IMPROVEMENT OF HYBRID PHOTOVOLTAIC/THERMAL SOLAR ENERGY SYSTEMS.

A THESIS SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND CHEMICAL ENGINEERING (MCE), ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT).

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DECLARATION

This is to clarify that the work in this thesis is an outcome of the analysis, measurement and research carried out by the author themselves under the watchful supervision of Prof. Dr. Md. Abdur Razzaq Akhanda.

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We seek excuse for any errors that might have in this report although we have tried our best.

ABSTRACT

Hybrid photovoltaic thermal (PV/T or PVT) solar system combines a simultaneous conversion of the absorbed solar radiation into electricity and heat. In this paper the design of an experimental PVT dual system with modifications in the air channel using Sinusoidal, Triangular and Rectangular corrugated ribs are presented. All collectors are of same capacity, projected area, water heat extraction method and average depth. Natural convection is applied instead of forced convection to increase the system net electrical output and thereby the overall system efficiency. This system is simple and suitable for building integration, providing hot water or air depending on the season and the thermal needs of the building. Significant results have been obtained with this stated modification comparing with the previous models.

Performance Study was carried out in the months of July to August , 2013 at IUT campus. We performed our study on a bright sunny morning with a square setup. We found that on an intense sunny day the maximum temperature for water was 42°C and the average efficiency was 48%.

Keywords

Hybrid PVT solar system, photovoltaic thermal collector, solar energy, thin metallic sheet (TMS), painted black ribs.

Nomenclature

- A_s - aperture area, m^2
- G – incoming solar radiation, W/m^2
- m – mass flow rate, kg/s
- T_{pv} – PV module temperature, °C
- T_i – input fluid temperature, °C
- T_o – output fluid temperature, °C
- ΔT_w – temperature difference of water,(T_o-T_i), °C
- ΔT – temperature difference, (T_i-T_{amb}), °C
- η_{th} – thermal efficiency
- I_m – current at maximum load, amp
- η_{el} – electrical efficiency
- C_p – specific heat at constant pressure, J/kg.K
- K – thermal conductivity, W/m.K
- Q_{ab} – heat energy absorbed, W/m^2
- V_m – voltage at maximum load, Volt

Contents

Page No.

Chapter 1 INTRODUCTION

Chapter 2 LITERATURE REVIEW

Chapter 3 EXPERIMENTAL SETUP & TEST PROCEDURE

Page No.

Chapter 4 TEST RESULT FOR SETUP

Chapter 5 CONCLUSION

CHAPTER 1

INTRODUCTION

1.1 Photovoltaic/Thermal Solar System

Different Photovoltaic cell converts 5-15% of the incoming solar radiation into electricity, with the greater percentage converted into heat. The solar radiation converted into heat increases the temperature of the PV modules, resulting in the drop of their electrical efficiency. This undesirable effect can be partially avoided by applying a suitable heat extraction mode with a fluid circulation, keeping the electrical efficiency at a satisfactory level. Furthermore, this extracted heat can be utilized for heating air and/or water. For this purpose Hybrid photovoltaic/thermal solar systems can be introduced. The Hybrid PVT solar system consists of PV modules coupled to water and/or air heat extraction devices which convert the absorbed solar radiation into electricity and heat. This system is simple and suitable for building integration for providing hot water/air depending on the season and the thermal needs of the buildings.

Previous works on PVT solar systems includes the development of hybrid photovoltaic-thermal (PVT) collector technology using water as the coolant [1] (Saitoh et al., 2003). Through good thermal contact between the thermal absorber and the PV module, both the electrical efficiency and the thermal efficiency can be raised. Fin performance of the thermal absorber is one crucial factor in achieving a high overall energy yield. Design and performance improvements of hybrid PVT systems with water or air as heat removal fluid have been carried out at the University of Patras including modifications that contribute to the decrease of PV module temperature and to improve the total energy output (electrical and thermal) of the PVT systems. Design concepts, prototypes and test results for water and air-cooled PVT systems with and without additional glass cover are presented in [2] Tripanagnostopoulos et al., 2002. Three alternative modes of placing the water heat exchanger inside the air channel were tested [3] (Tripanagnostopoulos et al., 2007), with the water heat exchanger at PV rear surface giving the best results for water heat extraction.

