IMPROVEMENT IN EFFICIENCY OF SOLAR PHOTOVOLTAIC POWER SYSTEM THROUGH HEAT EXTRACTION

By

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Submitted

IN PARTIAL FULFILLMENT OF THE REQUIREMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY

TO

UNIVERSITY OF PETROLEUM AND ENERGY STUDIES

DEHRADUN
August, 2015

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ACKNOWLEDGEMENTS

My foremost and profound gratitude goes to my guides Dr. S.J. Chopra, Chancellor, University of Petroleum and Energy Studies, Dr. Kamal Bansal, DEAN, College of Engineering, University of Petroleum and Energy Studies and Dr. Dharam Buddhi , Director, Centre of Excellence – RSES, Gyan Vihar University, Jaipur for their proficient and enthusiastic guidance, useful criticism, moral support, continuous encouragement, and immense help throughout the research and believing in me all the time. I humbly acknowledge a lifetime gratitude to my mentors.

I am indebted to my father Sh. D. S. Arora and my mother Smt. Kamal Arora for their eternal support and everlasting blessings. I gratefully acknowledge the inspiration and unflagging support of my parents. I thank my husband Mr. Navdeep Sharma and son Anant Dev for their patience, encouragement and close cooperation during the tenure of this work.

Lastly, I owe a deep sense of gratitude to the All-Pervading, All-Sustaining Spirit whose divine light and warmth provided me the perseverance, guidance, inspiration, faith, and strength to carry on even when the going got tough.

DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

Madhu Sharma

(Madhu Sharma / 17th August, 2015)

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THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on **"Improvement in Efficiency of Solar Photovoltaic Power System through heat extraction"** by **Madhu Sharma** in partial completion of the requirements for the award of the Degree of Doctor of Philosophy (Engineering) is an original work carried out by her under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

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ABSTRACT

Solar photovoltaic cell's efficiency is negatively affected with increase in its temperature. It is necessary to take measure to increase PV cell efficiency and decrease accelerated wear by controlling the operating temperature of PV cell.

While PV panels absorb solar radiation and generate electricity its inherent temperature increases and to control this increased inherent temperature, a coolant system of circulating water has been developed. This cooling unit is mounted to back surface of the commercial panel and consists of rectangular reservoir. Modified panel has been tested for several water flow rates and optimized for minimum operating temperature of panel and thus results higher PV panel efficiency.

Electrical and thermal performance of modified panel has also been analyzed in comparison with reference one and modeled in MATLAB. It was found that the water flow rate of 0.01 kg/sec could maintain nominal module operating temperature 30.6 ˚C at 800 W/m^2, 20 ˚C ambient temperatures and 1 m/s wind speed at installed condition while the nominal module operating temperature of standard module was 50 ˚C under similar operating conditions.

It was found that at subjected temperature, PV module electrical conversion efficiency is 5.3% higher than a standard PV module conversion efficiency at an average radiation of 637 W/m^2 with passive cooling system and overall efficiency was more than one order magnitude of conversion PV module efficiency.

Further, reservoir construction material and its wall thickness have been analyzed on the basis of performance optimization and developed system has been scaled up to 1MW and cost benefit has been analyzed on annually basis and found economically feasible.

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LIST OF FIGURES

LIST OF SYMBOLS

V	Output voltage of Standard module
V_m	Output voltage of modified module
I	Output current of Standard module
I_m	Output current of modified module
P	Electrical output power of Standard module
P_m	Electrical output power of modified module
P_{th}	Thermal output power of modified module
T_b	Back surface temperature of standard module
T_{bm}	Back surface temperature of modified module
η	Electrical Efficiency of standard module
η_m	Electrical efficiency of modified module
η_{th}	Thermal efficiency of modified module
η_{total}	Total efficiency of modified module
T_i	Water inlet temperature
T_o	Water outlet temperature
T_a	Ambient temperature
G	Total solar radiation on tilted surface
v	Wind speed
$\Delta\eta$	Percentage increase in electrical efficiency
$\dot{m}$	Water flow rate
ΔT	Change in outlet and inlet water temperature
α	Cooling coefficient of output voltage
β	Cooling coefficient of output current
γ	Cooling coefficient of output power
H	Rate of heat conduction
k_{al}	Thermal conductivity of Aluminium

k_{al} **Thermal conductivity of Copper**

t_{cu} **Thickness of Copper sheet**

t_{al} **Thickness of Aluminium sheet**

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The chapter describes the function of solar PV cell and effect of operating temperature on PV module efficiency. The objective of this research work is also presented in this chapter.

1.1 INTRODUCTION

Solar photovoltaic technology has become increasingly popular all over the World among all renewable energy sources and solar energy industry is expanding rapidly. The research is focused on improving the electrical performance and life time of solar panel because of PV systems larger prevalence.

Mono crystalline and multi crystalline solar cells are most prevalent. Solar cells transform solar radiation or photons directly into electrical power. Solar cell is a P-N junction fabricated in a thin wafer of semi-conductor. Number of PV cells are connected in series to achieve required voltage and placed in a frame and called PV module.

Design of solar cell power system and its operation assessment must base on electrical characteristics of solar cells under various radiation levels and various temperature levels of cells.

Part of the solar radiation is transmitted to the solar cell is converted into electricity and rest transmitted to the back surface and heat up solar cells. Typically solar module surface is 15 – 20 °C higher than ambient temperature. In literature, 75 °C and above module surface temperature has been observed and reported by many. Conversion efficiency of photo voltaic module is linearly decreasing function of temperature. With a temperature coefficient temperature dependence of PV material can be defined.

Traditional linear expression for PV electrical efficiency is

$$\eta_c = \eta_{Tref} [1 - \beta_{ref} (T_c - T_{ref})] \quad (1.1)$$

Where η_{Tref} and T_{ref} is cell efficiency and cell temperature at Standard Test Condition (STC – 1000 W/m^2, 25^{o}C) and $\boldsymbol{\beta_{ref}}$ is temperature coefficient (^{o}C^{-1}).

Largely, available solar radiation and PV solar cell conversion efficiency affects the performance of PV module. And there important features depend on many physical parameters like, typical weather conditions, wind speed, ambient temperature, site latitude, panel tilt, azimuth angle, electrical load, obstruction and shadow effects.

Only in certain weather condition solar panels perform best. Always changing weather conditions, installation of solar panel in different climate region affect PV panel performance and panels do not operating in ideal conditions. Therefore ways can design for efficiency improvement of PV panel while operating in non-optimal condition. One of the ways of improving panel efficiency is to design a cooling system to keep PV panels within certain temperatures.

Cooling of panel can be active or passive. External power source is required in active systems to run. No added power is required in passive system to run. Active cooling system may use if added efficiency is higher than energy required for it in situation like solar power plant a desert.

Panels become quite hot even in outside temperature is cold on sunny days as absorbs solar radiation. Therefore, PV module with cooling system is a practical solution of increasing electrical power production.

Performance of photo-voltaic thermal system can be evaluated by total efficiency (n_T) as

$$n_T = n_e + n_{th} \quad (1.2)$$

Where n_e is electrical efficiency and electrical output power of PV cell (P_o) dependent on voltage (*V*) and current (*I*)

$$n_e = \frac{P_o}{GA} = \frac{VI}{GA} \tag{1.3}$$

Where, G is total solar radiation intensity on PV panel

A is area of PV module

n_{th} is thermal efficiency and thermal output power dependent on outlet temperature (*To*) and inlet temperature (*Ti*)

$$n_{th} = \frac{\dot{m}\, C_p (T_o - T_i)}{GA} \tag{1.4}$$

Where $\dot{m}$ and c_p are mass flow rate of water and specific heat of water.

To predict power output of PV module, to know operating panel temperature is important. Temperature coefficient describes the temperature dependence of a PV material.

The general equation for estimating electrical parameters at a particular temperature is given by

$$P_{module} = Temperature\ coefficient \times [T_{STC}(°\text{C}) - T_{module}\ (°\text{C})] + P_{rated} \tag{1.5}$$

Where

P_{module} is Power output at module temperature

T_{STC} is Temperature at standard test conditions

T_a is Module temperature

P_{rated} is Power output at STC

1.2 OBJECTIVES

Main objective is to keep PV panels within certain temperatures by extracting heat and increase its conversion efficiency and to investigate electrical performance and thermal performance under local weather condition in Dehradun.

To accomplish above objective, literature survey about "dependency of PV module performance on temperature and other environmental parameters" and "methods pf cooling PV modules" is done. Literature revealed the effect of environmental parameters and negative temperature coefficient for different types of PV modules on performance and degrading effects. Literature survey also enabled choosing correct design of cooling and correct testing method to evaluate performance.

To conduct performance tests determining required instruments and developing data acquisition system was the major part of the work in physically building test setup. After finding out a fabricator and retailers supplying required instruments a convention PV module is modified and experiment test set up is built in outdoor research facility of UPES. Finally by following selected methodology, both electrical and thermal performance evaluation is done by MATLAB.

Second objective of work is to indicate performance and economic feasibility of developed system.

To complete this objective, developed system has been scaled up to 1MW and cost benefit has been analyzed on annually basis and found economically feasible.

1.3 OUTLINES OF CHAPTERS

Chapter 1 presents the introduction to system theory and objectives.

Chapter 2 presents literature survey and final outcome from this survey

Chapter 3 presents the details of experimental setup, data acquisition and its components

Chapter 4 presents the result and discussion. Results based on varying atmospheric parameters and operating temperature of module is discussed and regression equations are developed. Also impact of water velocity on performance is discussed. And temperature indicators and cooling coefficients are derived.

Chapter 5 presents cost benefit analysis of solar PV power plant scale up to 1 MW.

Chapter 6 presents the conclusion and future scope.

CHAPTER 2

LITERATURE SURVEY

The chapter describes the literature survey that being carried out in understanding the concept of dependency of PV module performance on temperature and other environmental parameters. Literature survey helped in accurate designing of cooling system and correct testing methods to evaluate performance of developed set ups.

2.1 LITERATURE REVIEW

Output power of a PV module decreasing with cell temperature linearly and operating temperature plays central role in conversion process of PV [1].

In Ras AL Khaimah, at CSEM – UAE Innovation Centre outdoor testing facility for PV module was installed on the roof. 165 Wp multi-crystalline silicon module had been selected for experiment and was mounted at 30^o of fixed tilt angle facing true south. Day star I-V curve tracer and CSEM-UAE AMCU flyer unit gave I-V characteristics under varying load of selected module at different solar radiation in outdoor condition. Global radiation, module surface temperature, ambient temperature, current and voltage readings of PV module were recorded for analysis. Experimental results showed that module efficiency varies between 8-10%, which was differing 3-4 % from STC specified efficiency. And this efficiency drop is the results of high operating surface temperature (50-60^oC) of PV module [2].

The photon rate of PV cell increases with the temperature and hence reverse saturation current. This results in the change of current and voltage, which means marginal changes in current but major changes in voltage.

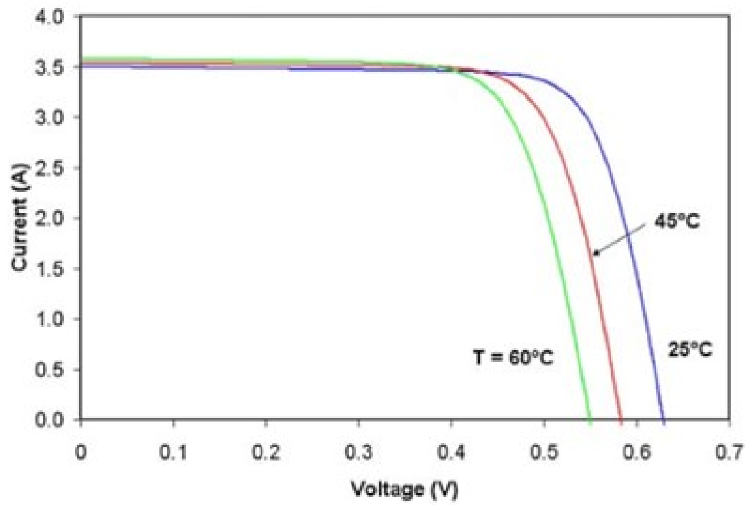

Fig 2.1: Shows how the I-V curve varies with varying temperature [3]

Gail-Angee Migan reported that NOCT of a typical module is 48^{o}C whereas; best operates at 33^{o}C and worst at 58^{o}C [3].

Difference between junction temperature of PV module and ambient temperature is a consequence of continuous solar radiation and the accumulation of thermal energy in the interior of modules lead to serious performance deterioration. Author found this temperature difference will increase linearly with radiation intensity rise, even if ambient temperature changes [4].

Besides solar irradiance the second most important factor which affects PV cell / modules performance is temperature. In countries particularly with high temperature has major impact on performance and degradation. In field module temperature depends on solar insolation, ambient temperature and wind speed and it is favorable to have low module temperature.

Operating temperature of the module depends on the radiation absorption properties, thermal dissipation, module encapsulating materials, module functioning and also depends on insolation, ambient temp, accurate installation status and wind speed. Module parameters like voltage, current, power and efficiency greatly influence by the module operating temperature and thus, it is very important to perform a quantitative analysis under real operating condition. Author investigated the temperature influence on PV parameters of amorphous-silicon (a-Si) and copper indium deselinide (CIS) thin film modules at Patras, Greece (latitude 38^o) where at Patras peak sun hours over 4.2 per day and working temp of the module between 16 to 60^oC. V_{oc} percentage reduction with temperature increase is greater of CIS than a-Si modules. CIS short circuit current temperature coefficient in position at low and medium temperature, and at entire working temperature range approximately constant with slight tendency to reduce. In case of CIS maximum power as a function of temperature decreases linearly. Annual behavior indicated that CIS module efficiency decreases with temperature and a-Si module was not severely affected [5].

The performance of PV modules significantly affect by its thermal characteristics. Thermal characteristics and junction temperature of PV modules are analyzed under various operating conditions. Using solar simulation, it was found that mainly short circuit current and output current affected by solar irradiation. And open circuit voltage of PV module influenced by varying temperature mainly under any specific solar intensities. With an increase in the solar irradiance there is linear increase in junction temperature and ambient temperature difference, even if change in ambient temperature [6].

Electrical yield and efficiency of a PV module depend on the absolute temperature coefficient of voltage and current. According to photon market survey 2008 of Photon magazine the average temperature coefficients were tabulated in table – 1 below [7]:

Table 2.1: COEFFICIENTS OF TEMPERATURE

Type of PV module	***Volts/K***	***Amp/K***
Mono crysttaline Si	-0.00364512	0.00046915
Poly crysttaline Si	-0.0037199	0.00047709
Amorphous Si	-0.00327806	0.00074003

Operating temperature of PV module directly affects its voltage. Manufacturers rate PV module at Standard Test Condition (STC) as V_{oc}, I_{sc}, V_{mpp}, I_{mpp} and temperature coefficient etc. Where STC are 1000 W/m^2 radiation, 25^{o}C operating temperature, 1m/s wind speed and AM 1.5 light spectrum. In this module temperature coefficient represents percentage voltage loss per degree centigrade above 25^{o}C. A common temperature coefficient for Silicon crystalline PV module is -0.38 %/ ^{o}C [8].

For every 1 degree centigrade rise in temperature about 0.45%,efficiency decreases for mono crystalline and poly crystalline silicon solar cells, For amorphous silicon cells temperature effect is less and about 0.25% efficiency decreases every degree rise in temperature [9].

During 2009 at Malaysia temperature dependence coefficient of crystalline silicon PV modules and amorphous silicon module have been obtained using linear regression techniques. Three modules a-Si, multi crystalline and mono-crystalline were installed in field with data monitoring using data logger. It was found that multi crystalline PV module is highly temperature sensitive among three types [10].

PV module temperature prediction is necessary in order to predict energy production of PV modules. PV module temperature is function of total radiation, ambient temperature, wind direction, wind speed and relative humidity. Out of these environmental parameters ambient temperature sets the base temperature of PV modules, temperature rise of modules predominantly sets by solar irradiance. There is slight influence of ambient humidity and influence of wind direction is negligibly small [11].

At required location, the availability of solar radiation and operating temperature of PV module are two main parameters on which the PV module performance strongly depends. Verification of non-linear effect of environmental factors on PV module both in sunny and cloudy days was carried out in demonstrated parameter estimation based model. To select correct product and to predict their accurate energy performance, there is great importance of reliable knowledge and PV module performance under different operating conditions [12].

Under variable climate conditions, real dynamic and average performance of PV system can be predicted by some electrical efficient module. However, general consensus has not been reached to use particular model. Also, most models are complicated structures, which themselves do not lead easy manipulation of performance of system. Additionally some detailed parameters are required usually, in practice which are normally unavailable [13-17].

At Bushland, TX, panel temperature of solar thin film panels was measured for several years. And 7-10% change from rated performance was estimated. For an average panel temperature of 22^oC during the months of December and January measured panel performance be 1% better than rated, put for an average temperature of 47^oC during the months of July and August measured panel performance be 6.5% worse than rated [18].

PV technology weakness is its negative temperature effect. For reliable evaluation, data provided by manufacturers are insufficient. Voltage – Current characteristics curve by manufacturer is at constant temperature or at constant radiation. And the thermo-electrical behavior of PV module in actual conditions cannot be correctly evaluated by this provided data. To estimate module operating temperature different correlations exist in literature and based only on passive behavior of the PV and do not include electrical behavior of the PV. Efforts had been made to assess operating temperature on real use condition and a correlation was proposed based on standard weather variables and electricity production regimes in proximity of maximum power points [19].

Simplest formula to calculate to calculate PV cell temperature was investigated by ROSS [20]

$$T_c = T_a + kG$$

Cell temperature is in linear connection with ambient temperature, irradiance and a constant called Rose coefficient depending on structure monitoring and gives a first orientation. But it is nearly impossible to determine Rose coefficient in before [20].

The output power of PV module is mainly function of solar irradiance and module temperature. Determination of relevant module temperature leads to Nominal Cell Operation Temperature an empiric method.

The IEC 61215/61646 norms specifies that NOCT = $(T_c - T_a)_{SRE} + 20^oC$

Where SRE Standard Reference Environment [800 W/m^2 radiance, 20^{o}C ambient temperature, 1m/sec wind speeds, nil electrical load, south oriented and 45^o tilt angle]

T_c – module operating temperature

T_a – ambient temperature.

There are rare recommended test conditions and sufficiently not determined by the norms at the end. The ratio of diffuse and direct irradiance is undefined and this is a main cause of finding measured NOCT in range of ±5K.

For a crystalline silicon PV module at different latitudes (Berlin, Madrid and Dakar) and for different NOCTs, relative energy yields are simulated at different installation sites as a function of NOCT. And it was found that for latitudes close to equator maximum difference in energy yield predicted as increase module temperature and ambient temperature [7].

PV industry provides technical data described in IEC 61214 which is based on standardized measurements under laboratory conditions.

The most important test procedures are

10.2 Standard Test Condition (STC)

10.5 measurement of Nominal Operating Cell Temperature (NOCT)

10.6 performances at NOCT

10.7 performances at low irradiance

NOCT is a equilibrium mean solar cell temperature within an open rack mounted module in Standard Reference Environment (SRE) as follows.

Total irradiance: 800 W/m^2

Ambient temperature: 20^{o}C

Wind speed: 1 m/sec

Tilt angle: at normal incidence to the direct solar beam at local solar noon

Electrical load: Nil (open circuit)

Open rack mounted PV modules with optimized inclination

Maximum power of PV module decreases about 0.5% / ^{o}C rise above 25^{o}C. This negative temperature effect makes measurement of NOCT of most interest [21].

To install photovoltaic module, system designer and inventor consider data sheet of modules to make choice of module type and brand. Data sheet include few primary characteristics like module peak power and efficiency at STC (standard test condition), temperature coefficient of power, open circuit voltage, short circuit current and sometimes low light behavior as STC rarely met in real time condition [22].

In STC, measurements are taken using a solar simulator under laboratory conditions and it is controversial as standard condition can never be found in real time. Climate parameters like solar insolation, ambient temp, wind speed etc., are the locality dependent variable on which the performance of PV module depends. For effective design of PV system, device rating measurements at the site is desirable and this allows actual power output prediction. In the outdoor environment, PV efficiency as a complex function of micro climatic parameters and working temperature of PV module plays a crucial role in rating determining. High radiance and high temperature combination leads lower efficiency compared to low radiance and low temp combination. Number of climatic parameters affecting the module performance simultaneously in a natural environment and to relate two parameters explicitly is very difficult [23].

For some irradiance, afternoon temperature difference (T_{mod} - T_{amb}) is higher than morning and cause difference of about 2 to 3^{o}C in NOCT final values. Using morning and afternoon minimum data points to calculate NOCT gives averaged values and represents module day behavior on energy output of module influence of temperature in order of second order. Inaccuracies observed were about ±3^{o}C in NOCT values despite uncertainties and also only about ±1.5% excessive errors introduced for annual performance estimation.

As a module temperature indicative NOCT (Nominal Operating Cell Temperature) is commonly use. NOCT is mean solar junction temperature in Standard Reference Environment (SRE) with in an open rack mounted module. SRE includes total irradiance 800W/m^2, wind speed 1m/s, ambient temperature 20^{o}C, tilt angle - at normal incidence to the direct solar beam at local solar noon and nil electrical loads. NOCT is a reference of how the module will work in real condition therefore is an important characteristic. To calculate NOCT there are several intimation standards EN-61215 for crystalline PV module, EN-61646 for thin film PV module, ASTM E1036M or both (non - concentrator terrestrial PV modules and arrays).

Fact on which all above standards are based is that T_m-T_a (module temp - ambient temp) difference is essentially linear to irradiance and largely independent of wind speed [24].

