STP060-12/Sb module with different temperature

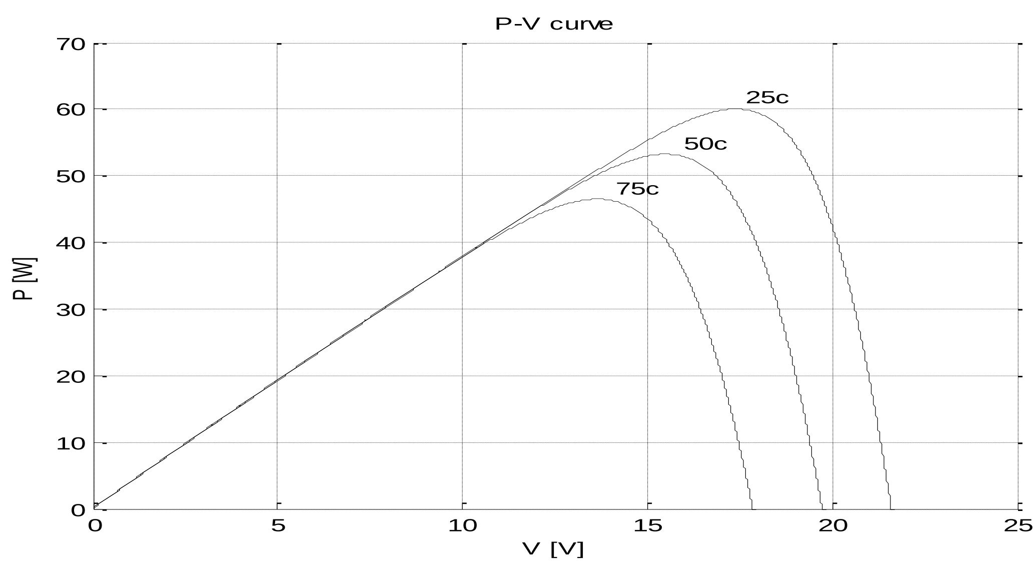


Figure 6-8: P-V curve of STP060-12/Sb module with different temperature

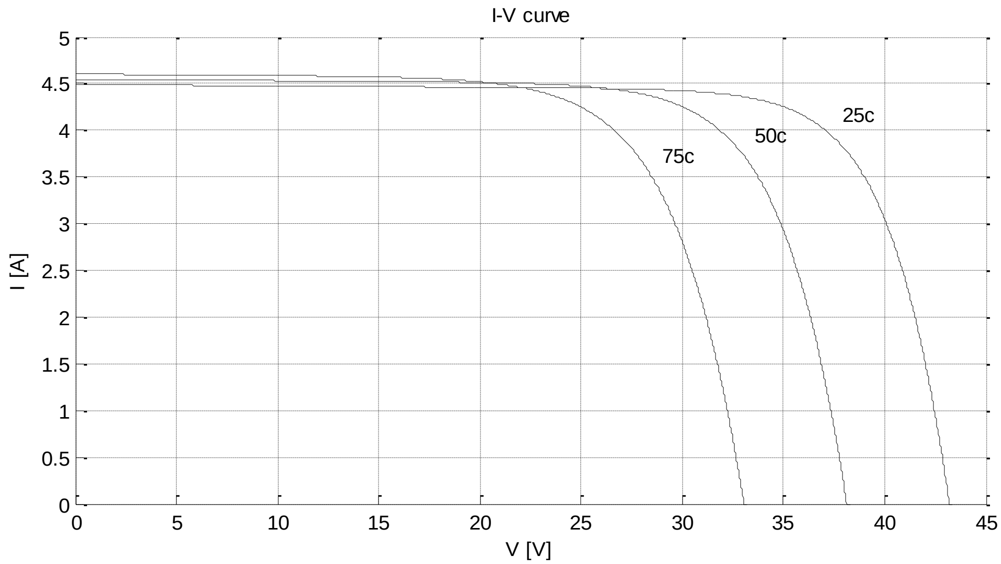


Figure 6-9: I-V curve of NSS-24 150M Module with different temperature

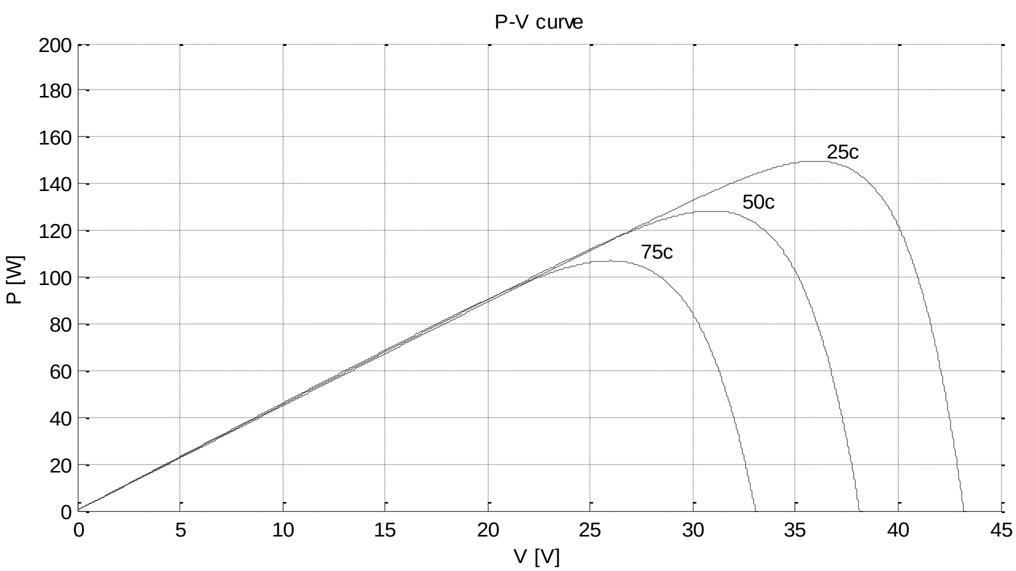


Figure 6-10: P-V curve of NSS-24 150M Module with different temperature

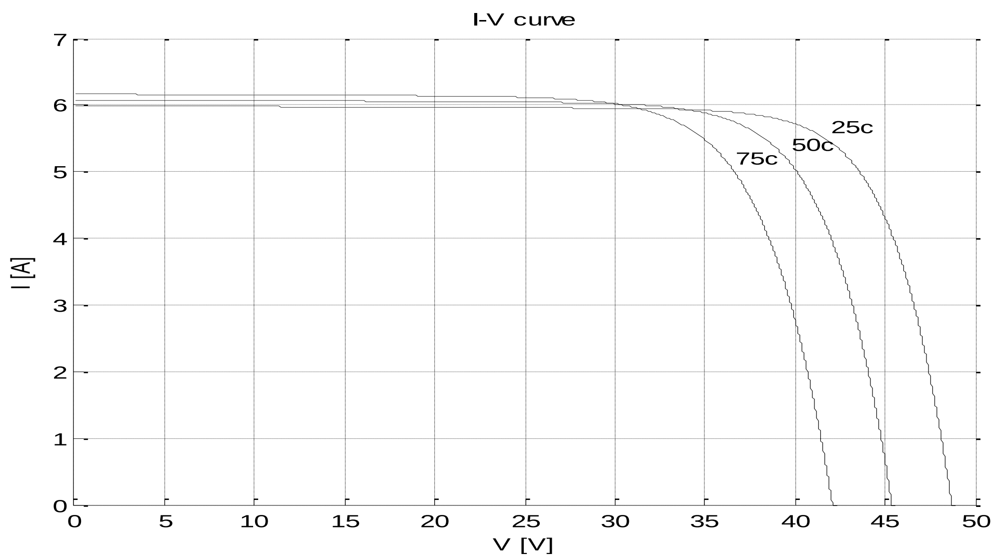


Figure 6-11: I-V curve of SPR-230-WHT-U module with different temperature

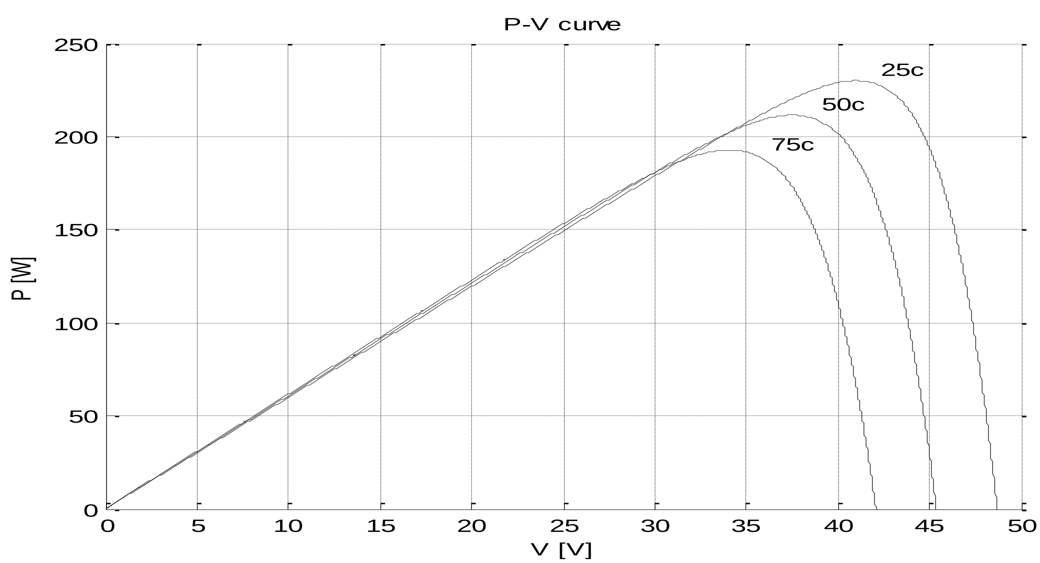


Figure 6-12: P-V curve of SPR-230-WHT-U module with different temperature

In general, we can say that there is an influence of irradiation and temperature on PV performance. The increase in the radiation has positive effect on PV module which causes an increase in the current and therefore the output power increases and Vice versa. However, the temperature has negative effect on voltage, PV module and output power.

6.1.2 Model Validation

6.1.2.1 PV/T Cooling Model

The thermal model of PV panel has been simulated. The differential equations with four temperatures are applied in MATLAB using ODE functions to study the behavior of these temperatures in the output. These temperatures are water temperature, glass temperature, cell temperature and storage temperature that are abbreviated as Tw, Tg, Tc, and Ts respectively. With duty cycle of irradiation, the output behaviour of these temperatures is studied using ODE functions based on the four equations of energy balance. Figure 6-13 shows output temperatures of thermal model with cooling. The amount of radiation has been calculated using equation (3.35) with ρ_{max} equal 1000, and t_0 equal 43200.

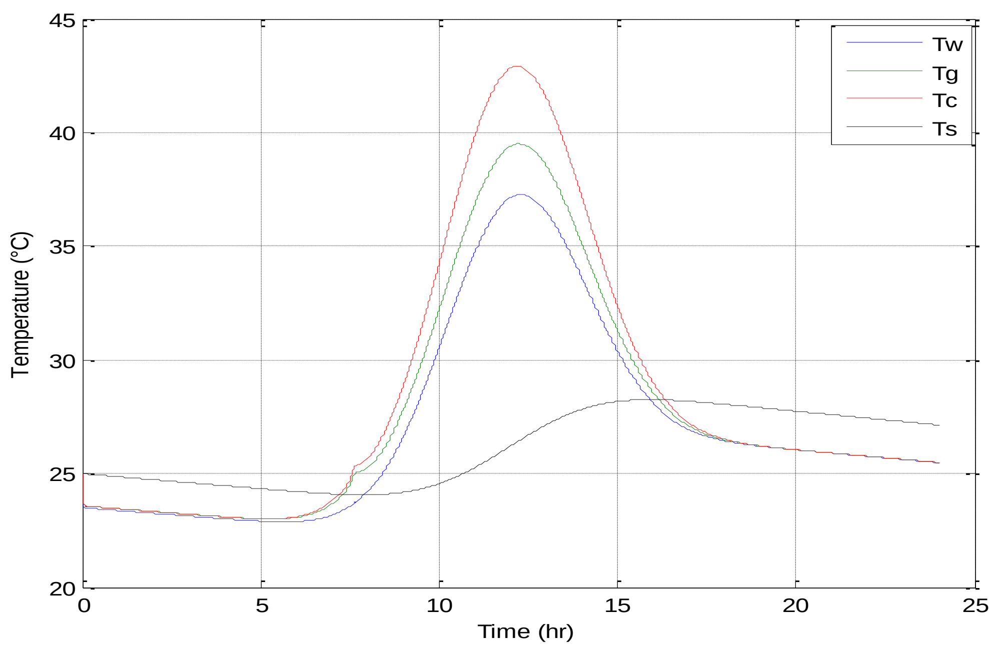


Figure 6-13: Test of behavior temperatures in thermal model

In addition, the flow rate mass was tested to study its influence on output temperature of thermal model. The figure below describes this influence on the cell temperature. This test is carried out for one day with 28°C and 1066 W/m^2 for ambient temperature and irradiation, respectively. Equation 6.1 describes the given relation mathematically.

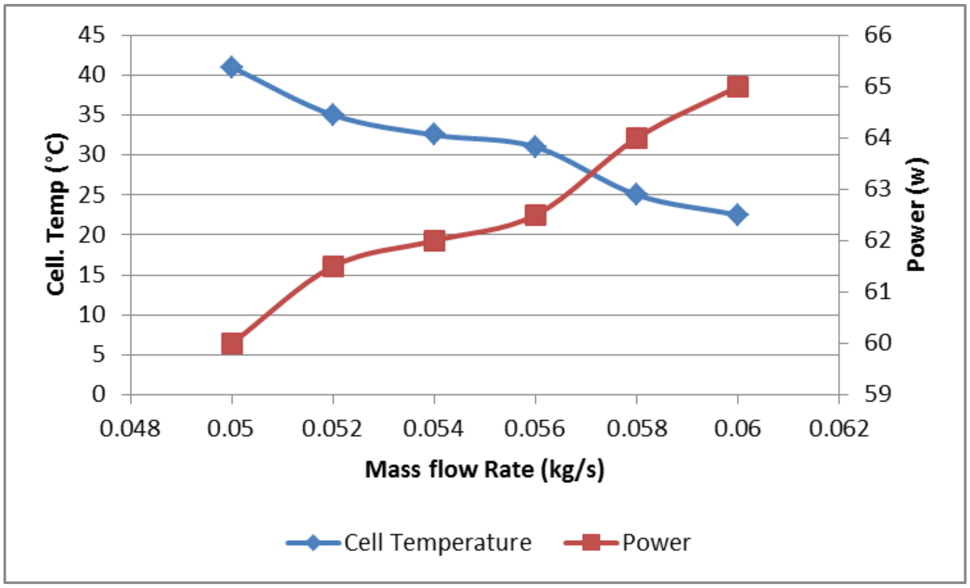
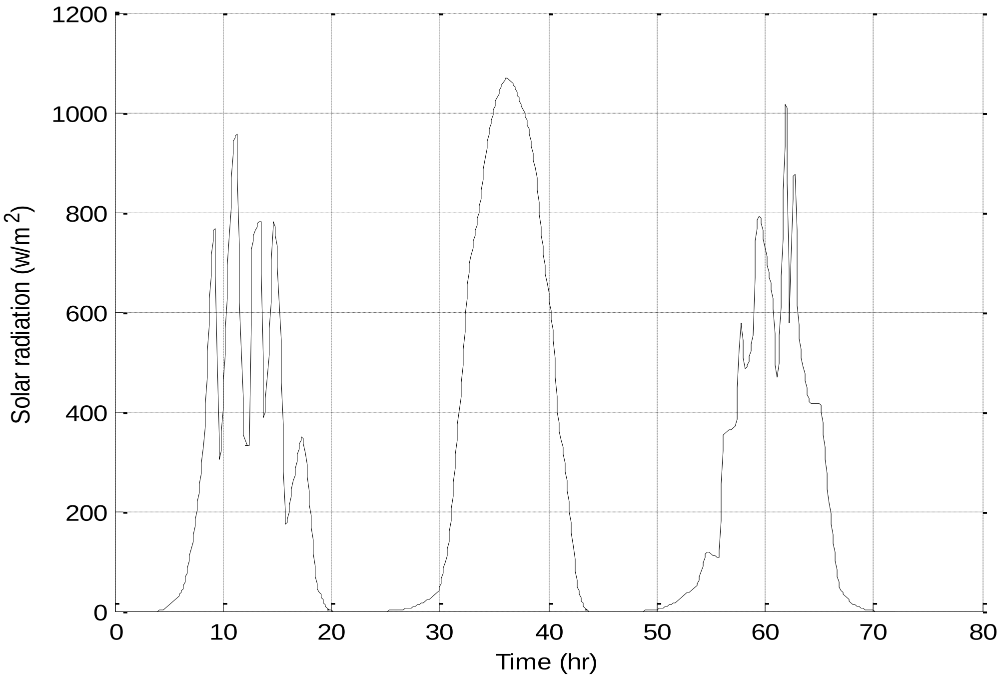


Figure 6-14: Test of influence flow rate on cell temperature and power

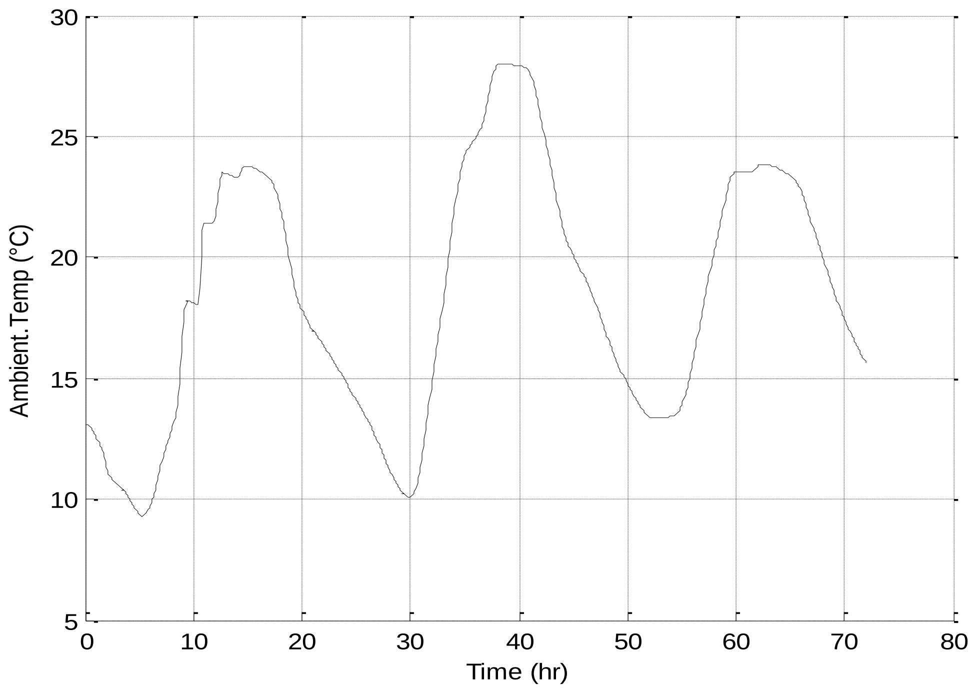
$$\dot{m} \propto \frac{P}{T_c} \tag{6.1}$$

From the above figure, it can be observed that the increase in the water flow rate mass causes decrease in the cell temperature as well as increase in output power.

