Cape Peninsula
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INTEGRATED SOLAR PHOTOVOLTAIC AND THERMAL SYSTEM FOR ENHANCED ENERGY EFFICIENCY

By

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DECLARATION

I hereby **OBIANG ASSEMBE CEDRIC**, declare that the contents of this proposal represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed…………………………………………………… Date……………………………….

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ACRONYMS AND CONCEPTS

PV:	Photovoltaic
PV/T:	Combined Photovoltaic and Thermal solar collector
STS:	Solar thermal system
DC:	Direct current
AC:	Alternative current
STT:	Solar thermal technology
PV/TLC:	Photovoltaic and Thermal Liquid collector
PV/TAC:	Photovoltaic and Thermal Air collector
PV/TCC:	Photovoltaic and Thermal Concentrators collector
CPUT:	Cape Peninsula University of Technology
GcPV's:	Grid-connected PV systems

NOMENCLATURE

A_{pv} : The PV module area [m^2];

A: The collector area [m^2];

C_p: Specific heat at content pressure [J/Kg. ℃]

E: irradiance on the collector surface [W/m^2];

FF : The fill factor

F_R : The heat removal factor;

g: Gravitational acceleration [m/s]

h_{cpg}: Convection heat coefficient between the plate and the glass cover [W/m^2K]

h_{rpg}: Radiation heat coefficient between the plate and the glass cover [W/m^2K]

h_{rga}: Radiation heat coefficient between glass and air ambient [W/m^2K]

h_w: Convection heat coefficient due to wind [W/m^2K]

I_{sc} : The current [A]

k_a: Thermal conductivity of air [W/m.K]

L_1: Spacing between absorber and the glass cover [m]

$\dot{m}$: is the mass flow rate [kg/s];

P_{in} : The Input power

P_{r_a}: Prandtl Number of air

Q_u: Useful thermal gain energy [W/m^2].

T_a : The Ambient temperature [℃];

T_{fi} : The fluid inlet temperature [℃];

T_{fo}: Temperature of the fluid out [℃]

T_g: Cover glass temperature (℃)

T_p: Collector Plate temperature (℃)

V_{oc} : The cell voltage [V]

v_w: Wind speed [m/s]

W: width of the panel [m]

α : Absorption coefficient of plate

ά: Thermal diffusivity (m^2/s)

β : Tilt angle °

σ: Stefan –Boltzmann value

τ : Transmission coefficient of glazing.

η_{th} : Thermal efficiency;

η_{ee} : Electrical efficiency

ν: Kinematic viscosity (m^2/s)

$\in_g$: Emissivity of the glass

$\in_p$: Emissivity of the Plate

δ_g: Thickness of the glass

SUMMARY

South Africa has raised concerns regarding the development of renewable energy sources such as wind, hydro and solar energy. Integration of a combined photovoltaic and thermal system was considered to transform simultaneous energy into electricity and heat.

This was done to challenge the low energy efficiency observed when the two solar energy conversion technologies are employed separately, in order to gain higher overall energy efficiency and ensure better utilization of the solar energy. Therefore, the notion of using a combined photovoltaic and thermal system was to optimize and to improve the overall PV panel efficiency by adding conversion to thermal energy for residential and commercial needs of hot water or space heating or space cooling using appropriate technology.

The PV/T model constructed using water as fluid like the one used for the experimental work, presented a marginal increase in electrical efficiency but a considerable yield on the overall PV/T efficiency, because of the simultaneous operation by coupling a PV module with a thermal collectors.

CHAPTER 1:

INTRODUCTION

1.1 STATEMENT OF RESEARCH PROBLEM

One of the challenges facing the world currently is how to minimize energy consumption using fossil fuels due to the negative socio-environmental impacts and price volatility. One of few approaches is to increase renewable energy sources such as solar as an alternative clean source to protect the environment, adhere to global and national policies geared towards clean energy development as well as increase energy access, to urban and rural areas. Solar energy can be converted to electricity or heat using two different conversion technologies: photovoltaic system and solar collector. Solar energy is mostly used in the form of electricity or heat for commercial or residential application. Therefore, integration of a combined photovoltaic and thermal system should be considered to address the low energy efficiency observed when the two solar energy conversion technologies are employed separately, in order to obtain higher overall energy efficiency ensuring better utilization of the solar energy and the solar panel.

1.2 BACKGROUND TO THE RESEARCH

Over the past century the world has been using fossil fuels such as crude oil and coal as an energy source. However they have negative socio-environmental impacts induced by the carbon dioxide emissions despite being more convenient and cheaper than others alternative sources. According to Baljit and Othman (2009) fossil fuels are gradually depleting and power plants are having a big impact on the global climate and the demands of energy are increasing. This attracted scientists to explore cleaner and environmentally benign energy sources such as solar; it is environmental friendly, abundantly available and can be supplied without any environmental pollution (*Tyagi et al., 2012; Baljit Singh*, 2009).

Recent technologies such as photovoltaic (PV) system and solar thermal system in this field have led to renew interest to generate electrical power and heat energy. Huizinga (2013) stated that usage of photovoltaic (PV) modules has been restricted by relatively high costs and low efficiencies. In all cases efficiency decreases when the cell operating temperatures increase due to the effect of solar intensity and ambient temperature (*Huizinga*, 2013; *Moradgholi et al*., 2014).

Since the 1970s researchers started to investigate combined Photovoltaic and thermal (PV/T) systems due to low energy conversion efficiency. Chow (2003) found in his work that when the module temperature was reduced, the PV efficiency increased by 2%. The PV/T collector or system is simply an integration of PV cells and a solar thermal collector in a single device, which should be able to convert solar energy into electrical and thermal energy simultaneously. However, using a PV/T system is mainly to optimize and to improve the overall PV panel efficiency by adding conversion to thermal energy for domestics, residential and commercial needs (*Andrews*, 1981; *Tripanagnostopoulos*, 2007).

1.3 RESEARCH QUESTIONS

This research project is based on two aspects, namely analytical or numerical model works, which will entail experimental work. Considering the above introduction of PV, STS and PV/T, the research questions is formulated to study how a PV/T collector type can help to increase the low energy efficiency, when it is used separately. The research questions are as follows:

- What kind of PV/T will be suitable for the solar energy technology?
- How does a combined PV/T liquid collector enhance energy efficiency?
- What types of cells, elements and mechanisms can be used to design a PV/T?
- Which principle need to be use to perform the analysis?

1.4 RESEARCH OBJECTIVES

The principal objective of this project is to enhance low energy efficiency using a combine PV/T collector type system under local climate, and weather conditions of the Western Cape Province in South Africa.

The second objective is to perform analytical or experimental work on the constructed PV/T model. To complete this aim, a study will be done by collecting data during the experimentation to determine the different energy efficiency output of the device.

1.5 SIGNIFICANCE OF THE RESEARCH

The purpose of using PV/T liquid system is to minimize energy consumption of fossil fuels and reduce the negative environmental impacts. It is known that renewable energy sources such as solar energy are an alternative clean source to protect the environment, decrease dependence on fuel energy and will never end. The PV/T technology reduces the consumption of power energy from Eskom. It contributes to customers saving on their bills and develops a new business area for the industry to create jobs. This research may contribute on several aspects listed below:

- A feasible model evaluating heat and electricity efficiency of PV/T liquid collector for residential house.
- Better energy performances that should be gained using a combined PV/T liquid collector.
- Experimental work to evaluate thermal and electrical output efficiency of a PV/T liquid solar collector.

1.6 DELINEATION OF THE RESEARCH

This research focused on the following hypothesis:

- Study of a PV/T liquid system for residential house
- Evaluate the heat and electricity efficiency using a combined PV/T system.

1.7 LIST OF RESEARCH OUTPUTS FROM THE THESIS

- Cedric.O, Raji. Ak & Kant. K. 2016. INTEGRATED SOLAR PHOTOVOLTAIC AND THERMAL SYSTEM FOR ENHANCED ENERGY EFFICIENCY. Transactions on Sustainable Energy journal paper. 24-Jul-2016 (Submitted and undergoing review).

CHAPTER 2:

LITERATURE REVIEW

2.1 INTRODUCTION

Chapter two provides a literature review on various aspects of photovoltaic systems and technology and energy production. The aim is to provide readers with a background understanding of solar and photovoltaic components so as to set a basis upon which the experiments are conducted.

2.2 PHOTOVOLTAIC (PV) SYSTEMS

2.2.1. PV system components:

A Photovoltaic (PV) system, also recognized as "Solar cell" can be described as a semi-conductor device designed to perform the direct conversion of electromagnetic radiation from the sun into electricity. In the middle of 1970s, PV cells became to be used for power in places where it was too expensive to use grid power, and in remote areas as well as islands. Today some countries like South Africa, many people are using electricity from PV systems than electricity from the main power grid since PV technology is now more efficient and cost less than ever at generating electricity from sunlight*(Hasan & Sumathy*, 2010).

The most basic system can use the following components:

- A "PV Module" which is the power source.
- A "Charge Controller" to avoid overcharging of the battery if using one.
- A "Battery" to simply store energy and use when there is no sunlight. It also supplies an extra power to the load that can exceed the power rating of the PV module or the PV array.
- A "DC distributor panel" for fuses, switches or circuit breakers for any protection.

As optional for complex PV systems, others components can be added on the system such as:

- An "inverter" and "AC distributor panel" which is only used for stand-alone residential system to power AC loads.
- A "standby" or a "backup generator" that should instinctively charge the battery at some predefined minimum state of charge.

- Other power sources that can operate in conforming to the PV module or the PV array.

Figure 1 below illustrates a basic PV system:

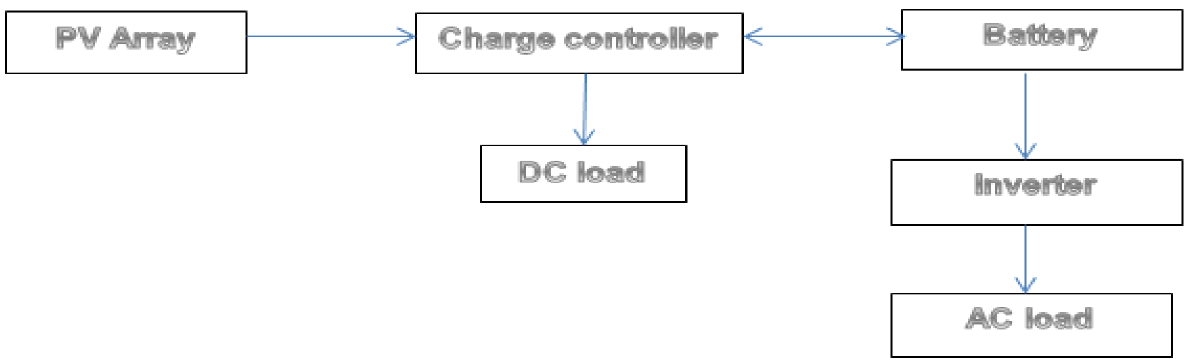

Figure 1: Step/Diagram of Photovoltaic System

PV systems are different and used for specific applications. The equipment is connected to other power sources and electrical loads. There are three principal classifications grid-connected system, stand-alone systems and interactive solar systems which is the combination of the grid and the stand-alone(*Anderson et al*., 2008).

The electricity is generated by the strikes of sunlight on the PV cell, and then the photons from the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons move through the cell to create energy (*Jack et al*., 1975).

Furthermore, most of energy that strikes the cell in the form of sunlight is lost before it is converted into electricity. Note that the maximum electrical efficiency of solar cells convert up to 30% (even for some very complex cell models), but the typical efficiency is 10% to 15%. This is why most of the ongoing work on the cells is directed to increase efficiency while reducing costs. The efficiency of certain cells limited by the physical processes is inherent and cannot be changed; others can be enhanced by appropriate design (*Baltas et al.*, 1986). These three classifications use four types of solar cell technologies:

- Silicon solar cells
- Group or multi-junctions solar cells
- Thin films solar cells
- Dye-sensitized solar cells.

2.2.2. Grid-connected PV system

Grid-connected PV systems (GcPV's) generate solar power which is connected to the loads and to the electric utility grid. They have become progressively popular like in building integrated applications. Directly connected to the grid by an inverter, batteries are not required on GcPV's because of the electricity generated by the PV is used locally and the excess fed to the grid if not stored on site. (*Hammond & Everingham*, 2003).

Having a grid-connected PV system is not different of having electricity from power station, except that some or all the electricity used comes from the sun. When there is no sunlight to generate PV electricity, the power from the grid will supply the demand. Alternatively these systems can be used as power stations. Figure 2 presents the grid-connected PV system schematically (*Zeman*, 2003).

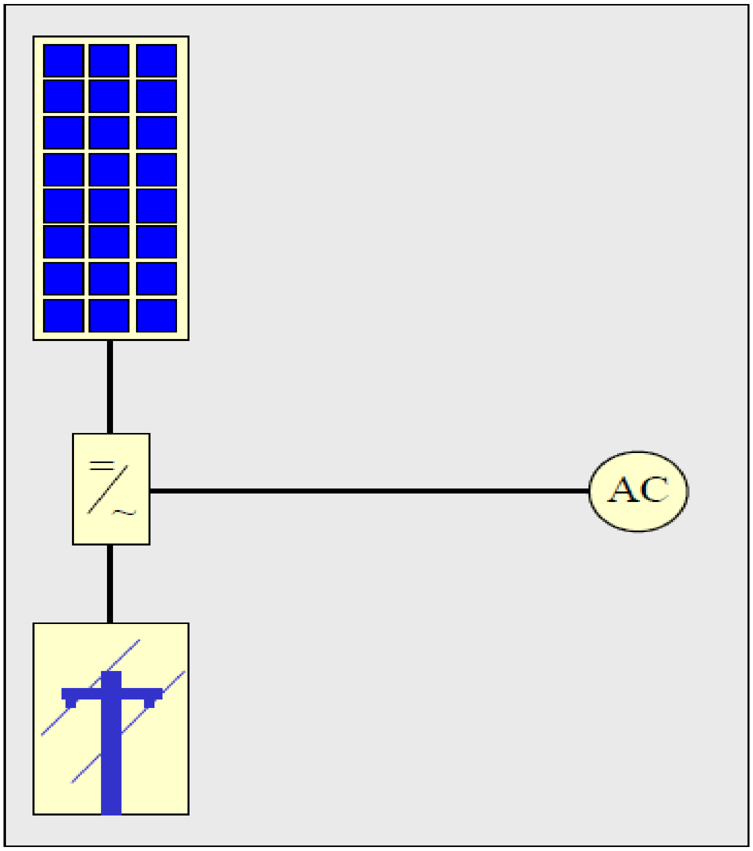

Figure 2: Grid-connected photovoltaic system with a load: AC as load (*Zeman*, 2003).

2.2.3. Stand-alone or Off-grid PV system

Stand-alone PV systems are the best option for many remote applications; they can operate reliably and independently from the grid and can work anywhere as presented in figure 3. An off-grid solar PV system can use rechargeable batteries to store electricity need when used under conditions where the output from the solar PV system is little. These systems sometimes require a charge controller to protect the battery against overcharging or deep discharge, add an inverter to convert the direct current (DC) PV array power to alternative current as show in Figure 4 which consists of PV system including, power conditioners, both DC and AC loads and a battery (*Hammond & Everingham*, 2003; *Tiwari & Dubey*, 2010).

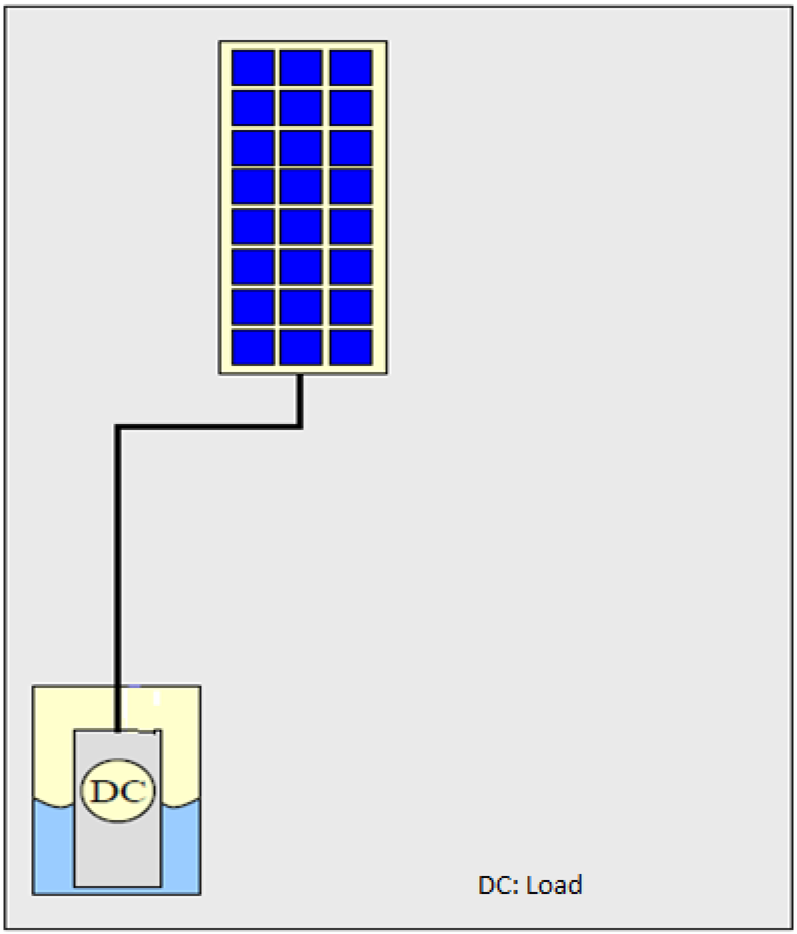

Figure 3: Stand-alone or off- grid photovoltaic system (*Zeman*, 2003).

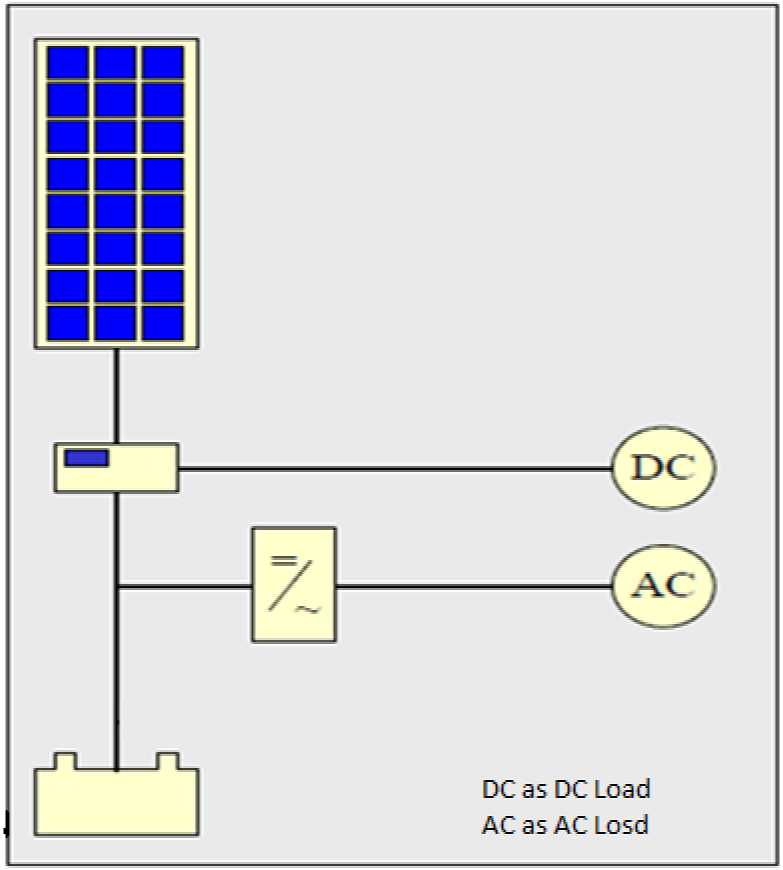

Figure 4: Off-grid with storage battery and an inverter (*Zeman*, 2013).

2.3. SOLAR THERMAL SYSTEM/COLLECTOR

Solar thermal system (STS) is a technology that transforms solar energy into thermal energy (heat). STS devices absorb incoming solar radiation, convert the solar energy into heat, and then transfer the thermal energy to a type of fluid used such as liquid or gases flowing through the collector (*Kalogirou*, 2004). Figure 5 below presents the basic work of a water STS that generate heat.

