EXPERIMENTAL INVESTIGATION ON THE THERMAL AND ELECTRICAL PERFORMANCE OF PV MODULES COOLED BY DUCT

D.Kaviyarasan[1]
[1]PG Scholar, Department of Mechanical Engineering, Muthayammal College of Engineering, Rasipuram, Tamilnadu.
E-Mail: kavimech2012@gmail.com

Sakthivel[2]
[2]Asst Prof, Department of Mechanical Engineering, Muthayammal College of Engineering, Rasipuram, Tamilnadu.

V.Velukumar[3]
[3]PG Scholar, Department of Mechanical Engineering, Muthayammal College of Engineering, Rasipuram, Tamilnadu.
E-Mail: velukumareng@gmail.com

R.Sabariselvan[4]
[4]PG Scholar, Department of Mechanical Engineering, Muthayammal College of Engineering, Rasipuram, Tamilnadu.
E-Mail: rsabariselvan@gmail.com

Abstract: Flat solar photovoltaic (PV) modules are widely used in domestic and industrial buildings for meeting the electric power demands. Higher operating temperatures of these PV modules results in lower electrical power yield and conversion efficiency. Hence to counteract this drawback of reduced power output, PV module temperature was cooled by passing air on the rear surface of the panel through the duct. The passive cooling of PV module by converging duct were conducted in the location of Tiruchirappalli (78.6°E & 10.8°N), Tamil Nadu, India with flat 12 watt PV module. After cooling the PV module, temperature got reduced by 5°C and the power output was increased by 1.48 W. Basic energy balance equation applicable for PV module was used to evaluate the module temperatures and a fair agreement was obtained between the theoretical and experimental values in the case of with and without cooling.

Key words: power, temperature, voltage, current, solar radiation.

I.INTRODUCTION

A. About Solar Energy

Environmental problems due to extensive use of fossil fuels for electricityproduction and combustion engines have become increasingly serious on a world scale in recent years. The continuous increase in the level of greenhouse gas emissions and the climb in fuel prices are the main driving forces behind efforts to more effectively utilize various sources of renewable energy. To solve these problems, renewable energy sources have been considered as new sources of clean energy. Solar energy can be converted easily and directly to the electric energy by Photovoltaic converters. Generally conversion system can be classified into two categories,

- Thermal system which converts solar energy into heat.
- Photovoltaic system which convert solar energy into electricity

B. Principleof Photovoltaic Cell

Solar cell is a device which converts photons in Solar rays to direct-current (DC)and voltage. The associated technology is called Solar Photovoltaic (SPV). A typical silicon PV cell is a thin wafer consisting of a very thin layer of phosphorous doped (N-type) silicon on top of a thicker layer of (P-type) boron doped silicon. An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction).When the sunlight hits the semiconductor surface, an electron springs up and is attracted towards the N-type semiconductor material. This will cause more negatives in the n-type and more positives in the P-type semiconductors, generating a higher flow of electricity. This is known as Photovoltaic effect.

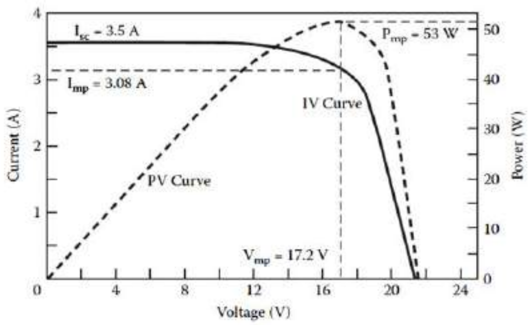


Fig.1 PV Cell operational parameters

The important parameters in the PV cell operation are open circuit voltage, short circuit current, maximum power operating current, rated maximum power voltage, maximum power, operating temperature, intensity of incident radiation. These are discussed below.

C.Open circuit voltage

Open-circuit voltage (V_{oc}) is the maximum voltage generated by the cell. This voltage is measured when no external circuit is connected to the cell.

D. Short Circuit Current

Short-circuit current (I_{sc}) is the maximum current generated by a cell or module and is measured when an external circuit with no resistance is connected (i.e., the cell is shorted). Its value depends on the cell's surface area and the amount of solar radiation incident upon the surface.