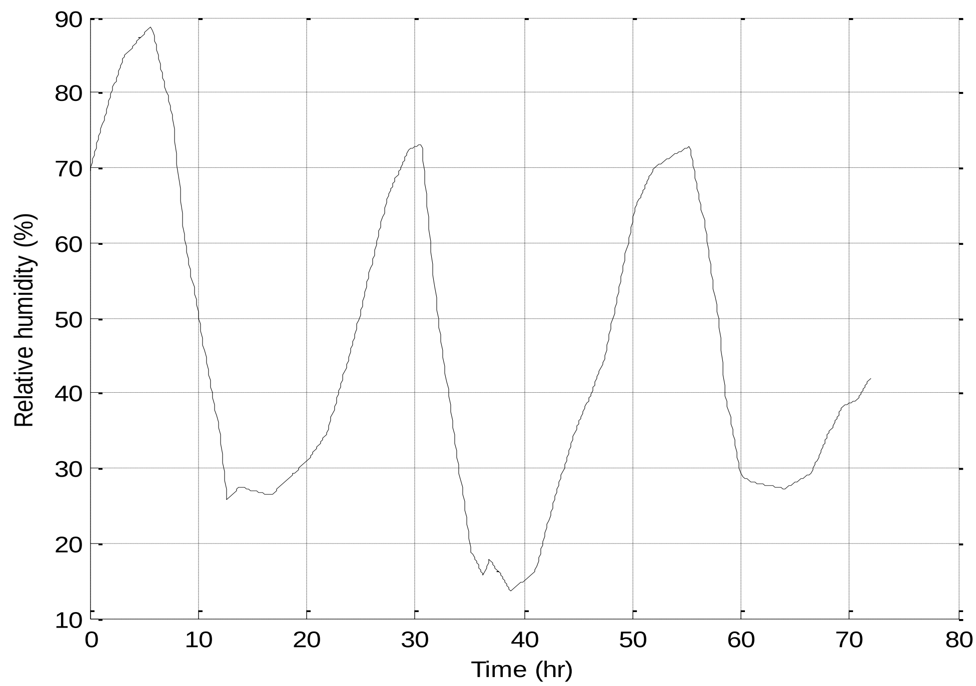
Initially, a validation model is carried out using the given data in [40]. Figure **6-15** shows the behaviour of the environmental conditions such as ambient temperature, wind speed, radiation and humidity that is used as the input data during three days.



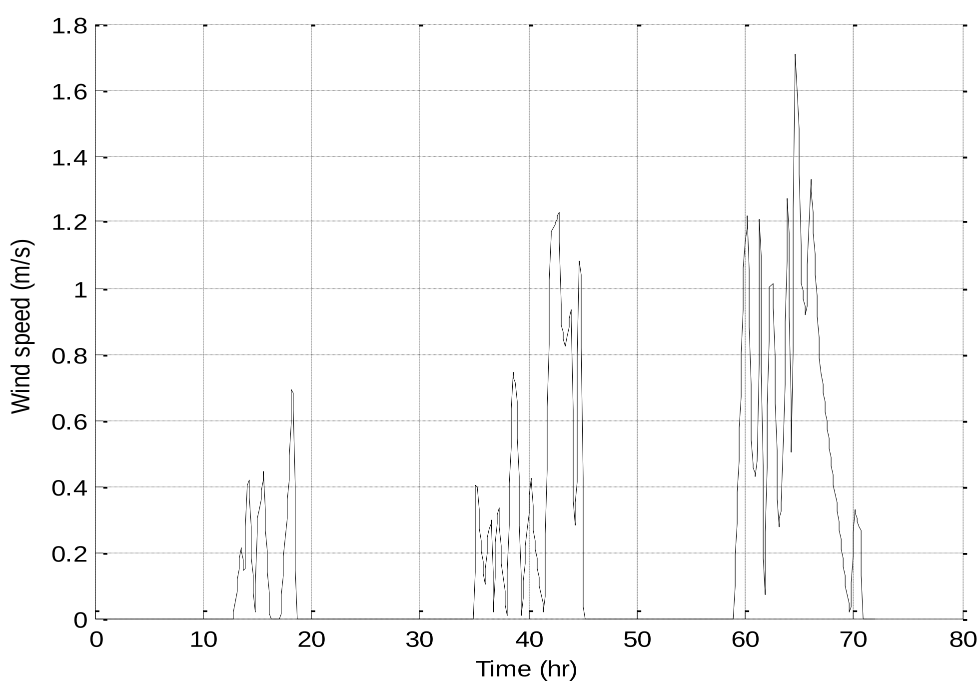
(a) Solar radiation



(b) Ambient temperature



(c) Relative humidity



(d) Wind speed

Figure 6-15: Required input data in [40] (a) Solar radiation (b) Ambient temperature (c) Relative humidity (d) Wind speed

In order to find the cell temperature, the equation (3.15) is used and applied in SIMULINK program. This equation depends on ambient temperature, irradiation, and NOCT condition. Figure **6-16** shows the behavior of cell temperature depending on ambient temperature and irradiation conditions in [40]. This temperature is taken to be the cell temperature without cooling. The result of temperature with and without cooling will be compared later.

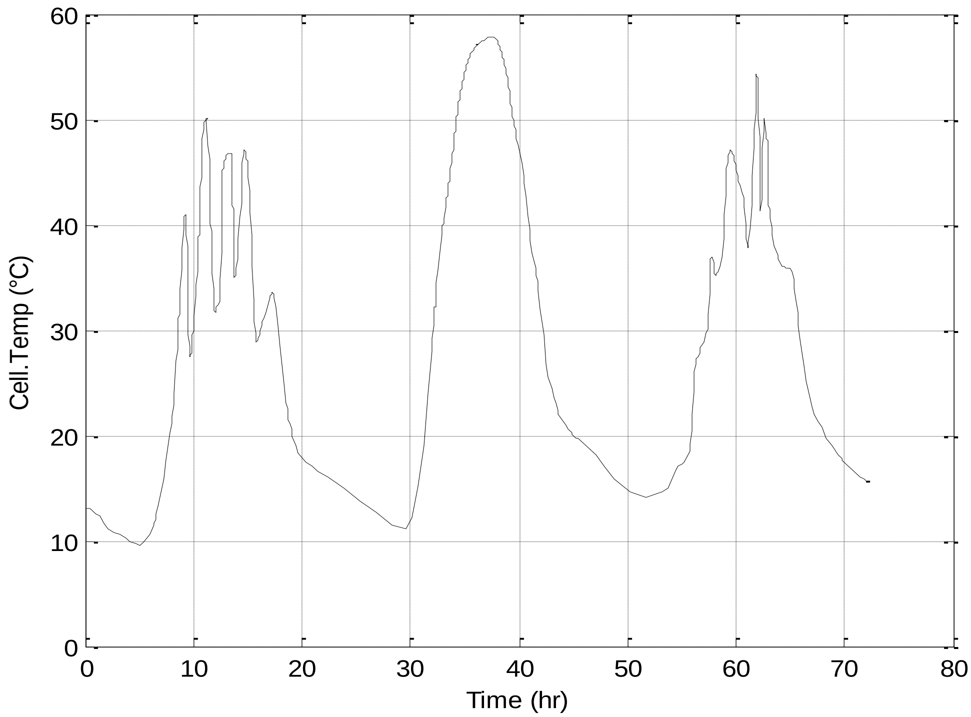


Figure 6-16: Calculated cell temperature

By using the thermal cooling model designed in the previous chapter, the output of cell temperature with cooling is analyzed in the figure below. This output depends on the amount of mass of water flow rate used to cool the panel. Figure **6-17** shows the simulated cell temperature with cooling using small value of flow rate. The output power with and without cooling are shown in Figure **6-18**.This is carried out using ST60W module parameters.

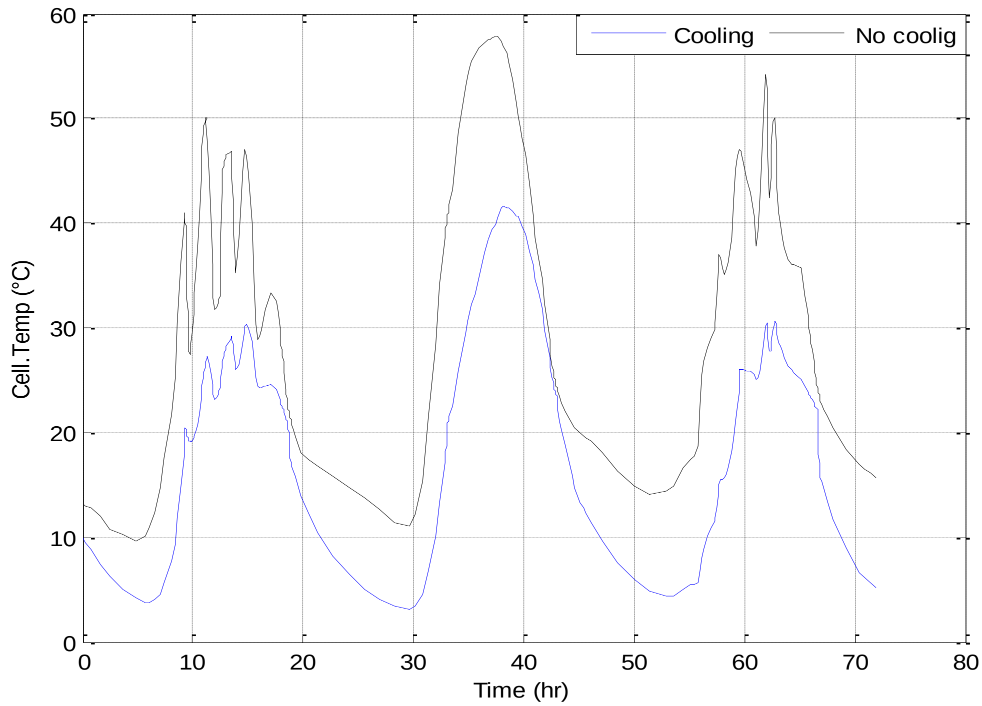


Figure 6-17: Cooling cell temperature

Figure **6-17** shows clearly that the cell temperature using the PV cooling model is decreased compared to the cell temperature without cooling. In the second day curve, the temperature of the solar cell drops from the peak of 57 °C – without cooling – to 41 °C – with cooling.

The output power at the given temperature in Figure **6-17** is calculated. Figure **6-18** shows the calculated power with and without cooling. It is clear that the power is increased to a maximum of 60 W.

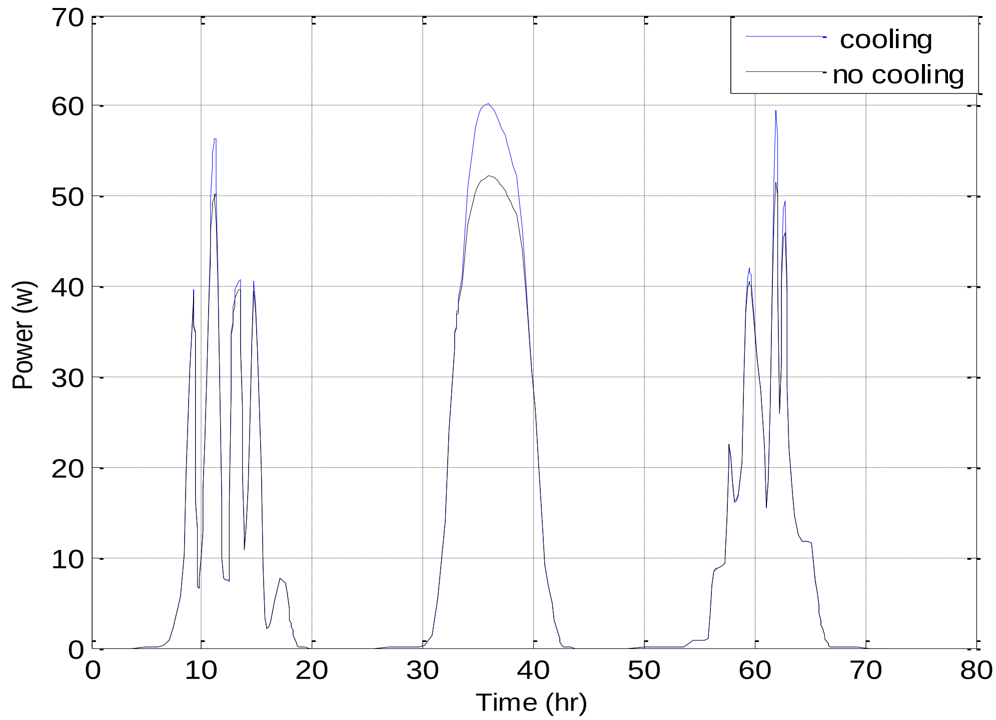


Figure 6-18: Power output with and without cooling

To study the effect of water mass flow rate on the output, different experiments are carried out using the same cooling model. Figure **6-19** shows the simulated cell temperature under different flow rate values. We also did the comparison with [40] and the results are shown in **Figure 6-20** . Figure **6-21** shows the output power corresponding to the cell temperature in Figure **6-19**. It is clear that the water mass flow rate is inversely proportional to the cell temperature and hence is proportional to the output power. The maximum output power obtained is about 62 W.

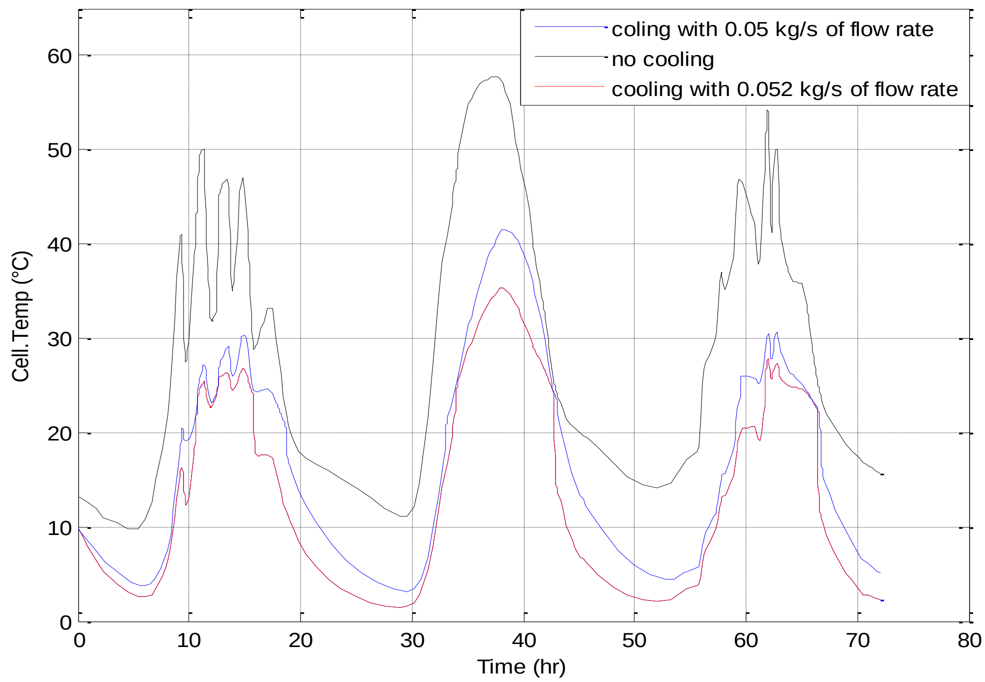


Figure 6-19: Cell temperature with cooling at different flow rate of water

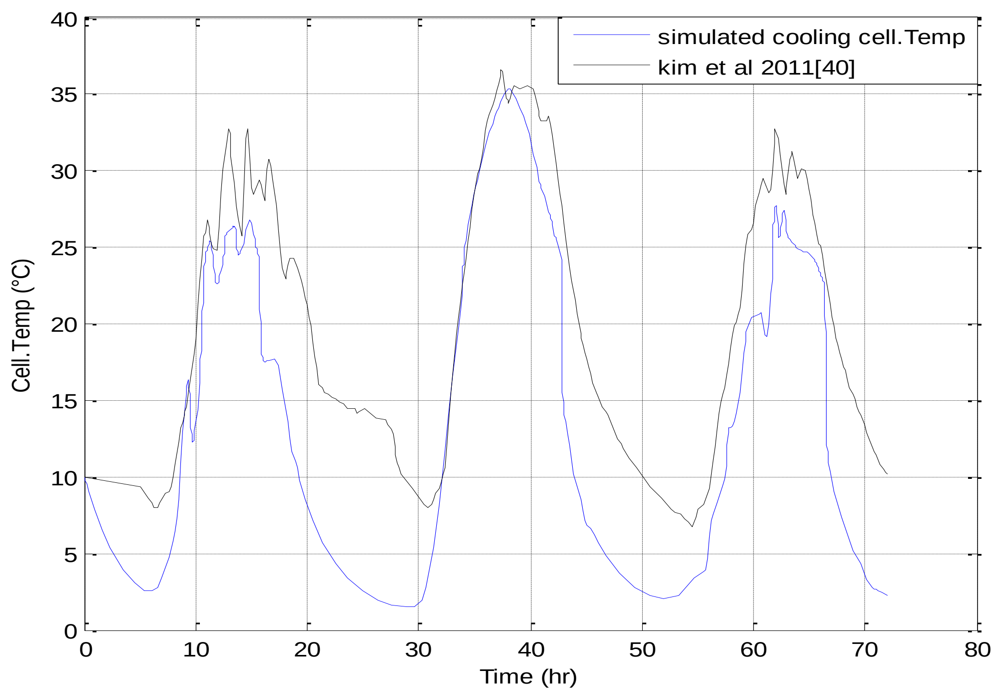


Figure 6-20: Simulated cell temperature compared with Kim et al result in [40]

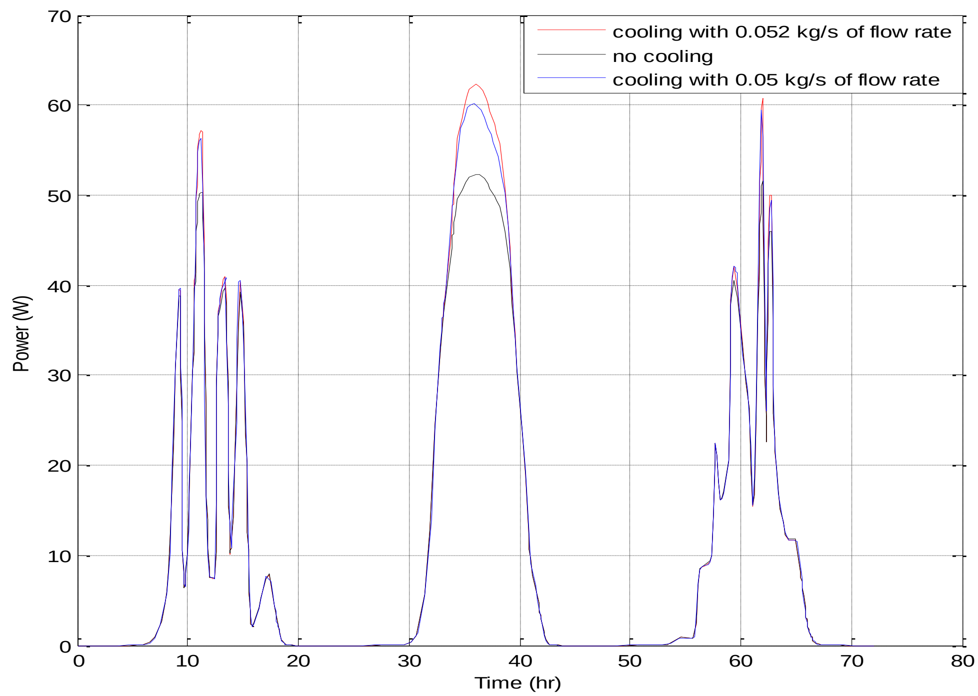


Figure 6-21: Power output with cooling at different flow rate of water

To sum up, the water mass flow rate is inversely proportional to cell temperature and hence is proportional to the output power. The cell temperature is decreased by the added cold water from the storage tank on the surface of the panel. The water through glass cover absorbs part of the cell temperature. In addition to solar radiation factor, the cell or silicon temperature plays an essential role on the output performance of PV the panel. Therefore, low cell temperature with high radiation resulted in high output power.

