Solar Panel Performance Enhancement using Active Cooling Technique

Thesis

Submitted to the

G.B. PANT UNIVERSITY OF AGRICULTURE & TECHNOLOGY, PANTNAGAR-263145, UTTARAKHAND, INDIA

By

Shivani Chauhan
B.Tech. (Mechanical Engineering)

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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First of all, I bow my head before 'God' who inspired me to face challenges of uneven times. All my sincere gratitude goes to him for the help he has given to me and his unfailing mercies over my life.

The author expresses her deep sense of reverence and heartfelt gratitude to Dr. Lokesh Varshney, Professor, and Head of Department, Mechanical Engineering, Chairman of Advisory Committee for his invaluable guidance, constant encouragement, abundant counsel and his critica land constructive suggestions throughout the investigation and in the preparation of manuscript. The author is extremely indebted to him and wishes to thank him from the bottom of the heart.

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This list is obviously incomplete but allow me submit that the omissions are inadvertent and I once again record my heartfelt gratitude to all those who helped me directly or indirectly in this endeavor.

Pantnagar
February, 2021

(Shivani Chauhan)
Author

CERTIFICATE-I

This is to certify that the thesis entitled ‘‘**Solar Panel Performance Enhancement using Active Cooling Technique”** submitted in partial fulfilment of the requirements for the degree of **Master of Technology** in Mechanical Engineering with major in **Thermal Engineering** of the College of Post-Graduate Studies, G.B. Pant University of Agriculture and Technology, Pantnagar, is a record of bonafide research carried out by **Ms. Shivani Chauhan ,** Id. No. **54078** under my supervision and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation and source of literature have been duly acknowledged.

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February, 2021

(Lokesh Varshney)
Chairperson
Advisory Committee

CERTIFICATE-II

We, the undersigned members of the Advisory Committee of **Ms. Shivani Chauhan,** Id. No. **54078,** a candidate for the degree of **Master of Technology** in **Mechanical Engineering** with major in **Thermal Engineering,** College of Post-Graduate Studies, G.B. Pant University of Agriculture and Technology, Pantnagar, agree that the thesis entitled **''Solar Panel Performance Enhancement using Active Cooling Technique"** may be submitted in partial fulfillment of the requirements for the degree.

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Chairperson
Advisory Committee

(D.S Murthy)
Member

(Prashant Verma)
Member

(Ravi Saxena)
Member

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LIST OF ABBREVIATIONS AND NOMENCLATURES

PV	:	Photovoltaic
Si	:	Silicone
nm	:	Nanometers
DC	:	Direct Current
CdTe	:	Cadmium Telluride
CIGS	:	Copper- indium- gallium- diselenide
PCM	:	Phase Changing Material
MPT	:	Maximum Power Point
EFF	:	Electrical efficiency of PV module
FF	:	Fill Factor
STCs	:	Standard Test Conditions
P_m	:	Maximum Electrical Power
V_{oc}	:	Open Circuit Voltage
I_{sc}	:	Short Circuit Current
A_m	:	Total area of PV module (m^2)
G	:	Incident Solar Radiation (W/m^2)
I_L	:	Light current
I_o	:	Diode Reverse Saturation Current
R_s	:	Series Resistance,
R_{sh}	:	Shunt Resistance
V_{pm}	:	Voltage at MPT
I_{pm}	:	Current at MPT
t_{av}	:	Average surface temperature
^oC	:	Degree centigrade

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Introduction

CHAPTER-1 INTRODUCTION

Fossil fuels are the most economical and viable source of energy for power generation. But due to increasing development in every energy sector, these will be insufficient to fulfill the future increasing demand as these are available in limited amount. However the requirement of energy is expected to keep on rising. As predicted by the United Nations, the energy need will increase by 50% in the time span of 2008 to 2035. Increasing price and the harmful emissions released during combustion of various fossil fuels are also limiting factors associated with these fossil fuels and conventional energy sources. Evidences show that emitted carbon dioxide from fossil fuels combustion contributes to more than 50% of anthropogenic greenhouse gases. As per Inter Governmental Panel on Climate Change (IPCC), the observed temperature increment was mainly occurred due to increase in atmospheric amount of greenhouse gases since the middle of the 20th century. This dramatic increment was resulted due to human activities such as establishment of industries, deforestation on large scale, combustion of fossil fuels for personal and commercial uses etc. **(IPPC Technical report, 2011).** The greatest antilogy is to expect that the energy demand increment must be accompanied by noticeable reduction in emission of CO_2 to achieve the target of international community of 2^o reduction in temperature **(International energy outlook, 2011).**

These issues have forced many researchers to switch over to non conventional and renewable sources of energy and found immense opportunities. The environmental concern has emerged as one of the biggest issue which has led to increase the use of unconventional energy sources tremendously. At the starting of 2009, out of total production capacity using different renewable energy sources including hydro, ocean, tidal, wind, solar, geothermal, biomass energy etc., hydro electricity share maximum percentage i.e. 83% **(REN21 Technical report, 2009).** However utilization of this energy source has faced a lot of difficulties including acquisition of water bodies, huge initial investment for constructing dams, damage to vegetation and water species. Therefore for the last few decades solar energy has become a promising alternative to fossil fuels due to limitations. As the earth receives more than enough sun's energy to fulfill the world's annual energy demand so it has come out as a great appealing source of power and electricity. Prediction shows that sun will keep shining for almost another 4.5 billion years which is far beyond from an average life span of a healthy human being. Since sun will continue to provide energy for so many years without much net investment so going solar will save a large amount of money also. According to divination the availability of solar resources are approximately 6000 times more than the total world energy exploitage. Thus only 0.025% of the total solar resources are enough to detract and teetotally substitute fossil fuels and nuclear power as an energy source as these are depleting continuously. This would result into less pollution also.

The utilization of solar energy can be extracted by direct conversion or indirect method. Direct conversion includes the employ of photovoltaic principle to convert light into electricity. Indirect method includes storage of sun energy in to thermal energy and then using it for converting into power. The concept of photovoltaic was first started in 1839, when A.E. Becquerel unearth the photogalvanic effect. Then **Chapin *et al.* (1954)** proclaimed the very first usable silicon solar cell with an efficiency of 6%. Four years later, solar cells were employed on a satellite. Regardless of poor optical absorptivity of silicone, it is the most commonly used base material for manufacturing of solar cells commercially. Also silicone is the second most ample material in earth's crust (approximately 27.7%), therefore raw material of solar cells is presumably inexhaustible. No harmful toxic gases are released during its manufacturing and electricity production. On a concludary note power generation from solar photovoltaic is purely clean and eco friendly. The non toxicity, easy availability, sufficiency and desirable properties of silicon make it the most favorable choice for solar cells. Since then the use of photovoltaic cells had started and in the last few dickers it become a worldwide accepted technology for commercial and personal as through the development that it has undergone built many attractive features for its acceptance. It is reliable with no movable parts which results into low maintenance and operating cost. Clean energy production with little maintenance requirement, modularity, decreased per panel cost, easily installation, can be installed on roofs as well. It uses solar energy which is free and unlimited to convert it into electricity. In forthcoming future it will prove to be one of the greatest mile stone in decreasing the rate of greenhouse gases concentration in the atmosphere.

1.1 Potential

1.1.1. Worldwide

According to **Smil *et al.* (1991),** 174 petawatts of the incoming radiation is received by the earth at the uppermost atmosphere. Out of which approximately 70% of insolation is imbibed by the clouds, atmospheric particles, clouds, oceans and land masses and remaining 30% is returned back to outer space. How much amount of solar radiations reaching the earth surface is greatly influenced by scattering, absorption and reflection due to particles, clouds etc. This results in global, diffused and direct solar radiation. Evidently energy from sun is exceptionally large. On an average energy received in one hour from sun on earth's surface is equipollent to annual energy requirement of total human population.

The world energy assessment by The UN Development Program in 2000 states that the yearly potentiality of energy by sun was 1,575-49,837 exajoules (EJ) which is several times ample than the entire worldwide energy consumption. In 2014, The IEA (international energy agency) forecasted that under its “high renewable” scenario, by 2050, around 16% and 11% of total worlds energy consumption would be shared by solar photovoltaic power and concentrated solar power respectively and would be the world's future largest electricity source **(IEA, 2014).** From 1990 to 2014 the yearly growth rate of PV system was 46.25% which are even more than the 24.3% of wind power, 13.2% for biogases and 11.7% of solar thermal. Overall, PV-systems have become one of the fastest growing energy systems globally. From 2010 to 2018, the Compound Annual Growth Rate (CAGR) of PV installations was 36.8%. The world wide crystalline Si based PV production accounted for 95% of total share in 2017, approximately having a market of 100 GW in 2018. For mono crystalline solar cells the lab recorded conversion efficiency is 26.7% and for multi-crystalline silicon wafer-based technology it is 22.3%. However due to less efficiency than mono crystalline, the contribution of multi-crystalline technology decreased from 70% (in 2016) to about 62% (compared to 70% in 2016) of overall production. According to the latest statistics published by IRENA, the world's total installed PV capacity has reached to 480.3 GW at the end of 2018 **(PV Magzine, 2019).**

1.1.2 In India

India is endowed with massive solar energy potential. Around 5000 trillion kilowatt hours (kWh) calculated solar energy per year is incident on India's terrain area with approximately 300 apparent and sunlit days. There are many states in India which are receiving more than 4 KWh/sq. m solar radiations with bright sunshine hours **(MNRE, 2020).** A recent document by the Ministry of New & Renewable Energy (MNRE) shows that the country's solar power potential as calculated by the National Institute of Solar

Energy is about 750 GW with an assumption that only 3% of the entire unusable land available is used. Fig. 1.1 shows the photovoltaic electricity power potential in India.

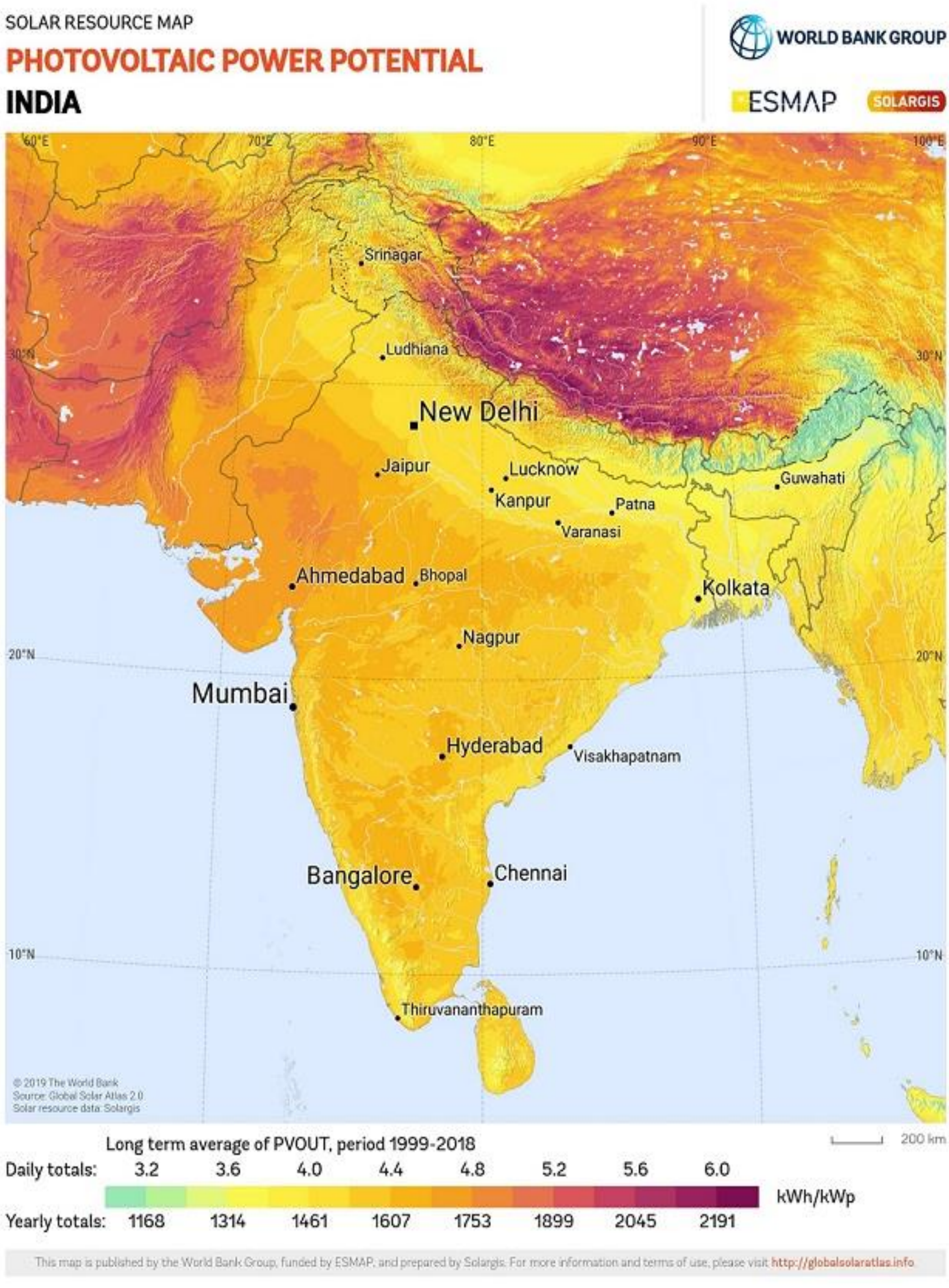


Fig. 1.1 Photovoltaic Electricity Potential in India (Solargis, 2019)

On instating the initial target of 20 GW much before than 2022, the government had raised the target to 100 GW including 40 GW rooftop solar power. Now it is among the rapidly growing and developing sector. From 2650 MW in May, 2014 to 20 GW in 2018 and then 28.18 GW in March, 2019, the solar generation capacity has become 8 times. In 2015-16, 3 GW of solar capacity was added, 5 GW in 2016-2017 and over 10 GW in 2017-2018. In February 2020, total installed solar capacity has reached to 34.404 GW **(Renewable Energy Goal Report, 2019).** While having a large scale grid connected photovoltaic power, for domestic energy needs the government is evoluting off-grid power through solar. To decrease the dependency on traditional sources and to meet the demands of vast population, it becomes crucial to make more proficient and improved PV systems.

Although these Si based photovoltaic technology have many limitations so as to rely more on non renewable especially solar energy, old PV systems must be replaced with advanced and new technology like quantum dots co sensitized and pervoskite solar but currently such replacements are negligible and are still under research. The existing new technology is also limited due to difficulty and complications in their manufacturing and high market price for current market capabilities. So more focus is emphasized on increasing the performance of Si based PV cells as these Si based will still dominate the market and play a central role for sustainable power production in the upcoming years.

1.2 Solar photovoltaic fundamental

The basic principle behind the working of solar cell is the photovoltaic effect which uses the solar energy for producing the electricity. Here solar irradiation is used to set up a potential difference (measured in volts). When photons (energy packets) of different energies and of different wavelength strikes on semiconductor, some of the light's portion is reflected, transmitted and rest of the portion is absorbed by the materials. If the incident light's intensity posses energy greater than band gap energy, these will excites few of the electrons to form electron hole pairs. These free holes and electrons play an essential role in creating electricity in photovoltaic cell**.** For solar cell, to generate the free electrons the photoelectric effect works in such a way that electrons do not leave the material surface. In most of the materials the recombination of electrons with ions is very fast. Only materials in which it is feasible to prevent the recombination of ions are ideal candidates for solar cell. Such materials are semiconductors. Here the VB (valence band) and CB (conduction band) are disconnected by a potential difference. The photons coming energized the electrons of valence band and force them in to conduction band. Fig. 1.2 shows the schematic diagram of working of a solar cell.

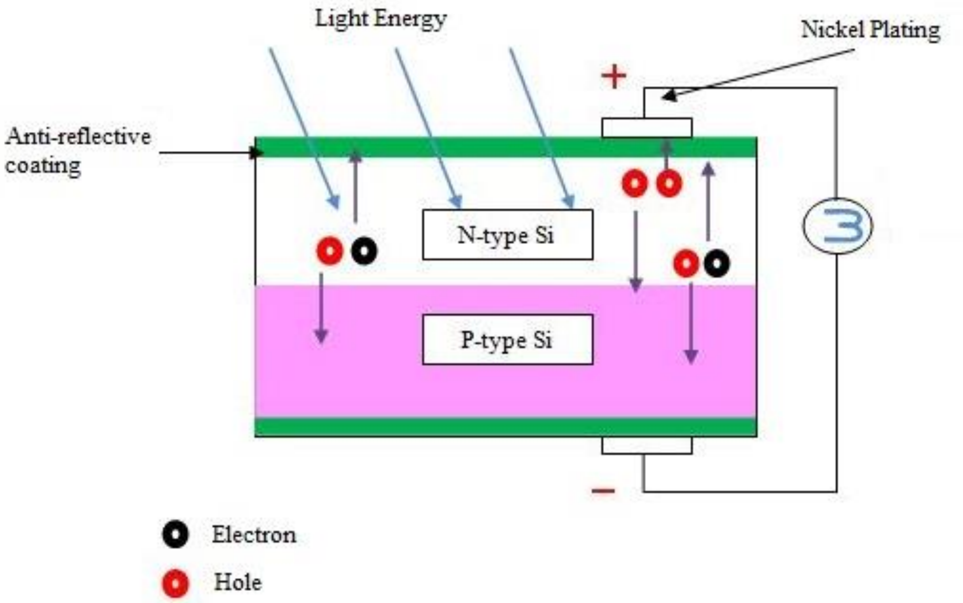


Fig. 1.2 Schematic diagram of Solar Cell

These photovoltaic are generally made of silicon or germanium semiconductors, preferably silicone and consists of minimum two layers of semiconductor, one with a positive and the other with negative charge. The semiconductors here are doped with some impurities known as dopant to form p-n junctions. These dopants are either pentavalent (donor impurities) or trivalent (acceptor impurities). The donor impurities make n-type semiconductors and trivalent impurities make p-type semiconductors. When these p type and n type material are combined together electrons move from n side to p side and holes from p side to n side thus creating charge imbalance. The electric field builds up due to negative and positive charged across the region called as depletion layer, opposes the further movement. As result equilibrium is established after this there is no more migration of charge carriers on either side. Due to this there is always a built up fixed potential barrier which is essential for cell working. The photons having energy larger than the band gap energy it will extract electron hole pair and because of potential barrier flow of electron takes place from the outside load path. Thus electrical current is produced. Fig. 1.3 shows the equivalent circuit of a solar cell.

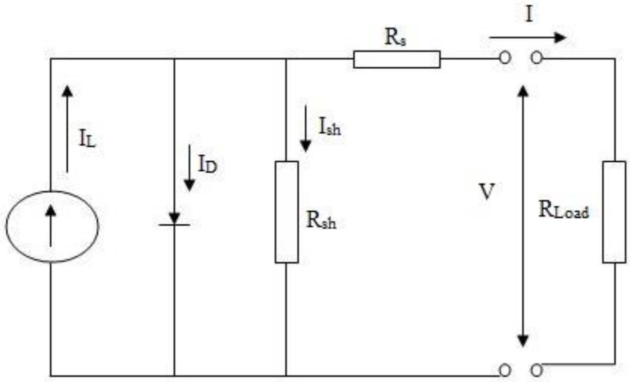


Fig.1.3 Equivalent circuit of a solar cell

The current and voltage equation for the above equivalent circuit of a solar cell at constant temperature and solar irradiation is given by equation:

$$I = I_L - I_D - I_{sh}$$

$$I = I_L - I_O \left[exp\left(\frac{V + IR_S}{a}\right) - 1\right] - \frac{V + IR_S}{R_{sh}}$$

The above circuit requires five parameters which all these depend on the temperature of the solar cell and solar radiations incident on it. The five parameters in the model are obtained using measurements of the current and voltage characteristics of a module at reference conditions supplied by the manufacturer and other known PV characteristics. The produced power is given by:

$$P = I \times V$$

The obtained outputs from such photovoltaic devices vary from microwatts to megawatts depending on the application these are used for. Advantages of using these are simple design and little maintenance. Now a day's use of photovoltaic is a wide growing market. Some applications include power generation for industrial and residential buildings, water pumping, space vehicles, satellites, communications, and for large power plants etc.

1.3 Types of solar cells

Photovoltaic cells are named according to the semiconducting material used for their manufacturing. These consist of either single layer or multi layer of semiconducting material. Today four different generations of solar cells are available to us.

First generation (1G) solar cells also termed as traditional or conventional cells. These are based on thick film of crystalline Si as its material which results in more efficiency but high cost too. These cells still dominate the solar market till date now and will also continue in near future also. Second generation (2G) cells are based on thin film technology with the aim of reducing the cost of first generation cells at the expense of reduction in efficiency. These include amorphous or crystalline Si, CIGS, CdTe cells etc. Third generation (3G) solar cells come into origin in orderto compensate for the lower efficiency of 2G cells. These are the emerging technology that includes nano crystalline films, PVs based on active quantum dots. These are still in their research phase aiming to achieve the goal of highly efficient and most economical solar cells **(Verma, 2016).** Following is a brief overview of few solar cells.

i. Mono crystalline Si solar cells

This is oldest technology employed in solar cells. Such cells are made of pure mono or single crystal silicon having the highest recorded lab efficiency of 26.7% **(Fraunhofer ISE report, 2020)**. In this lattice of silicon crystal is continuous without having any grain boundaries. These have uniform dark look and rounded edges. Due to the pyramidal pattern of these cells in the panel, have a larger surface area to collect more energy from the sun's rays resulting in greater power output. Such panel posses greater resistance against heat. High initial cost is its limitation. Their average life span is around 25 years as long as the PV panel is kept clean.

ii. Polycrystalline solar cells

These are also known as Multi crystalline. To produce them melted Si is cooled and then sliced into wafers creating a polycrystalline shape. Their lab recorded efficiency is 22.3% which is less than mono because of lower silicon purity. Manufacturing process is simple and requires less initial cost. On comparing to mono crystalline cells, these have slightly lower heat resistance. To produce the same electrical power output it generally need to cover a large surface.

iii. Thin film solar cells

These are made from deposition of one or multi thin photovoltaic material layer on a substrate. These are made from cadmium telluride (CdTe), amorphous silicon (a-Si), and Copper Indium Gallium Selenide (CIGS). The thickness of film transmorgify from a few nanometers (nm) to tens of micrometers (μm) resulting in lower weight, cheaper but less efficient than traditional solar cells. CIGS solar cell consists of four absorber elements i.e. copper indium gallium and selenide placed in between the two conductive layers while semiconductor materials of gallium-free variants type are concise as CIS. The world's largest CIS energy provider, Solar Frontier, has achieved the highest recorded conversion efficiency of 22.3% for 0.5 cm^2 thin film solar cell. They achieved this in consolidated research with the New Energy and Industrial Technology Development Organization (NEDO) of Japan, using CIS technology. This is a increment of 0.6% as compared to industry's trailing thin film cell efficiency of 21.7% **(Solar Frontier, 2015).**

iv. Dye sensitized solar cells/Gräetzel cell

It was invented by Professor Michael Graetzel and Dr Brian O'Regan, Switzerland in 1991. It is a low cost solar cell rooted on a thin film of between an electrolyte and a photo-sensitized anode, in short a photo electrochemical system. These are simple to manufacture. Although its conversion efficiency is still relatively lower than traditional solar cells. Also such cells have limitation of degradation of dyes when unveiled to UV radiations.

v. Quantum dots co sensitized solar cells

Dye in DSSCs is subrogated by various inorganic quantum dots like cadmium chalcogenides, CdX where X can be S, Se or Te, lead chalcogenides PbX, green quantum dots which serve as a sensitizing material. Such cells utilize quantum dots for absorbing the radiations. Bulkiness of cells is reduced here.

vi. Pervoskite solar cells

In such cells a perovskite structured compound, most commonly a hybrid organic-inorganic lead or Ti halide-based material is used as a light harvesting active layer **(Hamers, 2015).** Based on the absorber material's ABX_3 crystal structure the name 'perovskite solar cell' is enlisted which is commonly termed as perovskite structure. Over the time its efficiency has showed tremendous improvements from 2.2% in 2006 to 20.1% in 2014 to 25.2% in 2020 in single-junction architectures **(NREL Report, 2020).** Processing is simple with low potential material, have light weight, flexible etc. are few advantages. While facing problems like stability, toxicity of lead, scaling up etc. these are still in their early stage of commercialization. Fig. 1.4 shows the lab recorded efficiency chart of different types of solar cells by NREL.

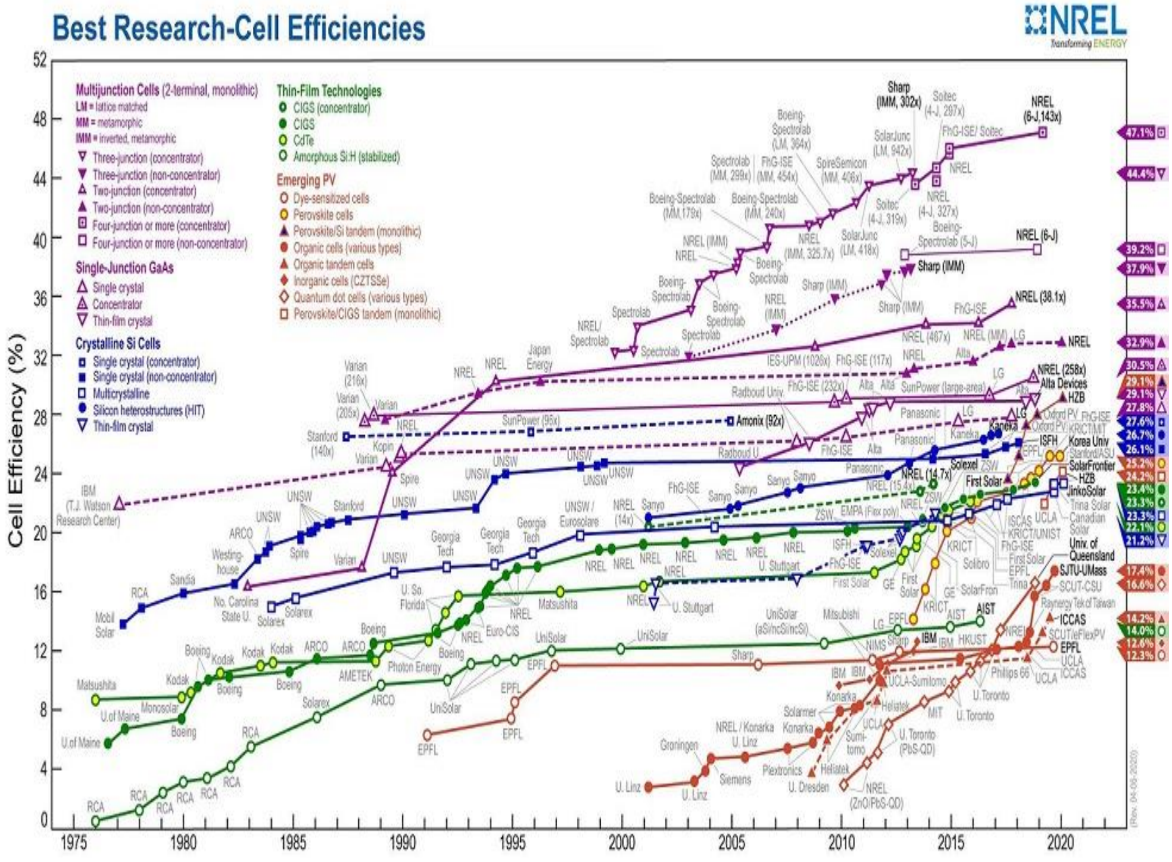


Fig. 1.4 Chronology of solar cell efficiency according to different methodology by NREL (NREL Efficiency chart, 2020)

1.4 Characteristics of PV Module

I-V characteristics show the propinquity between voltage and current at the existing circumstances of temperature and irradiance with different load conditions. This relationship is shown by the graphical representation. It variesfrom the short circuit current (I_{sc}) at zero output volts, to zero current at the full open circuit voltage (V_{oc}). It is clearly seen from the Fig. 1.5 that none of these two extreme conditions produces any electrical power. The maximum power is generated somewhere in between these two conditions near the bend in the curve. To draw the I-V curve, the resistance across the load is varied and the corresponding values of current & voltage is recorded. P-V characteristics curve shows the variation of power output with the corresponding voltage. Power is obtained by multiplying the voltage and current. The voltage equivalent to the maximum power output is the maximum power point. These curves are used to find the possible optimal peak power point. Hence are useful in determining the solar cell or module's power output and efficiency. The maximum power is generated somewhere in between these two extreme conditions near the bend in the I-V curve. The MPP, maximum power point is given by:

$$MPP = I_{mp} \times V_{mp}$$

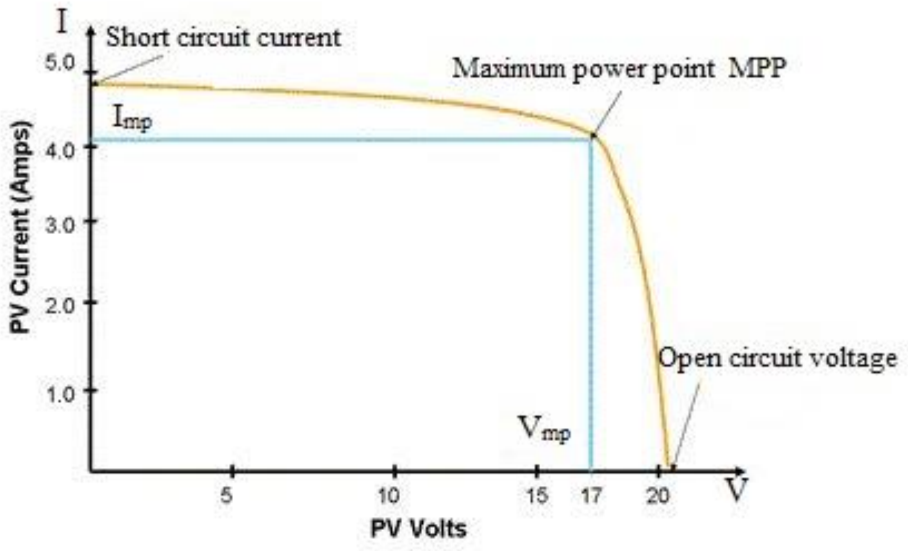


Fig. 1.5 I-V curve of a PV panel

1.5 Electrical efficiency of a solar cell

For comparing the photovoltaic cell's performance, a parameter termed as efficiency is used. It is defined as the fraction of the energy output produced by the solar cell to the total energy incident on it. In general it measures the percentage of solar radiations incident on the solar panel is converted into usable electricity. For example, under STDs i.e. standard test conditions a solar panel having an area of 1 m^2 with 20% efficiency will produce 200 kWh/yr. Let us consider a panel with an efficiency of 15%, it simply means that it converts 15% of the solar radiations incident on it into electricity. It is estimated by capturing the electrical current generated when radiations incident on panel. It can be expressed as the how much amount of incident power is converted to electrical energy.

The maximum electrical power of a PV panel is given by:

$$P = V_{OC} \times I_{SC} \times FF$$

Let G be the incident solar radiation in W/m^2, the total energy incident on a panel having an area of A m^2:

$$P_{in} = A_m \times G$$

Electrical efficiency is given by equation :

$$\eta = \frac{Voc \times Isc \times FF}{A_m \times G}$$

1.5.1 Solar cell parameters

i. Fill factor

It is defined as the ratio of power available at the maximum power point to the product of the open circuit voltage and short circuit current. It is a measure of solar cell's quality. Typically its value ranges from 50% to 82%. A normal silicon PV cell has a fill factor of 80%. The fill factor for a normal silicon PV cell is 80%.

ii.Short Circuit Current (I_{sc})

When the two terminals are directly connected with each other, the maximum current available is short circuit current. The terminals at this point have zero voltage. The reason responsible for this is the procreation and accumulation of light generated carriers.

iii.Open Circuit Voltage (V_{oc})

It is the maximum voltage across the PV cell when the flowing current is zero as cell is not connected to any load. Generally the value of open circuit voltage of solar cell is approximately equal to 0.5 to 0.6 volt. Further voltage goes on decreasing with the connection of load. It also decreases with temperature.

iv. Maximum power point MPP

It is a operating point on the I-V curve where the power provided by the module i.e. product of current and voltage is maximum. It conforms to the knee or peak point of the curve.

v. Watt-Peak

It is a measure of the nominal power of a solar cell device under standard illumination and operating condition i.e. a light intensity of 1000 W/m^2 with a spectrum similar to sunlight bitting the earth' surface at latitude 35° in the summer (air mass 1.5) and a temperature of 25°C.