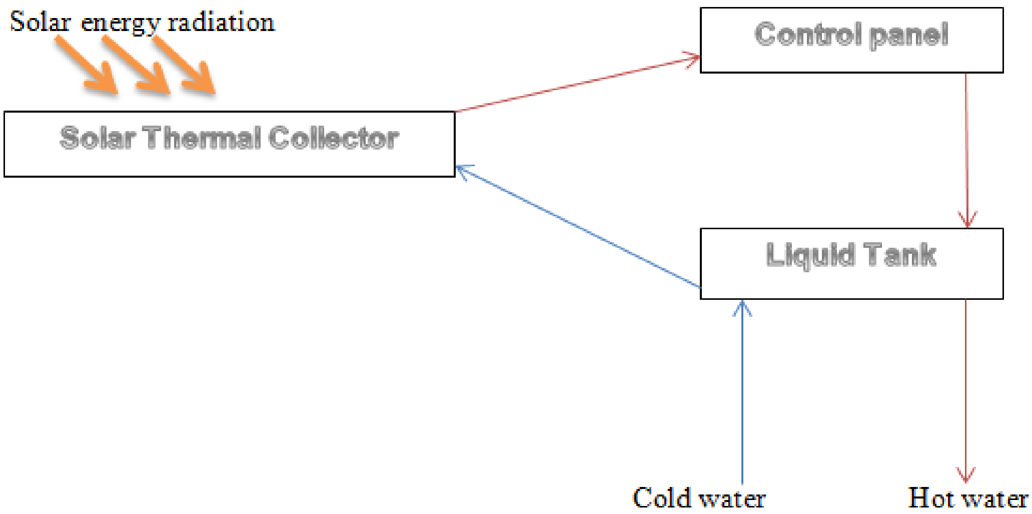

Figure 5: Basic process of generating heat

There are many solar collectors available on the market. Two main types of solar collectors include: non-concentrating or stationary and concentrating, which are not discussed in detail in this research. However, the interest of this study is based on the understanding the different functions of a STS (*Twidell & Weir*, 2015).

Solar energy is absorbed by the collector designed to heat the fluid moving through the pipes. The heated fluid from the collector transfers its thermal energy to water stored in the storage tank, which feeds primary water heating system if necessary. If a boiler is used when fed with solar heated water, the fossil fuel powered water heating system is either not activated or activated for less time (*Messenger & Abtahi*, 2010). Figure 6 taken from (Spirit Energy Solutions website, 2015) perfectly illustrates this.

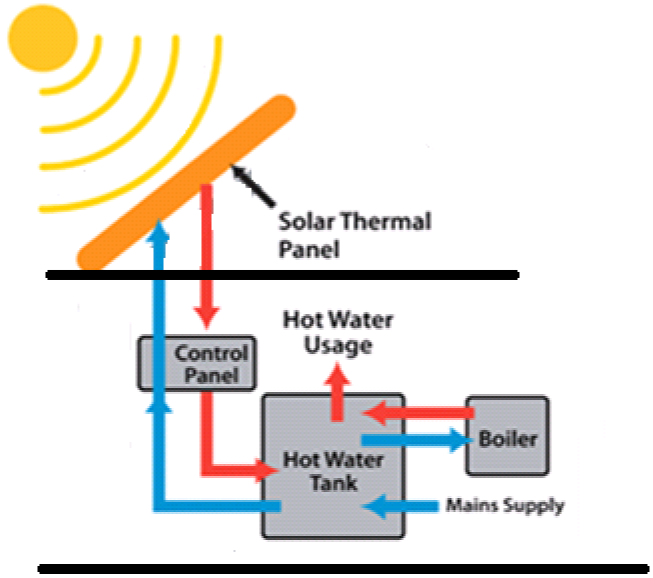

Figure 6: An illustration of a solar thermal system (Spirit Energy Solutions website; 2015)

Solar thermal technologies (STT) are used for key applications that require low temperature heat, such as swimming pools, domestic hot water and space heating, and so on. The component used to convert solar energy into heat is called a collector, which can be either non-concentrating or concentrating. Its working condition temperatures are often between 60°C and 80°C with a conversion-efficiency around 40 to 60 per cent that can be achieved with flat-plate collectors for domestic. There is a huge advantage to use solar system in countries where solar radiation is about 1,800 kWh/ (m^2, a), and convert that solar energy from collector into low or high temperature heat for domestic usage (*Zondag et al.*, 2006; *Kalogirou*, 2004).

According to Zondag (2006), non-concentrating collector fully utilizes the global radiation while concentrating collectors use only the direct beam of the radiation by focusing the irradiation on the absorber to increase the intensity of energy on the former. This process is driven by three types of solar thermal collectors:

- Flat plate collector
- Evacuated tube collector
- Concentrating collectors

2.4. COMBINED SOLAR PHOTOVOLTAIC AND THERMAL

The combination of a PV cells and a thermal collector is called a Combined Photovoltaic and Thermal system (PV/T). These two solar technologies are assembled together because photovoltaic cells performance decreases while the temperature of the units increases. Therefore the addition of a thermal collector at the panel back allows the extraction of the heat from the PV cell with a circulating fluid through the pipe to increase the cell's performance. In the case that heating is required for a boiler; the extracted PV heat will also assist to increase performance (*Zondag et al*., 2006; *Tripanagnostopoulos*, 2007).

There are several alternatives of integrated PV/T which include: air, water or evaporative collectors. Various researches have been conducted on PV/T technologies over the past few years with an increase rate of activities, Chow (2003) and Zondag (2006) carried out an analysis on efficiencies of a PVT water collector. In a PV/T collector or system a PV cell does not only generate electricity, it can also serve as a thermal absorber. This justifies the fact that PV/T systems simultaneously produce heat and power (*Hasan & Sumathy*, 2010). Furthermore, the production of electricity is the main objective of a combined PV/T panel application. When the cell operates at low temperature, the probability to increase the efficiency of electricity becomes better(*van Helden et al., 2004)*. There are four types of solar collector developed in the field of Solar PVT which are:

- PV/T Liquid collectors
- PV/T Air collectors
- Ventilated PV with heat recovery
- PV/T Concentrators

2.4.1. PV/T Liquid Collectors

Designed to heat up the water and instantaneously produce electricity, liquid PV/T collectors (PV/TLC) are similar to flat plate collector water heating system. In a PV/TLC, the PV cells absorb a huge amount of solar radiation that helps to generate undesirable heat, which can be reused in water pre-heating uses and there are mostly used for different domestic and industrial applications (*Charalambous et al*., 2007).

PV/TLC can either be glazed or unglazed. Unglazed liquid type PV/T collectors ensure a higher electrical performance and a lower thermal performance. A glazed liquid collector can generate a greater heat loss and resultantly lower operating temperatures (*Anand Bisen*, 2011). According to Tyagi (2012) in order to achieve higher electrical performance, unglazed PV/T should be considered whereas glazed PV/T should be used for higher thermal efficiency. Furthermore water, air or refrigerant can be used as the heat removal support to cool the solar cells. The most convenient liquid to use is actually water, not only because of its high thermal capacity, but due to its optical properties (*Daghigh et al.*, 2011).

2.4.2. PV/T Air Collectors

PV/T air collectors (PV/TAC) are only used when there is a demand for heating air for domestic or industrial purposes. In PV/T air collectors, the air goes through the collector instead of water; these are collectors with low cost and risk of freezing (*Chow*, 2010). The main disadvantage of using a PV/TAC comes from the fact that it delivers a lower thermal performance characteristics compared to a PV/TLC. Furthermore, low density of air in the collector produces a volume transfer which is significantly higher than in liquid types. Thereby, pipes with higher volume are needed from which a low area application is not suitable, and is not aesthetically pleasing. Finally, in case of a leakage, there is a higher heat loss absorbed compared to PV/TLC. Despite these disadvantages, the PV/TAC types are suitable choices for heated air due to their lower cost (*Baljit Singh*, 2009).

2.4.3. Ventilated PV with Heat Recovery

According to Misha (2014) in his review on thermal modelling, PV technologies that are hooked on a wall section or a rooftop of a building are named Ventilated PV systems with heat recovery. It uses the heat of the collectors through heat recovery from a ventilated PV system using natural convection of air going through arrays PV on the rooftops. The advantage of building integrated

PV collectors lies on the cooling load that decreases in summer with the aim of shielding the building (*Rosli* et al., 2014).

The inconvenience of these ventilated PV collectors lies on its design which is done separately for any typical kind of building because there are perfectly fitted to certain conditions (*POPESCU et al*., 2013). Since it requires pipes with high volume, they are used but their cost may not be suitable for certain applications. Hence, due to the nature of air and the exposed state of the collectors, a low temperature and high heat loss are observed when using a ventilated PV with heat recovery (*Zondag*, 2008).

2.4.4. PV/T Concentrators Collectors

Andrews (1981) presented photovoltaic and thermal concentrator collectors as a combined heat and power approach. It shows high performance in order to produce both electricity and thermal energy at low, medium or high temperatures. PV/T Concentrators collectors (PV/TCC) systems collect solar rays, and reflect those rays to a central point where the PV/T cells are located. A PV/TCC has some particular characteristics compare to other PV/T systems since it can operate at a higher temperature, it uses reflector material less expensive and less PV cells. The use of PV/T in combination with concentrating reflectors has a significant potential to increase the power production from a given solar cell area (*Hasan & Sumathy*, 2010).

The inconvenience of using PV/TCC lies on the fact that it requires a stable cooling system because of the high temperatures. In addition to that, the system becomes problematic if the temperature of the system increases. For better performance, these technologies need to be tracked due to their bulky shape. PV/TC is not really suitable for building integration compared to others PV/T collectors, because of the high working temperatures that increase degradation of the materials (*Zondag et al*., 2006).

According to a research published by Amrizal (2012), a PV/T system combines the functions of two technologies: photovoltaic panels and thermal solar collector. The thermal section has the main function to produce heat in the system while the PV section produces the electricity.

Currently, the combination of the two systems in one piece generates simultaneously heat and electricity as shown in Figure 7(*Nalis & others*, 2012).

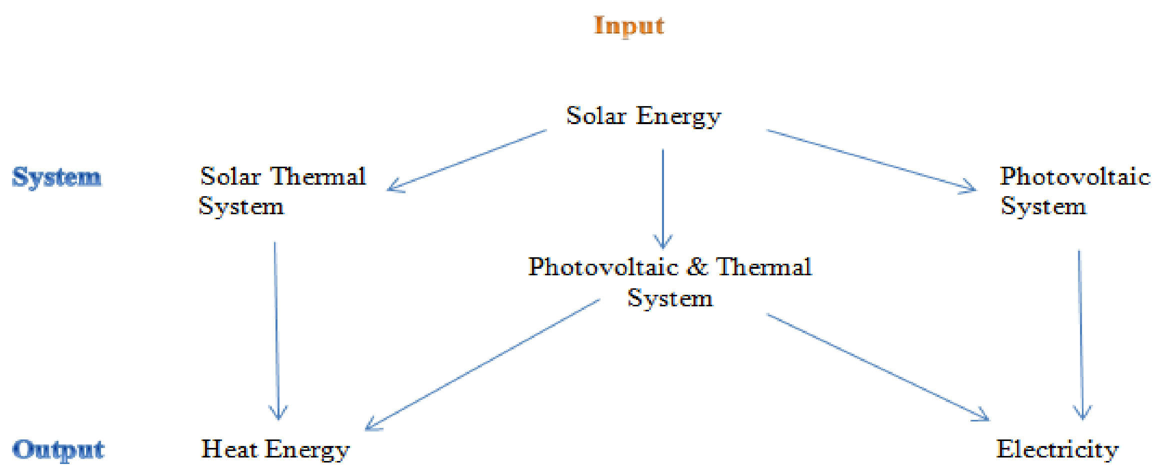

Figure 7: Drawing details showing output of solar energy system

2.5 PHOTOVOLTAIC TECHNOLOGY (PV)

Photovoltaic technology relies on the use of cells containing semiconductor materials. These materials, which are referred to as solar cells, are responsible for collecting and transforming solar radiation into electric power. The cell temperature and ambient temperature are important parameters which influence the cell characteristics and are considered in the modelling of a PV system (*Skoplaki & Palyvos*, 2009).

2.5.1. Solar cells

The photovoltaic cells of solar panels are made from a sandwich of two layers of semi-conducting materials. The layer exposed to the sunlight is a negatively charged semiconductor (or N-type semiconductor) and the bottom layer is a positively charged semiconductor (or P-type semiconductor) (*Zeman*, 2003). That assembly is known as a p-n junction. These solar cells show in Figure 8 are the semiconductors device of electricity by solar energy conversion. Moreover, the solar cells are the unit that actually delivers an amount of electrical power.

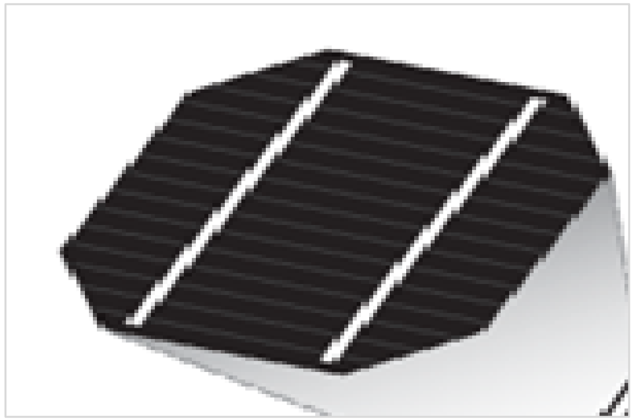

Figure 8: Solar cell element (Salmex Solar 2006)

2.5.2. Photovoltaic types of cells

Crystalline silicon and thin film which are newer, are two broad categories of technology used for PV cells as shown in Figure 9 for PV cell production. Crystalline cells are made from ultra-pure silicon raw material such as those used in producing electronics chips. Silicon conducts electricity and it is the main material for photovoltaic cells. Thin film is made by depositing thick layers of semiconductor material onto glass or stainless steel substrates (*Stoffel et al*., 2010).

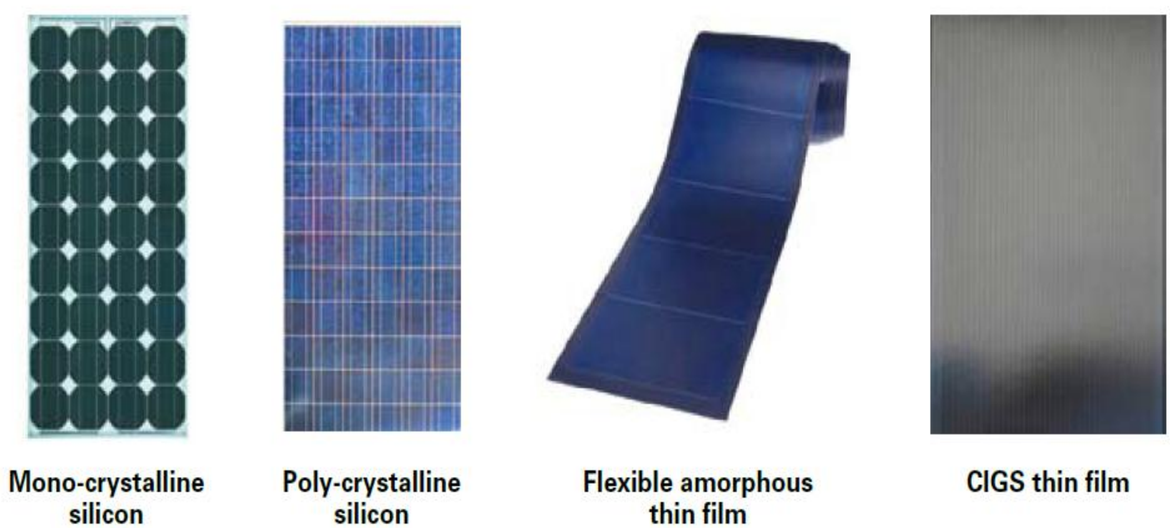

Figure 9: Photovoltaic Types of Module

(Handbook for Solar Photovoltaic (PV) Systems, 2010)

2.5.3. Photovoltaic Module

When the solar cells are connected together, it forms a solar panel known also as a PV module as shown in Figure 10 which produces a particular voltage and current to use solar electricity for devices that operates using solar electricity for their application (*Zeman*, 2003). These photovoltaic cells look like solar panels but they work differently because solar panels are used to produce hot water while photovoltaic panels convert the sun's radiations directly into electricity.

Figure 10: Assembly of solar cells known as PV module (Salmex Solar 2006)

2.5.4. PV Array

Two or more PV modules connected together to obtain a desired voltage and current is called photovoltaic array as shown in Figure 11. The array unit is the group of photovoltaic module already encapsulated as a group of solar cell. The output characteristic of PV array is influenced by the cell temperature, solar radiation, and output voltage of the array itself. Several PV arrays are tied together either in series or parallel assembly, with a centralize inverter which in turn converts the DC generated to AC (*van Helden et al*., 2004).

Figure 11: Photovoltaic Array Illustration (Salmex Solar 2006)

The technology of solar PV systems can be considered based on the end-use application. PV systems are operated using different types of configuration structures: Grid-connected (or grid-tied) and off-grid (or stand-alone) solar PV systems are the two main types of solar PV systems used currently.

2.6 PHOTOVOLTAIC ENERGY PRODUCTION

The energy generated from a PV module does not only depend on the power attained from sunlight, but also on the orientation angle between the sun and the PV module. It is important to consider the seasons and the times changes when designing any type of system that relies on solar radiation energy production. It is also helpful to consider the amount of solar radiation incident on the PV tilt angle which is perpendicular to the module surface.

2.6.1. PV Tilt and Orientation Angles

The PV panel is placed at different orientation and tilt angle. There are two different angles that described the sun position. The solar azimuth angle defined as the angle between the sun and the cardinal direction of true north. The solar altitude angle defined as the angle of the sun's position from the horizontal (angle of insolation). However, the angle of incidence cannot be a measure of the sun's position; instead it can be a measure of the amount of radiation incident on a vertical surface (*Rouholamini et al*., 2013).

The tilt angle plays a significant impact on the solar radiation incident on a surface and, it is defined as the angle between the plane of the solar device and the horizontal. For a fixed tilt angle as shown in Figure 12 below, the maximum power can be obtained when the tilt angle is equal to the latitude of the location. The tilt angle of a PV changes due to factors such as the geographic latitude, climate condition, utilization period of time, etc. These factors highly influenced the performance of the PV module (*Chang & others*, 2008; *Betts et al*., 2006).

Furthermore, many investigations have been done by researchers like Yellot and Lewis to determine or at least to estimate the best slope angle for solar systems. They suggested two values for the tilt angle, one for the summer and one for the winter, such as Φ ± 20°, Φ ± 8°, where Φ is location latitude angle, "Plus (+)" for winter and "mines (-)"for summer (*Agarwal et al*., 2012).

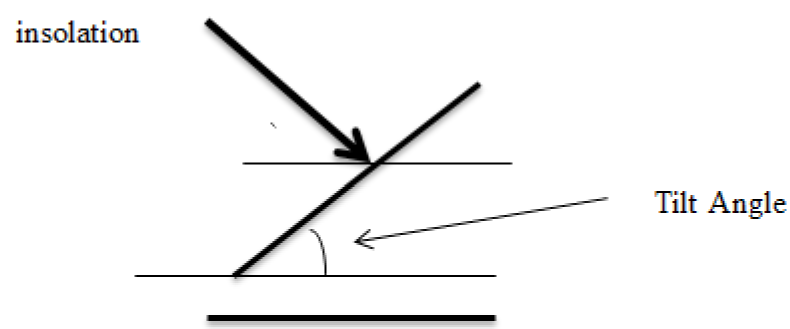

Figure 12: Representation of the Tilt angle and the angle of Insolation

2.6.2. PV Efficiency

The PV efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun, efficiency is the most used parameter to compare the performance of different solar devices. It depends on the range and intensity of the incident sunlight and the temperature of the PV module. Therefore, the PV efficiency of the module can be determined as the fraction of incident power which is converted to electricity and is defined as follow:

Since,

$$P_{max} = FF * I_{sc} * V_{oc}$$

Then,

$$\eta_{ee} = (FF)\frac{I_{sc} * V_{oc}}{P_{in}}$$

Where;

- I_{sc} is the current [A]
- V_{oc} is the cell voltage [V]
- FF is the fill factor
- P_{in} is the Input power , which is equal to : $P_{in} = A_{pv} * E$
- E is the irradiance on the collector surface [W/m^2].
- A_{pv} is the PV module area [m^2];

Knowing the efficiency of a panel is important in order to choose the correct panels for the appropriate photovoltaic system(*Erdil et al*., 2008).