1.2 Hybrid Photovoltaic/Thermal Solar Energy System

Hybrid PVT solar systems consists of PV modules coupled to water and/or air heat extraction devices which converts the absorbed solar radiation into electricity and heat. The PV modules that are combined with thermal units, where circulating air or water of lower temperature than that of PV modules is heated constitute the Hybrid PVT solar systems and provide electrical and thermal energy, increasing therefore the total energy output from PV modules.

The improved PVT systems have aesthetic and energy advantages and could be used instead of separate installation of plain PV modules and thermal collectors. As the main priority is to produce electricity so the operating temperature should be within certain range to keep the electrical efficiency at sufficient level.

There are three basic types of hybrid PVT systems:

- PVT/air system, where air is used for heat extraction from PV panel rear surface, thus electricity and hot air is output.
- PVT/water system, where water is used for heat extraction from PV panel rear surface, thus electricity and hot air is output.
- PVT/dual (water & air) system, where both air and water is used for heat extraction, thus the outputs are both water and air with electricity.

Fig. 1.1 shows a schematic diagram of hybrid PVT system.

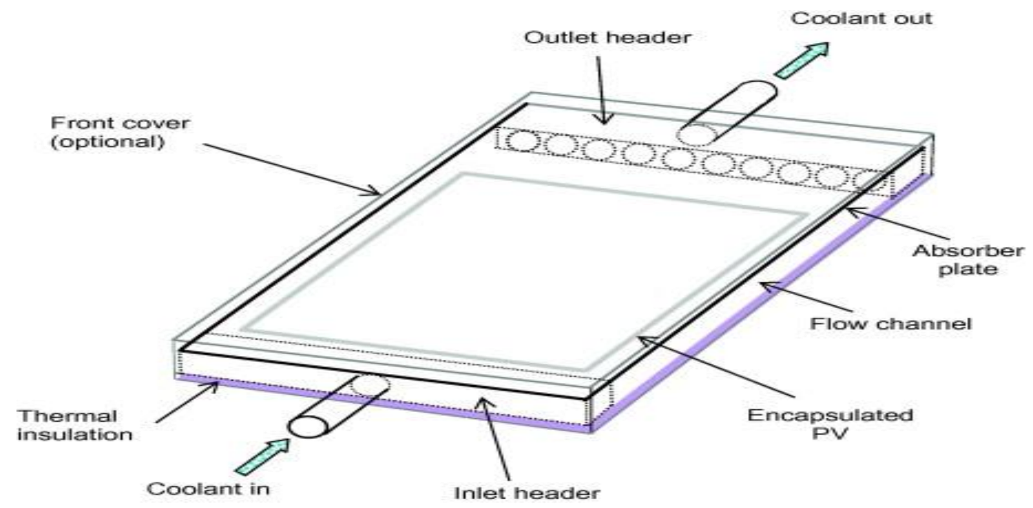


Fig 1.1: Schematic diagram of a hybrid PVT system.

The PVT solar system can be effectively used in the *domestic and the industrial sectors.* Considering water as heat removal fluid, it can be used in residential buildings, hotels, hospitals etc. Considering air for heat extraction, it is used for space heating, natural ventilation etc. The system can be suitable for building integration for providing hot water/air depending on the season and the thermal needs of the buildings.

CHAPTER 2

LITERATURE REVIEW

2.1. Basic concepts

A solar cell has its threshold photon energy corresponding to the particular energy band gap below which electricity conversion does not take place. Photons of longer wavelength do not generate electron–hole pairs but only dissipate their energy as heat in the cell. A common PV module converts 4–17% of the incoming solar radiation into electricity, depending on the type of solar cells in use and the working conditions. In other words, more than 50% of the incident solar energy is converted as heat (after deducting the reflected portion). This may lead to extreme cell working temperature as much as 50 °C above the ambient environment.

There can be two undesirable consequences:

(i) A drop in cell efficiency (typically 0.4% per °C rise for c-Si cells) and
(ii) A permanent structural damage of the module if the thermal stress remains for prolonged period.