1.6 Factors affecting efficiency of a cell

Despite of having many advantages and applications in different fields, researches reveal that there are several factors which affect the efficiency and performance of solar panels as all of the solar energy that reaches a PV cell is not fully converted into electrical energy. These are the factors which affect the amount of the current and power produced by PV cells which includes external or environmental factors, internal or system's itself factors, cost factors and some miscellaneous factors. Environmental factors includes irradiance, temperature of panel, accumulated dust over glass of module, shading and soiling deposition etc. have major effects. Systems or internal factors comprises material with which it is made from, atomic structure, band gap energy, module efficiency, its I-V characteristics, inverter, battery efficiency. Factors like installation set up, tilting angle, orientation, inequality (mismatch) effects also have decisive effect on panel's performance. With time, modules performance also degraded due to various factors. PV module's manufacturers perceive a panel to be degraded when 80% of its initial or nominal power is lost as per **Wohlgemuth*et al.* (2005).**

Several studies have done to find the effects of these factors. According to **Fouad *et al.*(2017)** out of all the studies on factors affecting PV panel performance, approximately 50% have focused on discussing environmental factors, 20% on PV system internal factors, 35% focused on installation factors, 5% on cost factors, 18% on decadence of PV systems with time and a little fraction on other aspects.

1) Solar irradiations

The amount of total solar radiations incident on per unit surface area is the irradiance. The quantity of energy generated by a solar cell is directly associated with solar irradiation which varies with site to site and thus is location dependent. The change in sun's altitude causes the sun to change its position throughout the day and season to season. The angle made by the sun's rays with the horizontal plane is altitude angle. These global solar radiations consist of direct, diffused and reflected radiations out of which direct radiations shares largest proportion. When directed on module's surface, the amount of solar irradiation to be incident further depends on panel's orientation, its tilting angle from horizontal, type of module installation and mounting. When module is at 90^{o} angle to direct radiations, maximum irradiance is observed.. Studies showed that the output from PV panel increases with increase in irradiance and found to be directly proportional. Due to linear relationship between irradiance and performance, the effect of solar irradiation on panel performance can't be represented in quantified form by a definite magnitude of percentage increase.

2) Shading

Shading losses include the losses due to shadows caused by trees, buildings, poles, leaves fall on modules, birds and birds droppings on panel etc. Due to these, panel is not able to produce the maximum power output that it should be and hence lower power output is produced. Shadow not only directly influence the current flow in shaded cells but also in the entire module as cells are connected in series. **Quaschning & Hanitsch's, (1996)** numerical simulation showed that only 2% of shaded area causes the performance loss by 70%. Viitanen revealed that shading of 5-10% causes the power output to be reduced by 80%. Thus the amount of shading losses that to be occurred are depend on the portion of module shaded, cell's material and connection between the cells as well as modules. Additionally depends on the nearby trees, building height.

3) Dust accumulation & Soiling

Dirt and dust deposited on panel surface blocked the incoming solar radiations. This blockage reduced the sunlight transmittance and causes a significant amount of losses and hence less power is produced than nominal power of module. A typical annual dust reduction factor is taken to be 93% or 0.93 i.e. if a 100 W module is taken, then it will produce 93 W or 7 W of power is lost due to dust deposition. Approximately 80% of short circuit voltage is reduced with deposited 73 g/m^2 of cement dust on panel surface as depicted by **El-Shobokshy and Hussein (1993)**. Another study by Mastekbayeva and Kumar showed that for a dust deposition of $5g/m^2$ reduced the transmittance by 11% in a month. For an exposure of about six months, air borne dust deposition causes an efficiency decrement by 32.3% as investigated by **Hassan *et al.* (2005).** However the amount of dust accumulation typically depends on the location's climate, type of dust and thus it is site or climate specific. This dust deposition further causes soiling. Sometimes dirt even stay on module surface even after heavy rainfall and mostly accumulated at the lower edges. This accumulation shaded the cells which reduces the power. But this loss in power can be restored once module is cleaned properly and thus dependent on cleaning rate. Studies showed that a linear relationship exists between power loss and soiling mass. Some studies showed that soil mass increases due to new dust accumulation over existing ones but that doesn't hinder the light further. Soiling losses also depends on the composition, shape and size of dust particles. Fine particles hinders the light more as compared to larger ones as these have higher cross sectional area to volume ratio.

4) Optical losses

Factors like shading due to many reasons, the angle of the sun, passing clouds, hazy weather, dust deposition and air pollution can affect irradiance levels. By limiting the amount of radiations absorptions, cloudy weather and shading of panel directly affects the effectiveness of radiation collection. These also reflect some of the sun's rays. Some amount is reflected and refracted due to cover glass as shown in Fig. 1.6.Unreflected portion reach the solar cells. The lesser the amount of light transmit, lesser is the amount of power produced. A cell's performance decreases with the amount of radiations reflected from a cell's surface. In other words with increase in optical losses the short circuit current decreases. Light which could have resulted in generation of electron hole pair but not able to do so due to reflection are considered as optical losses. Untreated silicon reflects more than 30% of incident light. SiO_2, MgF_2, TiO_2, $Si3N_4$, and ZrO_2 materials are widely used in anti-reflection coatings. Generally reflective index for cover glass of panel is 1.52 and main purpose of coatings is to bring the reflective index approximately 1. Others methods include minimizing the top contact coverage of the cell surface, making the solar cell thicker so as to increase the absorption, using surface texturing and light trapping's combination to increase the optical path length in the solar cell.

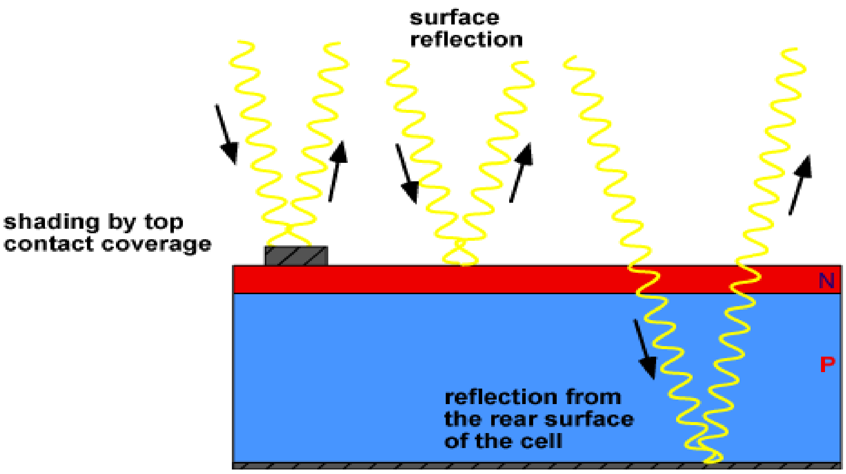


Fig. 1.6 Optical losses from top and back surface of a cell

There are various ways to minimize these optical losses. One way is by minimizing the amount of reflected light from panel surface by using different anti-reflection coatings (ARC) and textured surfaces result in improvement in efficiency. Others are minimizing the top contact coverage of the cell surface, making the solar cell thicker so as to increase the absorption, using surface texturing and light trapping's combination to increase the optical path length in the solar cell. According to a model that was developed by a group of researchers, photovoltaic system efficiency without rainfall decreases by an average of 0.2% per day in arid climates. Depending on the system location, this daily loss is equivalent to an annual energy loss between 1.5-6.2%. The humidity also reduces the photovoltaic panel efficiency thus producing less quantity of output energy. With time, it deteriorates the performance.

6) Temperature

The photovoltaic system is the most proficient when the temperature of the cell is about 25°C. However in actual practice, the temperature is not exactly 25°C, above during summer days and below during winter seasons. It is found that the performance of a cell decreases with increase in temperature. The effect of temperature on its efficiency is discussed below. Therefore, the concern to find methods to decrease the operating temperature of the cells is requisite.

1.7 Effect of temperature and Need of cooling

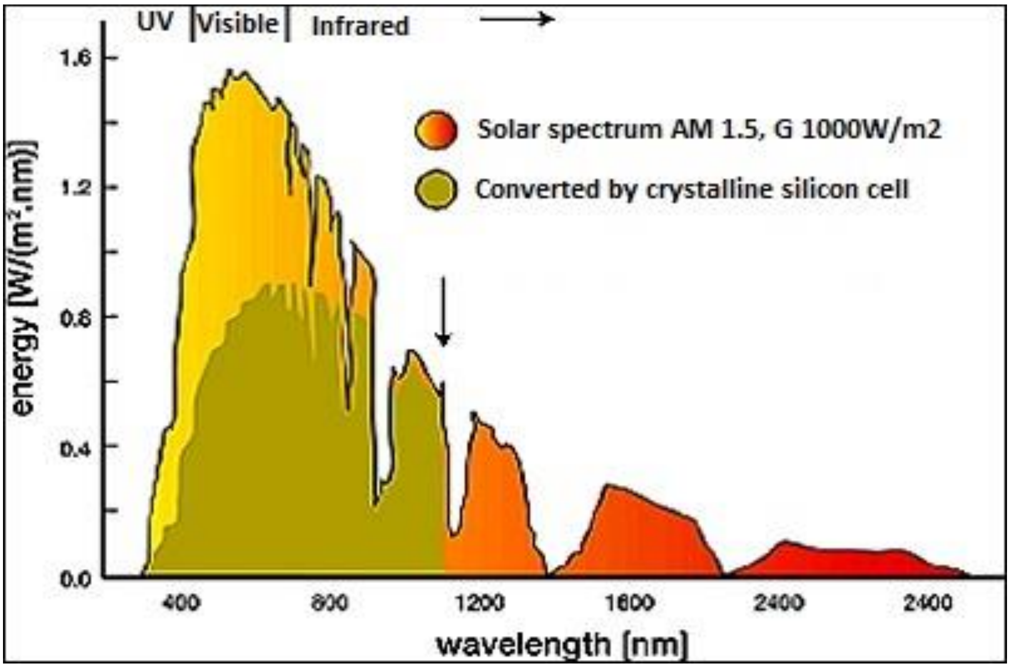


Fig. 1.7 Solar and solar cell spectrum (Solar Cell Efficiency Limits, 2020)

In recent years Photovoltaic, invented by Charles Feritts in 1886, is a fast growing market. It is one of the most popular and used technology in renewable energy field. Solar energy is directly converted into electrical energy with the help of photoelectric effect. For this solar cells need to absorb a range of energy which corresponds to the solar spectrum. A typical solar spectrum has a wavelength range varying from 100 nm to 1 mm but most of the irradiance occurs between 250 nm to 2500 nm. These PV cells absorb solar irradiance of wavelength ranging from 300 nm to 1100 nm, major portion is from visible region, and small portion from ultra and infrared region on solar spectrum. The Fig. 1.7 shows the sunlight energy distribution. As visible region in spectrum contributes maximum wavelengths ranging from 400-700 nm which means that a solar need needs to imbibe as much as in the visible region. Here the photons in the mustard color range can only be absorbed by a crystalline silicon cell and results in to generation of electricity. The wavelengths in red color region do not posses enough energy and yellow color wavelengths have too much energy than the requirement of a cell. Although yellow colored wavelengths results in to generation of electron hole pairs and generates electricity but most of the extra energy of is lost and dissipated in the form of heat. For silicon, the maximum wavelength that results in to generation of power is 1150 nm and above this value, energy is dissipated in the form of heat. This dissipated heat results in increment of the temperature of solar cell. The main effect of the increase in cell surface temperature is on its open circuit voltage.

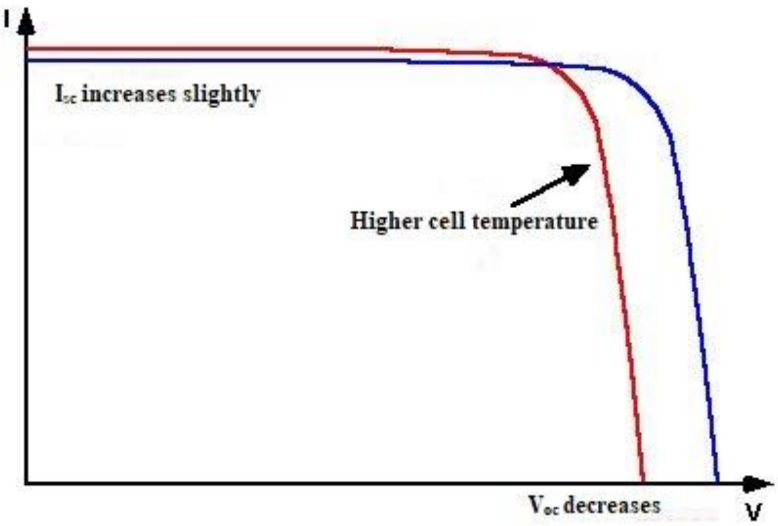


Fig. 1.8 Variation of output voltage and current curve for PV performance with temperature V_{oc} (PV Education, 2020)

Figure 1.8 shows how with increase in temperature the short circuit current increases slightly but causes a substantial linear decrement in the open circuit voltage. The decrement in voltage is much higher than increment in current so overall effect is the reduction of the solar cell performance parameters. As a result the power output and efficiency of a solar module drops by a significant amount. This has been equated to a reduction in PV modules conversion efficiency of approximately 0.4-0.5% for every degree Celsius of temperature. On an average the performance of these panels, open circuit voltage, fill factor and power output degraded about 2-2.3 mV/ºC, 0.1-0.2%/ºC and 0.4-0.5%/ºC respectively when exposed to elevated temperatures which is significant decrement **Sing, (2013).**

Secondly the high surface temperature has also been found to greatly reduce the effective working lifespan of the solar panels. This is due to the increment in the thermal fatigue, causing excessive thermal stresses in solar cells **Bahaidarah *et al.* (2016).** For instance the typical life span of a PV module is 20 years, where 1% of degradation is expected each year. High temperatures greatly increase the stress on solar cells. It has been found, that if the same constant rate of incident solar radiation was applied it would take four times as long at 65°C to cause the same amount of degradation as seen at 85°C. This approximately reduces the lifespan of the module to 5 years, with 4% lifespan degradation each year.

Therefore for the panels to work efficiently it is desired to keep the operating temperature low for which different cooling techniques are used mainly air cooling or water cooling. Other important benefit of cooling is that it also increases the total life time of a PV panel. The main aim of applying cooling techniques is to enhance the panel efficiency by removing the extra heat produced due to high temperature as around 85% of solar radiations are converted to heat .These cooling techniques are classified into active and passive cooling.

1.7.1 Active and Passive Cooling

Active cooling methods are defined by **Lechner, (2009)** as "use of mechanical devices to satisfy the requirements of cooling and not provided naturally". In other words it is a cooling technique that involves usage of external power continuously. Such methods consume external electricity and heat as power source, mainly in the heat reduction process. The most commonly used are three: fans, evaporative coolers and heat pumps (compression and absorption cooling machines) that promotes the full circulation. Here forced flow rate is utilized. Such methods results in more cooling and thus more accessible thermal energy from systems and helpful in producing more output power.

While passive cooling methods refers to use of technologies to extract and reduce the heat absorption without any additional power usage. In this majority of heat is extracted through natural convection and conduction. It involves transferring the heat from where it is produced and dissipating it in to the environment. Vast variety of passive cooling choices is available. The basic form involves the use of high thermal conductivity metals such as aluminum, zinc, copper or array of extruded surfaces i.e. fins to amplify the heat transfer. Other methods involve use of PCMs and several methods for natural circulation, in addition to the use of heat pipes that are efficient to transfer heat through a boiling condensing process. However active cooling techniques result in more efficient cooling than passive and are more expensive.

In the present study solar panel with cooling configuration is tested in lab for which there is a need to create the sunlight artificially. A solar simulator is used for this purpose.

1.8 Solar Simulator

A solar simulator is a device which provides the illumination, solar irradiance and solar spectrum similar to natural sunlight to enable the researcher to do controllable indoor testing in the laboratory under standard conditions in less time.

The easiest way for testing is to test under clear sky but it is very time consuming. Problems like fluctuation in sunlight intensity with time, ambient temperature, velocity are faced everywhere. Therefore indoor testing as compared to outdoor testing are widely acknowledged and even suggested by ASHRAE. It enables the user to vary and control the parameters and conditions according to requirement and allows greater degree of freedom. A number of solar simulators have been used. However the manufactured simulators are quite expensive and not economical to use for testing at this level. For photovoltaic testing generally there are two common standards used for classification of solar simulator which are IEC 60904-9 Edition 2 and ASTM E927-10 standards which are a common specification for solar simulators. According to both artificial lights from solar simulator should be within acceptable range of spectral content, spatial uniformity and temporal stability. Each dimension is classified in one of three classes: A, B, or C. For each class, the specification according to ASTM is listed in below table 1. The solar simulation spectrum is specified by irradiance across wavelength intervals ranging between 300 nm and 1400 nm. Details of this can be found in ASTM.

1.9 Organization of thesis

The improvement in performance parameters using active cooling technique with dc fan is primarily focused in this study. The structure of this thesis contains the introductory knowledge of solar cells, background, experimental procedures, results and analysis, discussion of results, and summary and conclusion with recommendations and future scope. Additionally, references and appendices are provided after the main body of the report.

In **Chapter 1**, an introductory background of solar energy, solar photovoltaic, and motivation of subject of area of study is presented.

Chapter 2, Review of Literature offers a brief review of related literature of previous cooling methods and studies and documented the effectiveness of each, which was utilized to select promising cooling techniques that were investigated in this study.

In **Chapter 3**, Materials and Methodology, materials and methodology of experimental study is discussed. Brief introduction of materials and equipments used is presented along with necessary equations. Additionally, this section includes images of the test setup.

Chapter 4, Results and Discussion, discussed the obtained experimental results and necessary calculation. This section provides an in-depth performance analysis and summarizes the results for each design. The Results and Analysis section will be followed by the Discussion of Results section. The Discussion of Results section explains precisely what is learnt provides a comparison of the designs and the relevance of the results.

In **Chapter 5**, Summary and conclusion, summarize the findings and final conclusion of experimental study is provided. Additionally, this section provides recommendations for future work and concludes the study. The Conclusion section is to be followed by References and Appendices,

Review of Literature

CHAPTER-2 REVIEW OF LITERATURE

PV systems for power generation in its initial phase did not get accepted widely because of their low efficiency and high cost involved. However these had immense power to decrease dependency on fossil fuels as it based on renewable energy. Since then a lot of research work has been done to enhance its efficiency which was major concern. Many researchers studied different materials and arrangement. Most of the studied was focused on to increase the power output, performance and to decrease the cost. Silicon found to be the best material and silicon based PV panels have been widely accepted both for commercial and residential purposes. However it was found that the increment in working temperature of solar cells resulted in reduction in its efficiency. Researches revealed that there are also other factors which have adverse effects on its performance.These factors include like cloudy weather, dust deposition, temperature, humidity, panel orientation, and reflection of radiations from panels i.e. optical losses. It is quite familiar that the photovoltaic system is the most efficient when the temperature of the cell is about 25°C. However in actual practice, the temperature is not exactly 25°C, above during summer days and below during winter seasons.

The sole purpose of this chapter is to give a light on the background of different solar simulators that have been fabricated for indoor testing and cooling techniques that were adopted till now to improve the performance of solar photovoltaic panels. This literature review gives a brief overview and discusses the cooling techniques adopted as heating is a crucial factor which has direct negative impact on system's performance. The main focus is to summarize the different cooling techniques in an integrated manner and tabulate them in a single table. This chapter is categorized in to two parts; first part is literature review of solar simulator and second is review of various cooling methods adopted.

2.1 Solar simulator

Garg *et al.* (1985) developed a solar simulator for indoor testing of solar devices like variety of evacuated tube and flat plate solar collectors. The setup consists of 14 quartz Philips halogen lamps, each rating 1000 W which provide a testing area of 1.69 m^2 and fixed on an iron frame. Halogen lamps were positioned at a separation of 35 cm. Using regulator or dimmer three variable transformers used in the circuit the irradiance varied from 400 W/m^2 to 1500 W/m^2 by regulating the input voltage. Single lamp was first tested to measure the output radiation produced by using pyranometer. Quality of fabricated solar simulator was tested in terms of similarity with sun's spectrum, uniformity, flux intensity and stability and its range. The obtained results were in agreement with the standards set up by for a solar simulator however spectral energy distribution was carried slightly at varied voltages. It was concluded that a stable flux can be obtained with halogen lamps.

Aristizabal *et al*. (2011) presented a low cost and improved tungsten light based simulator for testing of PV cells. Commercially available filters were used to increase the color temperature and spectral distribution equal to sun's temperature. A better spectrum was achieved by using this filter to reduce the infrared range. This set up can be used for testing of both silicon and organic based PV cells. Array of six halogen bulbs (300 W), each rating of 120 V, 50 W used and positioned perpendicular to cell surface so as to provide the maximum radiation. Each bulb was provided a separate regulator to vary the voltage separately. All six bulbs on consuming 300 W of power input could produce maximum solar irradiance of 3500 W/m^2. As there is a mismatch between the tungsten light and sun spectrum so this set up did not create the actual spectrum.

Shatat *et al.* (2013) initially test a uniform geometrical design of solar simulator which contains 16 halogen floodlights, each with a capacity of 400 W so as to optimize the source to target distance, efficiency and irradiance. It covered a total area of 2.32 m^2. Various distances were tested experimentally. Observed optimized distance was come out to be 23 cm. Radiation at different points was measured and maximum unevenness calculated. Initially the unevenness was high due to plenty of shaded areas. Number of lights was increased to 30. Based on this, maximum unevenness percentage was 9.1% which is within the limits of allowable unevenness percentage as set by British Standards for solar simulator testing.

Salam *et al*. (2014) proposed an inexpensive solar simulator using halogen tungsten bulbs. A water tank was placed in between the bulbs and solar panel for controlling the increment in temperature. Commercially available 240 V, 50 W halogen tungsten bulbs are installed on simulator stand. There are total of 36 such bulbs (total 1800 W/m^2) are used which are positioned in 4 by 9 grids whose light intensity governed by IGBT using high frequency switching. The fabricated simulator generated irradiation equal to 1 Sun i.e. 1000 W/m^2. Water tank in between reduced the panel temperature to half of temperature attained without water tank. Capability of fabricated simulator was tested by involving a case study.

Yandri *et al.* (2018) fabricated a compact halogen lamps simulator and calibrated it. The simulator stand made from aluminum. It was constructed such that the module faced downwards to simulator with dimensions 430 mm × 390 mm × 1000 mm. the optimized distance between the light source and module is 32 cm for which maximum non uniformity found to be within limits set by British standards for solar simulator testing as 9.7%. Results showed that the PV panel power output reduces by 0.36% and efficiency by 0.076% for every degree rise in temperature due to huge amount of heat emitted by halogen bulbs. Total of 16 halogen bulbs (Ushio JDR 50, 50 W/110 V) were fixed positioned in an array of 4bulbs and total of 4 arrays on an aluminum plate with an average spacing of 35 mm. 380 mm × 350 mm of plate with thickness of δ3 mm was used. Each lamp could be switched off separately. On increasing the distance, the irradiation decreased. However it becomes more uniform with distance. The calculated optimized distance between module and light source was 32cm with maximum non uniformity to be 12%. The indoor testing results were compared with outdoor testing results with identical setup. The ratio of solar output to halogen output observed to be 1.9. This study concluded that uniformity can be enhanced by setting optimized spacing between bulbs, reflector angle etc.

2.2 Cooling techniques

Radziemska*et al.* (2003) investigated the effect of temperature on power decrement and electrical properties of crystalline silicon solar cells. He used thick copper plate (thickness of 10 mm) as a heat sink to prevent overheating and performed experiment under an artificially produced solar irradiance (618-756 W/m^2) through halogen lamp simulator. The performance of solar module was measured at module temperature ranging from 28^{o}C-80^{o}C. The obtained results showed that the output power decreased by 0.65%/K, fill-factor by 0.2%/K and of the conversion efficiency by 0.08%/K. **Subhash *et al.* (2015)** studied the effect of cell temperature on the electrical factors of mono crystalline silicon cell under light intensities of 215-515 W/m^2 taking module temperature range to be 25-60^{o}C. It was found that open circuit voltage, maximum power, fill factor and efficiency were decreased with cell temperature.

Hence experiments proved that temperature has much adverse effect than these others factors. So it is necessary to keep the working temperature low and within the specified manufacture's limit. Hence researches were started focusing on keeping the working temperature low for which cooling proved to best. Since then many researchers developed different cooling methods and techniques. Both passive and active cooling techniques are used to enhance solar cells performance. Different cooling techniques that have been used for PV panels are discussed briefly in this section.

Akbarzadeh and Wadowski (1996) introduced a thermo syphon cooling system, a passive method which effectively cool the solar cells.Also a wacky profile for the reflecting surfaces had been developed so that the solar cells are uniformly enlightened under any degree of concentration. The proposed method contains two copper heat exchangers with initially evacuated. The both sides of evaporating surface of the cooling system tubing are installed with polycrystalline solar cells having length of 25 mm and width of 20 mm. It was found that temperature rose to 84°C and power output to be 10.6 W. Then tubes were filled with R-11 cooling refrigerant.The cell temperature dropped to 46°C while power output increased to 20.6 W. Thus improved performance had been achieved by using proposed cooling system.

Tonui and Tripanagnostopoulos (2007) developed a theoretical model based on air cooling due to minimal utiization of material and low operating cost regardless of its poor thermal and physical properties. To keep the working temperature under acceptable limit, modification in the channel were made. Calculated theoretical results were compared with the experimental data and found in good agreement. They suggested the usage of slender flat even metal sheet flaccid at the center or finned back wall of an air channel. These both arrangements could be easily incorporated and improved thermal and electrical properties. The finned back surface improved the thermal efficiency effectively while thin flat metal sheet suspended at the middle present better tutelage of the building structure from the unwanted excessive heating by guarding the back wall of the channel as well. The efficacy of the channel dimension including its length and depth and mass flow rate on thermal and electrical efficiency, cooling and pressure drop were also studied.

Tang *et al.* (2010) used a novel micro heat pipe array for cooling of silicon solar panel having highest efficiency in the range of 10-15% under standard conditions of temperature of 25°C, and solar radiation of 1000 W/m^2, peak power of 10 W and an area of 0.0625 m^2.They invested air as well as water cooling under natural convection. First they investigated panel under air cooling and found that with the daily radiation value 26.3 MJ, the maximum working temperature decreased by 4.7°C and hence improvement in conversion efficiency by 2.6% and increment in power output by 8.4%. With using water cooling instead of air cooling, the maximum temperature reduced by 8°C while power output improved by 13.9% and photoelectric conversion efficiency increased by 3% when the daily radiation value is 21.9 MJ.

Cuce*et al.* (2011) studied the effects of passive cooling on performance parameters of crystalline silicon solar cells. Using the outcomes of a constant heat transfer analysis size of the passive cooling device were deter-mined. A heat sink of aluminum was fitted at the back surface of panel for dissipating the excess waste heat generated from a photovoltaic (PV) cell. Ambient temperatures and illumination intensities up to 1 sun under solar simulator were varied. Results showed that power conversion efficiency of a PV cell increased considerably with the introduced cooling technique. An increment of 20% in power output was observed when exposed to 800 W/m^2 radiation condition. PV cell with fins provide more electrical energy than without. Increment in power output is 8, 27, 46 and 65 with 200,400, 600 and 800 W/m^2, respectively observed. Heat transfer analysis showed that the amount of heat dissipated with fins is 5.49, 9.06 and 12.03 W for 400, 600 and 800 W/m^2, respectively. While the PV cell without fins dissipates 4.54, 6.91 and 9.61 W of heat for the same intensity levels. However the passive cooling is proved to be inefficient for low irradiance level as the temperature difference was only 1.1°C between the ambient air and the fins.

Nikhil and Premalatha (2012) evaluated silicone oil cooling of the solar module surface. They employed a solar module having maximum power of 7W for experiment. Cooling medium was spread over the module surface and the experiments were conducted in batch mode. For various thickness of the cooling medium ranging from zero to six mm performance of module was evaluated throughout the day. A mathematical model also presented by them for predicting the variation of the maximum power when the module surface is cooled using silicone oil. The cooling resulted in improvement of module efficiency to above 20%.

Teo *et al*. (2012) designed, fabricated and experimentally scrutinized a hybrid photovoltaic thermal solar system. Four 55 watt polycrystalline solar panels used for the experiment. For homogenized distribution of air a parallel array of ducts with inlet and outlet manifold were mounted at the back side of a PV panel and a blower was employed for extracting the air from the surrounding. Fins were also fitted inside the duct to fasten the cooling rate. Comparative study was done between the panel with and without cooling. Without employing the cooling system to the panel the maximum working temperature that attained was 68°C and it would achieve only an efficiency of about 8-9%. However with cooling system on the back side reduced the working temperature significantly to 38°C and efficiency of 12-14% was achieved. Air flow rate of 0.055 kg/s was found to be optimum to absorb the maximum quantity of heat from the panels.

A self adjusted jet impingement active cooling technique was proposed by **Rahimi *et al.* (2014)** and experimentally tested for photovoltaic solar panels. Air flow was induced to create a cooling effect. Special designed conic tubes using self adjusted wind vanes was mounted on 5 W polycrystalline silicon cells whose rated maximum efficiency to be 16%. Additional wind turbine was assembled to act as an extra electricity source (dynamo). Indoor testing was carried out under a solar simulator where panel was exposed to different irradiation of 570 W/m^2, 910 W/m^2 and 1100 W/m^2. Panel with non cooling system showed much higher temperature than nominal operating temperature and found to be 57.6°C, 85.4°C and 105.4°C, depending on the applied level of solar irradiation. For a solar irradiation level of 510W/m^2 the proposed cooling technique reduced the operating temperature to 40.4°C from 57°C with air flow rate of 340 m^3/h. It was observed that cooling rate also depends on quantity of air flow.

Meysam *et al.* (2014) recommended a novel PV/T heat system assembled with two cooling jackets. This set up was mounted on 40^o tiled 20W mono crystalline silicon solar panel whose nominal efficiency to be 13.88%. The testing setup along with panels, double cooling jackets attached with an MPPT was placed in climatic condition of Iran (Mashad) where solar irradiation levels being around 990W/m^2 up to 1080W/m^2. The ambient air temperature observed to be 26.5°C in spring and 36.9°C in summer. With this set up, the operating temperature was reduced by 13% and electrical efficiency increment by 9%. In spring this system provided more power output by 0.72% and by 0.885% more in winter as compared to without cooling.

Irwan *et al*. (2015) performed the experiment under indoor condition with light intensity of 413, 620, 821 and 1016 W/m^2 from an artificial solar simulator. Halogen lamp bulbs which act as a natural sunlight, were fitted on a steel frame. To provide cooling over the front surface water was made to flow and flow rate was maintained by employing a DC pump. For four different fixed solar radiations the decrement in temperature and other electrical parameters were measured. It was found that the maximum temperature decrement occur by 23°C for 1016 W/m² while minimum by 5°C for intensity of 413 W/m². Water cooling also increased the output power by 9.76%, 87%, 18.19% and 22.81% for intensity 413, 620, 821 and 1016 W/m² respectively.

Gotmare1 *et al.* (2015) in his study utilized passive fin natural convection cooling. Different cross sectional perforated fins was attached at the rear side of the panel of 37 W having an area of 0.351 m^2. Two panels of same configuration were used. Without cooling at an irradiation of 1000 W/m^2 and ambient temperature of 25°C the utmost output current and voltage developed by the panel are 2.09 A and 17.7 V respectively. Aluminum fins of 0.8 mm thickness were glued with thermal grease evenly to the backside of the panel. Total nine perforated fins of different cross section with a constant spacing of 50 mm were attached alternately. This was done to restrict the flow of air for improving the heat transfer rate from the PV panel. The perforation on fins had been done by a 10 mm drill bit. Average temperature of 59.5^{o}C & 62^{o}C were recorded with and without cooling mechanism. It resulted in decrement in working temperature by 4.2% and increment of 5.5% in power output of the module with fin under natural convection cooling.

Chandrasekar *et al.* (2016) combined the aluminum fins with cotton wick and used them as a passive cooling medium to maintain the temperature of the PV panel. Three aluminum fins each having dimension 630 × 100 × 60 mm with cotton wick were attached to the rear side of the crystalline silicon PV cells. The maximum module working temperature decreased by 12% and power output increased by 14% as compared to condition when no cooling system was attached.