2.7. CONCLUSION

In this chapter, the literature guiding this research has been discussed. The overall structure and the difference of a PV and Solar thermal system have been reviewed. The combination and the types of PV/T collectors have also been highlighted. In addition, energy production of the PV and efficiency of the device were reviewed. The next chapter talks about the design and efficiency of the PV thermal system**.**

CHAPTER 3:

DESIGN OF PV THERMAL SYSTEM AND EFFICIENCY

3.1 INTRODUCTION

This chapter describes three distinctive aspects including the design of different types of PV/T, the various possible PV/T structures and the operational mode of the energy efficiency of a PV/T using the electrical and thermal performance evaluation. The material (equipment used in this study) and their suppliers, the experimental design and the experimental procedures employed in this research are subsequently presented.

3.2 HYBRID PV/T COLLECTOR DESIGN

PV/T systems are known to have separate systems that include a single solar collector and a PV module. They are bound together to work simultaneously for generating electricity and thermal energy. Therefore, for this research only water type systems were considered because hybrid water PV/T systems can be used effectively on the actual season, especially in regions where ambient temperature is usually below 20 degrees like in Europe (*Kalogirou & Tripanagnostopoulos, 2006)*. Following Takashima (1994) research, a PV/T system can be made by a PV panel placed on top of a solar thermal collector, with a gap between them to achieve an effective PV cooling(*Takashima et al*., 1994).

3.2.1. Flat-plate PV/T Pipe Collector

This PV/T water pipe collector is a simple split flow design using tube as heat absorber which was attached to the back surface of PV panel with the idea being using tubes was elaborated to extract the heat energy that is trapped in PV panel more efficiently. The examples on figure 13 and 14 are drawings of tube heat absorber.

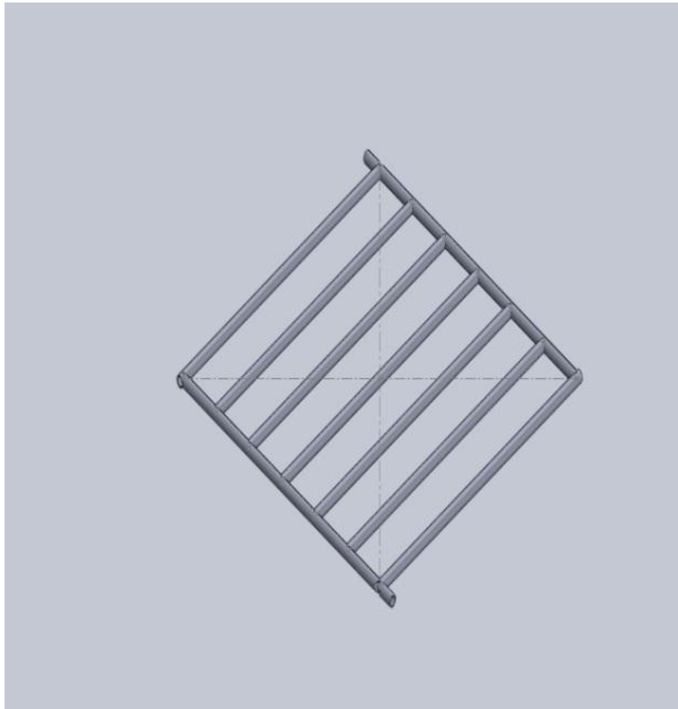

Figure 13: Pipe connection of the collector drawing

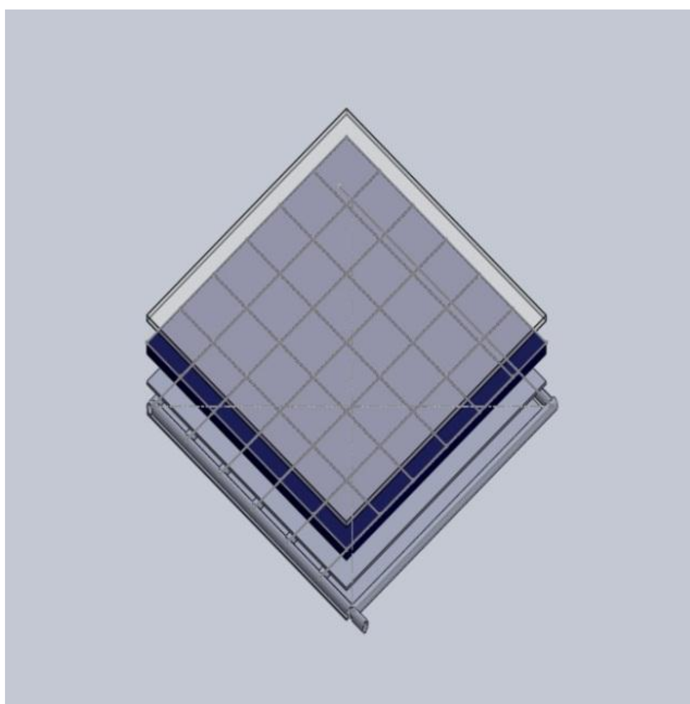

Figure 14: Photovoltaic and thermal pipe collector drawing

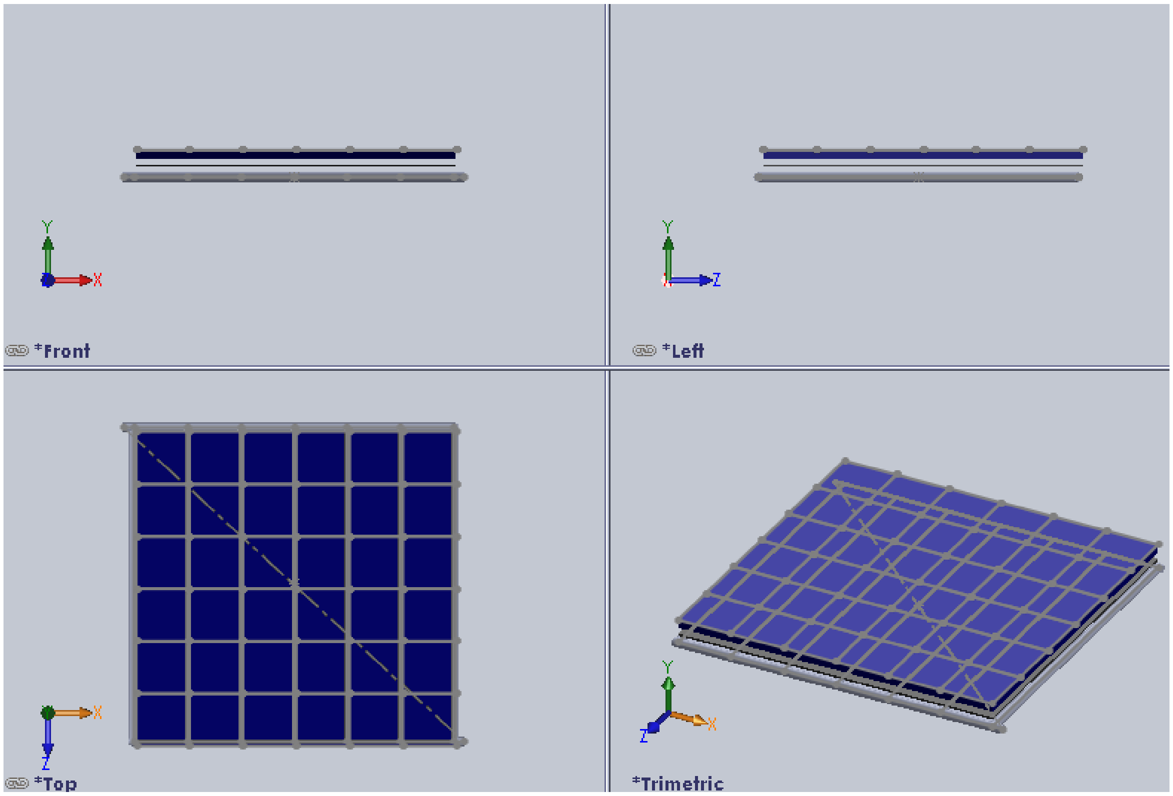

Figure 15: Flat-plate PV/T pipe collector illustration drawings

3.2.1. Flat-plate PV/T water Based Collector

Flat-plate PVT water based collectors are different due to their water flow pattern. The differences can be seen by observing the flow of water under the cells. In this PVT collectors type, it is also distinguished by considering the water flow customs. Flat-plate PVT water based collector as shown in Figure,16,17 and 18 due to its low cost and less material usage was preferred than the water pipes PVT collector as shown in Figure 15. This method of generating heat and electricity efficiency using water as a thermal energy transfer can be operated using natural flow of water in the collector.

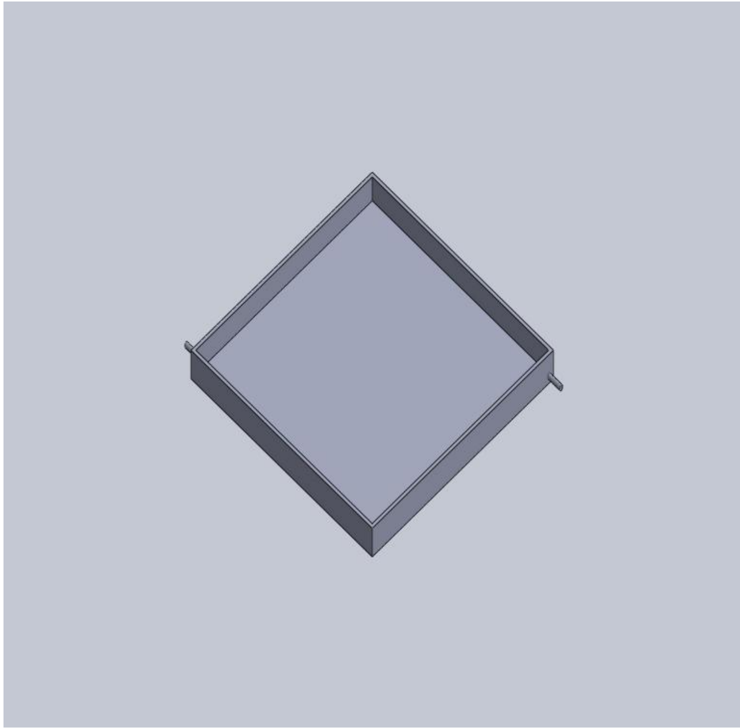

Figure 16: Water Collector drawing

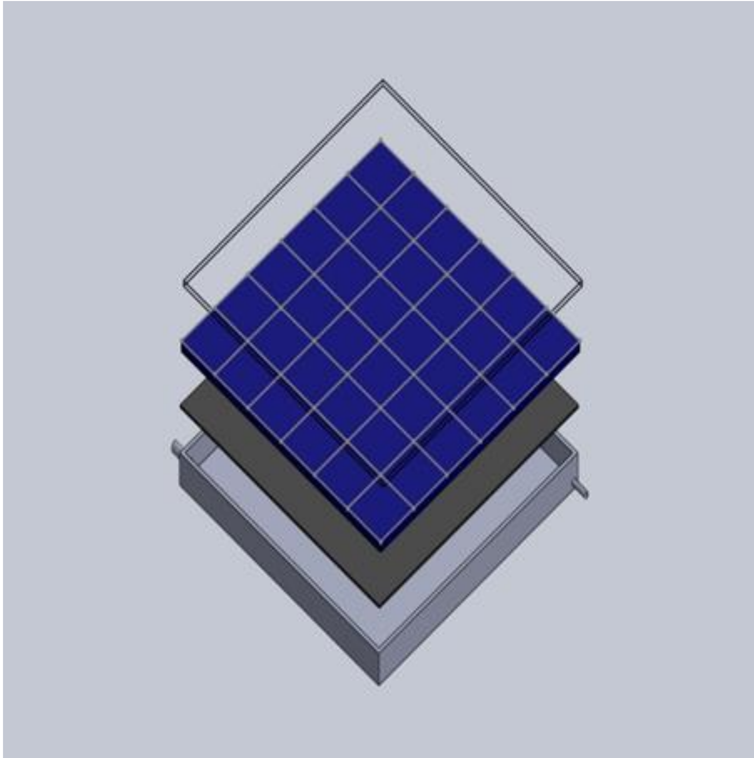

Figure 17: Photovoltaic and Thermal Water Collector drawing

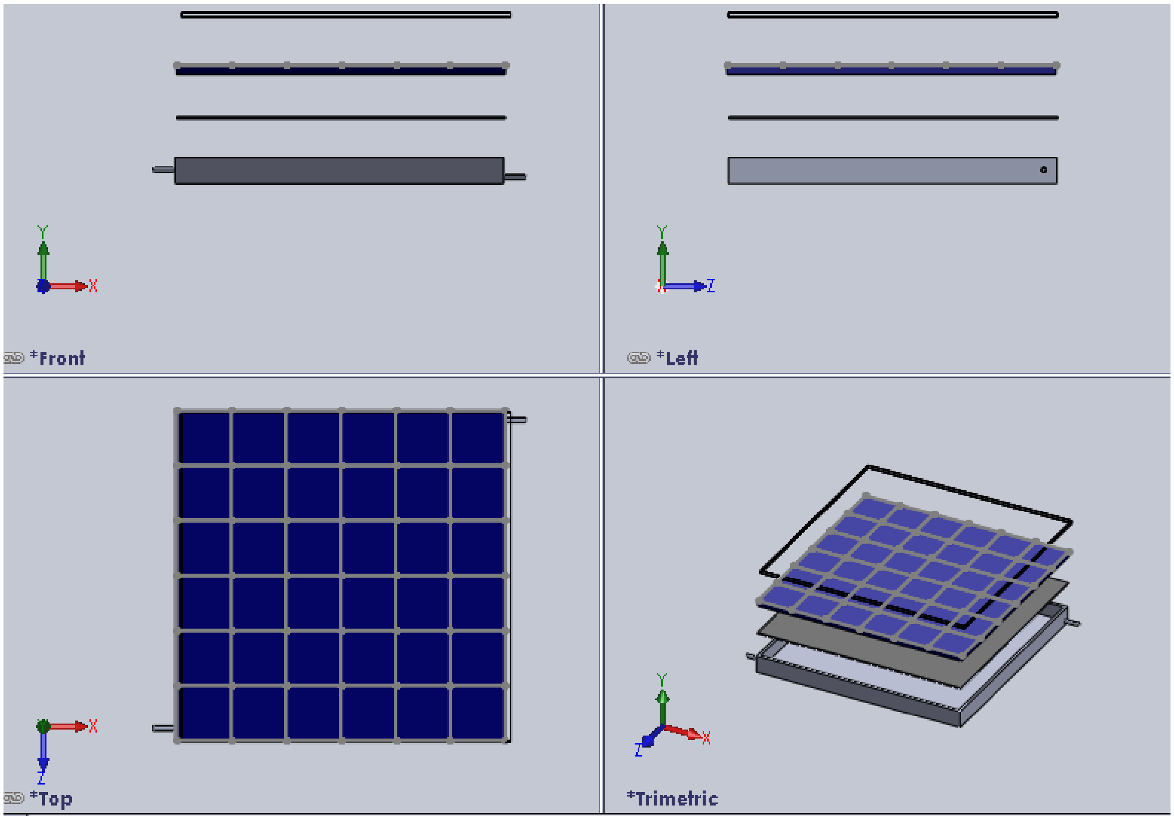

Figure 18: Flat-plate PV/T Water based Collector Illustration drawings

3.3. DESCRIPTION OF THE OVERALL DESIGN:

Following Chow (2010) studies on building energy and environment technology, it was concluded that the covered flat plate collector of a PV module should give better thermal and electrical performance from the photovoltaic and thermal collector (PV/T) water heating system due to the low temperature on the PV cells. From his observation, the approach made on designing this model or device was looking at having different components illustrated in Table1 below with the purpose of designing a device that will be assembly in one system (*Chow*, 2010).

Different forms of PV/T liquid systems exist like spiral flow, oscillatory flow etc., but it depends on its design. Figure 19 drawn from Solid Works shows the type of PV module installation, the concentration of incoming radiation and also the type of heat removal fluid in which this case is water. The bonding of the PV module and the flat plate thermal collector are the first part of the assembly. The solar radiation will generate a physical process in which the PV module converts sunlight into electricity called "the photovoltaic effect".

The solar thermal collector absorbs the incoming solar radiation from the PV module, and then converts it into heat. It is transferred to the fluid flowing through the collector. Heat exchange should be possible due to the good thermal capacity of water and the solar energy collected from the actual circulating fluid which is carried directly by the water to an insulated storage tank from which hot water should be stored as shown in Figure 19 (*Ibrahim et al*., 2011).

Additionally the present PV/T design concept consists of joining the PV module and the flat plate thermal collector and turning one of the main disadvantages of PV panel efficiency when the panel is heat up into an advantage. Water is heated using the excess heat that is produced by the photovoltaic portion of the PV/T module as the solar radiation shines on and that hot water is put away to be stored in the tank. The global temperature of the PV module is kept cooler and increases the electrical efficiency (*Du et al*., 2012).