Numerous correlations expressing cell temperature and efficiency as functions of the pertinent weather variables and cell working conditions are summarized by Skoplaki and Palyvos. By cooling the solar cells with a fluid stream like air or water, the electricity yield can be improved. But conceptually the better design is to re-use the heat energy extracted by the coolant. Then the energy yield per unit area of panel (or facade in the case of building-integrated installation) can be improved. These are the incentives leading to the evolvement of PVT hybrid solar technology.

2.2 Literature on PVT systems

Theoretical and experimental studies of PVT were documented as early as in mid 1970s. Wolf, Florschuetz , Kern and Russell and Hendrie on different occasions presented the key concept and the data with the use of either water or air as the coolant (i.e. the PVT/a and PVT/w systems in abbreviation). The technical validity was soon concluded. The research works that followed were mainly on flat-plate collectors, like the contributions from Raghuraman and Cox and, Braunstein and Kornfeld and Lalovic in the 1980s. The works of O'leary and Clements, Mbewe et al, Al-Baali and Hamdy et al included performance analysis on light concentrating PVT systems.

Bergene and Lovvik proposed a detailed physical model of a flat-plate PVT/water collector system for performance evaluation. The fin-width to tube–diameter ratio was investigated and the total efficiency was found in the range of 60–80%. As for thermosyphon systems, Agarwal and Garg showed that the thermal efficiency depends on the packing factor, but this is not the case for cell efficiency; the quantity of water in the storage tank also has an effect. Their study was extended to acquire experimental data on a flat-plate PVT/water collector system equipped with simple parabolic reflectors.
With the use of modified Hottel–Whillier model, de Vries investigated the steady–state long-term performance of various PVT collector designs in Netherland. The single-covered design was found better than the uncovered design (of which the thermal efficiency is unfavorable) or the double covered design (of which the cell efficiency is unfavorable).

In the above studies of flat-plate collectors, the calculated thermal efficiency of PVT/liquid systems are generally in the range of 45–70% for unglazed to glazed panel designs. For PVT/air systems, the thermal efficiencies can be up to 55% for optimized collector design.

The increase in PVT research in the 1990s apparently had been a response to the global environmental deterioration and the growing interest of the construction industry towards the building-integrated-photovoltaic (BiPV) options. PVT collectors provide architectural uniformity at the building facade and are aesthetically better than the two separated arrays of PV and solar thermal collectors being placed side by side. Alternative cooling features of the BiPV systems have been examined by different research teams, such as Clarke et al, Moshfegh and Sandberg, and Brinkworth et al. Hollick reported the improved overall efficiency when solar cells were added onto the solar thermal metallic cladding panels.

As for concentrator-type (c-PVT) systems, Akbarzadeh and Wadowski made suggestions on a heat-pipe-based coolant design which is a linear, trough-like system. Each cell is mounted vertically at the end of a flattened copper pipe with a finned condenser area. The system is designed for 20× concentration, and the cell temperature was reported not exceeding 46 °C on a sunny day, as opposed to 84 °C in the same conditions but without coolant flow. Luque et al successfully developed the EUCLIDES prototype – a concentrating array using reflecting optics and one-axis tracking. They also discussed the temperature distribution at a solar cell under concentration with inhomogeneous illumination, when the cell is electrically isolated from the heat sink.

On the other hand, combining PVT and solar-assisted heat pump (SAHP) technology has been seen as an alternative approach for achieving higher hot water supply temperature and better PV cooling. This involves the direct coupling of a PVT panel (designed for direct expansion of refrigerant) to a heat pump system. In this arrangement, liquid refrigerant vaporizes at the tubing underneath the flat-plate collector, which is now the PVT evaporator. By means of the Rankine refrigeration cycle operation, solar energy is absorbed at the PVT evaporator that operates at a lower temperature than the ambient environment, and later on released at the water-cooled condenser at a higher temperature.

Cell efficiency is then higher than the standard operating efficiency. The coefficient of performance (COP) of the heat pump is also improved because of the higher evaporating temperature than the air-source heat pump. Based on this working principle, Ito et al. and constructed a PVT–SAHP system with pc-Si aluminum roll-bond panels. The experimental results indicated that the COP of the heat pump is able to reach 6.0, and with hot water supplying to the condenser at 40 °C. It was also found that the presence of solar cells affects little the thermal performance of the SAHP. But the complication in control can be a concern.