INOCT i.e. Installed Nominal Operation Cell temperature is the cell temperature of installed module connected to load and also mounting configuration of the module is taking into account. In open rack case it is recommended that one use a value of INOCT 3^{o}C less than NOCT value [25].

Based on data set a correction factor is applied for average wind speed and ambient temp from following graph [26] :

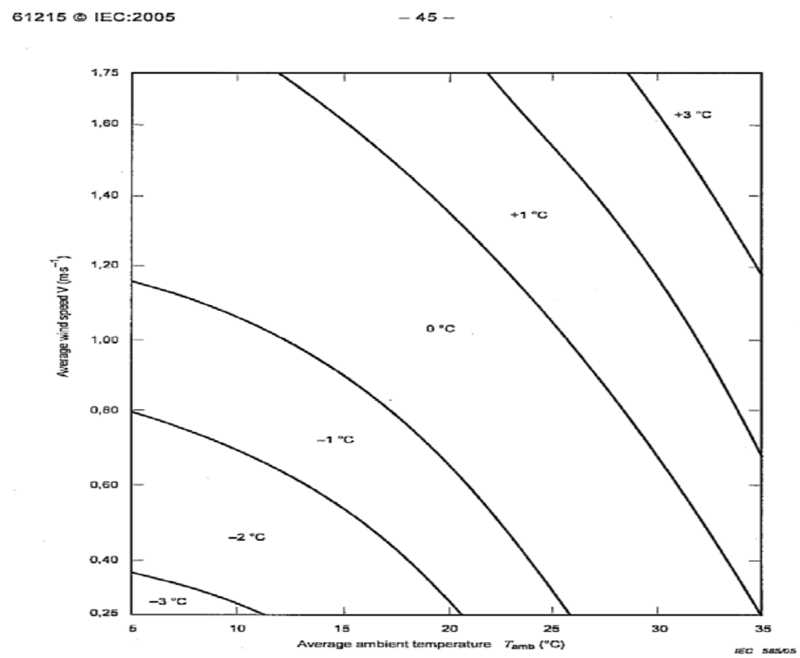

Fig 2.2: To correct NOCT for average wind speed and average ambient temperature [26]

As long as PV modules do not operate at too high temperature, they have good conversion coefficient. When photon carrying high energy heat is released and absorbed by module and its temperature rises. While estimating module temperature with solar radiation and wind speed also should be considered.

IV curve define the PV cell performance for a given solar radiation. PV cell has two limiting parameters short circuit current (Isc) when V=0, and open circuit voltage Voc when I=0 with rise in temperature of PV cell Isc increases slightly while Voc drop significantly. Open circuit voltage drops 2mV/^{o}C rise of temperature for silicon materials. In solar modules operation, temperature is an important issue as temperature rise significantly reduces electrical output, increases thermal stress and degradation rates. Author suggested that with appropriate cooling system with air or water, electrical efficiency can significantly enhance. Combining both technologies, photovoltaic & thermal as hybrid PVT to generate electricity and heat water in a house for instance is another way to handle heat issue [27].

Out of total energy produced, electrical output is only one component with typical ideal conversion efficiency in the range of 15% from PV module. Remaining produced energy is heat. As this heat energy is neither utilized nor captured, increases PV module temperature which actually influence their overall performance.

There is more than 25 % performance reduction of PV module, as modules operate over 50^{o}C above ambient temperature commonly. To make significant gains in PV system performance, its operating temperature can be lowered by dissipating heat from the module and this heat can be utilized for practical heating purposes.

Generated electricity from grid tied PV system only sold with generous incentive program as having high initial cost. Recover waste solar heat from PV modules and use it to lower heating costs is possible solution to the long payback situation [28].

Individual impact of operating parameters like solar radiation, ambient temperature, air velocity, etc. on overall performance coefficient and efficiency of the developed solar PV with loop heat pipe heat pump system was investigated. And results indicate that enhance electrical efficiency and reduced thermal efficiency at lower ambient temperature, lower solar radiation, smaller cover number and higher air velocity [29].

Photovoltaic cell electrical efficiency is adversely affected by cell operating temperature. Without active cooling PV module attain 68^{o}C and electrical efficiency significantly reduced to 8.6 %. When blower in used for cooling of PV module, operating temperature maintained at 38^{o}C and electrical efficiency could also be kept at around 12.5 %. Temperature and temperature gradient over the PV module to boost electrical efficiency are considered critical [30].

Electrical efficiency of PV module can be improved at a reasonable level by cooling. To remove waste heat from back side of commercial PV module, natural or forced air circulation is simple and low cost method but less effective for ambient temperature above 20^{o}C. And that is why water heat extraction system had been suggested [31].

A film of water is applied over the PV panel of 60 Wp using a tube with a slit along it and tube was installed on top end. 0.25HP(186.5 W) pump was used to feed water to tube and water flows as a thin film over the panel at a flow rate of 1lit/min and maximum temperature difference was observed 18.7^{o}C . PV panel efficiency had been increased but 186.5 Watt of pump for 60wp panel was used [32].

Available options to improve efficiency of solar PV module by maintaining close to Standard Test Condition (STC) have been analyzed by Author. Paper reports that PV/T systems by cooling fluid (air or water) produce both electricity and thermal output and total converted energy yield may triple.

After investigation on PV thermal hybrid system and performance analysis of incorporated heat pipes author observed some of short comings like extra expense of pump and extracted power for forced circulation, extra space for natural circulation, limited quality of heat transfer and risk of reverse flow of hot water at night etc. Author suggested that further cost analysis and comparison of the system for electrical and thermal performance may be achieved by using an appropriate energy rating [33].

Out of total striking solar radiations on mono and poly crystal PV surfaces only about 12-15% is converted in electrical power. Remaining solar energy warms the PV element undesirably and leads to decrease in electrical efficiency and panel lifetime. If there is 1^{o}C rise in temperature of crystalline panel above 25 ^{o}C, on every 1 ^{o}C voltage on clamps decreases by 0.4%. For the film panels, decreases in voltage is two times less [34].

Split flow design absorber made up of copper tubes and band thin aluminum plate fit among the copper tubes was placed underneath a PV module and tested in laboratory conditions for different radiations and mass flow of water(by pump). From the result obtained it was concluded that

- With increase in cell temperature electrical efficiency decreases.
- There is increase in electrical efficiency by adding heat absorber and also get thermal output.
- Thermal performance will be improved by increasing mass flow rate but high performance in electrical efficiency will only at certain mass flow rate [35].

Solar radiation up to 80% is absorbed by PV panels. Out of this incident energy, only 5-10 % is converted into electricity as dependent on used PV technology and remaining energy converted into heat energy as shown in figure below.

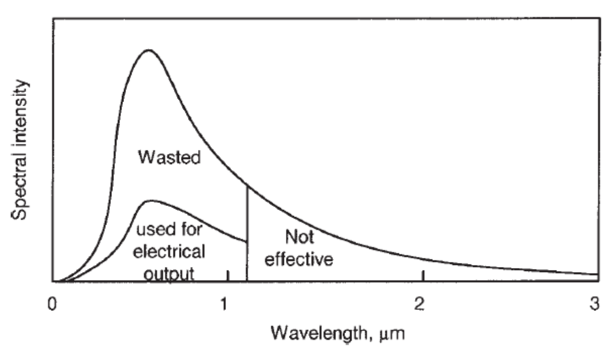

Fig 2.3: Conversion of incoming sunlight in Electricity and heat as function of wavelength [36]

Reliability of PVT cannot be expected similar to that of solar thermal collector and of solar PV module. In Dutch climate, prototype PVT collector temperature has been measured up to 126^{o}C as heat is not with draw due to pump failure. And high temperature resistance of plastic layer in PV laminate and encapsulate are demanded to handle such high temperature. Large thermal stress may occur between PV laminate and collector fluid if collector is switched on around noon on a sunny day causing inhomogeneous and fast thermal contraction.

In metal sheet and tube contraction in a PVT module electrical conductance may cause problems. Additional demand of electrical insulation between metal rear and PV cells, especially the electrical contacts became of large electrical conductivity.

Heat emission minimization, solar absorption optimization, internal heat transfer optimization and reliability of module are some aspects range from fundamental materials to be addressed need R&D [36].

At the university of Patras, in year 2004-05 polycrystalline-silicon modules and amorphous-silicon combined with water heat extraction units made from copper sheet and pipes and protected thermally with polyurethane thermal insulation constructed and tested and with TRNSYS program this hybrid PV/T system were modeled and simulated at three different latitudes Nicosia (35°), Madison(43°) and Athens(38°).

Kept in mind to achieve satisfactory thermal output models were covered with 4mm thick glazing (transparent cover) to reduce convection and radiation losses, although, electrical energy produced by PV panel reduces.

Author concluded that system employed with poly crystalline solar cell produces more electrical production than amorphous one, but less contribution of solar thermal.

Low cost method of removal of heat from the PV module is forced or natural air circulation. But over 20 degree centigrade ambient air temperature these methods are less effective.

Heat extraction by circulating water from rear surface of module can overcome this effect and if thermal unit additional cost is low photovoltaic thermal systems could be cost effective [9].

An Eastern Mediterranean island, Cyprus has high solar insolation. In Northern part of Cyprus, a typical household electrical consumption is 7 kwh and can be produced with 1600W PV system and area occupancy is of $10m^2$.

To utilize undesirable heat produced by PV modules in water pre-heating applications, a hybrid system is constructed and tested at Cyprus geographic location. This hybrid system consists of PV module 55W peak and solar thermal collector, in which cooling medium is applied in front rather than at rear of a solar module. Water once circulated between module and glazing was stored in insulated storage tank as pre heated water for domestic applications. Glass and water high transmittance ensures most of visible radiation received by silicon cells to generate electricity without much sacrifice. 1% of electrical energy loss is observed and i.e. well offset by large gain in thermal energy makes this hybrid module economically attractive [37].

To provide the hot water to washer machines consuming 60°C of hot water around 3500 liters/day in Banglamung hospital of Chonburi, Thailand, two PV panels are attached on top of the heat extracting system from the panel and the complete system has a low iron tempered top glass cover to reduce heat loss by the wind.

The cost of thermal energy generated by the developed system is lower than SWH system because the added cost is lower than initial cost of SWH system about 19.5% but glass cover in this system causes higher cell temperature and PV efficiency did not increase [38].

In 2008, TN Anderson theoretically analyzed a design of building integrated photovoltaic/thermal solar collector through Hottel-Whillier model. A prototype BIPVT collector is developed and experimental data was validated.

In study result it was found that fin efficiency, thermal conductivity between PV cells and their supporting structure and the lamination methods were key design parameters and both thermal and electrical efficiency of BIPVT had significantly influenced by these key design factors.

Facts and suggestions of his study were:

1. Collector manufactured from pre coated steel because of lower cost and collector base material made little difference to thermal efficiency. The disadvantage of using steel was that the electrical efficiency decreased marginally.

2. Ratio of cooling tube width to spacing – this parameter was shown to improve both the thermal and electrical efficiency.

3. It was also highlighted that good thermal contact between PV cells and the absorber need to be made to improve both thermal and electrical efficiency.

4. Improvement in absorption of long wave radiation should also be considered by additional modification that can be made.

5. Increase in transmittance/absorptance product results in high increase in thermal efficiency without greatly reducing the electrical efficiency [39].

To reduce the energy consumption in buildings and to provide thermal and electrical energy for domestic usages, thermal and electrical behavior of wall mounted solar PV/thermal collector have been illustrated through a numerical model by Jie Ji in 2006.

The simulation results showed that it is beneficial for PV cooling to increase the mass flow rate of working fluid. But this benefit diminishes after critical flow rate has been passed and thermal efficiency decreases subsequently. Operation of PV/thermal system can improve only at optimum flow rate [40].

T.T. Chow in 2008 tried to tackle the issue of glazing in viewpoint of thermodynamics in photo-voltaic thermal technology. No straight forward answer is there for suitability of glazed or unglazed collector system in different usefulness of thermal energy and electrical. Six selected operating parameters (internal-PV cell efficiency, packing factor, ratio of water mass to aperture, external-solar radiation, ambient temperature and wind velocity) were area evaluated and validated in numerical models to study of the appropriateness of glass cover.

It was found that to maximize the quantity of thermal output or overall energy output glazed PV/T system is suitable (and increase is on site-radiation and ambient temperature land favorable) and from energy analysis point of view to increase PV cell efficiency, packing factor and water mass to collector area ratio k wind velocity are found favorable to go for unglazed system [41].

Building-integrated photovoltaic/ water heating system – a dynamic simulation model based on approach of finite difference control volume was developed and modeling approach validity (operating conditions desired daily efficiencies) was demonstrated with one assured data from an experimental rig at Hong Kong City University in 2007 fully covered summer and winter periods in thermosyphon and pump operated modes.

Author found that on comparing to thermal model of the water heating and storage system is more complicated. There was a little difference between simulation result and experimentally derived thermal efficiencies but there was a considerable discrepancy between simulated and experimentally derived electrical efficiencies and deviator is around 28% on average for summer and 13% on average for winter [42].

A building integrated PV/water-heating system's energy performance has been analyzed and experimental data is verified by numerical model. After investigation of both natural and forced circular modes author has found that natural circulation mode can perform better since power of pumping can be saved. (PV gain of forced and natural circulation generally overlapping and heat gain performance of forced circulation was very close to natural circulation in summer months and in other period of year natural circulation is better) [43].

To avoid undesirable effect of temperature on solar module a mathematical model cooling unit with flow circulation is developed and simulated. This system consists of PV cells attached at the other side of the absorber surface and form a single pass, single duct solar collector. Performance curves were obtained by simulated model with seven different gases (Hydrogen, air, oxygen, water vapor, Nitrogen, Methane and Carbon-dioxide) and analyzed for maximum heat transfer, minimum flow rate, and minimum number of fins, maximum electrical efficiency and minimum specific power. Hydrogen is found most suitable option [44].

Water production rate per degree rise in temperature is increased by 3 % in Seawater Reverse Osmosis (SWRO). Also 18 % of energy consumption of NF – SWRO membranes was reduced by preheating feed water by 5°C. Optimum feed water temperature for SWRO membranes was about 35°C for potable water [45].

Temperature is most important parameter which affects membrane performance. Capacity of membrane / water production rate increases about 3% per ℃ rise in feed water temperature. As temperature increases, applied pressure decrease and this alone reduced Energy consumption. It was found that RO operation is better at higher feed water temperature [46].

2.2 CONCLUSION FROM LITERATURE SURVEY

As seen from literature survey that various paper has been published and presented on concept that how PV module performance is dependent on temperature and other environmental parameters. Negative temperature effect is weakness of PV technology and data provided by manufacture are insufficient and rarely met in real time condition. Multi crystalline silicon PV cells are most sensitive to temperature among mono crystalline, poly crystalline and thin film.

Literature shows that, always PV panels operate far from standard conditions. As solar radiation, operating temperature, electrical load and other environmental parameters do not corresponds to standard conditions, having reliable model for electrical performance of PV module is very important. Available models of predicting performance of PV system in real time condition are of complicated structures and do not lead easy manipulation of performance of system and usually required detailed parameters are unavailable. It is found that existing co-relation to estimate module operating temperature based only on passive behavior of PV and electrical behavior of PV is not included.

To design and dimension PV power supply, PV panel characteristics knowledge is a prerequisite. As standard test condition can never be found in real times, device rating measurement at the site and also at installed condition is desirable.

It is found from literature that many attempts have been made to extract heat from PV module, but are more focused on thermal characteristics in comparison to electrical one.

Extra space requirement, extra expenses of blower in air cooling, extra expenses of pump in liquid cooling and high cost of thermal component are some factors which does not make hybrid electrical and thermal collector commercially viable till date. Thermal contact between PV module and heat absorber is also crucial for overall performance.

CHAPTER 3

SYSTEM DESCRIPTION AND OUTDOOR TESTING

The chapter describes the building of test set-up in outdoor facility of University for electrical and thermal performance evaluation. Chapter also explains experimental observation methods and MATLAB programming.

3.1 EXPERIMENTAL METHODS

Experimental system as shown in Fig. 3.1 consists of:

i) Reference module - Conventional poly crystalline PV module of 75 Watts and 0.57 m^2

ii) Modified module - similar conventional poly crystalline PV module of 75 Watts and 0.57 m^2 as above with thermal contact (glued with electrically insulated and thermally conductive paste) in heat extraction system as made up of two copper tanks 1 liter each (304.8 X 711.2 X 5 mm^3) joined side by side with one inlet and outlet. Inlet and outlet had been arranged opposite to each other so that water to flow in reverse direction and cover76 % of back surface area underneath. Absorber tanks are thermally insulated to avoid heat loss and hot water can be used as a utility for heating purposes.

iii) Both the modules, non-cooling and with cooling unit were mounted at an optimum angle of 30^o tilt equal to the latitude of the location oriented due south for best year round performance and operating in similar environmental conditions and similarly loaded.

iv) Data acquisition system and its major components are:

- Max 232(level converter)- convert TTL to RS level and vice
- USB to Serial cable-This provide the interfacing between coordinator node and personal computer
- Personal Computer-Data logged off on PC with the help HyperTerminal and V1.9b Terminal
- Data acquisition system consists of standard meters and thermocouples to measure for every 15 minutes. Measured parameters included:
    - Solar radiation on tilted surface
    - Ambient air temperature in the shade
    - Wind speed
    - Voltage, current, and back surface temperature of reference module
    - Voltage, current and back surface temperature of modified module
    - Water inlet and water outlet temperature

  Above electrical, thermal and environmental parameters monitored and average readings were logged at interval of 15 minutes during experiment using a data acquisition system employing RS 232 interface using MAX232 level converter IC. All measurements are saved to an excel file for further calculation and analysis.

  For graph generation and analysis of above data programming is done in MATLAB. (Appendix – A)

v) Flow was measured by bucket method using a stop watch and a breaker. Flow was preset for each testing day

There was a height difference between inlet and outlet water storage tank. Water flows naturally by gravity and controlled by water valve.

Proposed system is a passive heat extraction system as pump was not used. Heated water collected in the outlet storage tank placed at the lower end of the panel mounting and can be used.

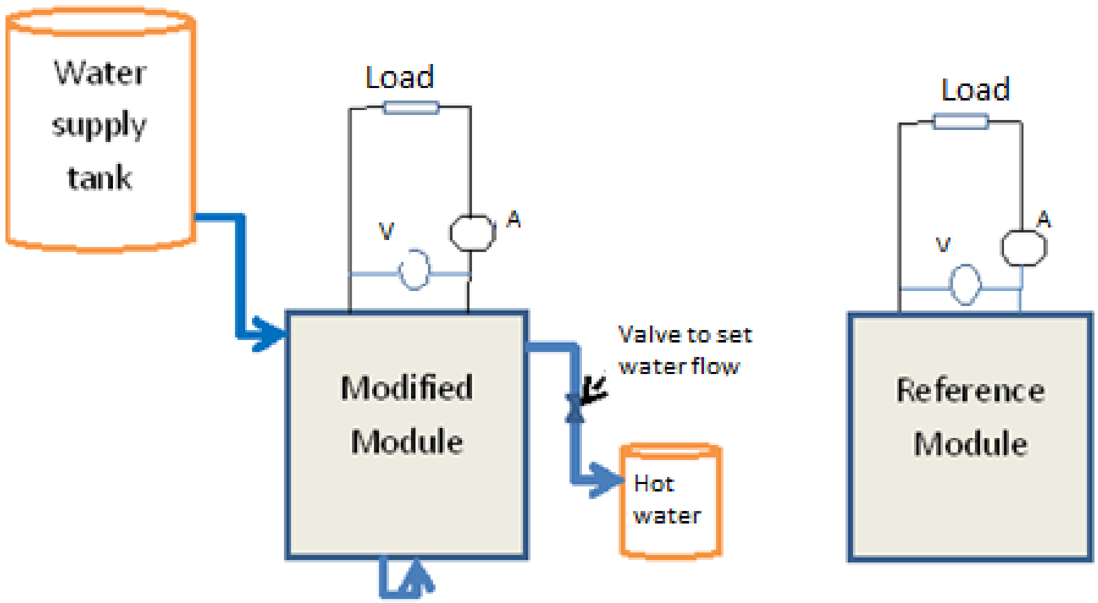

Fig 3.1: Experimental setup

Azimuth is the array's east-west orientation in degrees. In most of the solar PV energy calculator tools, an azimuth value of zero is facing equator in both northern and southern hemispheres. Positive 90 degrees is facing due west, negative 90 degrees is facing due east. The compass angle shows 180° for south, 90° for east and 270° for west.

In northern hemisphere, between the latitudes of 23 and 90 degrees, the sun is always in the south. Therefore, the modules on an array are faced to south in order to get the most out of the sun's energy.