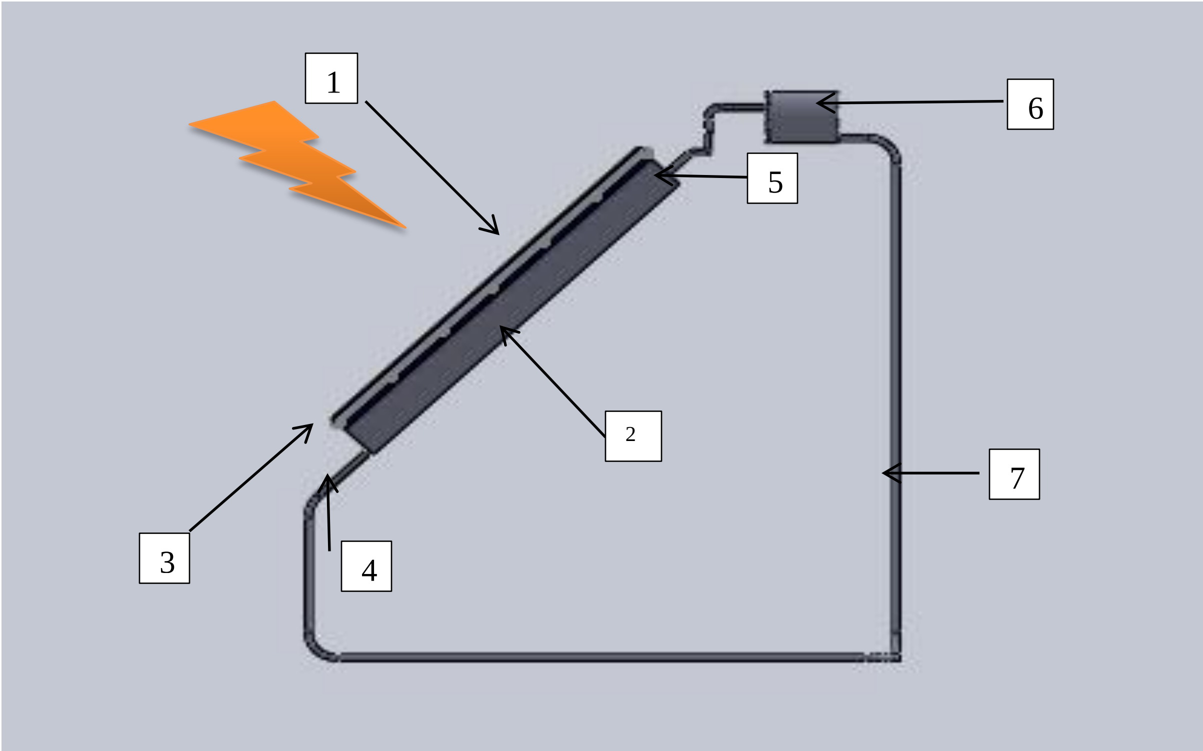

Figure 19: Assembly of the PV/T Collector System side view drawing. (1) Cover plate; (2) Thermal collector (water flow); (3) Photovoltaic cell (PV module); (4) Inlet water flow; (5) Outlet water flow; (6) Tank; (7) Flexible pipe or water conduct

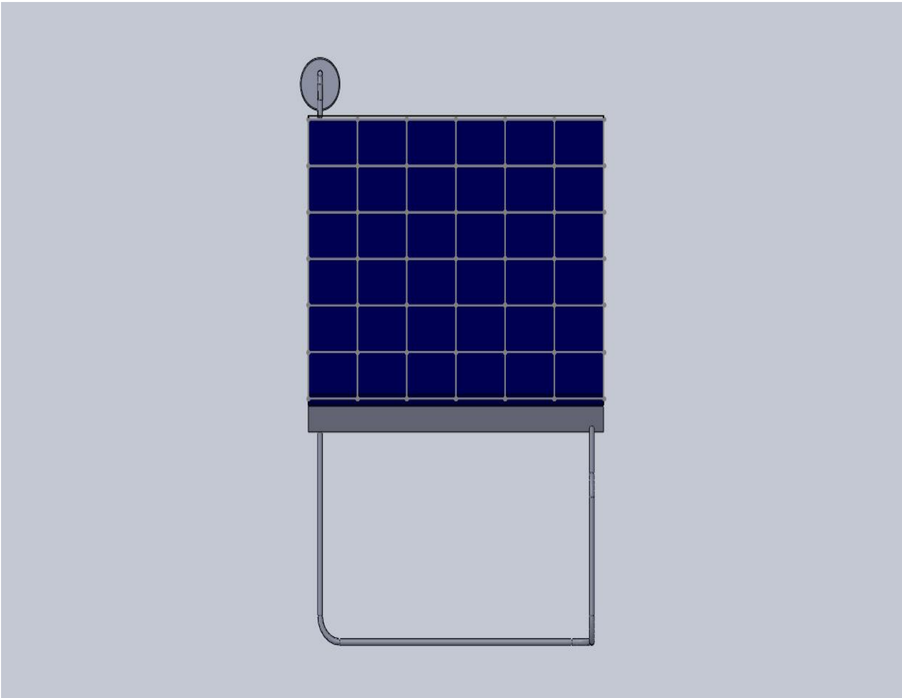

Figure 20: Left side view drawing of the design

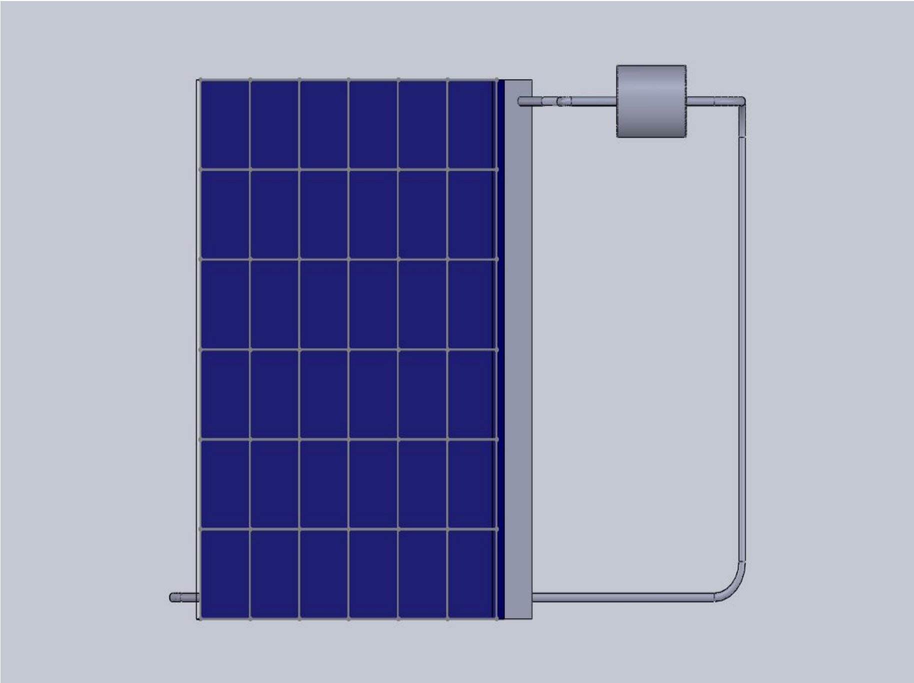

Figure 21: Top side view drawing

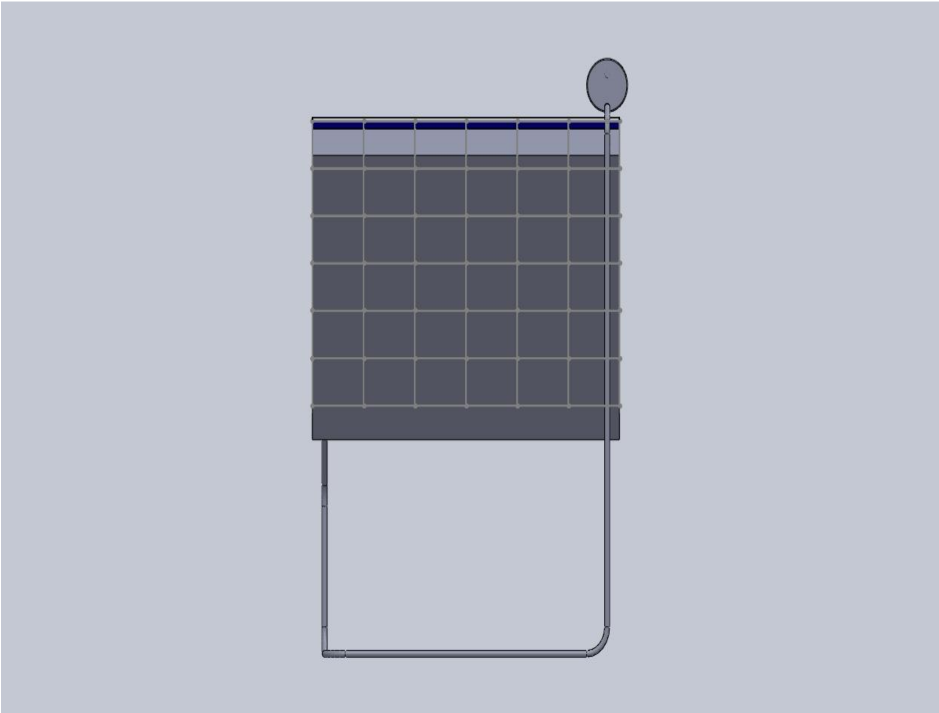

Figure 22: Back side view drawing

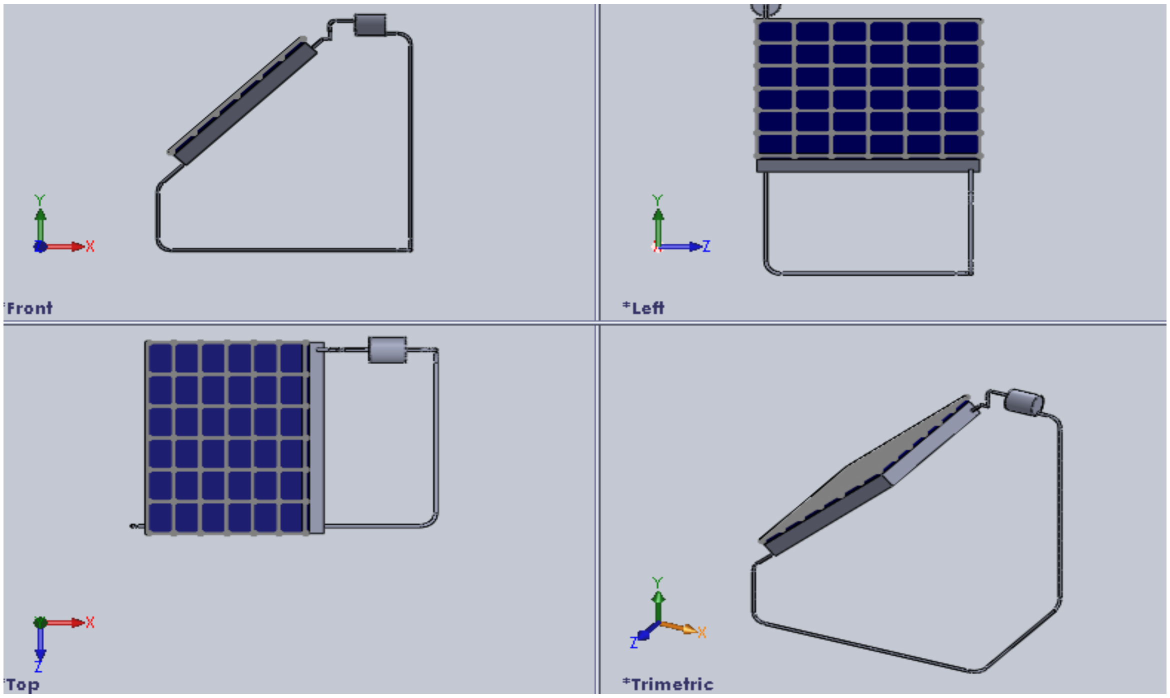

Figure 23: Close loop of the final model of the PV/T water based collector drawing

Table 1: Photovoltaic Panel types

	Panel Types
PS	Poly-silicon
MS	Mono-silicon
MC	Monocrystalline
MuC	Multi-Crystalline
PCS	Polycrystalline silicon
AmS	Amorphous-silicon

For this report, the PV module type was selected from "SETSOLAR renewable energy solution company" see on **Figure 24** with the different characteristics that describe all the necessary information concerning the PV cells as referred in **Table 2**.

Figure 24: Selected PV module "SETSOLAR Renewable Energy Solution Company"

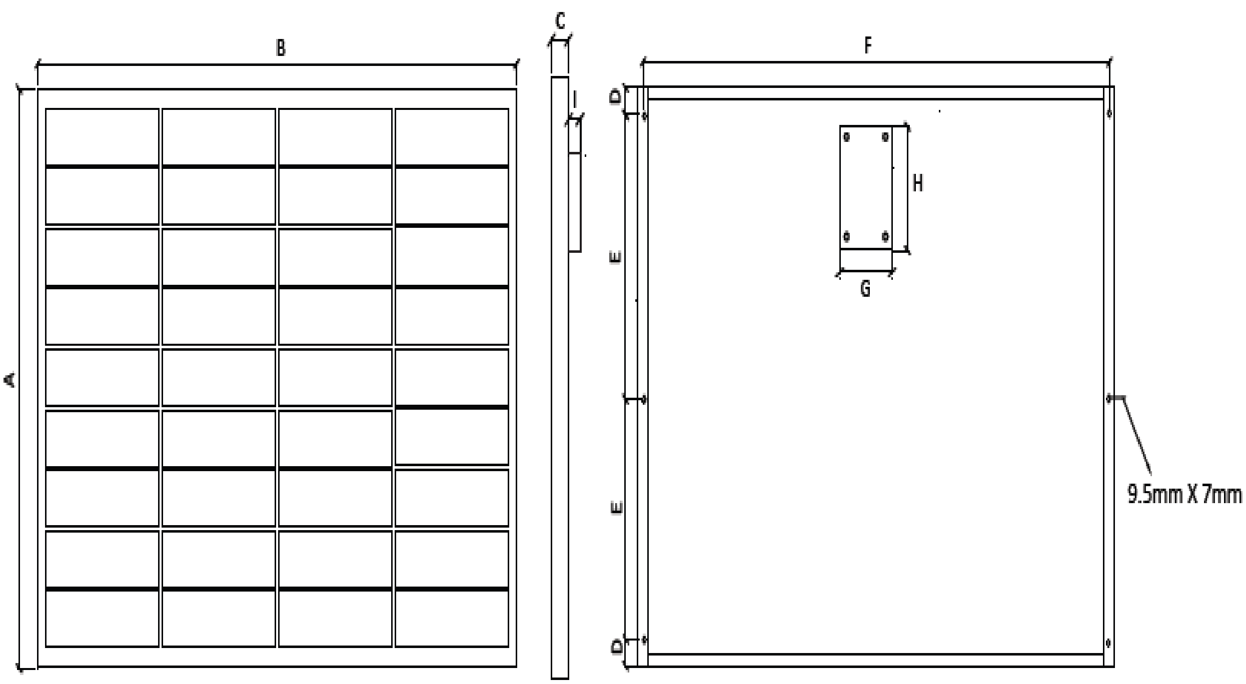

Figure 25: 2D of the PV module with dimensions "SETSOLAR Renewable Energy Solution Company" such as A: 530; B: 670; C: 25; D: 20; E: 245; F: 632; G: 110; H: 165; I: 16

3.4. PERFORMANCE REVIEW OF PV/T COLLECTORS:

Many studies done by Chow and Zondag (2006) mentioned in chapter 2 have defined methods and procedures to determine the performance of PV/T collectors. To test a combined PV/T system, it has to be done separately into thermal and electrical approaches, since there are no standard procedures for simultaneous thermal and electrical efficiency analysis of PV/T. This performance testing of electricity and heat of the PV/T system depends on solar energy input conditions such as the ambient temperature, the operating temperature of parts and, the wind speed and the heat extraction mode (*Zondag et al*., 2006).

However, this research focuses only on liquid PV/T collector (PV/TLC) system efficiency performance. There are two types that exist in the market but different designs conceptions. The two types are:

- Glazed PV/T collectors system, which produce more heat but have slightly lower electrical yield and very similar in appearance to flat-plate solar thermal collectors.
- Unglazed PVT collectors, which produce relatively less thermal energy but show somewhat higher electrical performance and more similar to regular PV panels.

The performance of the PV/T depends on the PV module type as seen in the Table 1 above that shows the different types of photovoltaics. PV module can be constructed with Multi-crystalline (MuC), polycrystalline silicon (PCS) and the newly developed thin films of amorphous-silicon (AmS) types of cells which are not considered in this case. Crystalline silicon has by far the largest market share of all PV technologies. Nevertheless, Multi-crystalline (MuC) was chosen due to its low cost compare to others (*Kalogirou*, 2004).

3.4.1. Energetic Efficiency Approach

In a PV system most of the solar radiations are not converted into electricity and there are several methods to collect solar energy that is absorbed. The incident solar radiation to produce electricity is utilized by a small fraction of PV cells. It mainly turns the remainders into heat waste in cells to increase temperature of PV cells causing the drop energy efficiency of the module. Hence, the fact of cooling the module either natural or by forced circulation should reduce the PV cell temperature.

Kim (2012) had used the notion of energetic efficiency to evaluate the performance of PV/T systems. In this way a total efficiency of 60-80% cases were achieved using the following procedure. Thermal and the electric efficiency were determined separately to have an approach of the PV/T energy efficiency (*Radziemska*, 2009) (*Kim & Kim*, 2012).

3.4.1.1. Thermal efficiency

The thermal efficiency is determined as a function of the solar radiation (E), the input fluid temperature (T_i) and the ambient temperature (T_a). The thermal efficiency is calculated by the following equation:

$$\eta_{th} = \frac{F_R A[E\alpha\tau - U_L(T_{fi} - T_a)]}{AE} \tag{1}$$

Where:

- η_{th} is the thermal efficiency;
- A is the collector area [m^2];
- T_{fi} is the fluid inlet temperature [°C];
- T_a is the Ambient temperature [°C];
- $\dot{m}$ is the mass flow rate[kg/s];
- F_R is the heat removal factor ;
- E is the irradiance on the collector surface [W/m^2];
- α is the absorption coefficient of plate
- τ is transmission coefficient of glazing;

The thermal efficiency (η_{th}) of the PV/T collectors was conventionally calculated as a function of the ratio ΔT/E

With:

$\Delta T = (T_{fi} - T_a)$;

3.4.1.2. The electrical efficiency

It is possible nowadays to generate electric power by conversion of solar radiations into electric power. This technology is known as “photovoltaic" (PV), (*Srinivas & Jayaraj*, 2013). Photovoltaic technology relies on the use of cells containing photovoltaic materials. These cells referred to as solar cells are responsible for collecting and transforming solar radiation into electric power.

The electricity efficiency depends mainly on the incoming solar radiation and the temperature of PV module that was used in the tested PVT collectors and is calculated with the following:

$$\eta_{ee} = \frac{I_{sc} * V_{oc}}{AE} \qquad (2)$$

Where:

- I_{sc} is the current [A]
- η_{ee} is electrical efficiency
- V_{oc} is the cell voltage [V]

To maximise the electrical output in this case, the PV module must be at the lower operating temperature under certain conditions of incoming solar radiation intensity, ambient air temperature and wind speed.

3.4.2. PV/T energy Efficiency Determination

PV/T modules are more productive with the ability of generating more energy per unit surface area than side by side PV panels and solar thermal collector. The results regarding the PV/T efficiency can be obtained by addition, since it depends on the thermal and electrical efficiency of the device or the hybrid system (*Tripanagnostopoulos et al.*, 2003).

$$\eta_{PV/T} = \eta_{ee} + \eta_{th} = \frac{W + Q}{H} \qquad (3)$$

Where:

- W is the mechanical work or the electricity produced,

- Q is the thermal energy delivered,
- H is the input energy

And $\eta_{ee} = W/H$ and $\eta_{th} = Q/H$ are respectively representing the electric efficiency and heat efficiency.

3.5. CONCLUSION

Photovoltaic and thermal system was designed to produce heat and electricity from one device. Several concept designs were presented and one was chosen to build the studied model in this work. In addition, a review of PV/T performance of the panel was discussed; drawings of the final design were done in Solid Works simulation software and presented the selected PV panel.

CHAPTER 4:

PV-THERMAL SYSTEM CONCEPTION AND DETERMINATION OF PARAMETERS

4.1 INTRODUCTION

Chapter four discusses the PV/T systems using water as heat extraction agents. It presents the model constructed and also covers the analytical and experimental models of a photovoltaic thermal PV/T water solar collector's as well as the determination of the electrical and thermal efficiencies of the PV/T solar collector.

4.2. PV/T MODEL

The PV/T model consists of a single basin with an area 0.3819m^2 (670mm x 570mm) and thickness 4mm made out of black painted aluminium sheet metal at the back of the PV.
This PV/T contains water as a thermal transfer fluid for the solar collector model; it was built in accordance to what was envisaged earlier in the previous design see Figure 20, 21,22 and 23.

4.2.1. Conception of the PV/T

The construction of the PV/T water system was done using the following items:

- A container
- A Photovoltaic module
- Aluminium metal sheet
- Tubes
- Glue
- Woods for the frame
- Joints
- Thermometers

An aluminium metal sheet was cut and bound at the back of the PV module Figure 24 and 25 seen above instead of using pipes, after drilling two holes through the panel frame for water circulation. This metal was used as a solar collector to be attached together with the PV module. To perform the closed loop system, a water inlet and outlet holes were drilled on the container, just next to the hole two thermometers were fitted to read the water temperature before adding tubes and joints to close the PV/T system as shown in Figure 26 below. The specifications of the PV module used for this work are shown in Table 2 above.

Table 2: Panel type Information

TEMPERATURE COEFFICIENTS	
Voltage	-79.20mV / degree C
Current	+1.50mA/ degree C
Power	-0.46% / degree C
NOCT (degrees)	45
CELLS	
Type	Multi-Crystalline
Dimensions	156mm x 52mm
Layout	36 cells (4rows x 9cells)
GENERAL INFORMATION	
Maximum Power	55 W
Type of connection	Junction box
Frame	25mm black powder-coated aluminium
Weight (kg)	11
Open circuit voltage	21.90 v

Figure 26: Constructed PV/T model for experimentation

4.2.2. Operation of the PV/T device

The system of this solar energy device operates using water is shown in Figure 27 as a heat extraction agent. Tap water was used as a heat transfer fluid because of its availability and good thermal properties: it has good thermal conductivity, a large thermal capacity, low viscosity, and presents no hazard. The water carries heat from the PV module by cooling the cells; the water is then released out of the device by a natural convection or free circulation (as shown in Figure 27. However the system used for this research was a closed loop PV/T system; because the heated water was not drained to cool it off for the next water cycle circulation. Therefore the heat from the module is conducted through the panel by water; this heat can be converted into thermal energy in order to enhance the electricity performance of the PV module, and heated fluid flows into the container.