6.1.2.2 PV/T Model Control

The SIMULINK control module that is designed in the previous chapter is tested. The cell temperature signal from the thermal model is controlled by using PID. The cell temperature is compared with the set point value which is the fixed desired value used as a condition to get better output. The difference between the set point value and the feedback signal – the error – is given to PID controller. Then, the PID controller minimizes the error to get a cell temperature equal the set point value.

In this part, the simulation under environmental conditions in [40] is carried out and the results are observed. The set point temperature values are assumed to be 15, 20 and 30 in Degree Celsius (°C).

Figure **6-22** describes the result of the controlled cell temperature using PID controller with 15°C. In this case, the PID controlled the cell temperature of the thermal model to be closed to the set point value by controlling the flow rate. The behavior of the flow rate is explained in Figure **6-23**. The behavior of output power is shown in Figure **6-24**.

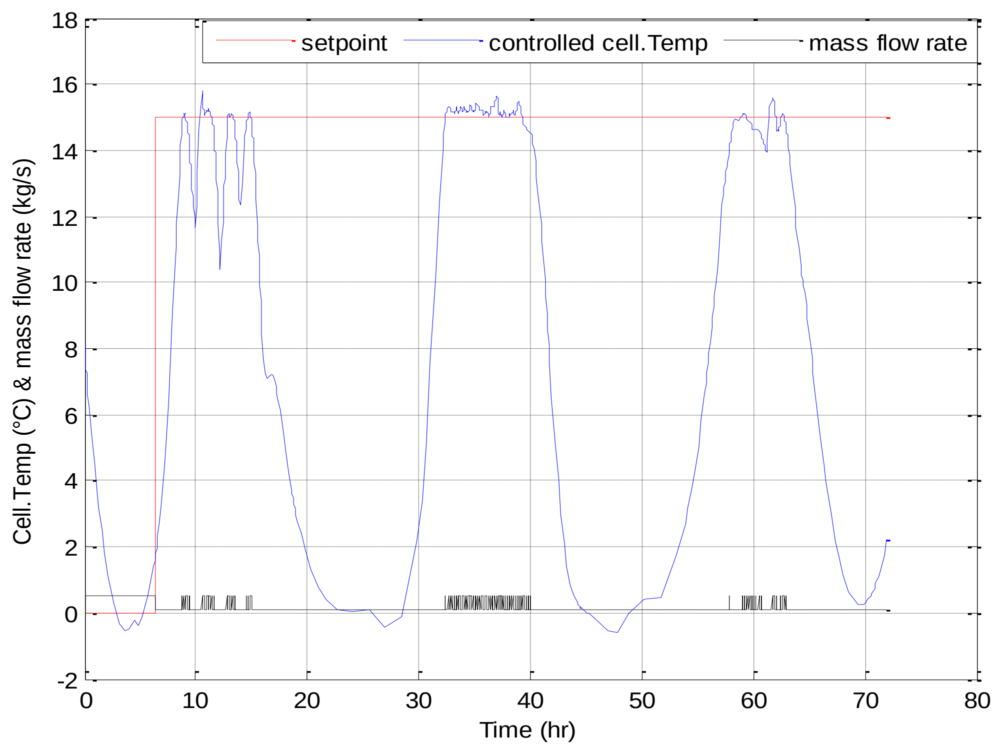


Figure 6-22: Cell temperature control, 15°C

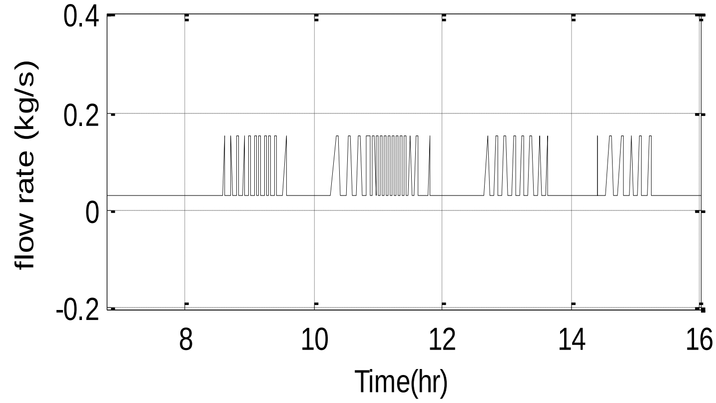


Figure 6-23: flow rate signal from PID controller for one day

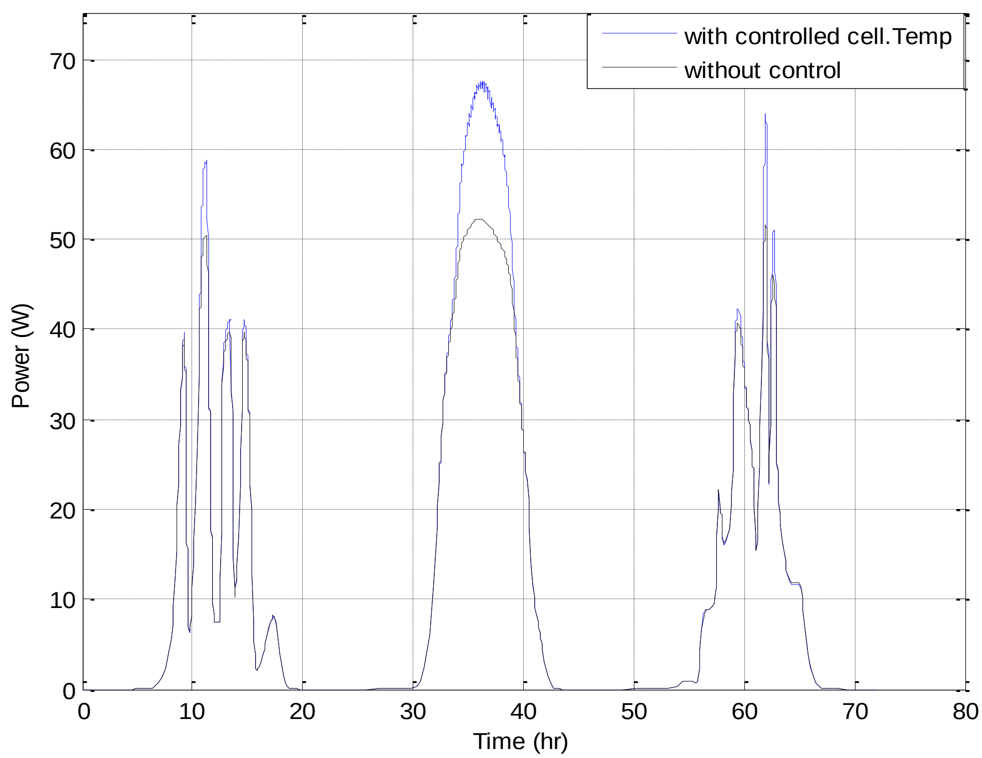


Figure 6-24: Power output with cooling control at 15°C

The above figure shows the increase in the output power because of the controlled cooling of the cell temperature compared with the output power without controlled cooling. Similarly, the same procedure is carried out with the other two reference values, i.e. 20°C and 30°C. The results are shown in Figure **6-25** and Figure **6-26**. The output power of all reference values is shown in Figure **6-27**. The maximum power for second day curve is about 67W, 65W and 62W in controlled cell temperature 15°C, 20°C and 30°C, respectively.

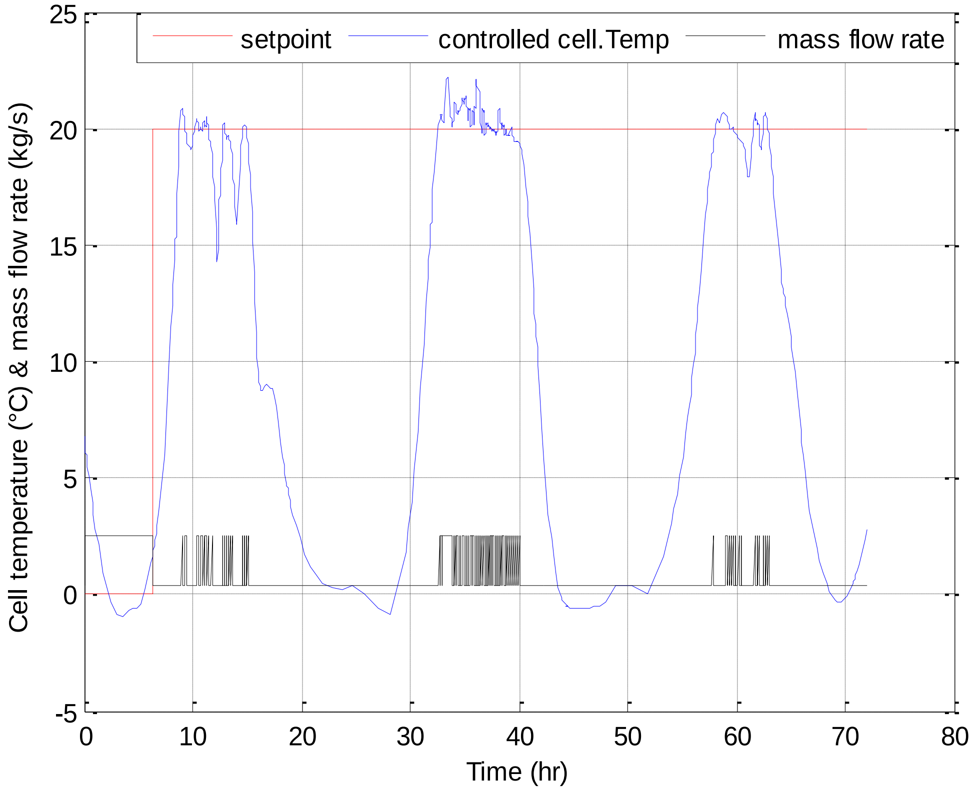


Figure 6-25: Cell temperature control, 20°C

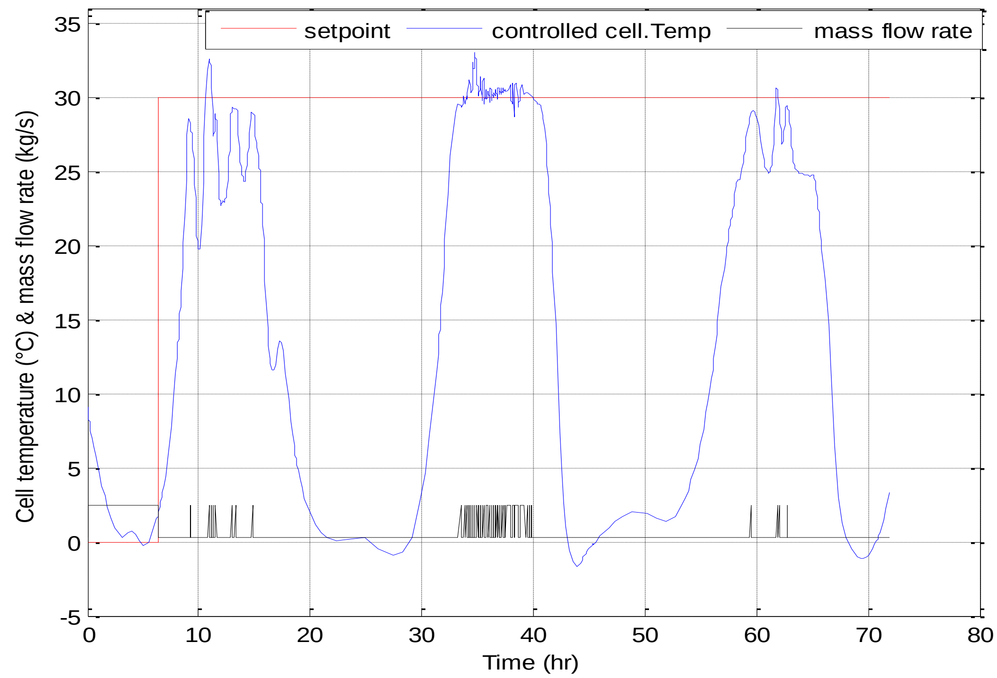


Figure 6-26: Cell temperature control, 30°C

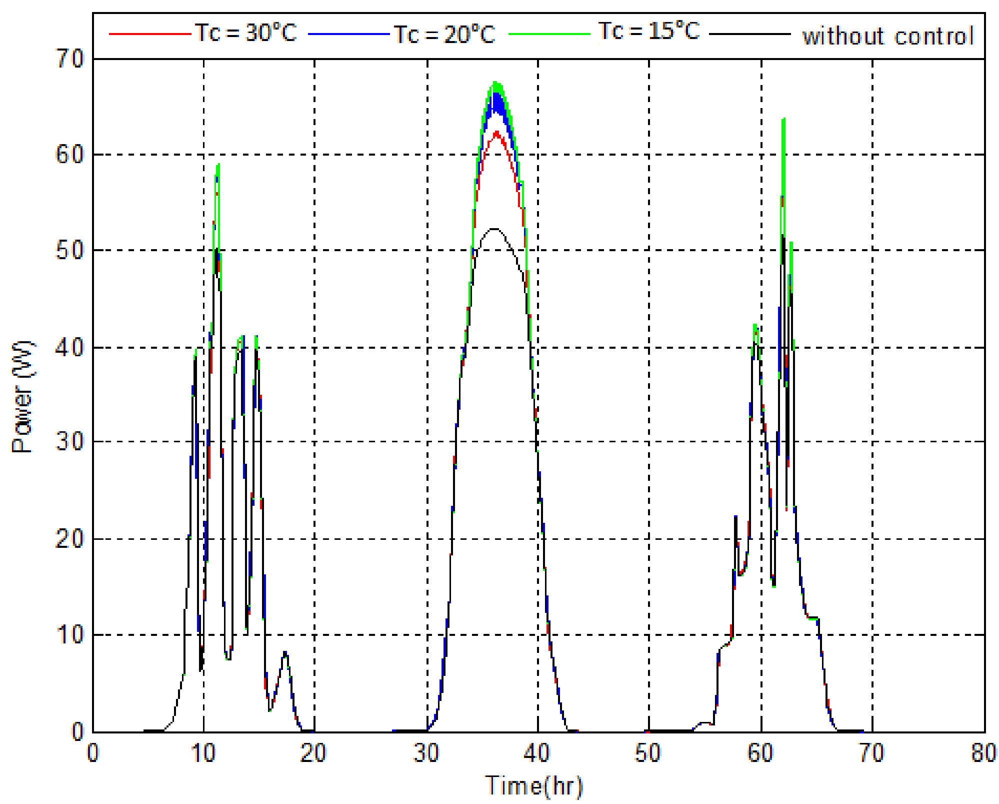


Figure 6-27: power output with control at different cell temperature

6.1.3 KFUPM Module Simulation

The same process described in Section 6.1.2 is performed using the climate conditions of Dhahran city, Saudi Arabia. The simulation using PV/T SIMULINK module has been applied using SPR-230-WHT-U Module under Dhahran weather condition in KFUPM area. The data of this area is recorded during three days. The recorded values are the solar radiation, wind speed, ambient temperature, dew point temperature and humidity as is shown in the figures below. These values are used as the required input data of this module. The cooling system module using the collected KFUPM data conditions is studied with and without cell temperature control. The maximum irradiation during the three days is around 800W/m^2, and the ambient temperature is about 45°C.