Amelia *et al.* (2016) developed a forced circulation cooling system based on DC fan. These fans were attached on the back of PV panel which will expected to abduce the heat energy distributed and help in cooling of the PV panel. Experiments were conducted cooled and non cooled system in outdoor weather conditions. It was concluded that there must be an optimized number of DC fans needed as cooling mechanism for maintain low working temperature and producing proficient electrical output from a PV panel and it depends on various factors like atmospheric condition, speed and airflow DC fan used and size of the PV panel. These fans would operate only when a certain PV operating temperature will reach. For this study 35°C temperature was set up as limit, above which

DC fans were used. Each DC fan cooling mechanism was fitted at the rear side of panel. The DC fan was installed with zinc sheet, which can work as the heat transfer application. The fans were installed in such arrangement that air from outside enters to the backside of PV panel. When number of fans were increased from 2 to 3 and 4 the power output increased to 67.70 W, 72.43 W, and 76.54 W respectively. This corresponds to 37.17%, 41.28% and 44.34% increase power output of a PV panel. On an average the panel temperature decreased by 22.22% approximately when all four fans were employed.

Nižetić *et al.* (2016) applied a water spray cooling technique on both sides of PV panel. Nozzles were mounted on front and rear side of 50 W mono crystalline panel's surface and connected with water distribution system. The solar irradiation varied from 810 W/m^2 to 850 W/m^2 and ambient temperature from 27°C to 30°C in typical Mediterranean climate conditions. Air velocity was under 1 m/s. The panel was subjected to three different cooling conditions, namely front side cooling only, back side cooling only and both side cooling with constant water temperature to be 17°C. Highest temperature reduction was observed with both sides cooling with reduction of 30°C i.e. from 56°C to about 24°C. Overall electrical efficiency of panel improved to 14.3% however including the power loss to water distribution system the net efficiency enhancement was about 5.9%. The associated efficiency improvement was from 12% to 14.3% and net enhancement from 5.45% to 7.7% with operating temperature ranged from 23°C to 32°C. The recommended cooling technique was also analyzed economically and found to be economically viable. Economical viable means that more output than input i.e. more electricity was produced than consumed work. Effect of evaporation and its net effect economically were also analyzed.

Ali and Celik (2017) used air and water both for cooling the photovoltaic system. A fan was installed at the back of solar panel which was used to blow the air on its rear side. The front surface of the photovoltaic panel was cooled by flowing water. For this purpose PVC pipe of 1.27 centimeter diameter with 3 mm holes drilled along the entire length of the pipe was incorporated at the upper most edge of the panel by using duct tape. To direct the flow of water from tap resilient and pellucid pipe was connected with the PVC pipe. Experimental results showed that using only air for cooling enhanced the power output by 2.4% as compared to without cooling. While water cooling system increased the power output by 4.75% and 6.3% for flow rate of 1 gpm and 2 gpm respectively.

Hachem *et al.* (2017) studied the effect of pure white petroleum jelly and combined white petroleum jelly with graphite and copper on thermal and electrical behavior of photovoltaic panel. Correlation of system's thermal performance with electrical outputs was also established using transient energy balance. Performance of three system's prototypes was compared. First prototype consisting of 30W panel (50×50 cm^2) tilted at an angle of 34^o was tested without use of PCM and used as reference for comparison. An un-insulated aluminum container was installed at the rear side of second and third prototype which contains pure PCM and combined PCM respectively. Aluminum container absorbs the excess heat resulting in more heat transfer and electric flow. Combined PCM in mass ratio of 70%, 20% and 10% increased the thermal conductivity up to 95.38 W/mK from 0.18 W/mk. With pure PCM, on an average the electrical efficiency improved by 3% and by 5.8% with combined PCM. Decrement of panel's temperature by an average of 2.7^oC and 5.6^oC with pure and combined PCM was observed respectively. The use of combined PCM found to be more promising as the percentage of energy rate stored in solar panel decreased from 5.7% to 5.2% with pure PCM. Transient energy balance approach also showed these improvements and enhancing behavior of panel's performance.

Idoko *et al.* (2018) used cooling configuration with multi concept that utilizes three different types of passive cooling; these are water passive, air passive and conductive cooling. Two solar panels each of 250 W were mounted at 37 cm to generate space for air-cooling. Along with this at the front surface of one of the solar panels, water cooling is applied in order to decrease the surface temperature to 20^oC. The back side of same panel was attached with an aluminum heat sink. The other set up employed water cooling and heat sink attachment with which aluminum fins attached for boosting the cooling. Reduced water temperature was achieved by introducing ice blocks which enhances the panel surface cooling. Using a derating factor of 80% dissection for photovoltaic array power output was carried out with the help of the equation. The output power increased to 20.96 watts and increment in efficiency of 3% recorded. Results also showed that using module, heat sink and water cooling decreased the module surface temperature to 20^oC.

Sahu and Dube (2018) used array of water tubes at the back of solar PV panel for maintaining the working temperature to its normal operating temperature. Before performing this method, individually both air cooling and water cooling models were investigated under normal operating condition. Comparison between with and without cooling was done. Results showed that tube array with air cooling produced 2.6% of maximal photoelectric conversion of efficiency difference and the temperature decreased by 2-3ºC. It enhanced the output power production efficiency by 2.3% when the daily radiation value was 26.3 MJ. When used the water as cooling medium through tubes, the highest imparity of the photoelectric conversion efficiency was 3% and 8% decrement in temperature was observed. When solar radiation value was 21.9 MJ, the output power was increased maximally by 13.9%.

Rajvikram *et al.* (2019) focused on a novel technique for improving the solar panel efficiency by using PCM OM-29 with aluminum sheets at the backside of panel as TCE. OM-29 is a organic material with melting point and freezing point around 29.0°C and has 229 J/kg latent heat capacity. The maximum operating temperature of the PCM is 120°C. PCM with aluminum occupied an area of 0.0361 m^2. Experiment conducted under natural sunlight for three months and observed results of 2days are attached. Two 12V and 5W panels having dimension 19 cm × 19 cm were used. One panel was attached with aluminum thickness was of the range of few millimeters. Both the panels were inclined at an angle of 45º with a tracking mechanism so that radiation incident on solar panel will be high. Comparative analysis between panel with and without PCM and aluminum was conducted. The PV panel efficiency with attached cooling system was enhanced by mean of 24.4% and mean working temperature by 10.35ºC. Approximately 2% increment in electrical efficiency was recorded. On introducing this proposed cooling system, FLIR images showed that a maximum decrease in temperature of 13°C for the Day 1 and 7.7°C for the Day 2. On comparative note average increment of 30% of electrical power was observed with cooed PV panel. It was concluded from the thorough investigation that aluminum sheet boost the diffusion rate of heat to surrounding. This proposed technique was proved to be more effective than other PCM cooling methods under natural solar irradiance.

Tashtoush *et al.* (2019) investigated the effect of water flow rate and maximum allowable difference in temperature of photovoltaic panel. Water cooling was utilized to study the performance enhancement of PV system experimentally. Additionally dust accumulation effect, ambient temperature, relative humidity was observed. Cleanness factor was used to find out the consequences of accumulated dust. Experimental set up was built at the campus of Jordan University of Science and Technology and experiments were conducted for four months with panel having dimension 1.640 m × 0.992 m. Water was made to flow over the panel surface through nozzles having diameter in the range of 0.001 m to 0.003 m. Trial and error method was used to choose the number of nozzles, namely 6, 9, 12 and 15. Three different water flow rate of 0.9, 0.6, and 0.3 m^3/h used termed as high, medium and low flow rate respectively. For all mass flow rates, 0.002 m diameter nozzles proved to be more effective than other ones and optimum number of nozzles to be 9 for all flow rates. Total 18 nozzles of 2 mm diameter for two panels were positioned to cover the whole panels. The optimum value of the water flow rate for better efficiency and fewer water losses was found to be 0.9 m^3/h. Excess energy productions with effective designed cooling system was found to be around 15.28-17.75% with minimal water losses.

Various studies were conducted on finding the effect of temperature on solar panels. Based on these, it was identified that efficiency of PV panels are significantly affected by the temperature. So various investigators have applied different techniques as a mitigating method till now and studied their effects on performance of solar photovoltaic panels. Till date, use of air with natural and forced heat transfer, water, PCM, nanofluids etc. as a cooling medium have been studied. Active and passive cooling depending on the panel size both was used. Some were proved effective but need more arrangements and cannot be applied for practical use. Few methods brought negligible or a little changes in performance. On reviewing the past papers for cooling methods adopted experimentally, following gaps are identified in the literature:

1. Most researchers have focused on relatively small scale testing i.e. on small rating panels.
2. Many of literature showed efficient performance but with minimum material cooling configuration are few.
3. Available literature is limited only to one way entry and exit of air through duct. This provides a great opportunity to carry the study further.
4. Very few investigators measured the amount of heat extracted from applied cooling technique experimentally. Also very less importance was given to effective and better utilization of heat extracted.

5. Lack of adjustable arrangement in fabricated solar simulator if indoor testing is to be done.

So keeping in mind the above factors there is a need to carry out the further study experimentally on large size panels. Based on the above factors, after going through different ideas, a new way of positioning the dc fan on solar panels will be applied. In this air entry will be from two sides. The extracted air carrying heat from panels can be utilized for various purposes including drying of products, room heating in winters, crop vegetation etc.

2.3 Objectives

Since the day one proposed practical photovoltaic cell has gone through lot of improvement and advancement in terms of performance, technology, material and cost factors. However as discussed earlier the operating efficiency of photovoltaic panel is always less as compared to its maximum efficiency at standard operating conditions. Several losses take place which affects its performance and life directly and practically PV panels never operate under STD. In outdoor conditions, performance of PV module is greatly influenced by various factors. Most of solar energy incident is converted into heat and therefore needs to be cooled for better performance. Therefore certain measures need to be taken to mitigate the heating effect. Based on the literature discussed in this chapter most of the focused pertaining to increase the conversion efficiency. Thus the primary focus of present study is to perusal the impact of different cooling modifications on panel parameters like its efficiency, temperature, power output etc by proof of concept i.e. by experimental means.

The air inside the duct if entered through one side and exit from other side flows under laminar flow conditions which results in lower heat transfer through the duct. In some applications where thermal heat transfer requirement is low, this fact is an advantage but the goal of present study is to enhance the heat transfer and to reduce the surface temperature of solar panel so that it is capable of increasing the turbulences in the duct. This provides a great opportunity to carry the study further by allowing the air to enter the duct through different directions. Keeping this fact in mind it is decided to have the entry of air from opposite directions in the duct. Air is allowed to enter through the holes on two vertically opposites sides of duct. This is done to increases the turbulences. It is known that when turbulence increases, boundary layer increases results in higher rate of heat transfer and hence more cooling will be attained which is advantageous for solar panel performance. So attempts are made to apply the mitigation methods experimentally with the following objectives.

1. To construct an inexpensive and economical solar simulator using halogen tubes so as to artificially create the sunlight. Buying a solar simulator is too expensive and performing the test in outdoor environment does not compatible as radiations fluctuates throughout the day.

2. To observe the effect of temperature on parameters of the panel with and without cooling.

3. To find out the effect of mitigation method adopted on the performance of solar photovoltaic panel.

4. To make a comparative analysis of adopted mitigation method on solar photovoltaic panel with without cooling case.

Materials and Methods

This section provides a concise idea about the materials and methods adopted for the fabrication of experimental setup and tests that were conducted. Indoor testing was done in laboratory at College of Technology, Pantnagar with latitude (29° 3′ N, 79° 31′ E). Economical solar simulator was designed and fabricated by using halogen tubes of 500 W each for producing even solar irradiations on solar panel. Suitable configuration will be installed on solar panel for cooling purpose. This section also highlights the terminologies and methodologies that are being used for study. The purposed work is to fabricate efficient, cost effective and simple to use simulator and to ameliorate the cooling in terms of cost and efficiency.

3.1 Designing and Fabrication of Solar Simulator and Solar Panel stand

Experimental set up of solar simulator stand (a constant light source) and solar panel stands has been designed in Creo Parametric 2.0 and fabricated as shown in Fig. 3.1. One stand for solar panel and one stand for solar simulator have been designed. Design of solar panel stands fabricated using MS Angle, flats and wooden ply board. MS angle of 32 and 40 inches, flats of size 3 cm and ply board 6 and 12 inches thickness are used. Designs of all the stands are made as per dimensions given in table 3.1(a) and 3.1(b).

Table 3.1 (a) Solar panel and simulator dimensions and parameters

Parameter	Solar panel stand	Solar Simulator stand
Length	151 cm	151cm
Breadth	68 cm	88 cm
Height from ground i) From left side ii) From right side	 15 cm 88.4 cm	Variable 34 cm-81cm 105 cm-115
Tilting angle	29.1^{o}	29.1^{o}

Table 3.1 (b) Solar simulator and duct parameters

Parameter	Value
Distance between solar panel and simulator	Variable (6 cm to 42 cm)
Duct size on rear side of one of the panel i) Length ii) Breadth iii) Depth iv) Hole size	 151 cm 68 cm 11.5 cm 2 cm

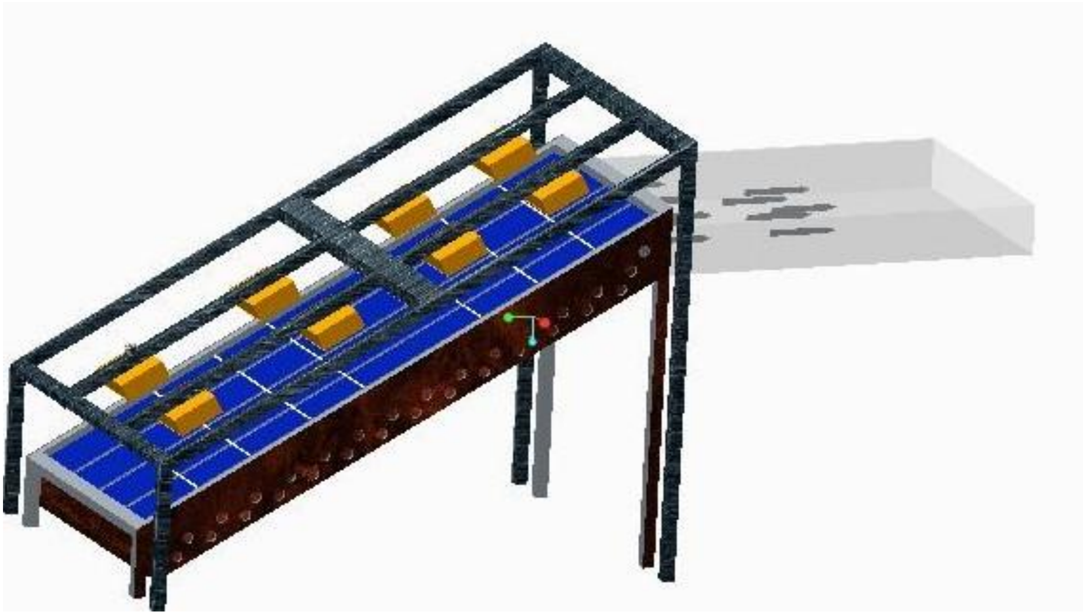


Fig. 3.1 Design of whole setup in Creo Parametric 2.0

All stands are fabricated using mild steel sheet. These are fabricated as such to keep the distance from the solar panel to light source constant throughout its length. This distance is first experimentally optimized. This is done to get the solar radiation maximum and of constant intensity. All stands are fabricated at constant inclination angle of approximately 29.1°. This is done to validate the results with outdoor testing in future as solar irradiance incident on fixed mounted solar panel surface is maximum at an angle equal to latitude of that position **(Tiwari *et al.*, 1994).**

Duct is fabricated at rear side of solar panel and its depth is taken according to the **Brinkworth *et al.*, (2006)** literature and the calculated and obtained range can be varied in the restraints of 7.475 cm to 15.475 cm. It is made air tight from all corners to avoid the leakage and is fabricated at back side of one of the solar panel by using ply board of 6 mm thickness. Holes of size 2 cm are made on both stationary sides of duct to let the air flow inside it. Thermocouples are attached at various points on solar panel rearward surface in order to measure its temperature. Following material and method are used in this fabrication.

3.1.1 MS Angle

These are the L shaped mild steel cross section which is used to fabricate the different structures. A 90^o angle with both sides of equal length is the most commonly used. Here it is used to construct the stands for solar panels and solar simulator. These are designated with the dimension of sides and thickness.

3.1.2 Arc Welding

Arc welding is a welding process which uses an electric arc between an electrode and base material for generating enough heat to melt and join the metals at the contact point. It is used to join the ms angles and flats to fabricate the stands of required dimensions.

3.1.3 Drill machine

BOSCH GSB 550 drill machine is used to make holes on both sides of duct. For this drill bit of size 2 cm is first made in workshop as bit of this size is not available. Total of 51 holes are made on each side.

3.1.4 Black paint

Primer is first applied on entire frame so that the paint doesn't soak into it by sealing the original material. Acrylic wall putty by soldier paints is applied on all possible corners to avoid the leakage of air. After then black paint and premium coating is applied on entire frame and on ply board as well to avoid corrosion as well.

Figure 3.2 and 3.3 show the photographic images of fabricated stands of solar panel and solar simulator painted with black paint.

Fig. 3.2 Photographic image of solar panel stand

Fig. 3.3 Adjustable height Solar Simulator Stand

3.2 Fabrication of Solar simulator

The motive of this section is to discuss the materials that will be used in solar simulator fabrication and factors that will be taken in to consideration during designing and fabrication. Details of materials used are:

3.2.1 Halogen tubes

The critical item needed for a solar simulator is a constant light source. Different light sources like LEDs, xenon, halogen or in combination have been employed for this purpose. Among them halogen have been used widely due to its easy availability, low cost, high light and heat power and spectral similar to natural sunlight. Its wavelength spectra vary from 350 nm to 3500 nm as similar to sunlight. Halogen tubes has a ductile tungsten filament in fused quartz or high silica glass tubesand are filled with little amount of halogen gas mainly iodine or bromine at 7-8 atmospheric high pressure. Quartz is usually used to bear the higher pressure. Halogen gases are used to forbid the thinning and the blackening of the filament made up of tungsten.Total of eight double sided halogen tubes each 500 W, 220-240 V are used. Figure 3.4 shows the photographic image of a halogen tube.

3.2.2 Halogen tube holders

Halogen tubes are fitted inside holders to prevent the bulbs from any damage as these produce a lot of heat. Holders provide the mechanical support, electrical connections and allow tubes to be safely located. The holders that are used here are made of porcelain which is a ceramic material to stand against high temperature.

Fig. 3.4 500 W Halogen Tube

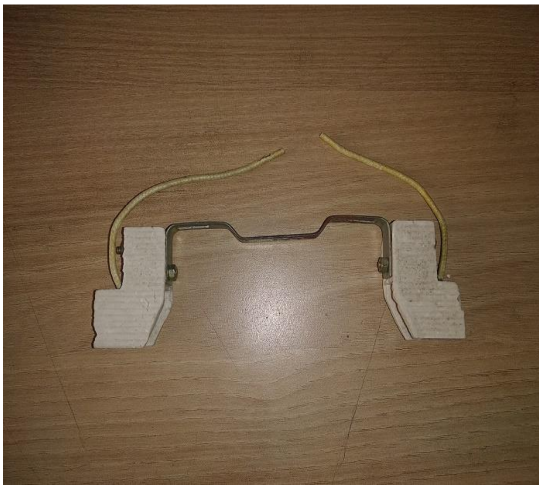


Fig. 3.5 Halogen Tube Holder

A usual halogen tube or bulb when operated reaches to a temperature of above 540°C and concentrates a huge amount of heat as these have smaller surface envelope to work. Therefore needed to hold with some high temperature resistant material and porcelain holder fulfill this requirement. Fig.3.5 shows the photographic image of halogen tube holder used during the experiment.

3.2.3 Reflectors

The purpose for using reflectors instead of only halogen tubes is to provide directional light and to spread the uniform intensity of light as bulbs only provide the radiations in a smaller region i.e. to create a wide beam angle. These help to minimize the number of halogen bulbs used for same degree of solar irradiance on a larger surface area. Reflectors with 500 W of halogen tube are used. Glass cover from them is removed to prevent overheating of wires as and their wire is covered with PVC sleeve to prevent them from melting as shown in Fig. 3.6.

Fig. 3.6 Reflector

Fig. 3.7 Regulator

3.2.4 Regulator

These are the electric devices whose function is to regulate the brightness of light easily and readily as per requirement simply by changing the voltage supplied to the bulb. It dims the intensity with convenient control. Although there are many devices used for controlling voltage and specific name "dimmer" is given to such gadget that intended to organize the light from halogen, incandescent bulb, LEDs etc. It ranges from low power units to high. 1000 W, 240 V, 50 Hz anchor regulator is employed to control brightness of 2 tubes. So total of 4 anchor regulators devices are fitted on simulator stand as shown in Fig. 3.7.

3.2.5 Wiring and cables

To make connections of halogen bulbs with their holders and then with reflectors, regulators and power supply copper wire of diameter 1.5 mm^2 from by Falcon wires and cables, is used.

3.3 Factors taken into consideration

While designing a solar simulator following given factors are taken in to considerations and some steps are taken to optimize these values experimentally.

i) Non Uniformity of solar simulator

It is to be noted that the coverage of light intensity on given test area should be uniform. It is one of the extremely difficult characteristic among all factors to meet. This term "non uniformity" is generally defined in terms of uniformity which can be calculated as a measure of how the solar radiations transmorgify over a selected test area. It is calculated from mean value of minimum and maximum irradiation gauged on a available area and is given by following relation:

$$\boldsymbol{NonUniformity = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}\ X\ 100\%}$$

A comparison is made between the highest and lowest magnitude of irradiations and based on that the uniformity solar simulator is classified in to three different classes, coined as class A, B and C. Different standards to find the non-uniformity of a solar simulator have been used by various organizations. Most popular is ASTM standard outlines of which are:

1. First divide the defined test area into at least 36 equally sized (by area) test positions. Using the irradiation measurement devices, note down the solar irradiation in each of the test spots.
2. The irradiation measurement equipment's size must not be greater than the individual test position's area.
3. The uniformity device shall be large enough that the area of the device times the number of test positions is higher than 25% of the entire defined test area.

ii) Resemblance with sun's spectrum/ Spectral match

The chosen light source for making solar simulator must have similar spectrum as that of the sun and changes in the light intensity by altering the input voltage should not affect spectrum's nature.

iii) Temporal instability

Temporal instability represents the fluctuations of measured value during the interval needed to completely attain a current voltage curve depending on the type of application. It can be described by the minimum and maximum solar irradiation incident on the test surface during the time of exposure and application. Two parameters are used to understand this short and long term instability. Short temporal instability is characterized by the most unfavorable measured value and relates to the sampling time of data (current, voltage and irradiance) during I-V measurement whereas long term instability is linked to the exposure time period where upper and lower value of irradiance depends on the application.

iv) Optimized distance between light source and solar panel

It is the distance between the light source (i.e. halogen reflectors) and the test surface for which the irradiation from light source on panel surface must be maximum with minimum fluctuations. To find the optimized distance, initially a single light source is placed perpendicularly at some distance from panel surface and noted the irradiation in W/m^2 using solar remote unit. Now the perpendicular distance is varied and the respective irradiance is noted down.

v) Optimized number of Halogen reflectors

The numbers of halogen reflectors needed to cover a test area of 0.99 m^2 are calculated by doing experiment first with a single light source (reflector). Using reflector instead of alone halogen tubes provides a large beam angle. Based on the observation and calculation for a area of 0.99 m^2 test area, optimized number of halogen reflectors are installed on solar simulator.

3.4 Method of experimental setup of solar simulator

Due to confined sources, focus of study is limited to only maintaining the uniformity of fabricated solar simulator. As discussed earlier a simulator must provide uniform solar radiations and it can be adjusted by an appropriate combination of space between various reflectors and optimizing the space between the reflectors (light source) and test surface. To perceive the nature of halogen reflector, two types of experimental tests are conducted one with a halogen tube and other with a halogen reflector. Firstly, experiment is conducted with a halogen tube fitted in its holder only and characteristics are measured with a PV analyzer solar remote unit. The sole aim of single tube test is to find how much irradiance is produced and its coverage area by altering the distance. As shown in figure the perpendicular distance between the solar simulator and solar panel is varied from 12 cm to 36 cm and respective irradiance is measured. The irradiance is also altered by changing the voltage input to halogen tube with the help of a regulator and recorded manually. Then the same procedure is reciprocated with a halogen reflector and find out its coverage area. The motive of the halogen tube test with the photovoltaic panel is to find out its coverage area and distance at which fluctuations in radiation intensity are minimum. Based on obtained result, number of halogen reflectors and their position is decided.

3.5 Technical details of solar simulator

The fabricated solar simulator consists of 8 each 500W halogen reflectors fitted on MS angle and flat frame. The locations and layout of all reflectors is demonstrated in Fig. 3.8. These are fixed at an average center to center separation of 36 cm. 500 W halogen tube with is a gaseous discharge type quartz line source which operated at 220/250 V AC supply is fitted inside these reflectors. These light sources have a life period of about 2000 hr. The 8 reflectors are arranged as 2×4 i.e. two lamps in four rows as shown in Fig. 3.8. Two reflectors are connected with a single regulator to change the voltage supplied so as to vary light intensity. Thus total 4 regulators are used.

Fig. 3.8 Arrangement of halogen reflectors on solar simulator stand

The power to simulator is provided by three phase AC. The MS angle frame fitted with 8 reflectors is fixed on a four legs of stand made of 2.5×2.5 cm^2 angle. Four wheels are provided to the stand for simulator's freely motion. Arrangements are made to vary the perpendicular height of simulator from solar module surface by using simple nut bolt arrangement. Maximum and minimum distances that can be reached from ground are 104 cm and 151 cm from right side and 34 cm to 81 cm from left side. The total area covered by simulator is about 1.17 m^2 and effective covered area is 0.99 m^2.

3.6 Fabrication of Cooling Configuration and Installation

3.6.1 Duct

A duct is installed at the backward side of a solar photovoltaic module for cooling purpose. The absorbed solar energy by panel and appearing as heat should be transferred to the cold inlet air in the duct and be exhausted to the atmosphere by forcing it with the help of DC fans at the exit of duct. This helps in reducing the temperature of the module so that its performance gets increased. Its length and width are determined by the size of the solar panel (66.5×149.5 cm^2). So it is clear that the principal design variable here is its depth. This depth needs to be taken such that the maximum value of top surface panel temperature that can be attained should be lowest. A design thumb rule was given by **Brinkworth *et al.*, (2006)** that the ratio of length to depth should be approximately 20.

Fig. 3.9 Fabrication of cooling duct

This is robust rule such that the value being nearly independent of other parameters like slope of array, installation is whether on roof or walls.So the minimum value of depth is calculated to be 7.475 cm and from various literatures it is concluded that the maximum range is up to 15 cm. So depth range should be varied from 7.475 cm to 15.475 cm. First variation of depth is taken according to the size of dc fan that to be installed at exit of duct. It is made air tight from all corners to avoid the leakage and is fabricated at back side of one of the solar panel by using ply board of 6 mm thickness. Holes of size 2 cm are made on both stationary sides of the duct to let the air flow inside it as illustrated in Fig. 3.9.

3.6.2 DC cooling fan

DC cooling fans of rating 18 V, 0.225 A and 4.05 W power consumptions are used to force the heated air out and help in cooling of panels. Total of four number of dc fans are used at the exit of duct to fulfill the air flow requirement. All these are operated from direct solar panel power output. Fig. 3.10 shows the photographic image of installed DC fans at the exit of the duct. These are run from the power output generated by the solar panel directly.

Fig. 3.10 Installation of DC fans at duct exit

3.7 Solar panel

It is an assembly of photovoltaic cells that convert the solar light directly into direct current electricity. Since the discovery of photovoltaic cells, different types of panels have been developed. Most of the solar photovoltaic panels that are in use today are silicon crystalline based. Polycrystalline solar panels of each 150 W have been used with the following specifications as given in table 3.2.

Table 3.2 Specifications of polycrystalline solar panel

Specifications	Symbol	Value	Test Condition
Rated power	P	150 W	1000 W/m^2 25^{o}C
Open circuit voltage	V_{OC}	21.8 V	
Short circuit current	I_{SC}	8.81 A	
Voltage at maximum power	V_{MP}	18.3 V	
Current at maximum power	I_{MP}	8.34 A	
Fill factor	F.F	79.4%	
Module Temperature	t	27.9^{o}C	
Module Efficiency	η	15.3%	
Module Area	A_m	0.99 m^2	

3.8 Temperature sensor

2 wire K- Type Thermocouples of diameter 18 SWG are employed in experiments. K- Type Thermocouples are the most common and general purpose thermocouples with a sensitivity of approximately 41 µV/°C.K type thermocouples have positive and negative element made of chromel being positive and alumel being negative element. Chromel is an alloy of nickel and 10% chromium while Alumel is a nickel alloy with 5% aluminum and silicon. The purpose of using thermocouples is to measure temperature of solar surface temperature located at various positions and atmospheric temperature.

3.8.1 Thermocouple junction formation

Thermocouple beads are made in laboratory using thermocouple wire, variac or variable autotransformer which helps to regulate the voltage, electric wire and mercury. Following procedure is adopted to make thermocouple junction:

1. First step is to cut the thermocouple wire in to required length and then remove the insulation from both ends of thermocouple wire.
2. Twist the insulation removed element from one side of thermocouple wire together by using a plier.
3. Connect the other side of thermocouple wire to one terminal of variac.
4. Connect the other terminal of variable transformer with an electric wire to complete an electric circuit.
5. Take small quantity of mercury in to bottle's lid and then held other side of electric wire in to it.

6. Set the voltage at 10 V with the help of knob of transformer and on the power supply.
7. Now dip the twisted elements of thermocouple wire in to mercury.
8. As soon as tip of twisted wire touches the mercury, circuit gets completed and a spark is generated.
9. Finally both the twisted ends of thermocouple wire get fused together resulting in to a thermocouple bead. Fig. 3.11 shows the process of formation of thermocouple junction.

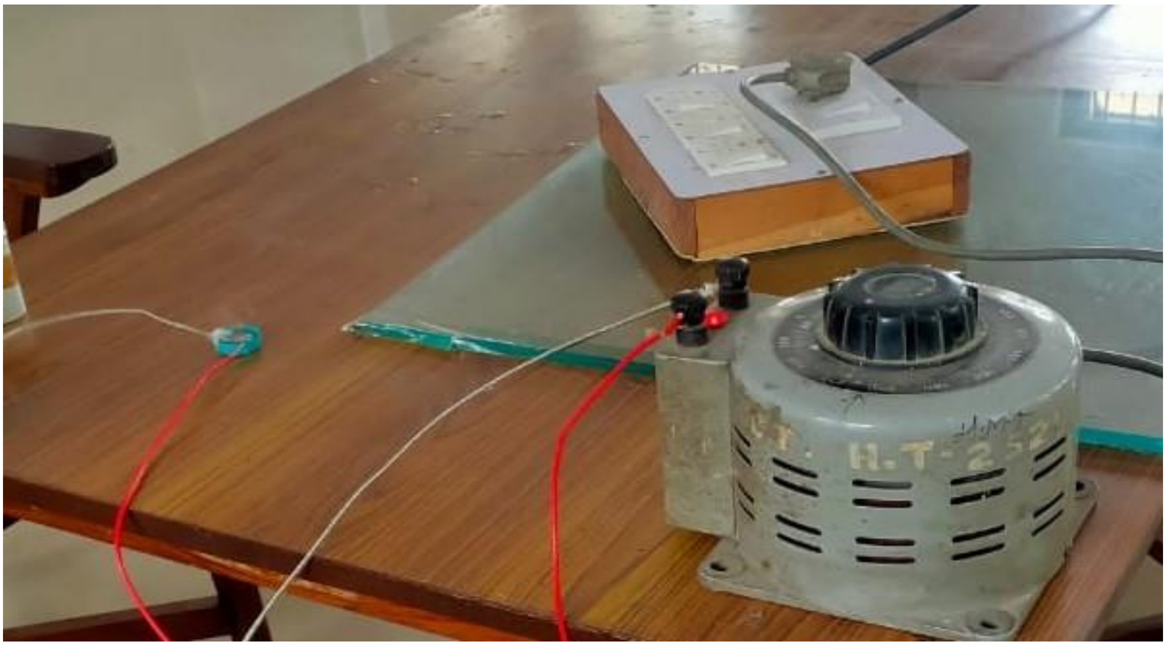


Fig. 3.11 Formation of thermocouple junction

3.8.2 Thermometer

A mercury based thermometer is used to calibrate the thermocouples. Temperature of hot and chilled water is measured with the help of thermometer and the obtained readings are compared with the temperature of same material sensed by thermocouples at the corresponding time byplotting a curve between them.