E.Maximum Power

Maximum power (P_{mp}) is the maximum power available from a PV cell or module and occurs at the maximum power point on the I-V curve. It is the product of the PV current (I_{mp}) and voltage (V_{mp}).

F.Cell Temperature

As temperature increases, the band gap of the intrinsic semiconductor shrinks, and the open circuit voltage ($V_{oc)}$ decreases and hence the reduction in cell output.

G. Fill Factor

The fill factor is most commonly determined from measurement of the IV curve and is defined as the maximum power divided by the product of Isc*Voc.

FF =Vmp Imp/ VocIsc

Typical commercial solar cells have a fill factor > 0.70.Reject crystalline cells like those found on eBay , or grade B cells , have a fill factor usually between 0.4 to 0.65, and in amorphous solar cells or thin film cells between 0.4 to 0.7. The fill factor can all so be used to determine the series resistance of solar cell.

II.EXPERIMENTAL SETUP

A.Experimental Work

The experimental setup consisted of a flat PV module, a digital multi-meter for measuring the module power output in terms of current and voltage, K type thermocouples, a six channel temperature indicator and fabricated duct made up of sheet metal. A rheostat (350Ω and 1.25 A) was used to vary the load during the measurements of IV characteristics. A converging duct (D_H = 21.5mm; A_I = 0.088m² and A_O= 0.013m²) made of 2 mm thick sheet metal were fabricated in-house and screwed to the photovoltaic modules. K type thermocouples with a resolution of 0.1°C were used for measuring the ambient and module temperature. The module temperature was measured by thermocouples that were fixed to the top side of the panel at location T_1 as shown in Figure 3.1. The irradiation data were measured on the module tilted surface by solar pyranometer. This experimental set up is installed on a height of 170 cm from the ceiling roof and the experiments were conducted under clear sky and sunny conditions from 9AM to 5 PM at regular intervals.

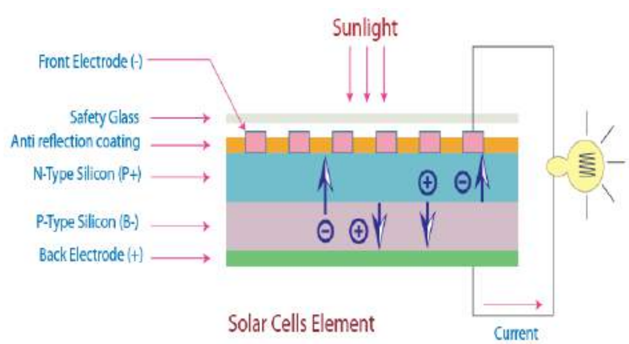
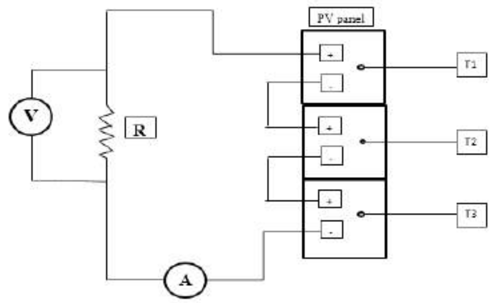
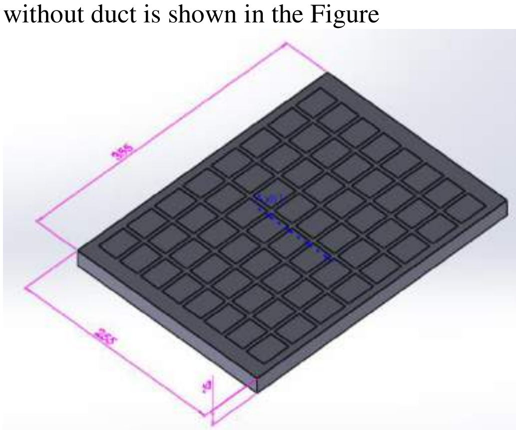