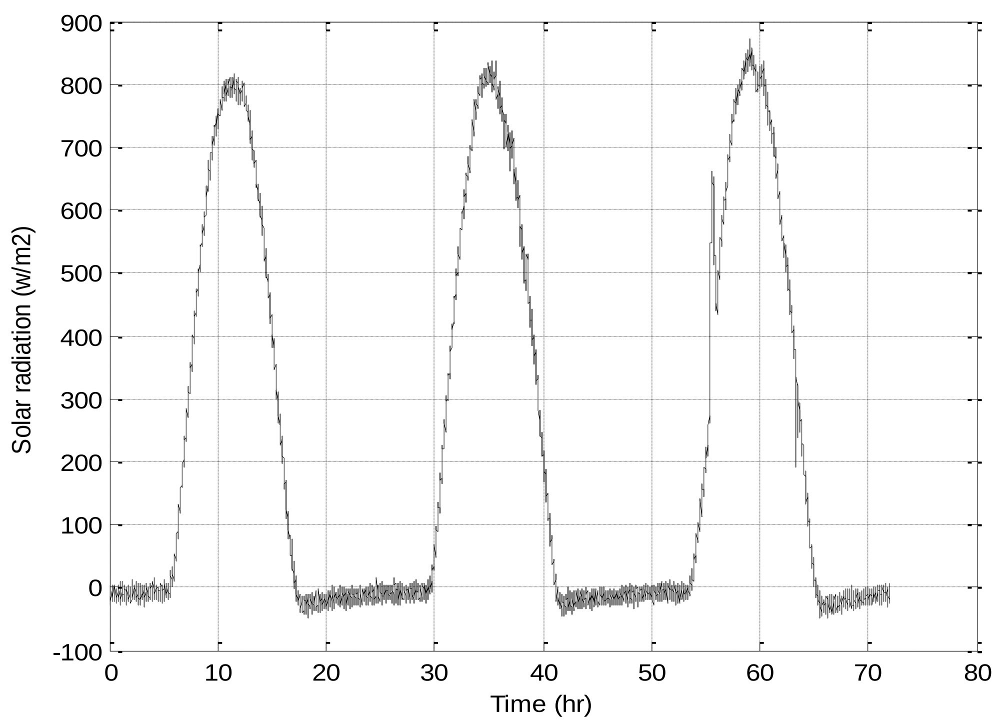


Figure 6-28: Measured solar radiation for 3 days in KFUPM area

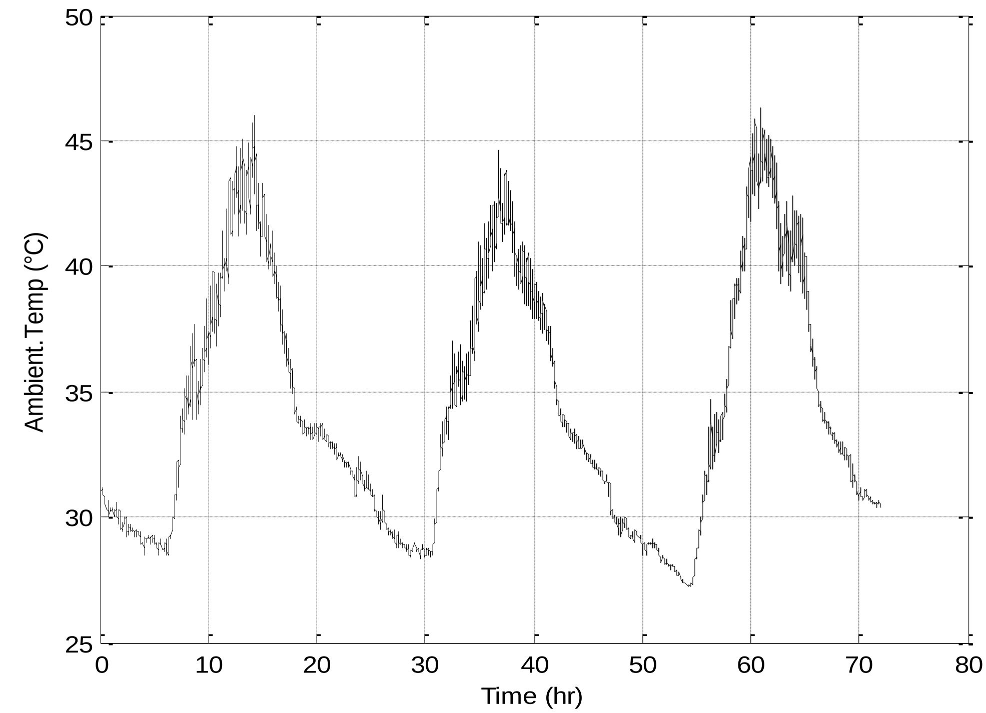


Figure 6-29: Measured ambient temperature for 3 days in KFUPM area

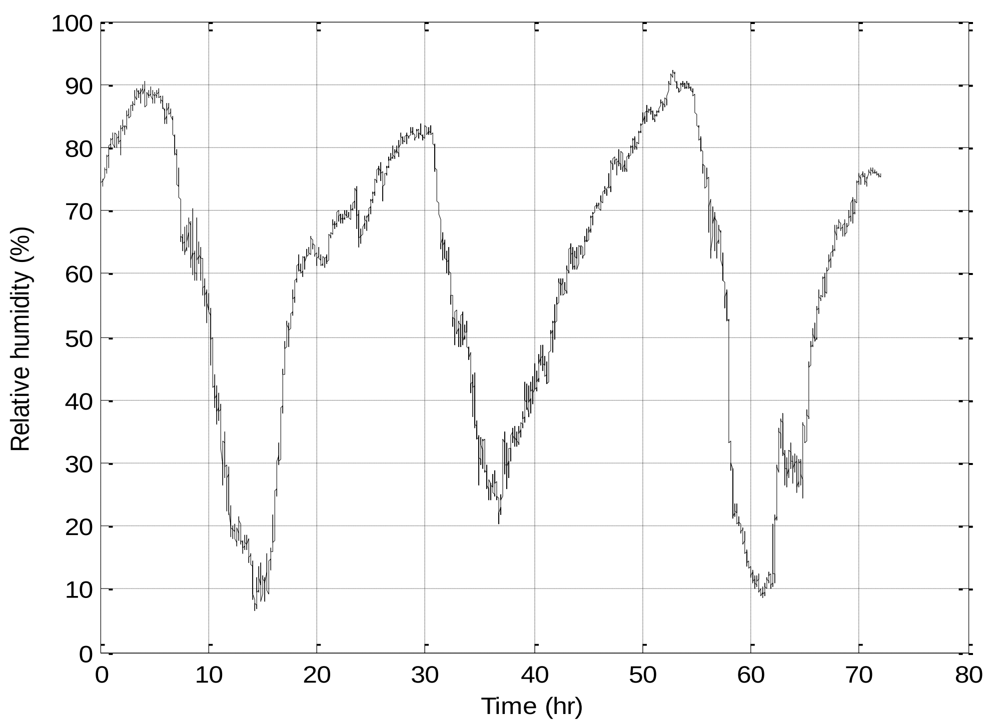


Figure 6-30: Measured relative humidity for 3 days in KFUPM area

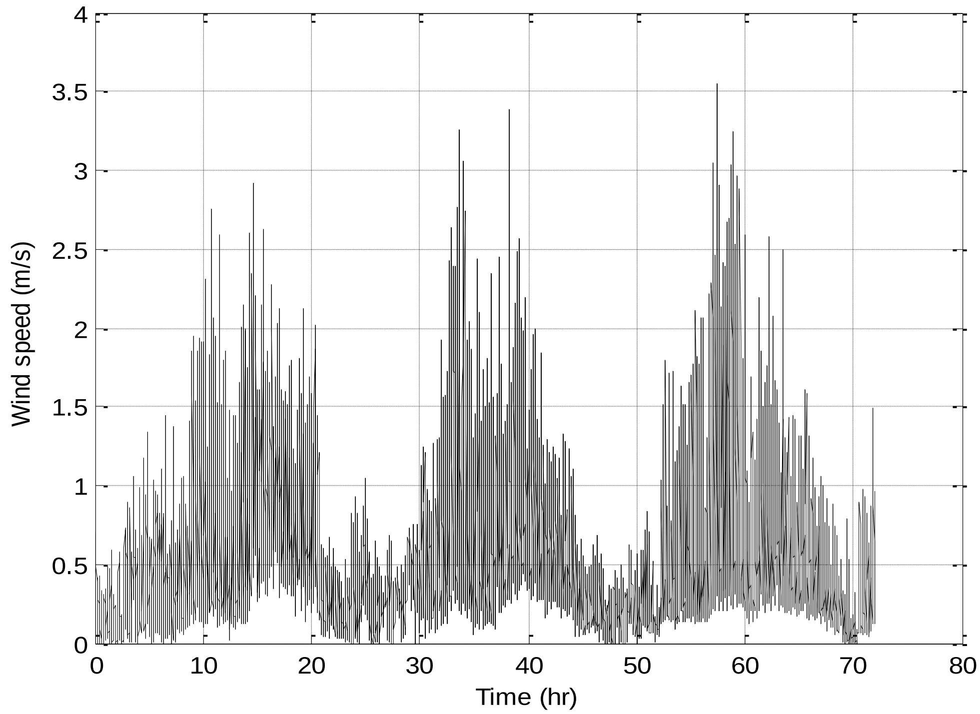


Figure 6-31: Measured wind speed for 3 days in KFUPM area

Figure **6-32** describes the measured dew point temperature, (Td) in KFUPM area. In addition, this temperature could be calculated mathematically depending on the ambient temperature and the humidity by using the following equation and the obtained result is shown in Figure **6-33**

$$T_d = \left[\left(\frac{HR}{100} \right)^{0.125} \times \left(112 + 0.9T_a \right) \right] + 0.1T_a - 112 \tag{6.2}$$

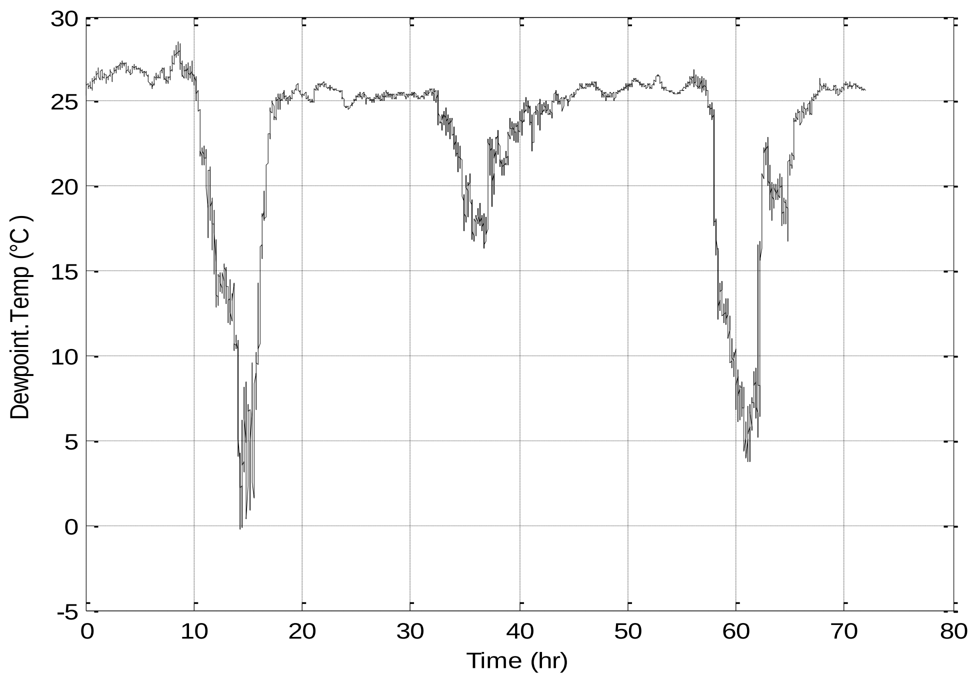


Figure 6-32: Measured dew point temperature for 3 days in KFUPM area

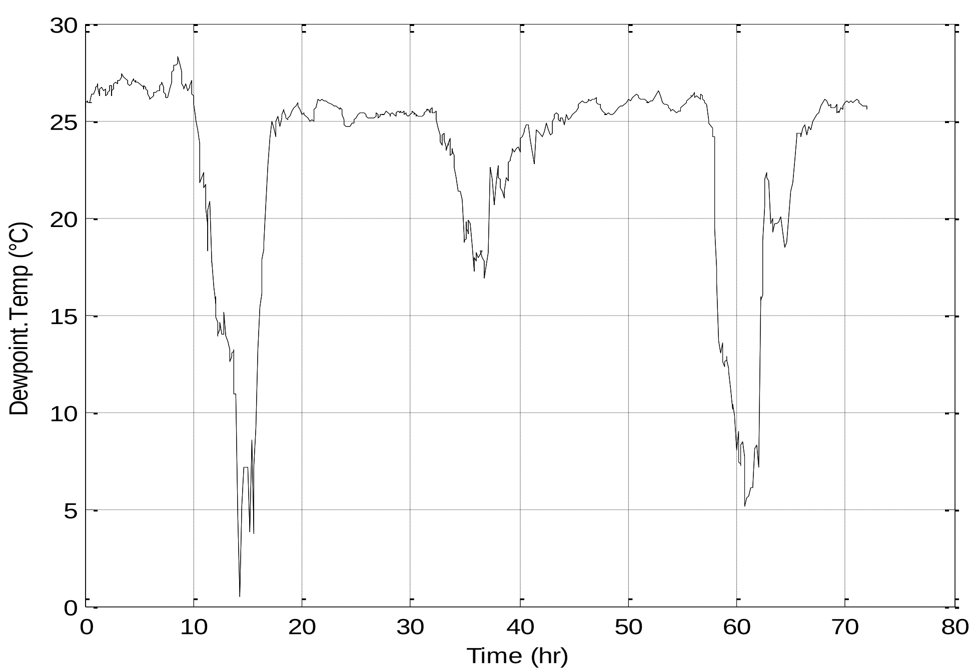


Figure 6-33: Mathematical dew point temperature for 3 days

All collected data are used in PV/T SIMULINK cooling module as a required input data. The output power mainly depends on the amount of irradiation and cell temperature that produced from thermal model. In addition, the cell temperature could be found using equation (3.15). Figure **6-34** shows the calculated temperature without cooling depending on the environmental conditions such as irradiation and ambient temperature.

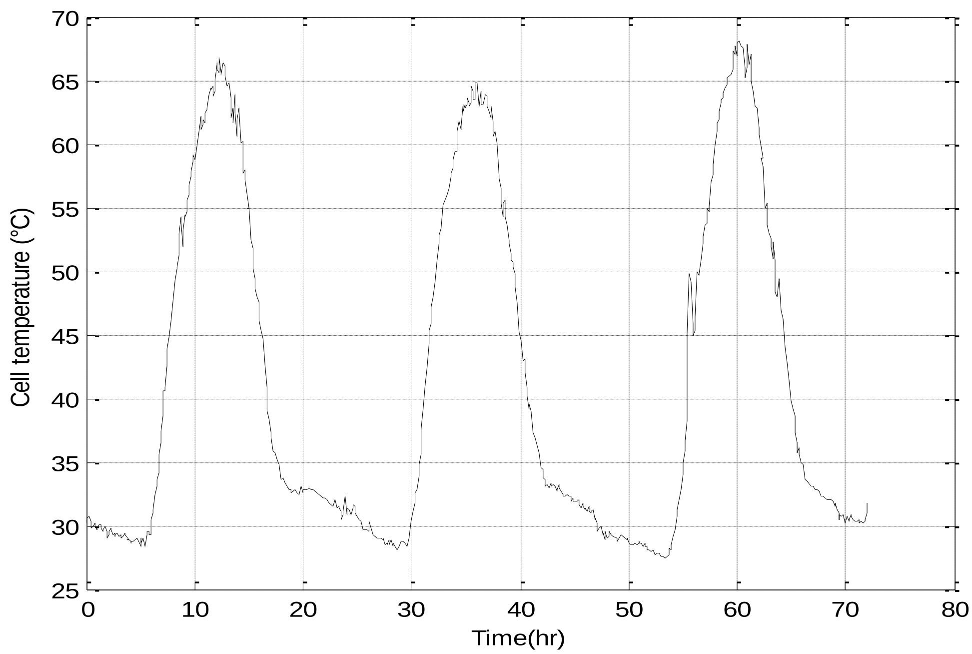


Figure 6-34: Mathematical Cell temperature

The PV cooling model with those input data is running with specific values of the flow rate. The following figure shows the cell temperature result with cooling for three days. In This figure, the value of the cell temperature is reduced to 35°C, 33°C and 34°C in the peak. This temperature is used in the electrical model to find the output power as is shown in Figure **6-36**. The output power in this figure increased after cooling compared with the output power without cooling because of the reduction of the cell temperature by the cooling.

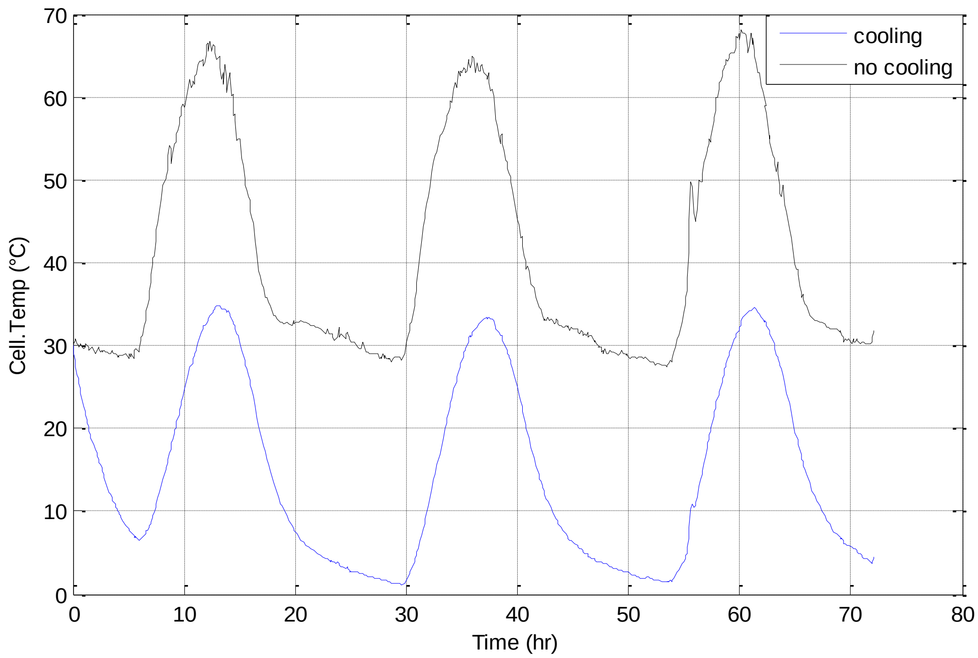


Figure 6-35: Cell temperature with and without cooling

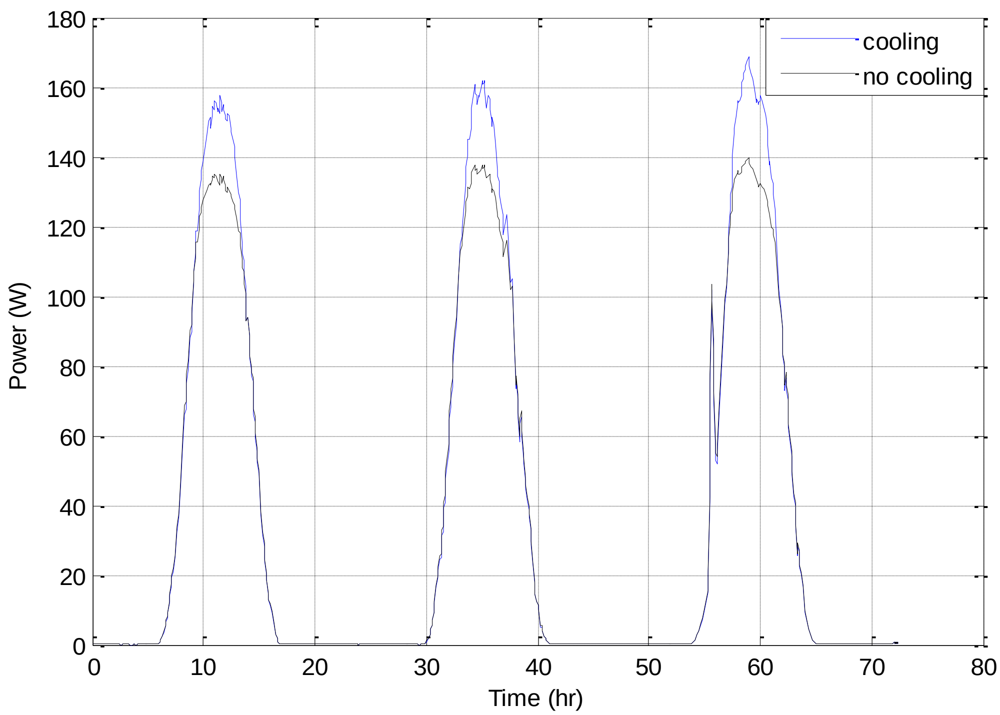


Figure 6-36: Power output with and without cooling

The same process of cooling is carried out using a PID controller depending on the environmental conditions in KFUPM. In this model, the cell temperature is controlled automatically to obtain high output performance. The following two figures describe the controlled cell temperature and the output power, respectively. The desired value of cell temperature according to the set point value assumed to be 20°C.

