ELECTRICAL AND THERMAL PERFORMANCE EVALUATION OF SOLAR PHOTOVOLTAIC/ THERMAL (PV/T) AIR SYSTEM

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FACULTY OF ENGINEERING

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ABSTRACT

Major application of monocrystalline PV modules is to convert solar energy into electrical energy. One of the weaknesses of PV module is its efficiency is depends on temperature. In simple way, it can be describe that as temperature increase, the efficiency of PV module decrease. Most of the researchers nowadays recommend using PVT concept in order to decrease the PV temperature. Solar PVT collectors are devices that convert solar energy into electrical and thermal energy. They are available in several designs, but the basic operating principles remain the same which is to collect heat generated from PV module to increase its efficiency. Combination of PV module and thermal collector with flowing fluid to extract heat will provide electrical and thermal output at low cost which is a benefit in renewable energy field. In this research, an indoor and outdoor testing to investigate the electrical and thermal performance of air based PV/T system has been carried out. A new design of thermal collector has been proposed. The structure has been attached to the PV module before running the experiment. The experiment is conducted indoors with controlled environment and several conditions. During indoor testing, parameters like angle, irradiation level and air speed are varied in order to differentiate the performance of PVT system under such conditions. As irradiation level increases, the electrical efficiency decreases. This is due to the rapid increment of temperature as irradiation level increases. The data collected is compared to PV module without thermal collector. Field experiments under Malaysia's climate are conducted and compared with indoor testing. There is not much difference in electrical and thermal efficiency for every system since the PV module used is too small. Compared to indoor testing, low thermal efficiency has been achieved for outdoor testing. This is due to the variation of irradiation level where it is not constant like

during indoor testing. From both experiment, electrical efficiency achieved is around 10% while thermal efficiency is 9%.

ABSTRAK

Aplikasi utama modul PV monohablur adalah untuk menukar tenaga solar kepada tenaga elektrik. Salah satu kelemahan modul PV adalah kecekapannya bergantung kepada suhu operasi. Dalam cara yang mudah, ia boleh digambarkan bahawa apabila suhu meningkat, kecekapan modul PV jatuh. Kebanyakan penyelidik kini mengesyorkan penggunaan konsep PVT untuk mengurangkan suhu PV. PVT adalah peranti yang menukarkan tenaga solar kepada tenaga elektrik dan tenaga haba. Ia boleh didapati dalam beberapa reka bentuk, tetapi prinsip-prinsip asas operasi kekal sama iaitu untuk mengumpul haba yang dijana daripada PV modul untuk meningkatkan kecekapan. Gabungan modul PV dan pengumpul haba dengan mengalirkan cecair untuk mengekstrak haba akan menghasilkan tenaga elektrik dan haba pada kos yang rendah dan memberi manfaat dalam bidang tenaga boleh diperbaharui. Dalam kajian ini, ujian dalaman dan luaran untuk menyiasat prestasi elektrik dan haba udara sistem berasaskan PV/T telah dijalankan. Satu reka bentuk baru pengumpul haba telah dicadangkan. Struktur akan digabungkan kepada modul PV sebelum eksperimen dijalankan. Uji kaji dijalankan dalam bilik dengan persekitaran terkawal dan beberapa syarat. Semasa ujian dalaman, parameter seperti sudut, tahap penyinaran dan kelajuan udara diubah untuk membezakan prestasi sistem PVT di bawah syarat tertentu. Dengan meningkatnya tahap penyinaran, kecekapan elektrik berkurangan. Ini adalah disebabkan oleh kenaikan pesat suhu seperti kenaikan paras penyinaran. Data yang dikumpul dibansingkan dengan modul PV tanpa pengumpul haba. Uji kaji lapangan di bawah iklim Malaysia telah dijalankan dan dibanding dengan ujian dalaman. Tidak ada banyak perbezaan dalam kecekapan elektrik dan haba bagi setiap sistem kerana modul PV digunakan adalah terlalu kecil. Berbanding untuk ujian dalaman, kecekapan haba yang rendah telah dicapai untuk ujian luaran. Ini adalah disebabkan oleh perubahan paras

penyinaran di mana ia tidak berterusan seperti semasa ujian dalaman. Dari kedua-dua eksperimen, kecekapan elektrik dicapai adalah kira-kira 10 % manakala kecekapan haba adalah 9%.

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NOMENCLATURE

A	Ampere
BIPV	Building-integrated photovoltaic
BIPVT	Building-integrated photovoltaic thermal
CPC	Concentrating photovoltaic collector
CPV	Concentrating photovoltaic
CPVT	Concentrating photovoltaic thermal
DC	Direct current
EES	Engineering Equation Solver software
GUI	Graphical User Interface
LCD	Liquid Crystal Display
LCPVT-HP	Low-concentrating solar photovoltaic thermal integrated heat pump system
MIT	Massachusetts Institute of Technology
NOCT	Nominal Operating Cell Temperature
PV	Photovoltaic
PVT	Photovoltaic Thermal
TRYNSYS	Transient System Simulation Tool
UMPEDAC	University of Malaya Power Energy Dedicated Advanced Center
USB	Universal Serial Bus
V	Voltage
W	Watt
μ_e	Electrical efficiency
μ_r	Reference efficiency
μ_{th}	Thermal efficiency
$\mu_{overall}$	Overall system efficiency
T_c	Cell temperature
T_r	Reference temperature
Q	Heat
m	Mass flow rate
C_p	Specific heat capacity

ΔT	Temperature difference
A_c	Area of thermal collector
F_R	Heat removal factor of thermal collector
$(\tau\alpha)_n$	Transmittance absorptance of PV/T
G_T	Solar radiation at NOCT
T_i	Inlet temperature
T_a	Ambient temperature
F'	Collector efficiency factor
F	Efficiency factor
U_L	Total loss coefficient
D_h	Diameter of the hydraulic
h_{ca}	Heat transfer coefficient between cell and absorber
w	Tube spacing
h_{fi}	Heat transfer coefficient inside tube
k_{abs}	The absorption surface thermal conductivity
k_{PV}	The photovoltaic thermal conductivity
L_{abs}	The thickness of the absorption surface
L_{PV}	The thickness of the photovoltaic
L_b	The back insulation thickness
K_b	The back insulation thermal conductivity
U_t	Top loss coefficient
U_b	Bottom loss coefficient
U_e	Edge loss coefficient
N	Number of glass cover
T_{pm}	Mean plate temperature
h_w	Wind heat transfer
ε_p	Emittance of plate
ε_g	Emittance of glass
β	The collector tilt

CHAPTER1: INTRODUCTION

1.1 OVERVIEW

In this chapter, a brief concept of the research will be discussed. It includes the background of the research which will describe the basic of solar energy technology and problem statement that led to this research. This chapter also includes the objectives of the research and followed by the scope of work involved. This chapter continues with the outline of the thesis that will briefly explains the content of each chapter.

1.2 RESEARCH BACKGROUND

Rapid global development and population growth, causes a tremendous rise in energy consumption year by year. This is due to demands of comfort, a higher mobility and a larger world population. At present, fossil fuels like coal, oil and gas are used to meet this energy demand. This leads to the serious problem of environmental pollution due to the huge usage of fossil fuels. To reduce the environmental pollution and save the environment, renewable energy is an alternative source of energy to replace fossil fuel (Morris et al., 2012). It is known that among renewable energy sources, solar energy is a reliable energy source (Bahadori & Nwaoha, 2013) and in most of the countries like USA and India, government is providing incentive to setup the solar energy based power plants (Chandrasekar & Kandpal, 2005; Sarzynski et al., 2012). In order to convert solar energy to other forms of energy suitable for human needs, there are several thermodynamic pathways. In general, heat, kinetic energy, electric energy and chemical energy can be provided via solar energy conversion. Photovoltaic (PV) is the direct conversion of radiation into electricity. Photovoltaic systems contain cells that convert sunlight into electricity. Inside each cell there are layers of a semi-conducting material. Light falling on the cell creates an electric field across the layers, causing electricity to flow. The intensity of the light determines the amount of electrical power each cell generates. The semiconductors based solar cells were first investigated in the 1960s and at the same time, polycrystalline Si (pc-Si) and thin-film solar cell technologies were also developed to provide high production capacity at low material cost with low energy input in fabrication process (Chaar et al., 2011). Nowadays, PV is a reliable device that can generate clean electricity using solar energy. However, the installations of PV system worldwide are still low and supplied only 0.1% of the total electricity generation. However, there are some market report shows that PV installations are increasing at almost 40% in average annual rate (IEA, 2010). PV technology has reduced its unit costs to roughly one third of where it stood 5 years ago, alongside continuous technical advancement and researches to further increase its efficiency. PV will certainly continue on the fast-growing pace and eventually become an important energy supplier in the world. It is predicted by report on the solar photovoltaic electricity empowering the world that PV will deliver about 345 GW around 4% by 2020 and 1,081 GW by 2030 (EPIA, 2011).