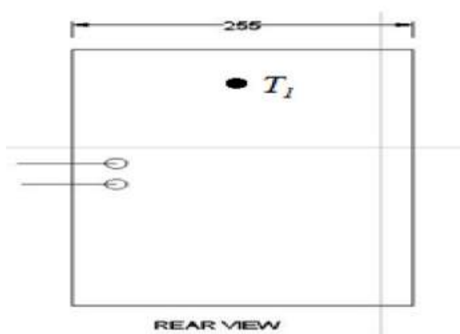
Fig.2. PV Cells element

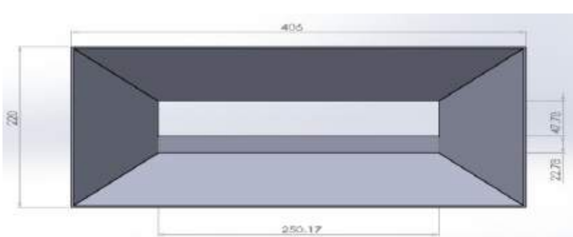


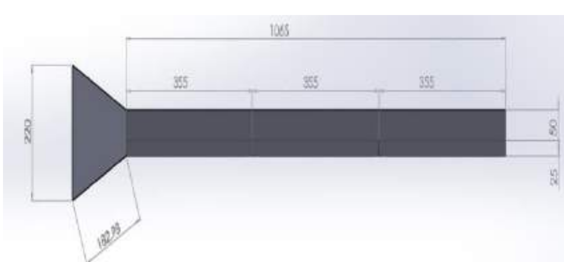
III. SCHEMATIC DIAGRAM

The schematic diagram of the PV panel with and without duct is shown in the Figure









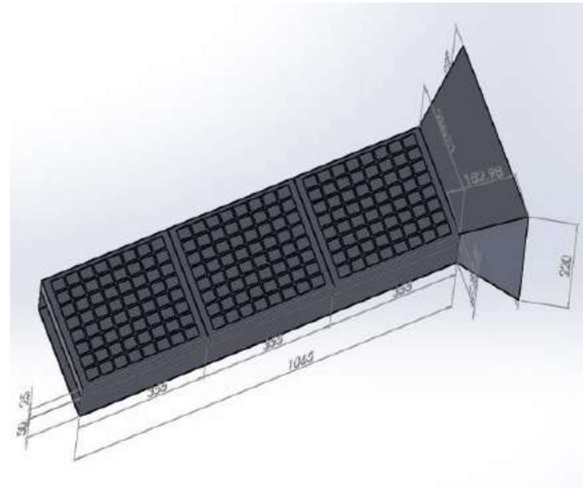


Fig.3. Modeling of the cooling duct

IV. LIST OF COMPONENTS AND EQUIPMENTS USED

A. PV Panel

A polycrystalline PV panel is used for this experiment. The two panels of almost same rating are used, one of which was cooled and another one left uncooled. For cooling, the converging duct is placed under the panel. The PV panel specification and location of the experiment are given in the Table.

PARAMETERS	**SPECIFICATION**
PV PANEL	**Electrical Characteristics** Nominal Voltage : 36V Maximum Power : 36W No. of Cells : 36 V_{oc} : 61V I_{sc} : 0.7A **Dimensions** Length : 355 mm Width : 255 mm Thickness : 20 mm Weight : 1.20 kg Area : 0.0905m²
DUCT	Material = MS Hydraulic Dia = 21.5mm Inlet area = 0.088m² Outlet area = 0.013m²

B. Duct Design

Usually, the length L and width W of the duct are determined by the dimensions of the array, so that the principal design variable is the depth H of the duct. Therefore for maintaining the temperature at an optimum level will increase the efficiency of the PV array. The hydraulic depth of the duct D for a given width is defined by

$$\mathbf{D} = \frac{2WH}{(W+H)}$$

A design rule-of-thumb was given that the ratio L/D should be around 20.

V.METHODOLOGY

A. Experimental Description

The main objective is minimizing the rise in PV panel operating temperature during elevated temperature levels and high irradiance level. The panel temperature is regulated by fitting a duct at the rear side of the PV panel and the panels are cooled by radiation and free convection as ambient air rises through the duct due to buoyancy. Here both experimental and theoretical panel temperature was determined and its difference is compared for panel with cooling and without cooling. Also comparison is made for the drop in power for panel without cooling and with cooling for achieving the maximum solar to electric conversion. Experiments were conducted in the period of August 10 to November 2 2016 during which the performance of both the PV modules (with cooling and without cooling) is observed and readings are recorded for each day between 10:00am to 3:00pm.