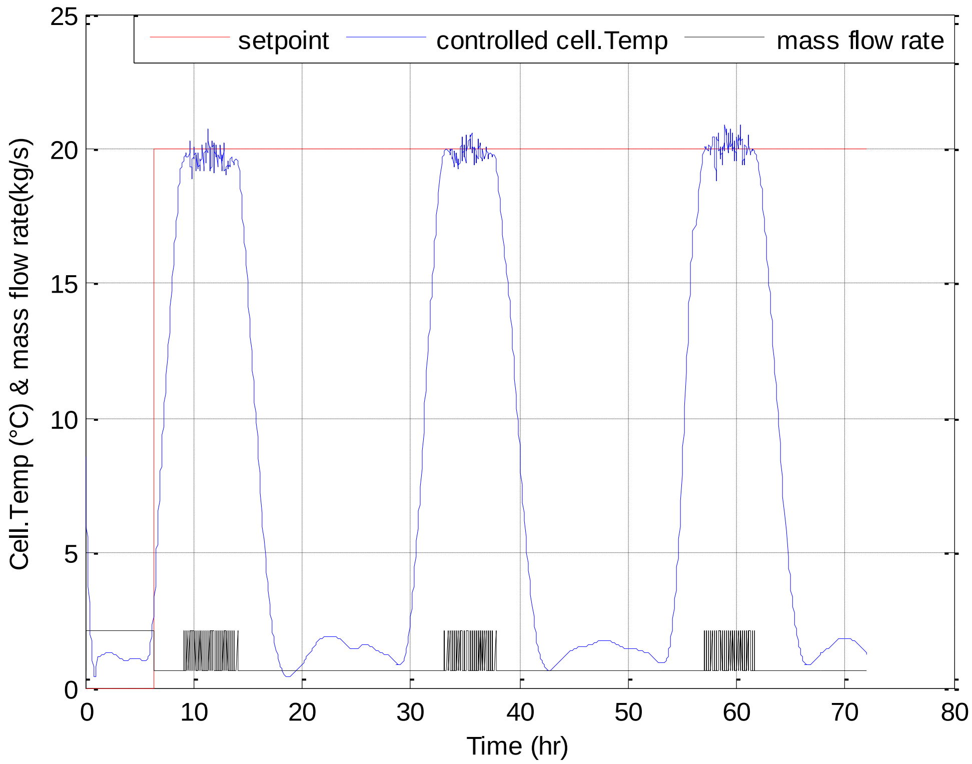


Figure 6-37: Cell temperature control and flow rate

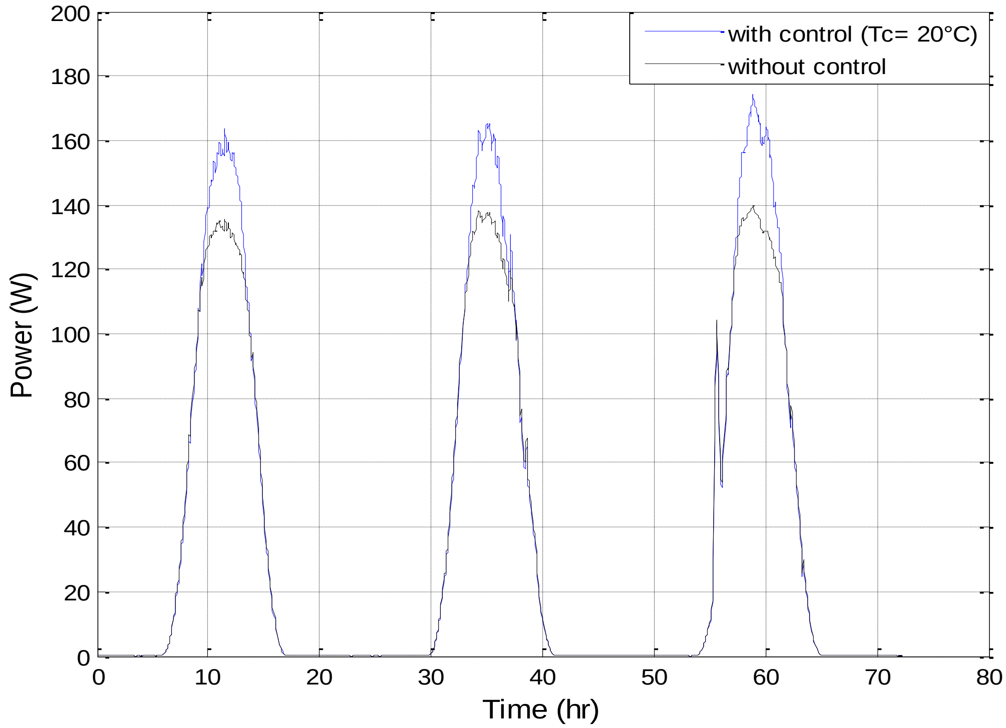


Figure 6-38: Power output control, 20°C

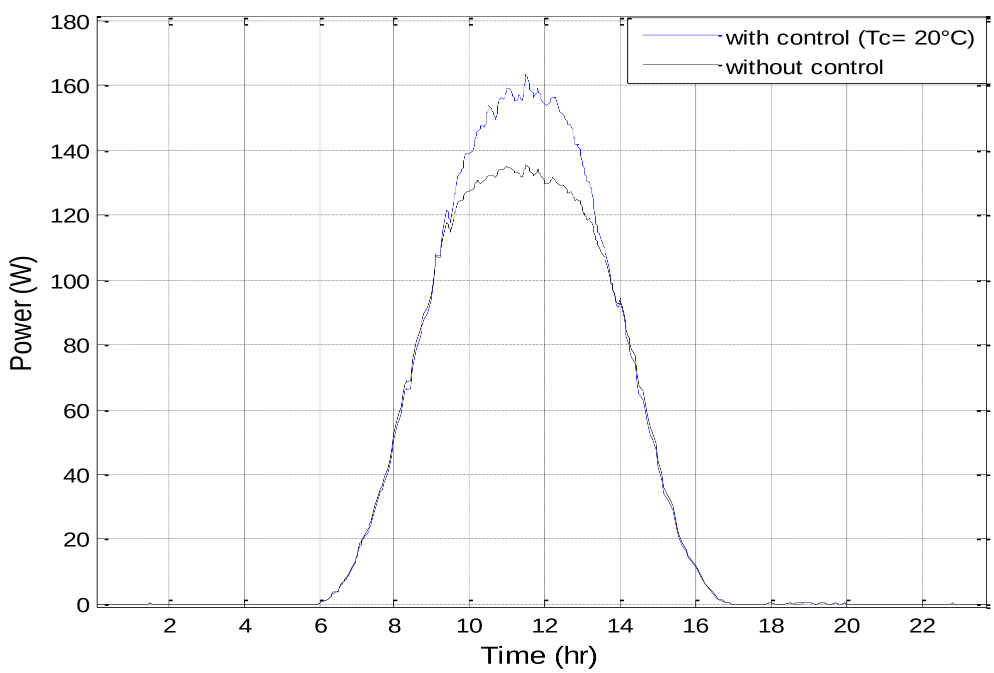


Figure 6-39: power output control in one day, 20 °C

After that, the desired value of cell temperature is changed to be 30°C as a set point. The figures below explain the simulated cell temperature control in the desired value and the output power.

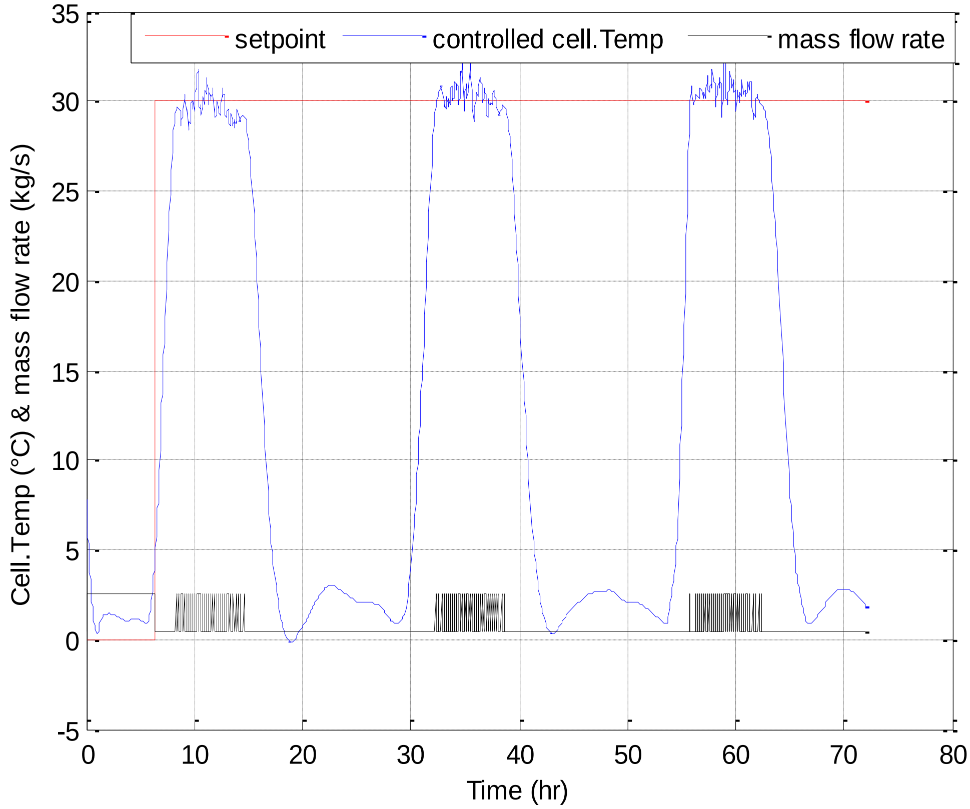


Figure 6-40: Cell temperature control, 30°C

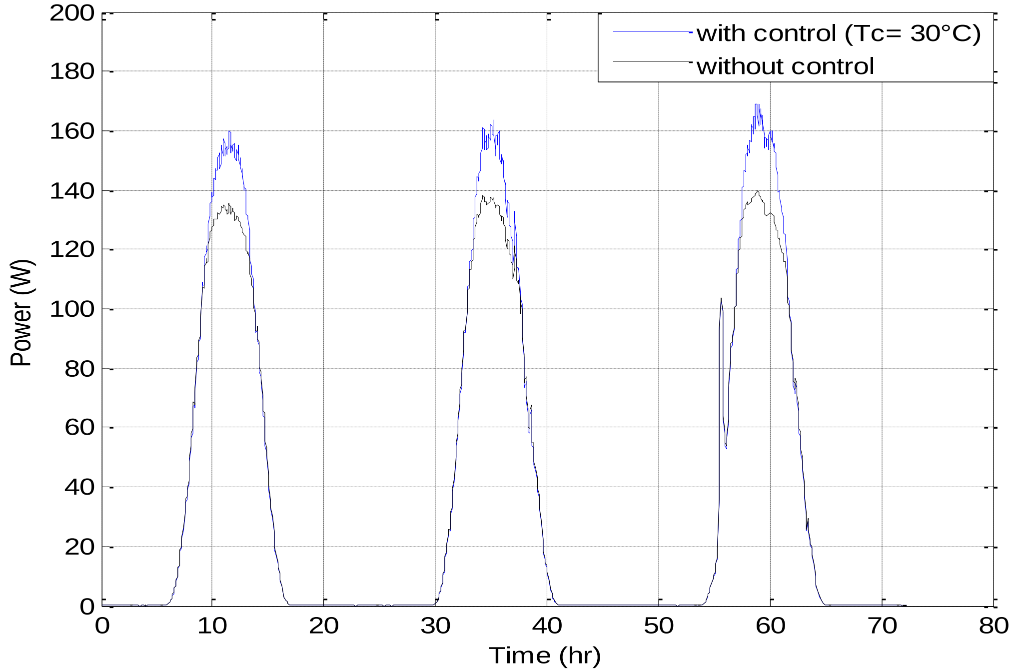


Figure 6-41: Power output with and without control at 30°C of cell temperature control

6.2 Experiment Results

This section describes the experimental results of the proposed cooling system. There are many environmental conditions influence PV performance, such as irradiation, ambient temperature, wind speed, humidity, and dust. These conditions have a direct impact on the PV resistances. The experiments carried out in KFUPM, Dhahran city during December 2014 to June, 2015 with two situations. These situations are cooling without control using manual valves and cooling with control using ON/OFF valves. The controlled cooling started in April 2015.

A voltmeter device is used to measure the open circuit voltage and the short circuit current before and after cooling and cleaning the panel. The open circuit voltage can be measured by setting the resistive load to infinity (100%) while in the case of the short circuit current; it can be measured by setting the resistive load to zero (0%). These measurements are recorded during the period (10:15 am - 10:20 am). Table **6-2** lists the recorded values.

Table 6-2 : Test of PV module performance

Case	Radiation	Voc	Isc	Time
Before cooling	815W/m2	41.5V	4.13A	10:15
After cooling	815W/m2	44.5V	5.43A	10:20

IV and PV Curve Test:

During the experimental study, the IV and PV curves are tested for the used panel. The figures below show the IV curve and the PV curve with and without cooling, respectively. The values are recorded on May 14, 2015 during the period (10:30 am - 11.00 am). The test is implemented based on the block diagram shown in Figure **5-18**. The resistive load is used to measure voltage load and current load. The value of power is calculated by multiplying both load values. This test is handled by gradually varying the resistive load manually between 15-30 steps from minimum to maximum. Two digital millimeters are used to take the measurements of the current and the voltage across the cell panel. The open circuit voltage can be measured by varying the resistive load from minimum to maximum across the cell where the current value equals zero. On the other hand, the short circuit current can be measured by varying the resistive load from maximum to minimum where the voltage equals zero. The amount of radiation is between 863 W/m^{2}and 876 W/m^2, and the ambient temperature is approximately 40°C

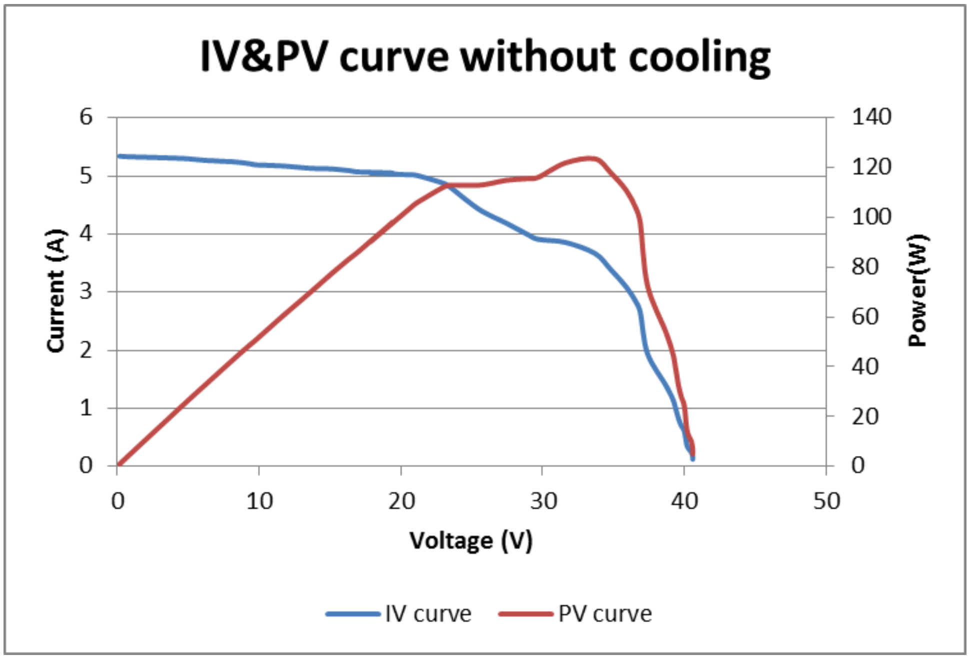


Figure 6-42: I-V & P-V curve performance without cooling

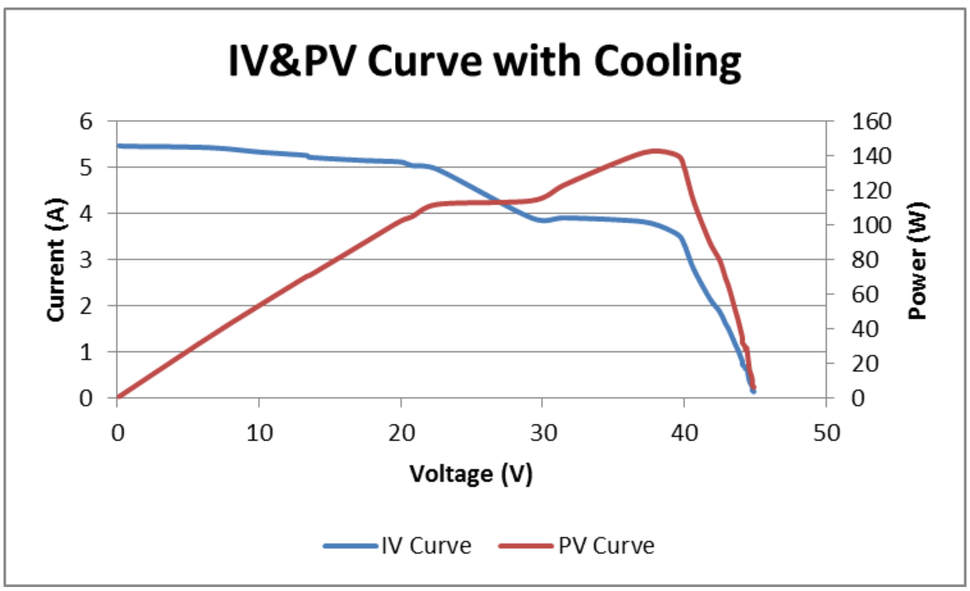


Figure 6-43: I-V & P-V curve performance with cooling

PV cooling using water:

The experiments of PV performance are implemented monthly many times to collect the required data. The radiation and the operating cell temperature are the two main required input data for PV modules' performance. The increase in the amount of radiation has a positive influence on the panel performance. However, the increase in temperature has an adverse effect. As a result, it is important to keep the panel temperature low to get good output performance. Hence, the cooling system is used to reduce high temperature in the PV panel. The output power takes the same trend of irradiance, but at different rates that would be also affected by the cell temperature.

With Manual Valve Regulator:

Many tests are carried out with and without cooling in December, 2014. The cooling over this month increases the efficiency of the PV panel by 19%. The results of one day test with cooling and another day without cooling are given in the figures below. The sky was clear and the maximum recorded peak of irradiation was around 800W/m^2, and the average temperature was 24°C for ambient and 38°C for cell panel. Figure **6-44** shows the output power without cooling. Because of the shade of the building nearby the experiment's place, the sun reaches the surface panel during this month at 10:00 AM.

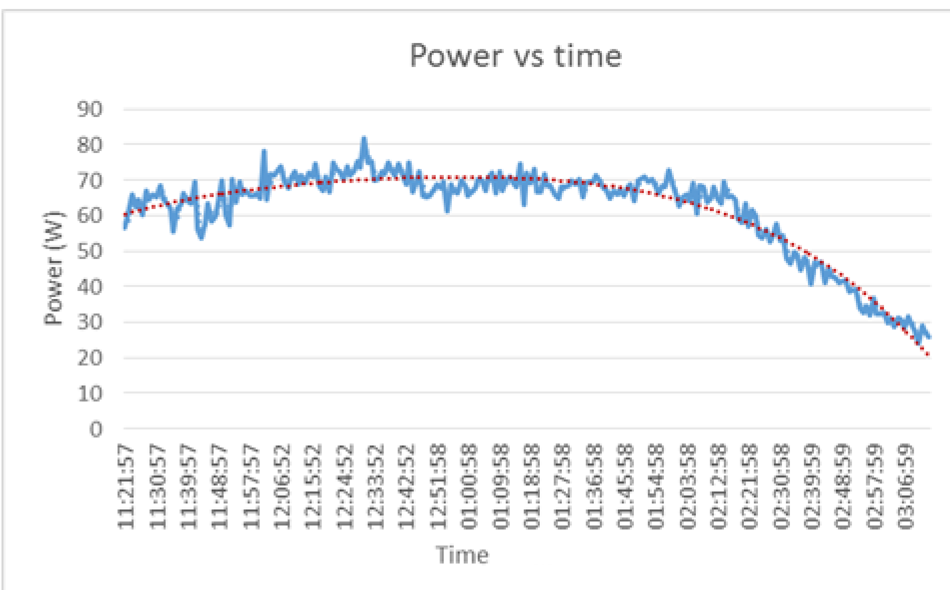


Figure 6-44: Power output without cooling

The behavior of cell temperature and ambient temperature during this experiment is shown in Figure **6-45**. It is clear from the figure that the cell operating temperature is higher than the ambient temperature.