3.9.1 Data Logger

Thermofisher DT85 series 3 with 16 input channels is used. Total 9 thermocouples of K type fitted at various positions of solar panels are connected at different channels numbering from 1 to 9. Corresponding temperature sensed by thermocouple connected to a particular channel is displayed on data logger software dEX® 2.0 which allows to configure and program the data logger. All the temperature readings are retrieved in to excel file. It is an electronic equipment with many input channels which is used to automatically sense, measure, monitor and record the environmental parameters like temperature, humidity, power usage, voltage, current, pulses, counts, etc. at various locations and allows the user to documented the measured data. For receiving the information it contains a sensor and a computer chip for data storage. That stored information can be exported to computer or laptop for further analysis of data. Although data logging can be done manually but constant human observation is quite rigorous, time consuming and chances of errors will be more. However, using an electronic device is much more accurate and reliable thus saving a lot of effort and time. Photograph of data logger used in experiment is shown in Fig. 3.12.

Fig. 3.12 DT85 series 3 data taker

3.9.2 PV system analyzer

PV system analyzer is a tracer for tracing I-V characteristics for a solar panel system. It provides different parametric measured values like irradiation, average panel surface temperature, open circuit voltage, short circuit current, maximum voltage and current, maximum power output, series resistance etc. It is available with following important features:

i) Analyzer and moisture proof Remote solar detector and are connected by Bluetooth wireless communication. Remote solar unit is also provided with a thermometer sensor.

ii) Maximum solar power system P_{max} with a capability of 12000W (1000 V and 12 A) and search by feature of auto scan.

iii) Efficiency calculation in %.

iv) All characteristics curve of solar panel can be measured, analyzed and recorded for time period of one hour (for instance) with data logging/open function.

v) For verifying the solar module performance it provided the OPC and STC test reports by converting I-V curve under operating parameter condition to data under standard test condition based upon IEC standard by showing OK or NO OK.

vi) It enables the user to set up the solar panels parameters through software keyboard and can measure and analyze the performance of many solar modules in a single measurement.

vii) It is helpful in converting the efficiency of DC to AC power conversion and calculate the efficiency of the maximum power output.

viii) Built - in Calendar Clock with rechargeable Lithium Battery provided with warning of low battery feature and AC power adaptor to charge it.

ix) PC communication through optical USB cable.

Fig. 3.13 shows the photographic image of PV system analyzer along with RSD i.e remote solar detector for measuring the solar radiations.

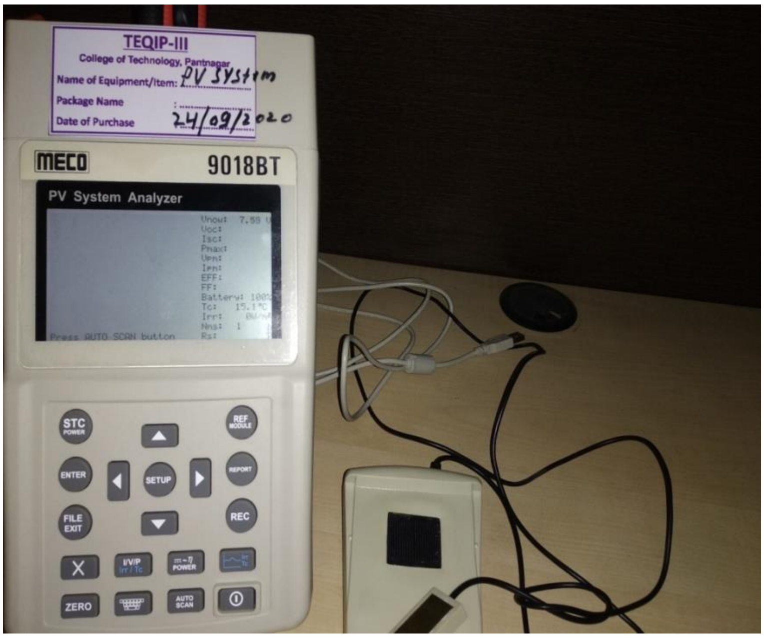


Fig. 3.13 PV system analyzer with RSD

3.9.3 Digital Thermo Anemometer

Digital thermo anemometer is a measuring portable test device which is used to measure the air flow and temperature. These are convenient for applications where quick or constant measurements required to be taken. HT-91 anemometer is used in this study whose photographic image is shown in Fig. 3.14.

Fig. 3.14 Photographic image of Digital thermo anemometer

Fig. 3.15 Photographic image of Infrared camera

3.9.4 Thermal Imaging Camera

Thermal imaging is a process in which a thermal imaging camera captures and creates an image of any object by converting infrared radiations emitted from that object in to electric signals. The captured image represents the temperature of that object. It can even provide a clear image in a dark environment also. We know infrared radiations have a wavelength in the domain of 700 nm to 1 mm. Thermal imaging camera uses this energy to generate thermal images and the camera lens focuses the energy greater than the visible region energy i.e. infrared energy on to a set of detectors that create a thermogram (a detailed pattern). These thermograms are then transformed in to electric signals to produce thermal image that we can easily see and interpret. Testo infrared camera is used in this study whose photographic image is shown above in Fig. 3.15.

3.10 Calibration of Thermocouples

Calibration of any equipment must be done before using them. For this two scales primary and secondary are used. The primary measurement scale is usually a reference scale and measurements made on this scale are relatively more precise than other. As thermocouples have different response even under identical conditions as it depends on the perfect formulation of the metals used to construct in that particular thermocouple. In calibration of thermocouples, mercury thermometer (measuring range -10^oC to 360^oC) is used as a primary scale and thermocouple reading as secondary. Thermocouple reading is taken with the help of digital temperature indicator. Following procedure is followed for calibration process.

1. Take a beaker and crushed some ice cubes in to it.
2. Along with thermocouple wire place the thermometer bulb in it.
3. Note the temperature shown by mercury thermometer and digital temperature indicator.
4. Now do calibration for higher temperature.
5. Set a fix temperature in constant temperature water bath.
6. Note the readings after increasing set temperature of water bath by 5^oC.
7. Repeat the same procedure up to temperature of 100^oC.
8. Further note the reading after an decreasing interval of 5^oC.
9. Construct a calibration curve by comparing thermocouple and thermometer output as shown in graph.

(a) Cold temperature calibration **(b) Calibration in water bath**

Fig. 3.16 Photographic view of calibration process

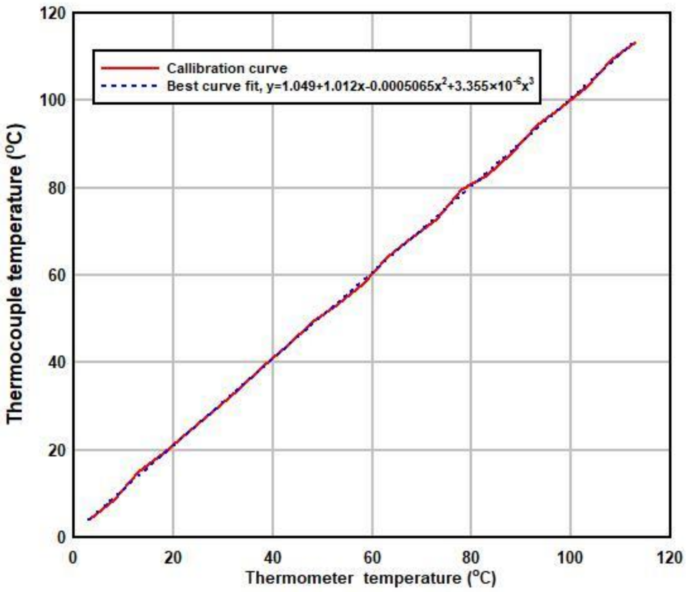


Fig. 3.17 Thermocouple calibration curve

Figure 3.16 (a) and 3.16 (b) shows the clicked photographic view of calibration process and calibration graph is plotted with outputs of experiment. Fig. 3.17 shows the clicked photographic view of calibration process and calibration graph is plotted with output reading of experiment. Red line shows the curve plotted through readings obtained during calibration process while blue dotted line shows the best curve fit obtained and third order equation for the same is depicted in the dialog box of the graph.

3.11 Experimental setup and procedure

Figure 3.18 illustrated the complete experimental setup for indoor testing and Fig. 3.19 shows the same experimental set up for outdoor testing excluding the solar simulator.

Fig. 3.18 Experimental set up for indoor testing

Fig. 3.19 Experimental set up for outdoor testing

The following steps are followed in the present investigation:

1. The experiment starts with the placing the solar panels with and without cooling configuration under the fabricated solar simulator and artificial irradiation of varying is projected on them.
2. Connections with PV system analyzer and data logger are made.
3. Monitoring the solar radiation, temperature, solar panel performance and air flow rate in case solar panel with cooling configuration at every 5 seconds. The experiments are conducted till 4:30 pm for different solar radiations.
4. The same procedure is repeated by changing the operational parameters like intensity of irradiation, distance between light source and panels, number of cooling fans etc.
5. The same experiment and procedure is conducted under natural sunlight.

Results and Discussion

This chapter deals with the discussion of results obtained from experiments conducted on a fabricated solar simulator and incorporating variable number of fans. Different irradiation levels have been considered in the experiments. Experiments are carried out at Pantnagar. Initially experiments are conducted with fabricated solar simulator for its uniformity, temporal stability and optimized distance between the solar panel and the light source. Later experiments are conducted with solar panel to observe the effect of temperature on its performance including power and efficiency and then effect of cooling configuration adopted with 1, 2, 3, and 4 numbers of fans. One panel is used as a reference and other is provided with air active cooling setup. Outdoor testing is also done to see the effect of applied cooling configuration on panel's performance in actual conditions.

The motive of experiments is to study the performance of cooled polycrystalline silicon panel with different number of DC cooling fans. Previous studies showed different amount of panel power and efficiency enhancement by applying various cooling techniques. These improvements have been reported as a result of lowering in temperature by extracting generated heat in the system. A comparison is made between indoor and outdoor test results.

4.1 Testing of solar simulator

The performance of the solar simulator is tested in terms of spectral resemblance to the sun's spectrum, uniformity of illumination, collimation, flux intensity, flux stability and obtainable flux range. It is not possible to achieve the exact simulation as that of sun therefore standards set by different agencies including ASHRAE are used for comparative analysis.

Before fabrication of set up of solar simulator, intensity of halogen tube of 500 W is tested. It is connected with a voltage regulator to vary voltage and intensity of flux. A 1000 W anchor regulator is sufficiently used to control the voltage. Area of illumination on the solar panel is also measured. It is observed that it covers only two cells of a 100W polycrystalline solar panel as it concentrates the light only in a small region. Then same procedure is adopted by using a reflector inbuilt with halogen tube as it is provided with another surface which reflects the light from tubes and provides illumination on larger area. It is illustrated that its light intensity covers four cells of same panel therefore further tests are carried out with halogen reflector on 150 W of polycrystalline solar panel.

With halogen reflector light source, experiment shows that the maximum intensity of radiation is found to be at the center of reflector and as distance from the center of light source increases radiation value decreases along with major and minor axes i.e. along x and y axis both on solar panel. However, the decrement is more along minor axis as clearly depicted in Fig. 4.1 which shows the pattern of illumination of a single lamp along two axes. For some randomly selected distance between solar panel and light source (30 cm), the maximum radiation is observed to be 854 W/m^2 which is at the center of reflector and away from its center radiation intensity decreases. Along x and y axis, for a distance of 20 cm on both sides from center, the observed irradiation is 430 W/m^2 and 300 W/m^2 respectively and as distance goes beyond 20 cm the obtained light intensity is very small. As used panel has a cell dimension of 16.1×16.1 cm, so a single reflector uniformly illuminates four cells, each of dimension 16.1 cm. Therefore to cover the whole panel uniformly, total of 8 reflectors are used.

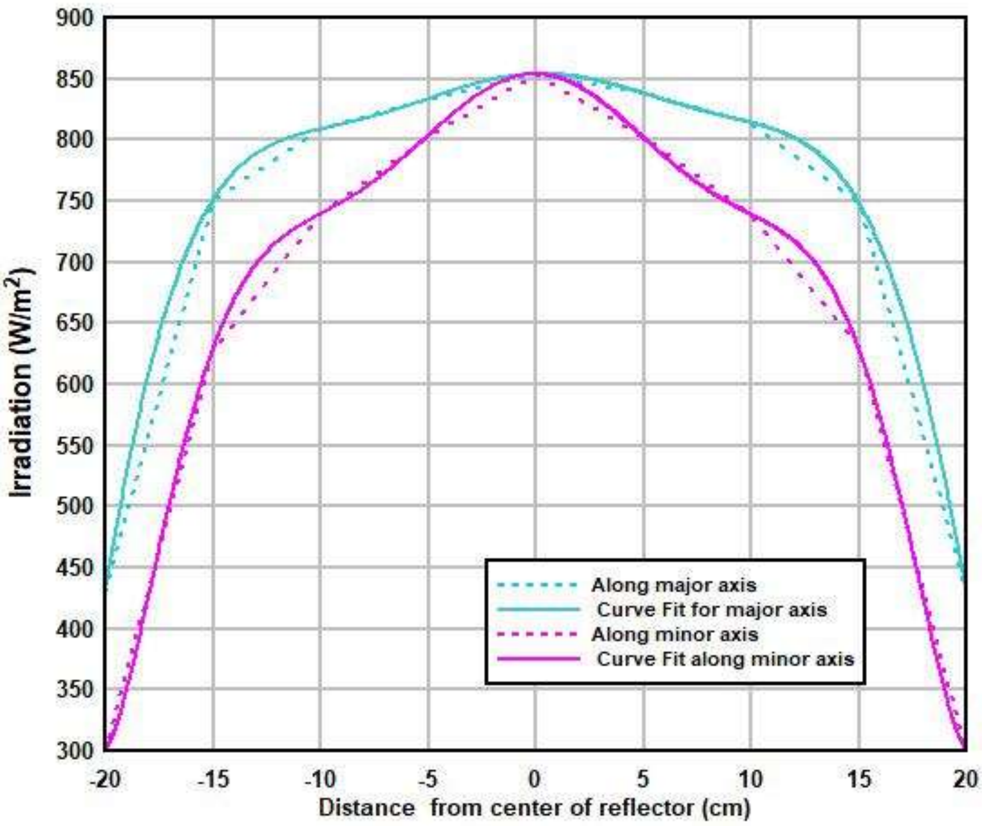


Fig. 4.1 Illumination of a single halogen reflector along x and y axis

4.1.1 Variation of solar irradiation across different cells of a solar panel

Figure 4.2 illustrated that the distribution of solar radiation shows high fluctuations and unacceptable difference in intensities across the different cells of solar panels and variations in radiation with distance between the solar panel and solar simulator.

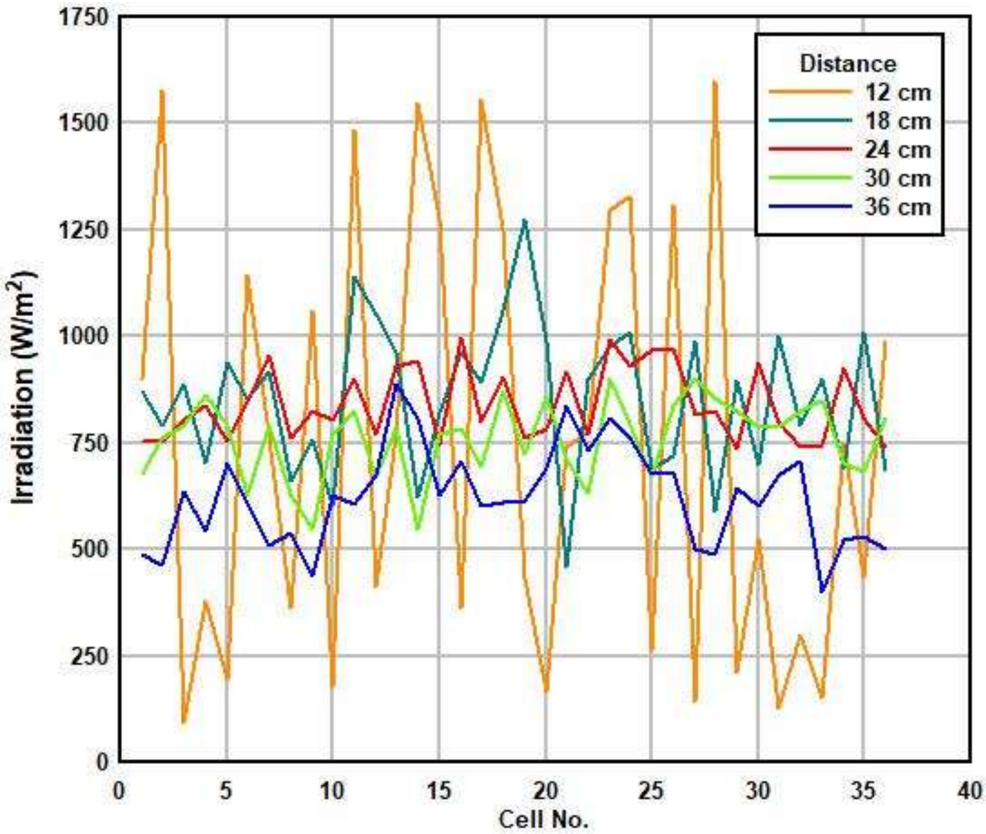


Fig. 4.2 Fluctuations in solar intensity across different cells for variable distance

Therefore, several experiments are conducted taking the distance between the test surface and light source as variable. Irradiation value is taken randomly for each cell, comprising of 36 cells of solar panel. It is observed from experimental results that for a distance of 12 cm, the irradiation obtained is higher compared with higher distances but with more fluctuations. For this distance intensity at certain points is very high in the range of 1600 W/m^2 and at other points it is in the range of even 151 W/m^2. This variation appears because the reflector light doesn't get enough space to spread, instead it gets concentrated in a small region. Very low intensity is measured at areas other than the center of reflector. Same steps are repeated for other distances. It is found that as the distance increases the light intensity at various cells become more uniform and up to certain distance the fluctuations become minimum and then again starts increasing. It is determined that there is an optimized distance for both fluctuations and intensity that provides a balanced result. The optimum distance is found to be 24 cm with maximum uniformity and minimum fluctuations. The investigation shows that at two points at the lower most corner of solar panel, the non uniformity reaches to 23.314% and 21.06%. This is because of the fact that these points are slightly deviated and reflector does not illuminate them as much as others cells. However, excluding these two points, the maximum non uniformity achieved to be 14.81% which is compatible with the British Standards values (spatial non uniformity to be less than 15%) for testing the solar simulator. Similarly it is clearly seen in Fig 4.2 that the intensity of light increases as distance decreases.

4.1.2 Variation of Non Uniformity with distance between test surface and reflector

Figure 4.3 shows the percentage of non uniformity of the solar irradiation as a function of distance between the solar surface panel and the light source.

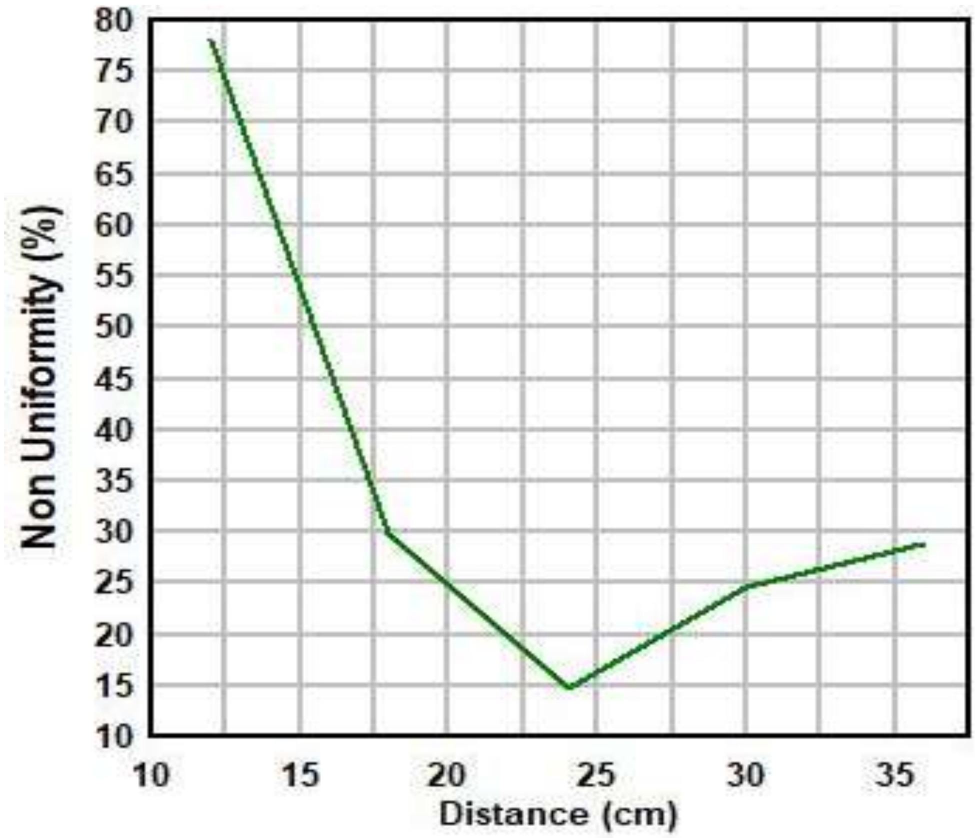


Fig. 4.3 Variation of non uniformity (%) with distance between test surface and reflector

It is observed that the unevenness of radiation decreases as the distance between test surface and light source increases reaches to a minimum value and then increases again with further increase in distance which is in accordance with the ASTM procedure for simulators testing **(ASTM Standards).** This variation in non uniformity shows that there must be an optimum distance for which uniformity will be maximum. For a distance of 12 cm the non uniformity is highest having a value of 78.01%. On moving towards right the non uniformity decreases to 29.89% for 18 cm, reaches to a minimum value of 14.81% for a distance of 24 cm and then again starts increasing. For a distance of 30 and 36 cm, non uniformity is found to be 24.5% and 28.7% respectively.

4.1.3 Temporal stability of fabricated solar simulator

For reliable measurements and results, the vital parameter needed for a solar simulator is to produce the steady state illumination. Steady state illumination means that it should provide constant radiation intensity during its whole operating time. However, during the preliminary experiments and analysis of simulator, it is observed that the light intensities from halogen tube get concentrated around specific area only.

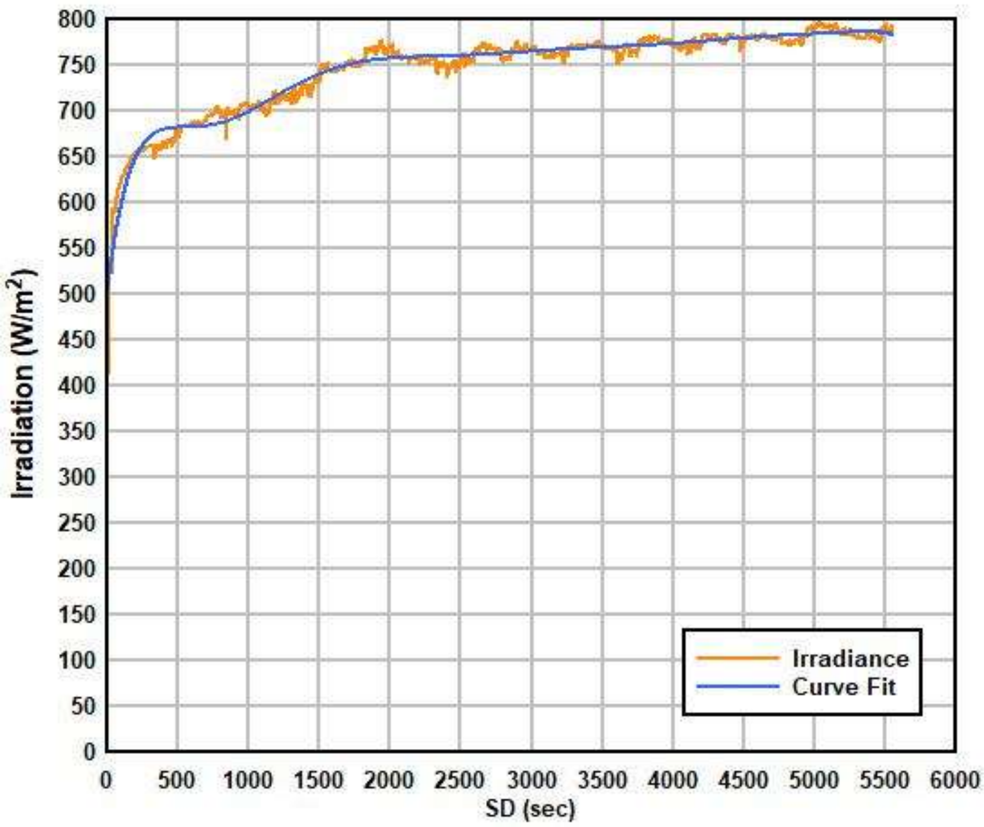


Fig. 4.4 Temporal Stability of irradiance of tungsten halogen solar simulator at optimized distance between panel surface and simulator

Therefore it was decided to use reflector which illuminates light in larger area than before. However the light intensities with both are fluctuating and unstable. In order to tackle this problem, the reflectors are left working for approximately 30 minutes prior to the starting of the tests. As soon as reflectors are ON, the solar intensity suddenly increase to 410 W/m^2 and onwards as the solar duration increases the solar radiation intensity continues to increase in highly fluctuating manner resulting in steeper curve up to 1500 seconds of solar duration. From 1500 to 1976 seconds of solar duration the curve slightly flattens and fluctuation in intensity is decreased and becomes more stabilized. Continuous observation and reading showed that the light source that is used takes about 35 minutes to get stabilize and reach steady state intensity. Fig. 4.4 shows the variation of solar radiation with time at some point on solar panel.

4.2 Effect of irradiation on solar panel average surface temperature

It is quite obvious that with increase in intensity of solar radiation, more energy is transmitted to solar panel which results in to higher temperature of its surface. Fig 4.5 shows increment in solar irradiation results in higher temperature of solar panel.

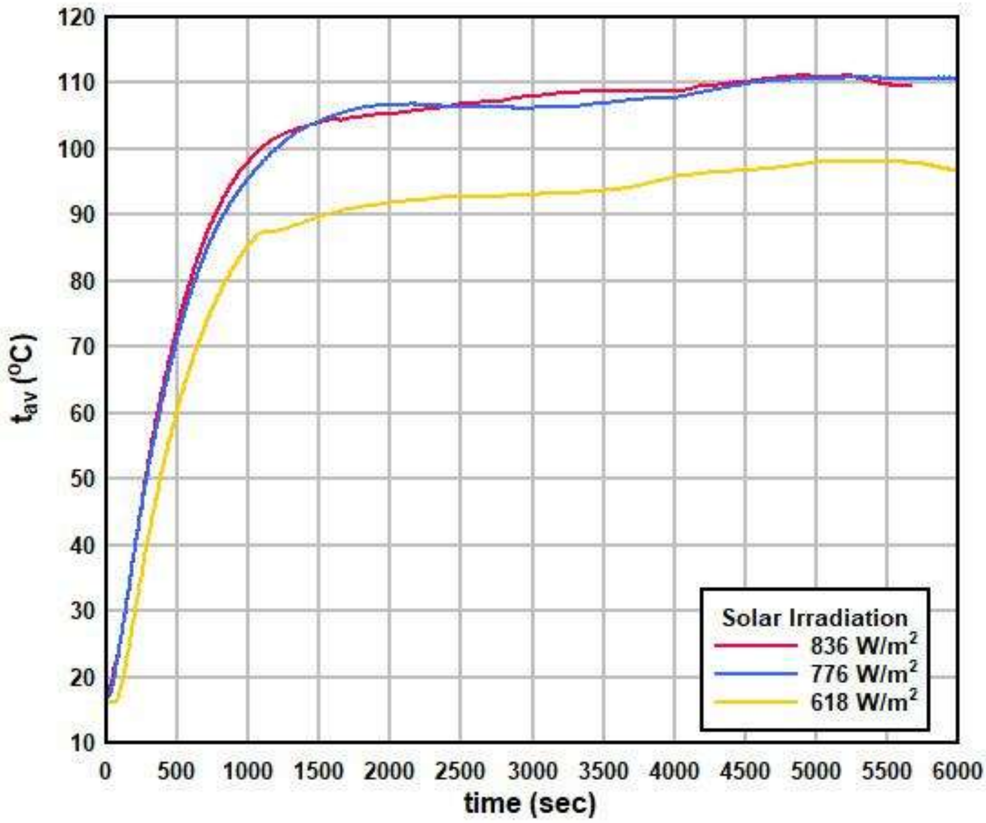


Fig. 4.5 Average surface temperature of solar panel with three different solar irradiations

The increment in solar panel surface temperature is directly proportional to the intensity of solar insolation. As solar radiation increases from 618 W/m^2 to 836 W/m^2 more heating is observed which results in to higher average surface temperature. For irradiation of 836 W/m^2, the highest average surface temperature that panel attain is 111.1 ^{o}C, 110.8 ^{o}C with irradiation of 776 W/m^2 and 98.2 ^{o}C with 618 W/m^2. As panel has an efficiency of 15.3% only i.e. it converts only 15.36% of the incident light on it into electrical output and remaining 84.7% is converted into heat which raises its surface temperature and this large amount of heat results in decrement in its performance. Fig. 4.6 shows the temperature distribution of solar panel surface without any cooling configuration.

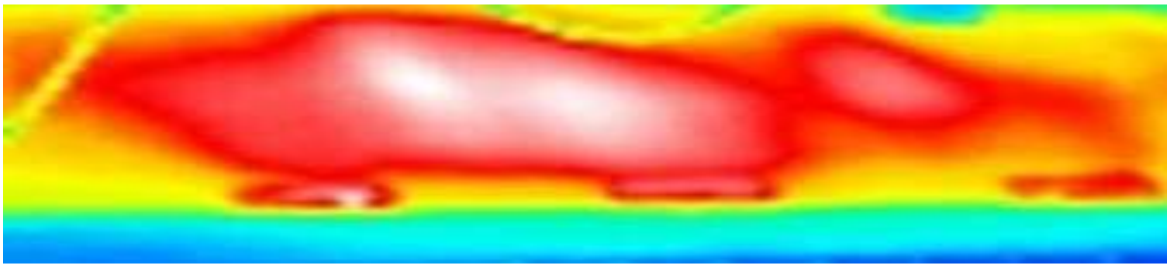


Fig. 4.6 Thermal image of solar panel under artificial sunlight

4.3 Temperature influence on I-V characteristic of polycrystalline solar panel

As solar panel is standardized for particular standard conditions of temperature 25oC, irradiation of 1000 W/m^2 and air mass of 1.5 but the actual practical conditions are obviously different form STCs. Also the experiments are conducted on a setup under an artificial sunlight of halogen tube containing reflectors; therefore the performance level of solar panels is quite different from the manufactures data. As discussed in introduction chapter, temperature greatly affects the performance and characteristics curve of solar panel. For three different radiation level of 836, 776 and 618 W/m^2 the effect of temperature on I-V and P-V characteristic of 150 W polycrystalline solar panel is observed as presented in Fig. 4.7 (a), 4.7 (b) and 4.7 (c).

It is clearly visible from graph that the I-V characteristic curve for every radiation level shifts downwards as the temperature increases from 25 ^{o}C. It is due to the fact that maximum portion of incident light results in generation of heat which increases panel temperature. Only a small portion (equal to panel's efficiency) of incident energy is converted to electrical energy and remaining percentage of photons energy is higher than the band gap energy of silicon semiconductor. Thus, the production of heat energy will lead into increments of PV panel temperature. This increment results in to gradual increment in panel current while it decreases the panel voltage proportionally. However the increment in current is little as compared to decrement in voltage. Overall panel power decreases since the rate of voltage decrement rate is more than the increase in current rate.