1.2.1 WORLDWIDE STATUS OF PV TECHNOLOGY

The global production data for solar cell in 2010 vary between 18 GW and 27 GW. Since 2000, total PV production increased almost by two orders of magnitude, with annual growth rates between 40% and 90% (Razykov et al., 2011). From 2008 to 2011, PV electricity system prices have been reported to decrease by 40% (JRC, 2011). To this date, it has been reported that world electricity consumption will increase at 2.4% rate per year until 2030 (IAEA, 2004). As the material technology for PV developed, the use of solar power worldwide also increases rapidly year by year. Silicon materials are covering more than half of PV market while thin film materials are chasing rapidly. Figure 1.1 shows the annual production of solar cell by material. Besides that, new technology like polymer/organic and hybrid solar cell is still in research stages.

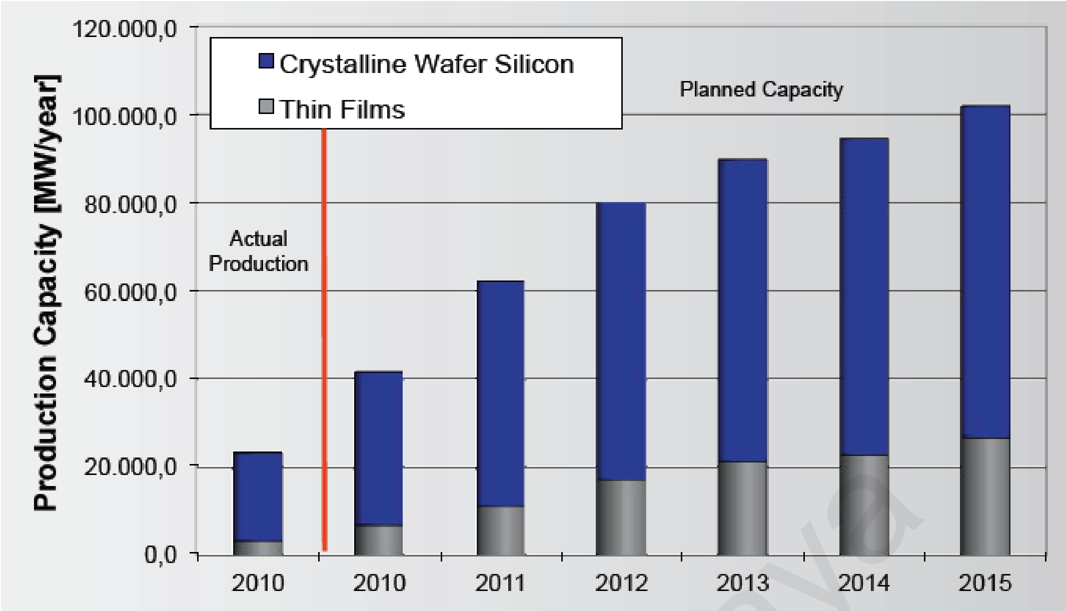

Figure 1.1: Annual and expected production capacity of PV panel by material technology (JRC, 2011)

From Figure 1.2, China leads in solar cell production. At present, several companies are producing solar cell worldwide and most of them are located in China. However, European countries are leading in PV installation with 39GW power output by the end of 2011. In European countries, PV installation in Germany, Spain and France are 7.4GW, 3.9GW and 1.05 GW respectively. Meanwhile, developing countries from Asia & Pacific region like India, Malaysia, Taiwan, Korea, Thailand and others also show a good improvement in PV installation since the respective governments are providing full support in the form of financial incentive for renewable energy projects. According to JNNSM (2011), India is also pursuing solar electricity production and other renewable energy sources more seriously. This is resulted by the setup of a national solar mission to make India as a leader in solar energy and have targeted for 500GW power production through solar energy by 2030 (JNNSM, 2010). Based on the REN21's (2012) study, more than 100 companies are producing solar cells based on polycrystalline silicon.

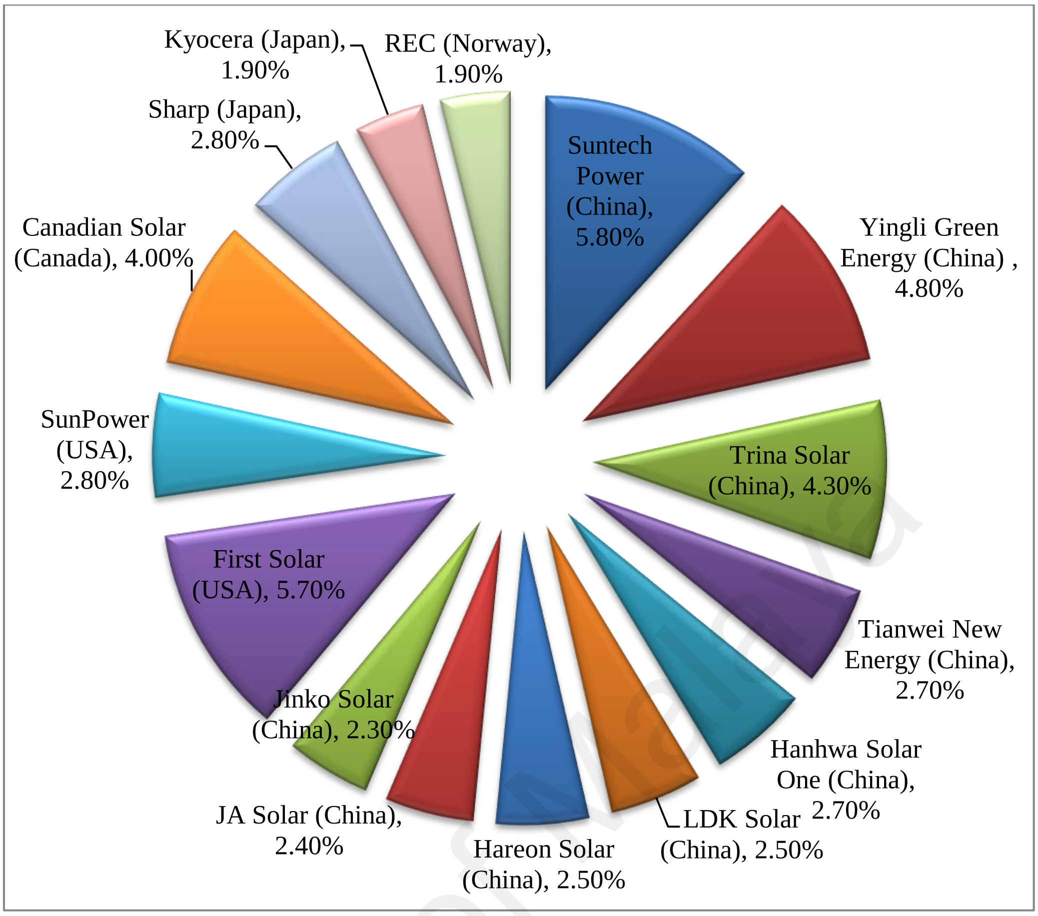

Figure 1.2: Top solar PV manufacturer worldwide (REN21, 2012)

1.2.2 FUNDAMENTAL OF SOLAR ENERGY TECHNOLOGY

Generally, solar energy from the sun is very important for all living things on Earth. It is the basic need for plants to generate food for human and animals. Technically, in renewable energy area, solar energy are used for active solar heating, passive solar heating and to generate electricity from PV (Delisle, 2008). It is widely known that the performance of PV modules strongly depends on its working condition. High working temperature will negatively affect the electrical efficiency of the module. The efficiency of solar cells is one of the important parameter in order to establish this technology in the market. Currently, extensive research is carried out regarding efficiency improvement of solar cells for commercial use. The temperature has a critical factor that creates differences in PV efficiency and its power output. Increase of temperature causes the band gap to shrink thus dropping the open circuit voltage (Shenck, 2010). During this time, energy charge carriers from valence band to conduction band increase since more incidents light have been absorbed (Dincer & Meral, 2010). Temperature influence have high impact on mono crystalline silicon compared to poly crystalline silicon and thin film solar cells. According to Zhao et al. (1999), light trapping in polycrystalline solar cell and improvement of contact and surface of the cell help in increasing the efficiency. The polycrystalline solar cell achieved a 19.8% efficiency to this date but the commercial efficiency only sees between 12-15% (Razykov et al., 2011). The work of Fraunhofer ISE in the field of high-efficiency silicon solar cells is strongly dedicated to the transfer of high-efficiency cell structures into industrial production (Glunz, 2007). The work focused on fabricated Laser-fired Contacts (LFC) cells on very thin substrates. In order to compare this new technology with a standard laboratory high-efficiency process scheme, Laser-fired contacts (LFC) and PERC solar cells have been fabricated on monocrystalline p-type silicon in a resistivity range between 0.5 and 10 Ω cm. On n-type silicon, the cells were fabricated with a resistivity of 1Ωcm in the same solar cell batch. The highest silicon solar cell practical-size (4100cm^2) conversion efficiency of 22% was achieved by Tsunomura et al (2009). They developed a cleaning process that achieved a clean c-Si surface and an improved textured structure, a lower-damage-deposition process, a lower-light- absorbing TCO, and a finer grid electrode with reduced spreading area. Chen and Zhu (2012) simulated a-Si/c-Si heterojunction solar cell with high conversion efficiency by the help of computer. They designed a prospective a- Si:H/N+ c-Si solar cell of high performance with high efficiency of 21.894%, high fill factor of 0.866 and high open voltage of 0.861 V. The simulation results are valuable for further development of high conversion efficiency and low cost solar cells. Effect of temperature on PV output can be seen in Figure 1.3.