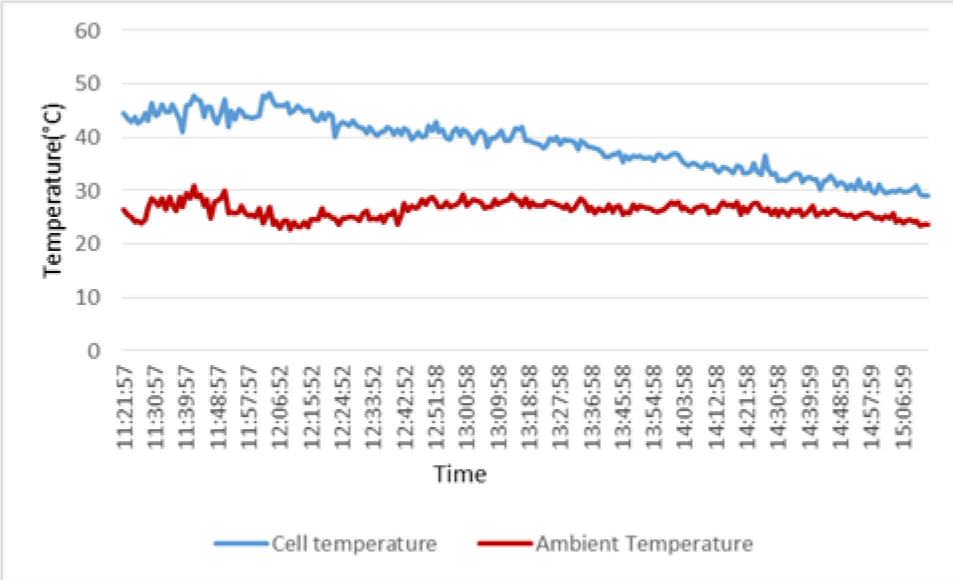


Figure 6-45: Cell and ambient temperature without cooling

The other test during this month was with cooling using manual valves. The water flow passes on surface panel during 4hr. The results are reported in the figures below

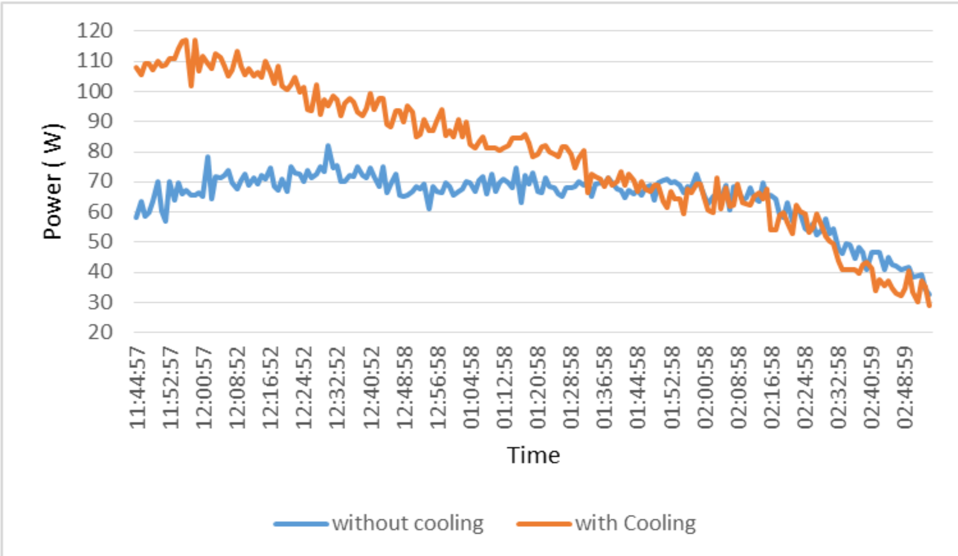


Figure 6-46: Power output with cooling

During the cooling, the cell temperature dropped to be almost like the ambient temperature

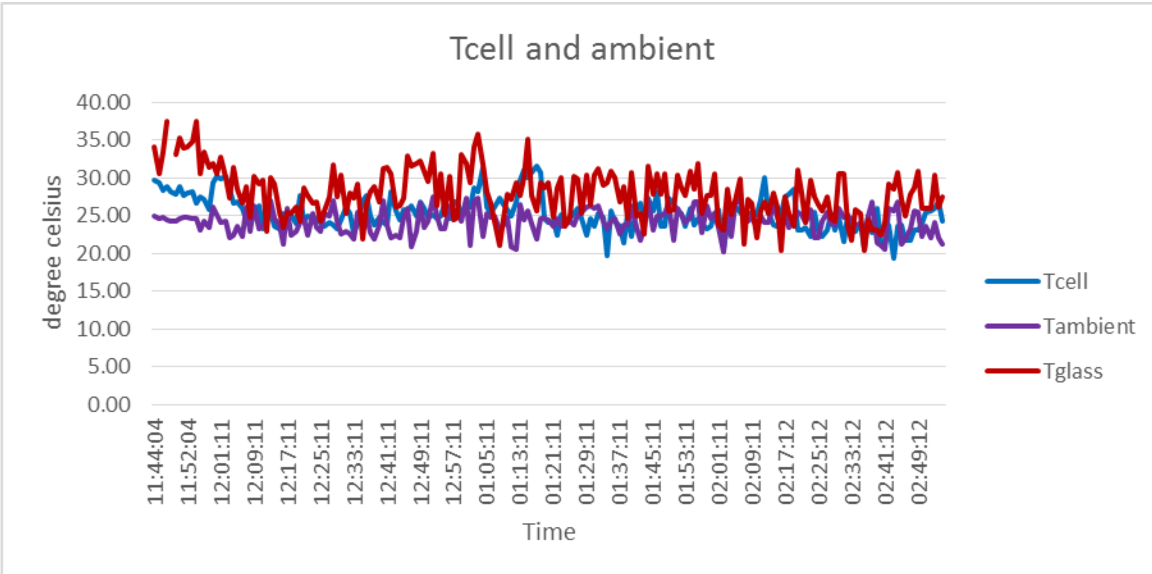


Figure 6-47: Cell, glass and water temperatures with cooling

No experiments conducted during the month of January, 2015. The experiments resumed on February 19, 2015. After such a long break, the system and parameters of PV panel such as Voc, Isc and the maximum power are checked with small test before and after clean and cooling during the period (10:00 am - 10:30). The maximum recorded power during this experiment before cooling is 171W with 41.5V of Voc and 4.13A of Isc and the radiation is 815 W/m^2. After cleaning and cooling, the maximum power increased to 240W with Voc and Isc conditions of 44.5 V and 5.43A, respectively. After that, another experiment without cooling is carried out. Figure **6-48** illustrates the output power where the maximum power is recorded around 126W with 900W/m^2 and 26°C of irradiation and the average temperature, respectively.

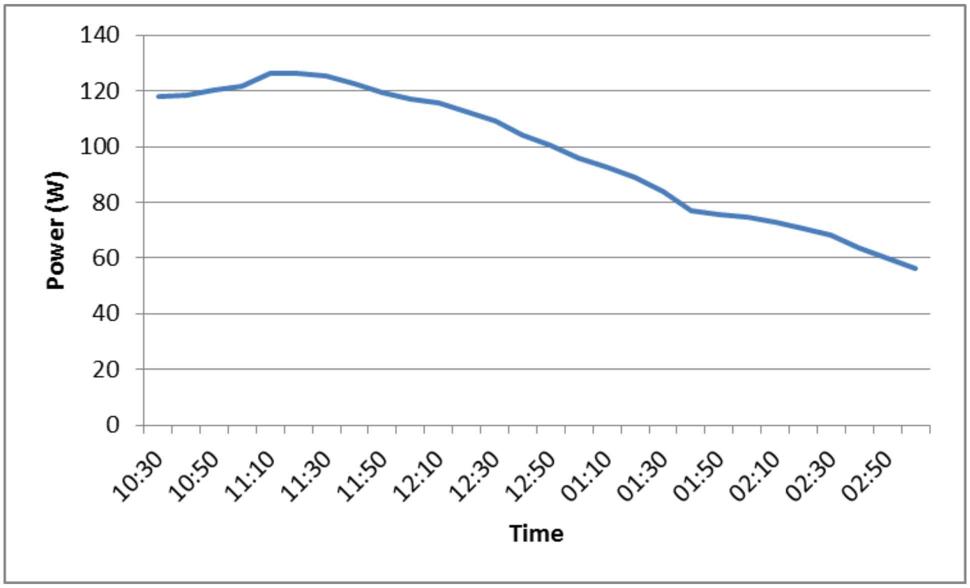


Figure 6-48: Power output without cooling in Feb.2015

Another experiment with and without cooling is handled to study the effect of cooling on the performance. When cell temperature reaches up to 50°C, the valve of water flow is turned on for approximately ten minutes. Figure **6-49** explains how the cell temperature and the voltage effect by cooling. The peak of radiation has reached near to 1000W/m^2 at 11:50AM.

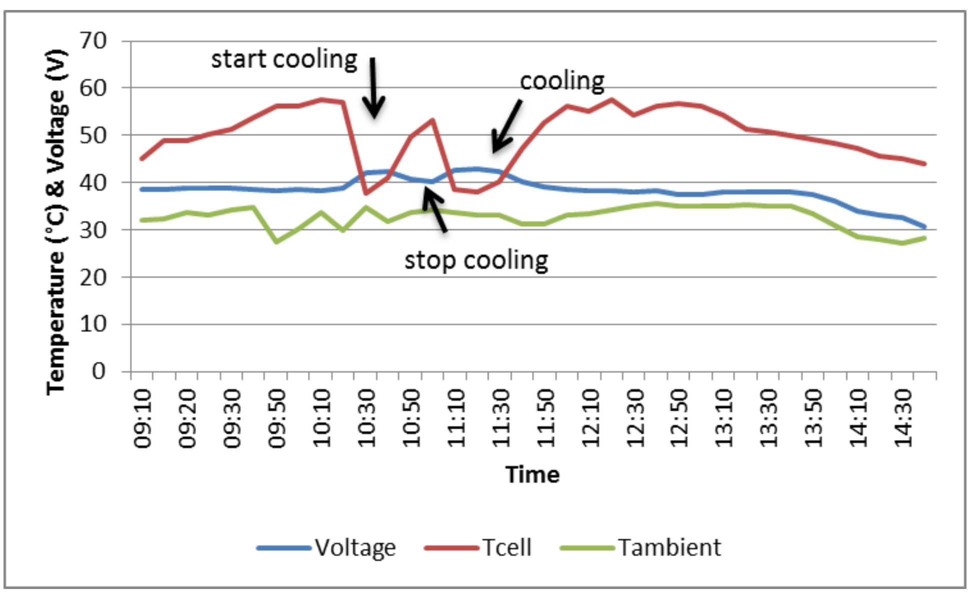


Figure 6-49: The cooling influence on the voltage and Temperature of panel in March

From the above figure, it is clear that the cell temperature is decreased to less than 40°C at the moment when the water is passing over the front surface of the panel. In addition, the voltage evolution increased at the same time of the cooling. The cooling affected the voltage and the cell temperature and that results in improving the power efficiency. Figure **6-50** shows that there is an increase in the power by 20%. This experiment indicates that the temperature influences the voltage of the PV panel and keeping it in a low level is helpful in improving the panel efficiency.

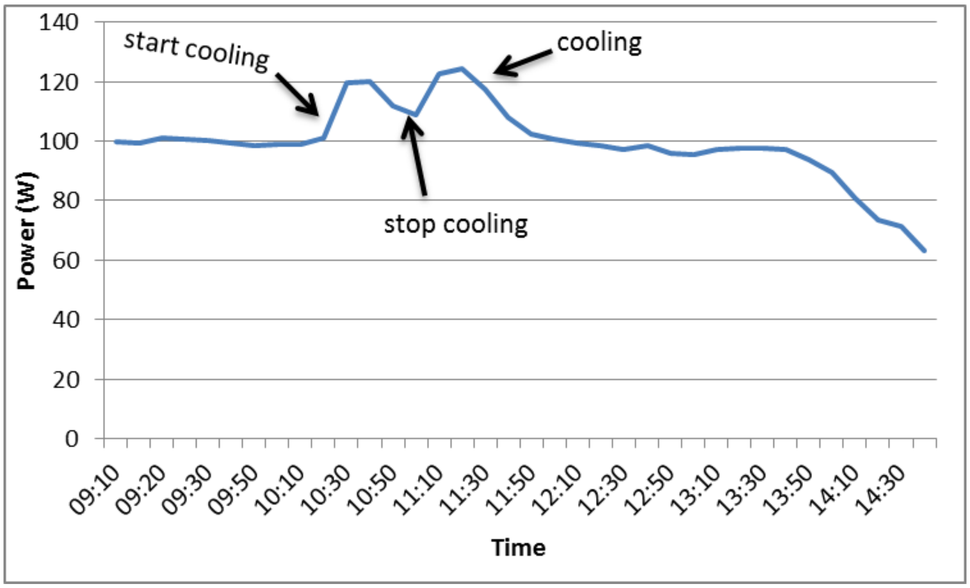


Figure 6-50: Power output with and without cooling in March

ON-OFF Valve Control:

All previous experiments are conducted using a manual valve regulator for cooling. There are different techniques used to control the cooling system automatically. The manual valve regulator is replaced by ON/OFF control valve which is controlled by using the Ardiuno code under specific conditions as explained in the flowchart in chapter 4.

During the month of April, 2015; many experiments are conducted starting from 18th to the end of this month because the weather is rainy and dusty before that. The control valves are installed and checked during this month under irradiation, panel temperature and efficiency. Many experiments without cooling before and after cleaning and with cooling using controller valves are conducted. The results are shown in the figures below. On April 24, 2015 an experiment started by measuring the electrical performance through measuring the voltage and the current and as well as determining the output power as is shown in Figure **6-51**. After one hour the thermocouples are connected for temperature measurement, see Figure **6-52**.

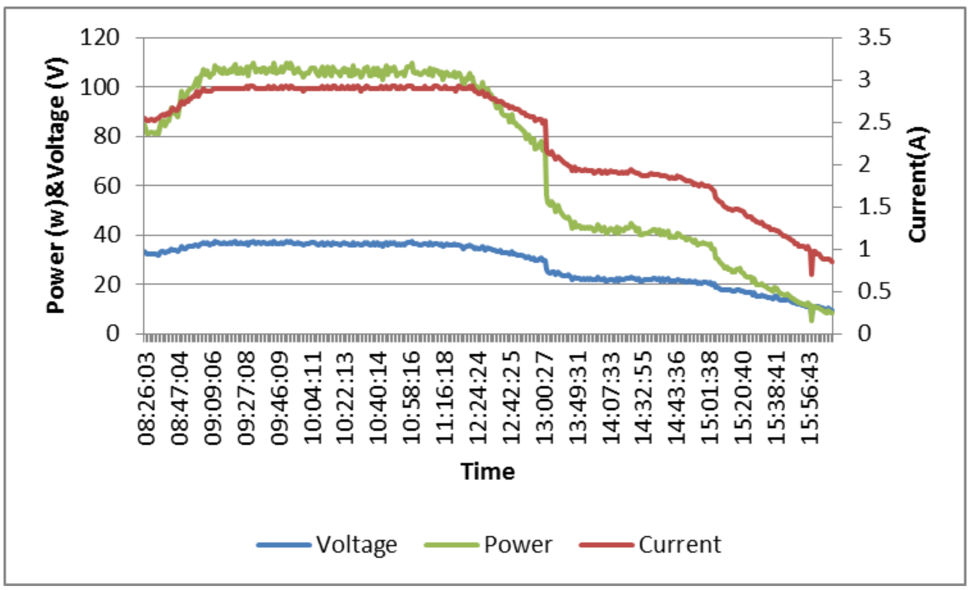


Figure 6-51: Output measurement for voltage, current and power on April 24

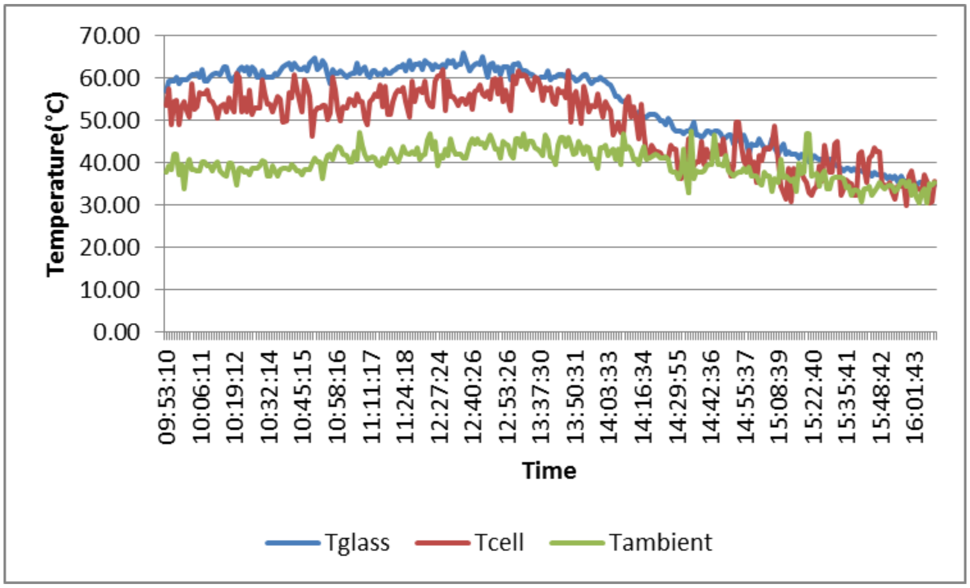


Figure 6-52: Cell, glass and ambient temperatures on April 24

In the next day, an experiment is conducted without cooling and with dust. The results of this experiment are shown in figures below. Figure **6-53** presents the output power that results from multiplying the current by the voltage as shown in the same figure.

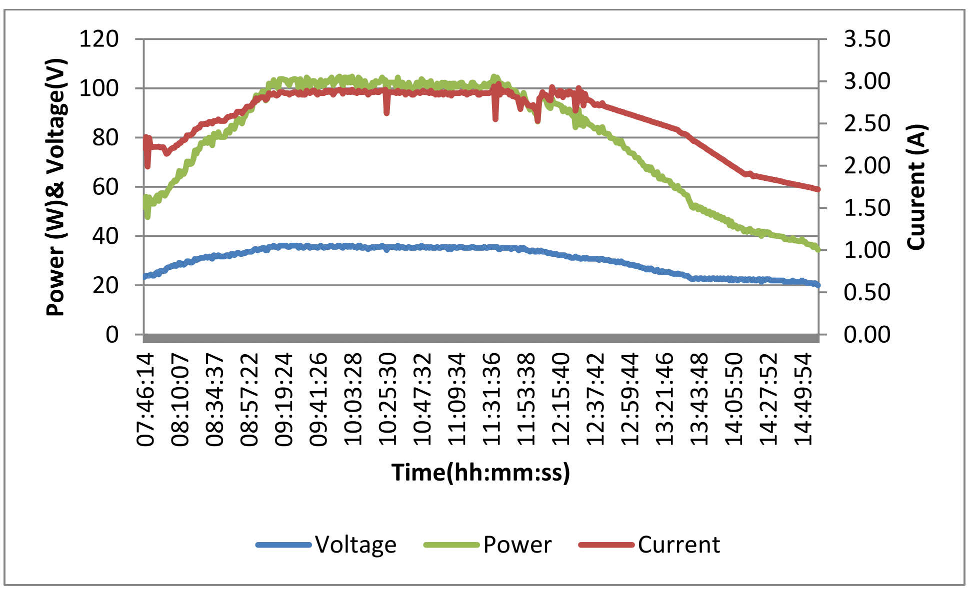


Figure 6-53: Output measurement for voltage, current and power on April 25

Figure **6-54** demonstrates the operating cell temperature, the glass temperature and the ambient temperature during this experiment.