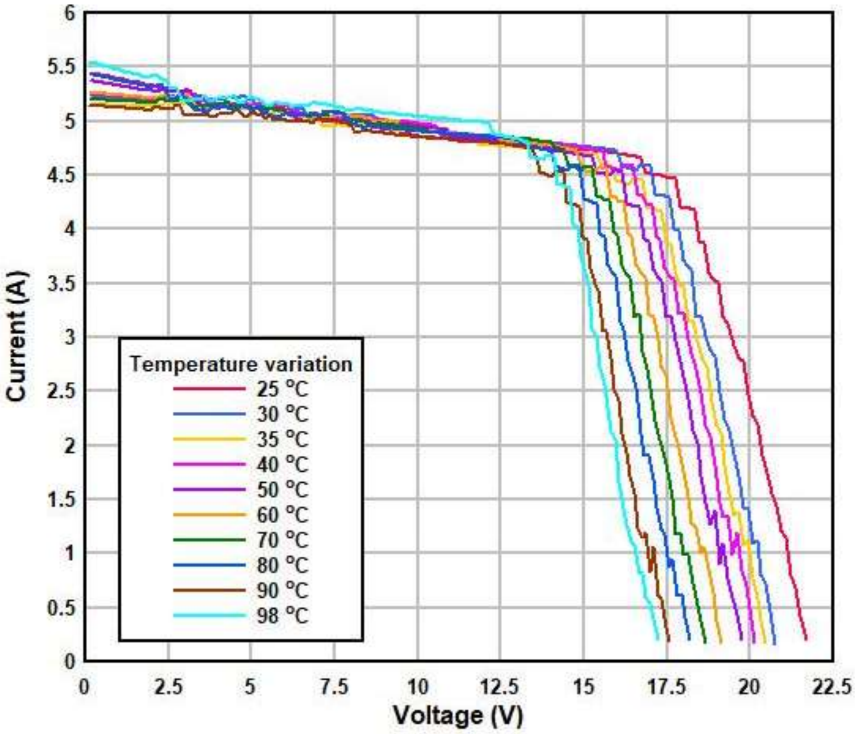


Fig. 4.7 (a) Effect of temperature on I-V characteristic under irradiation of 618 W/m^2 at 35 W DC load

For irradiation level of 618 W/m^2, the panel short circuit current increases from 5.45 A to 5.55 A while open circuit voltage that is obtained from panel decreases from 21.67 V to 17.22 V as temperature increases from 25 to 98 degree centigrade. The current increases by 0.099 A and huge reduction in voltage by 4.45 V is observed as compared to current. In terms of percentage the I_{sc} increases by only 1.817% while V_{oc} drastically decreases by 20.53%. Similarly the voltage at maximum power point V_{pm} decreases from 17.74 V to 14.09 V resulting in to 20.057% reduction while current at maximum power point I_{pm} increases from 4.467 A to 4.673 A resulting in to negligible increment of 0.206 A. The same pattern is observed with higher irradiation level but more changes are observed as average surface temperature increases with increase in solar insolation.

The short circuit current increases from 5.45 A to 6.53 A for irradiation of 776 W/m^2 as compared to 618 W/m^2. Fig. 4.7 (b) shows that for this radiation level the short circuit current attained increases from 6.53 A to 7.80 A resulting in increment of 1.27 A while open circuit voltage decreases from 21.06 V to 16.69 V thus resulting in decrement of 4.37 V as temperature increases from 25 to 110 degree centigrade. In terms of percentage the I_{sc} increases by only 1.94% and V_{oc} decreases by 20.75%. The voltage V_{pm} at MPT decreases from 17.38 V to 13.89 V resulting in reduction of 20.08% while current I_{pm} increases from 5.47 A to 5.52 A resulting in negligible increment of 0.89%. Thus temperature produces an unfavourable effect on panel characteristics.

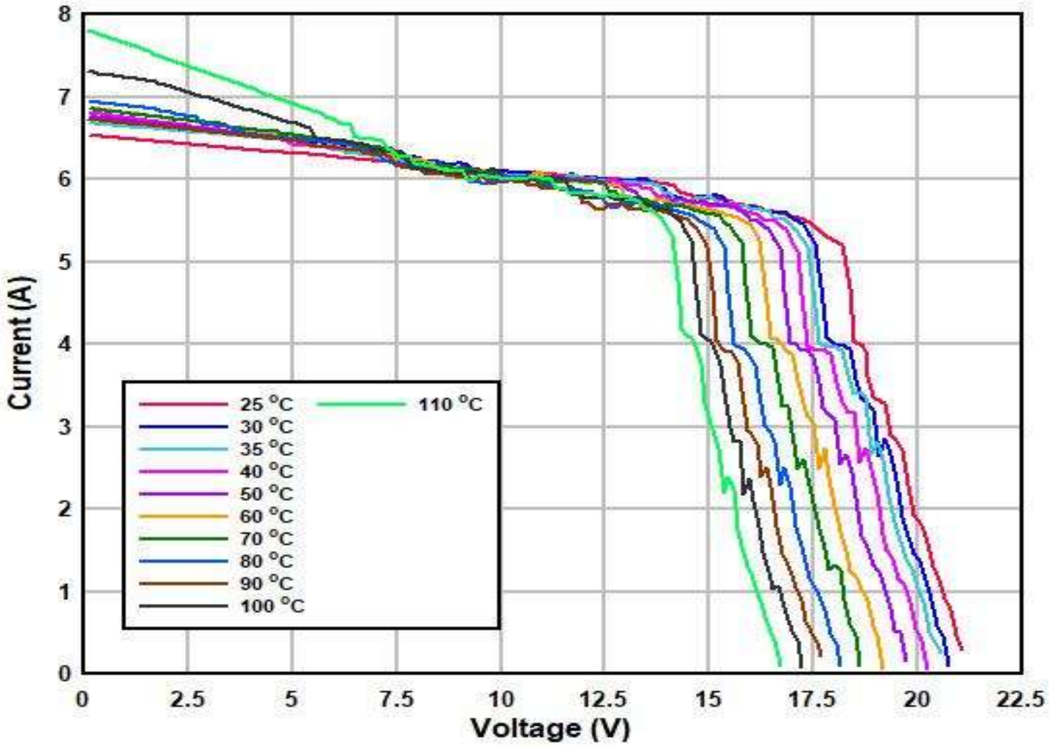


Fig. 4.7 (b) Effect of temperature on I-V characteristic under irradiation of 776 W/m^2 at 35 W DC load

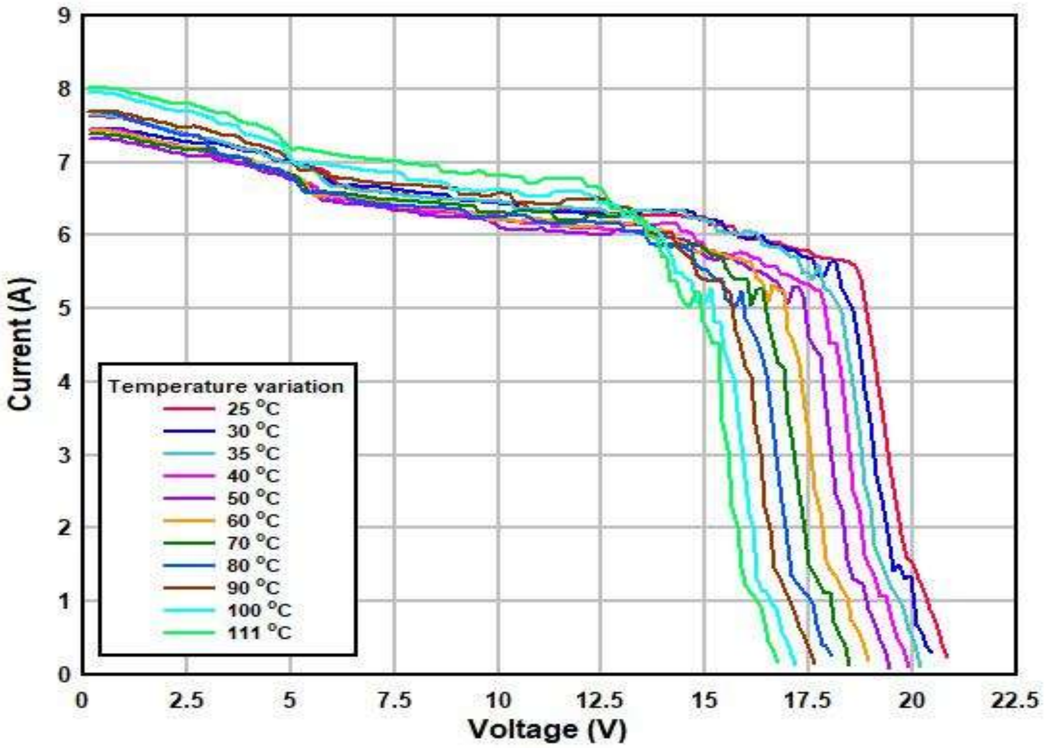


Fig. 4.7 (c) Effect of temperature on I-V characteristic under irradiation of 836 W/m^2

For irradiation level of 836 W/m^2, the current as compared to first one gets increased by 1.5 times as it is directly proportional to the radiations while voltage gets slighlty reduced as it has logarithmic relation with the radiation. Here the short circuit current I_{sc} that is obtained from solar panel increases from 7.63 A to 8.80 A while open circuit voltage V_{oc} decreases from 20.85 V to 16.76 V as temperature increases from 25 to 111 degree centigrade. The current increases by 0.39 A and huge reduction in voltage by 4.09 V as compared to current. In terms of percentage the current increases by only 5.14% and voltage decreases by 19.21%. The voltage V_{pm} at MPT decreases from 18.47 V to 13.27 V resulting in decrement of voltage by 4.2 and 22.73% reduction while I_{pm} increases from 5.64 A to 5.90 A resulting in to negligible increment of 0.25 A. This shows how temperature greatly influence the operating voltage of a solar panel.

4.4 Temperature influence on P-V characteristic of polycrystalline solar panel

The power curve according to the characteristic curve shown is obtained by the following equation.

$$P = V * I$$

However these values are directly obtained from PV system analyzer. As power output is product of obtained current and voltage, even slightly change in any one of the voltage or current value changes the power and these both are affected by temperature as discussed in section 4.2. So temperature also affects the power curve as well. Effect of temperature on P-V curve for three radiations is shown in Fig. 4.8 (a), 4.8 (b) and 4.8 (c). As the temperature increases, the power curve is shifting downwards. Accordingly the maximum power point is also shifting downwards.

Theoretically power decrement with the temperature increment is given by the temperature coefficient of solar panel as given by the manufacturer which is - 0.47%/^{o}C i.e. for each degree temperature rise the module power decreases by 0.47% i.e. it should be 2.3% for every 5 ^{o}C rise. However the actual reduction varies from reported value by manufacturer. For irradiation of 618 W//m^2, the maximum power from 79.25 W reduces to 65.85 W thus reduction occurs by an amount of 13.4 W as temperature rises from 25 ^{o}C to 98 ^{o}C. Thus the total power loss occurs by 16.89% which is a large amount. Accordingly the maximum power point shifts from 17.74 V, 4.467 A to 14.09 V, 4.673 A. As the temperature increases 25 ^{o}C to 30 ^{o}C, the power reduces by 2.12% which is less than manufacturer's provided value of 2.35%. This has happened because the theoretical temperature coefficient is calculated under some particular conditions while actual operating conditions are quite different from those.

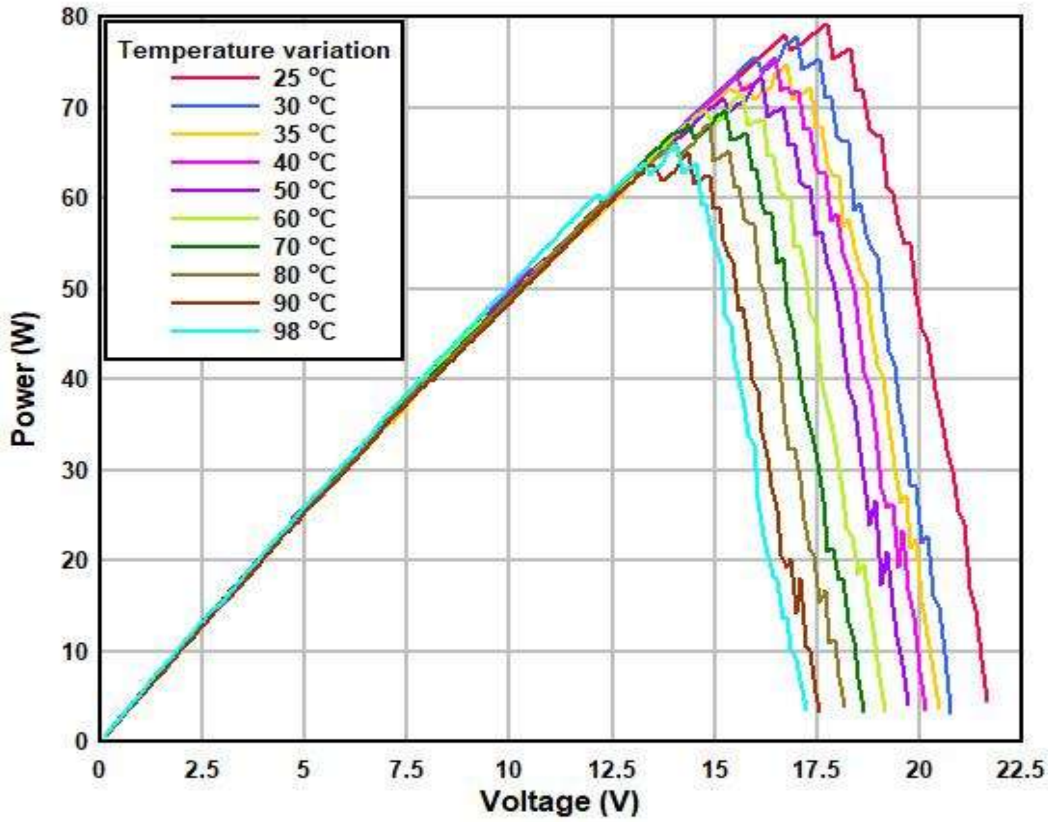


Fig. 4.8 (a) Variation of P-V curve of a solar panel at different temperatures at 618 W/m^2

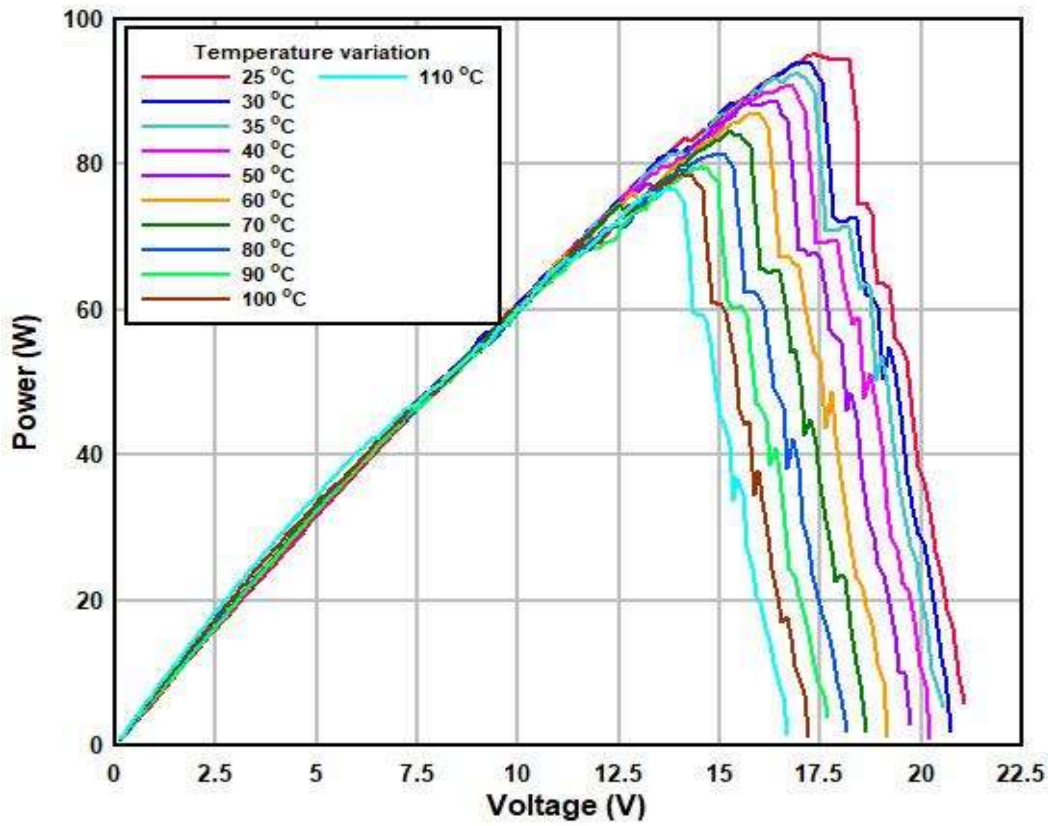


Fig. 4.8 (b) Variation of P-V curve of a solar panel at different temperatures at 776 W/m^2

As irradiation increases the maximum power produces by solar panel also increases as power depends on amount of solar radiation incident on module. For irradiation of 776 W//m^2, the maximum power obtained is 95.16 W which is more than power at 618 W/m^2 which reduces to 76.65 W resulting in to reduction by an amount of 18.51 W as temperature rises from 25 ^{o}C to 110 ^{o}C as seen in Fig. 4.8 (b). Thus the total power loss occurs by 19.45%. Accordingly the maximum power point shifts from 17.38 V, 5.47 A to 16.69 V, 4.954 A. Also as the temperature increases 25 ^{o}C to 30 ^{o}C, the power reduces by 2.89% which is higher than from the reported value of 2.35%.

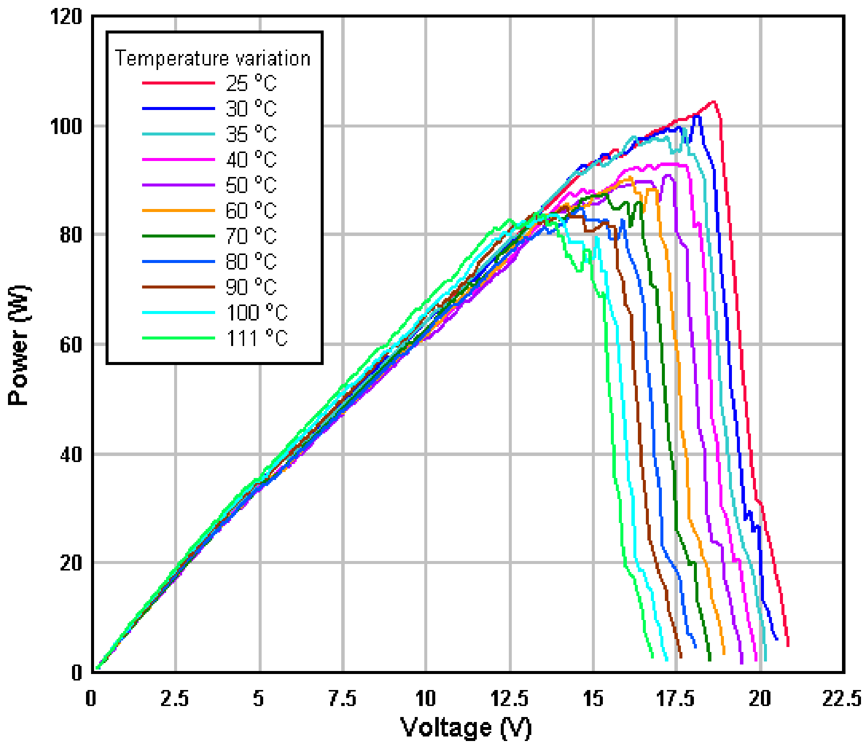


Fig. 4.8 (c) Variation of P-V curve of a solar panel at different temperatures at 836 W/m^2

As compared to 618 W/m^2, the maximum power for 836 W/m^2, increases by amount of 25.01 W. Thus for increment of radiation by 35.7%, the power output increases by approximately 32% which shows that the amount of radiation will increase the power by approximately same amount. For irradiation of 836 W//m^2, the maximum power obtained is 104.26 W which reduces to 84.23 W resulting in to reduction by an amount of 20.85 W as temperature rises from 25 ^{o}C to 111 ^{o}C as shown in Fig. 4.8 (c). Thus the total power loss occurs by 19.20%. Accordingly the maximum power point shifts from 18.47 V, 5.645 A to 14.27 V, 5.903 A. Also as the temperature increases 25 ^{o}C to 30 ^{o}C, the power reduces by 4.07% which is more than from the reported value of 2.35%. Table 4.1 shows the comparative differences obtained in solar panel characteristic values at three different irradiation levels of 618 W/m, 776 W/m^2 and 836 W/m^2. It is clearly differentiable that the voltage is decreasing at much higher rate than current and therefore losses in power output of a solar panel occurs as temperature increases from 25 ^{o}C to higher temperature.

Table 4.1 Effect of temperature on 150 W polycrystalline solar panel parameters

Solar irradiance	**Drop in voltage at maximum power point (ΔV_{pm})**	**Rise in current at maximum power point (ΔI_{pm})**	**Drop in power at maximum power point (ΔP_m)**
618 W/m^2 (from 25 ^{o}C to 100 ^{o}C)	4.45 V	0.099 A	13.39 W
776 W/m^2 (from 25 ^{o}C to 108 ^{o}C)	4.37 V	1.27 A	18.52 W
836 W/m^2 (from 25 ^{o}C to 110 ^{o}C)	4.09 V	0.39 A	20.025 W

4.5 Effect of cooling on temperature for different irradiation levels

To reduce the effect of temperature on performance of solar panel, DC fans are installed at the exit of duct beneath the module which extract certain amount of heat generated. Observations are made by running one, two, three and four fans when average surface temperature of solar panel reaches to 45^{o}C as normal operating temperature of solar panel lies in the range of 45 to 50^{o}C. Temperature comparison is made for 618 W/m^2, 776 W/m^2 and 836 W/m^2 as shown in Fig 4.9 (a), 4.9 (b) and 4.9 (c). The detailed evaluation is conducted on thermal and electrical parameters including temperature, current, voltage, power and efficiency. Based on these observations the necessary number of fans required for effective cooling is also proposed.

It is clearly seen from Fig. 4.9 (a) the average surface temperature attained by cooled solar panel is lesser than with conventional panel. For irradiation of 618 W/m^2 the maximum temperature attained without cooling is 98.39 ^{o}C at room temperature of 15^{o}C. When a single fan is turned ON at its maximum flow rate, the anemometer placed at the exit of the duct near the fan to measure the flow rate of fan and temperature of air sucked, shows a gradual increment in temperature reading. It shows that the heat is sucked out which decreases the panel maximum average temperature from 98.2 ^{o}C to 91.85 ^{o}C by an amount of 6.54 ^{o}C resulting in reduction of 6.64%. The anemometer shows an increment of 6.8 ^{o}C of air temperature at duct exit. As two fans are turned on the maximum attained temperature reduces to 90.8 ^{o}C which further reduces to 76.37 ^{o}C and 75.45 ^{o}C with three and four fans respectively. The maximum average temperature reduction occurs while cooling with four fans which is 22.9 ^oC corresponding to 23.3% reduction. However this reduction is not much as compared to cooling with 3 fans which is 22.02 ^oC.

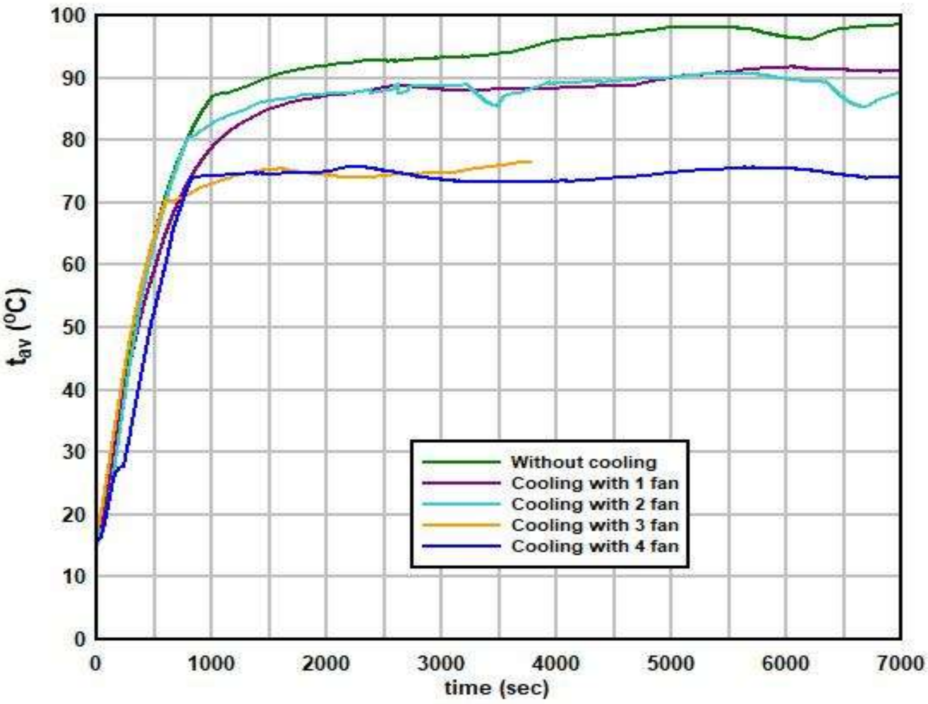


Fig. 4.9 (a) Effect of cooling on average surface temperature of solar panel at 618 W/m^2

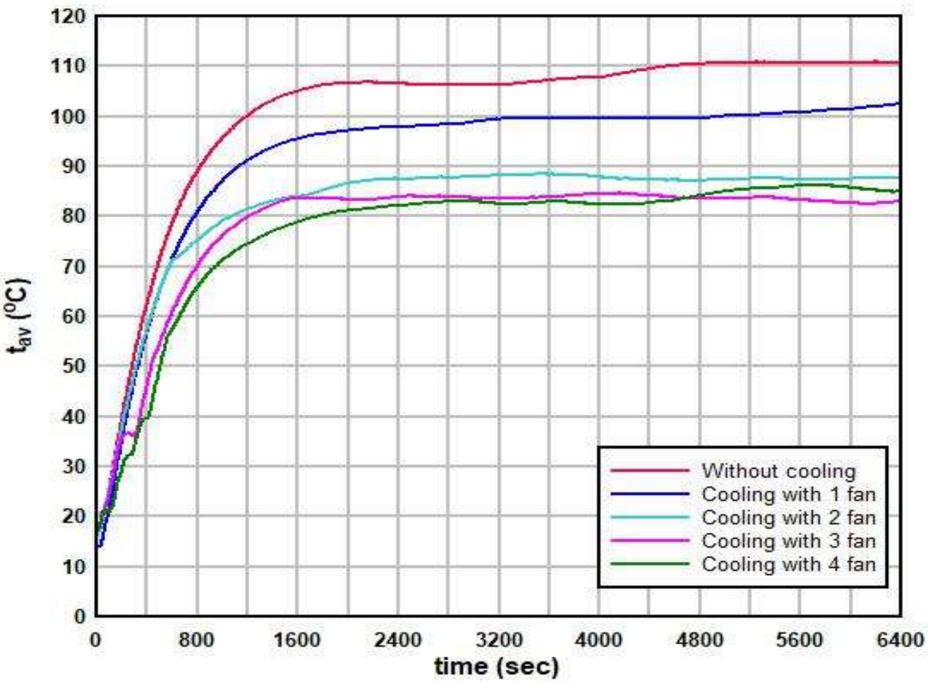


Fig. 4.9 (b) Effect of cooling on average surface temperature of solar panel at 776 W/m^2

As it can be seen in Fig. 4.9 (b), PV panel with an irradiation of 776 W/m^2 is experiencing higher level of operating temperature as compared to 618 W/m^2. The maximum average PV panel surface attained is found to be 110.8 ^{o}C at 17 °C room temperature for PV panel with no cooling attachment. As soon as the panel surface temperature reaches to 45 ^{o}C cooling starts with one, two, three and four dc fans at its maximum flowrate, the reduction in maximum average surface temperature is observed. With one fan the temperature reduces to 103.08 ^{o}C resulting in to a reduction of 8 ^{o}C. Similarly with two, three and four fans, the temperature reduces 99.16 ^{o}C, 84.39 ^{o}C and 84.1 ^{o}C which corresponds to reduction of 21.64 ^{o}C, 26.41 ^{o}C and 26.78 ^{o}C respectively. Here the difference in temperature decrement is negligible for cooling with three and four fans.

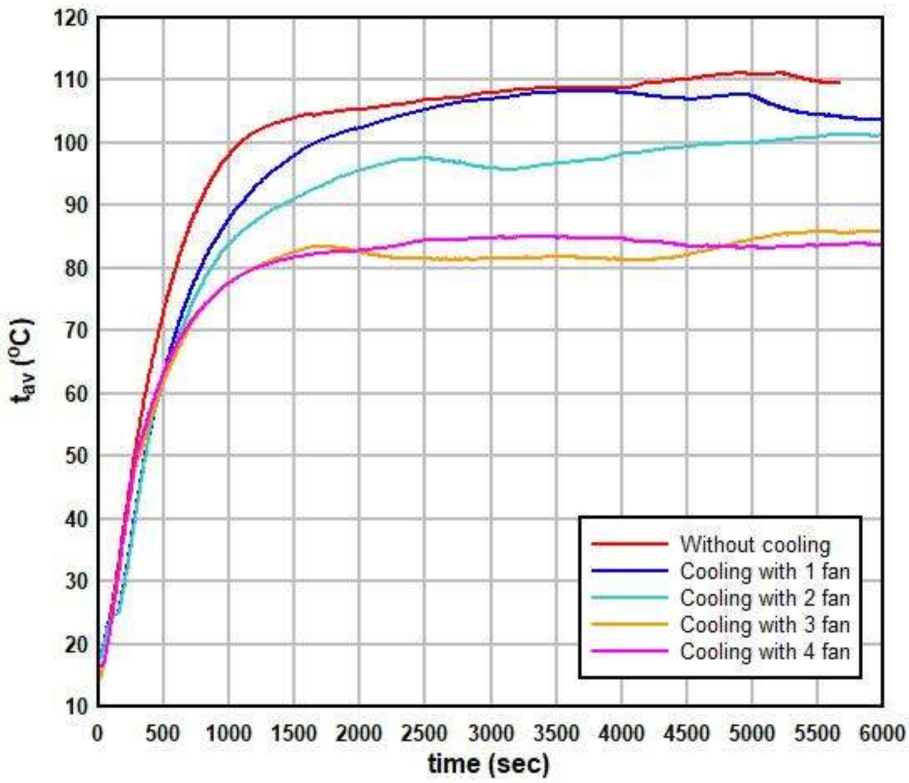
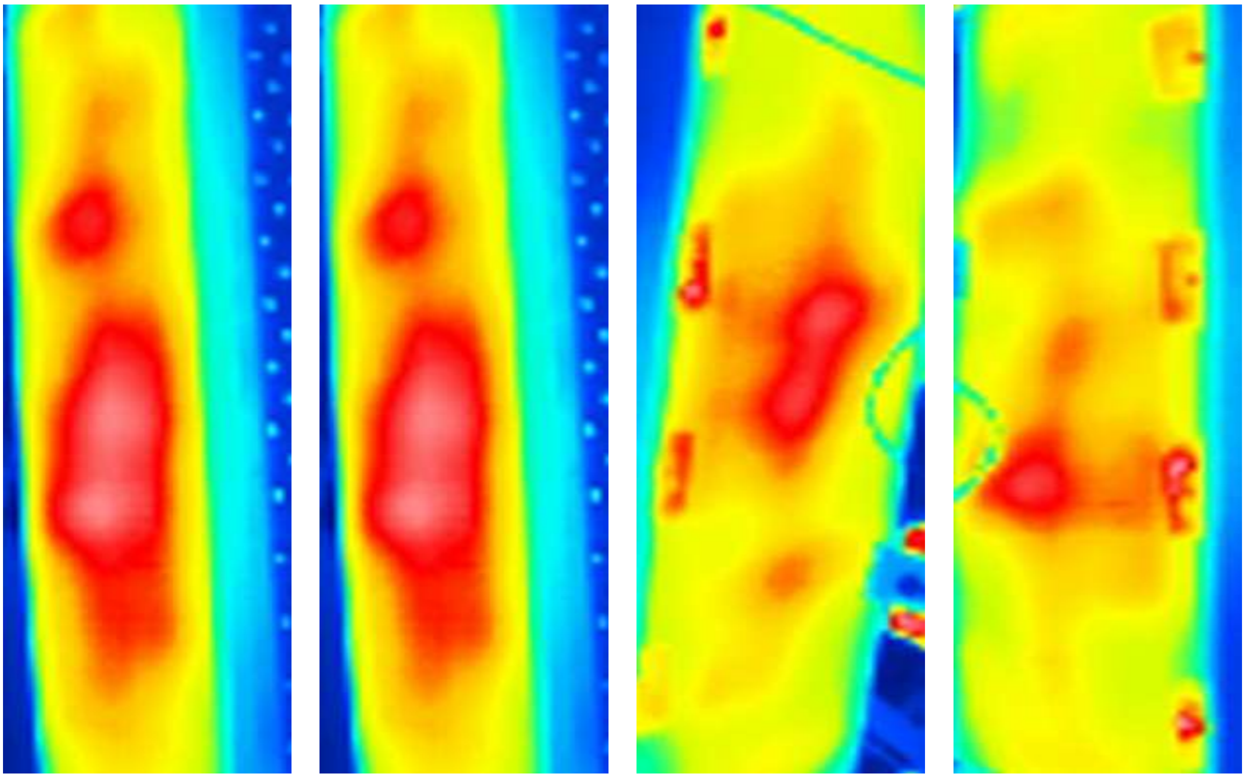


Fig. 4.9 (c) Effect of cooling on average surface temperature of solar panel at 836 W/m^2

It is depicted in Fig. 4.9 (c) the average surface temperature attained by non cooled solar panel is higher than with cooled panel. For irradiation of 836 W/m^2 the maximum temperature attained without cooling is 111.8 ^{o}C at room temperature of 18 ^{o}C. When a single fan is turned ON it sucks the heat generated through the duct. A anemometer is placed at the exit of the duct near the fan to measure the flow rate of fan and temperature of air sucked, shows a gradual increment in temperature reading. It shows that the heat is sucked out which leads to decrement in the panel maximum average temperature by amount of 4.2 ^{o}C resulting in to 3.78% reduction. The anemometer shows an increment of 11.6 ^{o}C of air temperature at duct exit. As two fans are turned on the maximum attained temperature reduces to 101.37 ^{o}C which further reduces to 85.98 ^{o}C and 85.197 ^{o}C with three and four fans respectively. The maximum average temperature reduction occurs with cooling with four fans which is 25.60 ^{o}C which corresponds to 23.1%. However this reduction is not much as compared to cooling with 3 fans which is 24.82 ^{o}C.