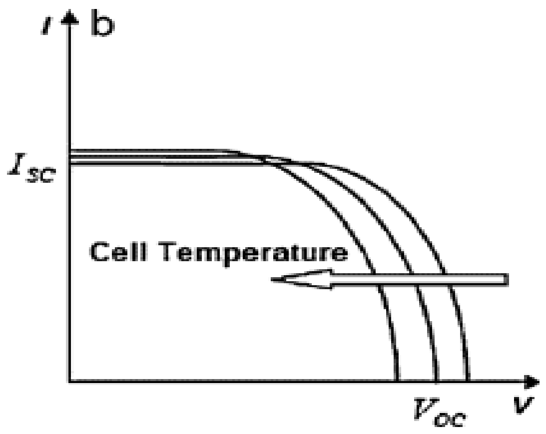

Figure 1.3: Effect of temperature on PV cell characteristic (Kumar & Rosen, 2011)

Singh and Ravindra's (Singh & Ravindra, 2012) analysis of temperature dependence on solar cell performance was carried out in the temperature range of 273–523 K. They calculated the efficiency for three cases with temperature i.e. temperature creasing temperature, reverse saturation current increases, and therefore Voc decreases which decreases the fill factor, hence the efficiency of the solar cell as well. At the same time, the band gap also decreases with increasing temperature. This resulted in an increase in Jsc which acts to improve the efficiency of the cell. Therefore, the tendency of Voc to decrease and Jsc to increase with increasing temperature in the solar cells resulted in a decline in efficiency with increasing temperature.

Most of the researchers nowadays recommend using PVT concept in order to decrease the PV temperature. Solar PVT collectors are devices that convert solar energy into electrical energy and thermal energy. They are available in several designs, but the basic operating principles remain the same which is to collect heat generated from PV module to increase its efficiency. Combination of PV module and thermal collector with flowing fluid to extract heat will provide electrical and thermal output at low cost which is a benefit in renewable energy field. Rapid development on PVT project sees researchers using different approaches in order to increase the heat transfer between PV and thermal collector to improve the efficiency of the system. However, such an interesting system like PVT also has its own advantages and disadvantages (Ibrahim et al., 2011).

The advantages of PVT:

- Clean and renewable energy
- Low maintenance
- Have a very long life span (20-30 years)
- Reliable system
- Zero pollution

The disadvantages of PVT:

- Longer payback period
- Need more space for installation of the system
- Cooling cycle not uniform
- Highly dependent on weather.
- The device is heavy since it is the combination of two system

Even though the researches of solar thermal system are still in the development stages, there are several basic systems that have been commercialized in certain European countries. Developed countries like Germany, Spain and Austria have started installments of advance solar thermal system in hotels, large-scale plants for district heating, and also for air conditioning purpose. It is interesting to note that in 2010, a total of 1818462m^2 solar air collector that can produce 1273 MW_{th} had been installed worldwide (AEE INTEC, 2012).

Table 1.1 and 1.2 show the list of flat plate collector manufacturers for solar water heating system and commercially available PVT products respectively. There are presently three types of solar thermal collector available which are unglazed, glazed flat-plate and evacuated tube (The World Bank, 2011).

Table 1.1: Flat plate solar water heating system manufacturers worldwide (SOLRICO, 2011)

No.	Ranking of the largest flat plate collector manufaturers 2010 worldwide	Country
1	GREENone Tec	Austria
2	Bosch Thermotechnik	Germany
3	Ezinc Metal	Turkey
4	Soletrol	Brazil
5	Viessmann Werke	Germany
6	Prosunpro	China
7	Rheem/Solahart	Australia
8	BDR Thermea	Netherlands
9	Chromagen	Israel
10	Five Star	China
11	Eraslan	Turkey
12	Vaillant	Germany
13	Schuco	Germany
14	Wolf	Germany
15	Nimrod	Israel
16	Solimpeks	Turkey
17	Wagner	Germany
18	Sunda	China
19	Riposol	Austria

Table 1.2: Commercially available PVT products (IEA SHC, 2006)

Company	Website	Type of PVT product
Aidt Miljo- Solar venti	http://www.solarventi.dk/	PVT air collector
Grammer Solar-Twinsolar	http://www.grammer-solar.com/	PVT air collector
Conserval Engineering-PV Solar Roof	http://solarwall.com/	PVT air collector
Secco Sistemi- TIS	http://www.seccosistemi.it/	Ventilated PV with heat recovery
PVTWINS	http://www.pvtwins.nl/	PVT liquid collector
Millenium Electric	http://www.millenniumsolar.com/	PVT liquid collector
Arontis solar solution	http://www.arontis.se/solar/	PVT concentrators
HelioDynamics	http://hdsolar.com/	PVT concentrators
Menova Engineering Inc	http://www.powerspar.com/index.html	PVT concentrators

1.3 PROBLEM STATEMENT

The PV module is built by many solar cells consisting of semiconductor materials that can convert high energy photons of incident solar irradiation into electrical energy. The lower energy photons are absorbed by the PV module thus generating heat within the cell. This increases its temperature. High increment of temperature can affect the performance of PV module. Due to this, research arises in the area of performance maintenance by extracting the heat using thermal collector. Various designs have been proposed in previous works to maximize heat transfer from PV module to thermal collector keeping in mind technical and economic aspects.

In this research, a new design of thermal collector has been proposed. The structure will be attached to the PV module before running the experiment. The experiment is conducted indoors with controlled environment and several conditions. During indoor testing, parameters like angle, irradiation level and air speed are varied in order to differentiate the performance of PVT system under such conditions. The data collected is compared to PV module without thermal collector. Field experiments are also compared with indoor testing.

1.4 OBJECTIVE

Due to rapid development and growing research in PVT field, new approaches have been proposed in this study. The objectives of this research are as follows:

- To study thermal and electrical performance of a solar PVT air system.
- To compare the result of a PVT collector performance with electrical performance of PV module
- To study the effect of temperature on PV module and PVT collector performance.

1.5 SCOPE OF THE STUDY

The scope of the study covers:

- Design and development of new thermal collector unit based on material, cost, heat transfer rate and shape.
- Collection of data by conducting indoor and outdoor experiment for validation purpose. Parameters such as temperature, air speed and irradiation level for electrical and thermal output are considered.
- Study of mathematical model to evaluate the temperature effect on PV and PVT system.
- To conduct indoor and outdoor test of PV and PVT system.
- Comparison between PV and PVT performance including electrical and thermal efficiency during indoor and outdoor experiment.

1.6 THESIS OUTLINE

This thesis consists of five chapters. The first chapter states the introduction and background of research. Besides that, it also consists brief information about the research such as problem statement that lead to the development of the research, objectives and scope of work involved.

In Chapter 2, this section includes literature review of relevant works of PVT collector technology and also its mathematical model to analyze the electrical and thermal performance of the system.

Next, Chapter 3 discusses on the research methodology. This will be the description about the hardware used and how the indoor and outdoor experiment had been conducted to perform the research effectively and successfully.

Following that, Chapter 4 discusses the result and analysis of the research. This also includes examining relevant arguments and theories further. Finally, Chapter 5 concludes the research findings with future recommendation in order to enhance and improve any imperfection of this research.

CHAPTER 2: LITERATURE REVIEW

2.1 OVERVIEW

This chapter described the theory of the PVT system in detail. Relevant works are also included in this chapter for reference purpose. The mathematical model used for data collection and analysis to determine the performance of the PVT system is presented.

2.2 PVT COLLECTORS BASIC CONCEPT

Renewable energy sources are key in helping to reduce pollution and conserve the environment. Among these energy sources, PV is most reliable as it is simple and environmental friendly. Depending on solar cell material, commercial PV's peak efficiency normally lies between the ranges of 9–12%. Only 20% of the solar irradiation that hits on the PV module will be converted into electrical energy while the other 80% are wasted to the ambient in the form of heat. Heat produced will increase the solar cell temperature hence decrease its conversion efficiency.