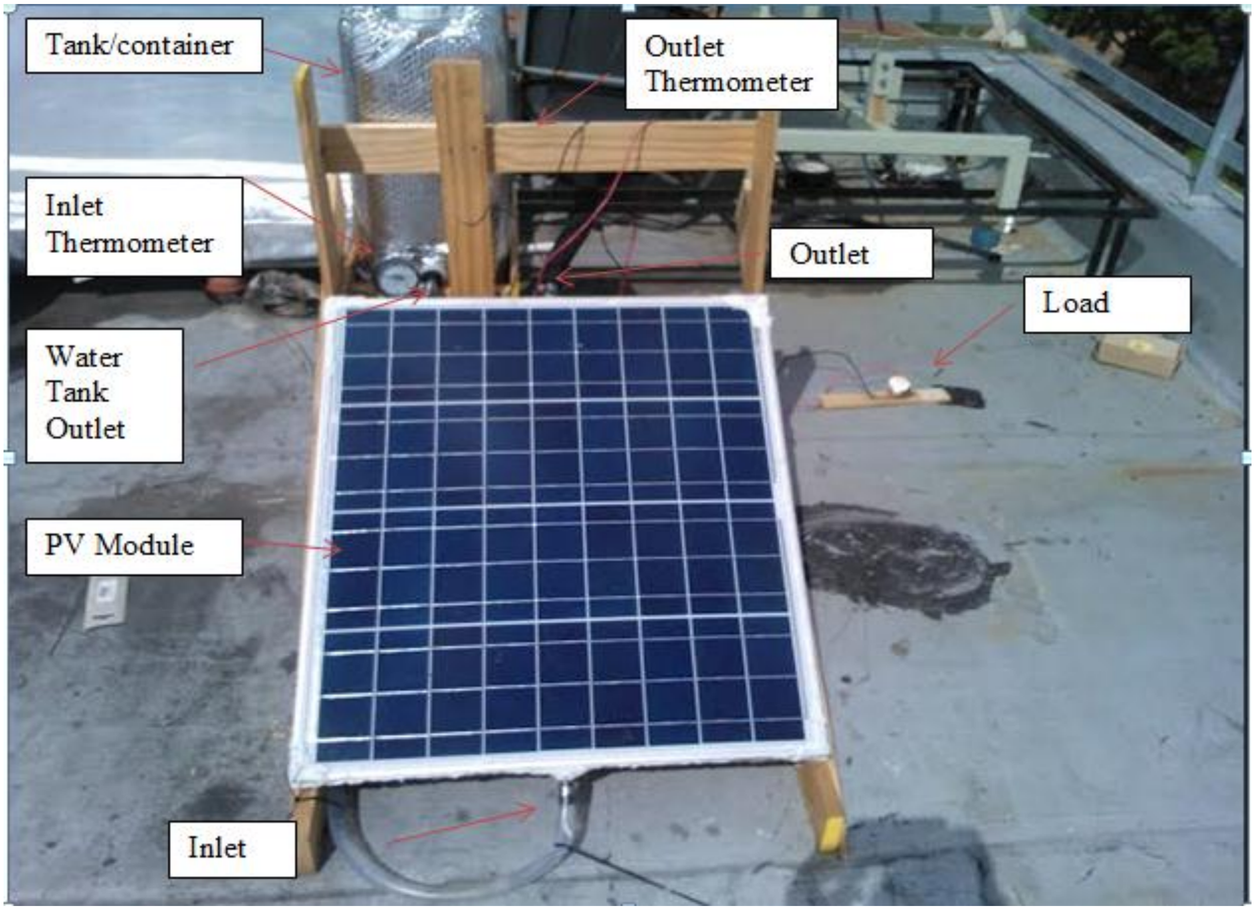

Figure 27: View of the PV/T used for the experiment.

4.3. THEORETICAL THERMAL ANALYSIS OF THE COLLECTOR

In a PV/T water solar collector, the energy absorbed by the cell is distributed to thermal losses and energy gain over the top, the back and the edges. The heat loss through the system was evaluated in term of convection and radiation heat transfer mechanisms between different components. This convective heat loss is expressed in term of thermal equivalent length of the illuminated surface (*Iordanou*, 2009).

4.3.1. Heat loss of the PV/T water solar collector

The determination of the heat loss coefficient depends on the nature of heat transfer. The types used in this research are convection and radiation heat transfer. These heat transfer modes of a surface are influenced by the geometry of the PV/T surface as well as its tilt angle.

They also depend on the variation of temperature on the surface and the properties of the fluid and the materials. Natural convection heat transfer is correlated in term of three (3) parameters which are the Nusselt Number (N_u), Rayleigh Number (R_a) and Prandtl Number (P_r), but only the relationship between Nusselt and Rayleigh Number was considered in this work as shown in equation 4 (*Betts et al*., 2006).

$$N_u = 1 + 1.44\left[1 - \frac{1708(sin1.8\beta)^{1.6}}{R_a cos\beta}\right]\left[1 - \frac{1708}{R_a cos\beta}\right]^{+} + \left[\left(\frac{R_a cos\beta}{5830}\right)^{\frac{1}{3}} - 1\right] \quad (4)$$

(+) exponent mean that only positive values of the term in the bracket should be considered, if negative uses zero.

Rayleigh number can be determined by;

$$R_a = \frac{g\beta' \Delta T W^3}{\nu_a \acute{a}} \quad or \quad R_a = \frac{g(T_g - T_p)W^3(P_r)}{\nu_a^2 \frac{(T_g - T_p)}{2}} \quad (5)$$

With,

W: width of the panel.

To calculate the (Ra) Holman(2004) used a correlation to evaluate the air properties as the arithmetic mean of the corresponding temperature of the collector (*Mittelman et al.*, 2007)

- $k_a = 0.0002067 \ \ T_m^{0.85}$ (6)
- $\nu_a = [9 + 10^{-5} T_m^2 + 0.004 T_m - 4.17] * 10^{-6}$ (7)
- $P_{r_a} = 1.0602 - 0.602 * \log T_m$ (8)

Where;

k_a: Thermal conductivity of air (m^2/s)

P_{r_a}: Prandtl Number of air

With mean temperature;

$$T_m = \frac{T_t + T_b}{2} \tag{9}$$

Where:

$\Delta T = T_g - T_p$

T_b: Collector Plate temperature (°C)

T_t: Cover glass temperature (°C)

ν_a: Kinematic viscosity of air (m^2/s)

ά: Thermal diffusivity (m^2/s)

The collector overall lost coefficient (U_L) was determined by evaluating the sum of the PV/T losses which are the top , the back and the edges, but in this case the edges losses were considered to be negligible, sensibly equal to zero (*Dg*, 2002).

$$U_L = U_t + U_b \tag{10}$$

Where the top heat loss coefficient may be given by,

$$U_t = (h_{cpg} + h_{rpg})^{-1} + (h_w + h_{rga})^{-1} + \frac{\delta_g}{K_g} \tag{11}$$

And the back heat loss coefficient gave;

$$U_b = \frac{K_a}{L_1} \tag{12}$$

K_p: Thermal conductivity of aluminum

K_g: Thermal conductivity of the glass

4.3.2. Determination of heat loss coefficient at the top

Convection and radiation heat from the device were considered to evaluate the top heat loss coefficient, to obtain the expression for the heat loss between the different materials. Heat loss from the absorber plate to the glass cover give:

$$q_t = (h_{cpg} + h_{rpg})\,(T_t - T_b) \tag{13}$$

And from the cover to atmosphere by:

$$q_t = (h_w + h_{rga})\,(T_t - T_b) \tag{14}$$

Where,

$$h_{cpg} = \frac{N_u * K_a}{L_1} \tag{15}$$

$$h_{rpg} = \left\{\frac{\sigma}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_g} - 1}\right\}\left({T_t}^2 - {T_p}^2\right)\left(T_t - T_p\right) \tag{16}$$

$$h_{rga} = \sigma * \epsilon_g \frac{\left({T_t}^4 - {T_a}^4\right)}{(T_t - T_a)} \tag{17}$$

At 30°

$$h_w = 7.70 + 2.9 v_w \tag{18}$$

Where:

σ: Stefan –Boltzmann value

h_{cpg}: Convection heat coefficient between the plate and the glass cover;

h_{rpg}: Radiation heat coefficient between the plate and the glass cover;

h_{rga}: Radiation heat coefficient between glass and air ambient;

h_w: Convection heat coefficient due to wind

v_w: Wind speed

Hence, the equation 10 of heat lost should be;

$$U_L = [\frac{N_u * K_a}{L_1} + \left\{\frac{\sigma}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_g} - 1}\right\}\left(T_p{}^2 - T_g{}^2\right)\left(T_p{}^2 - T_g{}^2\right)]^{-1} + (h_w + \sigma * \epsilon_g \frac{\left(T_g{}^4 - T_a{}^4\right)}{\left(T_g - T_a\right)})^{-1} + \frac{\delta_g}{K_g} + \frac{K_1}{L_1}$$

4.3.3. Determination of useful energy

Duffie and Beckmann (1991) suggested in their research on solar collector for a steady state that the useful energy gain should be the difference between the absorbed solar radiation and the thermal loss or the useful Energy output of a collector. It was defined by the following expression;

$$Q_u = A[E\alpha\tau - U_L(T_m - T_a)] \tag{19}$$

4.3.4. Mass flow rate of natural circulation

Mass flow rate is seen as an important parameter in designing a PV/T system. The convection heat transfer coefficient is sensitive to mass flow rate variations. Nowee (2014) stated in his investigation on PV/T that the energy collected was converted to the thermal energy of water in the system, which defined Q_u as the amount of heat that was recovered in the photovoltaic/thermal system, the rate of extraction heat from it can be measured by means of the amount of the fluid passed through it, which is:

$$Q_u = \dot{m} C_p (T_{fo} - T_{fi}) \quad (20)$$

Where,

$\dot{m}$: Mass flow rate

C_p: Heat capacity

T_{fo}: Temperature of the fluid out

T_{fi}: Temperature of the fluid in

The water mass flow rate of this device can be calculated using the relation in the equation (20) and the equation for useful heat energy collected.

Thus,

$$\dot{m} = {Q_u}/{C_p (T_{fo} - T_{fi})} \quad (21)$$

Note that in practice this values were supposed to change instead of being constants, because heat losses will increase as the temperature of the collector rise further above ambient temperature due to thermal conductivity of the materials (*Moradi et al.*, 2013).

4.3.5. Heat removal factor

As mentioned on the paragraph above, under steady-state conditions the useful heat delivered by a solar collector is equal to the energy absorbed by the heat transfer fluid minus the direct heat losses from the surface due to the conditions around the PV/T. The useful energy collected from a collector can lead to obtain the removal factor using the following relation:

$$Q_u = F_R A [E\alpha\tau - U_L (T_{fi} - T_a)] = \dot{m} C_p (T_{fo} - T_{fi}) \quad (22)$$

Where inlet fluid temperatureT_{fi} was modified and used to substitute the average plate temperature to determine the heat removal factor included.

Hence;

$$F_R = \frac{Q_u}{A[E\alpha\tau - U_L(T_{fi} - T_a)]} \quad (23)$$

For incident angles about 35° , the product α times τ is essentially constant as referred to Table 4 below depicts the variation of absorptance, and Table 3 has the values used to for the calculation using All equations above.

Table 3: Variables and constants used for efficiency expressions

Variables	Value	**Unit**
Emissivity of the glass ($\in_g$)	0.9	
Emissivity of the Plate ($\in_p$)	0.88	
Thickness of the glass (δ_g)	0.003	m
Spacing between absorber and the glass cover (L_1)	0.035	m
Gravitational acceleration (g)	9.8	m/s^2
Tilt angle (β)	30	°
Thermal conductivity of aluminium (K_a)	211	$Wm^{-1}k^{-1}$
Thermal conductivity of glass (K_g)	0.8	$Wm^{-1}k^{-1}$
Area of the collector (A)	0.3819	m^2
Heat capacity (C_p)	1000	J/Kg.K

Table 4: Variation of absorptance adapted (*Anon*, n.d.)**.**

Incidence angle β(º)	Absorptance $\alpha\tau$
0–30	0.96
30–40	0.95
40–50	0.93
50–60	0.91
60–70	0.88
70–80	0.81
80–90	0.66

4.5. THEORETICAL ANALYSIS OF THE PV/T COLLECTOR PERFORMANCE

It was mentioned in the literature review that PV/T system was a separated systems that consist of a solar collector and a PV module attached together to generate simultaneously electricity and heat energy. The efficiency is an important parameter which has to be considered for this PV/T (*Miroslav Bosanac*, n.d.). The performance of this device which is the collector efficiency has to be calculated separately, since the solar water collector has a steady state thermal efficiency given by;

$$\eta_{th} = \frac{F_R A[E\alpha\tau - U_L(T_i - T_a)]}{AE} \qquad (24)$$

And the electrical efficiency for the photovoltaic module given by;

$$\eta_{ee} = (FF)\frac{I_{sc} * V_{oc}}{AE} \qquad (25)$$

So, the performance of the PV/T will be the sum of thermal and electrical efficiency.

$$\eta_{pvt} = \frac{F_R A[E\alpha\tau - U_L(T_i - T_a)]}{AE} + \frac{I_{sc} * V_{oc}}{AE} \qquad (26)$$

4.6. CONCLUSION

This part of the research was focus on theoretical aspects of Thermal analysis of the collector and the analysis of the PV/T collector Performance. The heat loss through the system was evaluated and radiation heat transfer mechanisms between different components.

CHAPTER 5:

EXPERIMENTAL RESULTS, DISCUSSIONS CONCLUSION AND RECOMMENDATIONS

5.1. INTRODUCTION

This chapter presents the entire work of this research, the experimental process, the result of the efficiency of the PV/T water solar collector , graphs representation of the main results using excel and interpretations of the results.

5.2. EXPERIMENTAL PROCESS

The experiment of a scale model constructed and tested PV/T water system was done in the Western Cape Province (South Africa). The experiments parameters were collected for seven (7) days during the period of March 2016 from 8:00am to 18:00pm each day. The solar radiation and atmospheric temperature data were collected from the weather station of the Mechanical Engineering Department of Cape Peninsula University of Technology (CPUT) in "Bellville campus".

The following measurements were collected from the weather station of the department which has been connected whit a data log monitor located on top of the building roof see appendices A, B & C:

- Solar irradiation or insolation
- Ambient temperature of the location
- Wind speed

The rest of the data were measured manually:

- Current and Voltage
- Top and the back temperature of the PV/T device.
- Temperature inlet and outlet of the fluid.

The PV/T water system was tested to determine its electrical and thermal performances at steady conditions for various operating temperature. The inlet temperature of water was not constant due to the type of system implemented "Close loop system", it changes as the outlet temperature changes too. For measuring the load current and load voltage multi-meters were used separately, besides an error of ± 0.3% was considered for all the measurements. The PV/T collector was operated at a variable mass flow rate during the experimentation. Digital infrared temperature gun was used to record the top and the back temperature of the panel.

For the determination of system thermal efficiency, the PV/T device was connected with a load to avoid PV module overheating and to simulate real system operation using the solar radiation that is converted into heat instead of electricity.

All the data related to the electrical and thermal performances of the PV/T were taken with thirty (30) minutes of interval between the values. This data were used to evaluate the overall efficiency of the PV/T solar collector water based. Figure 28 shows illustration of the different parameters measured to analyse the performance of the collector.

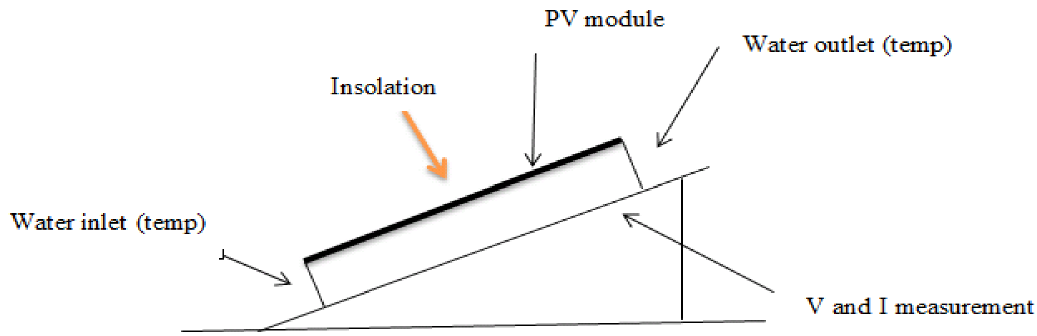

Figure 28: Schema to indicate different parameters measured during experimentation

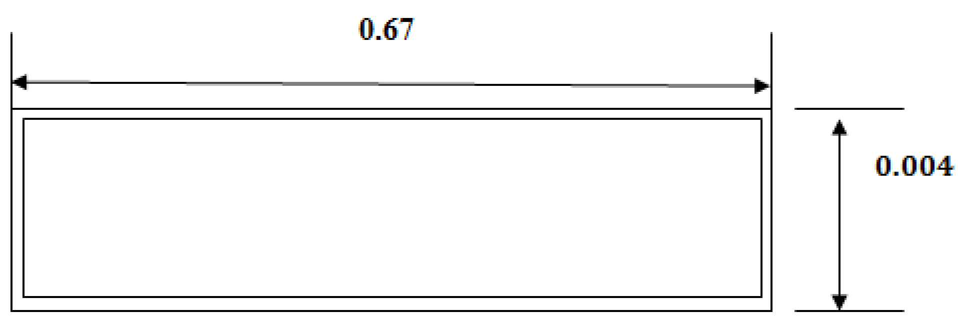

Figure 29: Schema of the PV/T collector side

5.3. RESULTS AND DISCUSSION

PV cells are suffering from low electrical energy efficiency due to the warming of the cells and the unavailability of low ambient temperature for cooling warm PV cells. Thus, by placing a solar thermal collector behind a solar photovoltaic PV module, the PV cells can be cooled up while at the same moment recovering the heat. In fact, the solar collector can return most of the energy that passed through the module that would probably be lost, then recovering it for useful and productive applications. In this situation, the PV cells were cooled by solar thermal collector with inlet and outlet fluid flow inside the absorber as shown in Figure 29. The heat produced by the solar cells was utilized to warm the water under the module in order to control the temperature of the PV by the flow of the cooling fluid.

The determination of the useful energy gain, the mass flow rate and the efficiency of the PV/T collector were calculated using equations (19), (20) and (26) with the aid of Microsoft Excel software. The hourly variation of the ambient temperature, water inlet and outlet temperature, solar radiation for the seven days are shown in appendix A, B and C. During the test, the maximum hot water temperature 44℃ of the system was obtained while the ambient temperature was at 38.8℃.

The efficiencies results plotted on the graphs below were based on performance analysis for seven days data obtained. All the value were recording with an intervals of 30 minutes on the days of experiments (from 14^{th} to the 20^{th} of March 2016) as shown on appendices A, B and C. Figures below show the efficiencies results of the collector versus time from the first day to the last day of experiment. The results on the graphs represent the values of thermal and electrical efficiency at a specific time of the day.