B. Experimental Objectives

The following are the main objectives of this project,

- Fabrication of duct to the hydraulic diameter around 20
- Implementation of converging duct in the PV module.
- Theoretical calculation of rise in module temperature.
- Dissipation of the heat generated in PV module.
- To find the variation of temperature and power generation of the PV module with and without cooling.
- Comparative analysis of PV module with air cooling by duct and without cooling.
- To obtain the maximum efficiency from the PV module.

C. Data Reduction

The thermal model for estimating the PV module temperature can be developed using the simple energy balance equation with the following assumptions.

- Heat transfer takes place in one dimension
- Quasi-static state
- Electrical losses are negligible

Therefore, the energy balance equation for unit area of PV module without cooling can be expressed as,

"[Solar Energy absorbed by the PV Module] = [Solar energy used for power generation + Solar energy wasted as heat by radiation and convection]" (1)

$$\mathbf{q_{in} = q_{pv} + q_{rad,b} + q_{rad,t} + q_{conv,t} + q_{conv,b}} \quad \textbf{(2)}$$

$$\boldsymbol{\tau\alpha I = \eta(\tau\alpha I) + \square_f \sigma\left(T_m^4 + T_{sky}^4\right) + \square_b \sigma\left(T_m^4 + T_g^4\right) + h_t(T_m + T_a) + h_b(T_m + T_a)} \quad \textbf{(3)}$$

Where ($\tau\alpha$=0.81) represents the portion of solar radiation reaching the solar cells after crossing the glass cover, emissivity $\square_f$= $\square_b$= 0.9,T_{sky} = (T_a-20) K for clear sky conditions and T_g= T_a [31].

The top and bottom side heat transfer coefficients were given by$\square_t$ = 5.82 + 4.07 V and $\square_b$ = 5.82 + 4.07 V respectively [32].

For the panel which was not cooled, the same atmospheric wind velocity V_1 is used for finding top and bottom side heat transfer coefficients. But for the panel which was cooled by means of air passing through the converging duct, the atmospheric wind velocity V_1 is used for finding the top side heat transfer coefficient and for the bottom side heat transfer coefficient the converging velocity V_2 obtained from the continuity equation (4).

$$\boldsymbol{V2 = (A1 \times V1) \div A2} \quad \textbf{(4)}$$

Thus, energy balance equation for unit area of PV module with cooling can be expressed as

$$\mathbf{q_{in} = q_{pv} + q_{rad,b} + q_{rad,t} + q_{conv,t} + q_{conv,b}} \quad \textbf{(5)}$$

Thus the final form of energy balance equation for unit area of PV module with cooling can be written as given in Eq. (5) and was used to estimate the module temperature.

$$\boldsymbol{\tau\alpha I = \eta(\tau\alpha I) + \square_f \sigma\left(T_m^4 + T_{sky}^4\right) + \square_b \sigma\left(T_m^4 + T_g^4\right) + h_t(T_m + T_a) + h_b(T_m + T_a)} \quad \textbf{(6)}$$

Figure 4.2 shows the energy balance taking place in a PV module,

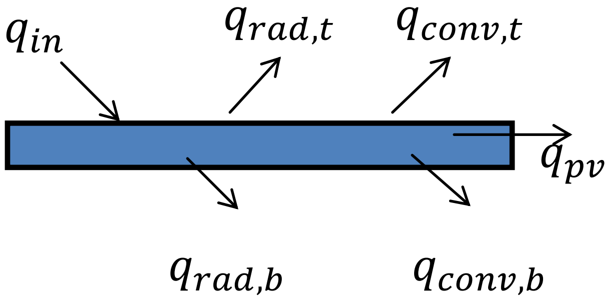


Figure.4 Energy balance in graphical representation

Efficiency of the PV panel can be obtained by calculating the electrical power developed, area of the panel and global irradiation constant and substituting in the efficiency equation (7) below

Efficiency $\eta = \dfrac{\textit{PanelOutputPower}\ (P)}{\textit{IncidentRadiationPower}\ (G \times A)}$ **(7)**

Where, G refers to global irradiation constant and its value is 5.46 W/m^2, A refers to the area of the PV panel and its value is 0.0905 m^2 .

D. Tabulations and observations

1. Temperature

Theoretical module temperature can be calculated by knowing the values of ambient temperature, irradiance and wind velocity and substitute in equation (6) of the energy balance. Ambient and actual module temperature is measured by using temperature indicator while the irradiance and wind velocity is measured by using Pyranometer and wind data obtained from meteorological institute [33] respectively. The ambient temperature, radiation intensity, Wind velocity, Converging Velocity, Theoretical and module temperature with and without cooling, and temperature difference were noted, calculated and they are tabulated in the Table.