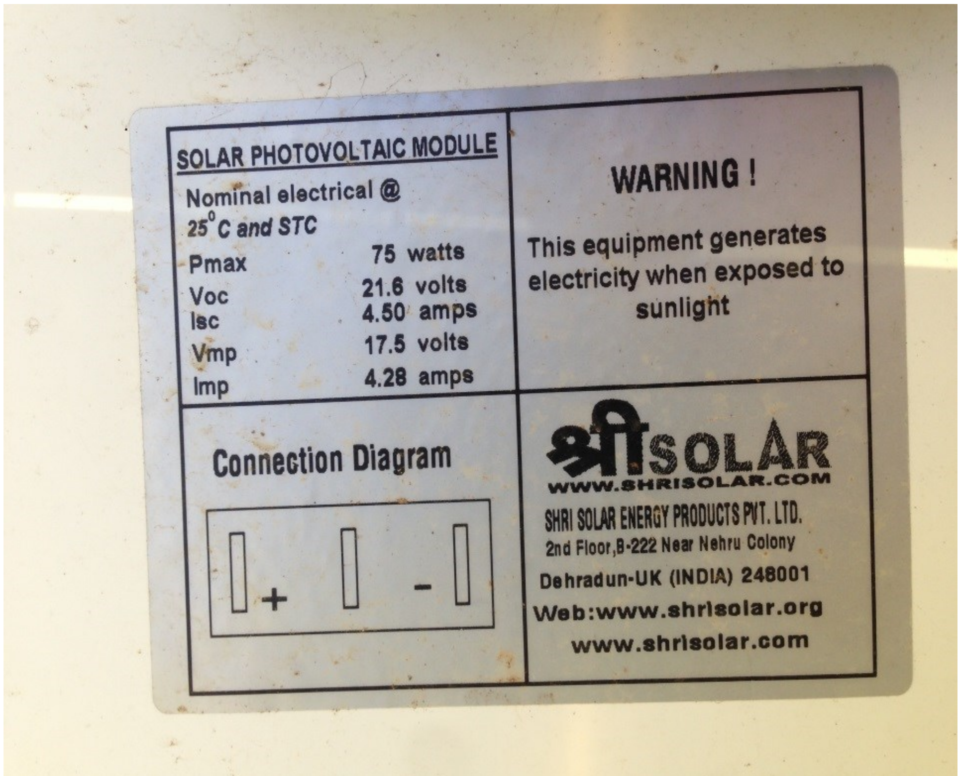

Fig 3.2: Module Specifications

Fig 3.3: To set orientation due south

Fig 3.4: Angle tilting mechanism

Fig 3.5: Measurement of solar radiation on tilted surface

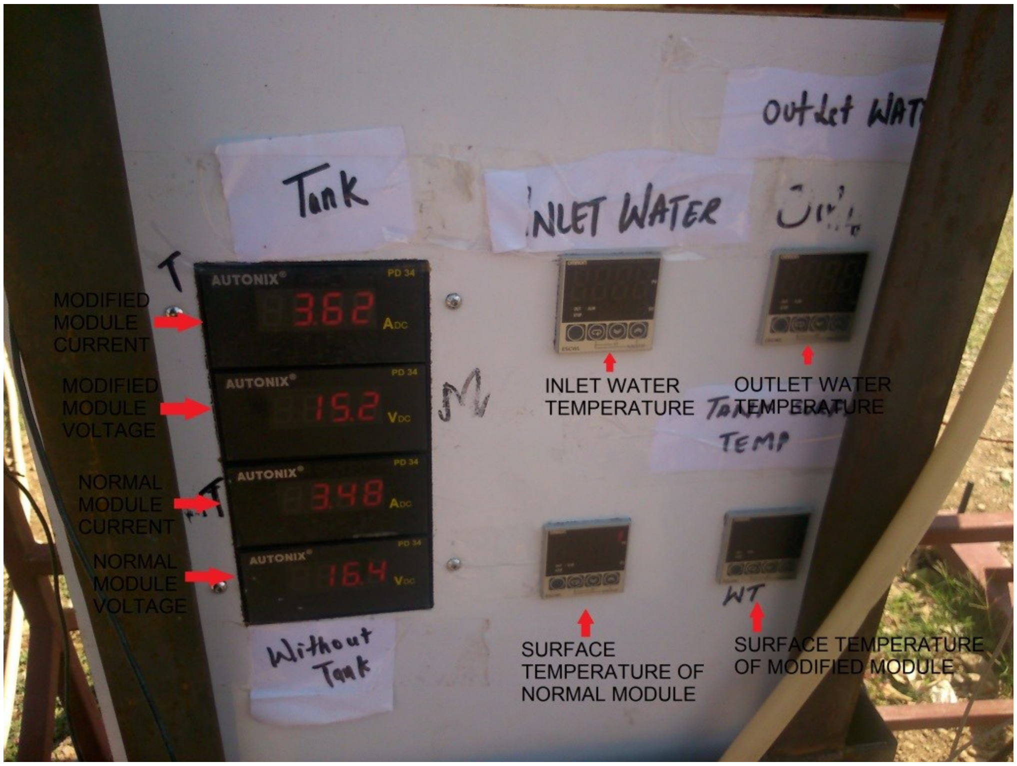

Fig 3.6: Digital meters displaying electrical and thermal parameters

Fig 3.7: Mechanism to set water flow rate

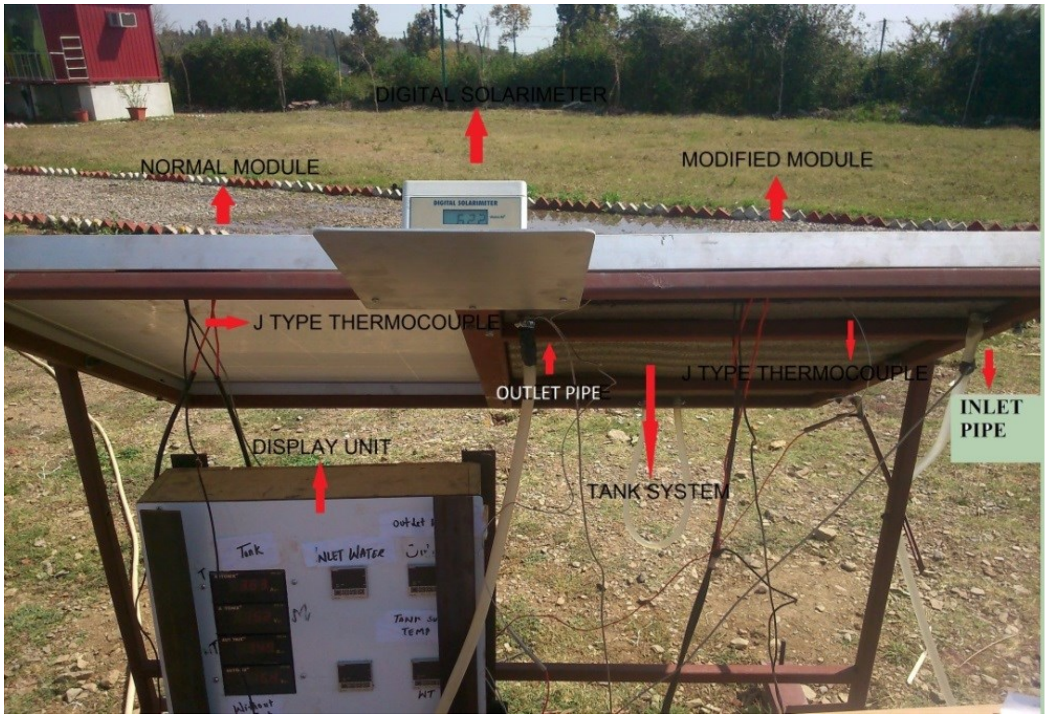

Fig 3.8: Photograph of measuring instruments, electrical and thermal connection

Fig 3.9: Prototype reference and modified PV panels installed at experiment site

Fig 3.10: Experimental setup view

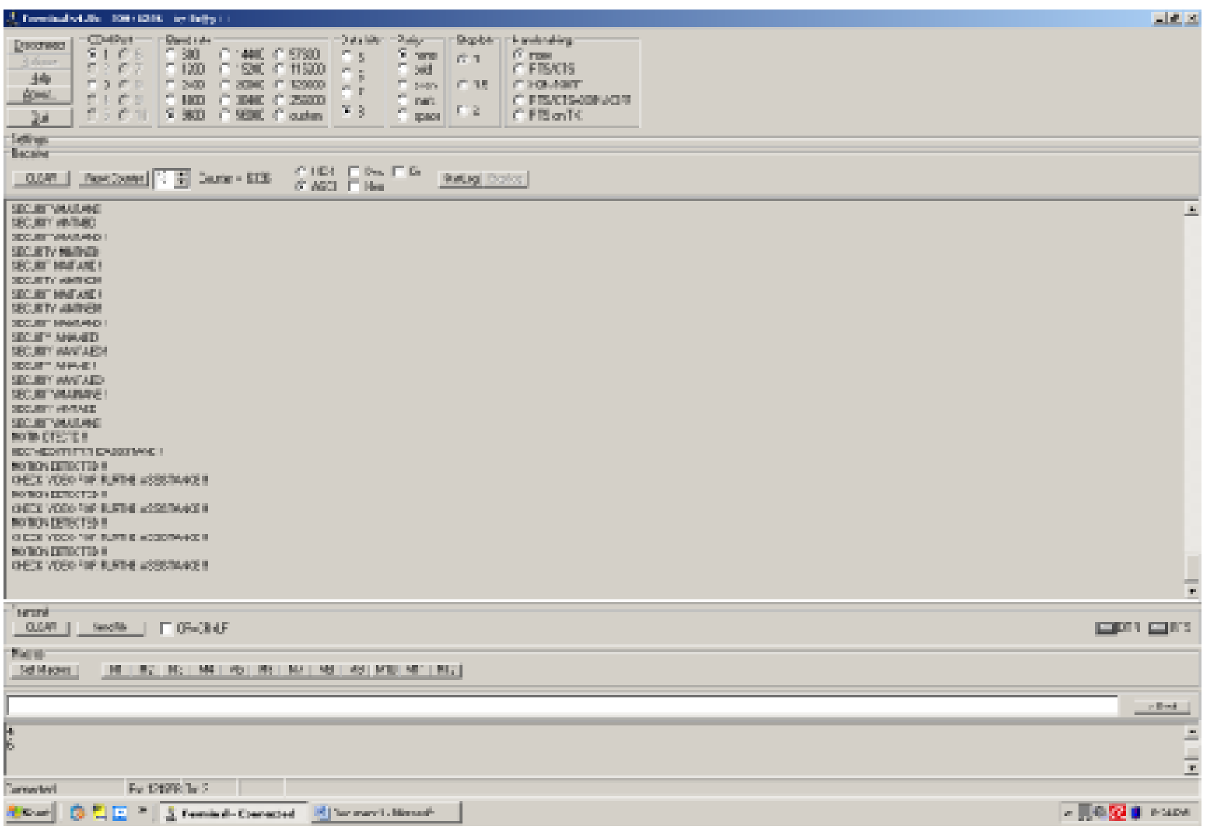

Fig 3.11: Snapshot of Terminal V1.9 b

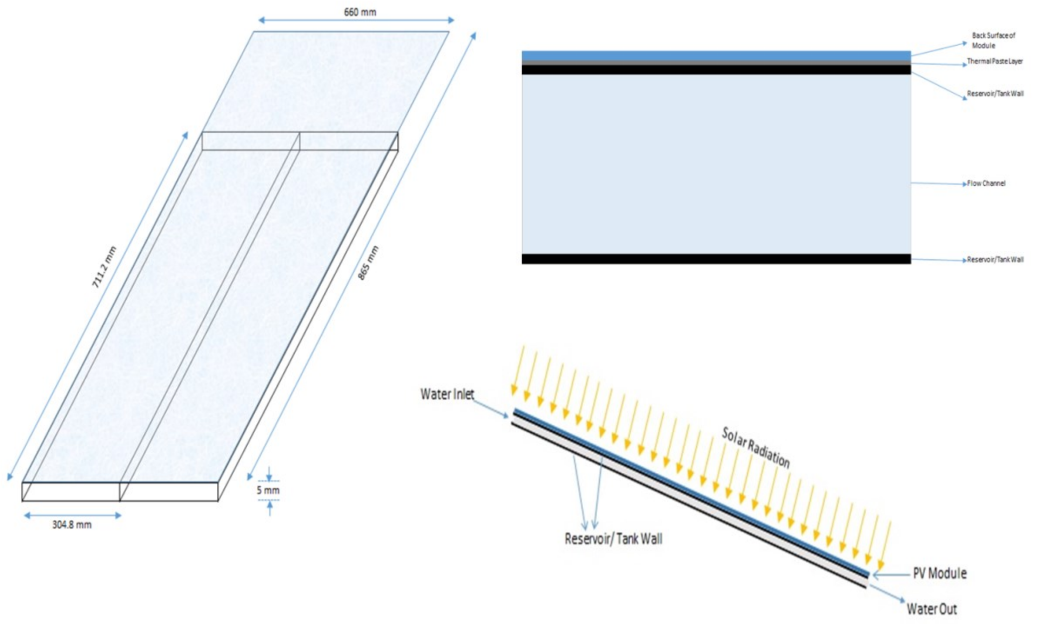

Fig 3.12: Design Element of Heat Exchanger

To reduce the operating temp of PV module, a PV surface cooling system is designed, developed and experiment set up is installed. Multi crystalline silicon PV module of 75 Wp is modified by applying cooling system underneath. Cooling unit is glued by thermal conductive paste on rear surface of module. And the performance of this modified module is compared with the normal module of same type, same rating and same make in similar operating conditions.

Both reference and modified module were experimentally tested in a series of field trials and their performance is determine and compared in next chapter.

3.2 CHAPTER SUMMARY

The system has been integrated and tested to function properly. The goal of real time electrical and environmental data transmission is achieved. The results have been obtained through Terminal v1.9b.

CHAPTER 4

RESULT AND DISCUSSION

In this chapter analysis of the recorded electrical, environmental and thermal parameters at different water flow rate is done and electrical output of modified module is compared with conventional PV module. Total efficiency of modified module is also determine and presented. Chapter describes regression analysis of environmental parameters and water flow rate on which electrical power output depends. Further emphasis is given to determine the impact of water velocity on module operating temperature. Chapter also describes analysis to obtain temperature indicators and cooling coefficients.

4.1 ENERGY PERFORMANCE

Electrical conversion efficiency of standard module (η) is calculated as

$$\eta = \frac{P}{GA} = \frac{VI}{GA} \qquad (4.1)$$

Where

P is electrical power output of standard module

V is output voltage of standard module

I is output current of standard module

G is total solar radiation intensity on PV panel in W/m^2

A is area of PV module = 0.57 m^2

Performance of photo-voltaic thermal system (modified module) can be evaluated by total efficiency (n_T) as

$$n_{total} = \eta_m + n_{th} \tag{4.2}$$

Where η_m is electrical efficiency and electrical output power of PV cell (P) dependent on voltage (V_m) and current (I_m)

$$\eta_m = \frac{P_m}{GA} = \frac{V_m \, I_m}{GA} \tag{4.3}$$

Where

G is total solar radiation intensity on PV panel in W/m^2

A is area of PV module = 0.57 m^2

n_{th} is thermal efficiency and

thermal output power dependent on outlet temperature (*To*) and inlet temperature (*Ti*)

$$n_{th} = \frac{\dot{m} \, C_p (T_o - T_i)}{GA} \tag{4.4}$$

Where $\dot{m}$ is mass flow rate of water in kg/s and

c_p is specific heat of water = 4187 J/kg °C

Relative performance of modified module with respect to standard in terms of electrical efficiency is calculated as -

Percentage increase in electrical efficiency (Δη)

$$\Delta\eta = \frac{\eta_m - \eta}{\eta} \; x \; 100 \; \% \tag{4.5}$$

The numerical simulation is carried out based on the climatic data of Dehradun. MATLAB is used for calculation and generation of graphs. Experimentation has been conducted on sunny days during month of April'2014.

Typical daily profiles during experimentation are shown below in figures 4.1 – 4.15.

Figures show variation of following parameters with time during experimentation days for 15 days from 04-04-14 to 25-04-14 for both reference and modified module:

- Measured solar radiation on tilt surface with an angle of 30^o
- Measured wind speed
- Measured ambient temperature and back surface temperatures
- Measured voltages
- Measured currents
- Calculated electrical and thermal powers
- Calculated electrical and total efficiencies
- Comparison in electrical efficiencies

Date and preset water flow rate of particular day of experimentation are also displayed in figures.

Average values of all parameters of the corresponding day are also given in table 4.1 – 4.15 below the graphs of the day.

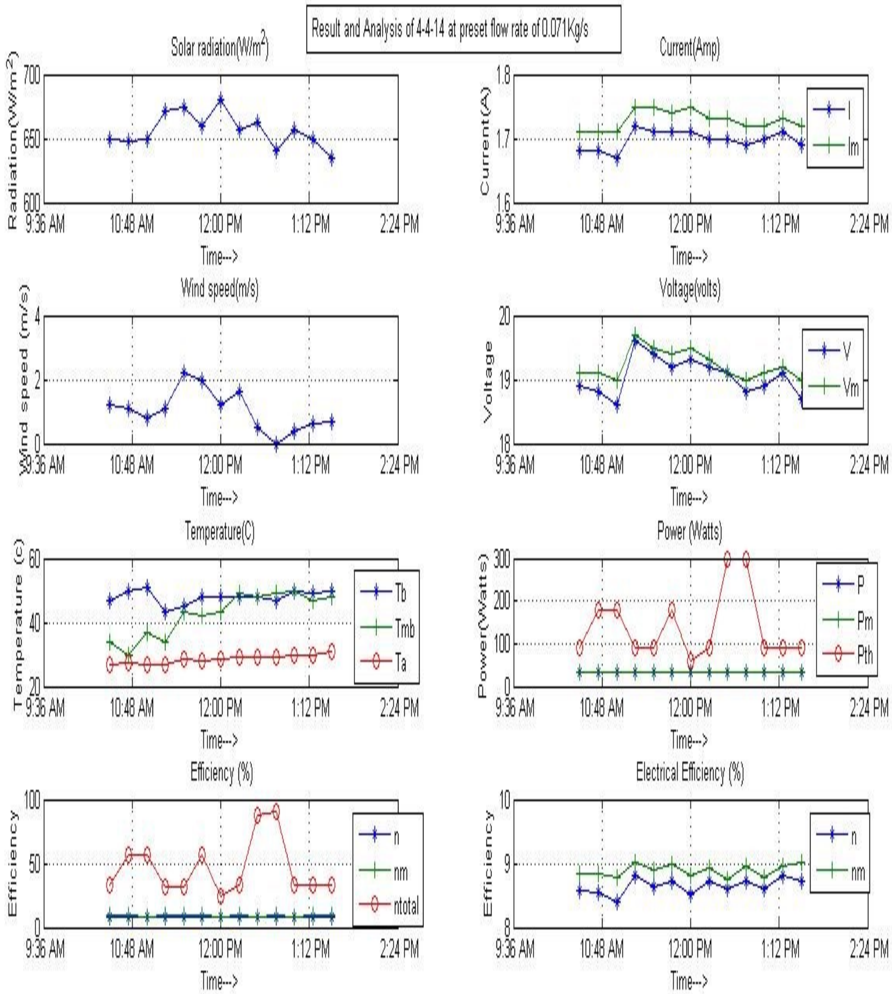

Fig 4.1: Result and Analysis of 04-04-14 at preset flow rate of 0.071 kg/s

Table 4.1: Average values of the day 04-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
19.05	1.698	32.34	8.64	48	19.23	1.728	33.24	8.89	42.62
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
23.38	23.85	139.5	37.4	46.31	28.6	656.3	1.031	**2.816635318**	

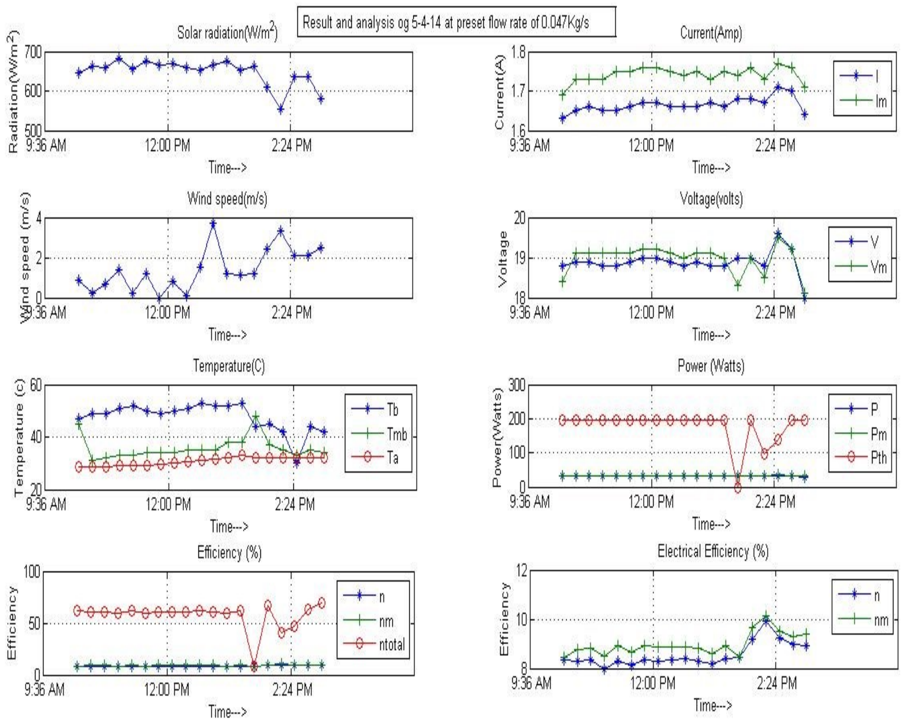

Fig 4.2: Result and Analysis of 05-04-14 at preset flow rate of 0.047 kg/s

Table 4.2: Average values of the day 05-04-14									
V	I	P	η	Tb	Vm	Im	Pm	ηm	Tmb
Volts	Amp	Watts	%	(oC)	Volts	Amp	Watts	%	(oC)
18.9	1.665	31.45	8.54	47.63	18.96	1.742	33.02	8.97	35.74
Ti	To	Pth	ηth	ηtotal	Ta	G	v	**Δη**	
(oC)	(oC)	Watts	%	%	(oC)	W/m2	m/s	**%**	
25.6	27.4	176	47.9	56.91	30.63	647.5	1.401	**5.011862**	

Between 1:30 – 2:00 PM there was no water in cold water tank and hence no flow through cooling unit and thermal output is zero. And back surface temperature of modified module is higher than standard one as also not cooled by natural air convention. Voltage of modified module is also reduced and found no variation in electrical efficiency when compared from standard.