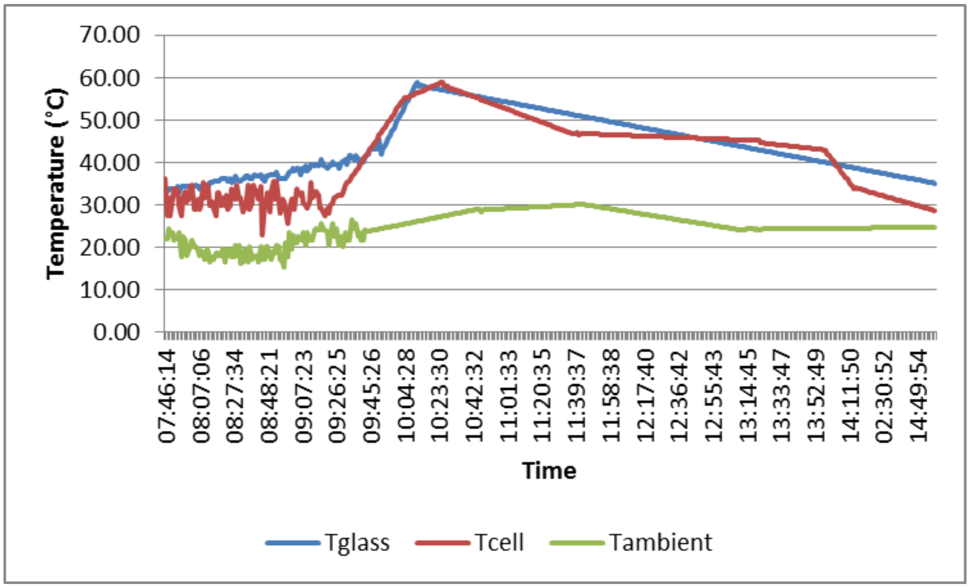


Figure 6-54: Temperature behavior for glass, cell and ambient on April 25

After that, the PV panel is cleaned and the reading is taken again on April, 26. In this experiment, the output power is increased when compared to without cleaning as shown below. The output efficiency is increased by 18%. Then, the experiment continues to collect data with cooling until the end of the month.

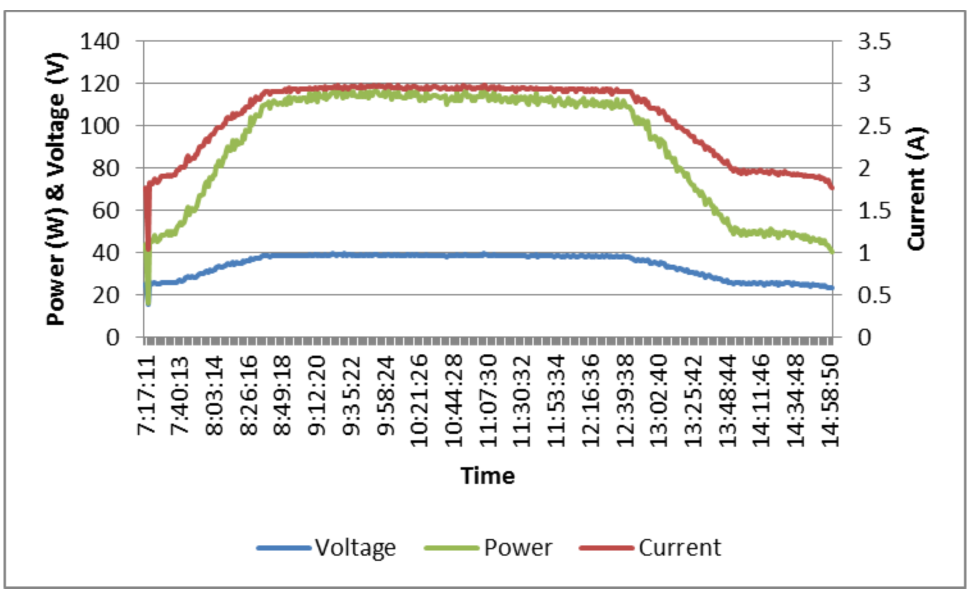


Figure 6-55: Output measurement of voltage, current and power after cleaned on April 26

Figure **6-56** describes the three types of temperature, glass surface temperature, cell temperature and ambient temperature. As noted in this figure the cell temperature is higher than the glass temperature and it is 55°C at around 11:00AM.

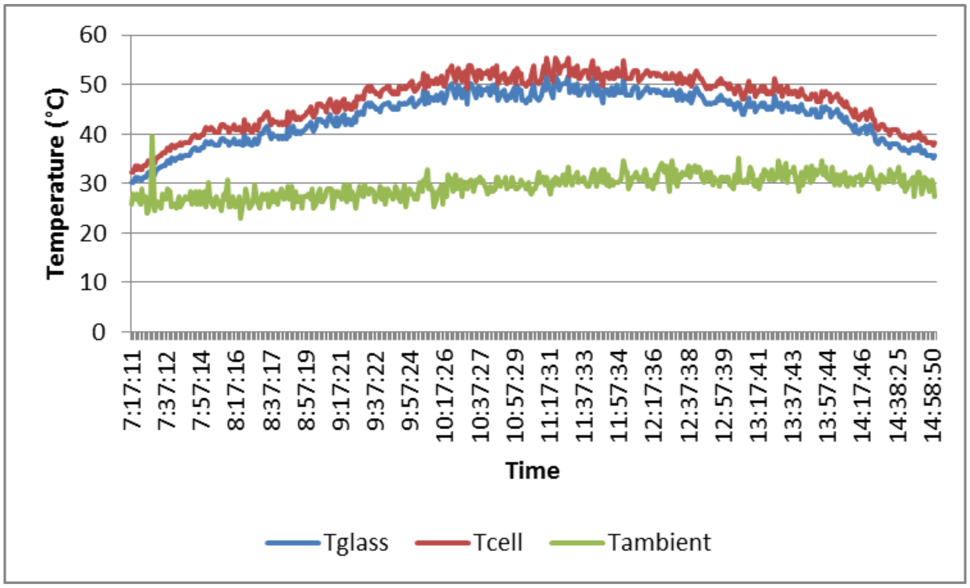


Figure 6-56: Temperature behavior for glass, cell and ambient on April 26

On the next day, an experiment is conducted with cooling using control valves for a half day while the other half is without cooling. This experiment aims to show how the efficiency will be affected with cooling using control valves comparing to that without cooling. The figure below explains the effect of cooling on the output results of the power, the voltage and the current for the first half work day. The first half is higher than the second half because of the cooling effect in the first half.

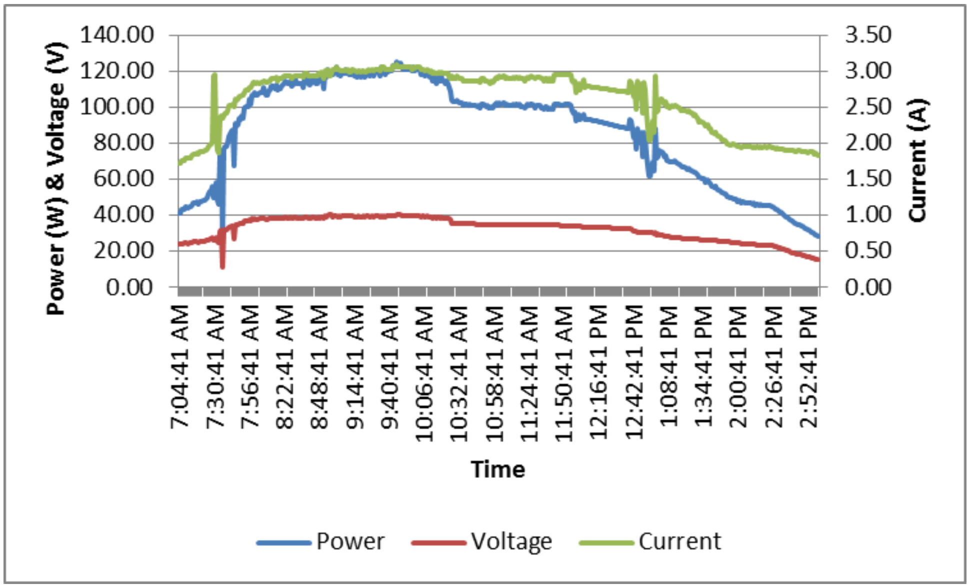


Figure 6-57: Output of voltage, current and power for half work day cooling on April 27

The temperature across the panel is decreased during the cooling period while it is increased when the cooling is stopped. Figure **6-58** describes the form of glass and cell temperature with cooling for half sunny day and the other half without cooling. Because the sun becomes behind the panel after noon, noticeable reduction in the curves are appeared.

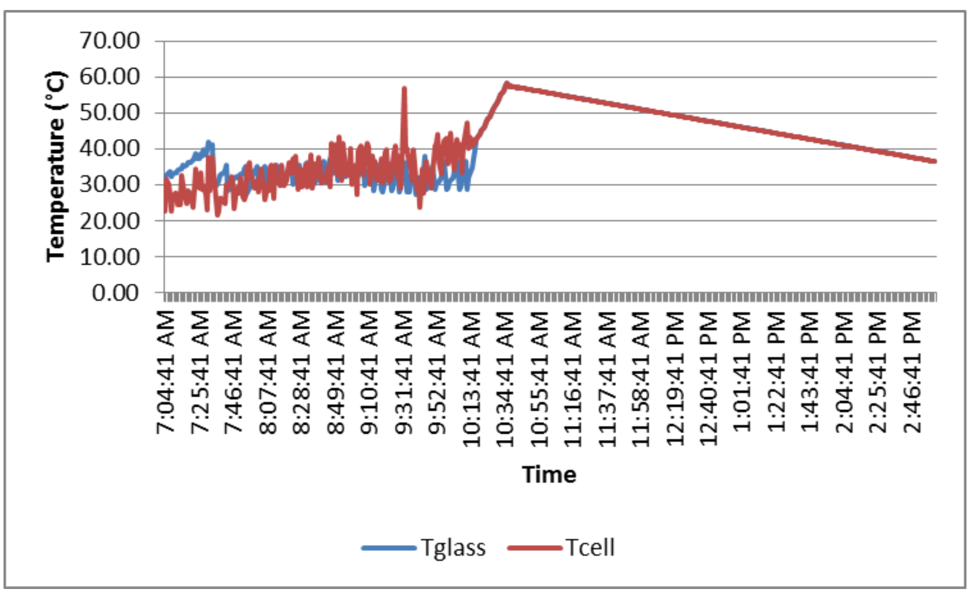


Figure 6-58: Temperature behavior for glass, cell on April 27

Assuming the continuation of cooling in Figure **6-57** for one day, the power output could be as in the figure below.

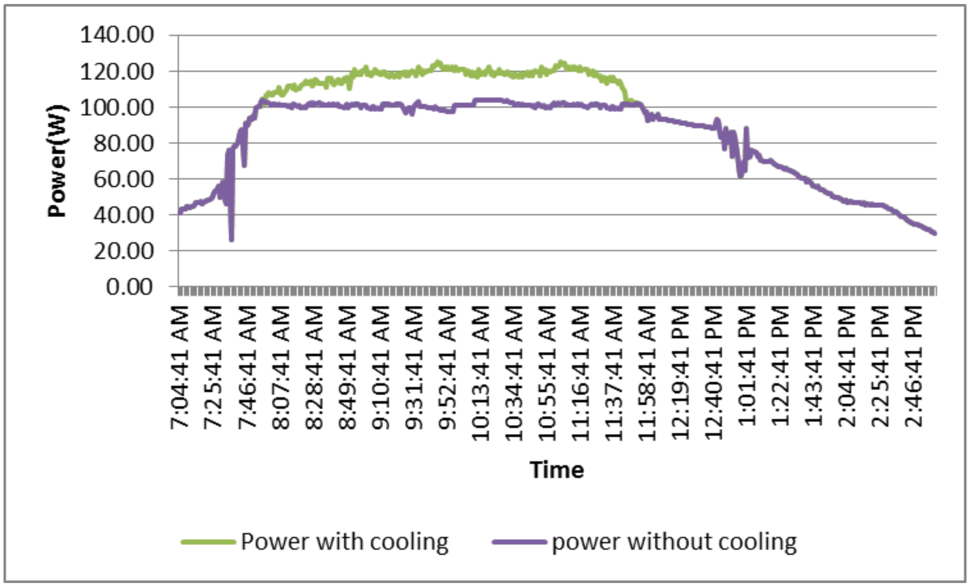


Figure 6-59: The assumed power output with and without cooling

From the above figure, there is a clear increase noted in the output power with water cooling. In this case, the percentage of the observed increase is about 20% compared to the output power without cooling.

In the last three days of April, different experiments are conducted with cooling by using three control valves that work in specific conditions such as irradiation, efficiency and cell temperature as explained in flowchart in Chapter three. The control valves during this experiment is turned on and off based on the temperature conditions shown in flowchart. The figures below summarized the results.

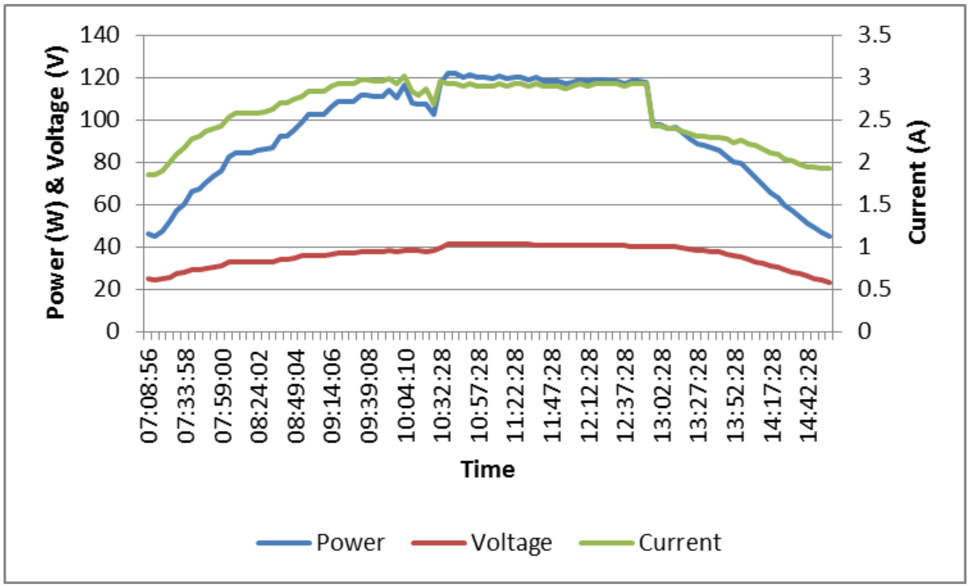


Figure 6-60: Output of voltage, current and power with cooling control on April 30

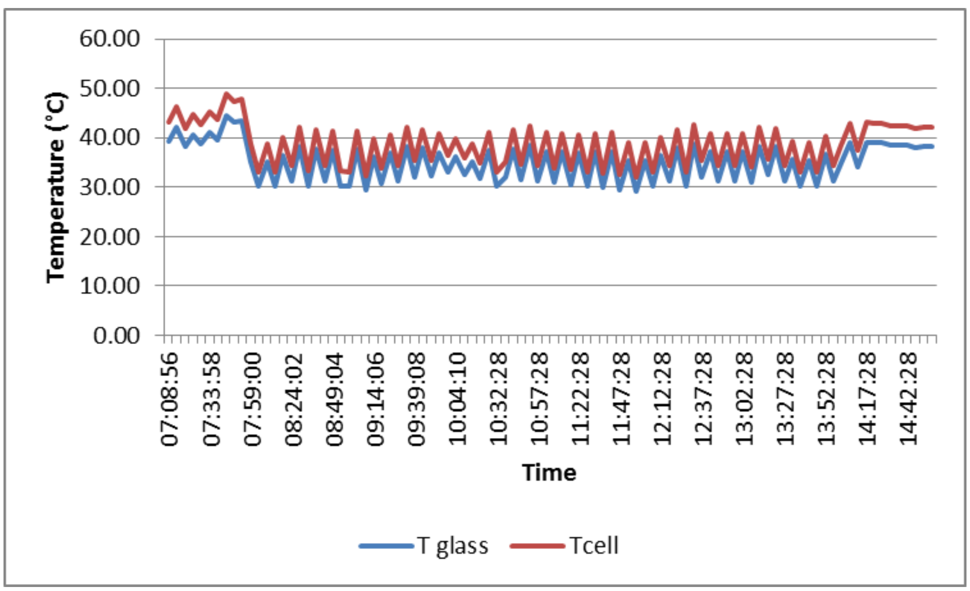


Figure 6-61: Output temperatures for cell and glass with cooling on April 30

As shown in the figure above, the maximum power value is achieved during (10:37 am - 12:52 pm) because of the good irradiation. Meanwhile, the controller system decreases the temperature of the PV panel when it reaches a specific value in order to get the best efficiency.

In May, 2015 where the temperature increases during summer days, different experimental results are recorded for six days, viz. May 6, 10, 18, 19, 22, and 27. These experiments are carried out with and without cooling. The average power efficiency is 19%. As a sample, Figure **6-62** shows the results of the experiment conducted on May 18. It shows the output power, voltage and current without cooling.

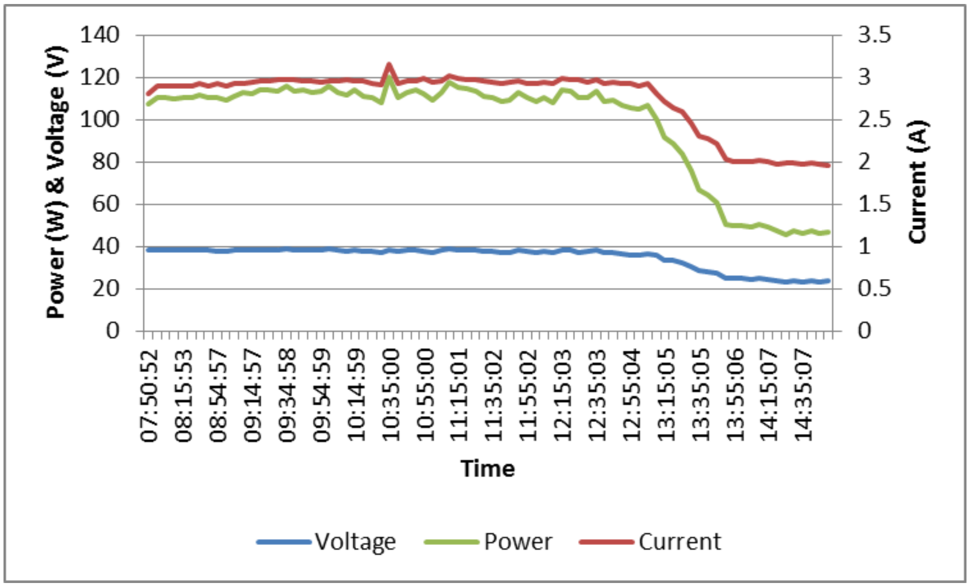


Figure 6-62: Output result of voltage, current and power without cooling on May 18

The behavior of the temperature for the front and the back panel are shown in the figure below

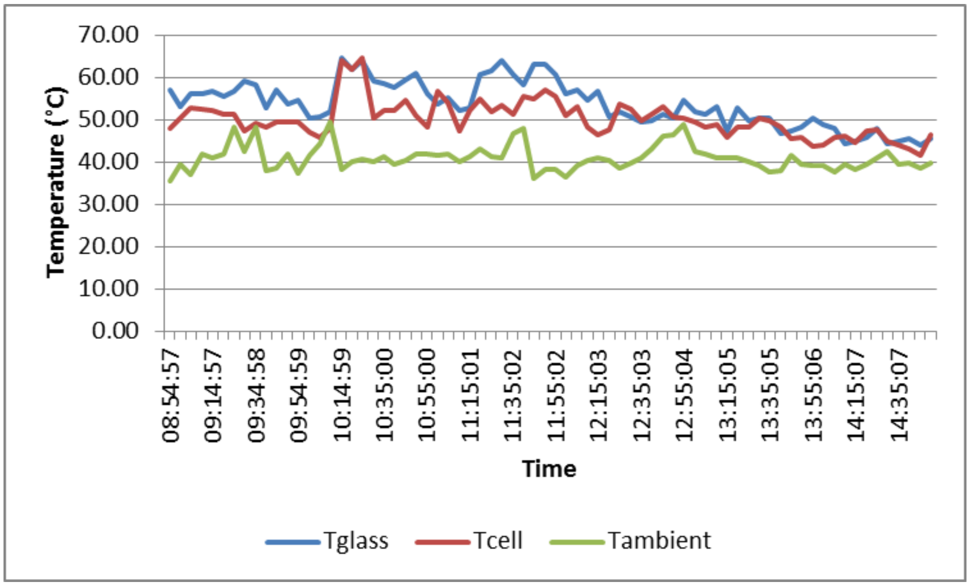


Figure 6-63: Temperature of cell, glass and ambient without cooling on May 18

Later on, an experiment with the water cooling control is conducted. Figure **6-64** and Figure **6-65** explain the output results with and without cooling on May 22 and 27, respectively. The amount of increase in the output compared to the result without cooling is about 20%. In these figures, the cooling started experimentally at 9:30 AM and continued for two hours.