Researchers have introduced PVT systems in order to solve the problem of temperature rising in PV cells. The basic idea is to cool down the PV cell temperature in order to maintain its efficiency using thermal collector.

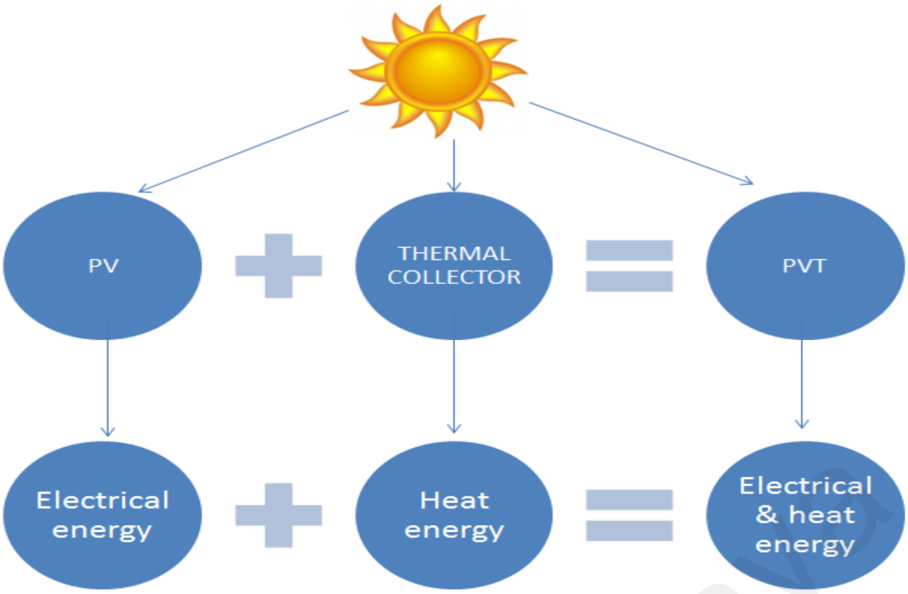

Figure 2.1: Basic concept of PVT

Basic concept of PVT system is briefly described in Figure 2.1. Thermal collector will be placed at the back or on top of the PV module to collect the heat in order to decrease the temperature of the PV module. With the temperature lowering, this helps to increase electrical output. Heat from the PV will be transferred to the thermal collector using cooling fluid such as water, oil or air flowed through it. Heated water or air can be used for other purposes such as air heating, crop drying and hot water for bathing. Air heating is important for European countries with cold climates. Several designs of thermal collectors have been created in order to increase the heat efficiency; enabling maximum amount of heat extraction whereby increasing the electrical output from PV module (Ibrahim et al., 2011; Kamthania et al., 2011; Bambrook & Sproul, 2012; Peng et al., 2010; Alta et al., 2010; Shahsavar & Ameri., 2010; Ramani et al., 2010; Thirugnasambandam et al., 2010; Raisul Islam et al., 2013).

In PVT system, both electrical and heat efficiency are important to ensure that the system is beneficial. Several factors affect the heat transfer ability from PV to the thermal collector such as:

i. Fluid flow rate: Heat transfer efficiency increases if the flow rate increases.

ii. Specific heat capacity: Heat transfer efficiency also increases if the fluid used in the thermal collector has high specific heat capacity. For example, PVT that uses water has high transfer efficiency as specific heat capacity of water is four times higher than air.

iii. Thermal collector material: Typically, metal is used as thermal collector since it is the best conductor. Metal with high specific heat capacity will help in transferring heat efficiently.

iv. Fin: Heat sink/fin can help increase the heat transfer from PV to thermal collector by increasing the total surface area.

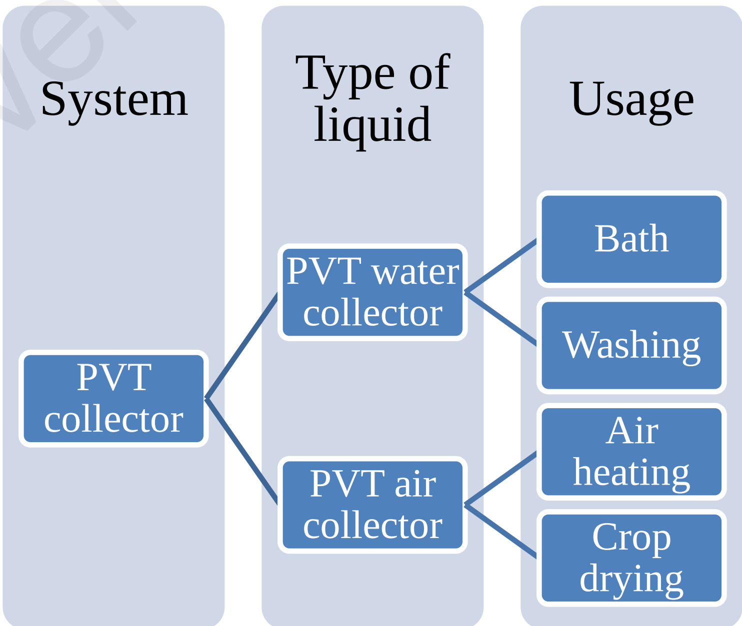

Figure 2.2: Common PVT System and its benefits

Figure 2.2 shows the most common flat plate PVT type that has been given much attention in research and for commercial purposes. By combining PV and thermal collector into one piece of device, less space will be used thus reducing installation costs. Removing heat from PV module using air is simple and easy as compared to water or other coolants such as refrigerant and oil. However, this lowers the effectiveness since specific heat capacity (c_p) of air is only 1.005 kJ/kg.K. To achieve high thermal efficiency, more heat can be extracted if the liquid used is water mainly due to its specific heat capacity (c_p) which is four times higher than air.

2.3 PV/ THERMAL SYSTEM TECHNOLOGY

Ancient history of solar energy collectors started with Archimedes' idea to burn Roman armadas in 212 BC. Concave metallic mirror was used to set fire using solar energy. During the 16th century, a scientist named Athanasius Kircher conducted an experiment using mirror to burn woodpile in order to prove the theory of Archimedes. However, no report on his findings is available. It is said that during the 18th century, furnaces that harness solar energy was built to melt iron, copper and other metals (Kalogirou, 2004).

The history of solar PVT collectors dates back to the 19th century along with the commercialization of PV cell. The price of solar cell was quite expensive decades ago but continuously decreases as the price of fuel energy increases due to the gradually diminishing source (Zondag, 2008). The first PVT air heating system was developed by Professor Böer from University of Delaware in late 1973 (Boer & Tamm, 2003). This work was later continued by other researchers from Sandia and Brown University (Raghuraman, 1981) which was then collaborated with MIT in 1978.

Rapid development of PVT air heating system started in early 1990s in Israel where unglazed PVT collector had used both liquid and air as cooling fluid (Elazari, 1998). PVT air collector were developed and commercialized later by Grammer Solar (EU, 2005), a German company, while Conserval Engineering in collaboration with Bechtel and CANMET were responsible for marketing PVT in Canada (Hollick, 1998). In order to maximize the heat transfer from PV module to thermal collector, researchers devised to put one thin metal sheet between the PV module and thermal collector. The technology of PVT grows when researchers continuously study and alter the model of basic PVT such as double pass PVT air collectors by (Tripanagnostopoulos et al., 2001; Tripanagnostopoulos et al., 2002; Tripanagnostopoulos et al., 2000; Tonui & Tripanagnostopoulos, 2006; Tripanagnostopoulos et al., 2006; Tonui & Tripanagnostopoulos, 2005; Sopian et al., 1996; Sopian et al., 1997; Sopian et al., 2000; Othman et al., 2005). Kumar and Rosen (2011) also conducted a study to investigate the effect of fins on the performance of a double pass PV/T solar air heater. In this study, electrical and thermal performance of PVT with and without fin had been compared under various irradiation levels and mass flow rate of air. From the observation, overall system efficiency increased with the usage of fin due to the increment of surface area and also able to reduce the cell temperature. Ho et al. (2009) compared the efficiency of three different designs of PVT which were: recycle only, recycle and fins and also recycle with baffled and fins. Experiments were conducted under constant irradiation with different mass flow rate of air. It has been concluded that PVT attached with recycle with baffled and fins have higher efficiencies compared to others. Baffled presence creates high turbulence of air and increase surface area so that the coefficient of heat transfer also increases. Gao et al., (2007) compared the performance of cross corrugated PVT with several designs under different conditions using experiment and analytical method. Cross corrugated absorbing plate and bottom plate improve the efficiency of the system by increasing the heat transfer rate and turbulence flow. Ho et al., (2010) investigated theoretically and experimentally the effect of rectangular flow conduits. This is in order to increase the convective heat-transfer coefficient to enhance collector efficiency under constant irradiation level. It is concluded that to increase collector efficiency, number of conduit pairs, recycle ratio or conduit aspect ratio need to be increased also. However, increasing the recycle ratio will increase the cost of the system. Figure 2.3 shows the rectangular flow conduit in this study.