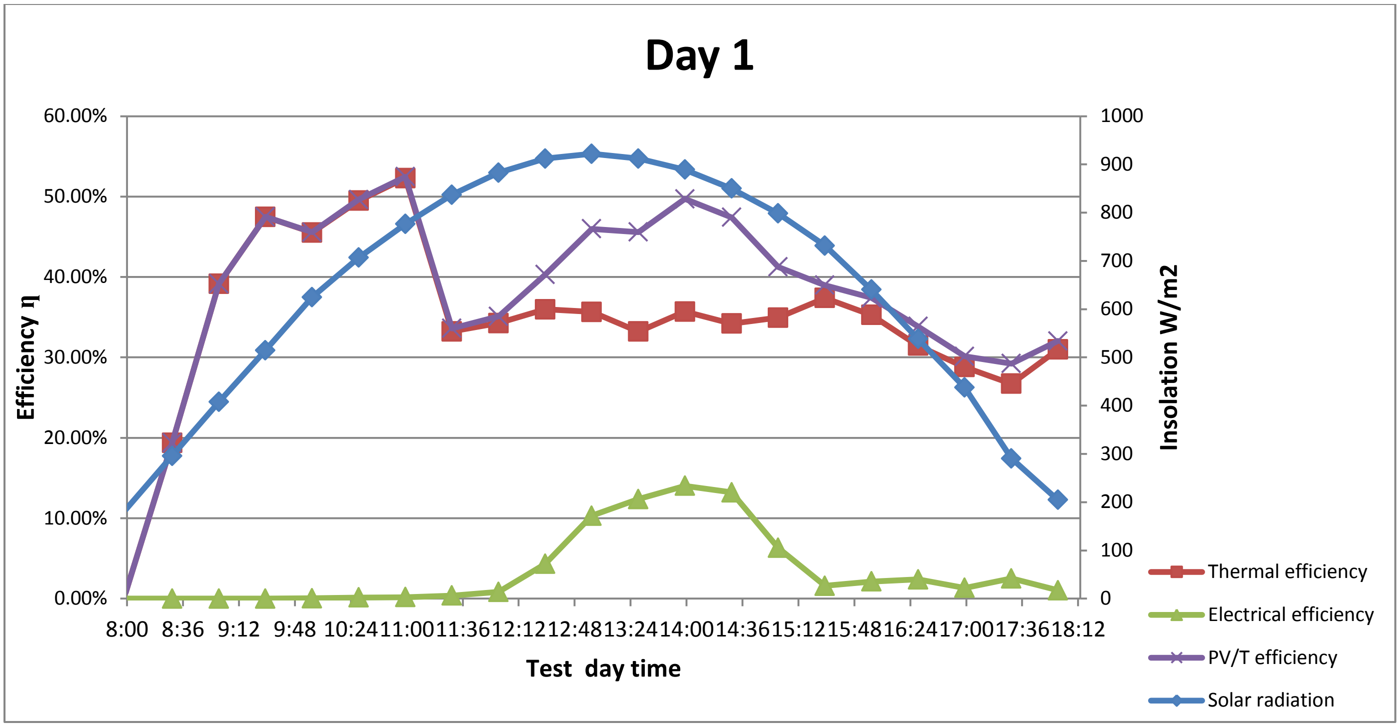

Figure 30: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 1.

Figure 30 presents efficiencies of four distinctive parameters (Thermal efficiency, electrical efficiency, PV/T efficiency, solar radiation) with time assessed in Day 1. The results show that from 08:00 to 11:00 am, Thermal and PV/T efficiencies exhibit increase fluctuation that reached a maximum of 53% that later decreased to 33% between 11:00 and 11:30 am. Conversely, from 12:00 to 18:00 pm the aforementioned efficiencies repetitively increased and progressively decreased with PV/T dominating over thermal efficiency. On the other hand, the solar radiation efficiency shows a parabolic tendency with a progressive increase up to 55 % from 08:00 to 12:30 pm that continuously dropped to 11% between 12:30 to 18:00 pm. Finally, from 08:00 to about 11: 36 Am, the electrical efficiency was 0% and steadily rose to 13% from 11:50 am to 14:00 pm and drastically dropped to 2% from 14: 30 to 15:30 pm and became constant till 18:00 pm.

Here, the first peak observed at 11am was due the connexion of the load on the circuit to be able to read the current generated by the PV module. The curves related to electricity and thermal efficiency shown the performance during the preparation of the experiment before the normal operating system. We also noticed when the thermal efficiency drop the inlet temperature started to rise from 18° to 20°.

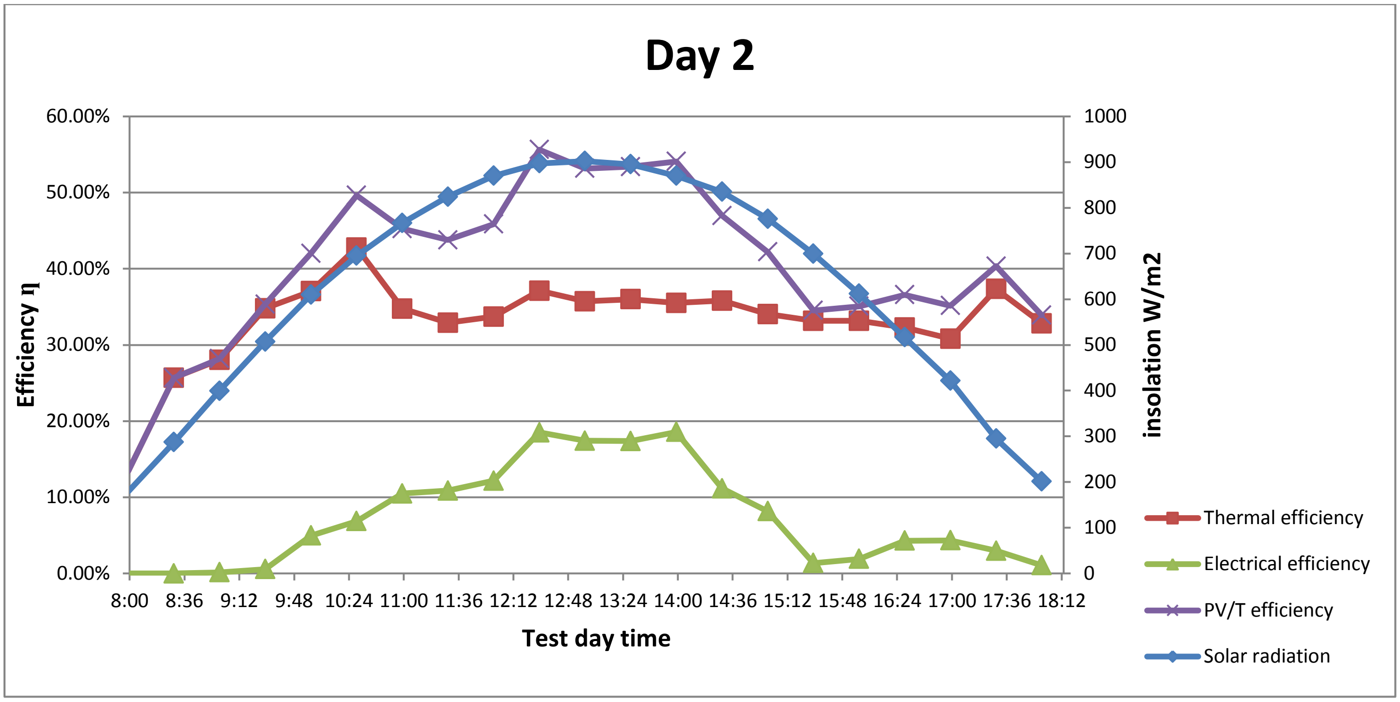

Figure 31: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 2.

The designed PV/T was responding as expected to the solar radiation, the results on the second day of the experiment were expressive compared to the starting day. The results plotted in Figure 31 show that from 08:00 to 10:30 am, Thermal and PV/T efficiencies exhibit increase until a value of 44% that later decreased a bit between 11:00 and 12:30 am. On the other hand from 12:12 to 18: 12 pm the above-mentioned efficiencies repetitively increased and progressively decreased with PV/T dominating over thermal efficiency. The solar radiation efficiency shows a parabolic tendency again with a progressive increase from 08:00 to 12:48 pm that continuously decrease to 11% between 12: 48 to 18: 12 pm. Finally, from 08:00 to about 9: 30 am, the electrical efficiency was 0% and steadily rose continuously from 11:50 am to 14:00 pm and drastically dropped from 14: 00 to 15:30 pm. The highest value on the electrical efficiency was obtained 18.89%. The thermal efficiency of the PV/T was influenced by thermal condition of heat exchange parameters such as heat losses and energy useful referred Figure 31.

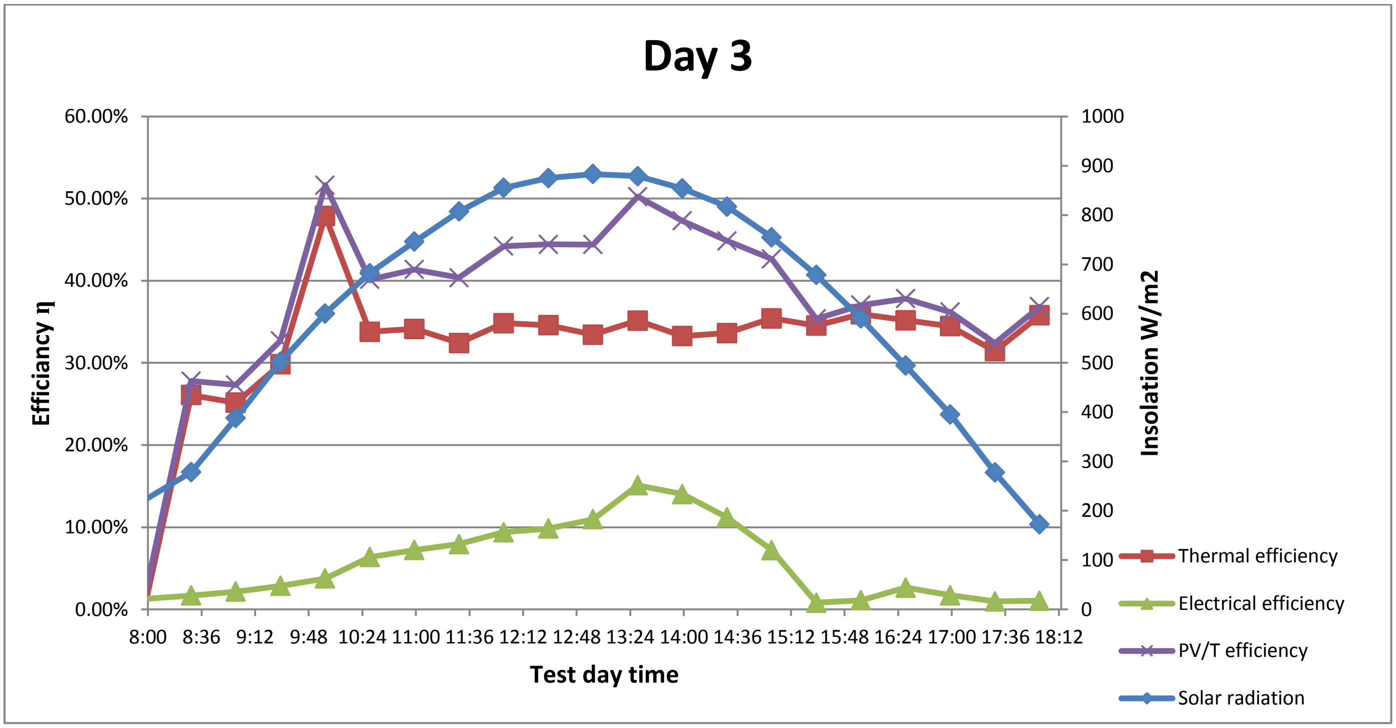

Figure 32: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 3.

From the recorded data calculated, Figure 32 presents values of four characteristic parameters (Thermal efficiency, electrical efficiency, PV/T efficiency, solar radiation) with time assessed in Day 3. The curves of thermal efficiency show a brutal drop point from 48% to 33% between 9:30 to 10:30; and the electrical efficiency curve shows an intense peak at 13.30pm with an efficiency of 15.09 %. These results are explained by the presence of the mixture of water in the system. . Also from 10:30 to 18:00 the Thermal efficiency swings slightly up and down like between 33% and 36%. The PVT shows the exact intense peak but with greater efficiency, while the electrical efficiency became quickly efficient compares to on day 1 and 2, reach its higher value around 13:30 sensibly of 16%.

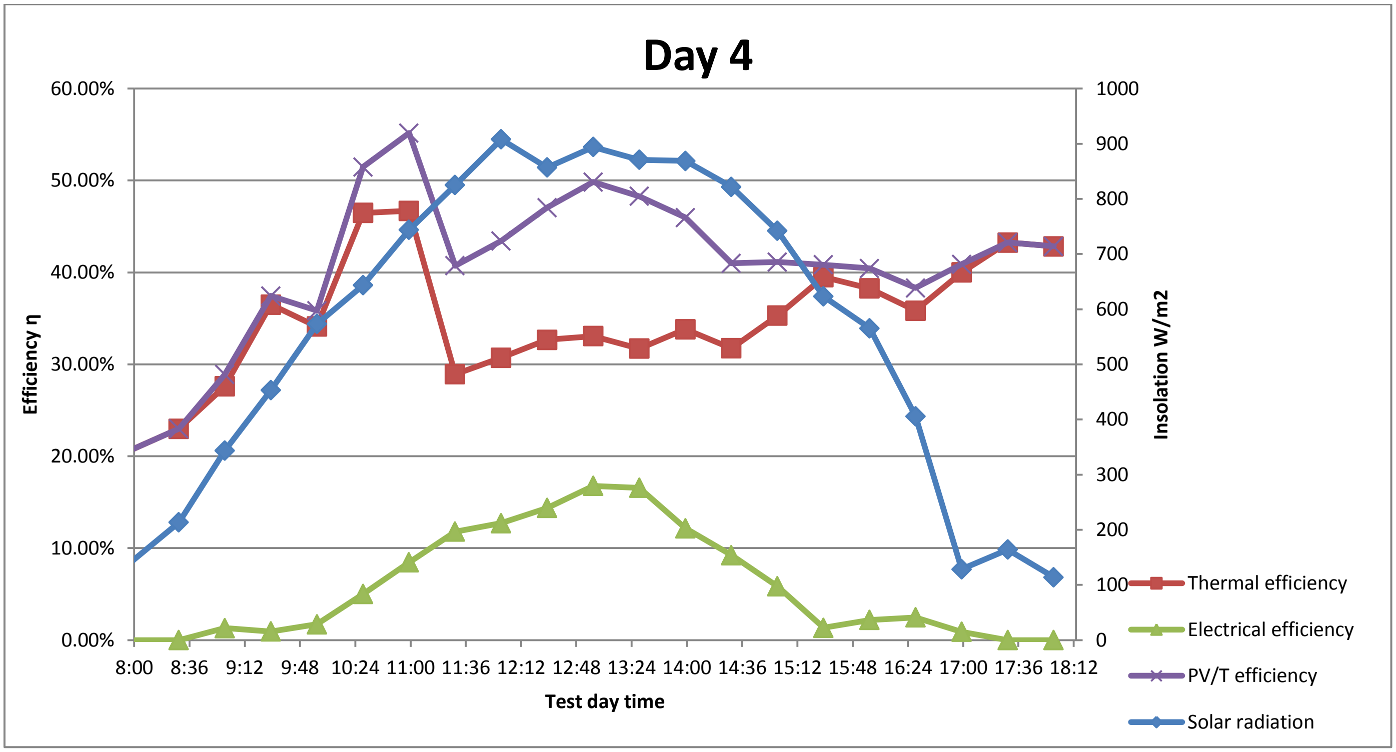

Figure 33: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 4.

The same observation as Figure 32 was done on the Figure 33, but with slightly differences on the time where the electrical efficiency occurred, the thermal efficiency dropped and a little change on the solar radiation. The parabolic curve observed from 9:30 to 15:30 on the electrical efficiency was due to the solar radiation. On the other hand the thermal efficiency reached a maximum between 9:30 and 10:30 of 48%, before dropped and started rise to 42% from 11:30 to 18:00. The maximum value of the PV/T efficiency was observed at 11:00. Moreover, the parabolic increase and decrease behaviour of solar radiation observed between 08:00 am and 18: 10 pm was due to the angle of the panel facing the sun.

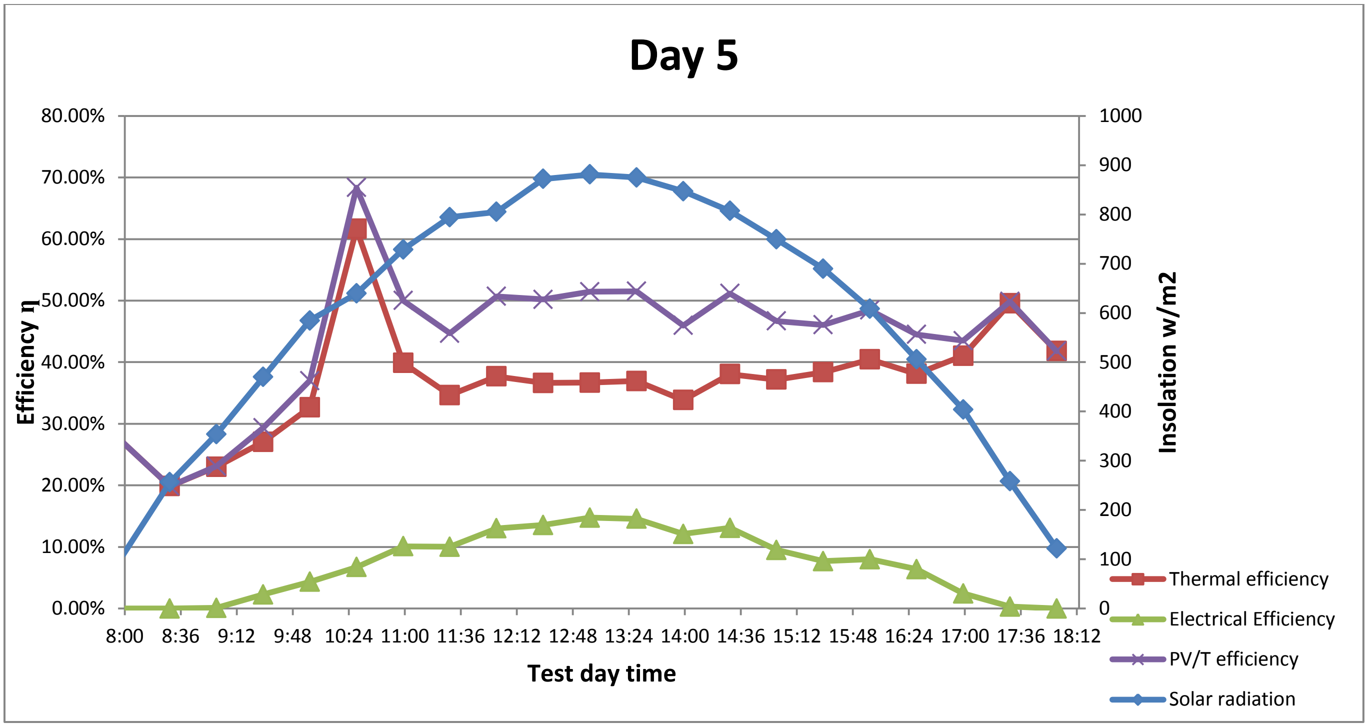

Figure 34: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 5.

In Figure 34, the quick rising of the electrical efficiency observed could be explain by the high insolation from 9:00 to 17:30, it varied and reached a maximum value of 13%. The thermal efficiency reached its peak to 62% at 10:30. This can be explained by the usage of a closed loop system because of the mixture of cold and warm water provoked a rising of inlet temperature which at a certain time of the day does not cool the PV module anymore to affect the electrical efficiency and the PV/T efficiency. Equally, from 11:00 to 18:00 the PV/T and thermal efficiencies repetitively increased and progressively decreased with PV/T dominating over thermal efficiency until the electrical efficiency were nil.