Time	T_{amb} (°C)	I (W/m^2)	V_1 (m/s)	V_2 (m/s)	T_{m1} °C	T_{m2} °C	T_{m3} °C	T_{m4} °C	ΔT_1 °C	ΔT_2 °C
10.1	28	670	3.055	38.326	38.84	29	33	30	9.84	3
10.4	28	679	3.055	38.326	39.96	30	34	30	9.96	5
11.1	29	695	1.944	24.390	43.65	33	38	34	10.65	4
12.1	31	661	1.944	24.390	44.88	35.16	39	36	9.72	3
12.4	31	717	1.944	24.390	46.06	35.52	42	37	10.54	5
13.1	32	748	1.944	24.390	48	39	43	38	9[illegible]	5
13.4	32	743	1.944	24.390	45.92	36.18	40	38	9.74	2
14.4	32	737	1.944	24.390	46.53	35.69	41	38	10.84	3
15.1	31	662	4.166	52.280	42.68	33.47	37	35	9.21	2
15.4	30	512	3.610	45.300	43.44	34.95	35	33	8.48	2

2. Maximum Power From Iv-Pv Curve

The maximum power is obtained by measuring voltage and current using multimeter at varying irradiance level is noted in the Table.

Without Cooling			With Cooling by Duct		
Voltage (V)	**Current (A)**	**Power (W)**	**Voltage (V)**	**Current (A)**	**Power (W)**
0	0.39	0	0	0.45	0
2.4	0.39	0.94	5	0.45	2.25
5.2	0.39	2.03	14.13	0.42	5.93
8	0.38	3.04	15.95	0.38	6.06
12.5	0.37	4.63	17.39	0.35	6.09
16	0.32	5.12	18.23	0.3	5.47
18.1	0.2	3.62	19.07	0	0
18.94	0	0	-	-	-

Voltage, current and power at radiation intensity of 500 W/m^2

Without Cooling			With Cooling by Duct		
Voltage (V)	**Current (A)**	**Power (W)**	**Voltage (V)**	**Current (A)**	**Power (W)**
0	0.48	0	0	0.5	0
2.6	0.48	1.25	4.7	0.5	2.35
7.8	0.48	3.74	10	0.48	4.8
9.9	0.47	4.65	16	0.45	6.98
15.84	0.4	6.32	18.36	0.38	7.2
18.11	0.2	3.62	18.77	0.18	3.38
19	0	0	19.13	0	0

Voltage, current and power at radiation intensity of 620 W/m^2

Without Cooling			With Cooling by Duct		
Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
0	0.66	0	0	0.68	0
2.7	0.66	1.78	7.5	0.68	5.1
5.3	0.64	3.39	12.5	0.67	8.38
13.5	0.6	8.1	17	0.58	9.86
18.94	0.5	9.47	19.82	0	0
19.68	0	0	-	-	-

Voltage, current and power at radiation intensity of 846 W/m^2

3. Variation of power over time

Voltage and current of the panel have been measured with varying time intervals and the output power of panel was calculated by multiplying the observed voltage and current. The observed readings are tabulated in the Table

Time	Without Cooling			With Cooling by Duct		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
10.1	7.8	0.48	3.74	10	0.48	4.8
10.4	12.5	0.37	4.63	17.39	0.35	6.09
11.1	15.8	0.40	6.32	10.76	0.69	7.42
12.1	13.5	0.6	8.1	17	0.58	9.86
12.4	14	0.59	8.26	15.42	0.67	10.33
13.1	13.26	0.6	7.96	14.02	0.65	9.11
13.4	10.96	0.62	6.8	12.80	0.67	8.57
14.4	9.51	0.58	5.52	10.82	0.69	7.47
15.1	8	0.38	3.04	6.55	0.61	4.06