The main objective of installing DC fan is to provide cooling so accordingly the temperature distribution of solar module is important. Fig 4.10 shows the variation of temperature over the panel surface through infrared thermal images. The module without cooling configuration experiences the highest level of surface temperature. As the cooling with one, two, three and four number of fans increases, the heat extraction is more and hence resulting in to lesser surface temperature. The red area on panel indicates higher heating as compared to other area. Red area is highest for non cooled solar panel. As number of fans increases the red zone decreases and become minimum with four numbers of fans.



(a) (b) (c) (d)

Fig. 4.10 Thermal images of solar panel surface (a) cooling with 1 fan (b) cooling with 2 fans (c) cooling with 3 fans (d) cooling with 4 fans

It is clearly depicted from infrared thermal images that cooling mechanisms observed to influence the temperature reduction through PV panels. Results also implied that the operating panel temperature obviously dropped with the increasing number of DC fan. As it is clearly seen, by using four units of DC fan as a cooling device, the average PV panel temperature reduces most significantly as compared to other cooling configuration. However there is not much cooling difference is occurred with 3 and 4 number of DC as clearly shown in table 4.2 which illustrated the amount of temperature reduction that occurred with one, two, three and four number of fans. It is quite obvious that power consumed by four fans is more than consumed by three so to avoid superfluous power from panel it can be proposed that with the cooling configuration that applied in this study, it is economical to use three instead of four units of DC fan. It can be concluded that the optimized number of fans would be 3 for cooling.

Table 4.2 Temperature reduction in ^{o}C through cooling at different irradiations for different number of fans

Solar Irradiation (W/m^2)	1 fan	2 fans	3 fans	4 fans
618	6.54	7.6	21.69	22.94
776	8	11.64	26.41	26.78
836	4	9.76	25.15	25.93

4.6 Effect of cooling on electrical performance of solar panel

It is earlier observed through experiments that the electrical characteristics of solar panel are greatly influenced by the temperature and with increases in temperature the panel characteristics dropped by larger amount. To improve these characteristics cooling arrangement is provided which greatly reduces the thermal behaviour of solar panel. Futher experiments are conducted to study the impact of temperature decrement on module electrical behaviour at different radiations and different number of fans.

4.6.1 Effect of cooling for irradiation of 618 W/m^2

In Fig. 4.11 the dotted lines of different colors shows the current output produced by PV panel through the experiment conducted on non cooled and cooled panel. Comparasion is shown with cooled panel with one,two, three and four number of fans. It is found that with the existing of cooling mechanism, the current output I_{pm} obtained at maximum power point slightly increased with the reduction in the photovoltaic polycrytsalline panel surface temperature. It is observed that the I_{pm} of a PV panel cooled by DC fans is higher than that produced by panel with no cooling attachment. For example, the highest current observed to be produced using one fan is 5.4 A at 75 ^{o}C. While, in the same condition, only 4.57 A have been produced when no cooling configuration is attached. For two, three and four fans, the increment in maximum current produced are 0.43 A, 0.80 A and 0.82 A respectively as compared to non cooled solar panel. This increment in the current with a reduction in temperature is due to a marginal increase in the photo-generation rate, which in turn is due to a reduction in band gap energy.

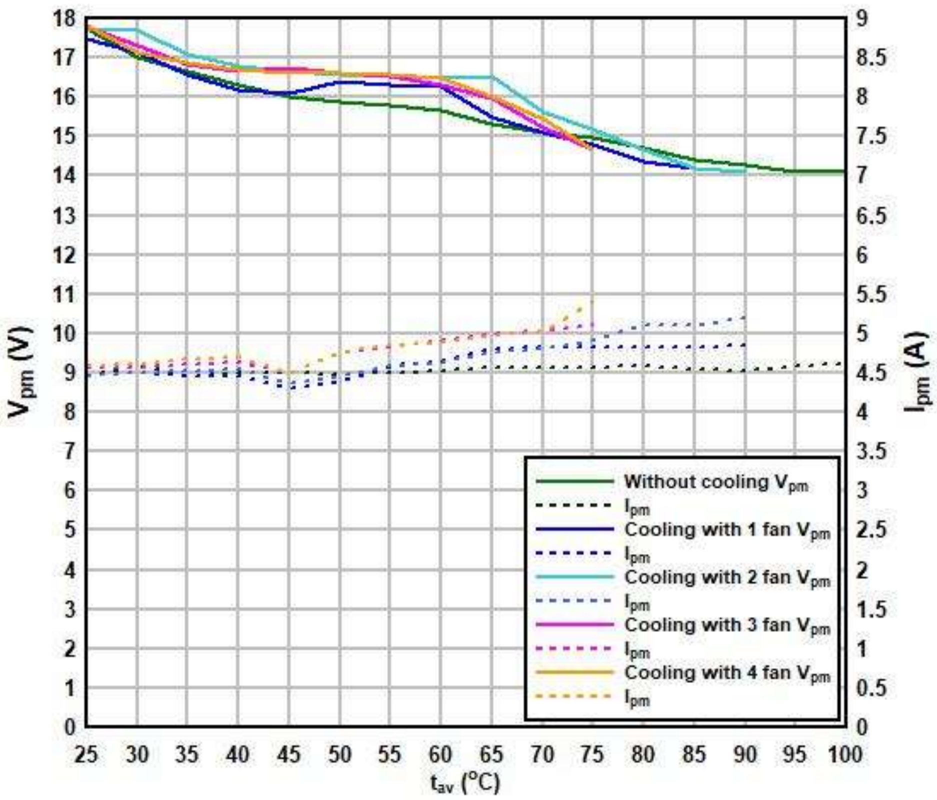


Fig. 4.11 Effect of cooling on voltage and current for 618 W/m^2 at load of 35 W

The effect of employing different number of cooling fans on output voltage at maximum power point of the solar module as compared to conventional cooling system is illustrated in Fig. 4.11. It is clearly visible from the figure that the cooling of panel results in increment in output voltage V_{pm} at MPT and it is also observed that when number of fans is increased from one to four the value of Vpm keeps increasing. At the same condition of irradiation, panel without cooling suffers a increased losses in its maximum voltage value while the losses decrease with cooling. The lowest value of V_{pm} with conventional panel at a temperature of 90 ^{o}C is 13.8 V while at the same temperature the voltage with one fan cooling is 14.1 V. Approximately 2.17% increment in voltage is obtained with one fan cooling only. However the voltage output has enhanced with the existing cooling mechanism. By increasing the number of fans the percentage increment is increased. About 11.19% , the maximum voltage V_{pm} is enhanced by using four units of DC fans. The increment in voltage is due to reduction in temperature of solar panel as voltage and temperature have inverse relation and current increases due to photogeneration effect.

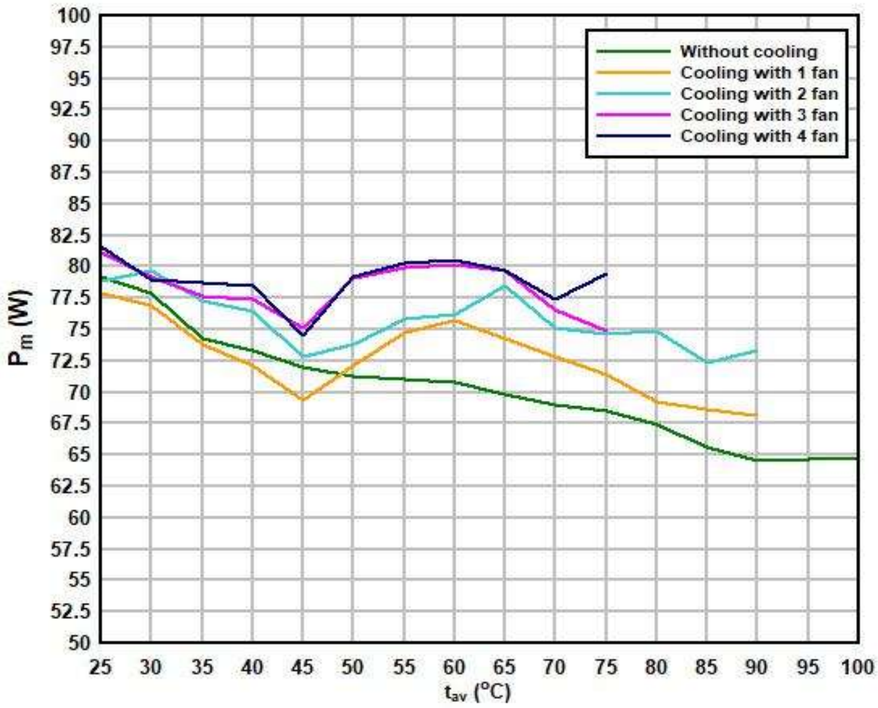


Fig. 4.12 Effect of cooling on maximum power for 618 W/m^2

Figure 4.12 describes the overall power output P_m produced for different modes employing one, two, three and four number of fans. As depicted in this figure, by increasing the number of DC fan, an appreciable increment in power output is obtained. With conventional photovoltaic panel, only 62.74 W of power is produced at a temperature of 90 ^{o}C while employing cooling with one fan cooling the produced power improves to 68.24 W resulting in to improvement of about 5.5 W corresponding to an increment of 8.76%. This is because with conventional panel more heat energy is generated rather than conversion in electrical energy. On comparing the maximum power produced after 45 ^{o}C the power output improved 72 W to 75.70 W corresponding to an increment of 3.70 W when panel is cooled with one fan. By increasing the number of fans the output power improved to 78.7 W, 80.13 W and 80.916 W with 2, 3 and 4 number of fans respectively. This corresponds to 8.24%, 10.14% and 11.01% increment in power output. The above figure also depicted that panel performance is worst without any cooling arrangement.

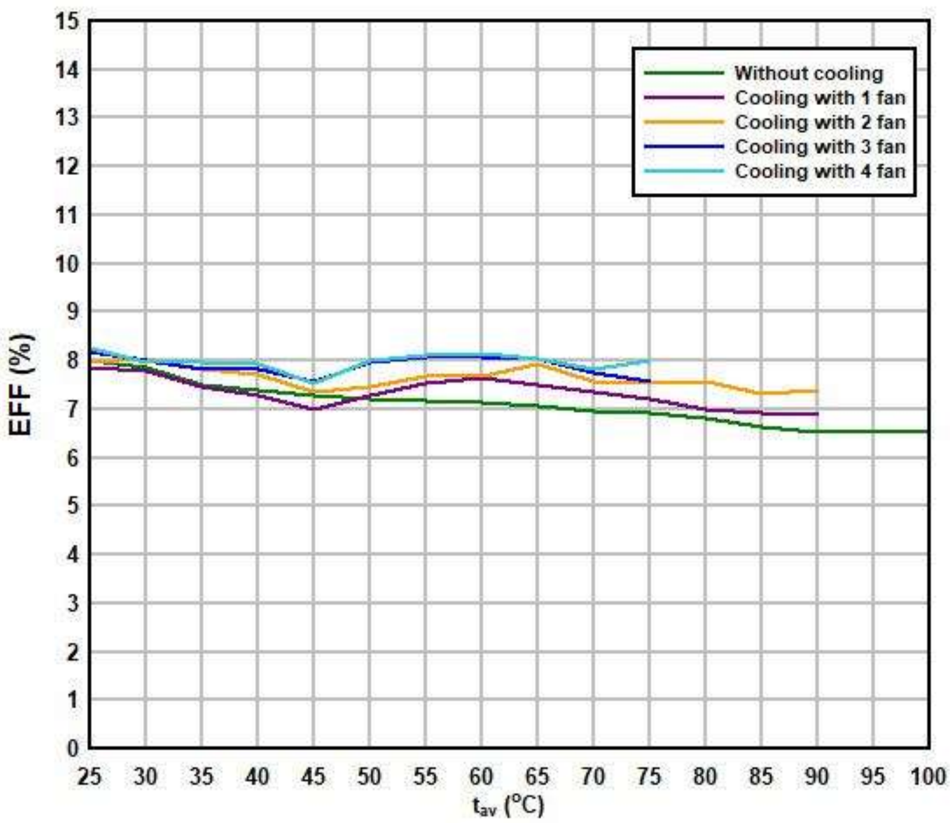


Fig. 4.13 Effect of cooling on efficiency for 618 W/m^2

Figure 4.13 shows an efficiency of solar panel vs its average surface temperature for different number of fans with and without cooling. Panel without cooling results in maximum amount of efficiency drop as compared to situation when cooling is done. With conventional panel the minimum efficiency obtained at 100 ^oC is 6.23% while it is 7.27% at 45 ^oC. On comparing the maximum efficiency that is obtained after cooling (after 45 ^oC) the efficiency obtained are 7.84%, 8.32%, 8.96% and 9.14% with one, two, three and four number of fans respectively. This enhancement in efficiency is expected as it directly depends on power output of solar panel and this power improves due to cooling.

4.6.2 Effect of cooling for irradiation of 776 W/m^2

Figure 4.14 illustrated that the value of current at I_{pm} and voltage V_{pm} maximum power point produced by the solar panel increases as the surface temperature of panel decreases by extracting heat using one, two, three and four number of fans.

Here the different colored dotted lines shows the current output and bold colored lines shows the maximum output voltage produced by PV panel through the experiment conducted on conventional and cooled panel. Comparasion is made with cooled panel with one, two, three and four number of fans. It is observed that the value of I_{pm} and V_{pm} of a conventional PV panel is lowest and both increases as panel cooled by DC fans. With non cooled panel the maximum current produced at 85 °C is 5.54 A and it increaes to 6.02 A at same temperature when panel is cooled using one DC fan which futher increaes to 6.22 A, 6.27 A and 6.40 A as the number of fans increases to 2, 3 and 4 respectively. This corresponds to 0.48 A, 0.68 A, 0.73 A and 0.86 A increment in current. When solar panel is operated without cooling the increment in current output is only 0.409 A when temperature increases from 25 °C to 110 °C while it increases to 0.72 A with 1 fan cooling, 0.88 A with two fans, 0.92 A with 3 fans and aprroximately 1 A in case of cooling with 4 fans. It is also distinctly seen in this figure that the cooling of panel results in to increment in output voltage Vpm at MPT and the increment in number of fans increases the value of V_{pm} as well. At constant irradiation of 776 W/m^2, panel without cooling suffers a great loss in its maximum voltage value by amount of 4.9 V while this loss decreases with cooling. The lowest value of V_{pm} with non cooled panel at a temperature of is 85 °C is 14.08 V while at the same temperature the voltage with one fan cooling is 14.19 V which further increaes to 14.41 V as number of DC units rises to four. Approximately 2.34% increment in voltage is obtained with four fans.

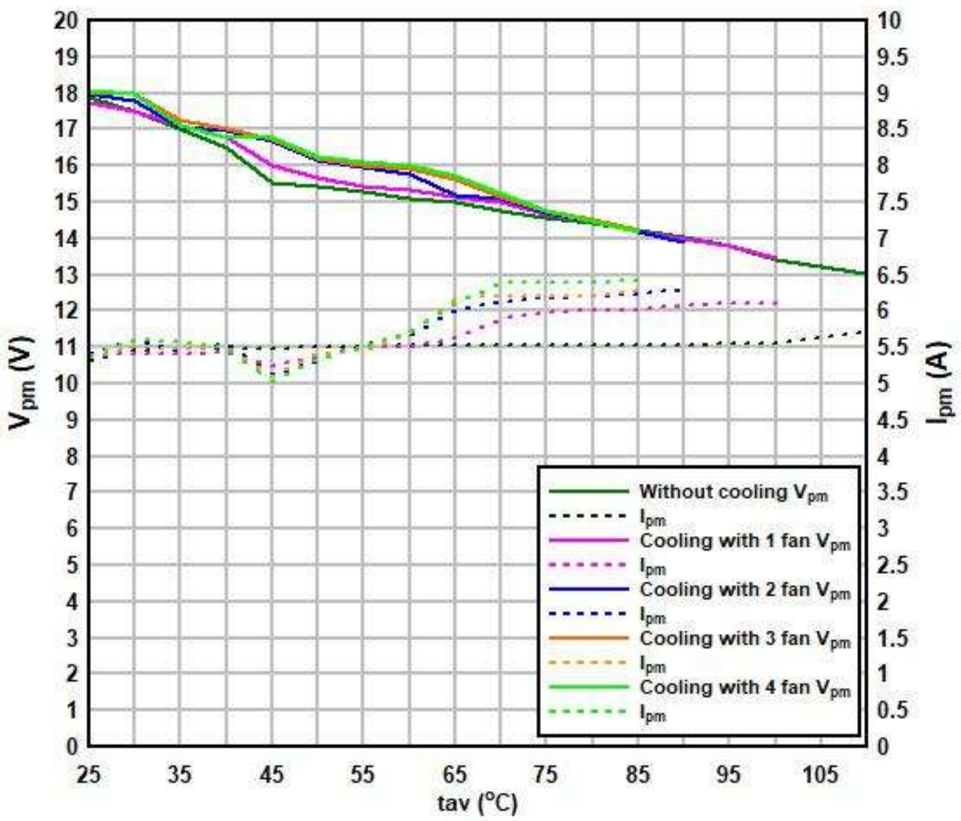


Fig. 4.14 Effect of cooling on voltage and current at maximum power point for 776 W/m^2

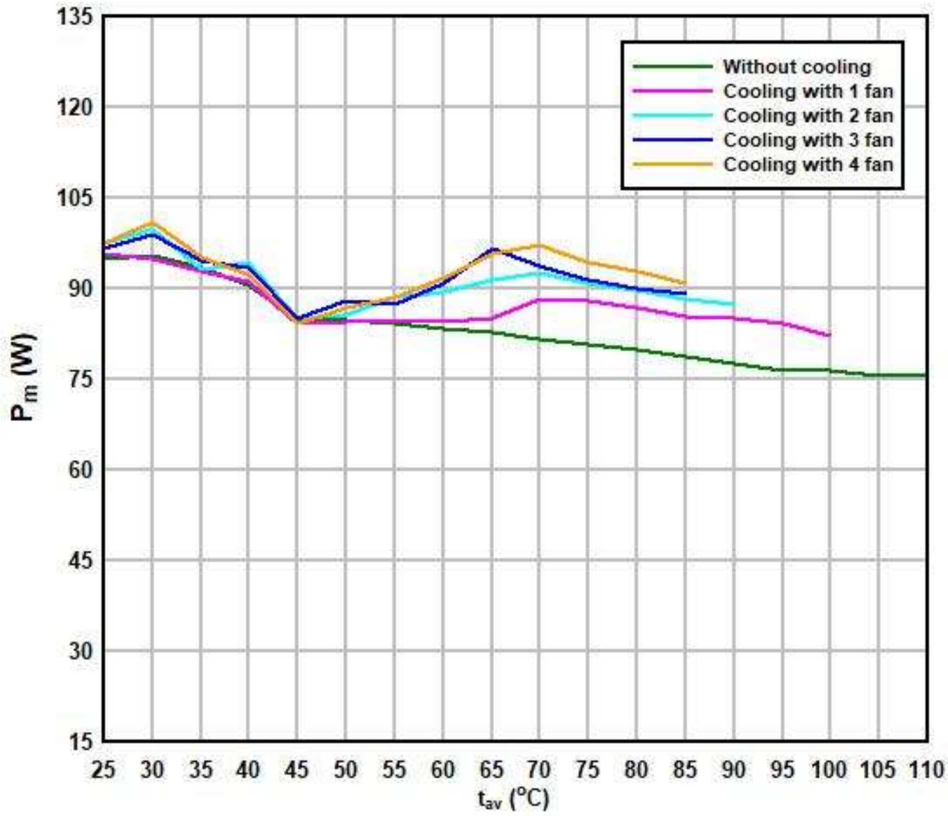


Fig. 4.15 Effect of cooling on maximum power produced at 776 W/m^2

Figure 4.15 illustrated the comparison between power output P_m produced by panel employed with and without cooling. As seen in the figure, by increasing the number of DC fan, an appreciable increment in power output is obtained. With non cooled photovoltaic panel, only 75.67 W of power is produced at a temperature of 100 ^{o}C resulting in reduction of power output by approximately 20 W. By employing different cooling configuration this power loss decreases. It is observed that with one fan the minimum produced power improves to 82.1 W at temperature of 100 ^{o}C which corresponds to an enhancement of 6.5 i.e. 8.5%. On comparing the maximum power produced after 45 ^{o}C the power output improved by 3.702 W from 85.2 W to 97.93 W with one fan cooling which corresponds to 3.53% enhancement in maximum power. By increasing the number of fans the output power improved to 92.6 W, 96.5 W, 97.32 W with 2, 3 and 4 fans. This corresponds to 7.95%, 11.67% and 12.39% improvement in power output.

The efficiency comparison of solar panel vs its average surface temperature for different number of cooling fans and without cooling is shown in Fig. 4.16. Here maximum drop in efficiency is observed without cooling panel. As cooling increases this reduction decreases. With non cooled panel the minimum efficiency obtained at 100 ^{o}C is

7.62% while it is 8.6% at 45 ^{o}C and 9.65% at 30 ^{o}C resulting in overall reduction of 2.03%. On comparing the maximum efficiency that is obtained after cooling (after 45 ^{o}C) the efficiency obtained are 8.90%, 9.36%, 9.83% and 9.75% with one, two, three and four number of fans respectively.

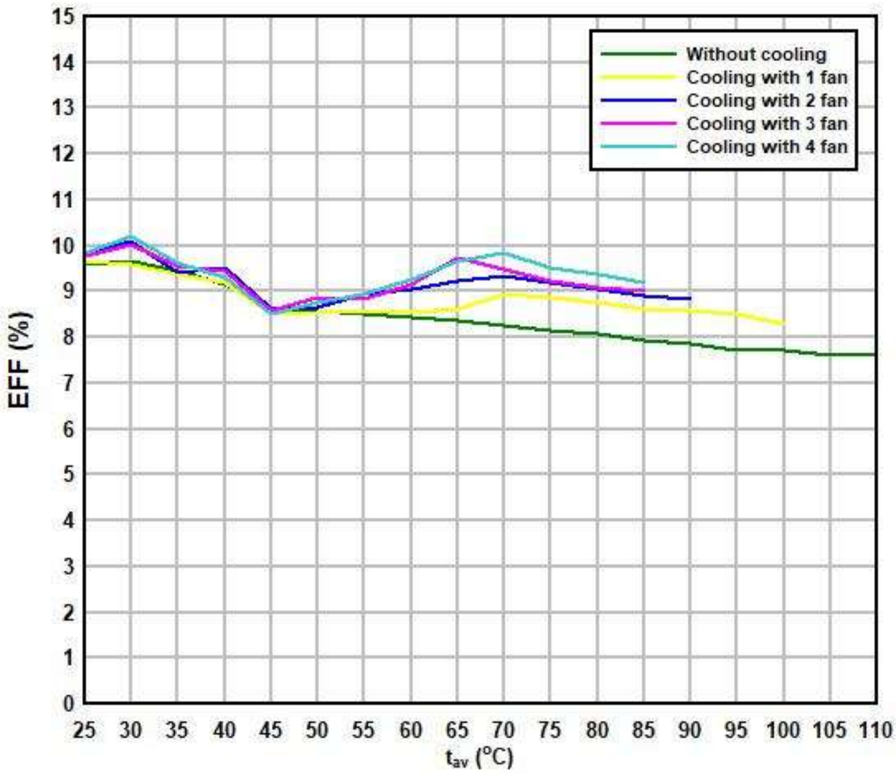


Fig. 4.16 Effect of cooling on efficiency for 776 W/m^2

4.6.3 Effect of cooling for irradiation of 836 W/m^2

In Fig. 4.17 a comparasion is made between voltage and current at MPT and panel average surface temperature for with and without cooling conditions. It is observed that by employing the existing cooling mechanism, the current output I_{pm} at MPT obtained increases slightly as discussed in section 4.5.1 and 4.5.2 with the reduction in the panel surface temperature. It is observed that the I_{pm} of a non cooled PV panel, increases by 0.15 A from 5.64 A to 5.8 A. But the same increases to 6.37 A from 5.45 A when cooling is done by a single fan. The highest value of current Ipm is observed to be 6.58 A by using four fans which corresponds to an increment of 0.78 A in highest obtained value of Ipm in comparison to conventional panel. For two, three and four fans, the maximum current produced are 6.34 A, 6.52 A and 6.58 A respectively as compared to conventional solar panel.

The effect of employing different number of cooling fans on maximum output voltage of the solar module as compared to without cooling is illustrated in same Fig 4.17. Here it is clearly observed that the cooling of panel results in increment in output voltage Vpm at MPT and the increment in number of fans increases the value of V_{pm} as well. At the same condition of irradiation, panel without cooling suffers higher losses in its voltage V_{pm} value while the loss decreases with cooling. Without cooling the maximum volatge V_{pm} suffers a loss of 5.99 V which is a large reduction. This loss reduces to 4.1 V with 3 and 4 units. The lowest value of V_{pm} with non cooled panel at a temperature of 85 ^{o}C is 14.01 V while at the same temperature the voltage with one fan cooling is 14.22 V. Approximately 1.49% , 1.57%, 1.64% and 2.07% increment in voltage is obtained with one, two, three and four fans respectively. Here maximum improvement in V_{pm} occurs with four fans cooling mechanism.

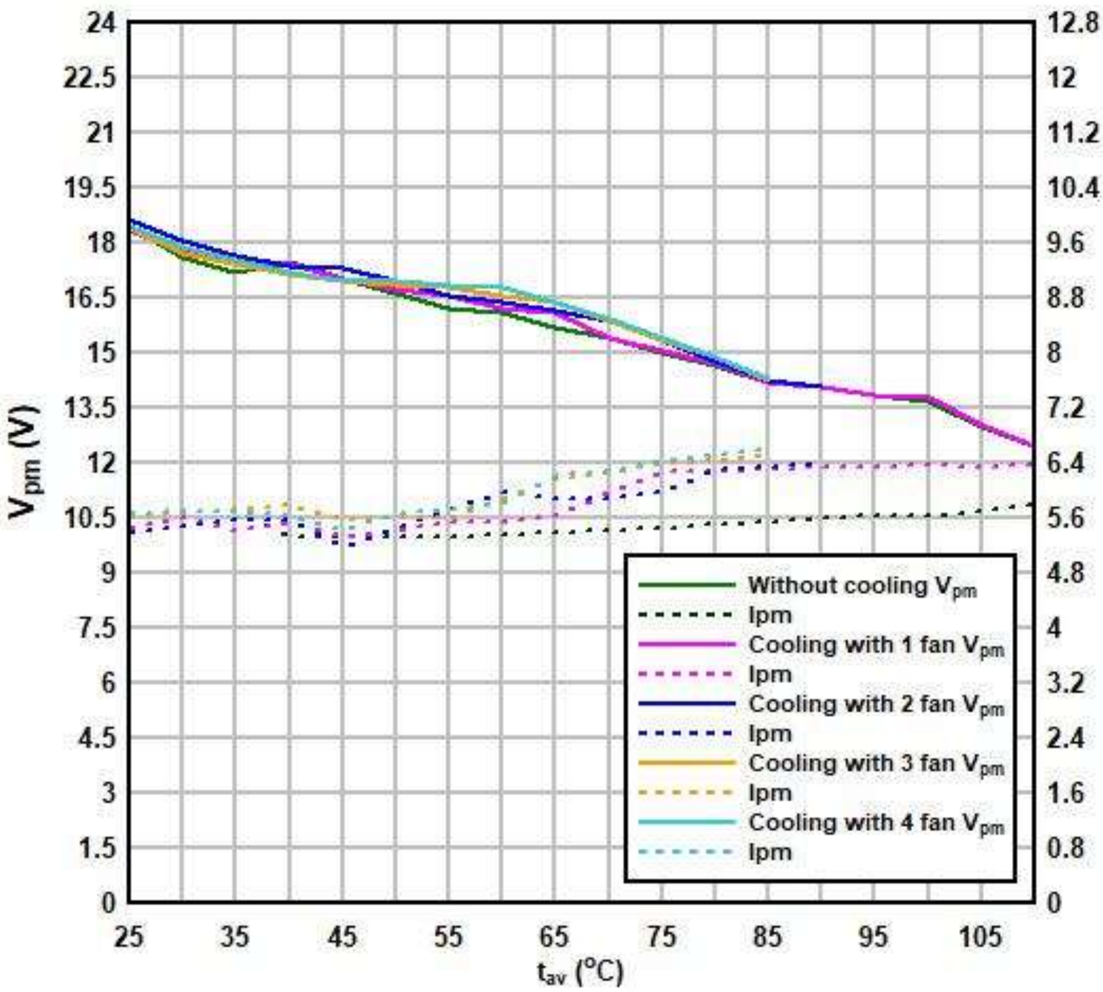


Fig. 4.17 Effect of cooling on voltage and current for 836 W/m^2

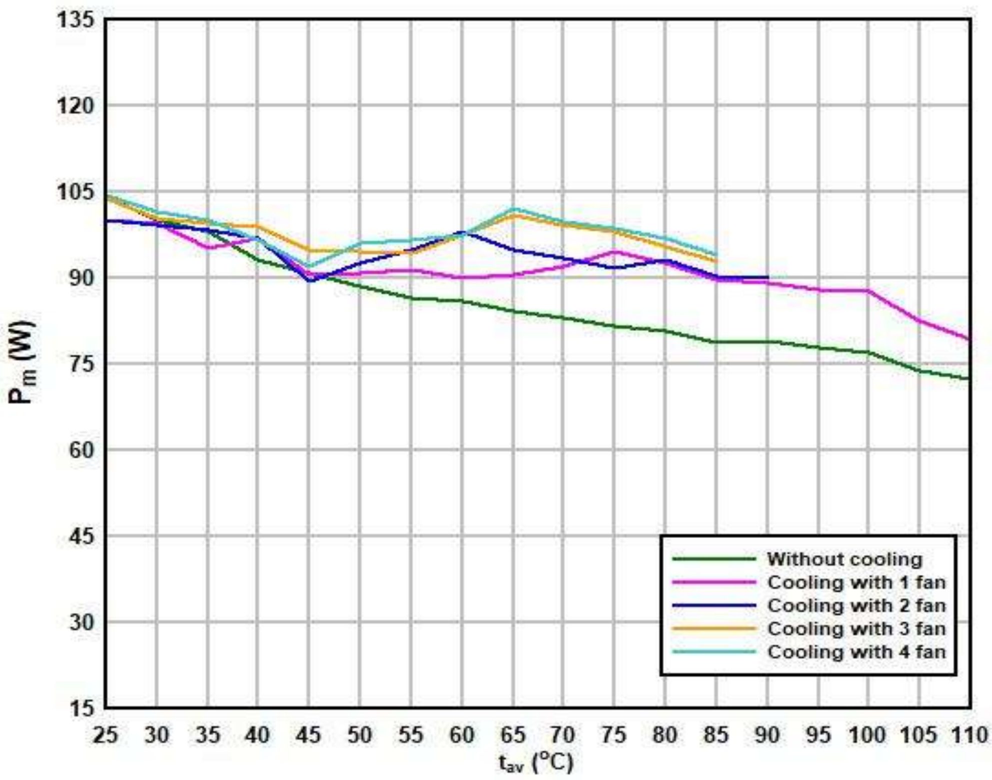


Fig. 4.18 Effect of cooling on power output of a solar panel for 836 W/m^2

As depicted in Fig. 4.18 by increasing the number of DC fan, a remarkable enhancement in maximum power output is obtained. With non cooled condition the power output decrement rate is more. With conventional photovoltaic panel, only 72.38 W of power is produced at a temperature of 110 ^{o}C and a power loss of 31.9 W occurs as t_{av} rises from 25 ^{o}C to 110 ^{o}C which is a very large amount. Employing cooling with one fan the produced power improves to 79.43 W resulting in improvement of about 7.05 W. As soon as the average surface temperature reaches to 45 ^{o}C, cooling starts. On comparing the maximum power produced after 45 ^{o}C it is found that the value of P_m improves to 94.5 W, 97.9 W, 100.9 W and 102.4 W with 1, 2, 3 and 4 fans respectively. This corresponds to 3.96%, 7.3%, 10.04% and 11.21% increment in power output.