Generally speaking, the R&D efforts on the PVT collector systems in the first 25 years or so had been on improving the cost-performance ratio as compared to the solar thermal and PV systems working side by side. For real-building project applications, the PVT/air systems were more readily adopted in the European and North American markets though the higher efficiency of the PVT/water system has been confirmed. Notwithstanding this advantage, solar houses that carried PVT/water panels were once sold commercially in Japan in late 1990s but the construction work was soon stopped because of the lack of market demand to support its profit making. The contemporary issues related to the PVT technology, including the marketing potentials, were summarized in the expert reports of the working teams commissioned by the Swiss Federal Office and the IEA (International Energy Agency). An overview of the applications and development directions was also presented in Bazilian et al.

CHAPTER 3

EXPERIMENTAL SETUP & TEST PROCEDURE

3.1 Design aspects of the experimental setup

Design Concepts:

- The PVT system can effectively operate at locations in low latitudes where favourable weather conditions exists, or marginally in medium latitudes to avoid freezing.
- Water circulation and the heat extraction can be done by flowing water through pipes in contact with a flat sheet placed in thermal contact with the PV module rear surface.
- Usually PV panels are constructed with :

  Crystalline-Silicon (c-Si)

  Poly-crystalline Silicon (pc-Si)

  Amorphous-Silicon (a-Si)

- The ratio of the additional cost per PV module area is different and almost double for a-Si compared to c-Si or pc-Si PV modules. So for cost effectiveness pc-Si has been selected for this project.

Components of the setup:

- Solar Photovoltaic (pc-Si) panel : 50 Watt,(839 × 537 × 50)mm
- Copper Tube (½″ diameter)
- Copper Pipe (1½″ diameter)
- Insulating materials (Glass wool)
- Wooden box