4. Efficiency

Efficiency of panel without and with cooling over time is tabulated in the Table

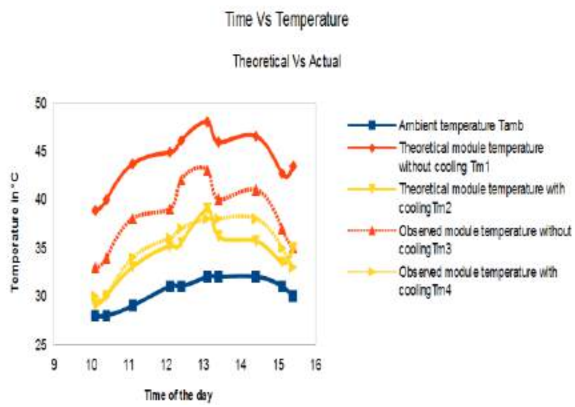
Time	Efficiency without cooling %	Efficiency with cooling by duct %	Increase in Efficiency %
11.00	12.008	13.307	1.299
11.30	13.754	14.310	0.556
12.00	14.136	15.147	1.001
12.30	13.97	17	3.03
1.00	16.035	16.477	0.442
1.30	13.72	16.789	3.065
2.00	8.209	15.813	7.604
2.30	14.774	15.143	0.369
3.00	10.693	13.688	2.995
4.00	9.470	10.438	0.968
4.30	8.825	9.241	0.416

VI. RESULTS AND DISCUSSIONS

A. Comparison of panel temperature

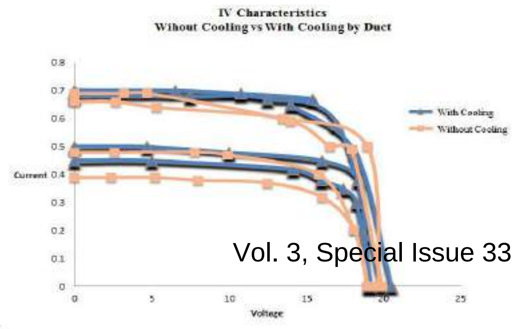
From the graph it is found that temperature of the panel gets increased with the increase in time. Also there is a significant difference in temperature levels between panel without cooling and panel with cooling.

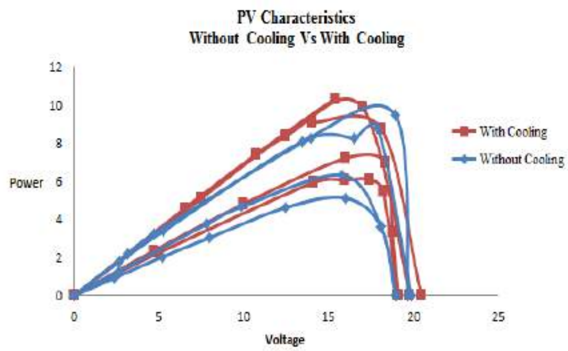
From the graph it was observed that the temperature of the PV panel can be reduced up to maximum of theoretical value of 10.65°C and to the maximum of 5 °C experimentally, when duct is attached behind the bottom surface of the duct. Reason being induced air flow by buoyancy effect in a duct behind the PV panel.



B. Comparison of maximum power

Figure refers to IV and PV characteristics of the panel without and with cooling.

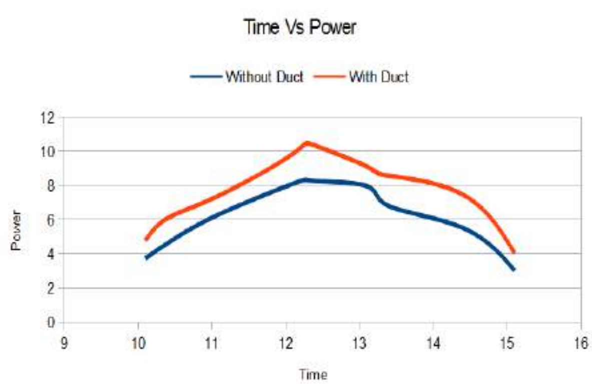




Whenever the module operating temperature of the PV panel without cooling increases the module voltage drops due to the reduction in band gap and heat within the cell which creates additional resistance to the movement of electrons. This lowers the output. But for the panel under cooled the output and voltage of a module gets increased due to air passing through the converging duct, which dissipates the internal heat generation. From the graph it was observed that the maximum power obtained by the PV panel without cooling for the irradiance 910 W/m^2 is found out to be 8.26W. Whereas for the PV panel with cooling by duct the power produced has been increased to 10.33W. Hence, with the introduction of duct behind the panel, the maximum power obtained was increased and open circuit voltage gets increased for the changing temperature and irradiance.