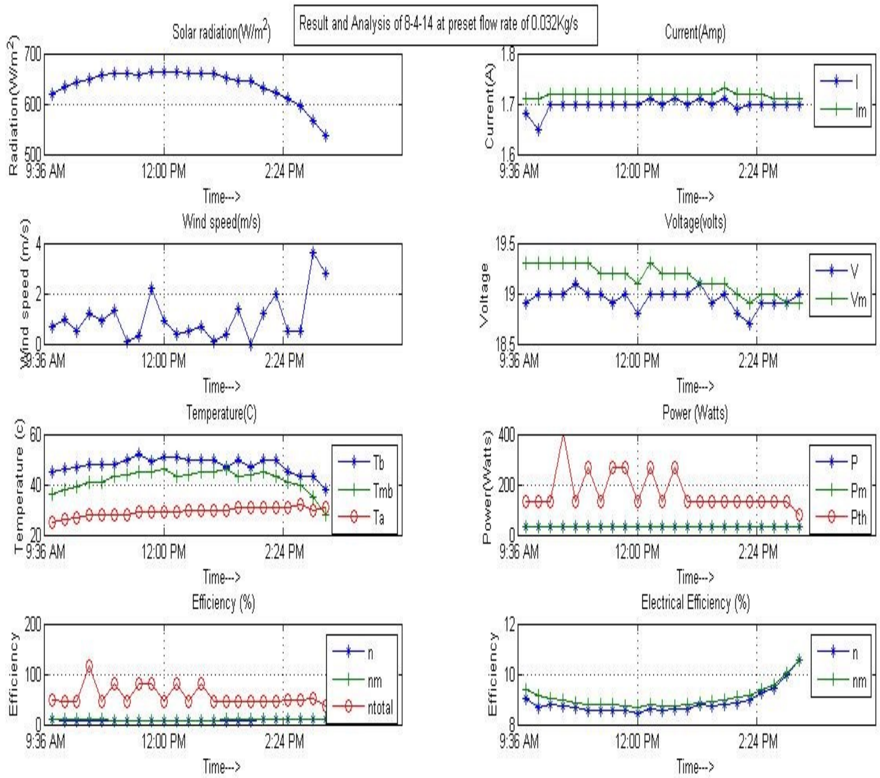

Fig 4.3: Result and Analysis of 08-04-14 at preset flow rate of 0.032 kg/s

Table 4.3: Average values of the day 08-04-14									
V	I	P	η	Tb	Vm	Im	Pm	ηm	Tmb
Volts	Amp	Watts	%	(oC)	Volts	Amp	Watts	%	(oC)
19	1.698	32.19	8.88	47.74	19.15	1.718	32.9	9.08	41.74
Ti	To	Pth	ηth	ηtotal	Ta	G	v	**Δη**	
(oC)	(oC)	Watts	%	%	(oC)	W/m2	m/s	**%**	
25.8	27.07	172.4	47.1	56.17	29.3	637.4	1.009	**2.227192**	

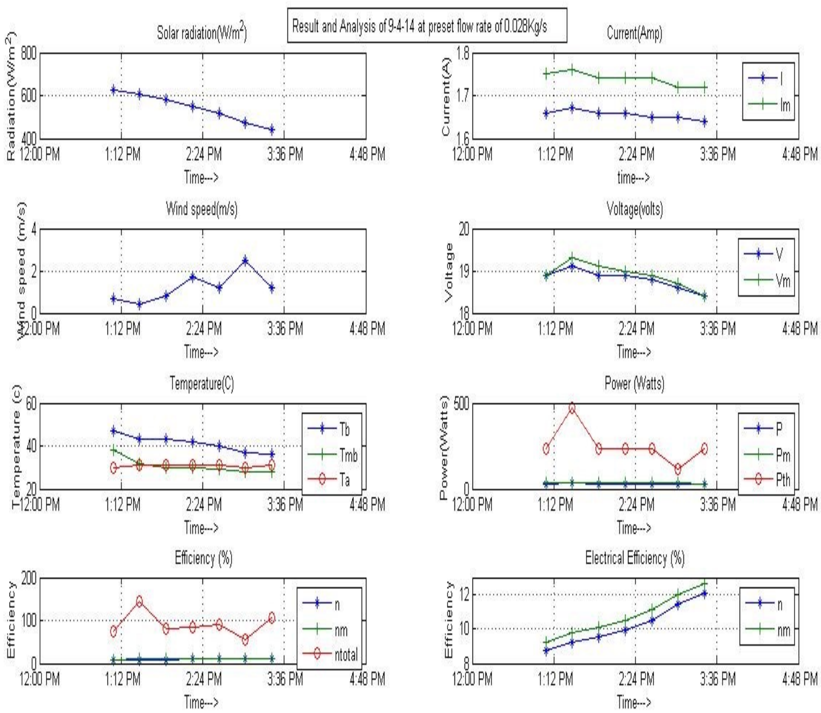

Fig 4.4: Result and Analysis of 09-04-14 at preset flow rate of 0.028 kg/s

Table 4.4: Average values of the day 09-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.8	1.656	31.13	10.2	41.14	18.9	1.739	32.86	10.8	30.71
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη %**	
19.43	21.57	251.2	80.5	91.23	30.71	542	1.214	5.563659792	

To see the effect of inlet water temperature ice is put in cold water tank in first half and measurement has been started at 1:00 PM. It was found that there is no variation in temperature difference between inlet and outlet water and it is a function of water flow rate.

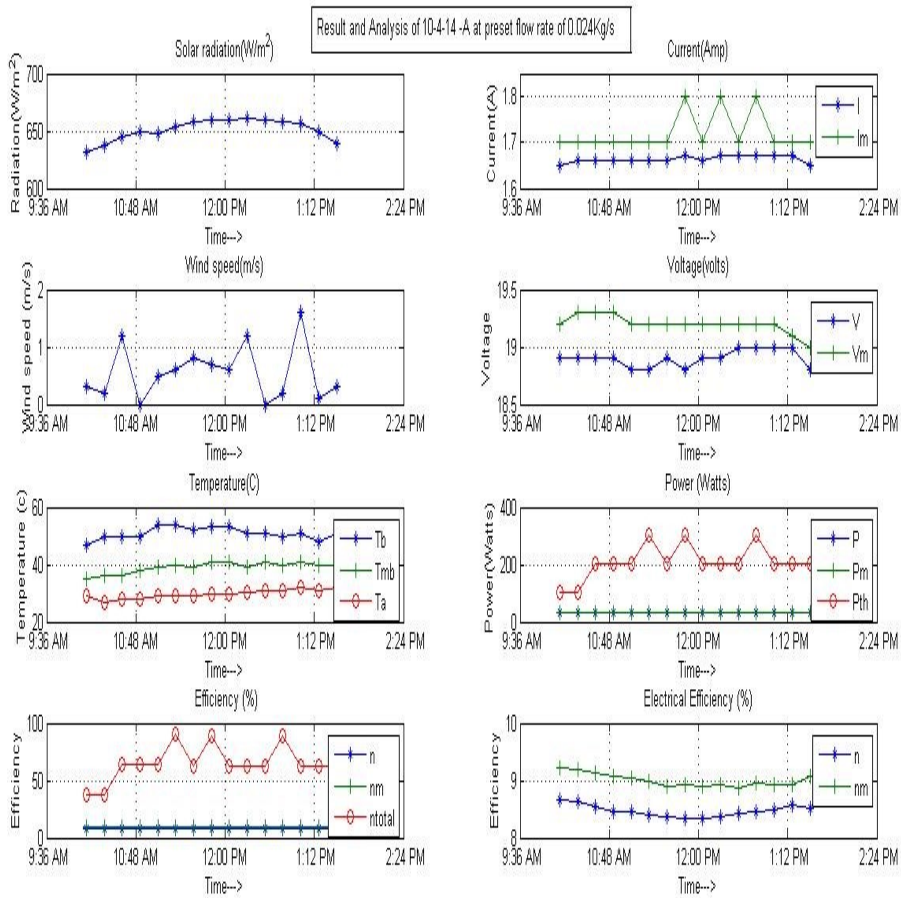

Fig 4.5: Result and Analysis of 10-04-14 (1st half) at preset flow rate of 0.024 kg/s

Table 4.5: Average values of the day 10-04-14A									
V	I	P	H	Tb	Vm	Im	Pm	ηm	Tmb
Volts	Amp	Watts	%	(oC)	Volts	Amp	Watts	%	(oC)
18.8	1.65	31.02	8.52	51	19	1.74	33.4	9.17	40
Ti	To	Pth	Hth	ηtotal	Ta	G	v	**Δη**	
(oC)	(oC)	Watts	%	%	(oC)	W/m2	m/s	**%**	
28	30	201	55.2	64.34	32	639	0.3	**7.62**	

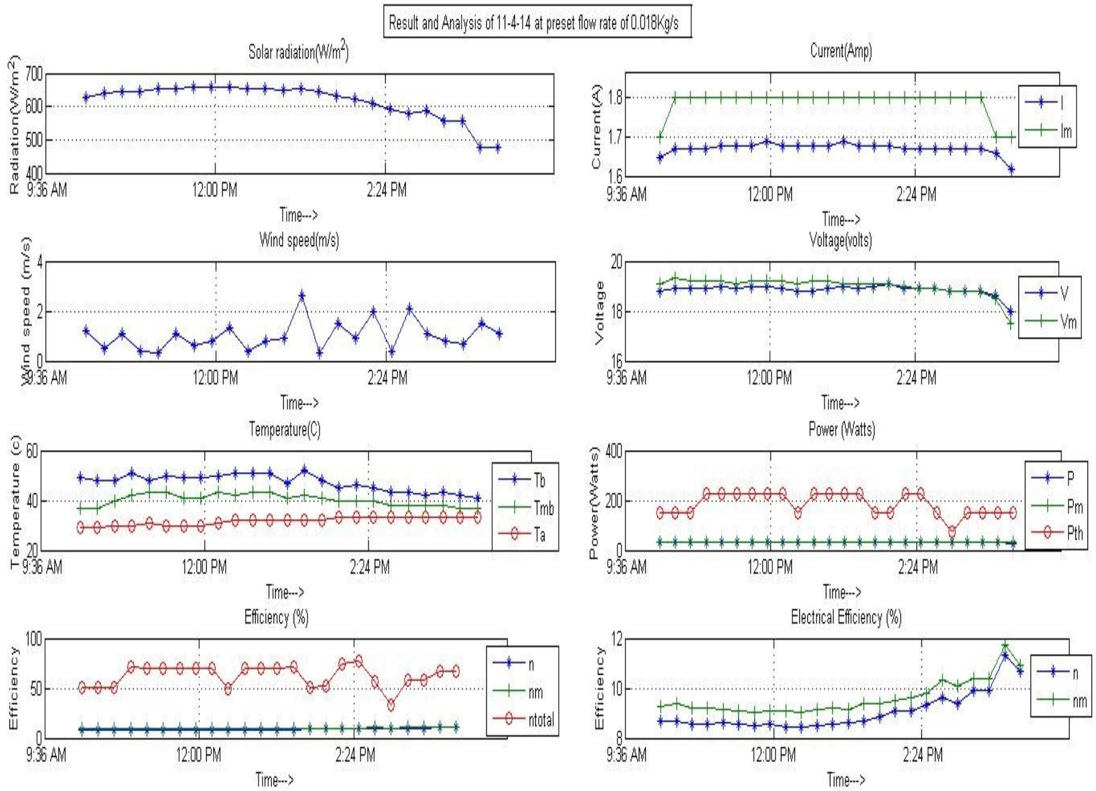

Fig 4.6: Result and Analysis of 11-04-14 at preset flow rate of 0.018 kg/s

Table 4.6: Average values of the day 11-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.9	1.673	31.54	9.04	47.17	18.99	1.76	33.54	9.61	40.21
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη %**	
28	30.46	185.3	52.6	62.22	31.63	616.2	1.017	**6.34636**	

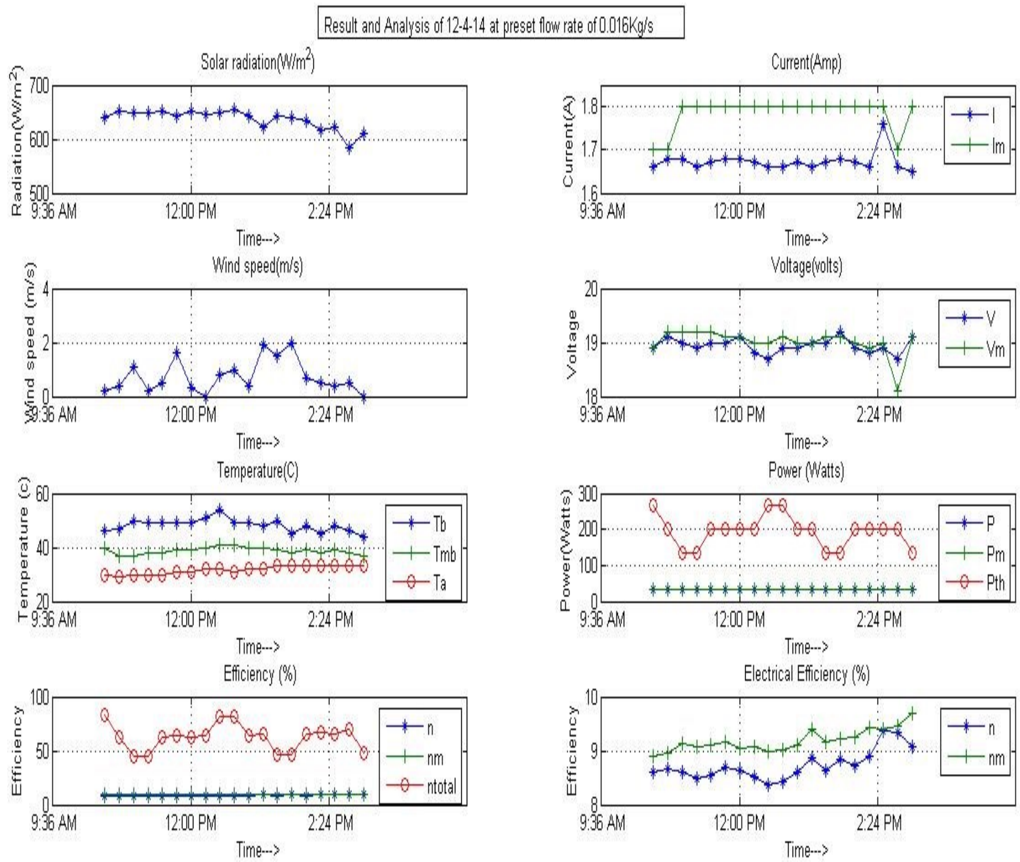

Fig 4.7: Result and Analysis of 12-04-14 at preset flow rate of 0.016 kg/s

Table 4.7: Average values of the day 12-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.94	1.673	31.68	8.73	48.21	19.02	1.75	33.33	9.18	38.84
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
27.95	30.84	193.9	53.4	62.59	31.63	637.1	0.737	**5.219628**	

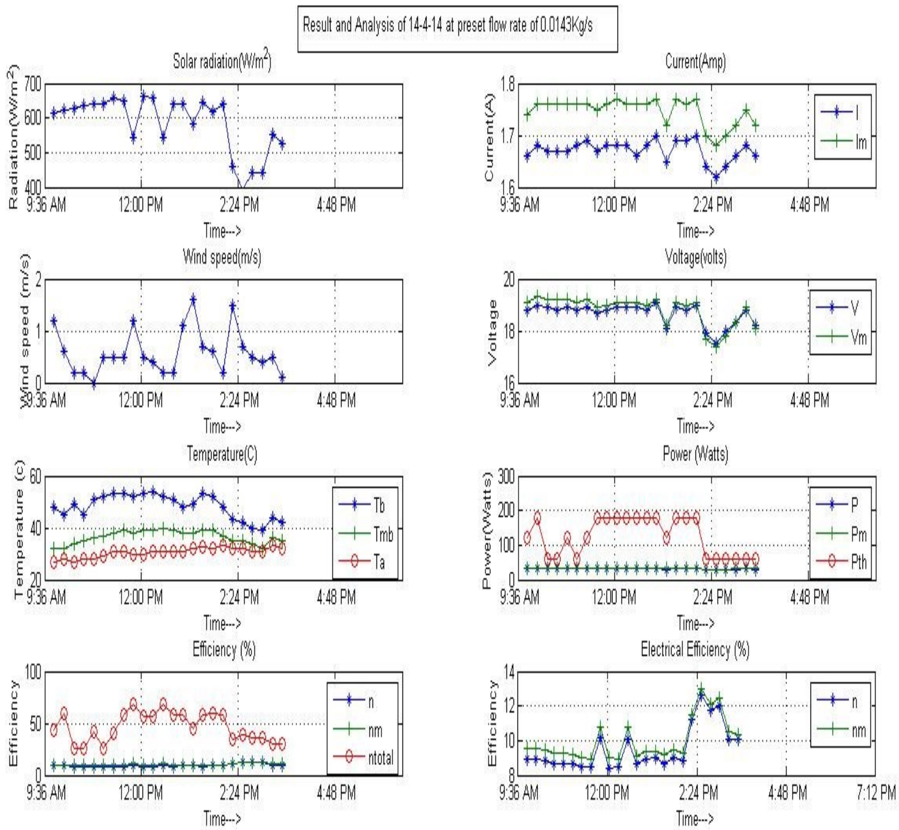

Fig 4.8: Result and Analysis of 14-04-14 at preset flow rate of 0.014 kg/s

Table: 4.8: Average values of the day 14-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.7	1.671	31.17	9.48	48.25	18.8	1.747	32.86	9.97	36.5
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη %**	
26.6	28.67	124.7	36.6	46.56	30.56	587	0.588	**5.370034**	

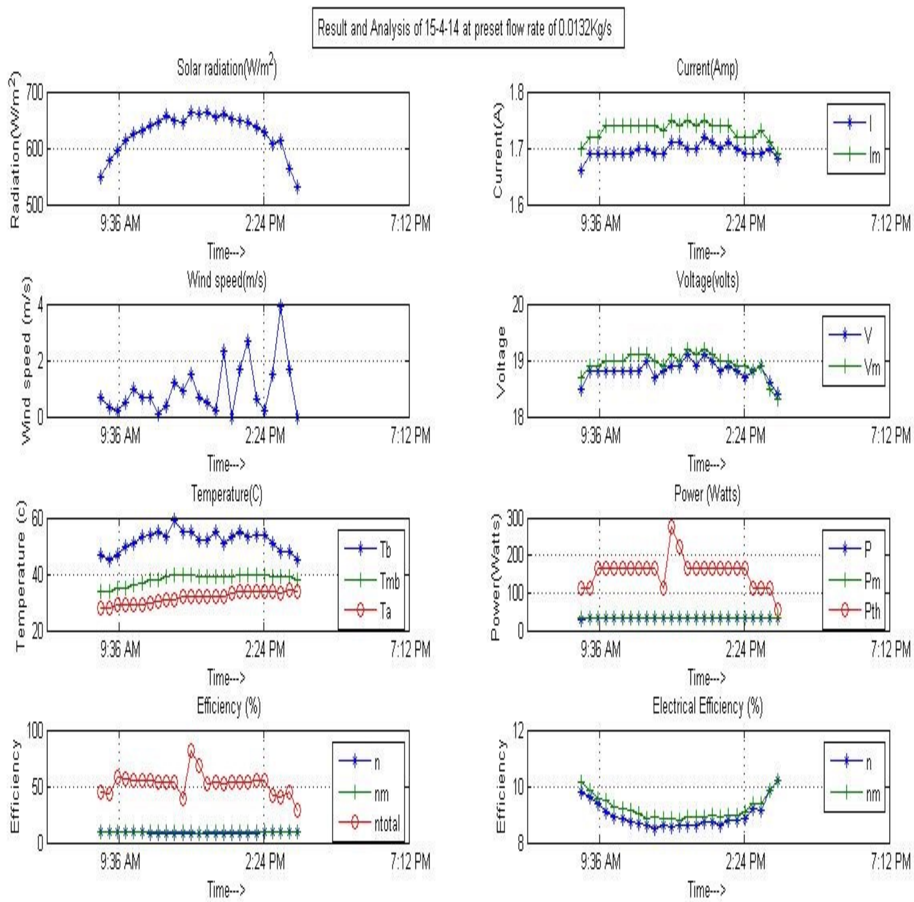

Fig 4.9: Result and Analysis of 15-04-14 at preset flow rate of 0.013 kg/s

Table 4.9: Average values of the day 15-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.82	1.696	31.9	8.97	51.8	18.95	1.732	32.81	9.22	36.2
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
26.92	29.72	154.8	43	52.22	31.64	626	0.968	**2.846987**	