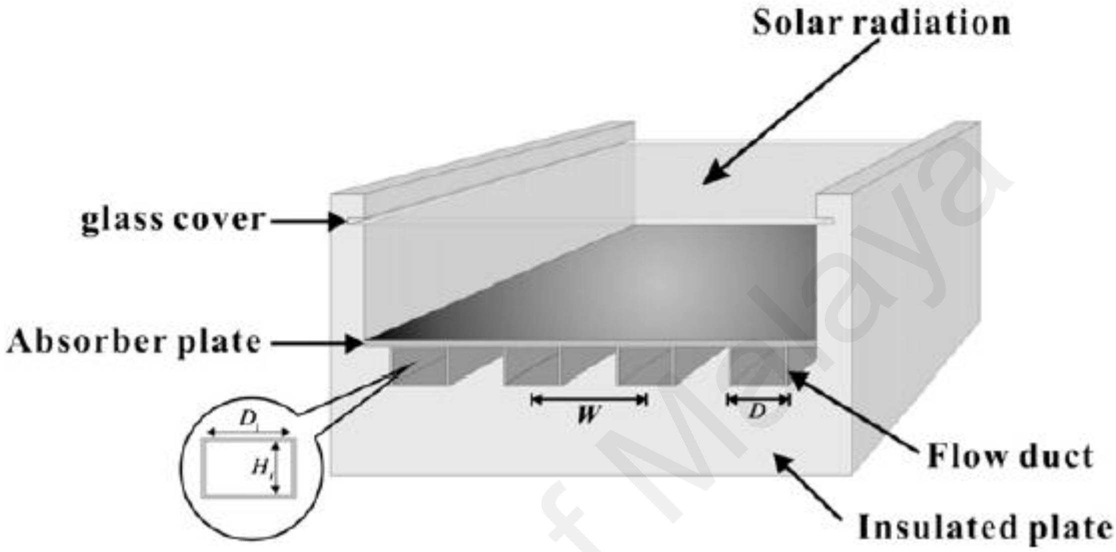

Figure 2.3: Rectangular flow conduit solar water heater (Ho et al., 2010)

Hegazy (2000), compared four types of PVT designs which air is flowing either over the absorber (Model I) or under it (Model II) and on both sides of the absorber in a single pass (Model III) or in a double pass fashion (Model IV). From the findings, model I gives lowest overall efficiency while model III can give better electrical output compared to others as can be seen in Figure 2.4.

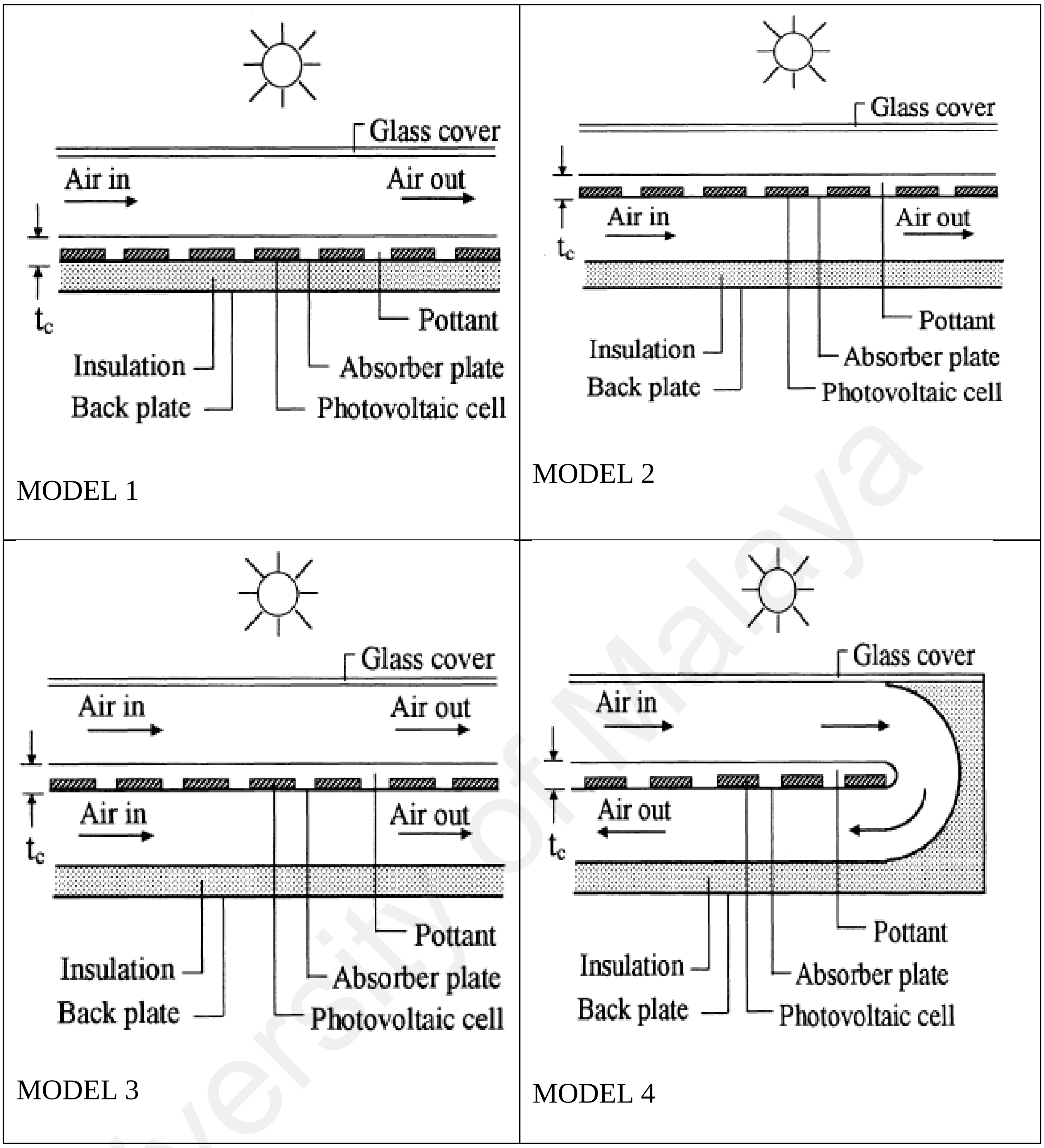

Figure 2.4: Various type of PVT models (Hegazy, 2000)

Researches on PVT are also actively carried out in India since they are using the heat collected for drying purpose. Garg et al., (1991) studied a theory of solar photovoltaic-thermal (hybrid) system consisting of a flat-plate solar air heater mounted with solar cells and a plane booster. The study investigated the case when the radiative and absorptive properties of the cell surface and the absorber plate value are almost same. Comparison using simulation model had been done for single-glass and double-glass configurations. Performances for these models had been calculated by inserting various parameters (Garg & Adhikari, 1997). Thermal efficiency of PVT air system with different types of absorbers were also simulated and the performance were assessed according to Delhi climate (Garg & Adhikari, 1999). Nayak and Tiwari (2008) integrated PVT air system into a greenhouse at I.I.T, Delhi, India in order to measure the exergy performance of the system. In a year, thermal exergy calculated is 728.8 kWh while electrical energy produced is 716 kWh. Joshi et al., (2009) conducted an experiment to compare total energy and exergy from PV and PVT air collector under New Delhi climate using two different methods which were Exergetic calculations using solar energy parameters and Exergy calculations using photonic energy. Experiments were conducted on the 27th March 2006 where it was found that energy efficiency for PV was lower compared to PVT air system.

The Solar Energy Research Group in Universiti Kebangsaan Malaysia developed four air collector systems for drying purpose which were the V-groove solar collector, the double-pass solar collector with integrated storage system, the solar assisted dehumidification system for medicinal herbs and the photovoltaic thermal (PVT) collector system. The double-pass solar collector is proficient in collecting heat while the V-groove solar collector is suitable for products like chilies, green tea, and dried fruits (Othman et al., 2006). Figure 2.5 shows the schematic of V-groove solar collector.