The comparison of efficiency of solar panel vs its average surface temperature for different number of fans with and without cooling for irradiation of 836 W/m^2 is illustrated by Fig. 4.19. It is clearly seen that higher efficiency is obtained at this radiation intensity as compared to 618 W/m^2 and 776 W/m^2. This is because more photon energy incident on panel surface. Here panel without cooling results in maximum amount of efficiency drop as compared to with cooling because of more heat generation. With conventional panel the efficiency obtained at 110 ^{o}C is 7.3% while it is 9.16% at 45 ^{o}C. Total of 3.22% reduction in efficiency occurs as temperature increases from 25 ^{o}C to 110 ^{o}C. However with cooling this large drop in efficiency reduces to 2.07%, 1.04%, 1.11% and 1% with 1, 2, 3, and 4 DC fans respectively. This reduction in efficiency loss occurs due to drop in temperature of solar panel. Also on comparing the maximum efficiency that is obtained after cooling (after 45 ^{o}C) the efficiency obtained are 9.54%, 9.89%, 10% and 10.3% with one, two, three and four number of fans respectively.

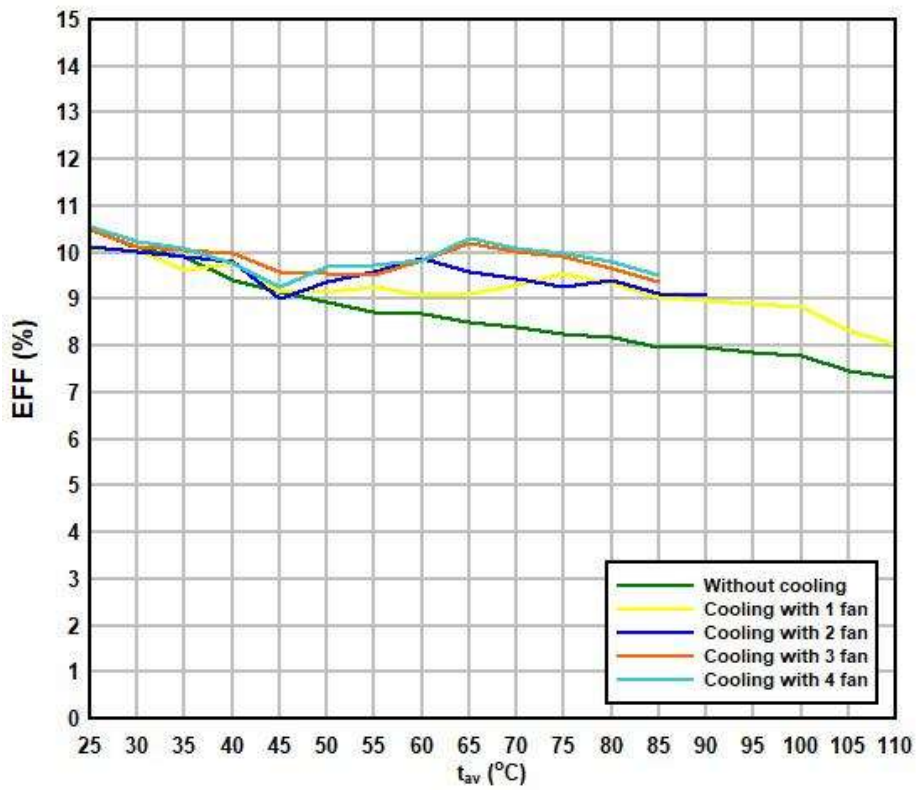


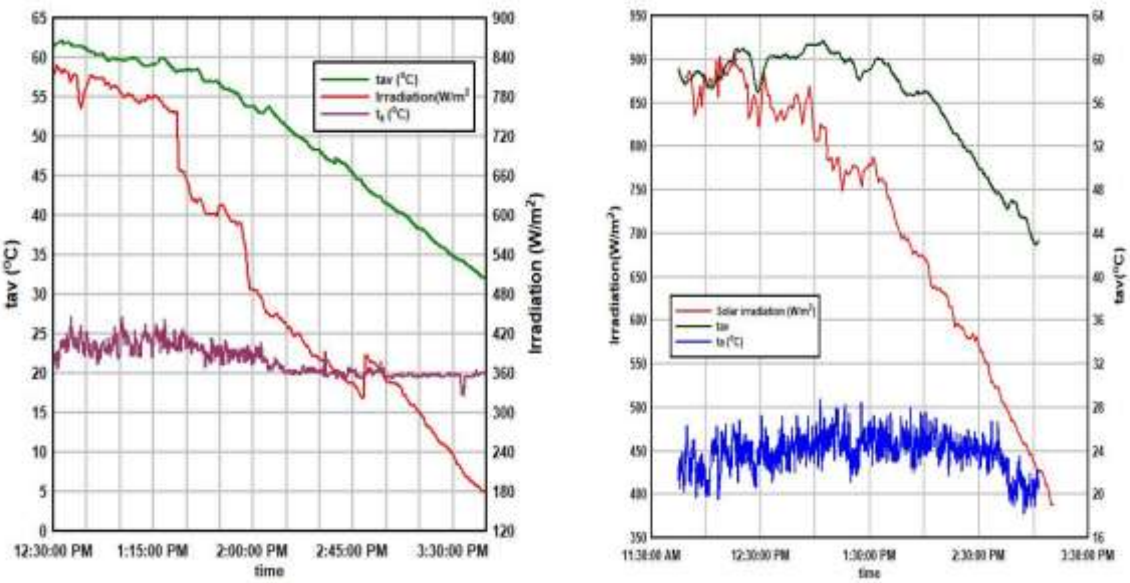
Fig. 4.19 Effect of cooling on efficiency of solar panel for 836 W/m^2

From all these results it is clearly seen that there is a clear trend of increasing in the power output of the PV panels by increasing the number of fans. This has happened since the PV transformation of solar energy to electricity increases as PV operating temperature decreases. Increasing the DC fan numbers improved the effect of heat transfer area of PV panel with more air circulation produced which leads to the reduction in temperature. The amount of increment in power and efficiency is sufficient to run the DC fans without any extra power consumption. Also it is observed that there is not much difference in temperature reduction, voltage, current, power and efficiency improvement observed by cooling with three and four fans so cooling with three fans is sufficient to make a remarkable improvement in solar panel characteristics.

4.7 Phase 3 Outdoor Testing

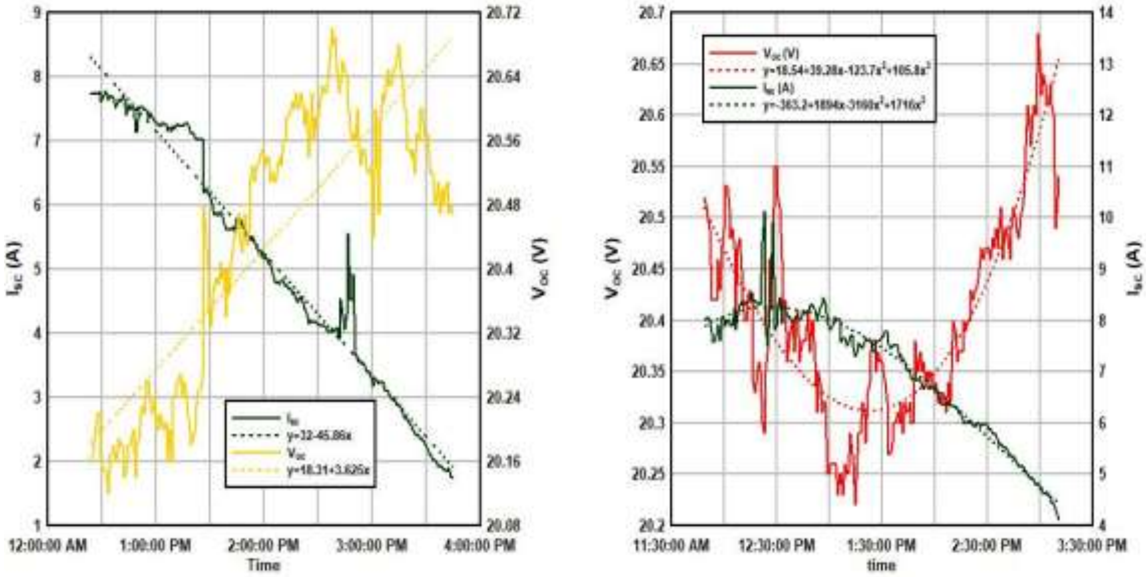
The outdoor experiments are conducted under actual meteorological condition of Pantnagar (Latitude 29.1 deg N and Longitude 79.3 deg E) in India. The whole setup including the cooling system is same as used under simulation condition. Total of 8 numbers of thermocouples are attached at the backside surface of the panel and one is open for measuring ambient temperature. The data logging of all these sensors is done with a data logger and readings are recorded in laptop through USB connecting cable. Cooling is done by running two and three fans as two fans results in more cooling effect than one and using four fans results in more power consumption. The average reading of these temperature sensors with and without cooling is taken to measure the average surface temperature of panel and to see the temperature reduction. The readings are taken for two days each with and without cooling because of winter weather and time limitation. The cooling of panel is done when average surface temperature of solar panel reaches to 50 ^{o}C. The radiation and panel characteristics are taken through PV System Analyzer and then transferred to laptop. Auto scan timing of 1 minute is set to record down the solar panel characteristics.

4.7.1 Solar panel parameters without cooling



(a) Without cooling on January 19, 2021 (b) Without cooling on January 28, 2021

Fig. 4.20 Solar irradiance, average surface temperature and ambient temperature vs time

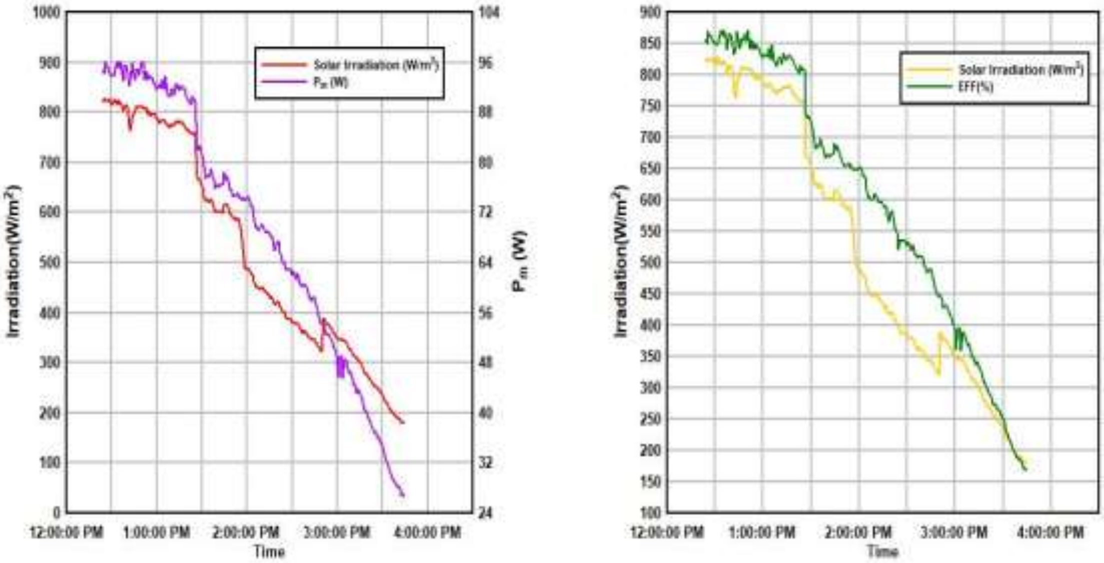


(a) Without cooling on January 19, 2021 **(b) Without cooling on January 28, 2021**

Fig. 4.21 Variation of V_{oc} and I_{sc} with time without cooling

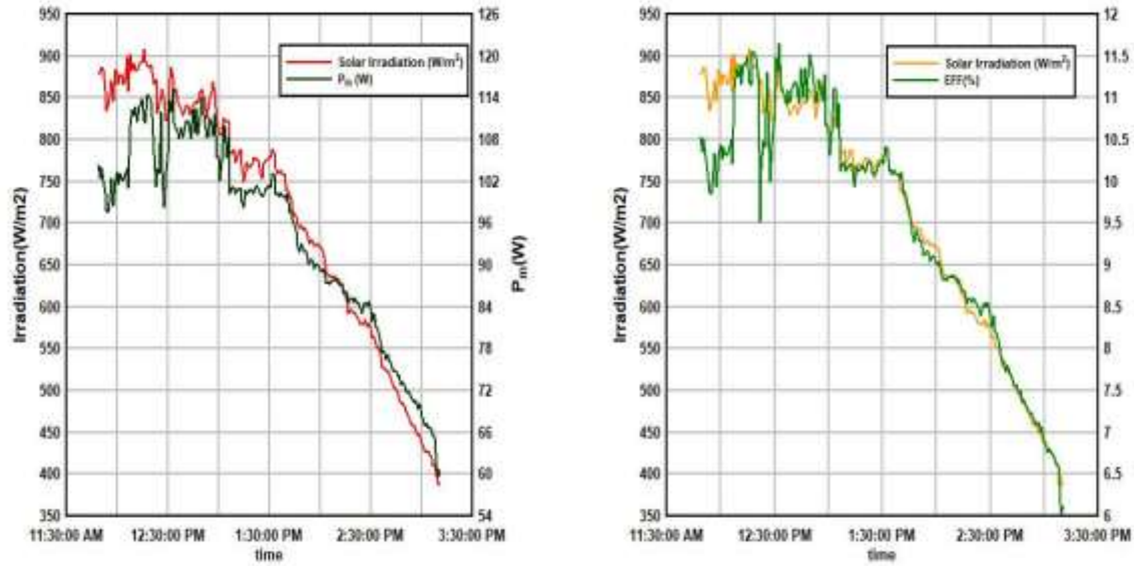
Without any cooling, the highest average temperature of panel reaches to 62.18 ^{o}C at 12:33 pm on January 19 and highest insolation received was 828 W/m^2 at 12:31 PM noon at an ambient temperature of 26.3 ^{o}C. On January 28, the maximum average surface temperature attained by the solar panel was 61.72 ^{o}C at an insolation of 826 W/m^2. So the highest average temperature reached by the panel was 61.95 ^{o}C. Figure 4.20 (a) and 4.21 (b) shows the variation of temperature and insolation with time on both the days. It is also known that with increase in temperature the open circuit voltage suffers from higher losses in its value and current increases slightly. The same is validated through above figures. The figures show that the maximum and minimum voltage obtained on January 19 and 28 are 20.7 V and 20.1 V and 20.68 V and 20.22 V respectively while current produced are 7.72 A and 1.75 A and 8.54 A and 4.13 A respectively resulting into an average of 20.42 V open circuit voltage and 5.53 A short circuit current.

Figure 4.22 (a), 4.22 (b), 4.23 (a) and 4.23 (b) show output power and efficiency for conventional 150 W PV module on two different days i.e. Jan, 19 and Jan, 28. The figure displays that both the power and efficiency varies in proportional to the solar irradiation. The maximum power attained at 12:32 pm is 115.27 W after which it lowered continuously and reduces to 60.58W at 3:10 pm on January 28 while it is 96 W and 26.7 W on January 19. This difference in power occurs due to cloudy weather and winds which act as a barrier.



(a) Maximum power vs solar irradiation **(b) Solar panel efficiency vs solar irradiation**

Fig. 4.22 Output parameters of solar panel versus solar irradiation: Without cooling on January 19, 2021

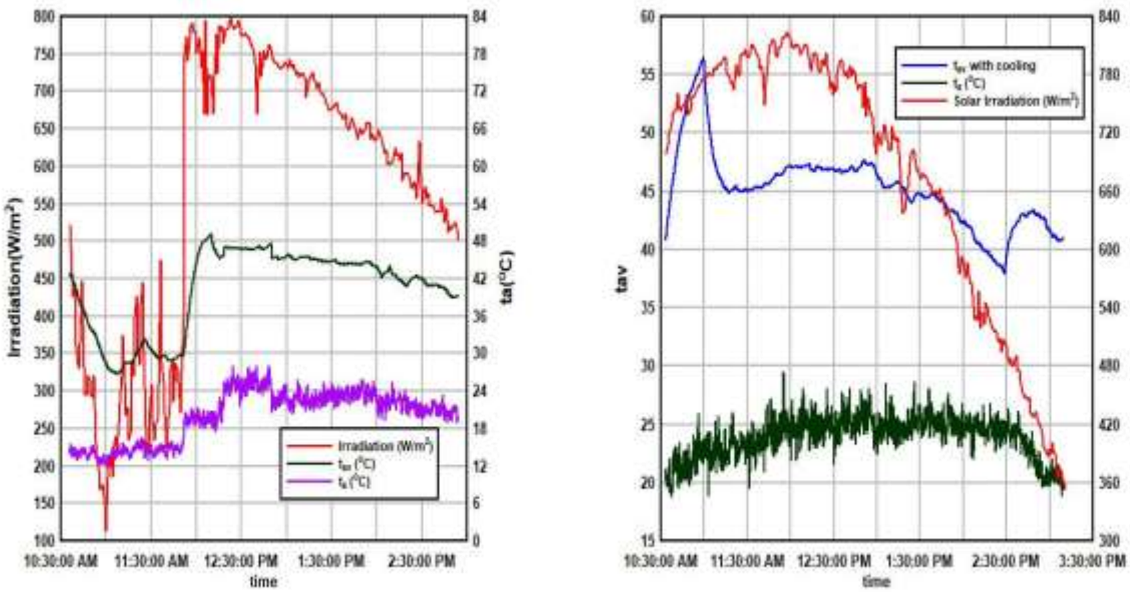


(a) Maximum power vs solar irradiation **(b) Solar panel efficiency vs solar irradiation**

Fig. 4.23 Output parameters of solar panel versus solar irradiation: Without cooling on January 28, 2021

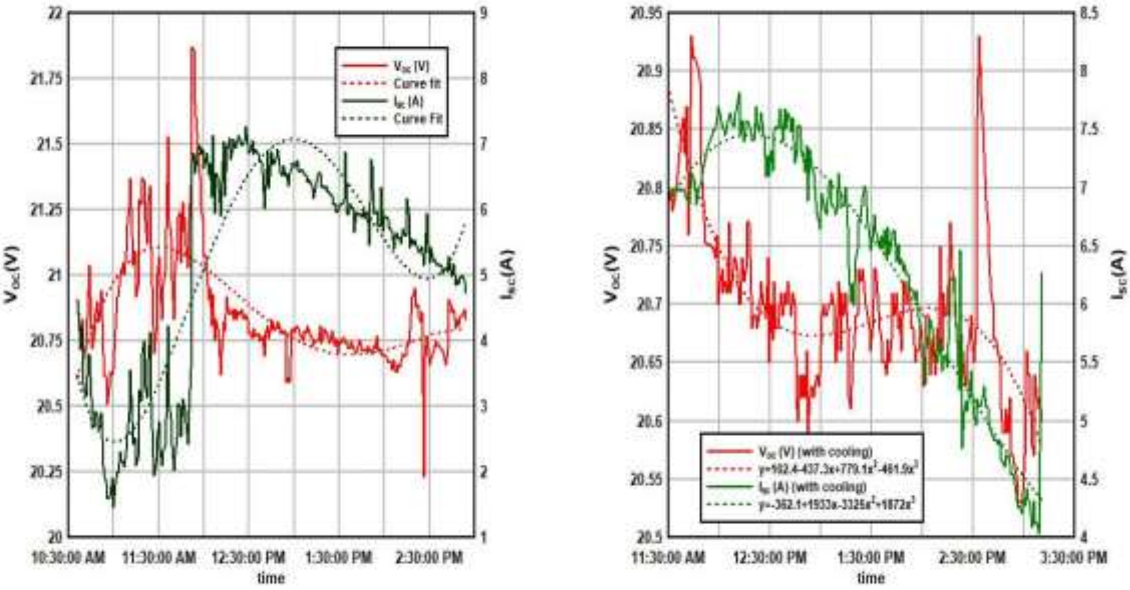
4.7.2 Solar panel characteristics with cooling

Two different configuration of cooling system were tested on January 22 and January 23 with 2 and 3 fans as these numbers of fans proved to be more efficient during indoor testing. As soon as the temperature rises to 50 ^{o}C, fans start operating. Fig. 4.24 (a) and 4.24 (b) shows the sudden reduction in temperature from 50 ^{o}C to 45.5 ^{o}C and 51 ^{o}C to 45 ^{o}C as cooling starts using two and three fans respectively. The highest temperature attained using two and three fans cooling are 47.64 ^{o}C and 47.73 ^{o}C respectively. Average temperature after 50 degree centigrade attained was 44.2 ^{o}C and 45.16 ^{o}C while it was 51.68 ^{o}C without cooling. This corresponds to temperature reduction of 7.48 ^{o}C and 6.52 ^{o}C. Here interesting thing that comes out to be is that cooling with two fan produces reduces temperature more in comparison to three which shows different variation as compared to previous one. This has happened because of cloudy weather and high wind speed on the day of cooling with two fans so during windy days it is recommended to use two fans instead of three to prevent the excess wastage of solar panel power. The effect of wind on panel temperature needs to be studied in details as well so as to optimize the number of fans for cooling purpose.



(a) With 2 fans cooling on January 22, 2021 (b) With 3 fans cooling on January 23, 2021

Fig. 4.24 Solar irradiance, average surface temperature and ambient temperature versus time



(a) With 2 fans cooling on January 22, 2021　　**(b) With 3 fans cooling on January 23, 2021**

Fig. 4.25 Variation of V_{oc} and I_{sc} with time

Figure 4.25 (a) and 4.25 (b) shows output voltage vs time for PV module with DC fans. In Fig. 4.24 (a) the highest and lowest open circuit voltage obtained after cooling with 2 fans is 20.95 V and 20.3 V respectively corresponding to an average value of 20.62 V. The maximum and minimum open circuit voltage with 3 cooling fans was 20.93 V and 20.53 V resulting in an average of 20.73 V open circuit voltage. The same figure displays the short circuit current for PV panel with 2 and 3 fans cooling. It is observed that the maximum and minimum current obtained are 7.26 A and 4.75 A with 2 fan and 7.82 A and 4.03 A with 3 fans cooling. The average output current obtained with 2 and 3 units of DC fans are 6 A and 5.93 A respectively. In comparison to conventional system, the open circuit voltage improves by 1% with 2 fans and 1.5% with 3 fans while the improvement in short circuit current using 2 and 3 fans are 7.8% and 6.74% which is good amount of enhancement and hence cooling proves to be an effective and efficient method for improving the performance of PV systems. Results are also in agreement with the indoor testing experiments as cooling results in to improvement in both current and voltage. Table 4.3 shows a comparative result of differences obtained with and without cooling system on solar panel electrical and thermal parameters.

Table 4.3 Comparison of solar panel parameters between with and without cooling condition

Condition	t_{av} (^oC)	V_{oc} (average value in Volts)	I_{sc} (average value in Amperes)
Without cooling	51.68	20.42	5.23
Cooling with 2 fans	44.2	20.625	6
Cooling with 3 fans	45.16	20.73	5.93

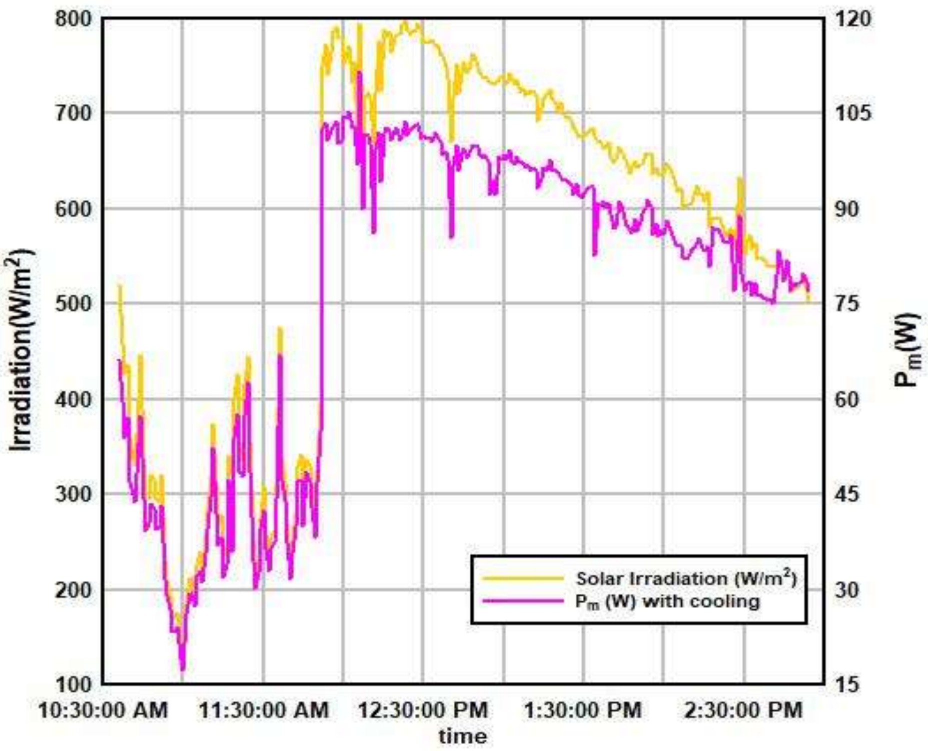


Fig. 4.26 (a) Maximum power vs solar irradiation with 2 fans cooling on Jan 22, 2021.

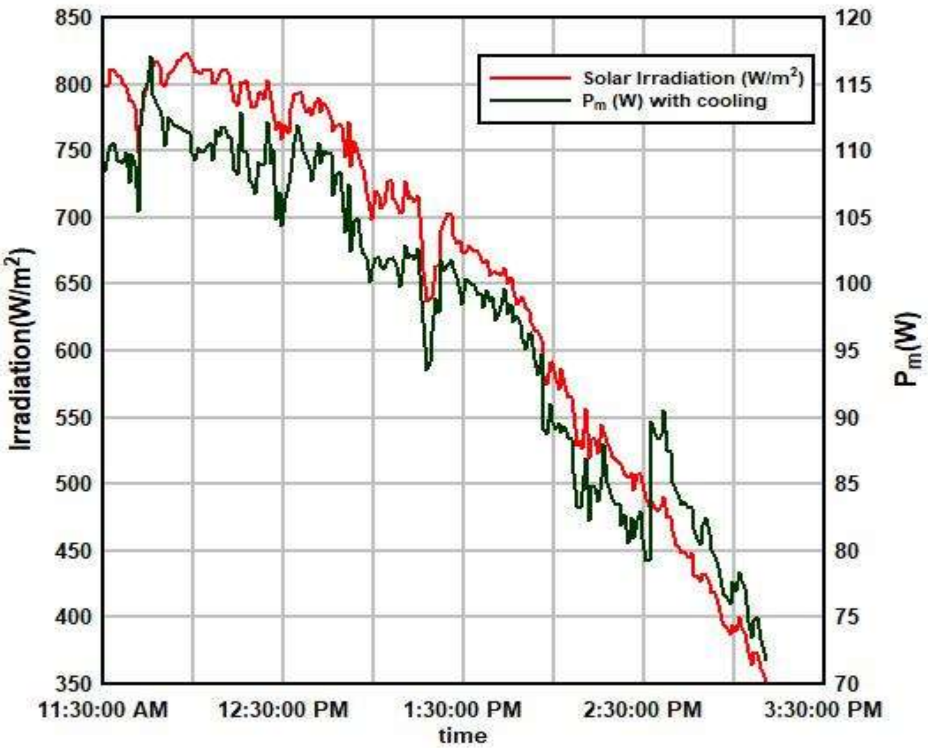


Fig. 4.26 (b) Maximum power vs solar irradiation with 3 fans cooling on Jan 23, 2021

The maximum power output produced by a150 W polycrystalline solar panel is 111.6 W at 12:06 PM which is obtained before temperature reaches to 50 ^{o}C. However, when cooling starts with 2 fans the maximum and minimum power produced are 103.84 W and 77.52 W respectively as shown in Fig. 4.26 (a) while the same values with 3 fans cooling are 117.15 W and 71.87 W as depicted by Fig. 4.26 (b) .Thus the average power output produced by the solar module after cooling are 90.68 W and 94.51 W using 2 fans and 3 fans respectively while without cooling it is 74.64 W. Cooling configuration with 2 and 3 fans result in an improvement of 16.04 W and 19.87 W respectively corresponding to an increment of 21.48% and 26.62%.

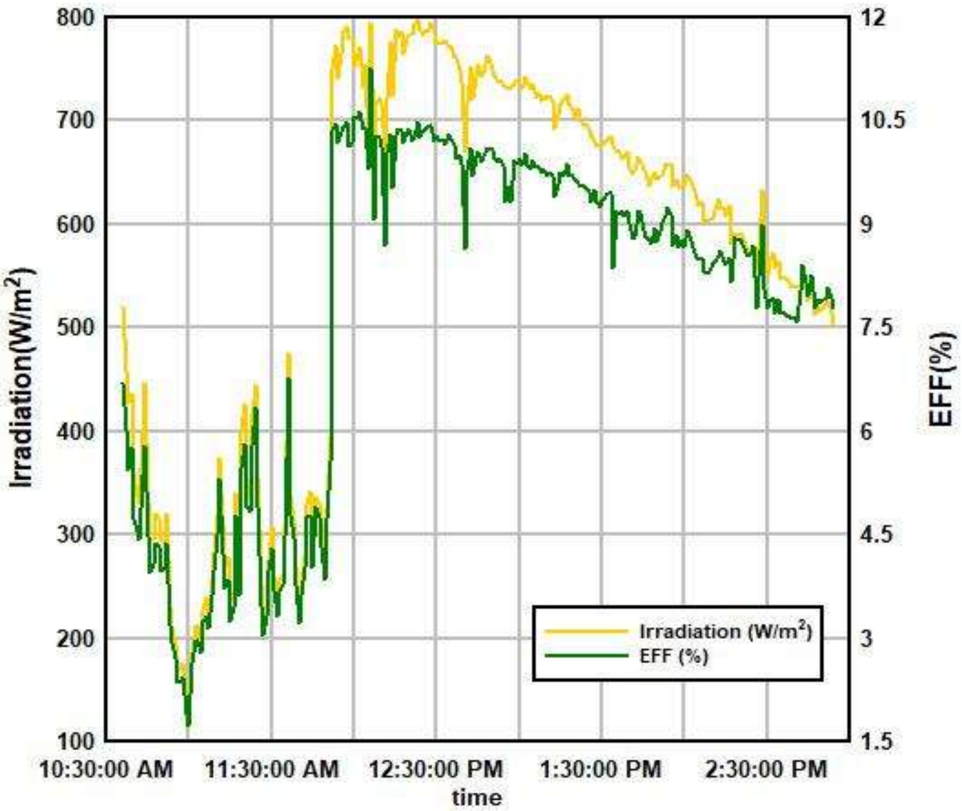


Fig. 4.27 (a) Solar panel efficiency vs solar irradiation usign 2 fans cooling on Jans 22, 2021

Figure 4.27 (a) and 4.27 (b) illustrated the variation of efficiency with irradiation. It is clearly seen that efficiency follows the same pattern as that of power output and varies in same proportion with radiation. Without cooling the average efficiency obtained with photovoltaic solar panel is 7.54% while cooling with two and three fans results in to an average efficiency of 9.13%and 9.54% respectively. This corresponds to an improvement of 1.59% and 2% which is a significant amount.