C. Time vsPower

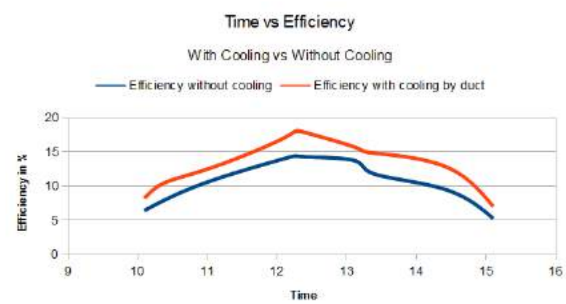
Figure refers to the variation of power for the panel which was cooled and not cooled with time.



It is clear from the figure that the power obtained for both the panels gets increased from early morning to peak noon time. Thereafter with increase in time the power gets decreased due to decrease in radiation intensity. The maximum power obtained during solar noon time was increased by 2.07 watts with implementation of duct behind the panel.

D. Time vs Efficiency

Figure gives the variation of efficiencies of PV panel with cooling and without cooling.



From the figure it was found that the panel efficiency got increased to a maximum value of 3.57% due to the air cooling by the converging duct.

VII. CONCLUSION

The temperature of panel plays a vital role in the efficiency of Photovoltaic module. The above said fact is clearly understood from the experimental test results. Increase of module temperature beyond certain limit clearly affects the efficiency of the panel and decreases the life time of module. Hence cooling system is necessary to improve the power output which inturn increases the efficiency of panel. From the graph the conclusions are,

A. Temperature variation

- Theoretical temperature of panel without cooling at peak hour is 46.06°C
- Theoretical temperature of panel with cooling at peak hour is 35.52 °C
- Observed temperature of panel without cooling at peak hour is 42°C
- Observed temperature of panel with cooling at peak hour is 37 °C
- Theoretical decrease in panel temperature due to cooling is 10.52 °C
- Observed decrease in panel temperature due to cooling is 5 °C

B. Power variation

- Increase in maximum power due to cooling is 2.07W
- Power of the panel without cooling at peak hour is 8.26W

- Power of the panel with cooling at peak hour is 10.33W
- Average increase in Power due to the effect of duct over time is 1.48W

C. Efficiency variation

- Efficiency of panel without cooling at peak hour is 14.24%
- Efficiency of panel cooling by converging duct at peak hour is 17.81%
- Average increase in efficiency due to the effect of duct over time is 2.55%

VIII. FUTURE SCOPE

Though present experimental work of cooling PV panel by duct increases the power of the panel, there exists many other ways to improve the proposed method. Some of which are as follows,

- By increasing the light intensity of solar radiations falling on the photovoltaic panel by using the concave glass trough.
- Attaching fins behind the panel which in turn dissipates the heat generated in the PV panel, hence power obtained gets increases.
- By introducing multiple ducts instead of single duct placing in single direction, we can utilise the wind for cooling panel in all direction.
- Implementing several types of ribs in the air channel for providing better performance for heat extraction.

REFERENCES

[1] Robert Foster, MajidGhassemi, Alma Cota, Solar Energy: renewable Energy and the Environment, CRC Press (2010), New York.

[2] G.N. Tiwari, R.K. Mishra, S.C. Solanki, Photovoltaic modules and their applications: A review on thermal modeling, Applied Energy 88 (2011) 2287–2304.

[3] A. Ndiaye, C.M.F. Kebe, A. Charki, P.A. Ndiaye, V. Sambou, A. Kobi, Degradation evaluation of crystalline-silicon photovoltaic modules after a few operation years in a tropical environment, Solar Energy 103 (2014) 70–77.

[4]N. Kahoul, M. Houabes, M. Sadok, Assessing the early degradation of photovoltaic modules performance in the Saharan region, Energy Conversion and Management 82 (2014) 320–326.

[5] T.T. Chow, A review on photovoltaic/thermal hybrid solar technology, Applied Energy 87 (2010) 365–379.

[6] E. Radziemska, E. Klugmann, Thermally affected parameters of the current–voltage characteristics of silicon photocell, Energy Conversion and Management 43 (2002) 1889-1900.