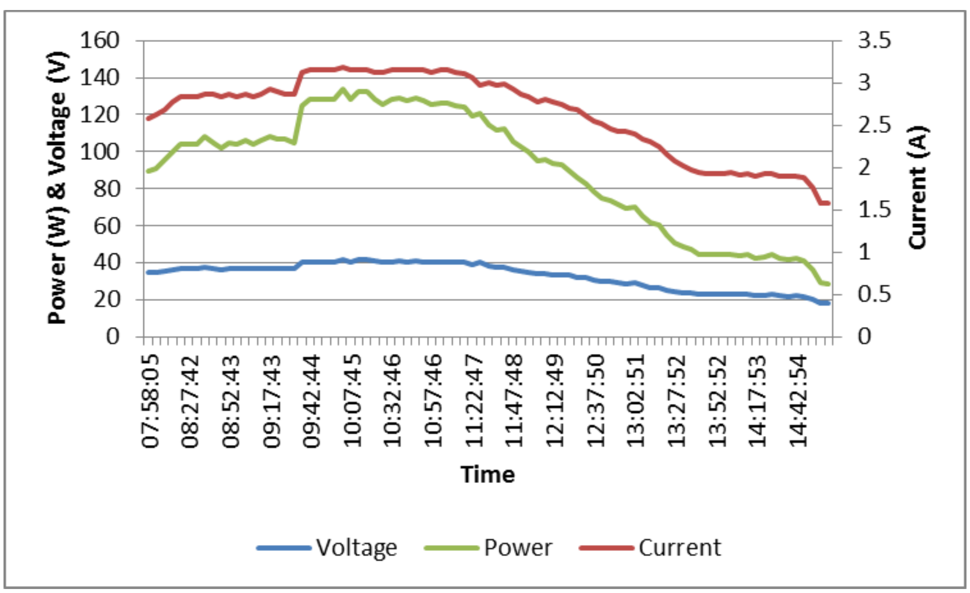


Figure 6-64: Output results of panel with and without cooling on May 22, 2015

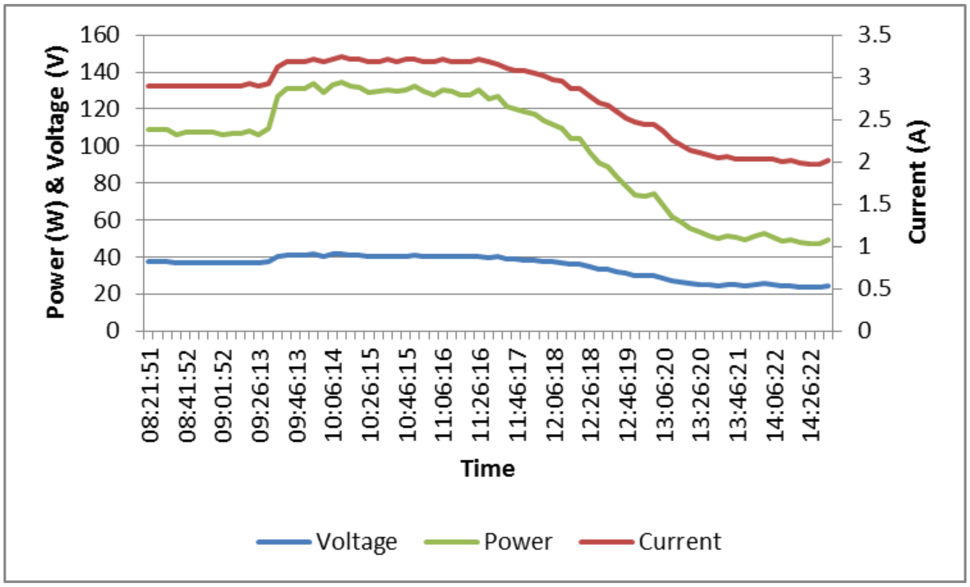


Figure 6-65: Output result of panel with and without cooling on May 27, 2015

The form of glass and cell temperatures for these two days is shown in the following figures.

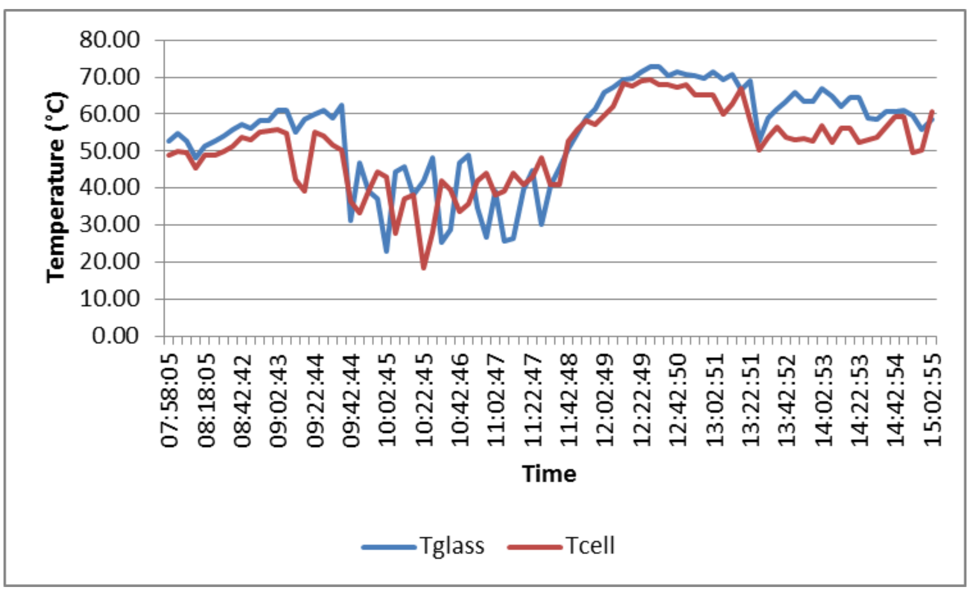


Figure 6-66: Temperature of panel with and without cooling on May 22, 2015

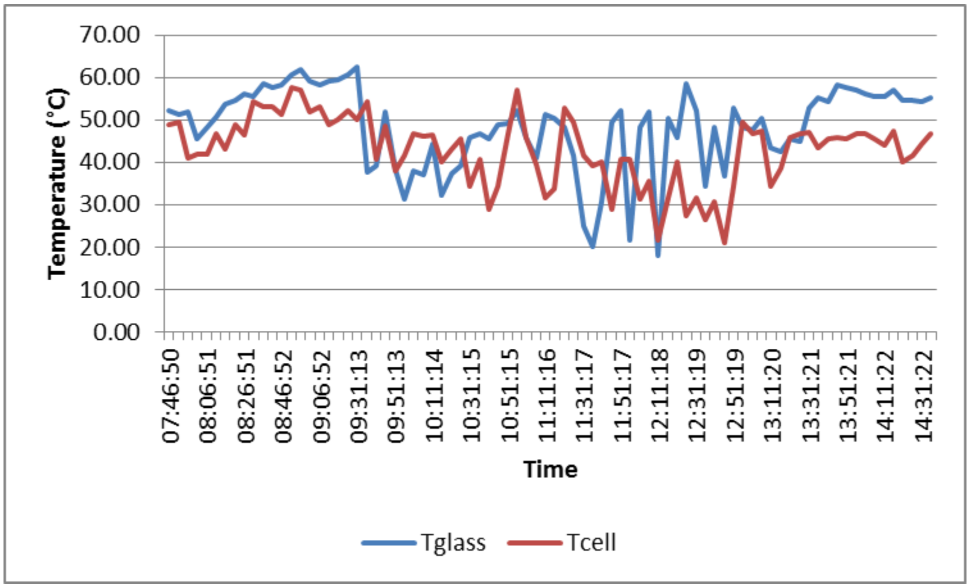


Figure 6-67: Temperatures of panel with and without cooling on May 27, 2015

During the month of June, the experiment is conducted with five tests. The weather was very hot and sometimes humid. The temperature reached during the day up to 45°C in peak hour and the irradiation is around 900W/m^2. Under these conditions of temperature and irradiation the data is collected. The maximum recorded power without cooling is about 110 W. The readings of experiment are taken in two parts in two days. The first part is without cooling in early morning until 9:30 AM, while the second part is with cooling. The results of the electrical performance and the temperature of the panel are shown in the following figures. The maximum power with cooling is about 133 W which is less than 110 W of the experiment without cooling.

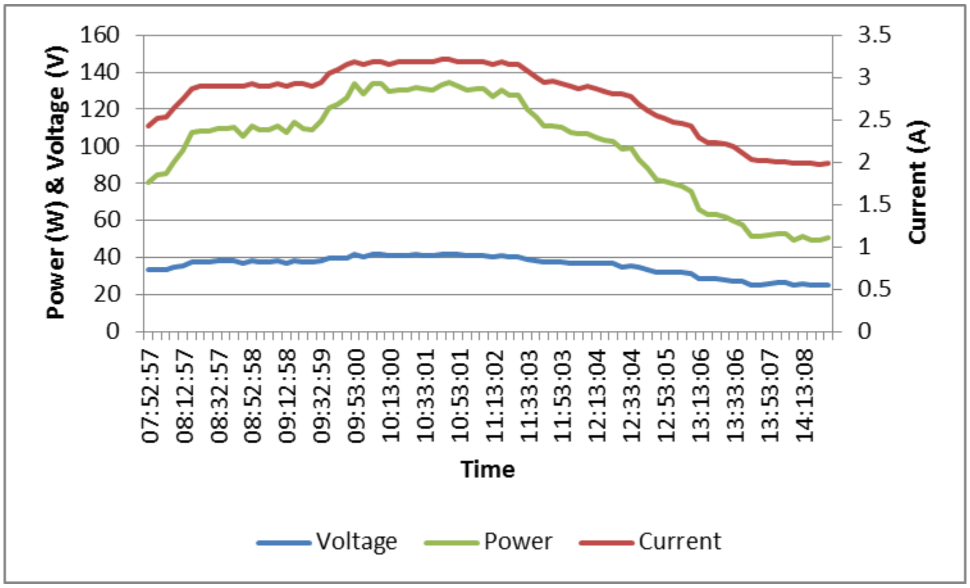


Figure 6-68: Output result of panel with and without cooling for one day in June, 2015

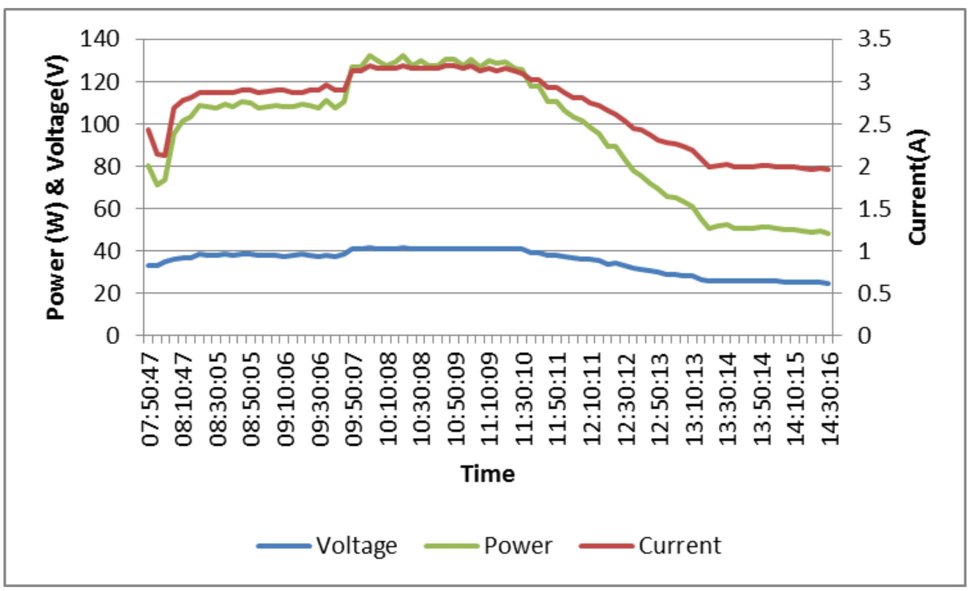


Figure 6-69: Output result of panel with and without cooling for next day in June, 2015

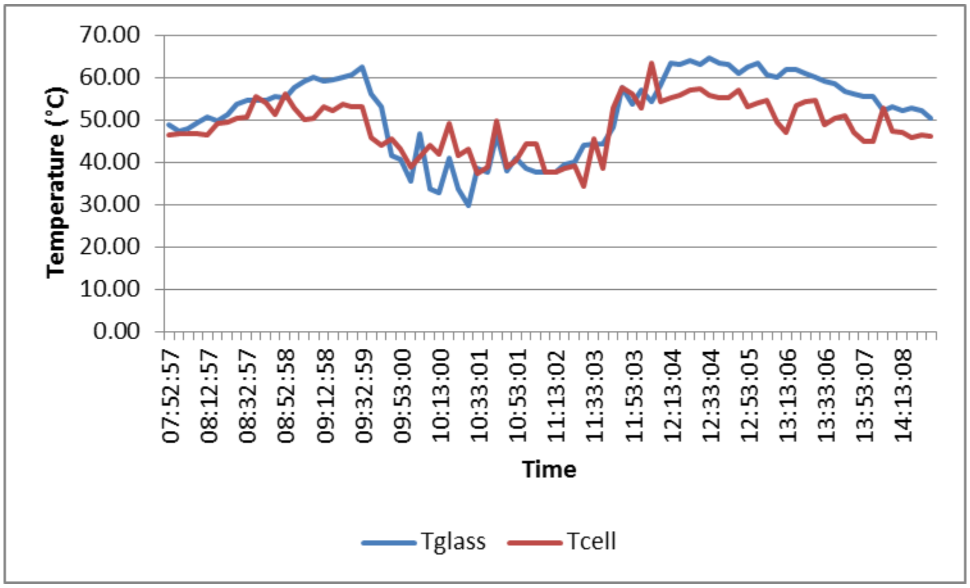


Figure 6-70: Temperature of panel with and without cooling for one day in June, 2015

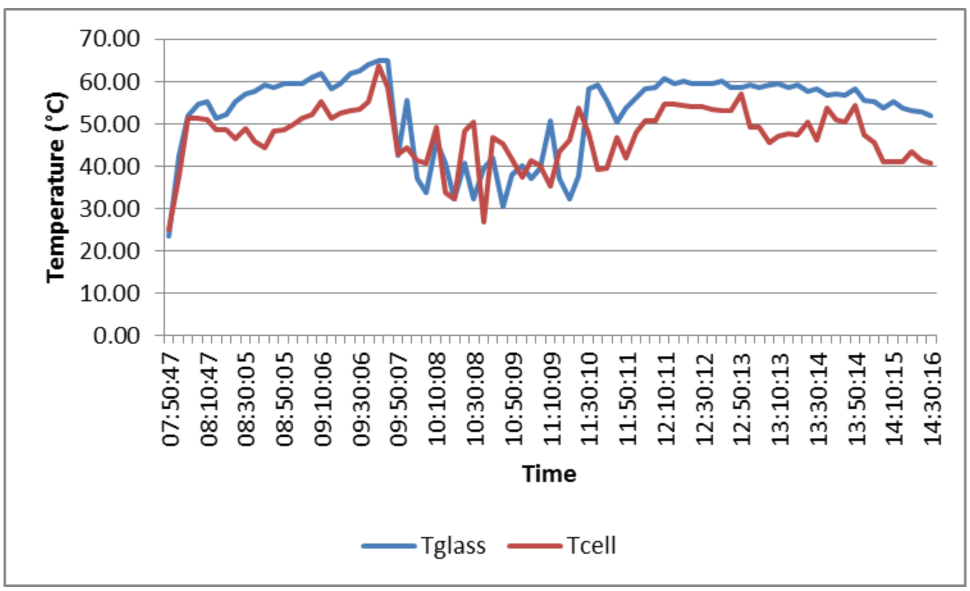


Figure 6-71: Temperatures of panel with and without cooling for next day on June, 2015

All the obtained results indicate that the operating cell temperature has a notable effect on the PV module performance. As it increases, the electrical performance decreases. The cooling using water method plays an important role in reducing this temperature and improves PV module performance. The rate of increase in all results ranges from 10% to 20%.

CHAPTER 7

CONCLUTION AND FUTURE WORK

7.1 Conclusion

In this work, the cell temperature was controlled to be in low value to improve the PV panel performance. The performance of the PV system is studied using two tasks; modelling using MATLAB/SIMULINK program and real experiments. An automatic cooling method using water flow on the front surface of the panel is proposed to improve the output efficiency of the PV module performance. The simulation program based on mathematical equations is developed using MATLAB/SIMULINK. In the simulation part, the PV module performance is validated using developed electrical and thermal models. The effect of the solar radiation and the temperature is investigated by studying I-V curves of PV modules. An increase for the amount of radiation causes an increase in the current as well as increase in the output power and vice versa. On other hand, the increase in the temperature causes a decrease in the voltage across the panel and decreasing the output power. In the thermal model, the operating cell temperature is studied and controlled manually by the use of different flow rates. It is noted that, if the cell temperature decreases, the output power will increase. The PID controller is used to control the cell temperature to get the maximum output power and improve the PV performance.

Different experiments are carried out to analyse PV system performance using the proposed thermal cooling system. These experiments were performed with and without cooling under Dhahran climate conditions. Experimental results show that the output performance of the PV system is increased by reducing the temperature of the solar cell using the proposed cooling system. The performance of the output power using water surface cooling is increased by an average of 20% compared with the efficiency without cooling. In addition, the proposed cooling system reduces the amount of consumed water. The proposed system operates depending on the cell temperature conditions and the solar radiation. Experimentally, the I-V curve was measured with and without cooling. It demonstrates that the cooling plays an important role in enhancing the output performance.

7.2 Future Work

The main aim of this work is to enhance the output power and the efficiency of the PV panel using water cooling surface control. In SIMULINK part, the controller was PID controller and in the experimental part the controller was on-off valve using Arduino. For future work, these are some suggestions:

- In this work, the performance of output power using water surface is studied with and without cooling using different experiments using one PV panel. However, the conditions of these experiments are not identical. As a future work, it is suggested to study the performance of the output power under the same conditions with two panels, such that one is used with cooling and another used without cooling.

- It is suggested to use other controllers to control the operating temperature such as fuzzy and MPC controller and compare the results with the PID controller.
- It is suggested to use ensemble of those controllers.
- It is suggested to perform cooling for the front and the back panel surfaces. There are three possible cases of cooling using this method, viz. cooling front only, back only, and both surfaces. This design of two ways cooling model will help to make comparison between performance results of these three cases. These cases can be controlled using valve control under specific conditions of radiation and temperature. This design of using two ways cooling model will enhance the performance of the output power.

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