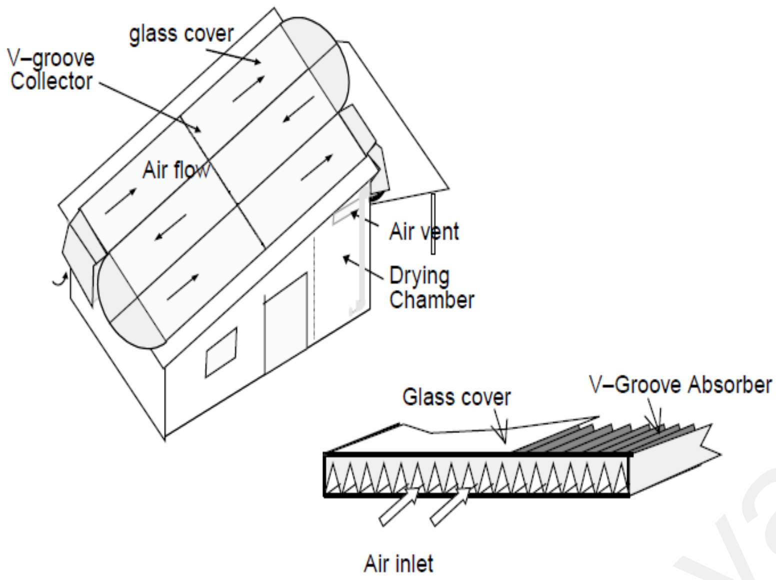

Figure 2.5: Schematic of V-groove solar collector (Othman et al., 2006)

Janjai and Tung (2005) investigated the performance of 72m^2 PVT collectors that was placed on a roof top of a farmhouse and concluded that it took 3-4 days to dry 200 kg of rosella flowers and lemon-grasses using the hot air produced by the PVT. Figure 2.6 shows the PVT integrated roof to produce hot air for the study.

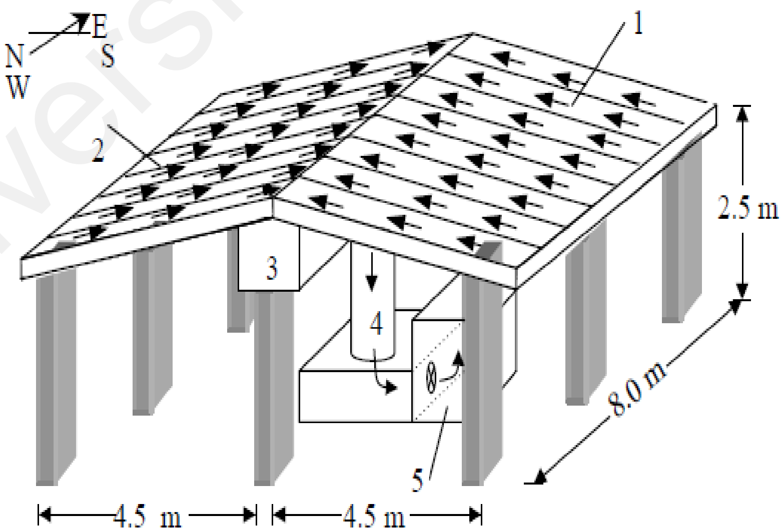

Figure 2.6: Roof integrated with PVT to produce hot air (Janjai & Tung, 2005)

A review for four types of solar dryers which are direct solar dryers, indirect solar dryers, mixed-mode dryers and hybrid solar dryers, was also done in terms of product being dried, technical and economic aspects (Fudholi et al., 2010). Experimental testing was conducted by Tiwari and Sodha (2007) to validate the performance of four different models of PVT which were unglazed hybrid PVT with tedlar, unglazed hybrid PVT without tedlar, glazed hybrid PVT with tedlar and glazed hybrid PVT without tedlar. For New Delhi climate, glazed hybrid PVT without tedlar displayed the best performance. Similar indoor testing for two cases of PVT air collector was investigated by Agrwal et al (2012). Experimental testing was carried out using various intensities to confirm the theoretical results with correlation coefficient and root mean square percentage deviation of 0.96 and 7.9 respectively. Results from this study showed that an average of 12.4% and 35.7% electrical and thermal efficiency can be achieved respectively.

Some researches studied the modification of PVT air system to maximize the electrical and heat efficiency at a low cost. Tonui and Tripanagnostopoulos (2007) suggested the use of metal sheet finned between the PV rear and thermal collector as can be seen in Figure 2.7. This is to help enhance the electrical output and maximize the heat transfer from PV back to the collector. Experimental testing carried out to validate this theoretical model achieved positive results. From the experiment and calculation result, usage of metal sheet and fin can improve the performance of the PVT air system.

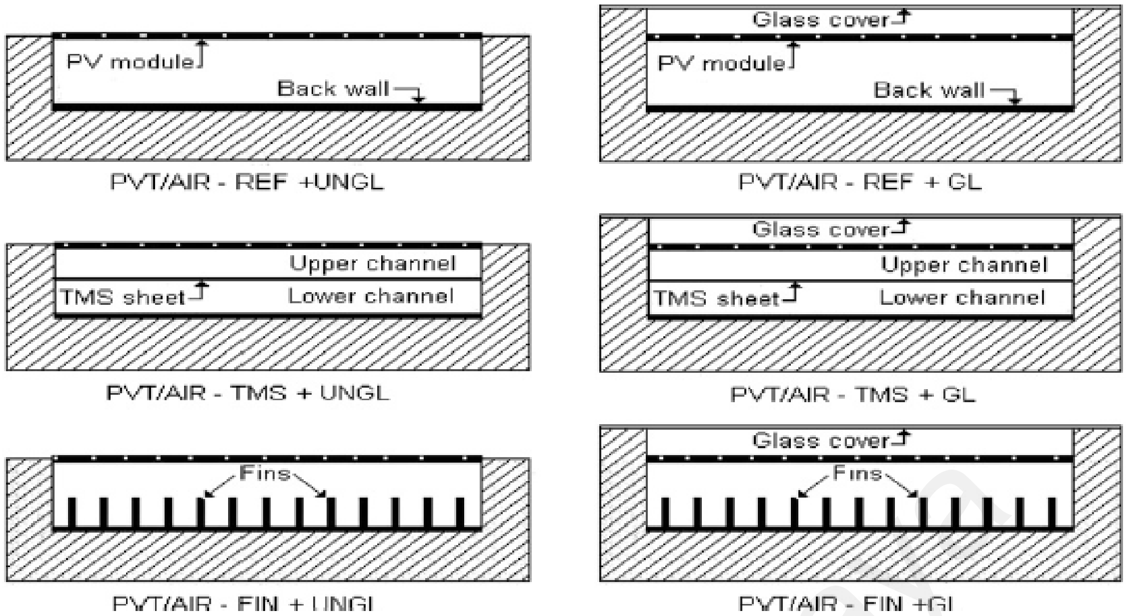

Figure 2.7: Schematic view of PV Thermal tested (Tonui & Tripanagnostopoulos, 2007)

Tripanagnostopoulos et al. (2002) investigated the performance of hybrid PVT systems with water and air as a cooling fluid. The hybrid PVT system had been tested under outdoor condition and the results presented show that using water and air as a coolant can increase the electrical efficiency of PV module. Performance of the system can be increased by using an additional glazing to increase thermal output, a booster diffuse reflector to increase electrical and thermal output, or both, hence giving flexibility in the system's design. Figure 2.8 shows the cross section of hybrid PVT system used in the study.

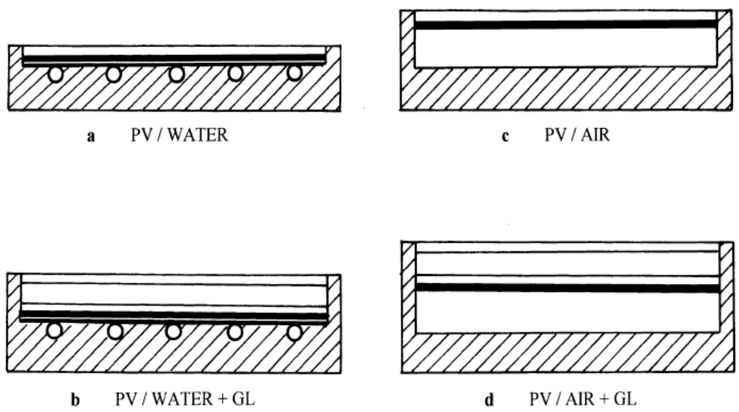

Figure 2.8: Cross section of hybrid PVT system (Tripanagnostopoulos et al., 2002)

Othman et al. (2007) studied the performance of double-pass collector system with fins attached to the other side of the absorber surface. Indoor testing under various intensities and operating temperatures were done to measure the electrical and thermal performance of the PVT system. It has been stressed in this study that the performance of the PVT system can be increased with the usage of fin. Figure 2.9 shows the double pass photovoltaic-thermal solar air heater.