3.2 Schematic Diagram of the setup

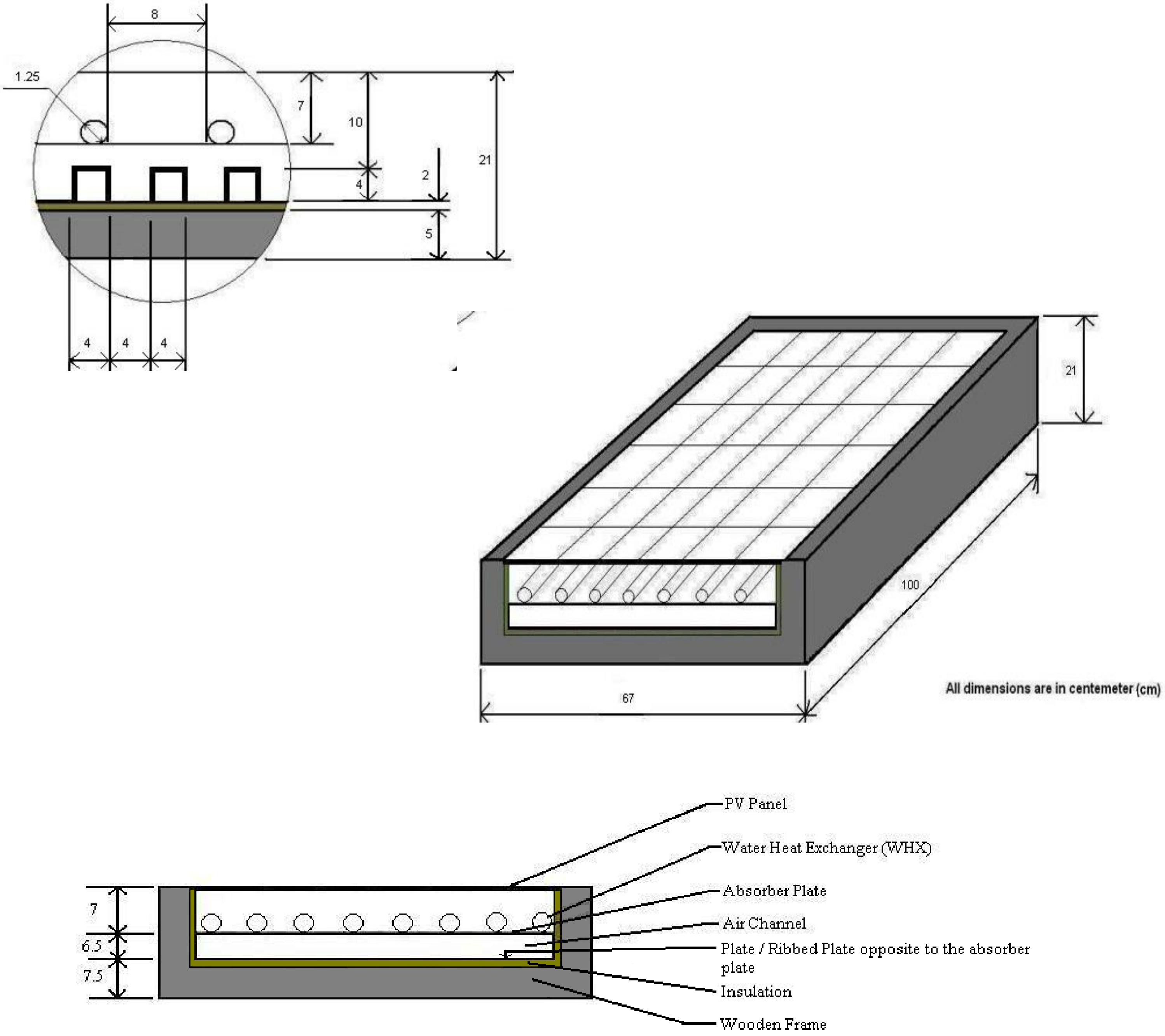


Fig 3.1: Schematic diagram of the setup with flat plate

3.3 Figure of the setup

Fig 3.2: Setup figure

Fig 3.3: Internal constructional view

3.4 Performance test: Related terminologies

- For the performance test of the Hybrid PVT system the three systems are to be tested simultaneously at outdoors under sunny weather condition.

- The following measurements are to be recorded for calculating thermal efficiency:
    - Input fluid temperature (T_i)
    - Output fluid temperature (T_o)
    - Water Heat Exchanger Temperature (T_{WHE})
    - PV module temperature (T_{PV})
    - Incoming solar radiation on PV module (G)
    - Mass flow rate of fluid (m)
    - Aperture area (A_a)

- The following measurements are to be recorded for calculating electrical efficiency:
    - Output Current (I_m)
    - Output Voltage (V_m)

3.5 Related equations

The following calculations are to be done:

- Thermal efficiency (η_{th})

$$\eta_{th} = mC_p(T_o – T_i) / A_aG$$

- Temperature difference , $\Delta T = T_i – T_o$

- Electrical efficiency, (η_{el})

$$\eta_{el} = I_mV_m / A_aG$$

3.6 Comparative study

- To compare the performances between the three experimental setups the results from the calculations are to be plotted in graphs.

- For the thermal efficiency comparison η_{th} vs $\Delta T/G$ graph is to be plotted.

- For the electrical efficiency comparison η_{el} vs PV Temperature (T_{PV}) graph is to be plotted.