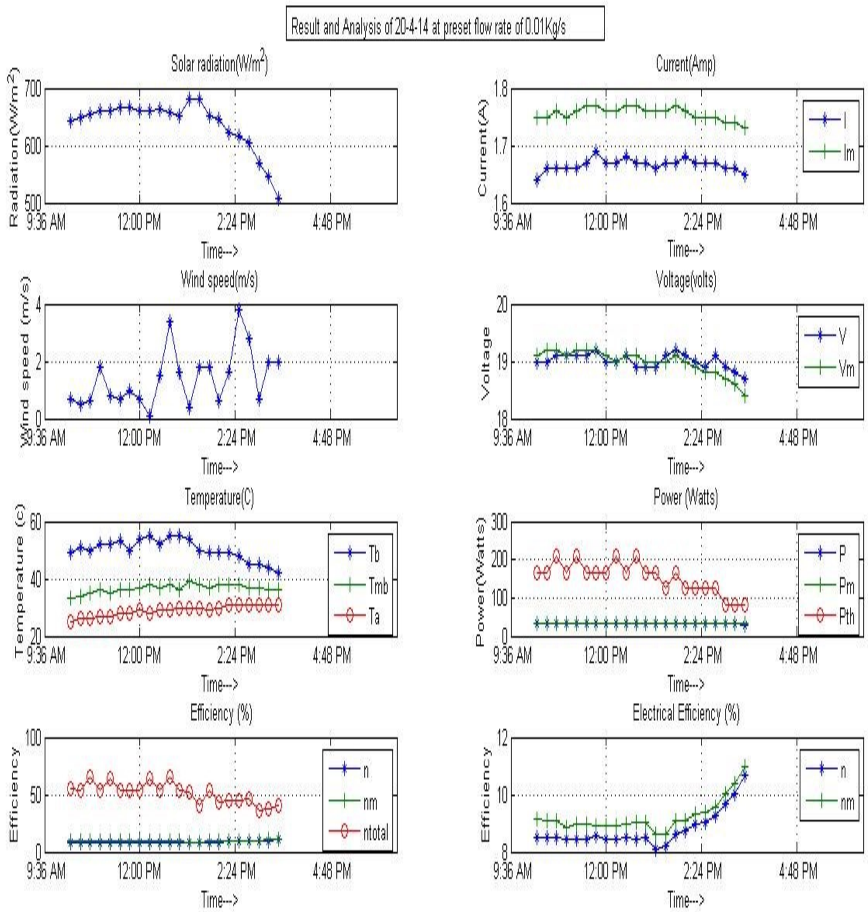

Fig 4.10: Result and Analysis of 20-04-14 at preset flow rate of 0.01 kg/s

Table 4.10: Average values of the day 20-04-14									
V	I	P	η	Tb	Vm	Im	Pm	ηm	Tmb
Volts	Amp	Watts	%	(oC)	Volts	Amp	Watts	%	(oC)
19	1.666	31.68	8.76	50.14	18.99	1.756	33.36	9.22	36.59
Ti	To	Pth	ηth	ηtotal	Ta	G	v	**Δη**	
(oC)	(oC)	Watts	%	%	(oC)	W/m2	m/s	**%**	
25.6	29.27	154.2	42	51.27	28.95	637	1.405	**5.303442**	

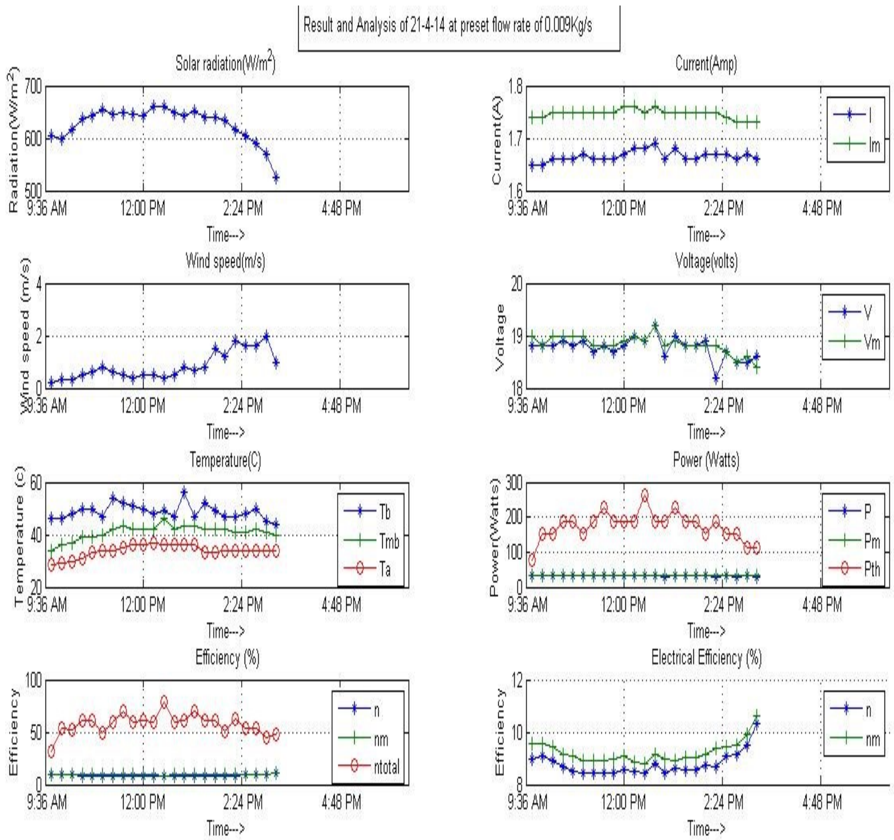

Fig 4.11: Result and Analysis of 21-04-14 at preset flow rate of 0.009 kg/s

Table 4.11: Average values of the day 21-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.77	1.666	31.26	8.77	48.83	18.84	1.747	32.92	9.23	40.93
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
27.61	32.22	173.7	48.3	57.54	33.76	626.9	0.83	**5.304792**	

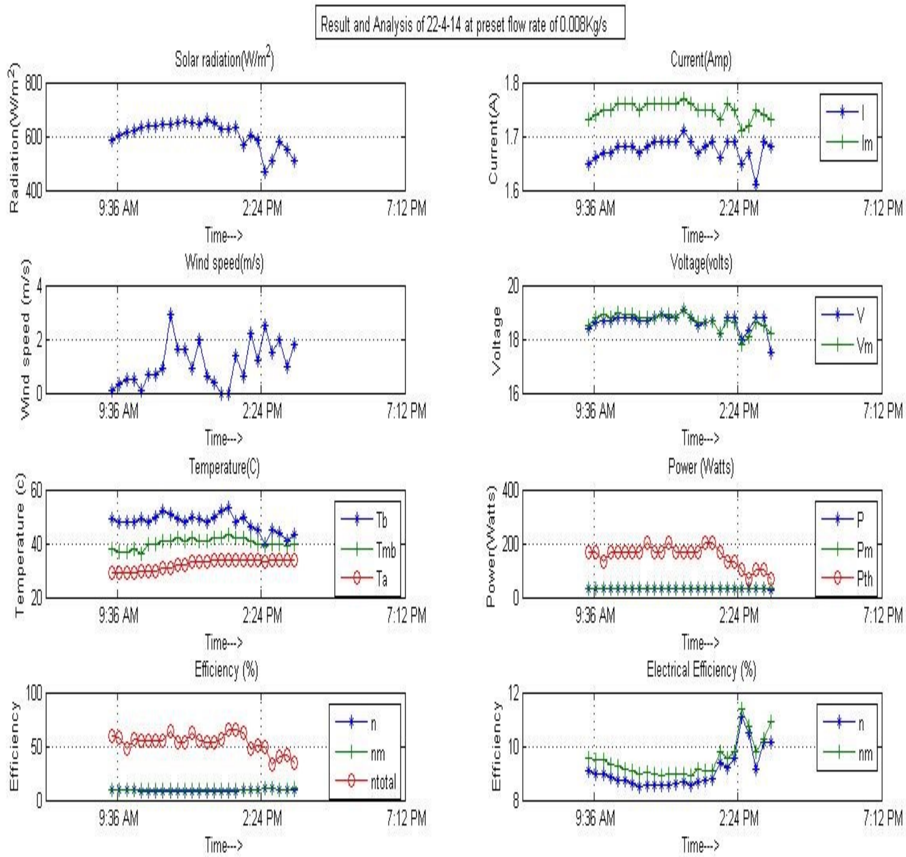

Fig 4.12: Result and Analysis of 22-04-14 at preset flow rate of 0.008 kg/s

Table 4.12: Average values of the day 22-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.6	1.676	31.23	9.08	47.85	18.67	1.749	32.65	9.49	40.19
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
28.8	33.42	153.3	43.8	53.31	32.23	607	1.077	**4.548539**	

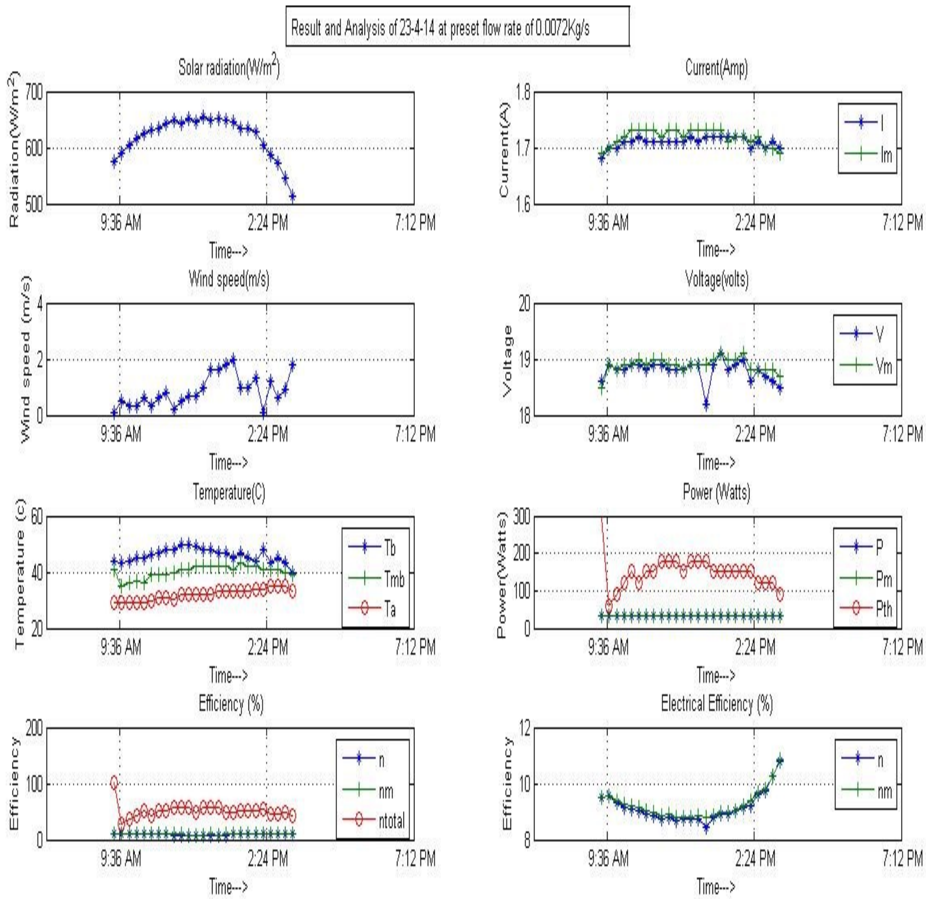

Fig 4.13: Result and Analysis of 23-04-14 at preset flow rate of 0.0072 kg/s

Table 4.13: Average values of the day 23-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.79	1.71	32.13	9.14	45.96	18.89	1.718	32.47	9.23	40.16
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
28.88	33.84	149.5	42.3	51.51	31.96	619	0.86	**1.030522**	

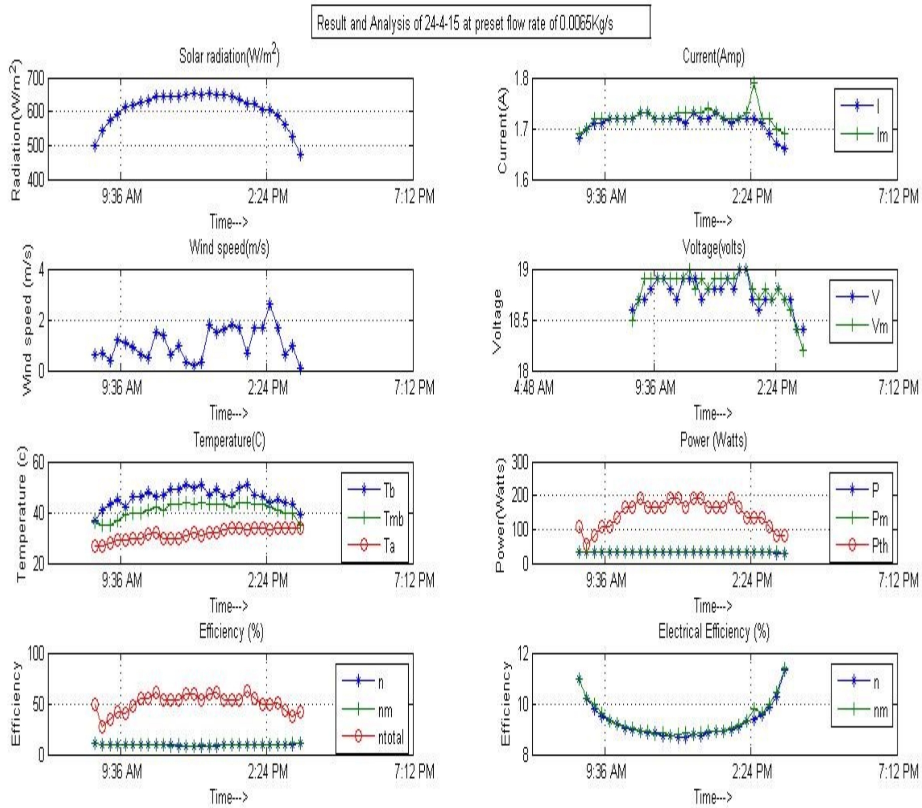

Fig 4.14: Result and Analysis of 24-04-14 at preset flow rate of 0.0065 kg/s

Table 4.14: Average values of the day 24-04-14									
V	I	P	η	Tb	Vm	Im	Pm	ηm	Tmb
Volts	Amp	Watts	%	(oC)	Volts	Amp	Watts	%	(oC)
18.8	1.713	32.13	9.3	46.04	18.8	1.723	32.38	9.37	40.93
Ti	To	Pth	ηth	ηtotal	Ta	G	v	**Δη**	
(oC)	(oC)	Watts	%	%	(oC)	W/m2	m/s	**%**	
29.4	34.68	144.8	41.2	50.54	31.52	609.6	1.064	**0.77743037**	

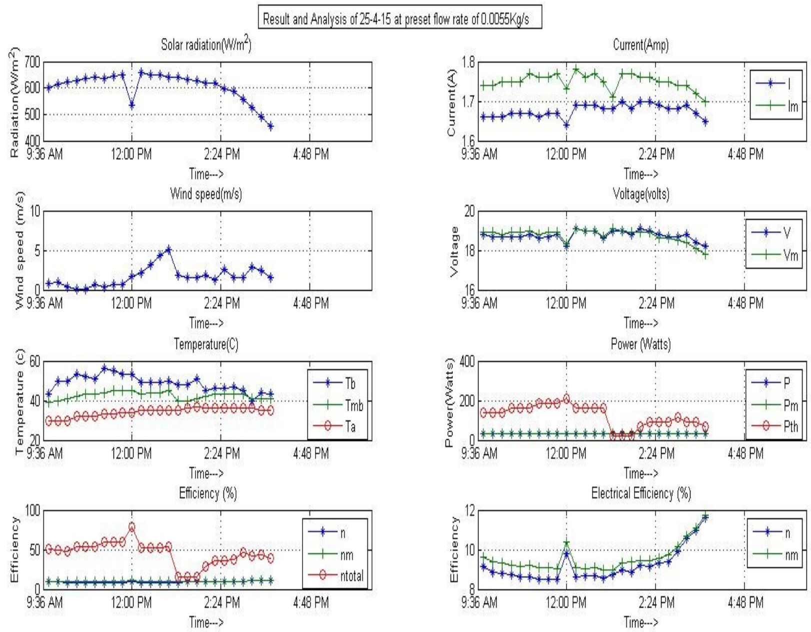

Fig 4.15: Result and Analysis of 25-04-14 at preset flow rate of 0.0055 kg/s

Table 4.15: Average values of the day 25-04-14									
V Volts	I Amp	P Watts	η %	Tb (oC)	Vm Volts	Im Amp	Pm Watts	ηm %	Tmb (oC)
18.76	1.676	31.44	9.17	48.64	18.76	1.75	32.83	9.56	42.44
Ti (oC)	To (oC)	Pth Watts	ηth %	ηtotal %	Ta (oC)	G W/m2	v m/s	**Δη** **%**	
31.72	37.08	123.4	35.7	45.22	34.14	606.1	1.668	**4.424742**	

About 12:00 PM the solar radiation was decreased from 648 W/m^2 to 534 W/m^2 and then again increased to 658 W/m^2 and accordingly voltage and current, but electrical efficiencies were higher as temperature also reduced. Around 1:15 PM water flow was disturbed and this immediately reflected on thermal output and hence on overall efficiency.

Polycrystalline silicon PV module combined with surface cooling system to extract heat was constructed and tested with respect to its operating temperature and compared with operating temperature of module of same rating without cooling system at the Geo graphic location of Dehradun installed similarly.

From all above performance graphs of different experiment days it is found that in late afternoon when solar radiation goes down, electrical efficiencies are higher as operating temperatures are also lower.

Relative performance of modified module with respect to conventional system reflects that there is not much increase in output voltage but significant increase in current and electrical efficiency. Experimentally current is increasing and not much increase in voltage while operating temperature is decreasing and this is not in-line with theoretical consideration and prior art. Found that current is more temperature sensitive than voltage.

4.1.1 Effect of environmental parameters of polycrystalline Solar PV module in Dehradun

Performance of solar module is best for certain weather conditions. Solar PV modules do not operate under normal operating conditions as weather always changes.

Power outputs of modules are dependent variable and function of independent variables solar radiation, ambient temperature, wind speed and water flow rate

$$P = f\ (G,\ T_a,\ v) \qquad (4.6)$$

$$P_m = f\ (G,\ T_a,\ v,\ \dot{m}) \qquad (4.7)$$

To obtain regression constants of above environmental parameters and water flow rate a statistical analysis of experimental data for variation in output electrical power of standard module with solar radiation, ambient temperature, wind speed and of modified module with solar radiation, ambient temperature, wind speed and water flow rate has been done and

Regression equations obtained from analysis are:

For standard module

$$P = 0.0084\,G + 0.0012\,T_a + 0.1074\,v + 26.3008 \tag{4.8}$$

For modified module

$$P_m = 0.0124\,G - 0.0274\,T_a + 0.0536\,v - 1.507\,\dot{m} + 26.0543 \tag{4.9}$$

4.2 WATER VELOCITY IMPACT

In table 4.16 below average values of all parameters are summarized date wise and analyze for optimum range of water flow for maximum possible ΔT, ηth and Tmb

Table 4.16 : Average values

Variables												
	Date	Flow	V	I	P	η	Tb	Vm	Im	Pm	ηm	Tmb
S.No.	April'14	kg/sec	Volts	Amp	Watts	%	˚C	Volts	Amp	Watts	%	˚C
1	4	0.071	19.05	1.698	32.34	8.64	48	19.23	1.728	33.24	8.89	42.62
2	5	0.047	18.9	1.665	31.45	8.54	47.63	18.96	1.742	33.02	8.97	35.74
3	8	0.032	19	1.698	32.19	8.88	47.74	19.15	1.718	32.9	9.08	41.74
4	9	0.028	18.81	1.656	31.16	10	41.75	18.91	1.736	32.84	10.6	32
5	10	0.024	18.8	1.65	31.02	8.52	51	19	1.74	33.4	9.17	40
6	11	0.018	18.9	1.673	31.54	9.04	47.17	18.99	1.76	33.54	9.61	40.21
7	12	0.016	18.94	1.673	31.68	8.73	48.21	19.02	1.75	33.33	9.18	38.84
8	14	0.014	18.7	1.671	31.17	9.48	48.25	18.8	1.747	32.86	9.97	36.5
9	15	0.013	18.82	1.696	31.9	8.97	51.8	18.95	1.732	32.81	9.22	36.24
10	20	0.01	19	1.666	31.68	8.76	50.14	18.99	1.756	33.36	9.22	36.59
11	21	0.009	18.77	1.666	31.26	8.77	48.83	18.84	1.747	32.92	9.23	40.93
12	22	0.008	18.6	1.676	31.23	9.08	47.85	18.67	1.749	32.65	9.49	40.19
13	23	0.0072	18.79	1.71	32.13	9.14	45.96	18.89	1.718	32.47	9.23	40.16
14	24	0.0065	18.76	1.7125	32.13	9.299	46.04	18.796	1.723	32.38	9.37	40.93
15	25	0.0055	18.76	1.676	31.44	9.17	48.64	18.76	1.75	32.83	9.56	42.44

Variables										
	Date	Ti	To	Pth	ηth	ηtotal	Ta	G	v	Δη
S.No.	April'14	˚C	˚C	Watts	%	%	˚C	W/m²	m/s	%
1	4	23.38	23.85	139.5	37.4	46.31	28.6	656.3	1.031	2.82
2	5	25.6	27.4	176	47.9	56.91	30.63	647.5	1.401	5.01
3	8	25.8	27.07	172.4	47.1	56.17	29.3	637.4	1.009	2.23
4	9	19.88	21.88	234.5	74.5	85.03	30.13	553.3	1.188	5.39
5	10	28	30	201	55.2	64.34	32	639	0.3	7.62
6	11	28	30.46	185.3	52.6	62.22	31.63	616.2	1.017	6.35
7	12	27.95	30.84	193.9	53.4	62.59	31.63	637.1	0.737	5.22
8	14	26.6	28.67	124.7	36.6	46.56	30.56	587	0.588	5.37
9	15	26.92	29.72	154.8	43	52.22	31.64	626	0.968	2.85
10	20	25.6	29.27	154.2	42	51.27	28.95	637	1.405	5.3
11	21	27.61	32.22	173.7	48.3	57.54	33.76	626.9	0.83	5.3
12	22	28.8	33.42	153.3	43.8	53.31	32.23	607	1.077	4.55
13	23	28.88	33.84	149.5	42.3	51.51	31.96	619	0.86	1.03
14	24	29.36	34.679	144.8	41.16	50.54	31.518	609.6	1.064	0.78
15	25	31.72	37.08	123.4	35.7	45.22	34.14	606.1	1.668	4.42

Thermal output depends on mass flow rate of water and change in inlet and outlet water temperature, (ΔT).