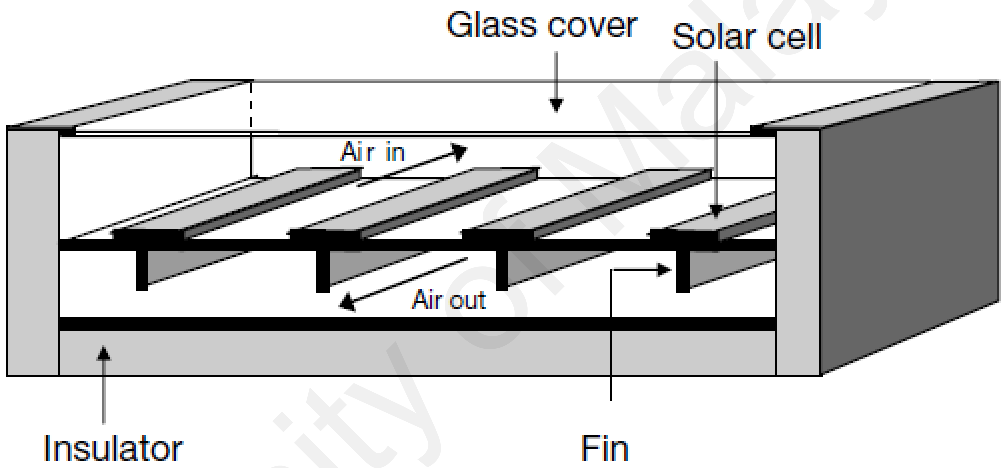

Figure 2.9: Double pass photovoltaic-thermal solar air heater (Othman et al., 2007)

Bazilian and Prasad (2002) constructed a numerical model to assess the performance of a residential-scale building integrated with photovoltaic (BIPV) cogeneration system. This BIPV system consists of thermal collector to extract heat from PV system. Simulation model was created using Engineering Equation Solver software package (EES) and validated by experimental result. Other than that, Bambrook and Sproul (2012) conducted an outdoor experiment at Sydney, Australia using six 110 Wp unglazed PV modules, single pass, open loop PVT air system and tilted 34° north facing. The experiment's varying mass flow rates of air resulted in thermal efficiencies between 28–55% and electrical PV efficiencies between 10.6-12.2% during midday. Sarhaddi et al., (2010) had also developed a PVT air collector and performed an energy and exergy analysis on the system. Furthermore, they also developed a new mathematical model for exergy efficiency of a PV/T air collector based on structure design and climate condition. Results from computer simulation were compared with experimental measurements with good agreement. From the result, it was calculated that thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector is about 17.18%, 10.01%, 45% and 10.75% respectively.

Cartmell et al. (2004) monitored the first European example of a roof mounted, multi-operational ventilated photovoltaic and solar air collector for six months. In Figure 2.10, it can be seen that PVT system was mounted on The Brockshill Environment Centre.

Figure 2.10: PVT system mounted on The Brockshill Environment Centre (Cartmell et al., 2004)

Mei et al. (2003) developed a thermal model for BIPVT for air heating system using TRYNSYS and tested it on the Mataro Library near Barcelona as can be seen in Figure 10. Warmed air was used to heat the building during winter season. They also investigated the impact of climatic variations on the BIPVT performance. Sakhrieh and Al-Ghandoor (2012) studied the performance of five different types of solar collectors which were blue and black coating-selective copper, copper, and aluminum collectors in addition to evacuated tubes collectors as can be seen in Figure 2.11. Outdoor experiment was carried out daily in April from 8:00 am to 4:00 pm with solar irradiation level varying between 154.0 to 1004.33 W/m^2. It was suggested that, for small applications, aluminum thermal collector is better.

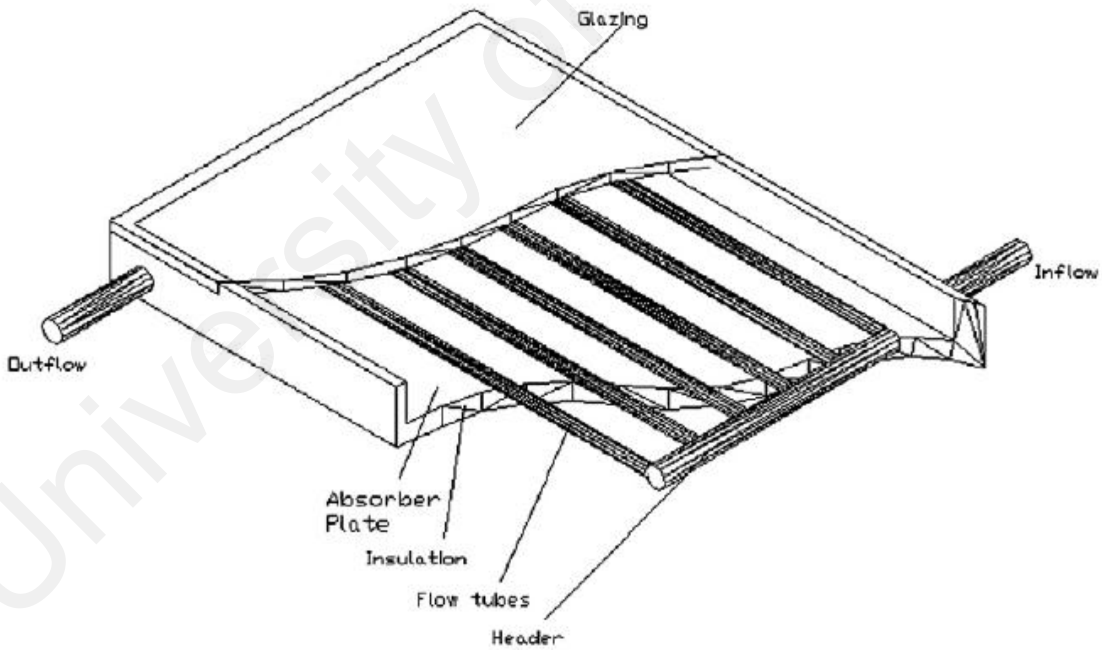

Figure 2.11: Design of thermal collector (Sakhrieh & Al-Ghandoor, 2012)

Conventional flat plate PVT system will only produce low grade thermal energy that is only enough for water and air heating purpose. As technology develops, researchers have investigated the potential of concentrating photovoltaic/thermal (CPVT) systems to produce high grade thermal energy for processes like refrigeration, desalination and steam production (Mittleman et al., 2007; Mittleman et al., 2009). Kribus et al. (2006) examined the performance of the photovoltaic/thermal collector field and a multi-effect evaporation desalination combination. The system proposed can produce electrical energy through CPV while thermal collector was used to extract heat for water desalination. Based on simulation result, CPVT desalination involved lower financial cost. Figure 2.12 shows the CPV unit during solar testing.

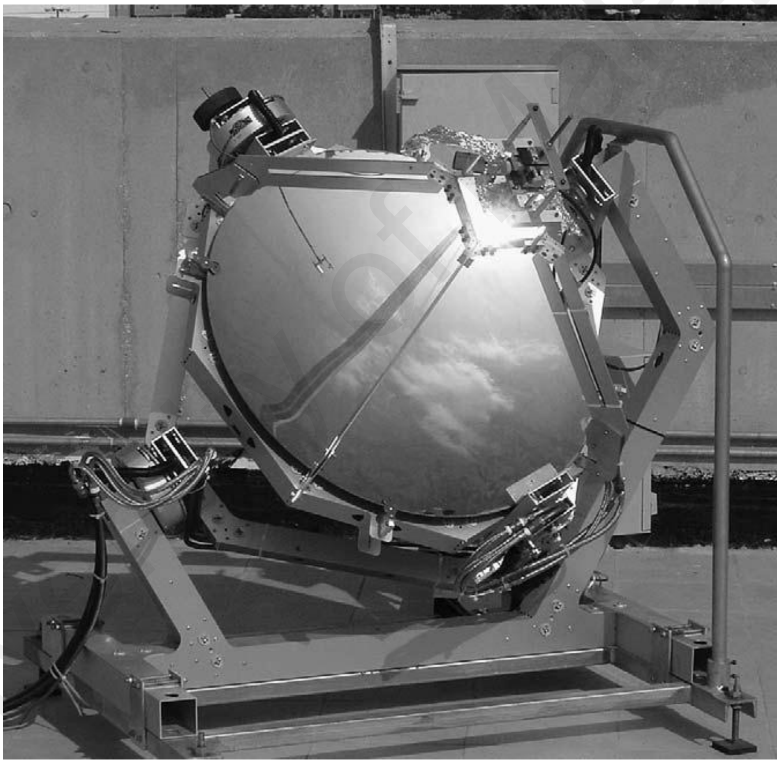

Figure 2.12: CPV unit during solar testing (Kribus et al., 2006)

Double pass photovoltaic thermal solar air collector with compound parabolic concentrator (CPC) had been designed by Othman et al. (Othman et al., 2005) as to study its performance under several working conditions. From the investigation conducted, it was concluded that increase in air temperature causes the electrical efficiency to drop. Coventry (2005) explored into the performance of a parabolic trough photovoltaic/thermal collector with a geometric concentration ratio of 37X. Field experiment carried out produced results of thermal efficiency at 58% and electrical efficiency at 11%. This result was compared with flat plate thermal collector and it can be seen that CPVT had lower efficiency at low temperature but as the temperature increased, thermal losses also increased slowly. Setup for the testing unit can be seen in Figure 2.13.