CHAPTER 4

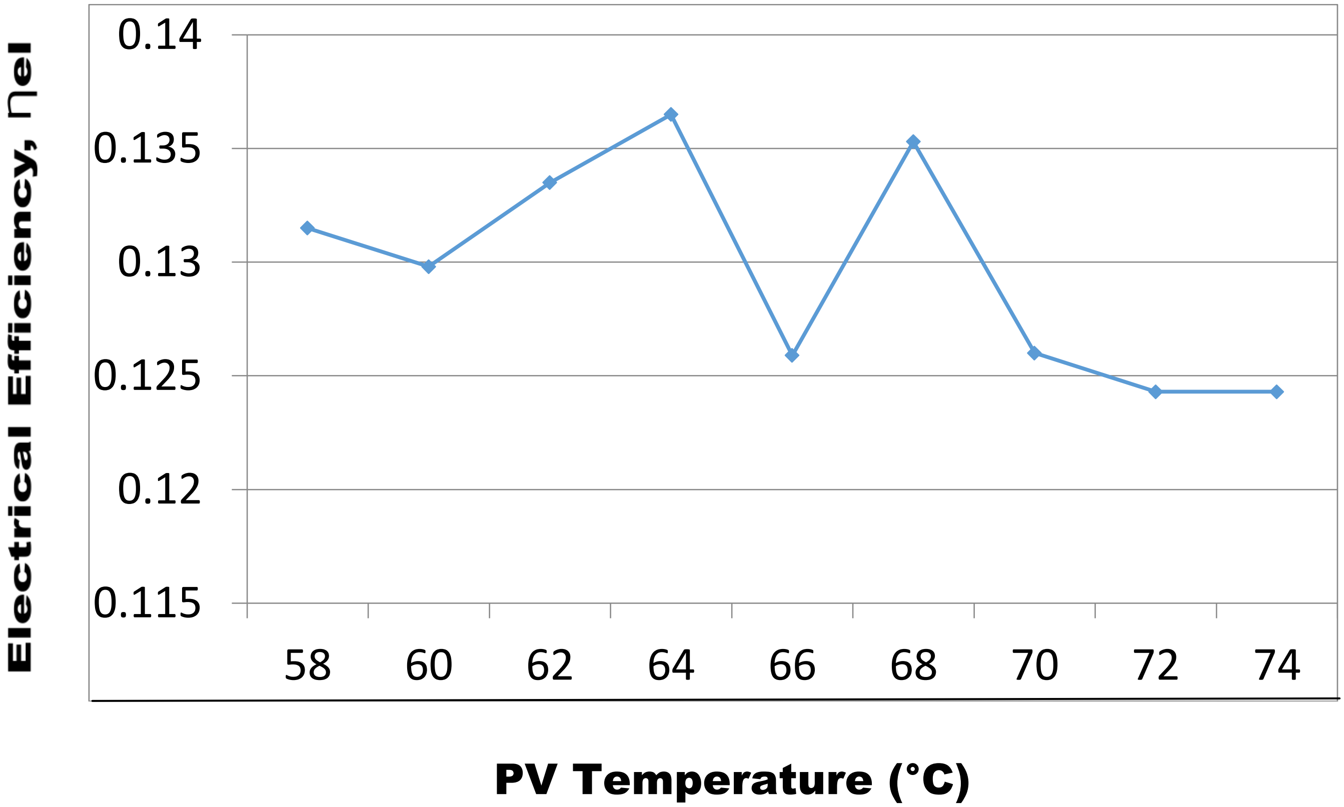
TEST RESULT FOR SETUP

4.1 Table: Data for Setup

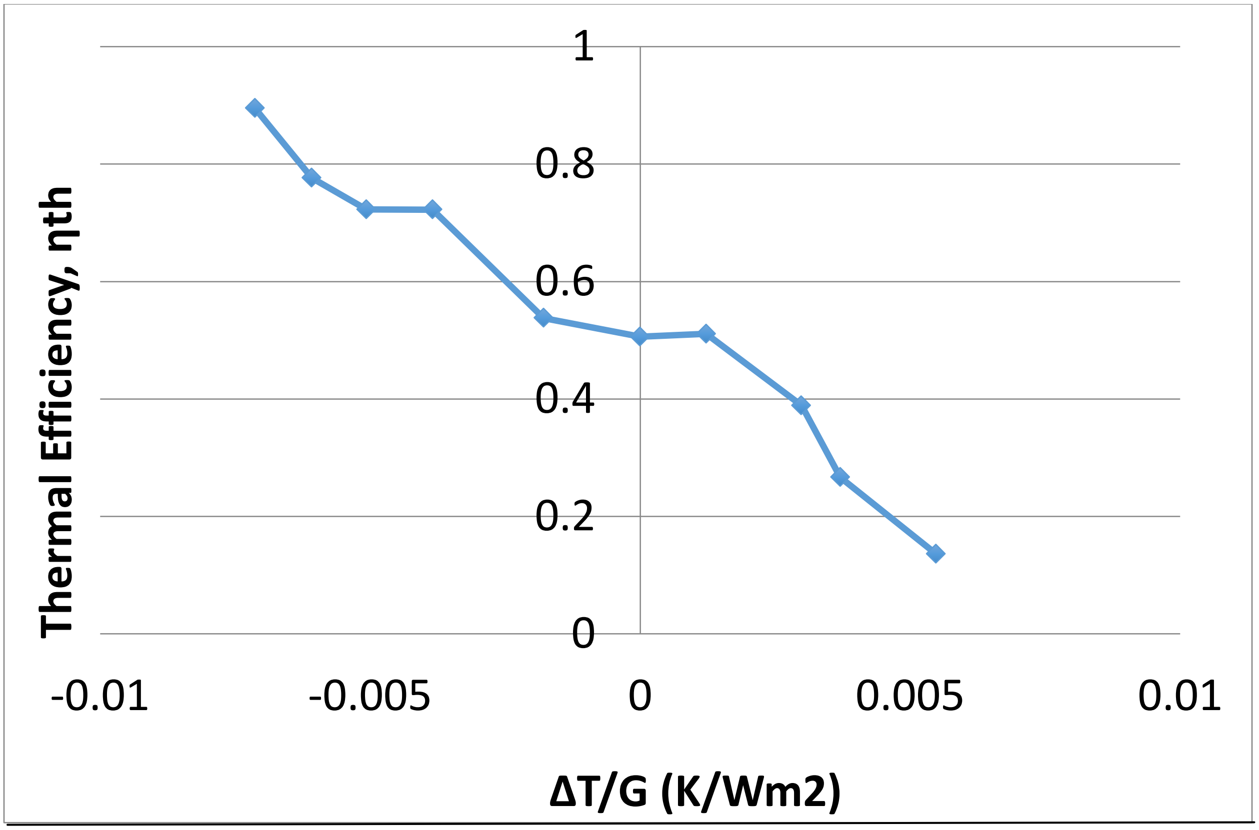
G (W/m^2)	T_o (˚C)	T_i (˚C)	T_{pv} (˚C)	T_{whx} (˚C)	m (kg/s)	V_m (Volt)	I_m (Amp)	ΔT/G	η_{th}	η_{el}
982	48	30.5	68	50	0.0054	19.7	2.95	-0.00713	0.895173	0.131512
938	45	31.5	65	49	0.0058	18.9	2.9	-0.00608	0.776507	0.129851
888	44	32.5	63	48.6	0.006	18.6	2.87	-0.00507	0.722808	0.133589
911	45.5	33.9	62	49.5	0.0061	19.3	2.9	-0.00384	0.72253	0.136529
952	44	35.4	59.4	48.5	0.0064	18.8	2.87	-0.00179	0.537809	0.125948
897	45	37	62	48.6	0.0061	18.9	2.89	0	0.506074	0.135318
980	46	38.2	63.5	48	0.0069	19.1	2.91	0.001224	0.510863	0.126034
971	45.5	39.7	64	48	0.007	19	2.86	0.002987	0.38895	0.124362
944	45	40.9	63.2	47.7	0.0066	18.8	2.81	0.003708	0.266651	0.12436

4.2 Test Result for Setup

- **Electrical efficiency Vs. PV temperature**



- **Thermal efficiency Vs. ΔT/G**



CHAPTER 5

CONCLUSION

5.1 Discussion

- Water and air temperatures increase with increasing of PV panel temperature and reach a maximum value at a maximum PV temperature around noon. All temperature then decrease slowly with ambient temperature.

- The energy absorbed in the system from 8 A.M. to 12 P.M. is higher than that absorbed in the afternoon for all systems.

- Thermal efficiency is maximum when water outlet temperature is maximum.

- Electrical efficiency will reduce with the increase in the PV panel temperature.

5.2 Limitations

Following are the limitations of our experiment:

- For proper experimentation the weather condition is important.
- The solar radiation was not constant and there were considerable variations during the experimental period.
- As an experimental setup the aperture area was limited. But in case of building integrations the aperture area can be increased to provide further increase of the efficiency.
- Due to recirculation of water in the same reservoir the temp. difference between the input and output fluid was gradually decreasing and thereby the η_{th} also decreased. In real situations the output water will be utilized from time to time. So, there is always some temperature difference expected.

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