The influence of water flow rate on the temperature difference between average outlet temperature and average inlet temperature of the day in presented in figure 4.16 below.

ΔT decreases with increase in flow rate.

ΔT is higher if resident time of water is longer in reservoir.

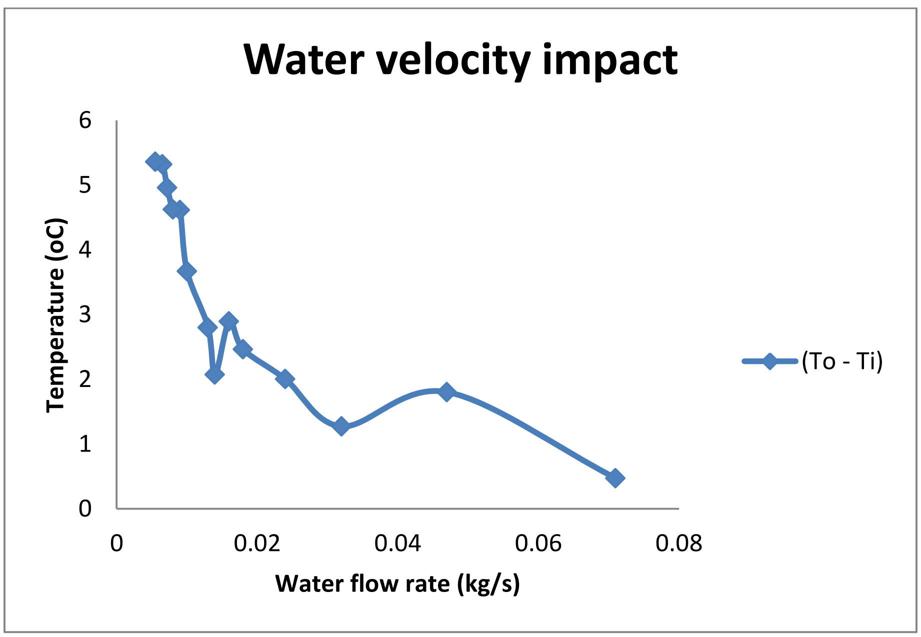

Fig 4.16: Water velocity impact on change in water temperature

The influence of flow rate of water on thermal efficiency is shown in figure 4.17 below.

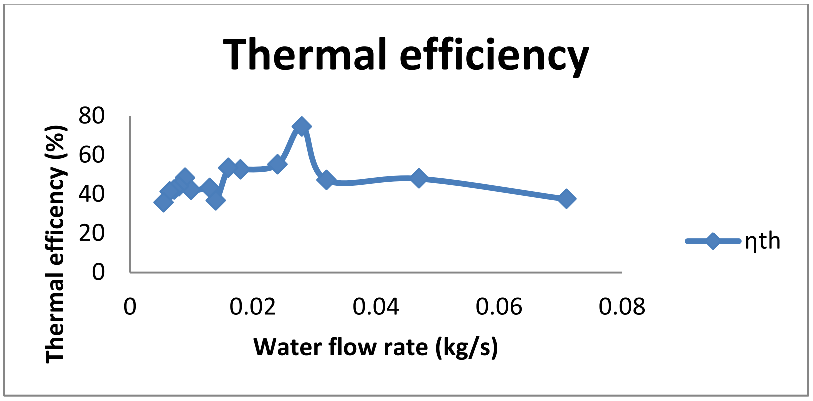

Fig 4.17: Water velocity impact on thermal efficiency

The thermal efficiency on date 09-04-14 is not considered as ice is put in cold water tank and testing is conducted only for second half and second half thermal efficiency average is 85 %. Higher thermal efficiency range is found on 10th, 11th and 12th when the water flow is about 0.02 kg/s.

The influence of flow rate of water on module operating temperature is shown in figure 4.18 below.

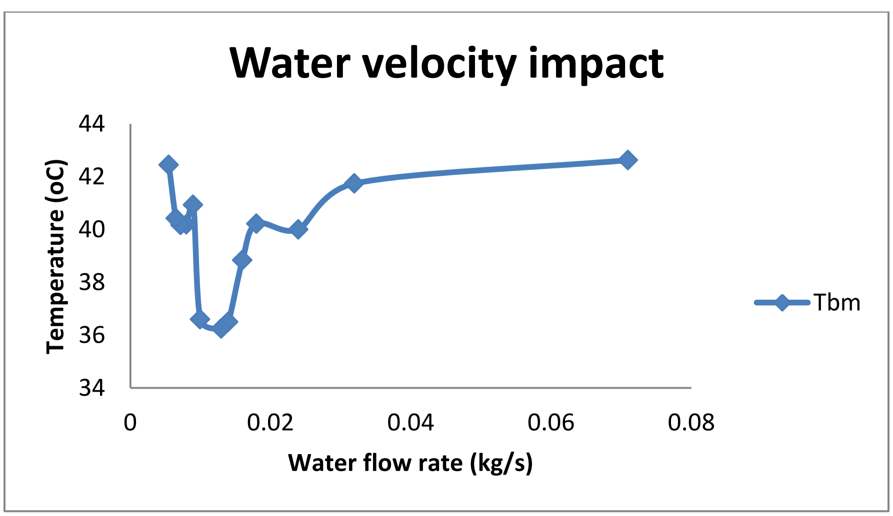

Fig 4.18: Water velocity impact on module operating temperature

Graph reflects that with increase in flow rate, module working temperature decreases until the flow rate reaches about 0.01 kg/s and after that start increasing with flow rate.

To maintain minimum operating module temperature, optimum flow rate of water through cooling unit is 0.01 kg/sec for designed system i.e. on 20-04-14.

Heat removed by the water flowing naturally by gravity through surface cooling unit at optimum flow rate is collected at the lower end of the panel and can be used as a utility for heating purposes.

On reference day it has been found that temperature of feed water is increased by 3.7 ℃.

Reverse Osmosis units or Water Softeners are installed in PV power plants. Huge water is required to clean and maintain PV power plants. 2000 liters to 6000 liters water is required per day for 1 MW plant, according to their water storage capacity and cleaning cycle.

Temperature of feed water to RO is very important parameter. Water production rate increases about 3 % per degree Celsius rise in feed water temperature [45-46].

The water temperature from open intake is of range of 15 ℃ to 20 ℃.

Taking average water requirement for 1MW plant is 4000 liters per day. And as feed water temperature to RO is of 3.7℃ higher, water production will increase by 11 % i.e. 400 liters per day more production and can save about 800 liter water per day (recovery ratio 30 % - 50%).

4.3 MODULE OPERATING TEMPERATURE INDICATORS

4.3.1 TEMPERATURE INDICATORS

To install photovoltaic module, system designer and inventor consider data sheet of modules to make choice of module type and brand. Data sheet include few primary characteristics like module peak power and efficiency at STC (standard test condition), temperature coefficient of power, open circuit voltage, short circuit current and sometimes low light behavior as STC rarely met in real time condition.

Operating temperature of the module depends on the radiation absorption properties, thermal dissipation, module encapsulating materials, module functioning and also depends on insolation, ambient temp, accurate installation status and wind speed. Module parameters like voltage, current, power and efficiency greatly influence by the module operating temperature and thus, it is very important to perform a quantitative analysis under real operating condition. As a module temperature indicative NOCT (Nominal Operating Cell Temperature) is commonly use. NOCT is mean solar junction temperature in Standard Reference Environment (SRE) with in an open rack mounted module. SRE includes total irradiance 800W/m^2, wind speed 1m/s, ambient temperature 20^{o}C, tilt angle - at normal incidence to the direct solar beam at local solar noon and nil electrical loads. NOCT is a reference of how the module will work in real condition therefore is an important characteristic. To calculate NOCT there are several intimation standards EN-61215 for crystalline PV module, EN-61646 for thin film PV module, ASTM E1036M or both (non - concentrator terrestrial PV modules and arrays).

Fact on which all above standards are based is that Tm-Ta (module temp - ambient temp) difference is essentially linear to irradiance and largely independent of wind speed.

INOCT i.e. Installed Nominal Operation Cell temperature is the cell temperature of installed module connected to load and also mounting configuration of the module is taking into account.

To analyze collected data of each day for both non - cooling and with cooling modules:-

- Module temperature rise above ambient temperature as a function of solar irradiance (>400 W/m^2) is plotted.
- To fit data, linear regression is used and temperature above ambient at 800 W/m^2 was determine by regression equation
- Finally installed normal operating module temperature were determined at reporting conditions by adding 20^{o}C and corrected for average wind speed and ambient temperature from the following graph shown in fig. 4.19 [26].

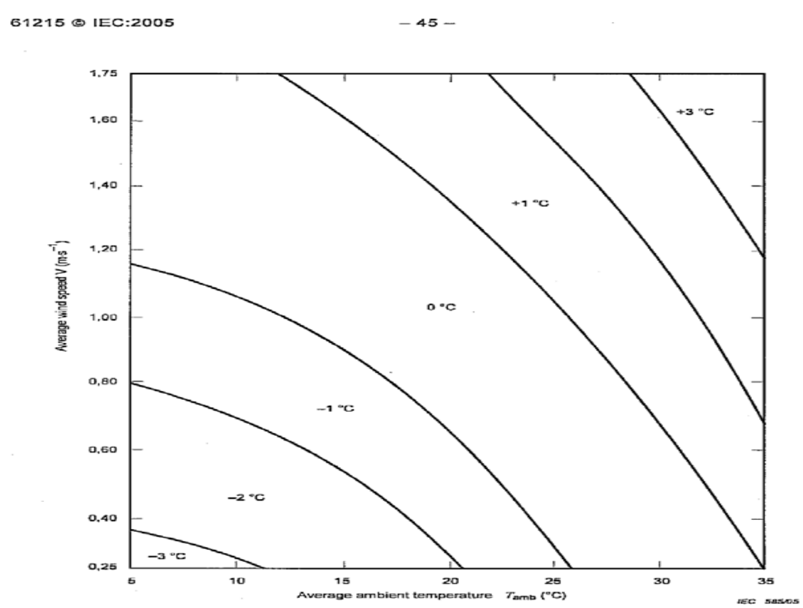

Fig 4.19: To correct NOCT for average wind speed and average ambient temperature [26]

4.3.2 CALCULATION OF INSTALLED NOMINAL OPERATING TEMPERATURE (INOCT)

Tests were conducted on different sunny days in the month of April 2014. For total eleven days are considered and out of these four test are depicted in figures 4.20 – 4.23 below and following equation is used to calculate INOCT on tested day:-

$$INOCT_{day} = \text{regression equation} + 20^{o}C + \text{correction factor} \tag{4.10}$$

Where

• Correction factor is determined by using graph shown in fig. 4.19 above for average ambient temperature and average wind speed

• Regression equation of fitting collected data is obtained from the graphs plotted for each day.

Finally INOCT is obtained by correcting regression equation to 800 W/m^2 and adding 20^{o}C and correction factor.