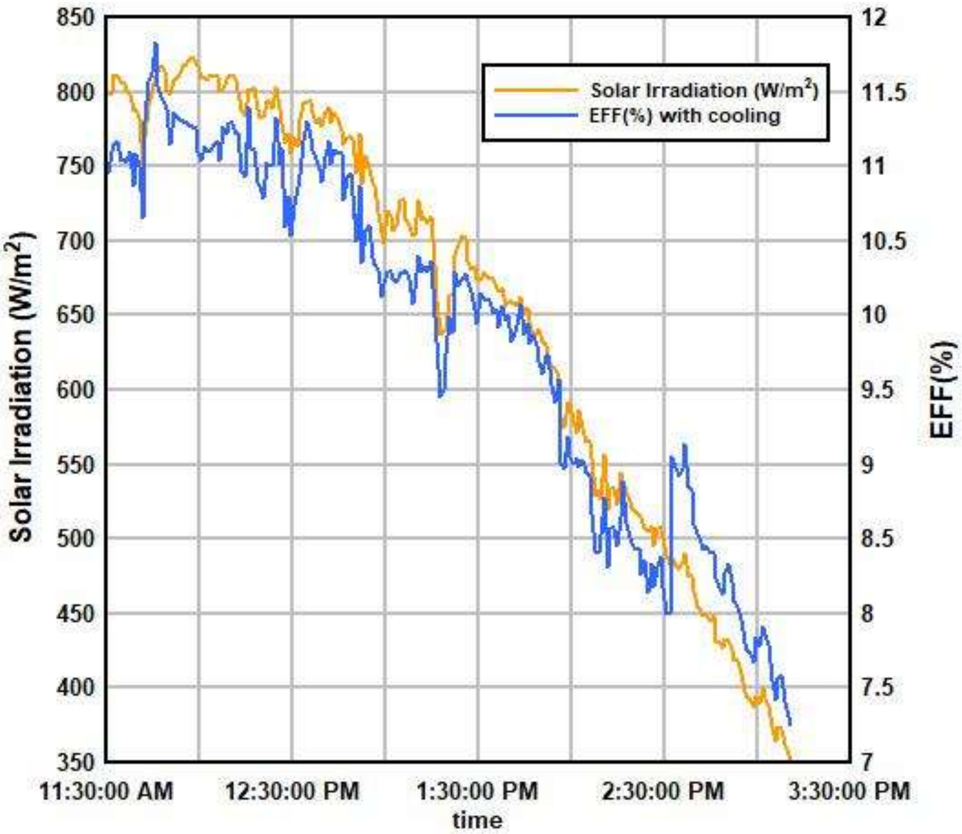


Fig. 4.27 (b) Solar panel efficiency vs solar irradiation with 3 fans cooling on Jan 23, 2021

Table 4.4 made a comparison between enhancement obtained by employing two and three fans. The solar panel when cooled by using two fans results in improvement of power by 16.05 W and efficiency enhancement of 1.59% while running three fans enhance the power output and efficiency by 19.88 W and 2% respectively.

Table 4.4 Improvement in average power and efficiency produced by cooled solar panel

Cooling configuration	Power (W) output enhanced by amount of	Efficiency (%) enhanced by amount of
Cooling with 2 fans	16.05	1.59
Cooling with 3 fans	19.88	2

4.8 Comparison between indoor and outdoor testing

It is clearly illustrated in Fig. 4.28 and Fig. 29 that adopted cooling enhances the performance of a polycrystalline solar panel more in outdoor conditions than in indoor conditions.

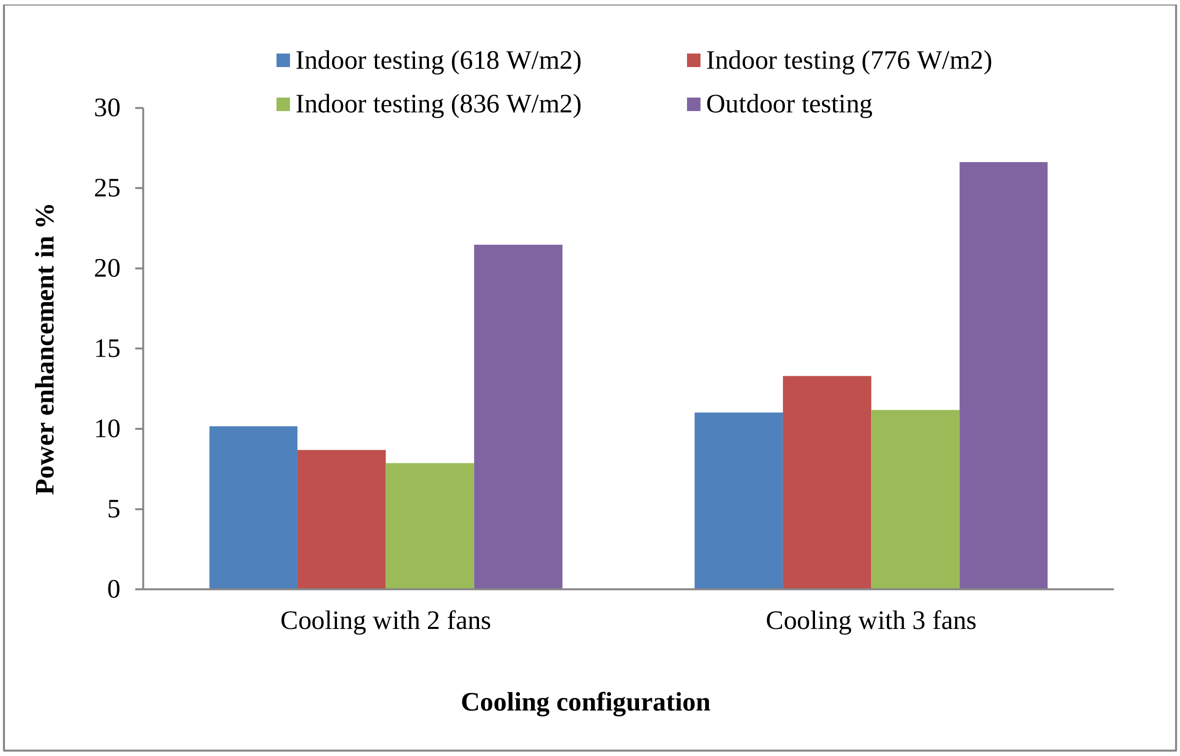


Fig. 4.28 Comparison between enhancements in power output of solar panel in indoor and outdoor conditions

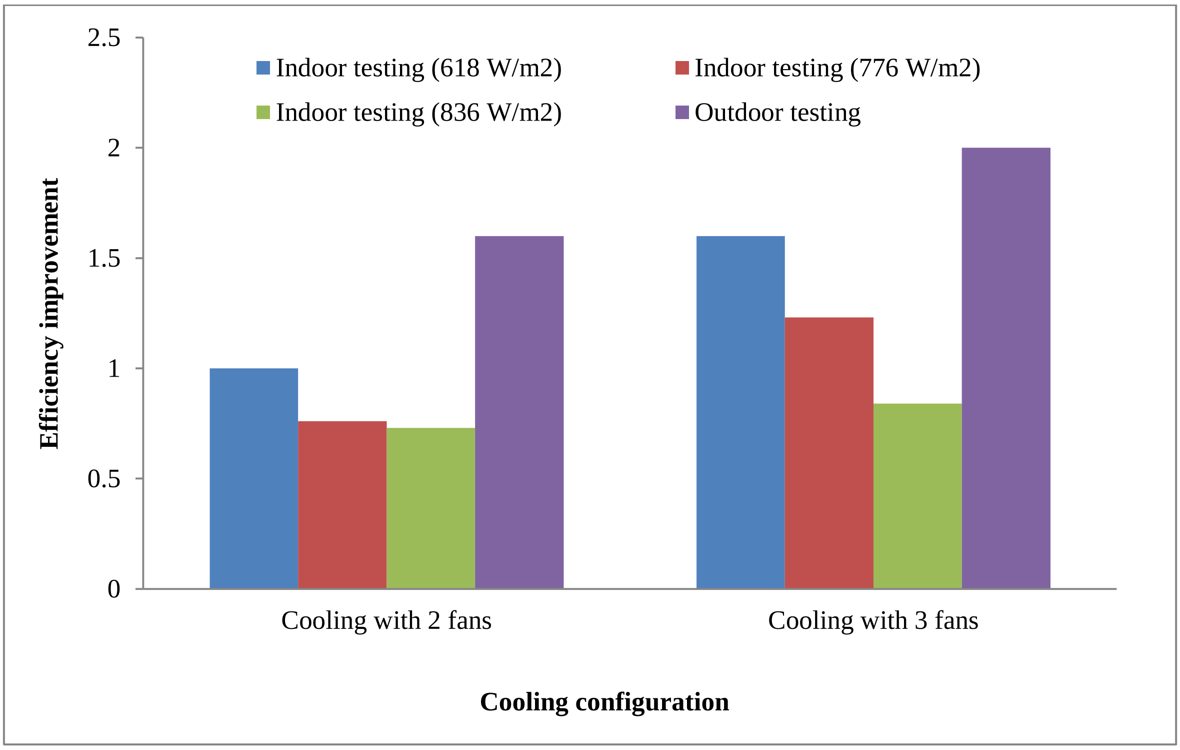


Fig. 4.29 Comparison between enhancements in power output of solar panel in indoor and outdoor conditions

Highest percentage of power output enhancement is obtained in outdoor conditions which is approximately 26.62% using 3 fans. While in indoor conditions under similar operating conditions the same was enhanced by 13.3%. So difference of 13.32% is obtained in power increment. Using three fans, the maximum improvement in efficiency of the same solar panel occurred by 1.69% in indoor testing conditions and by 2% in outdoor conditions resulting in difference of 0.31%. Such results are obtained due to more cooling in outdoor conditions even after using same number of fans. In indoor testing conditions air is stagnant and no change in its velocity occurs while air velocity changes in outdoor environment which produces a positive influence on the performance of the PV module. Along with the fan cooling, wind also contributes in cooling the solar panel surface naturally and causes more reduction in panel temperature. As a result the enhancement in solar module power output and efficiency is more. Therefore the contribution from wind speed can’t be ignored while designing the cooling configuration for outdoor conditions.

Summary and Conclusion

CHAPTER-5 SUMMARY AND CONCLUSIONS

The photovoltaic solar panels are designed to generate electricity with good efficiency under normal operating conditions and their performance has some constraints. They work best only under manufactures conditions and their performance degrades as conditions deviates from standard test conditions. The increment in solar panel temperature degrades its power and efficiency. Indoor testing had been conducted to combat this problem an active cooling technique with DC fans is experimented. Experiments were conducted in three phases:

Phase 1: As testing was to be done in winter months so indoor testing is opted. For this a solar simulator is fabricated using halogen reflectors. Total of 8 reflectors are fixed on an ms angle stand. Two reflectors are connected with a regulator to regulate the voltage and solar radiation intensity. 8 reflector arranged in four rows covered an effective area of 0.99 m^2 and maximum of 836 W/m^2 of average solar irradiation obtained. It was found that the non uniformity of simulator decreases with increase in distance between light source and test surface up to certain distance and then started increasing. The optimized distance for which the non uniformity is minimized was found to be 24 cm with a non uniformity of 14.8% which is under British standards. It is always recommended to leave the simulator turn on at least half an hour before utilizing the light intensity to get stabilized intensity. The fabricated solar simulator took about 35 minutes to minimize the fluctuations in its radiation intensity.

Phase 2: Phase 2 i.e. indoor testing is conducted in two parts, one is to observe the effect of temperature on 150 W polycrystalline solar panel and other is observe how efficient the adopted cooling configuration is. Both these are conducted under an artificial sunlight produced by fabricated solar simulator. It is observed that as average surface temperature of the solar module increases the open circuit voltage decreases as these two have inverse relationship. Due to this the panel power output decreases and hence conversion efficiency reduces. Therefore payback period of a solar panel is extended and results in to shorter lifespan of PV systems. It is found that as temperature increases from 25 ^oC to 100 ^oC, open circuit voltage reduces by 4.45 V i.e. 20.53% for irradiation level of 618 W/m^2. For irradiation level of 776 W/m^2, this reduction is by 4.37 V i.e. 20.53% as temperature increases from 25 ^oC to 108 ^oC and for irradiation of 836 W/m^2, temperature increases from 25 ^{o}C to 111 ^{o}C resulting in reduction of 4.09 V i.e. 19.21%. This reduction in voltage leads to decrement in power output by 16.89%, 19.45% and 19.21% for 618 W/m^2, 776 W/m^2 and 836 W/m^2 respectively.

The second part of this phase is to observe the effect of adopted cooling configuration utilizing the principle of forced convective heat transfer on PV panel performance. For optimum utilization of cooling system the cooling is done only for higher temperatures above 45 ^{o}C. Experimental results show that for solar insolation of 618 W/m^2 of the average surface temperature reduces by 6.65%, 7.72%, 22.04% and 23.31% using one, two, three and four fans cooling respectively. Similar results are obtained for irradiation level of 776 W/m^2 and 836 W/m^2 but with more reduction. However the difference in temperature reduction using three and four fans is negligible for all three radiations. As performance is highly affected by temperature rise so reduction in it will improves the power produced by solar panel. It is found that the power output enhancement occur by an amount of 4.9%, 8.24%, 10.15% and 11.02% using 1, 2, 3 and 4 fans respectively for irradiation of 618 W/m^2. Similarly the power output increases by an amount of 3.6%, 8.68%, 13.3%, and 14.94% for solar radiation of 776 W/m^2 and 4.12%, 7.87%, 11.17%, and 12.83% for solar irradiance of 836 W/m^2 by using one two three and four fans respectively. This shows that the adopted configuration is found to be efficient and effective.

Phase 3: In this phase the experiments are conducted in actual outdoor meteorological conditions of Pantnagar for two days each with and without cooling. Cooling is done using two and three fans as soon as average surface temperature of panel reaches to 50 ^{o}C. It is found that conventional solar module attained the average surface temperature of 51.68 ^{o}C while panel with cooling configuration using two and three fans attained 44.2 ^{o}C and 45.16 ^{o}C respectively corresponding to reduction of 13.67% and 12.61%. This reduction causes the power output and of module to enhance by 21.48% and 26.6% using two and three fans respectively.

It is clearly seen that the testing the performance of a PV module in outdoor conditions by employing cooling configuration in outdoor conditions proved to be more effective than in indoor test conditions. This is because in outdoor conditions air wind velocity also plays its significant role in cooling which results in more enhancements in panel performance.

The present study clearly shows that temperature has worst effect on characteristics of a solar module and temperature doesn't only reduce the performance of solar panel but also reduces its effective lifespan. So to tackle this problem a new cooling configuration using DC fans at the exit of duct is employed in this thesis research without any extra power consumption from outside source.

5.2 Conclusions

This study has fabricated a simple low cost halogen simulator for indoor testing and efficiently reduces the surface temperature of a 150 W polycrystalline solar panel by employing a new cooling configuration. The salient conclusions drawn from work done in the present dissertation are as follows:

1. A solar simulator is successfully fabricated using halogen reflectors so as to create an artificial sunlight for indoor testing purpose.
2. From the test conducted, the distance between halogen lights and solar panel determines the magnitude of solar radiations and uniformity. The smaller the distance, the higher the irradiance, but with more fluctuations, and vice versa.
3. The non-uniformity of irradiance was experimentally tested for different distances between solar simulator and tested surface. For a distance of 24 cm, fluctuations found to be minimum with non uniformity of 14.8% which is still within the limits allowed by British Standards for solar simulator testing.
4. However the uniformity could be improved by construction and configuration for example by setting the spacing between reflectors, by changing position of reflectors, using more number of halogen reflectors and changing angle of the reflector, etc.
5. Due to the high heat emitted by the halogen reflectors, PV panel performance decreases with the gradient of 0.18 W/^{o}C for 618 W/m^2, 0.22 W/^{o}C for 776 W/m^2 and 0.24 W/^{o}C for 836 W/m^2 under indoor testing conditions.
6. The PV performance can be enhanced efficiently by extracting the heat through a duct using different number of DC fans.
7. Increasing the number of DC fans for cooling purpose will consume more energy from a PV panel so there must be an optimum number of DC fans required for cooling of PV panel.

8. Using four fans for cooling purpose results in maximum improvement in solar panel performance for both indoor conditions.

9. However the difference in performance enhancement using four fans is not much as compared to using three fans.

10. For indoor conditions the power improvement occurred by an amount of 13.3% and for outdoor conditions it improved by an amount of 26.62% by using three fans.

11. Wind played a role of performance booster additionally and helped in reducing the module temperature.

12. Performance of solar panel improved more in outdoor conditions than indoor conditions so before optimizing the number DC fans several environmental factors such as atmospheric condition, speed etc. must be considered.

5.3 Recommendations for future work

The investigation that has been undertaken for this thesis has highlighted a number of gaps and loopholes on which further investigation would be beneficial for research purpose. The limitations in the present study have indicated following areas as recommendations for further work.

1. The solar simulator fabricated with height adjustable arrangement however it lacks the angle tilting mechanism so as to adjust the light source according to the tilting angle of PV modules. It could be also improved in terms of flux uniformity and better light source so as to reach radiations as that of sun.

2. As it is observed in the present study that cooling in actual conditions result in more power enhancement as compared to indoor conditions so it is desirable to predict the effect of wind velocity on panel performance accurately so one can optimize the cooling configuration.

3. Duct parameters particularly its depth are also critical factors while designing for cooling purpose. The present study is limited to only one depth size however the amount of cooling is affected by its depth. So effect of variable depth needs to be investigated so as to find an optimum value for which cooling will be maximum.

4. The amount of heat extracted is also influenced by the flow rate of DC fans. However present study is limited to only maximum flow rate of fans so this study can be further taken forward by varying the flow rate by changing the speed of fans through speed regulators.

5. In the present study holes are made on both opposite sides of duct to let the air in. However it will result extraction of some cooled air at the exit of the duct which is not desirable. So study could be made by closing the holes near the exit of duct.

6. It is also found in the past literatures that study lacks the effective and better utilization of extracted heated air. Initially it was decided to work on this but due to time limitation it couldn't be conducted.

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LITERATURE CITED

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Appendices

APPENDIX

APPENDIX - A

Discription Of Instruments Used And Their Accuracy

A.1 Equipment And Measuring Instruments

A1.1 Thermometer

Type	: Mercury in glass thermometer
Accuracy	: ±1 °C

A1.2 Thermocouple

Type	: K – type
Accuracy	: ± 2.2 °C
Range	: 0 °C – 1300 °C

A1.3 Anemometer

Type	: Vane type thermo anemometer
Air velocity range	: 0-30 m/s
Air temperature range	: 0-50 ^{o}C
Resolution	:0.01 m/s

A1.4 PV System Analyzer

Max. solar system power (P_{max})	: 1000V, 12A (12000W capability)
Battery life	: 400 times of linear scan, 8hrs standby mode
Temperature coefficient	: 0.1 % of full scale/^{o}C
Operating environment	: 5^{o}C – 50^{o}C, 85% RH

A1.5 Testo-870 Thermal image camera

Infrared Resoltuion	: 160x120
Focus: Fixed focus	
Thermal sensitivity	: 100mK
Data output display	: IR image
Operating temperature	: 5 to 122^{o}F
Battery type	: Fast charging, Li-ion battery
Battery life	: 4 hours

APPENDIX – B

Calibration certificate of DT85-3 data logger

Certificate of Traceable Calibration

Product Description

Model: DT85-3
Serial: 106610

Kernel Assembly: AS1238C1 1794-015
Terminal Assembly: AS1218C1 1798-056
Firmware: 85 Version 9.18.6291

Calibration Details

Calibration Date: 2015/12/08 13:12:59
Test Location: Apptek, Unit 7, 2 Pinacle Street Brendale QLD 4500
Ambient Temperature: 22.8 °C
NATA Certified Reference: Fluke 8840A Serial 5141011
Calibration Reference: DT8x Tester JIG-271 Version 1.50.0003, Calibrated 2015/11/17 13:05:04

Calibration Results

The following table lists measurements performed against traceable references.

Range	Channel(options)	Reference	Actual Reading	Allowable Error[1]	Error	Status
+30 V	1+HV(GL30V)	+10.0000 V	+10.0006	± 0.1 %	0.006 %	PASS
+3000 mV	1*V(GL3V)	+2500.3 mV	+2500.4	± 0.1 %	0.003 %	PASS
+300 mV	1+V(GL300MV)	+249.98 mV	+250.02	± 0.1 %	0.017 %	PASS
+30 mV	1-V(GL30MV)	+24.996 mV	+24.997	± 0.1 %	0.002 %	PASS
-30 V	1+HV(GL30V)	-10.0000 V	-10.0006	± 0.1 %	0.006 %	PASS
-3000 mV	1*V(GL3V)	-2499.1 mV	-2499.9	± 0.1 %	0.032 %	PASS
-300 mV	1+V(GL300MV)	-249.88 mV	-249.92	± 0.1 %	0.016 %	PASS
-30 mV	1-V(GL30MV)	-24.988 mV	-24.995	± 0.1 %	0.029 %	PASS
10 k Ω	1R(4W,I)	100.0000 Ω	100.003	± 0.2 %	0.003 %	PASS

[1] Allowable Error indicates the maximum allowable difference between the Reference and the Actual Reading, specified as a percentage of the Actual Reading, when the ambient temperature is between 5°C and 40°C.

The product covered by this certificate meets or exceeds the required performance specified by Thermo Fisher Scientific Australia Pty. Ltd.

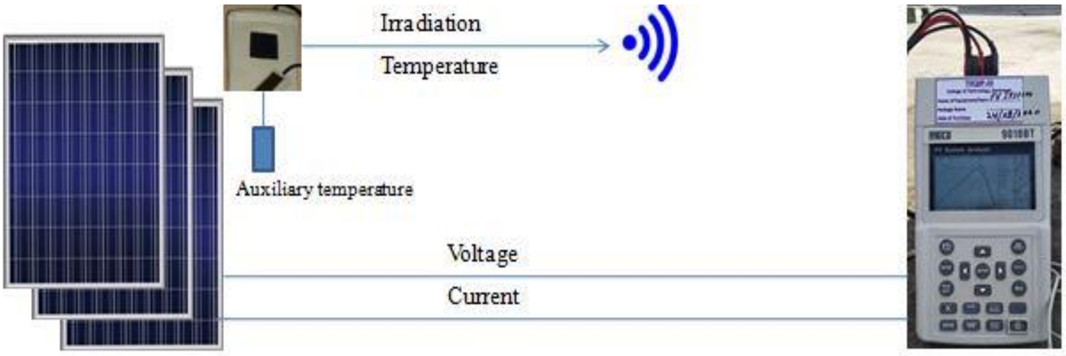
The measurements performed to generate this certificate are traceable to Australian national standards of measurement.

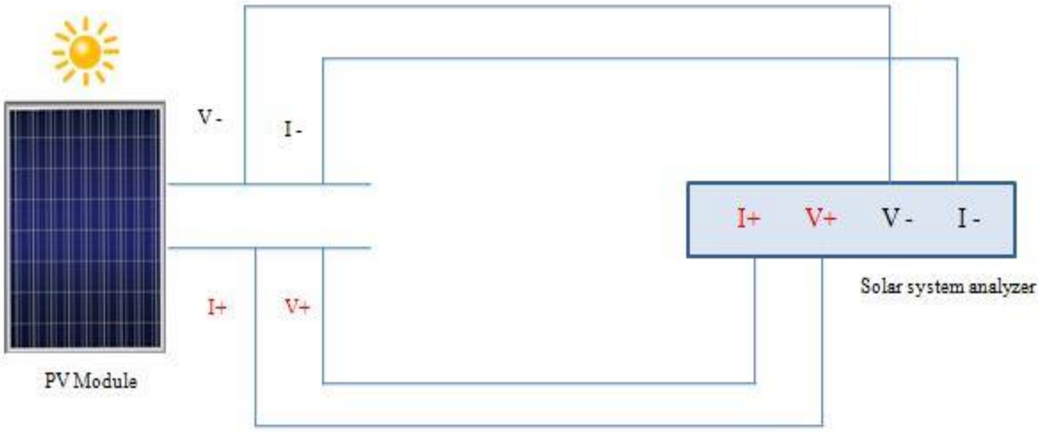
This product has been manufactured under an ISO9001:2008 quality system.

file:///G:/dt80/reports/DT85/html/DT85-106610%208-12-2015%201-12-59%20PM.html 8/12/2015

APPENDIX – C

Connecting diagram of solar panel with PV System Analyzer





VITA

The author, Shivani Chauhan, was born on 5th July, 1995 in Haridwar district of Uttarakhand. She passed her High School and Intermediate Examination from Angels Academy Senior Secondary School Haridwar (CBSE Board) in 2010 and 2012 respectively. Her B.Tech. degree in Mechanical Engineering is from College of Engineering Roorkee in 2016. She took admission in the College of Post Graduate Studies at Govind Ballabh Pant University of Agriculture & Technology, Pantnagar in August 2018 for M.Tech. degree in Mechanical Engineering with major in Thermal Engineering.

Address:

Shivani Chauhan
Village –Rohalki Kishanpur
Post- Bahadrabad
District –Haridwar
(Uttarakhand)
Pin code- 249402
Phone No.:9675234939
E-mail: shivanichauhan906@gmail.com

ABSTRACT

Name	:	**Shivani Chauhan**	**Id. No.**	:	54078
Semester & Year of admission	:	1^{st}, 2018-2019	**Degree**	:	Master of Technology (Mechanical Engineering)
Major	:	Thermal Engineering	**Department**	:	Mechanical Engineering
Thesis Title	:	**"Solar Panel Performance Enhancement using Active Cooling Technique"**			
Advisor	:	**Dr. Lokesh Varshney**			

Out of the total solar radiations incident on a typical photovoltaic solar module, it converts part of the incident energy equal to its efficiency. This is only 15.3% for the 150 W polycrystalline panel used in this study. The remaining irradiance absorbed is transformed into heat. For each degree rise in module's operating temperature result in decrement of efficiency by approximately 0.4–0.5%. This decrement also degrades its effective working lifespan. This effect can be minimized by keeping the temperature near to its standard operating temperature. For this a new cooling configuration has been proposed and investigated based on forced convection induced by using DC fans at the exit of the duct using a self fabricated solar simulator. Subsequently performance is evaluated in actual outdoor conditions also. DC fans extract the heat generated and help in cooling of PV panel. Experiments are done with and without cooling mechanism for three different radiation levels i.e. 618 W/m^2, 776 W/m^2 and 836 W/m^2. DC fans are operated by the solar panel power directly as soon as the average surface temperature reaches to 45^{o}C. Under indoor testing the used cooling configuration results in highest temperature reduction of 24.34% using four fans at constant irradiation level of 776 W/m^2. It is also observed that there is not much reduction in temperature obtained using three and four fans. Temperature reduction enhances the power output by 13.3% and 14.9% using three and four fans respectively. Similar changes are obtained for radiation level of 618 W/m^2 and 836 W/m^2. It is concluded that there is an optimum number of fans required for cooling purpose. Experiments are conducted using two and three fans in actual outdoor conditions in order to verify the results obtained under simulated conditions. The cooling configuration result in temperature reduction by 13.67% and 12.61% using two and three fans. This causes the power output of module to enhance by 21.48% and 26.6% using two and three fans respectively. The performance of a PV module in outdoor conditions by employing cooling configuration proves to be more effective as compared to indoor test conditions due to wind effect.

(Lokesh Varshney)
Advisor

(Shivani Chauhan)
Author

सार

नाम	:	**शिवानी चौहान**	**परिचयांक**	:	५४०७८
सेमेस्टर और प्रवेश का वर्ष	:	प्रथम, २०१८-२०१९	**उपाधि**	:	परास्नातक अभियांत्रिकी
मेजर	:	थर्मल अभियांत्रिकी	**विभाग**	:	यांत्रिक अभियांत्रिकी

शोध शीर्षक : **"सक्रिय शीतलन तकनीक का प्रयोग करके सौर पैनल के निष्पादन में वृद्धि"**

सलाहकार : **डॉ0 लोकेश वार्ष्णेय**

फोटोवोल्टेइक सौर मॉड्यूल पर गिरने वाली कुल सौर विकिरणों का कुछ प्रतिशत ही विद्युतीय ऊर्जा में परिवर्तित हो पाता है। यह प्रतिशत उसकी विद्युत रूपांतरण दक्षता के बराबर होता है। इस अध्ययन में प्रयुक्त १५० वाट पैनल के लिए यह मात्रा १५.३% है। शेष अवशोषित विकिरण ऊष्मा में परिवर्तित हो जाती है। मॉड्यूल के तापमान में प्रत्येक डिग्री वृद्धि के लिए दक्षता में लगभग ०.४-०.५% तक की गिरावट आती है। यह उसके प्रभावी जीवनकाल को भी अपकर्ष करती है। इस प्रभाव को उसके तापमान को कम करके काम किया जा सकता है। इसके लिए एक स्व निर्मित सौर सिम्युलेटर का प्रयोग करके डीसी पंखों का प्रयोग कर प्रेरित संवहन के आधार पर एक नया शीतलन विन्यास प्रस्तावित किया गया एवम् जांच की गई। इसके उपरांत निष्पादन का मूल्यांकन वास्तविक बाहरी परिस्थितियों में भी किया गया। डीसी पंखें उत्पन्न ऊष्मा को बाहर निकाल कर पैनल को ठंडा करने में सहायक रहते है। प्रयोगों को तीन अलग अलग विकिरण स्तरों ६१८ W/m^2, ७७६ W/m^2 एवम् ८३६ W/m^2 के लिए शीतलन तंत्र के साथ और उसके बिना किया गया। जैसे ही पैनल का औसत तापमान ४५°C पहुंचता है वैसे ही पंखों को सीधे पैनल की विद्युत ऊर्जा द्वारा संचालित किया जाता है। भीतरी परीक्षण में अपनाई गई शीतलन विन्यास से विकिरण स्तर ७७६ W/m^2 पर चार पंखों का प्रयोग करके तापमान में अधिकतम २४.३४% गिरावट दर्ज की गई। यह भी देखा गया कि ३ और ४ पंखों का उपयोग करके तापमान में बहुत अधिक अंतर नहीं रहा। ३ और ४ पंखों का उपयोग कर तापमान गिरावट से विद्युत ऊर्जा का उत्पादन क्रमशः १३.३% और १४.९% बढ़ा। विकिरण स्तर ६१८ W/m^2 और ८३६ W/m^2 के लिए भी समान परिवर्तन प्राप्त हुए। इससे यह निष्कर्ष निकलता है कि शीतलन उद्देश्य के लिए आवश्यक पंखों की एक अनुकूलतम संख्या होती है। प्राप्त परिणामों को परिस्थितियों से सत्यापित करने के लिए वास्तविक परिस्थितियों में समान प्रयोग २ और ३ पंखों को उपयोग करके किया गया। क्रमशः २ और ३ पंखों का उपयोग करके शीतलन विन्यास से तापमान में १३.६७% और १२.६२% की गिरावट दर्ज की गई। इससे विद्युत ऊर्जा का उत्पादन २१.४८% और २६.६% तक बढ़ा। शीतलन विन्यास के साथ बाहरी परिस्थितियों में पीवी मॉड्यूल का प्रदर्शन हवा के प्रभाव के कारण आंतरिक परीक्षण की तुलना में अधिक प्रभावी सिद्ध हुआ।

(लोकेश वार्ष्णेय)
सलाहकार

(शिवानी चौहान)
लेखक