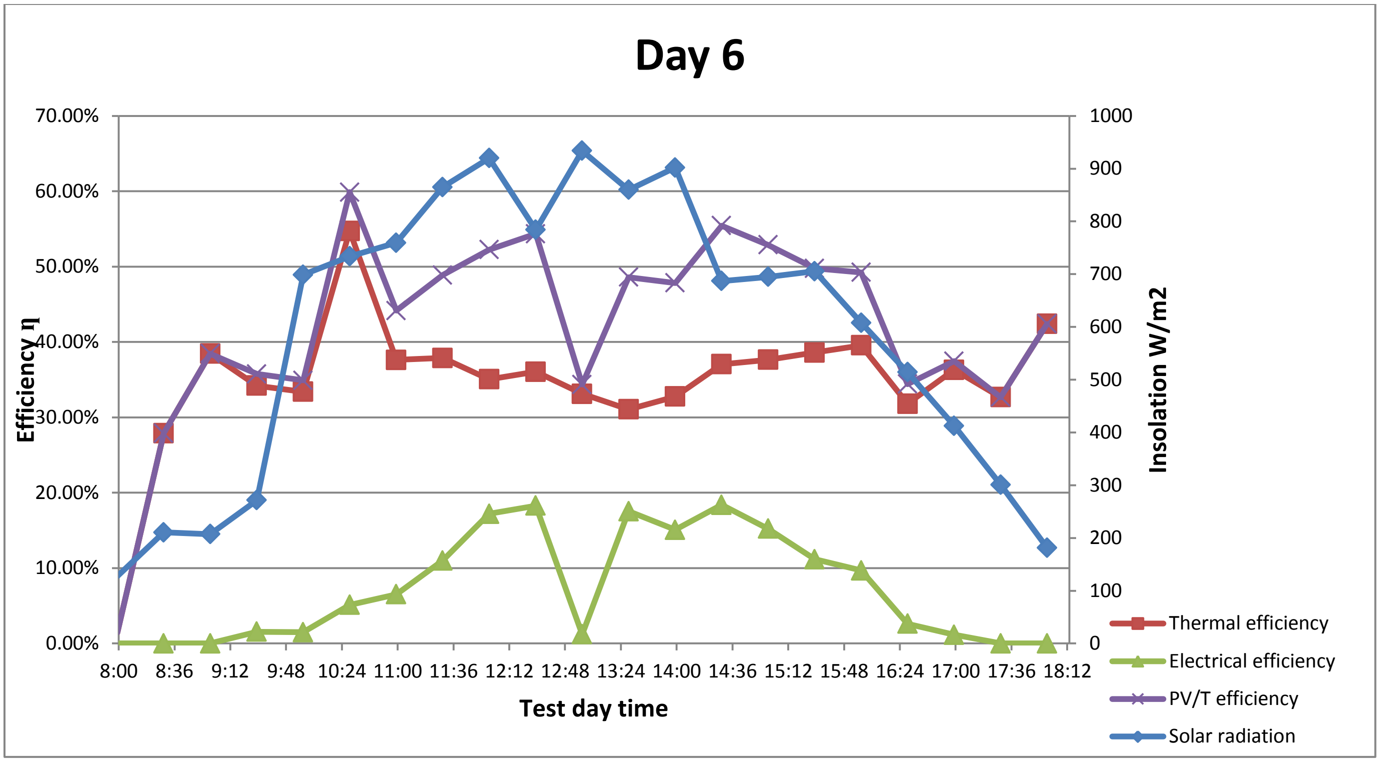

Figure 35: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 6.

The results on Figure 35 are completely different. Solar radiations dropped at 12pm from 902 W/m² to 785.1 W/m², with a dramatic slip of the electrical and PV/T efficiencies at 12:30. As the inlet temperature increased the thermal efficiency decreased and became more or less constant with a peak of 55% at 10:00. The fluctuation of the electrical efficiency remained very low compared to thermal efficiency, but more important compare to the previous days with five plotted value over 15% of efficiency. Finally, from 08:00 to about 9:30, the electrical efficiency was 0% and steadily rose to 13% from 10:00 am to 12:30 and drastically dropped to 0% from 12: 30 before rose again from 12:30 to 18% and progressively dropped till 18:00 pm.

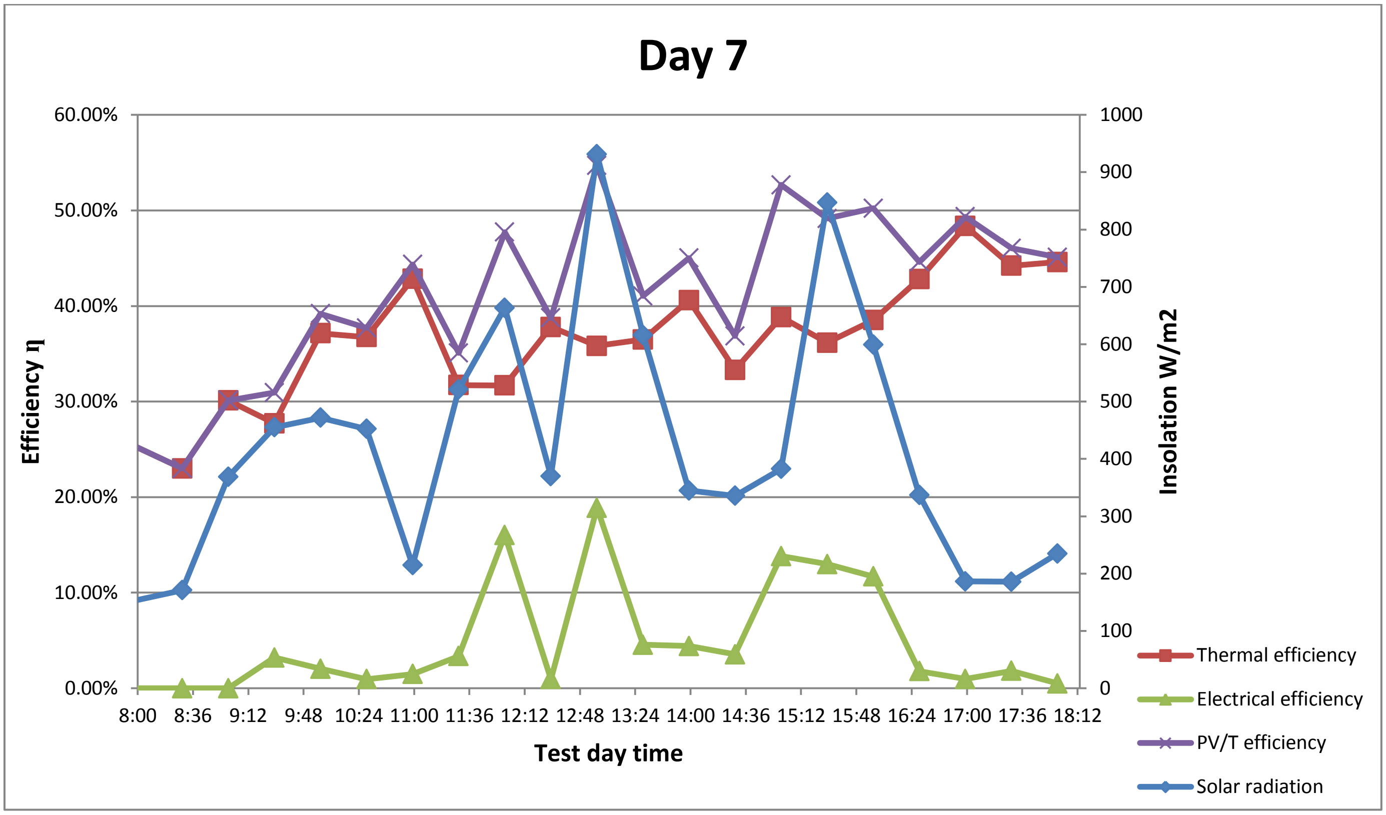

Figure 36: Graphical plot of test result of efficiencies (thermal, electrical and PV/T) as function of time during day 7.

In this figure, several peaks related on or to the different efficiencies are noticeable, therefore the reaction which occurs on solar radiations dropped at 12:00, 13:00 and 15:30 lead to the yield observed for these efficiencies. The Electrical efficiencies are low and not constant compared to thermal efficiency and it depends more on the solar radiation at the time of the day. Two peaks occurred for the electrical efficiency with the best efficiency of 19% at 13:00.

In general , electrical efficiency varied between 0% to 18.89%, thermal efficiency from 0.76% to 61.65% and for the PV/T water solar collector efficiency between 1% to 68% with an average value of 41%., Figures above are the perfect illustration of it. During testing days, the water got warm to a maximum temperature of 44℃.

5.4. CONCLUSION

The impact of low energy efficiency of PV module in the market globally and particular in South Africa increases the payback period of the system and increase the cost of energy produced. The main objective of this research was to develop, build and test a solar energy system that can help on resolving the problem of low efficiency. A literature review on available works, experiments, and analyses of PV/T liquid systems using water as fluid was presenting a low increase in electrical efficiency but a considerable yield on the overall PV/T efficiency, because of the simultaneous operation of this system coupling with a thermal collector. Design and constructed PV/T were described.

The electrical efficiency of the PV/T was obtained from the ratio of the output electricity to the incident solar radiation with a maximum value of 18.89%. The thermal efficiency of the water PV/T was defined as the ratio of the output heat to the incident solar radiation with a maximum temperature of water heated at 44℃. From the PV/T model, it was found that the results of thermal efficiencies was more favourable to be used, This showed that the effect could not be neglected in the calculation of the global PV/T efficiency. It was also shown that using water to cool the PVT system could help increase the electrical efficiency to a better performance with decrease of solar radiations on the PV module.

Additionally, the PV/T presented a considerable yield on the overall PV/T efficiency, because of the simultaneous operation of the PV module and the thermal absorber even if the results still need to be improved. The fact of enhanced the energy efficiency on the PV/T will increase the competitiveness of PVT collectors and utilization of renewable energy devices.

5.5 RECOMMENDATIONS

Future work should have different approaches, especially on the system itself. The principle of using a coolant should have met the expectation on the electrical efficiency at a certain temperature if the system was not a closed loop using the same circulating water. The eventual heat capacity of water should be considered non constant since it can change according to the ambient temperature to determine the mass flow rate. The celling between the PV module and the absorber should be properly done instead of usage of cheap glue, it will be probably better to well if the materials choose match. Also extend the period and time of experimentation to have a strong view during the four seasons (winter, summer, autumn and spring).

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APPENDIX A: DATA

					Collector					
Days	Time	Amb temp	inlet temp	outlet temp	Temp on top	Back temp	Current(I)	Voltage(V)	Irradiance	Wind Speed
03/14/2016										
	08:00	9.39	18	18	13.2	18.6	0	19.95	184.3	1.7
	08:30	12.99	18	18	16.7	20.4	0	19.95	296	1.7
	09:00	19.23	18	18	17.1	19.2	0	19.95	407.6	1.7
	09:30	20.39	18	20	14.6	15.6	0	19.95	514.8	2.45
	10:00	22.33	18	22	15.6	17.8	0.12	0.74	624.8	3.95
	10:30	24.69	18	28	18.4	13.2	0.38	1.02	706.6	3.2
	11:00	28.23	18	30	19.2	13.1	0.46	1.22	776.5	3.95
	11:30	28.81	19	32	34.1	32.1	0.8	1.54	837	6.2
	12:00	31.04	21	36	35.5	33	1.25	2.27	883	5.45
	12:30	31.81	24	38	38.6	26.9	2.44	6.16	912	4.7
	13:00	33.14	27	40	40	29.1	3.48	10.44	922	6.2
	13:30	32.82	30	41	42.2	33.4	3.65	11.82	912	4.7
	14:00	35.3	31	42	42.7	30.6	3.89	12.24	889	5.45
	14:30	34.66	32	42	43.2	32.7	3.52	12.18	850	4.7
	15:00	38.43	32	42	46.1	35.2	2.11	9.12	798.3	5.45
	15:30	39	34	40	45.4	30.9	1.62	2.74	731.7	5.45
	16:00	37.53	34	39	45.7	32.2	1.72	3.04	640.3	6.2
	16:30	34.09	34	39	45.3	31.8	1.7	2.9	538.3	6.2
	17:00	31.85	34	39	43.6	30.9	1.05	2.12	437.5	5.45
	17:30	31.96	34	38	40.2	32.7	1.18	2.36	290.7	5.45
	18:00	32.34	34	38	39.3	28.9	0.52	1.56	204.6	4.7
03/15/2016										
	08:00	12.93	19	19	15.4	19.1	0	19.95	179.2	6.2
	08:30	14.99	19	20	17.5	19.3	0	19.95	287.2	6.95
	09:00	17.98	19	20	22.2	22.1	0.24	0.94	399.3	6.95
	09:30	20.27	19	21	24.6	18.2	0.8	1.36	507.2	8.45
	10:00	23.34	19	22	25.5	20.6	2.4	4.82	609.6	9.95
	10:30	24.26	20	26	18.2	20.8	2.68	6.8	695	7.7
	11:00	26.56	20	28	32	25.2	3.12	9.85	766.5	8.45
	11:30	27.03	20	31	34.6	28.5	3.35	10.21	824	10.7
	12:00	28.48	21	34	35.4	29.2	3.76	10.75	870	9.2
	12:30	28.61	22	36	32.1	24	4.44	14.28	897	11.45
	13:00	28.79	23	36	34.6	25.4	4.3	13.96	902	12.2
	13:30	29.2	24	37	34.5	25.6	4.28	13.88	895	11.45
	14:00	30.52	26	38	37	27	4.34	14.22	870	12.2
	14:30	30.14	27	38	36.6	25.8	3.52	10.12	835	12.2
	15:00	31.2	28	37	38.5	30.1	3.02	8.01	775.7	10.7
	15:30	31.1	30	37	39	30.7	1.5	2.44	699.2	11.45
	16:00	31.66	30	37	39	30.9	1.61	2.79	611.6	9.95
	16:30	29.75	30	36	37.6	28.7	2.23	3.81	516.7	10.7
	17:00	28.74	31	36	36.2	28.6	1.86	3.77	421.6	9.95
	17:30	29.38	32	36	31.7	26.5	1.38	2.44	294.8	9.95
	18:00	28.8	32	34	33.3	26.5	0.72	1.14	201.2	9.95
03/16/2016										

APPENDIX B: DATA

	08:00	12.32	20	21	20.8	21.8	0.83	1.34	174.3	1.7
	08:30	16.16	20	21	18.3	20.6	1.08	1.66	278.3	3.95
	09:00	17.31	20	22	22.6	23	1.36	2.35	388.2	2.45
	09:30	20.96	20	22	24	26.9	1.86	2.96	502.3	3.2
	10:00	24.31	20	23	15.1	19.5	2.1	4.1	600.3	3.95
	10:30	28.59	20	26	31.4	31.5	2.44	6.8	682	3.95
	11:00	29.28	21	30	34.2	29.9	2.74	7.52	746.1	2.45
	11:30	30.01	22	34	36.4	34.1	2.9	8.45	807	4.7
	12:00	33.2	23	38	37.8	33.4	3.22	9.52	855	3.95
	12:30	35.21	24	42	40.5	35.6	3.34	9.84	875	2.45
	13:00	35.18	24	43	42.2	37.2	3.62	10.22	883	3.95
	13:30	38.8	25	44	43.8	38.1	4.06	12.48	879	6.95
	14:00	37.28	26	43	47.8	36.2	3.86	11.86	854	7.7
	14:30	37.08	28	42	44	38.1	3.45	10.14	817	7.7
	15:00	38.26	28	42	43.8	35.7	2.82	7.38	754.9	7.7
	15:30	38.3	29	40	46	35.2	1.04	2.04	678.3	7.7
	16:00	37.22	30	40	41.8	34	1.1	2.27	590.1	7.7
	16:30	35.91	30	38	40.9	33.2	1.6	3.12	494.7	8.45
	17:00	33.43	31	37	38.7	30.8	1.2	2.16	395.5	7.7
	17:30	31.66	31	36	37.5	30.2	0.8	1.28	277.6	6.95
	18:00	31.58	32	35	36.2	27.4	0.64	1.08	172.7	6.95
03/17/2016										
	08:00	13.37	20	20	14.7	16.5	0	19.95	144.4	3.95
	08:30	15.29	20	20	18.2	18.7	0	19.95	213.3	5.45
	09:00	16.73	20	20	20.8	19.8	0.82	2.06	343.3	3.95
	09:30	19.72	20	20	21.2	18.4	0.8	2.01	453.1	6.2
	10:00	21.34	20	21	24.5	21.8	1.24	3.04	573.1	6.2
	10:30	21.3	20	21	18.1	12.4	2.42	5.08	643.4	6.95
	11:00	23.33	20	22	19.3	12.6	2.92	8.22	743.9	4.7
	11:30	23.32	20	24	35.2	30.4	3.5	10.62	825	4.7
	12:00	25.9	21	26	36.4	31.7	3.8	11.6	908	3.95
	12:30	29.49	22	28	37.3	32.1	3.98	11.82	857	3.95
	13:00	30.99	22	30	39.5	32.4	4.39	13.04	894	4.7
	13:30	31.99	22	31	43.8	33.9	4.3	12.82	871	5.45
	14:00	34.19	23	32	44.1	32.1	3.7	10.9	869	5.45
	14:30	31.07	23	33	41.2	33.6	3.04	9.54	822	4.7
	15:00	34.52	24	32	41	31.2	2.54	6.51	742.2	4.7
	15:30	36.32	24	32	39.8	27.5	1.15	2.76	623.2	6.2
	16:00	33.63	25	31	38.2	26.4	1.35	30.5	565.5	6.95
	16:30	31.26	25	30	36.1	27.4	1.32	2.9	405.8	7.7
	17:00	29.4	25	29	33.3	24.3	0.39	1.12	128.4	7.7
	17:30	27.08	26	28	30.5	20.8	0	19.95	164.2	6.95
	18:00	25.1	26	27	28.4	20	0	19.95	114	7.7
03/18/2016										
	08:00	11.3	18	18	13.9	15.2	0	0	159.3	2.45
	08:30	12.25	18	18	15.5	17.7	0	19.95	256.3	1.7

APPENDIX C: DATA

	09:30	17.9	18	19	22.1	25	1.68	2.44	470	3.2
	10:00	21.21	18	20	24.6	23.8	2.28	4.25	584.6	4.7
	10:30	25	18	21	13.4	10.6	2.72	6.04	639.4	4.7
	11:00	27.31	18	22	25.9	22.7	3.1	9.08	728.7	6.95
	11:30	27.16	19	23	31.7	27.1	3.22	9.44	794.3	6.95
	12:00	28.78	19	24	29.4	25.9	3.71	10.78	805	4.45
	12:30	29.68	20	24	32.7	26.7	3.91	11.54	872	7.7
	13:00	29.49	20	26	32.8	26.1	3.98	12.48	881	6.95
	13:30	28.89	20	27	32.3	24.8	3.94	12.36	875	6.95
	14:00	30.4	20	29	37.9	30.1	3.68	10.65	847	6.2
	14:30	30.08	20	30	32.6	24.4	3.72	10.84	807	9.2
	15:00	32.13	22	28	35.2	27.9	3.22	8.44	749.4	7.7
	15:30	33.33	22	27	35	28.2	2.87	7.06	690	9.95
	16:00	31.92	23	27	32.4	25	2.86	6.5	608.4	9.2
	16:30	29.58	24	30	31.4	25.7	2.45	5.04	505.9	8.45
	17:00	27.1	24	29	27.8	21.8	1.41	2.66	404.15	9.2
	17:30	26.74	24	28	25.4	19.9	0.28	1.12	258.27	6.2
	18:00	23.93	25	26	26.2	20.1	0	19.95	122.1	6.2
03/19/2016										
	08:00	13.13	18	18	17.8	18	0	19.95	117.8	1.7
	08:30	14.32	18	18	15.6	16.7	0	19.95	210.5	1.7
	09:00	17.89	18	19	17.9	17.1	0	19.95	207.2	2.45
	09:30	20.07	18	19	19.7	22	0.8	2.02	271.4	2.45
	10:00	20.56	18	20	22.9	23.9	1.25	3.2	698.8	3.2
	10:30	25.04	18	20	14.3	12.5	2.4	5.98	733.6	3.95
	11:00	27.39	18	22	30.1	22.7	2.74	6.9	759.5	6.95
	11:30	26.68	18	23	28.2	22.4	3.34	10.88	865	4.7
	12:00	27.88	20	26	33.4	26.6	4.42	13.68	920	4.7
	12:30	31.44	20	28	37.1	27.2	4.24	12.92	784.1	4.7
	13:00	28.53	20	28	38.7	28.3	1.56	2.8	934	3.2
	13:30	28.98	20	30	42.2	30.8	4.34	13.28	860	4.7
	14:00	32.57	20	32	44.3	32	4.28	12.13	902	4.7
	14:30	33.24	22	32	37.7	28	4.19	11.52	687	6.95
	15:00	33.02	22	33	38.7	25.3	3.76	10.75	695	6.2
	15:30	33.4	22	33	38	24.8	3.24	9.29	705.4	7.7
	16:00	31.11	22	34	34.2	23.1	2.94	7.65	607.9	5.45
	16:30	28.36	22	34	37.5	26.6	1.35	3.8	514.1	6.2
	17:00	26.5	24	37	30.9	22.5	0.84	2.16	412.5	7.7
	17:30	26.1	25	36	31.6	23.9	0	19.95	301	7.7
	18:00	26.1	27	34	28.7	20.8	0	19.95	181.6	6.2
03/20/2016										
	08:00	13.3	18	18	14.6	15.3	0	19.95	153.3	3.2
	08:30	13.74	18	18	15.9	16.2	0	19.95	170.9	2.45
	09:00	13.66	18	19	14	18.1	0	19.95	368.8	3.95
	09:30	15.24	18	20	19.2	20.5	1.6	3.48	455.1	4.7
	10:00	21.97	18	24	22.4	21	1.24	2.97	471.8	5.45
	10:30	23.8	19	26	25.2	22.3	0.8	2.04	452.2	6.2
	11:00	25.01	19	25	24.6	22.1	0.68	1.8	214.6	6.95
	11:30	22.96	20	26	26.9	25.9	1.82	3.68	521.3	6.2
	12:00	23.77	20	28	29.8	26.9	4.05	13.45	663.5	6.2
	12:30	27.67	22	31	28.5	25.7	0.75	1.8	370	6.95
	13:00	25.31	24	32	27.6	25.1	4.85	15.44	931	9.2
	13:30	28.06	25	34	30.4	26	2.02	5.3	616	8.45
	14:00	28.84	26	33	28.2	25.8	1.64	3.54	344.9	6.95
	14:30	27.42	27	32	31.6	26.4	4.02	13.2	335.5	7.7
	15:00	28.23	28	34	31.3	22.9	3.4	9.94	382.4	6.2
	15:30	29.4	30	34	33.2	26.8	3.66	11.48	847	6.2
	16:00	31.64	30	35	32.8	27.3	3.02	8.86	599	8.45
	16:30	29.81	30	32	29.9	24.1	1.01	2.28	336.7	6.95
	17:00	27.78	30	32	27.4	22.5	0.55	1.25	186.3	6.95
	17:30	25.57	30	32	25.7	21.9	0.77	1.68	165.7	6.95
	18:00	24.41	30	31	24.5	19.8	0.42	1.06	206.9	6.95