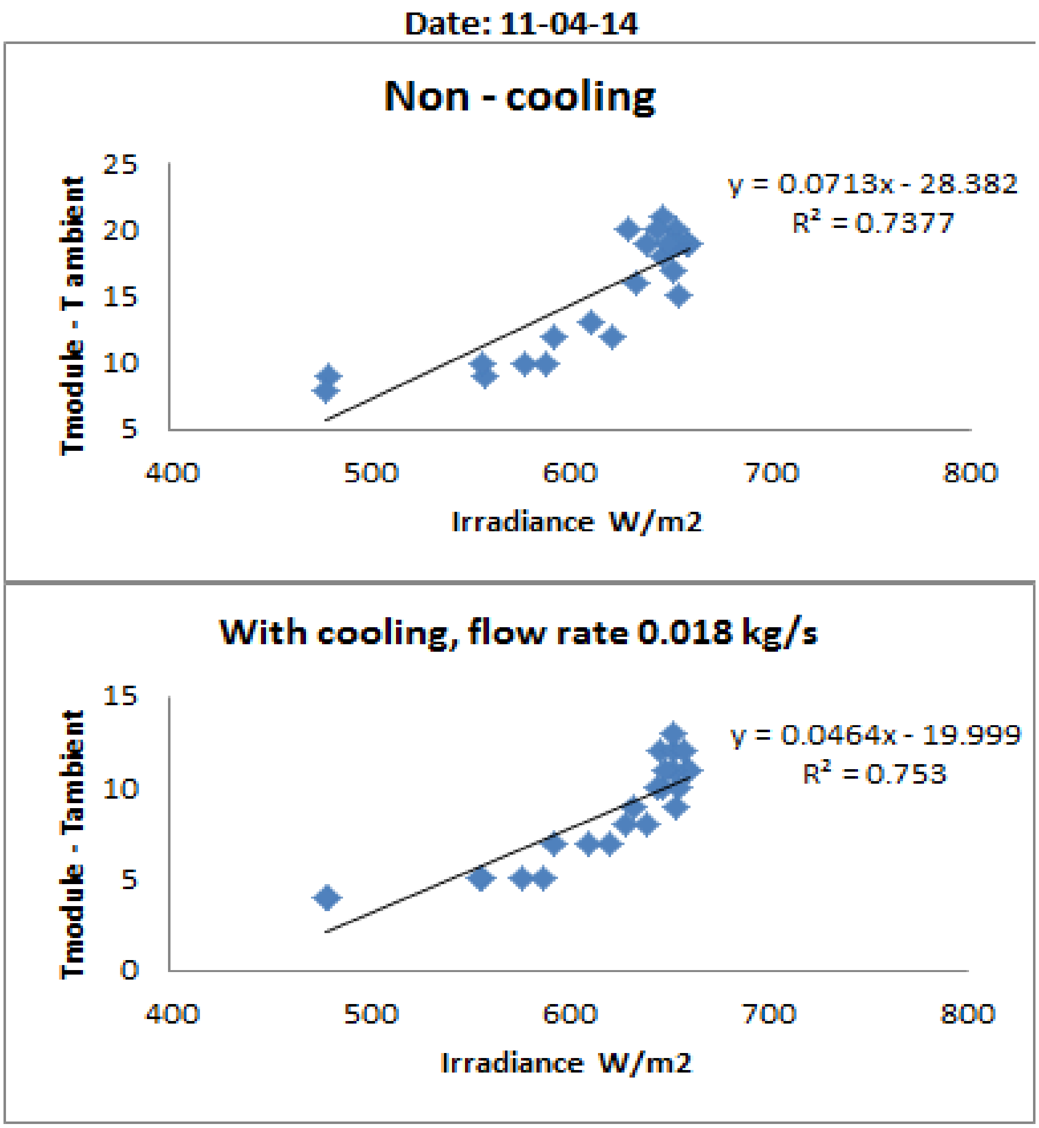

Fig 4.20: Test result of 11-04-14

Average wind speed = 1.02 m/s

Average ambient temperature = 31.63^{o}C

Correction factor = +1^{o}C

INOCT non-cooling,

T_{INOCT}= (0.0713*800-28.382) +20+1 = 49.66^{o}C

INOCT with cooling,

T_{INOCT} = 0.0464*800-19.999+20+1 = 38.12^{o}C

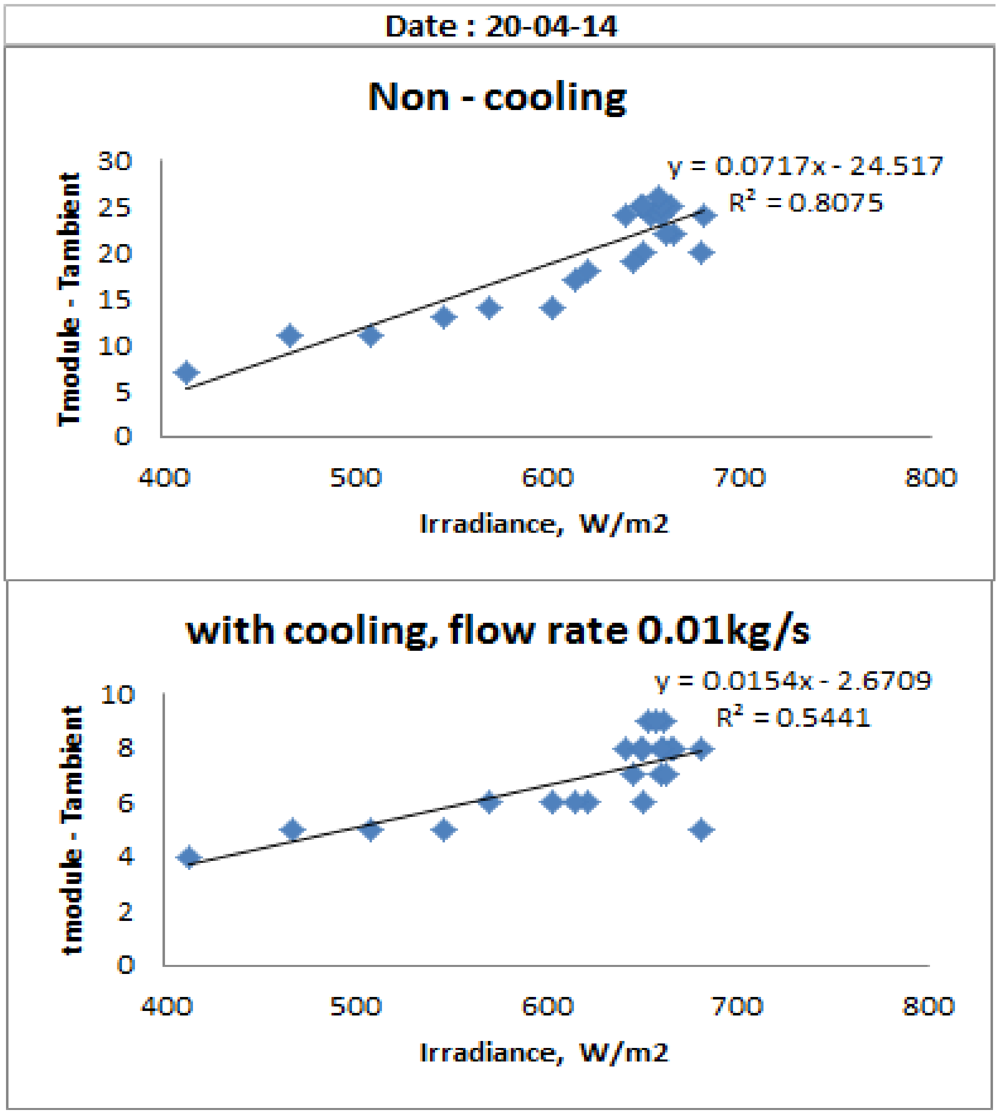

Fig 4.21: Test result of 20-04-14

Average wind speed = 1.15 m/s

Average ambient temperature = 29.2^{o}C

Correction factor = +1^{o}C

INOCT non-cooling,

T_{INOCT} = (0.0717*800-24.517) +20+1 = 53.84^{o}C

INOCT with cooling,

T_{INOCT} = 0.0154*800-2.6709+20+1 = 30.64^{o}C

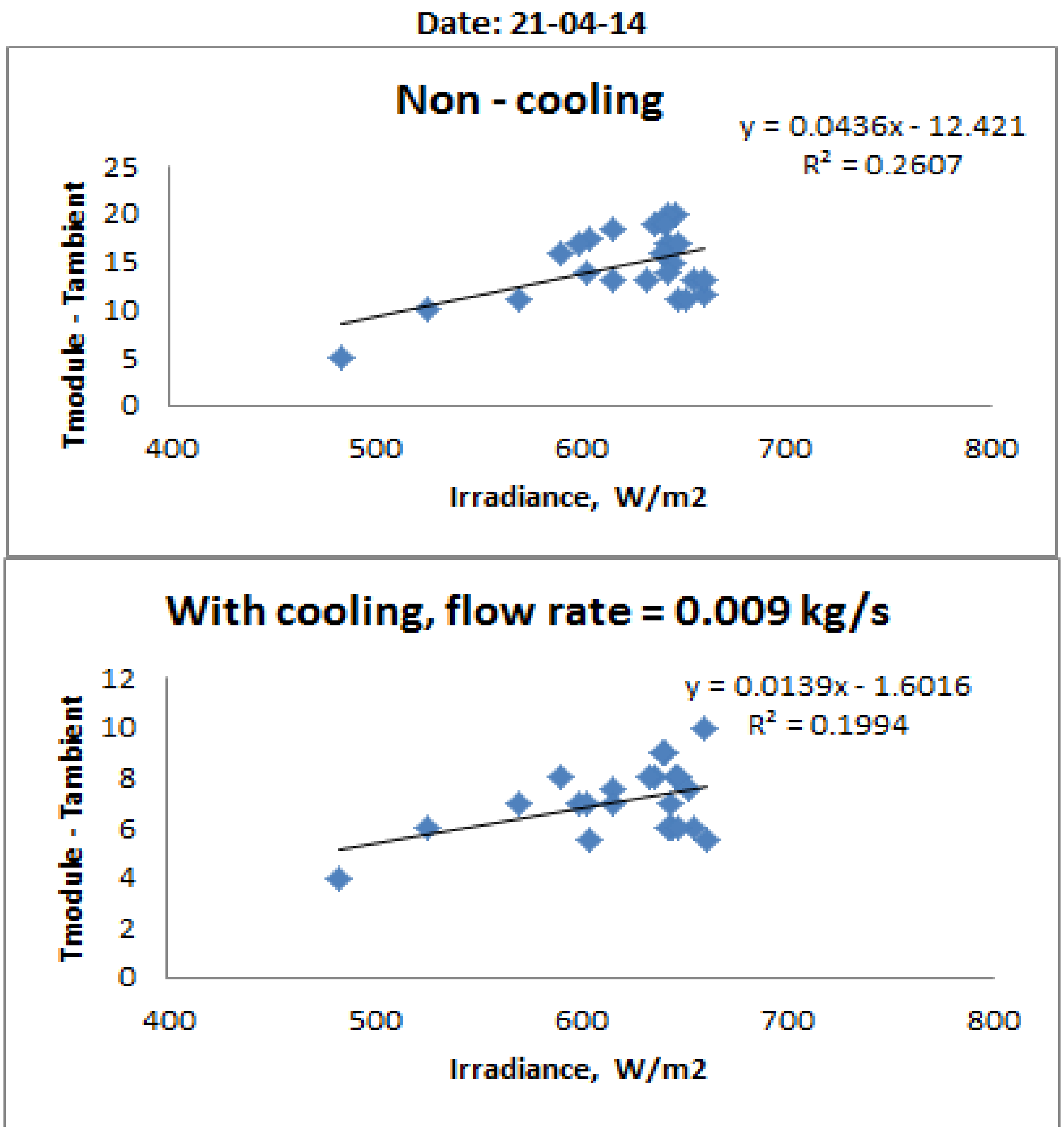

Fig 4.22: Test result of 21-04-14

Average wind speed = 0.858 m/s

Average ambient temperature = 33.77^{o}C

Correction factor = +1^{o}C

INOCT non-cooling,

T_{INOCT} = (0.0436*800-12.421) +20+1 = 43.5^{o}C

INOCT with cooling,

T_{INOCT} = 0.0139*800-1.6016+20+1 = 30.5^{o}C

Date: 24-04-14

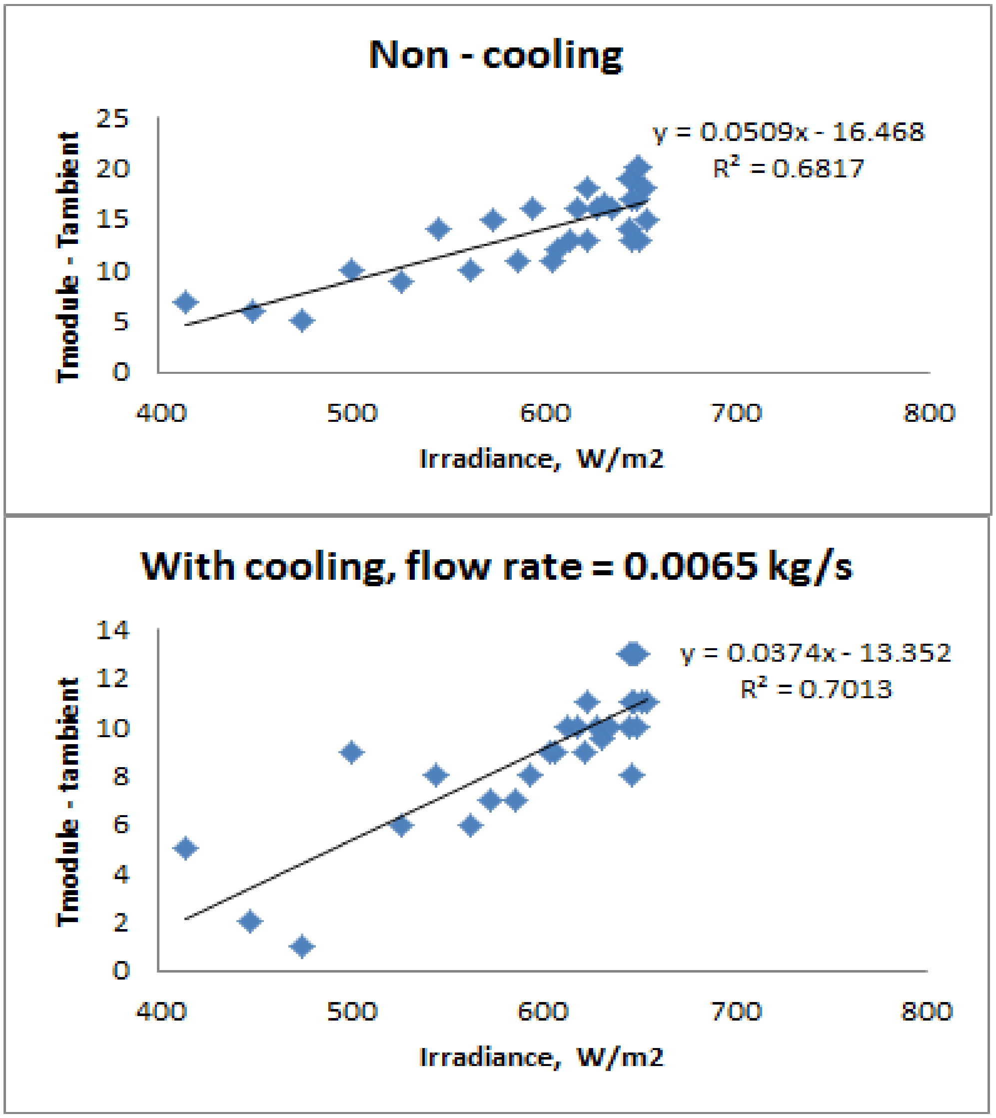

Fig 4.23: Test result of 24-04-14

Average wind speed = 1.09 m/s

Average ambient temperature = 31.61^{o}C

Correction factor = +1^{o}C

INOCT non-cooling,

T_{INOCT} = (0.0509*800-16.468) +20+1 = 45.3^{o}C

INOCT with cooling,

T_{INOCT} = 0.0374*800-13.352+20+1 = 37.6^{o}C

And result of all tests is summarized in table – 4.17 below

	Table – 4.17 : Field Test Results		
	Flow	**Operating Temp Non-cooled**	**Operating Temp with cooling**
	(kg/s)	(°C)	(°C)
8/4/2014	0.032	51	43
11/4/2014	0.018	49.7	38.12
12/4/2014	0.016	56.56	37
14/4/2014	0.014	48.8	30.83
15/4/2014	0.013	52.5	30.66
20/4/2014	0.01	53.84	30.64
21/4/2014	0.009	43.5	30.5
22/4/2014	0.008	48.3	33.33
23/4/2014	0.0072	44.5	33.4
24/4/2014	0.0065	45.3	37.6
25/04/2014	0.0055	47.7	34

Based on experimental data, the effect of flow rate on operating temperature of modified module is presented in figure 4.24 below:

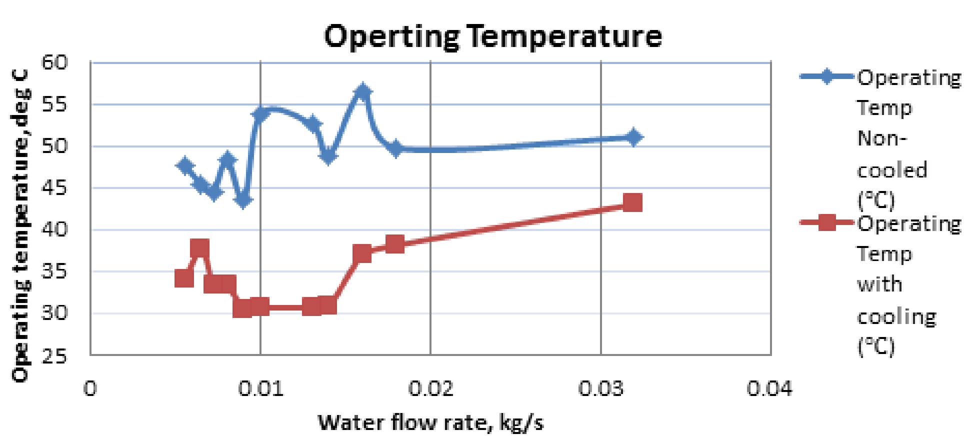

Fig 4.24: Test results at different flow rates

It is observed that non - cooling module is operating at much higher temperature than cooling one. Average operating temperature of non-cooled module is 49^{o}C.It is also observed that in the water flow range of 0.009 kg/s to 0.014 kg/s operating temperature of module with cooling unit is almost constant. For poly crystalline module modify with cooling unit water flow rate is optimized at 0.01 kg/s for best operating temperature of about 30.6^{o}C.

The calculated INOCT can consider as most representative of the module behavior. From available irradiance, ambient temperature and this INOCT value, module temperature can be calculated using equation below:

$$Tm = Ta + (INOCT – 20)\ E / 800 \qquad (4.11)$$

Where Tm is module temperature and E is solar irradiance.

From above analysis it is found that

- Under same metrological and mounting conditions:
  - Installed normal operating temperature of non- cooling case is much higher than cooling one
  - There is wide variation in operating temperature of non - cooling unit tested and operating temperature variation is less with cooling unit in specified range of flow rate of water.
  - To maintain minimum operating temperature, optimum flow rate of water through cooling unit is 0.01 kg/sec for designed system.
- Average installed nominal cell temperature of non-cooling module is found 49^{o}C and with cooling unit it is reduced to 30.6^{o}C at optimum water flow rate. And accordingly efficiency will increase by 9.2 % if efficiency loss conversion temperature coefficient is considered 0.45 %/^{o}C as provided by manufacturer.

4.4 DERIVATION OF COOLING COEFFICIENTS OF ELECTRICAL PARAMETERS

PV module efficiency is a complex function of micro – climatic parameters in outdoor environment and working temperature plays a crucial role in rating determination. Fall in PV efficiency with rise in cell temperature is well recognized. Operating temperature of PV panels influence by both electrical and environmental variables like ambient temperature, solar insolation, wind velocity, panel orientation and mounting structure. High yield solar radiation also enhances solar heat transfer and accumulation of heat gain on PV module increases PV cell temperature and decreases electrical efficiency.

From collected real time data cooling coefficients of electrical parameters of modified proposed module with respect to reference are derived by mathematical modelling and programming in MATLAB at optimized flow rate for minimum operating temperature.

Mathematical Modelling

Cooling coefficient is a measure of change in electrical parameter of modified module with respect to reference, if operating temperature of PV module is decreased by $1^{o}C$.

Cooling coefficient (x) of any parameter X with respect to temperature can be calculated by

$$x = \frac{1}{X}\frac{dX}{dT} \, x \, 100 \, \% \qquad (4.12)$$

Where, dX = change in consider electrical parameter

dT = decrease in temperature

Cooling coefficient of output voltage (α),

$$\alpha = \frac{1}{V}\frac{(V_m - V)}{(T_b - T_{bm})} x\ 100\ \% \tag{4.13}$$

Cooling coefficient of output current (β),

$$\beta = \frac{1}{I}\frac{(I_m - I)}{(T_b - T_{bm})} x\ 100\ \% \tag{4.14}$$

Cooling coefficient of output power (γ),

$$\gamma = \frac{1}{VI}\frac{(V_m I_m - VI)}{(T_b - T_{bm})} x\ 100\ \% \tag{4.15}$$

$$\text{Percentage increase in efficiency} = \frac{(V_m\, I_m - VI)}{VI} x\ 100\ \% \tag{4.16}$$

Numerous set of experiments conducted in a month of April’2014 during Sunny days in outdoor real time conditions. Each experimental day tests run for sufficient hours in clear sky. Cooling of module has been performed by circulating water at preset flow rate for the day. To keep operating temperature as low as possible water flow rate was optimized from the collected data and found that for flow rate about 0.01 kg/sec the installed nominal operating temperature (at 800 W/m^2 and 1m/s wind speed) was about 30.62^oC whereas of reference module is varying 43.5^oC to 54^oC as described in previous article.

For the days 14th, 15th, 20th and 21st April 2014, when the flow was set optimum to keep operating temperature minimum, possible effect of reduced operating temperature of commercial grade poly crystalline solar module upon electrical parameters is derived in terms of temperature coefficients. These temperature coefficients are cooling temperature coefficients which provide rate of change in electrical parameters with respect to decrease in operating temperature from reference module.

Cooling temperature coefficients of voltage (α), current (β) and power (γ) are illustrated in following graphs generated in MATLAB and shown in figures 4.25 – 4.28. Also flow rate in kg/sec, average solar insolation (G) in Watt/m^2, average ambient temperature (Ta) in ^oC and average wind velocity (v) in m/sec are mentioned on graph of particular day.

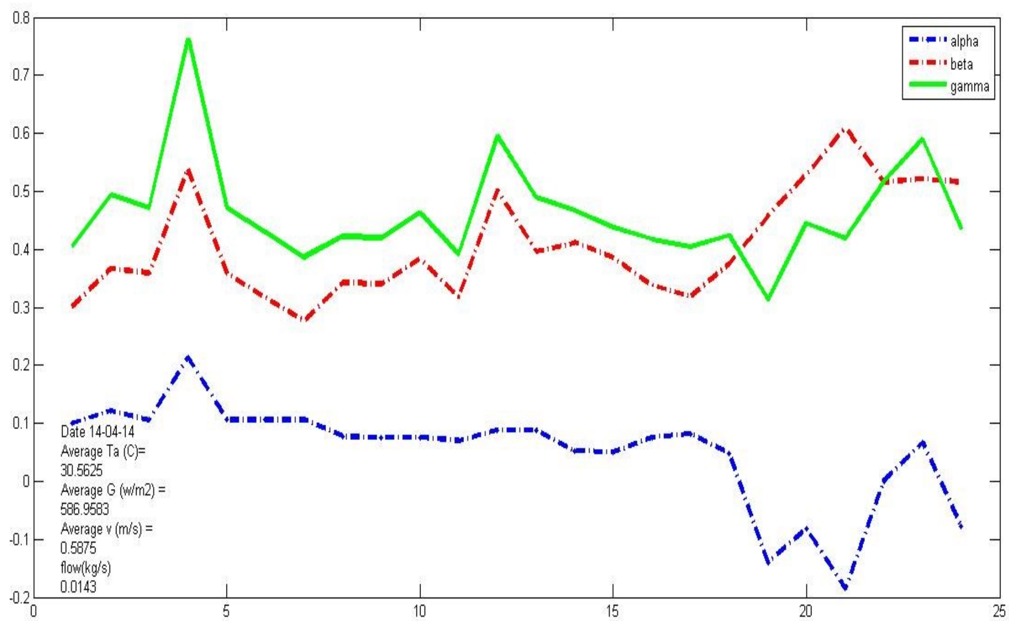

Fig 4.25: Cooling coefficient of current, voltage and power for 14-04-14

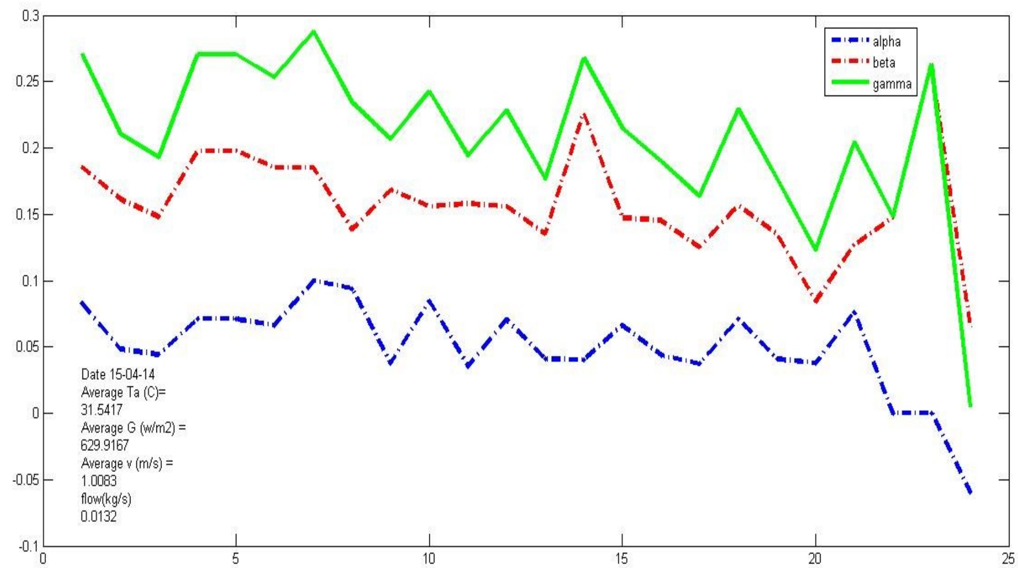

Fig 4.26: Cooling coefficient of current, voltage and power for 15-04-14

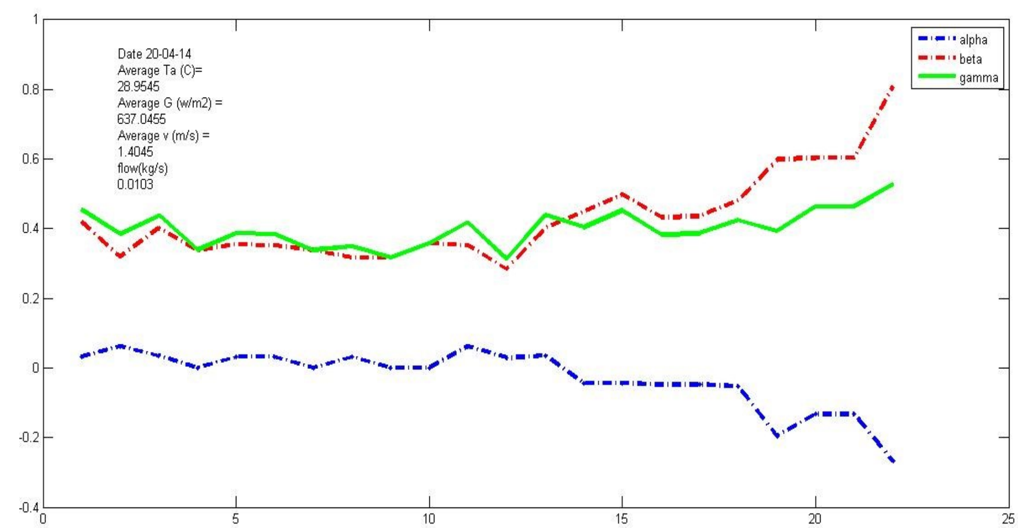

Fig 4.27: Cooling coefficient of current, voltage and power for 20-04-14

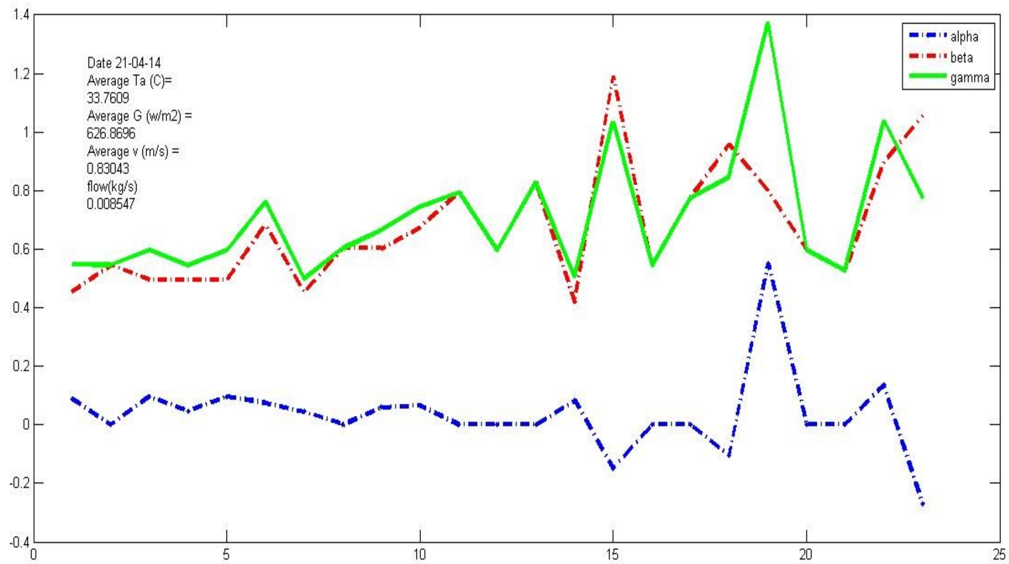

Fig 4.28: Cooling coefficient of current, voltage and power for 21-04-14

The results are also summarize in Table 4.18 below

Table 4.18: Test results of selected experiment days

S.No.	Date	Flow	Average						% increase in efficiency
			G	v	Ta	α	β	γ	
		Kg/s	W/m^2	m/s	^oC	%	%	%	%
1	14-04-14	0.014	587	0.6	30.56	0.05	0.40	0.46	5.37
2	15-04-15	0.013	626	1	31.64	0.054	0.162	0.218	2.84
3	20-04-14	0.01	637	1.4	29	-0.038	0.442	0.40	5.3
4	21-04-14	0.009	627	0.83	33.76	0.04	0.71	0.74	5.3

It is mentioned above that installed nominal operating temperature of modified module at optimized flow rate is 30.62^{o}C at standard reference conditions. But the operating temperature of modified module deviates from standard conditions as of reference module. Operating temperature of modified module also function of environmental parameters and the relation between operating temperatures with environmental parameter is also not linear.

From table 4.18 it can be observed that as average ambient conditions are different for each day of experiment and hence there is variation in cooling coefficients.

With solar insolation, ambient temperature and wind speed are also very important parameter to be considered.

There is significant percentage increase in efficiency of modified module. It is more when ambient temperature is higher and wind speed is lower.

4.5 CHAPTER SUMMARY

Cooling of PV module is significantly achieved. It has been shown that for each ^{o}C decrease in operating temperature, generated power increases. PV module efficiency is increased at satisfactorily value by extracting heat from PV module by proper circulation of water. For a developed optimized design of Solar PV with thermal unit, sea water desalination RO system is suggested as novel application where low temperature rise in water is an advantage. Cooling coefficients of electrical parameters has been calculated with respect to decrease working temperature only but it is also dependent on other environmental parameters.

CHAPTER 5

COST BENEFIT ANALYSIS

The chapter describes validity of project depends on the initial cost and amount generated. For the present work for economic analysis, spreadsheet application is used and economic analysis is performed in order to compare standard and modified system. A comparison is made in economic analysis for modification of solar PV system against the money saved because of more electricity generation.