[7] X. Han, Y. Wang, L. Zhu, The performance and long-term stability of silicon concentrator solar cells immersed in dielectric liquids, Energy Conversion and Management 66 (2013) 189-198.

[8] K.W. Boer, Cadmium sulfide enhances solar cell efficiency, Energy Conversion and Management 52 (2011) 426-430.

[9] J.K. Kaldellis, M. Kapsali, K.A. Kavadias, Temperature and wind speed impact on the efficiency of PV installations: Experience obtained from outdoor measurements in Greece, Renewable Energy 66 (2014) 612-624.

[10] Y. Tripanagnostopoulos, M. NousiaTh, Souliotis, P. Yianoulis, Hybrid photovoltaic thermal solar system, Solar Energy 72 (2002) 217–34.

[11] A. Tiwari, M.S. Sodha, Parametric study of various configurations of hybrid PV/thermal air collector: experimental validation of theoretical model, Solar Energy Materials and Solar Cells 91 (2007) 17–28.

[12] H.P. Grag, R.K. Agarwal, Some aspects of a PV/T collector/forced circulation flat-plat solar water heater with solar cells, Energy Conversion and Management 36 (1995) 87–99.

[13] J.K. Tonui, Y. Tripanagnostopoulos, Improved PV/T solar collectors with heat extraction by forced or natural air circulation, Renewable Energy 32 (2007) 623-637.

[14] B.J. Huang, T.H. Liu, W.C. Hung, F.C. Sun, Performance evaluation of solar photovoltaic/ thermal systems, Solar Energy 70 (2001) 443–448.

[15] S.A. Kalogirou, Y. Tripanagnostopoulos, Hybrid PV/T solar systems for domestic hot water and electricity production, Energy Conversion and Management 47 (2006) 3368–3382.

[16] T.T. Chow, W. He, J. Ji, Hybrid photovoltaic-thermosyphon water heating system for residential application, Solar Energy 80 (2006) 298–306.

[17] J. Ji, G. Pei, T.T. Chow, K. Liu, H. He, J. Lu, C. Han, Experimental study of photovoltaic solar assisted heat pump system, Solar Energy 82 (2008) 43–52.

[18] X. Zhao, X. Zhang, S.B. Riffat, X. Su, Theoretical investigation of a novel PV/e roof module for heat pump operation, Energy Conversion and Management 52 (2011) 603–614.

[19] X. Tang, Y. Zhao, Z. Quan, The experimental research of using novel flat-plate heat pipe for solar cells cooling, In: Proceeding of the Chinese thermal engineering physics of heat and mass transfer conference, 2009, p. 239–41.

[20] X. Zhang, X. Zhao, S. Smitha, J. Xu, X. Yu, Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies, Renewable and Sustainable Energy Reviews16 (2012) 599– 617.

[21] S. Krauter, Increased electrical yield via water flow over the front of photovoltaic panels, Solar Energy Materials and Solar Cells 82 (2004) 131–137.

[22] H.G. Teo, P.S. Lee, M.N.A. Hawlader, An active cooling system for photovoltaic modules, Applied Energy 90 (2012) 309–315.

[23] T.Kerzmann, L.Schaefer, System simulation of a linear concentrating photovoltaic system with an active cooling system, Renewable Energy 41 (2012) 254-261.

[24] B.J. Brinkworth, B.M. Cross, R.H. Marshall, H. Yang, Thermal Regulation of Photovoltaic Cladding, Solar Energy 61(3) (1997) 169–178.

[25] B.J. Brinkworth, M. Sandberg, Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays, Solar Energy 80 (2006) 89-103.

[26] M.Chandrasekar, S. Suresh, T. Senthilkumar, M. Ganesh Karthikeyan, Passive cooling of standalone flat PV module with cotton wick structures, Energy Conversion and Management 71 (2013) 43–50.

[27] Jones AD, Underwood CP (2001) A thermal model for photovoltaic systems. Sol Energy 70(4): 349–359.

[28] Mattei M, Notton G, Cristofari C, Muselli M, Poggi P (2006) Calculation of the polycrystalline PV module temperature using a simple method of energy balance. Renew Energ 31: 553–567.

[29] http://www.worldweatheronline.com/v2/charts.aspx?q=Trichy,%20India

APPENDIX

The photographic view of the experimental setup is shown below,

Figyre.6 Photographic view of experimental setup