APPENDIX D: RESULTS OF DIFFERENT PARAMETERS USED TO CALCULATE THE PV/T EFFICIENCY

Heat loss rpg	Hw	U(t)	U(b)	U(L)	Q(u)	m(flow rate)	Thermal eff	Electrical eff	Fr
4.14779E-05	12.63	25.99331839	0.620097511	26.61	1.40	0.001403354	0.76%	0.00%	0.026877212
2.27185E-05	12.63	23.41240673	0.706911032	24.12	57.31	0.057306613	19.36%	0.00%	0.350880693
7.16057E-06	12.63	23.76722616	0.693933042	24.46	159.52	0.159524996	39.14%	0.00%	0.378574624
1.35086E-06	14.805	26.95748102	0.593475558	27.55	244.40	0.244887658	47.47%	0.00%	0.436382098
7.23093E-06	19.155	25.12516773	0.646519209	25.77	284.48	0.285620785	45.53%	0.04%	0.399885494
3.82205E-05	16.98	26.0887448	0.616780957	26.71	349.72	0.353256776	49.49%	0.14%	0.40808151
5.37607E-05	19.155	25.6801905	0.628375263	26.31	406.05	0.410986043	52.29%	0.19%	0.400220347
1.18446E-05	25.68	16.39824082	1.156448313	17.55	278.10	0.28176651	33.23%	0.39%	0.285020567
1.91502E-05	23.505	16.11798041	1.190512396	17.31	302.51	0.307117287	34.26%	0.84%	0.296155833
0.000401066	21.33	16.39248055	1.146045977	17.54	328.07	0.332723126	35.97%	4.32%	0.324016132
0.000367226	25.68	15.95628485	1.199370261	17.16	328.79	0.333119927	35.66%	10.32%	0.331957664
0.00048004	21.33	15.29371314	1.294614486	16.59	302.81	0.306180362	33.20%	12.39%	0.328323408
0.00048004	23.505	15.49634953	1.261058734	16.76	317.29	0.320818203	35.69%	14.02%	0.342831206
0.000374303	21.33	15.28906693	1.298979943	16.59	290.79	0.293725588	34.21%	13.21%	0.338077141
0.00066808	23.505	14.82635277	1.377126704	16.20	278.94	0.281755897	34.94%	6.31%	0.320413871
0.00066808	23.505	15.18738775	1.30479653	16.49	273.61	0.275263975	37.39%	1.59%	0.348598368
0.000635049	25.68	15.06500222	1.32801743	16.39	225.86	0.226994418	35.27%	2.14%	0.335822832
0.000591282	25.68	15.13688797	1.316416016	16.45	169.33	0.170180115	31.46%	2.40%	0.326733444
0.000317412	23.505	15.42029399	1.278585479	16.70	125.96	0.126593536	28.79%	1.33%	0.327939126
0.000183422	23.505	15.60604333	1.255206949	16.86	77.67	0.077976996	26.72%	2.51%	0.317421365
0.000329954	21.33	16.07742817	1.186079103	17.26	63.41	0.063662357	30.99%	1.04%	0.377969987
2.11264E-05	25.68	24.55269561	0.664573725	25.22	24.10	0.024095368	13.45%	0.00%	1.27063996
5.33329E-06	27.855	23.50683726	0.702049253	24.21	73.77	0.07384153	25.69%	0.00%	0.412953511
1.98156E-08	27.855	20.7996977	0.821939976	21.62	111.96	0.11207208	28.04%	0.15%	0.309903369
7.84163E-05	32.205	21.22890393	0.79822282	22.03	176.45	0.176799551	34.79%	0.56%	0.342689057
4.95103E-05	36.555	20.24686163	0.850242329	21.10	225.83	0.226510046	37.05%	4.97%	0.333685057
1.17927E-05	30.03	22.60373473	0.737567636	23.34	297.23	0.299028699	42.77%	6.87%	0.387713755
0.000118309	32.205	17.73115685	1.021371089	18.75	266.41	0.2685561	34.76%	10.50%	0.310188752
0.000105025	38.73	16.78064274	1.110252836	17.89	271.22	0.274231675	32.91%	10.87%	0.295823824
0.000111076	34.38	16.57264509	1.132646993	17.71	293.13	0.296994299	33.69%	12.17%	0.302937777
0.00016464	40.905	17.91120901	1.00465134	18.92	332.91	0.337634026	37.11%	18.51%	0.337581356
0.000227159	43.08	17.2144678	1.063715527	18.28	322.25	0.326492926	35.73%	17.43%	0.331616457
0.000286274	40.905	17.18223698	1.065222269	18.25	322.21	0.326448917	36.00%	17.38%	0.337710453
0.000286274	43.08	16.60090789	1.123698792	17.72	308.94	0.312697085	35.51%	18.57%	0.337528222
0.000325563	43.08	16.81758182	1.099774985	17.92	298.88	0.302202066	35.79%	11.17%	0.34839912
0.000209603	38.73	16.04060114	1.191989512	17.23	263.99	0.266386221	34.03%	8.17%	0.330061726
0.000209603	40.905	15.91066951	1.208216597	17.12	231.83	0.233461345	33.16%	1.37%	0.335950764
0.0002254	36.555	15.89124456	1.211162834	17.10	202.74	0.204168078	33.15%	1.92%	0.329375043
0.000200595	38.73	16.32207693	1.157933011	17.48	166.74	0.167743991	32.27%	4.31%	0.339130394
0.00011455	36.555	16.54291453	1.135626951	17.68	129.86	0.130510981	30.80%	4.36%	0.355988644
7.03934E-05	36.555	17.56615613	1.036529037	18.60	110.07	0.110512026	37.34%	2.99%	0.46984447
0.000123686	36.555	17.2816309	1.060700912	18.34	66.06	0.066191702	32.83%	1.07%	0.491306109
7.80098E-06	12.63	21.05468648	0.810887213	21.87	3.07	0.003074452	1.37%	1.30%	0.064796462
9.20466E-06	19.155	22.66265518	0.735959807	23.40	72.63	0.072704951	26.10%	1.69%	0.409617327
3.26353E-07	14.805	20.44868427	0.842397467	21.29	97.68	0.097879654	25.16%	2.16%	0.309715306
1.91477E-05	16.98	19.07310366	0.924926135	20.00	149.86	0.150164322	29.84%	2.87%	0.298887451
2.99629E-05	19.155	24.51224274	0.666210725	25.18	287.49	0.288355169	47.89%	3.76%	0.419811782
2.81354E-08	19.155	16.8654885	1.107260952	17.97	230.41	0.231797907	33.78%	6.37%	0.284767562
5.30148E-05	14.805	16.69564665	1.125191029	17.82	254.69	0.256999154	34.14%	7.23%	0.294839622
1.6682E-05	21.33	15.89777666	1.219993974	17.12	261.61	0.264787691	32.42%	7.95%	0.28690576
6.16578E-05	19.155	15.81731624	1.230282738	17.05	297.84	0.302373982	34.83%	9.39%	0.299429689
8.17296E-05	14.805	15.36478043	1.30188881	16.67	302.72	0.308268225	34.60%	9.84%	0.294808689
8.87898E-05	19.155	15.09143849	1.349722113	16.44	295.35	0.301068764	33.45%	10.97%	0.286331263
0.000505589	27.855	14.81843005	1.385760738	16.20	308.96	0.314941364	35.15%	15.09%	0.289432958

APPENDIX E: RESULTS OF DIFFERENT PARAMETERS USED TO CALCULATE THE PV/T EFFICIENCY

0.000505589	30.03	14.69824165	1.415905697	16.11	284.05	0.288962411	33.26%	14.04%	0.283594149
0.000127835	30.03	14.88669887	1.388636638	16.28	274.86	0.278758694	33.64%	11.21%	0.294878294
0.000305969	30.03	15.01657202	1.351166893	16.37	267.45	0.271248181	35.43%	7.22%	0.299618665
0.000305969	30.03	14.89922175	1.37568677	16.27	234.39	0.236992586	34.55%	0.82%	0.292060397
0.000203637	30.03	15.32750552	1.297525079	16.63	212.03	0.214169126	35.93%	1.11%	0.308839861
0.000201622	32.205	15.47653773	1.272747969	16.75	174.08	0.175480669	35.19%	2.64%	0.303322423
0.000179282	30.03	15.95323109	1.205269093	17.16	136.35	0.137173093	34.48%	1.72%	0.323583517
0.000161375	27.855	16.169451	1.178683772	17.35	87.27	0.087704039	31.44%	0.97%	0.313965992
0.000220305	27.855	16.68751114	1.117726337	17.81	61.82	0.062006022	35.80%	1.05%	0.390490306
4.5217E-06	19.155	26.33640416	0.610138375	26.95	29.99	0.029991833	20.77%	0.00%	0.749204384
4.12638E-07	23.505	23.47321747	0.703670504	24.18	49.02	0.049024134	22.98%	0.00%	0.539349919
1.81605E-06	19.155	22.03296743	0.763210022	22.80	94.78	0.094782098	27.61%	1.29%	0.371658796
1.38872E-05	25.68	22.38005819	0.747201687	23.13	165.41	0.16541075	36.51%	0.93%	0.386022424
1.50977E-05	25.68	20.21678194	0.853376695	21.07	195.55	0.195743442	34.12%	1.72%	0.338077998
4.43253E-05	27.855	26.71033885	0.598482973	27.31	298.98	0.29928206	46.47%	5.00%	0.457744312
6.40535E-05	21.33	25.88967871	0.621754614	26.51	347.45	0.348148297	46.71%	8.45%	0.433001343
6.76065E-05	21.33	16.46891524	1.147533042	17.62	238.69	0.239644578	28.93%	11.80%	0.280646393
6.72892E-05	19.155	16.16236607	1.18460069	17.35	278.90	0.280303938	30.72%	12.71%	0.291531524
8.39399E-05	19.155	16.00757087	1.203794863	17.21	279.95	0.281641178	32.67%	14.37%	0.294179892
0.000162124	21.33	15.71495056	1.240556341	16.96	295.64	0.298028556	33.07%	16.77%	0.292523104
0.000490817	23.505	15.11653627	1.325118759	16.44	276.26	0.278763973	31.72%	16.57%	0.27614129
0.000490817	23.505	15.23641122	1.303342813	16.54	293.90	0.296567725	33.82%	12.15%	0.28832816
0.000193255	21.33	15.43081091	1.282960526	16.71	260.96	0.263596571	31.75%	9.24%	0.282424857
0.000436923	21.33	15.61779648	1.244954714	16.86	261.93	0.26404568	35.29%	5.83%	0.294337474
0.000436923	25.68	16.14544068	1.172761609	17.32	246.14	0.248123972	39.50%	1.33%	0.303264169
0.000296644	27.855	16.52884193	1.132646993	17.66	216.30	0.217602232	38.25%	19.07%	0.31108448
0.000222402	30.03	16.69840796	1.116232344	17.81	145.44	0.146173214	35.84%	2.47%	0.290253308
0.000224926	30.03	17.62913607	1.027439	18.66	51.35	0.051555712	39.99%	0.89%	0.250054816
0.000215905	27.855	18.88877873	0.931100793	19.82	71.02	0.071165966	43.25%	0.00%	0.396697038
0.000152759	30.03	19.60047731	0.886166837	20.49	48.84	0.048885486	42.84%	0.00%	0.536654025
2.19979E-06	14.805	27.6647627	0.575050488	27.09	86.11	0.08610975	26.94%	0.00%	0.269990073
7.18763E-06	12.63	25.25596352	0.643227061	25.90	50.94	0.050940312	19.88%	0.00%	0.524467648
4.68865E-05	12.63	22.1460744	0.758413797	22.90	81.54	0.081536882	23.03%	0.09%	0.310323658
1.77182E-05	16.98	20.01739216	0.865893954	20.88	127.25	0.127380063	27.08%	2.28%	0.283343076
1.38557E-06	21.33	19.67216534	0.886166837	20.56	190.85	0.191235693	32.65%	4.34%	0.304290039
8.41647E-06	21.33	31.68777041	0.488176075	32.18	394.16	0.395349355	61.65%	6.73%	0.469770174
2.22607E-05	27.855	19.60252709	0.889278443	20.49	290.71	0.291882157	39.89%	10.11%	0.326524319
5.56539E-05	27.855	17.47653342	1.045605028	18.52	275.36	0.276470451	34.67%	10.02%	0.301383405
3.03015E-05	20.605	18.13075407	0.992460653	19.12	303.38	0.304909433	37.69%	13.01%	0.316083529
9.56514E-05	30.03	17.36151646	1.054667138	18.42	319.56	0.32083882	36.65%	13.55%	0.314712463
0.000118268	27.855	17.44066045	1.04711634	18.49	323.28	0.325229541	36.69%	14.76%	0.316564154
0.000185055	27.855	17.73305462	1.019853118	18.75	323.23	0.325509557	36.94%	14.57%	0.321075498
0.000185055	25.68	16.13047308	1.18312195	17.31	286.73	0.289331085	33.85%	12.12%	0.288695608
0.000171437	34.38	17.74851321	1.018334748	18.77	307.19	0.310292446	38.07%	13.08%	0.318697752
0.000142253	30.03	16.77767865	1.110252836	17.89	278.71	0.280392594	37.19%	9.50%	0.30946185
0.000142253	36.555	16.75365875	1.111748245	17.87	264.77	0.266104525	38.37%	7.69%	0.30616257
0.000108298	34.38	17.69657503	1.024405837	18.72	246.08	0.247063824	40.45%	8.00%	0.327639813
8.73504E-05	32.205	17.75884758	1.019853118	18.78	192.86	0.194025971	38.12%	6.39%	0.326635774
7.32147E-05	34.38	19.32971935	0.904807852	20.23	165.94	0.166778383	41.06%	2.43%	0.368183778
6.12951E-05	25.68	20.48095897	0.837684361	21.32	127.99	0.128501087	49.56%	0.32%	0.417777475
7.70625E-05	25.68	20.19159294	0.853376695	21.04	51.03	0.051084793	41.80%	0.00%	0.538910762

APPENDIX E: RESULTS OF DIFFERENT PARAMETERS USED TO CALCULATE THE PV/T EFFICIENCY

6.40539E-08	12.63	23.99511338	0.685800044	24.68	1.89	0.00189424	1.48%	0.00%
1.7482E-06	12.63	25.74136194	0.628375263	26.37	58.75	0.058745149	27.91%	0.00%
1.00196E-06	14.805	24.35359666	0.672751653	25.03	79.69	0.079771714	38.46%	0.00%
9.86721E-06	14.805	21.66088142	0.78075106	22.44	92.82	0.092909705	34.20%	1.56%
2.09338E-06	16.98	20.1046573	0.861203748	20.97	233.46	0.233925213	33.41%	1.50%
3.88403E-06	19.155	29.29963475	0.536181112	29.84	401.58	0.402389776	54.74%	5.12%
0.00012933	27.855	18.59161907	0.954191998	19.55	285.84	0.286988783	37.64%	6.52%
7.61393E-05	21.33	19.10970289	0.920290365	20.03	327.69	0.32933267	37.88%	11.00%
0.0001241	21.33	17.26862634	1.063715527	18.33	322.45	0.324398091	35.05%	17.21%
0.000281893	21.33	16.58456569	1.128174458	17.71	282.67	0.28494666	36.05%	18.29%
0.000324148	16.98	16.23512577	1.168316522	17.40	309.39	0.31188945	33.13%	1.22%
0.000516342	21.33	15.52058867	1.256670346	16.78	267.11	0.269812355	31.06%	17.55%
0.000516342	21.33	15.22659461	1.30479653	16.53	295.47	0.299055081	32.76%	15.07%
0.00027651	27.855	16.38883848	1.149019767	17.54	254.48	0.257053327	37.04%	18.40%
0.000411584	25.68	16.5822748	1.123698792	17.71	261.70	0.264611557	37.65%	15.23%
0.000411584	30.03	16.74170828	1.105764475	17.85	272.25	0.275276511	38.59%	11.17%
0.000310103	23.505	17.66499954	1.022888662	18.69	240.43	0.243347687	39.55%	9.69%
0.000262522	25.68	16.60936141	1.125191029	17.73	163.49	0.165475377	31.80%	2.61%
0.000154495	30.03	18.45459033	0.963400804	19.42	149.75	0.151721635	36.30%	1.15%
0.00014719	30.03	18.0390301	0.99551079	19.03	98.36	0.099453482	32.68%	0.00%
0.000138185	25.68	19.3395504	0.90325704	20.24	77.02	0.07755831	42.41%	0.00%
6.55345E-07	16.98	27.13765525	0.588460676	27.73	38.73	0.038732263	25.27%	0.00%
1.29226E-07	14.805	25.84130401	0.625066485	26.47	39.31	0.039307701	23.00%	0.00%
2.41365E-05	19.155	25.81003333	0.625066485	26.44	111.08	0.111193725	30.12%	0.00%
3.00109E-06	21.33	22.35600877	0.748805226	23.10	126.17	0.126426046	27.72%	3.20%
3.80494E-06	23.505	21.08250424	0.807724407	21.89	175.23	0.176288099	37.14%	2.04%
1.78687E-05	25.68	19.89096131	0.8721406	20.76	166.18	0.167355332	36.75%	0.95%
1.30557E-05	27.855	20.10449585	0.859639345	20.96	91.97	0.092522945	42.86%	1.49%
2.36176E-06	25.68	18.6384638	0.954191998	19.59	165.38	0.166379793	31.72%	3.36%
2.13295E-05	25.68	17.86032186	1.013777238	18.87	210.24	0.211937802	31.69%	21.50%
1.90072E-05	27.855	18.33924172	0.975655123	19.31	139.86	0.141125534	37.80%	0.96%
1.47331E-05	34.38	18.64569433	0.952655675	19.60	333.54	0.336232812	35.83%	21.06%
1.39129E-05	32.205	17.91014876	1.00921611	18.92	224.83	0.226870677	36.50%	4.55%
1.39129E-05	27.855	18.38148549	0.972594102	19.35	140.05	0.141035903	40.61%	4.41%
7.01515E-05	30.03	17.60690736	1.033500594	18.64	111.75	0.112316274	33.31%	41.42%
9.44705E-05	25.68	18.31704393	0.975655123	19.29	148.52	0.149419239	38.84%	23.14%
9.44705E-05	25.68	17.26572684	1.063715527	18.33	306.33	0.307560763	36.17%	12.99%
8.57566E-05	32.205	17.24804672	1.065222269	18.31	230.73	0.231887415	38.52%	11.70%
6.86468E-05	27.855	18.36308929	0.972594102	19.34	144.19	0.144481139	42.83%	1.79%
4.15607E-05	27.855	19.27621141	0.909457481	20.19	90.12	0.090298856	48.37%	0.97%
3.07451E-05	27.855	19.85653382	0.873701026	20.73	82.09	0.082259467	44.21%	1.82%
4.37726E-05	27.855	20.78085652	0.821939976	21.60	104.77	0.104870092	44.60%	0.50%

APPENDIX F: Photos of the experiment