Experiment carried out on module of

Capacity: 75 Wp

Size: 660 X 865 mm^2

Area: 0.57 m^2

Heat extraction tank size = (304.8 x 711.2 x 5) mm^3 x 2 Numbers

Volume of reservoir = 2.15 litres

Module area covered by heat extraction unit = 304.8 x 711.2 x 10^{-6} x 2 = 0.43 m^2

Percentage area covered with heat extraction unit = 0.43 x 100 / 0.57 = 76 %

In experiment 0.2 mm thickness copper sheets are used for water tanks /reservoir.

5.1 COPPER VS ALUMINIUM

Heat transfer from back surface of PV module to water through reservoir wall of

$$\text{Rate of heat Conduction} \propto \frac{Area\ x\ Temperature\ difference}{Thickness} \qquad (5.1)$$

$$H = -kA\frac{dT}{dx} \qquad (5.2)$$

For the same heat transfer,

$$\frac{k_{al}}{t_{al}} = \frac{k_{cu}}{t_{cu}} \tag{5.3}$$

Where,

k_{al} is thermal conductivity of Aluminium = 237 W/m.^{o}C

k_{al} is thermal conductivity of Copper = 401 W/m.^{o}C

t_{cu} is thickness of Copper sheet in mm = 0.2 mm

t_{al} is required thickness of Aluminium sheet in mm

$$t_{al} = \frac{k_{al}}{k_{cu}} \, x \, t_{cu} = \frac{237}{401} \, x \, 0.2 = 0.12 \text{ mm}$$

5.2 SCALE UP TO 1 MW

Project cost of standard Solar PV plant of 1 MW = Rs. 700 Lacs

Annual Power generation from 1 MW Plant is taken as = 15.5 Lac units

Power rate = Rs. 6.28 /unit

Cost of hybrid photo-voltaic and thermal system includes:

- Modification cost of the PV systems and all other equipment such as piping, insulation required completing the system
- The market discount rate, interest rate and depreciation, etc
- Operation, maintenance and parasitic costs
- Extra income from more power generation @ 5.3 %
- Economic analysis period is taken as 20 years, although early PV installations showed that PVs life is more than 25 years

Followings are not included in economic analysis:

- Cost of storage tank, which presents in an installation
- Savings from utilizing thermal output of hybrid system

5.3 COST ANALYSIS WITH ALUMINIUM WALL RESERVOIR

Selected Module:

Capacity: 250 Wp

Size: 1660 x 990 mm^2

Area: 1.64 m^2

Area cover with heat extraction unit = 76 % of module area

Number of Modules required for 1 MW = 4000

Total area to be covered with cooling unit = 1.64 x 4000 x 0.76 = 4985.6 m^2

Volume of Aluminium required = Area x wall thickness x 2 (sides) x 1.05 (5 % extra)

$$= 4985.6 \times (0.1 \times 10^{-3}) \times 2 \times 1.05 = 1.05\ m^3$$

Density of Aluminium = 2.7 gm/cm^3 = 2700 kg/m^3

Weight of Aluminium required = 1.05 x 2700 = 2835 kg

Average cost of Aluminium including fabrication cost = Rs. 150/kg

Investment = 2835 x 150 = **Rs. 4,25,250 = Rs. 4.25 Lacs**

Annual Extra units generation @ 5.3 % = 15.5 x 0.053 = 0.82 Lacs units

Income from extra unit generation @ Rs. 6.28 /unit = 0.82 x 6.28 = Rs 5.15 Lacs

Simple payback period = 4.25 / 5.15 = 0.825 years = 10 months

5.4 COST ANALYSIS WITH COPPER WALL RESERVOIR

5.4.1 Further optimization of thickness of Copper reservoir wall

Required area to be cooled by a reservoir tank is large (1.24 m^2) when compared to its depth (0.005 m). As water is distributed over large surface area, thickness of material used for tank walls can be optimized.

5.4.2 Cost Analysis

Selected Module:

Capacity: 250 Wp

Size: 1660 x 990 mm^2

Area: 1.64 m^2

Area cover with heat extraction unit = 76 % of module area

Number of Modules required for 1 MW = 4000

Total area to be covered with cooling unit = 1.64 x 4000 x 0.76 = 4985.6 m^2

Volume of Copper required = Area x wall thickness x 2 (sides) x 1.05 (5 % extra)

= 4985.6 x (0.05 x 10^{-3}) x 2 x 1.05 = 0.523 m^3

Density of Copper = 8.9 gm/cm^3 = 8900 kg/m^3

Weight of copper required = 0.523 x 8900 = 4655 kg

Average cost of copper including fabrication cost = Rs. 500/kg

Investment = 4655 x 500 = **Rs. 23,27,500 = Rs. 23.5 Lacs**

Annual Extra units generation @ 5.3 % = 15.5 x 0.053 = 0.82 Lacs units

Income from extra unit generation @ Rs. 6.28 /unit = 0.82 x 6.28 = Rs 5.15 Lacs

Simple payback period = 23.5 / 5.15 = 0.825 years = 4.95 years

5.5 SOLAR POWER GENERATION, FINANCIAL AND IRR CALCULATION

Over project life, time adjusted earning is represented by Internal Rate of Return (IRR).

IRR is a rate at that present value of cash inflows equates to present value of cash outflows of the project. There is a distinction in Equity IRR and Project IRR while calculating IRR. And the difference is in terms of cash inflows. Return to all project investors signified by Project IRR and Equity IRR signifies returns to shareholders of company after the debt has been paid off.

Solar processes are generally characterized by high first cost and low operating cost.

To compare proposed hybrid systems (Standard PV system with heat extraction unit of copper reservoir / Aluminium reservoir, which also giving thermal output) with standard one, a case of 1 MW power plant installed in Tamilnadu is considered.

An economic analysis has been carried out, Project IRR and Equity IRR has been calculated as shown in following table 5.1 ----

TABLE 5.1: SOLAR POWER GENERATION; FINANCIAL & IRR CALCULATIONS					
S. No.		**Units**	**Standard PV Power Plant**	**Hybrid Solar PV Power Plant with Copper wall water reservoir**	**Hybrid Solar PV Power Plant with Aluminium wall water reservoir**
1	Capacity	MW	1	1	1
2	Project Investment	Rs Lacs	700	723.5	704.25
3	Land cost	Rs Lacs	20	20	20
4	**Means of Finance NBFC / BANK**				
	Estimated Loan (70%)	Rs Lacs	490	490	490
	Investor's Equity (30%)	Rs Lacs	210	210	210
	Depreciable Assets. (Investment - Land Cost)	Rs Lacs	680	703.5	684.25
	Corporate Tax	%	32.45%	32.45%	32.45%
	MAT	%	20.01%	20.01%	20.01%
5	Interest on Loan	%	13.00%	13.00%	13.00%
6	Repayment Period	years	10	10	10
7	Moratorium Period	year	0.5	0.5	0.5
8	Number of Installments	Nos.	38	38	38
9	Mode of Payment		Quarterly	Quarterly	Quarterly
10	Depreciation Rate	%	80%	80%	80%
11	Depreciation in Ist year (100 %)	Rs Lacs	680	703.5	684.25
12	O & M Charges	%	1.40%	1.40%	1.40%
13	O&M Escalation	%	5.00%	5.00%	5.00%
14	Genration in 1st year (Units)	Units Lacs	15.5	16.32	16.32
15	Power Rate in 1st year	Rs.	6.28	6.28	6.28
16	REC Rate in 1st Year	Rs.	0	0	0
17	Power Rate Escalation	%	0	0	0
18	Reduction in power gen.y-o-y	%	1	1	1
19	Equity IRR	%	13.42	14.97	17.46
20	Project IRR	%	15.64	16.19	16.95

5.6 CHAPTER SUMMARY

A financial analysis has done to ascertain the economic viability of 1 MW solar power plant using modified PV module. When compared to standard 1 MW PV power plant Equity IRR and Project IRR has increased to 1.55 % and 0.55 % respectively if copper material is used for walls of heat extraction unit. And for same electrical generation if aluminium material is used in place of copper for walls of heat extraction unit Equity IRR and Project IRR has increased to 4.04 % and 1.31 % respectively.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

A system is developed as an upgrade of a conventional Solar PV Module with addition of heat extraction unit. Outdoor Performance testing setup is developed for continuous measurement and collection of performance data of conventional and modified PV module. Effect of irradiance, temperature and other environmental factors on performance is investigated and used to system design improvement and to make more cost effective. The following conclusions are drawn from the research:

1. Mathematical modelling is capable to calculate electrical production, thermal production, conversion electrical and thermal efficiencies, overall efficiency and coefficients as a function of inputs related to operating conditions and climatic parameters.
2. Result of statistical analysis of experimental data shows strong/moderate positive linear relationship of module power with solar radiation, ambient temperature, wind speed and water flow rate.
3. Accumulated heat in the photovoltaic laminate recovered as thermal energy of low temperature resulting PV Module electrical conversion efficiency improvement.
4. Collective thermal plus electrical power increased significantly. At some hours overall efficiency (electrical and thermal) of modified PV system is more than one order magnitude of conventional PV module Efficiency.
5. NOCT & Cooling Coefficient: Influence of mass flow rate of water on system behavior has been investigated for better electrical performance

and to meet PV cooling requirement mass flow rate of water is optimized.

6. On basis of the performance optimization commercial product has been designed.
7. Developed system has been scaled up to 1MW and cost benefit has been analyzed on annually basis and found economically feasible
8. For a developed optimized design of Solar PV with thermal unit, sea water desalination RO system is suggested as novel application where low temperature rise in water is an advantage.

Validity of hypothesis has been most clearly demonstrated in the successful testing of experimental modified collector. It can be said that as there is more electrical unit production, hybrid system have better chances to success and this also is strengthened by improvement in economic viability of the system especially for locations of higher available solar radiation and in application where low temperature water is required.

6.2 FUTURE SCOPE

- Study on extension of the life cycle of PV module as operating at low temperature
- Explore the more possibility for practical applications of low thermal energy
- Following major observations found experimentally are not in-line with theoretical consideration and prior art:-
  - Current is more temperature sensitive than voltage
  - Experimentally current is increasing while decreasing operating temperature
  - Not much variation in voltage with decreasing operating temperature

Therefore further micro analysis of environmental parameters and component of diffuse radiation in total radiation are suggested.

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APPENDIX - A

<u>Graph Plotting</u>

```
clc;
close all;
clear all;
[d text]=xlsread('Final_24-03-15.xlsx','9-4-14');
result=d;
g=result(:,20)';
v=result(:,21)';
starttime = datenum('1:05 PM');
endtime = datenum('3:25 PM');
x= linspace(starttime,endtime,7);
subplot(4,2,1);
plot(x,g,'-*');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Solar radiation(W/m^2)');
ylabel('Radiation(W/m^2)');
xlabel('Time--->');
subplot(4,2,3);
plot(x,v,'-*');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Wind speed(m/s)');
ylabel(' Wind speed (m/s)');
xlabel('Time--->');
Tb=result(:,7)';
Tmb=result(:,12)';
```

```
Ta=result(:,19)';
subplot(4,2,5);
plot(x,Tb,'-*',x,Tmb,'-+',x,Ta,'-o');
%plot(x,result(:,[7,12,19])','-*',x,result(:,[7,12,19])','-+',x,result(:,[7,12,19])','-.');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Temperature(C)');
hleg=legend('Tb','Tmb','Ta');
ylabel('Temperature (c)');
xlabel('Time--->');
vo=result(:,3)';
vm=result(:,8)';
subplot(4,2,4);
plot(x,vo,'-*',x,vm,'-+');
%plot(x,result(:,[3,8])','-*',x,result(:,[3,8])','-.');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Voltage(volts)');
hleg1=legend('V','Vm');
ylabel('Voltage');
xlabel('Time--->');
i=result(:,4)';
im=result(:,9)';
subplot(4,2,2);
plot(x,i,'-*',x,im,'-+');
%plot(x,result(:,[4,9])','-*',x,result(:,[4,9])','-.');
 grid on;
datetick('x','HH:MM AM','keepticks');
title('Current(Amp)');
```

```
hleg2=legend('I','Im');
ylabel('Current(A)');
xlabel('time--->');
p=result(:,5)';
pm=result(:,10)';
pth=result(:,16)';
subplot(4,2,6);
plot(x,p,'-*',x,pm,'-+',x,pth,'-o');
%plot(x,result(:,[5,10,16])','-*',x,result(:,[5,10,16])','-+',x,result(:,[5,10,16])','-.');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Power (Watts)');
hleg3=legend('P','Pm','Pth');
ylabel('Power(Watts)');
xlabel('Time--->');
eff_n=result(:,6)';
eff_nm=result(:,11)';
eff_nth=result(:,17)';
eff_ntotal=result(:,18)';
subplot(4,2,7);
plot(x,eff_n,'-*',x,eff_nm,'-+',x,eff_ntotal,'-o');
%plot(x,result(:,[6,11,18])','-*',x,result(:,[6,11,18])','-+',x,result(:,[6,11,18])','-.');
grid on;
datetick('x','HH:MM AM','keepticks');
title(' Efficiency (%)');
hleg4=legend('n','nm','ntotal');
ylabel('Efficiency');
xlabel('Time--->');
subplot(4,2,8);
```

```
plot(x,eff_n,'-*',x,eff_nm,'-+');
% plot(x,result(:,[6,11])','-*',x,result(:,[6,11])','-+');
grid on;
datetick('x','HH:MM AM','keepticks');
title('Electrical Efficiency (%)');
hleg5=legend('n','nm');
ylabel('Efficiency');
xlabel('Time--->');
m =[g;v;Tb;Tmb;Ta;eff_n;eff_nm;eff_nth;eff_ntotal;i;im;vo;vm;p;pm;pth];
average=mean(m,2)
```

CALCULATION

```
clc;
close all;
clear all;
[d text]=xlsread('Final.xlsx','1-4-14');
result=d;
g=result(:,20);
m=result(:,13);c=4187;a=0.57;
result(:,5)=result(:,3).*result(:,4);
output_power=result(:,5)
result(:,6)=((result(:,5)./g)*100)/a;
efficiency_n=result(:,6)
result(:,10)=result(:,8).*result(:,9);
electrical_oppower=result(:,10)
result(:,11)=((result(:,10)./g)*100)/a;
elec_efficiency=result(:,11)
result(:,16)=c*(result(:,15)-result(:,14)).*m;
thermalPower=result(:,16)
result(:,17)=((result(:,16)./g)*100)/a;
```

```
thermal_efficiency=result(:,17)
result(:,18)=elec_efficiency + thermal_efficiency;
ntotal=result(:,18)
result(:,22)=((elec_efficiency - efficiency_n)./efficiency_n)*100;
delta_n = result(:,22)
```

To calculate coefficients

```
clear all
clc;
f='TCC.xlsx';

% %%%%%%%%%%%%%%%%%%%%%%%%%for date 14-04-14
v=xlsread(f,1,'C2:C25');
vm=xlsread(f,1,'F2:F25');

I = xlsread(f,1,'D2:D25');
Im = xlsread(f,1,'G2:G25');

Tb=xlsread(f,1,'E2:E25');
Tbm=xlsread(f,1,'H2:H25');

Ta = xlsread(f,1,'J2:J25');
Tav = mean(Ta);

G = xlsread(f,1,'K2:K25');
Gav = mean(G);

vel = xlsread(f,1,'L2:L25');
Velav = mean(vel);
```

```
 Flow = xlsread(f,1,'I2');

a={'Date 14-04-14', 'Average Ta (C)=' num2str(Tav),'Average G (w/m2) = ' num2str(Gav),'Average v (m/s) =' num2str(Velav),'flow(kg/s)' num2str(Flow)};
alpha= ((vm-v)./(v.*(Tb-Tbm)))*100;
figure (1)
plot (alpha,'b-..','LineWidth',3);
hold on
beta  = ((Im-I)./(I.*(Tb-Tbm)))*100;

plot (beta,'r-.','LineWidth',3)
gaama = ((vm.*Im - v.*I)./((v.*I.*(Tb-Tbm))))*100;

plot (gaama,'g','LineWidth',3)

GTEXT(a);

% %%%%%%%%%%%%%%%%%%%%%%%%%%for date 15-04-14

v=xlsread(f,2,'C2:C25');
vm=xlsread(f,2,'F2:F25');

I = xlsread(f,2,'D2:D25');
Im = xlsread(f,2,'G2:G25');

Tb=xlsread(f,2,'E2:E25');
Tbm=xlsread(f,2,'H2:H25');

Ta = xlsread(f,2,'J2:J25');
```

```
Tav = mean(Ta);

G = xlsread(f,2,'K2:K25');
Gav = mean(G);

vel = xlsread(f,2,'L2:L25');
Velav = mean(vel);

Flow = xlsread(f,2,'I2');

b={'Date  15-04-14',  'Average  Ta  (C)='  num2str(Tav),'Average  G  (w/m2)  =  '
num2str(Gav),'Average v (m/s) =' num2str(Velav),'flow(kg/s)' num2str(Flow)};
alpha= ((vm-v)./(v.*(Tb-Tbm)))*100;
figure (2)
plot (alpha,'b-..','LineWidth',3);
hold on
beta  = ((Im-I)./(I.*(Tb-Tbm)))*100;

plot (beta,'r-.','LineWidth',3)
gaama = ((vm.*Im - v.*I)./((v.*I.*(Tb-Tbm))))*100;

plot (gaama,'g','LineWidth',3)

GTEXT(b);
 %%%%%%%%%%%%%%% for date - 20-04-14
 v=xlsread(f,3,'C2:C25');
vm=xlsread(f,3,'F2:F25');

I = xlsread(f,3,'D2:D25');
```

```
Im = xlsread(f,3,'G2:G25');

Tb=xlsread(f,3,'E2:E25');
Tbm=xlsread(f,3,'H2:H25');

Ta = xlsread(f,3,'J2:J25');
Tav = mean(Ta);

G = xlsread(f,3,'K2:K25');
Gav = mean(G);

vel = xlsread(f,3,'L2:L25');
Velav = mean(vel);

Flow = xlsread(f,3,'I2');

c={'Date 20-04-14', 'Average Ta (C)=' num2str(Tav),'Average G (w/m2) = '
num2str(Gav),'Average v (m/s) =' num2str(Velav),'flow(kg/s)' num2str(Flow)};
alpha= ((vm-v)./(v.*(Tb-Tbm)))*100;
figure (3)
plot (alpha,'b-..','LineWidth',3);
hold on
beta  = ((Im-I)./(I.*(Tb-Tbm)))*100;

plot (beta,'r-.','LineWidth',3)
gaama = ((vm.*Im - v.*I)./((v.*I.*(Tb-Tbm))))*100;
 plot (gaama,'g','LineWidth',3)
 GTEXT(c);
 %%%%%%%%%%%for date 21-04-14
```

```
 v=xlsread(f,4,'C2:C25');
vm=xlsread(f,4,'F2:F25');
 I = xlsread(f,4,'D2:D25');
Im = xlsread(f,4,'G2:G25');
 Tb=xlsread(f,4,'E2:E25');
Tbm=xlsread(f,4,'H2:H25');

Ta = xlsread(f,4,'J2:J25');
Tav = mean(Ta);

G = xlsread(f,4,'K2:K25');
Gav = mean(G);
 vel = xlsread(f,4,'L2:L25');
Velav = mean(vel);
 Flow = xlsread(f,4,'I2');
 d={'Date 21-04-14', 'Average Ta (C)=' num2str(Tav),'Average G (w/m2) = '
num2str(Gav),'Average v (m/s) =' num2str(Velav),'flow(kg/s)' num2str(Flow)};
alpha= ((vm-v)./(v.*(Tb-Tbm)))*100;
figure (4)
plot (alpha,'b-..','LineWidth',3);
hold on
beta  = ((Im-I)./(I.*(Tb-Tbm)))*100;

plot (beta,'r-.','LineWidth',3)
gaama = ((vm.*Im - v.*I)./((v.*I.*(Tb-Tbm))))*100;
 plot (gaama,'g','LineWidth',3)
GTEXT(d);
```

PROFILE OF THE AUTHOR

Madhu Sharma is Doctoral student with University of Petroleum and Energy Studies (UPES), Dehradun, India. She has done her B.E. (Hons.) in Electrical Engineering from Government Engineering College, Jabalpur and M.Tech. in Energy Management from School of Energy and Environment (SEES), Devi Ahilya University, Indore.

She has more than 18 years of experience (3 years of Industrial experience and 15 years of academic experience) in the areas of electrical, power , renewable energy, energy efficiency and energy management.

She is presently working with University of Petroleum and Energy Studies as faculty – Assistant Professor (selection Grade).

She has deep interest in the Renewable Energy, especially in solar energy sector and keen to work towards the fullest potential that renewable has to offer safeguard the energy needs of India.

Ph.D PUBLICATIONS

1. Madhu Sharma, Kamal Bansal, Dharam Buddhi, "Real Time Outdoor Electrical Characteristics of PV Module With Passive Heat Extraction Unit, published in International Journal of Applied Engineering Research, Volume 10, Number 4 (2015)
2. Madhu Sharma, Kamal Bansal, Dharam Buddhi, "Real time Data Acquisition system for Performance Analysis of modified PV module and derivation of cooling coefficients of Electrical parameters", Procedia Computer Science, Elsevier, DOI - 10.1016/j.procs.2015.04.139, Volume 48, 2015, pages 582 – 588, http://www.sciencedirect.com/science/article/pii/S1877050915006481
3. Madhu Sharma, Kamal Bansal, Dharam Buddhi, "Operating temperature of PV module modified with surface cooling unit in real time condition", presented in IEEE 6th India International Conference on Power Electronics (IICPE – 2014), 8th – 10th DEC"2014 organized by NIT, Kurukshetra.