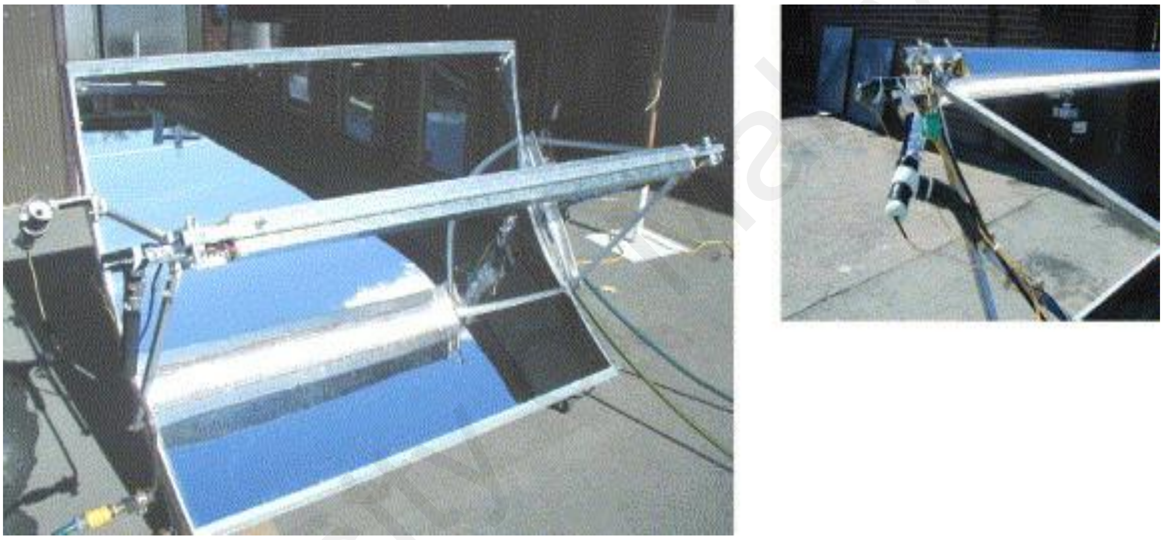

Figure 2.13: Testing unit for CHAPS (Coventry, 2005)

Guiqiang et al. (2012) investigated the performance of CPC-based PVT system with different concentration ratios and compared the results with common flat PVT systems. U-type pipe will act as a thermal collector to collect heat from the CPV and flat plat PV. From the result, it is concluded that as the concentration ratio increases, thermal efficiency also increases but electrical efficiency will drop. From simulation, CPC-based PVT system showed high thermal and electrical efficiency compared to conventional PVT system. Figure 2.14 shows the CPC-based PVT system for this research.

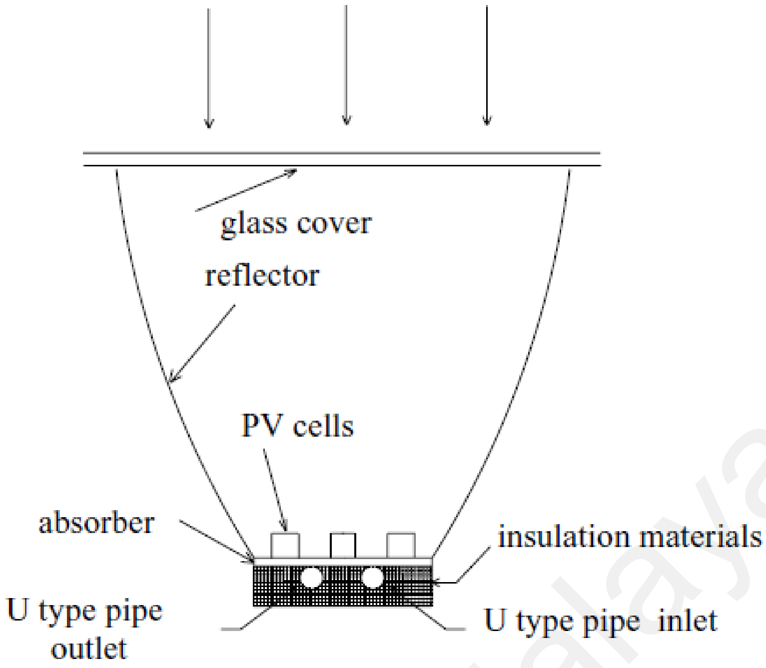

Figure 2.14: CPC-based PVT system (Guiqiang et al., 2012)

Han et al. (2011) proposed a several type of direct liquid-immersion (de-ionized (DI) water, isopropyl alcohol (IPA), ethyl acetate, and dimethyl silicon oil) to be used to cool the hybrid concentrating photovoltaic thermal (CPV-T). Simulations were carried out for all of the liquid-immersion candidates and the result showed that the use of liquid-immersion as a cooling fluid can maintain the cell array temperature thus increasing the power output. V-through solar concentrator was developed by Riffat and Mayere (2012) in order to compare its performance with common parabolic trough solar concentrators. Both indoor and outdoor experiments were conducted under various conditions and the result exhibited this new design of collectors was able to produce thermal efficiency up to 38% at 100°C operating temperature. In this study, they also concluded that usage of concentric pipe with coated double layer vacuum glass was better compared to conventional u-pipe tube. Figure 2.15 shows the experimental set-up of the new through solar collector system.

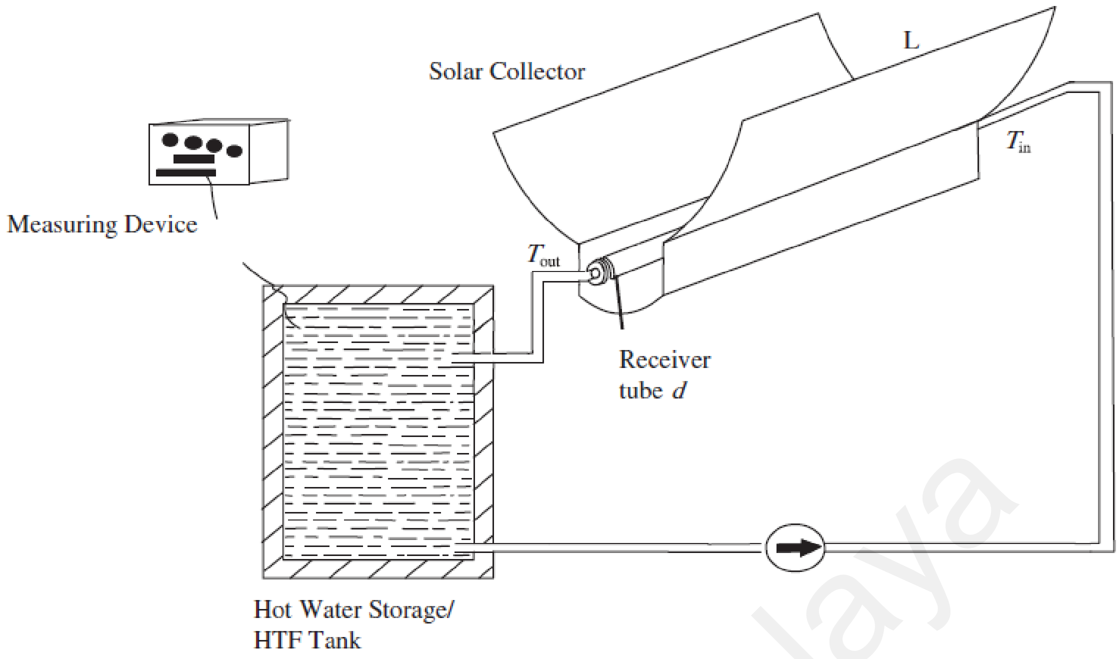

Figure 2.15: Experimental set-up of the new trough solar collector system (Riffat & Mayere, 2012)

Xu et al. (2011) investigated the performance of low-concentrating solar photovoltaic/thermal integrated heat pump system (LCPVT-HP) using R134a as a cooling fluid. Heat extracted from the refrigerant was used to heat up the water in the condenser. The study found that the system had produced electrical efficiency of 17.5% while capable to heat water from 30 °C to 70 °C on a sunny summer day.

Erdil et al. (2008) built a PVT water system using two PV modules of area approximately 0.6 m^2 in order to investigate the performance of the system under Cyprus climate as shown in Figure 2.16. Thermal energy collected was used for water pre-heating applications. As a result, the system built can generate a total of 2.8 kWh thermal energy per day. They concluded that their system is more economic since the payback period is 2 years and it is low cost.

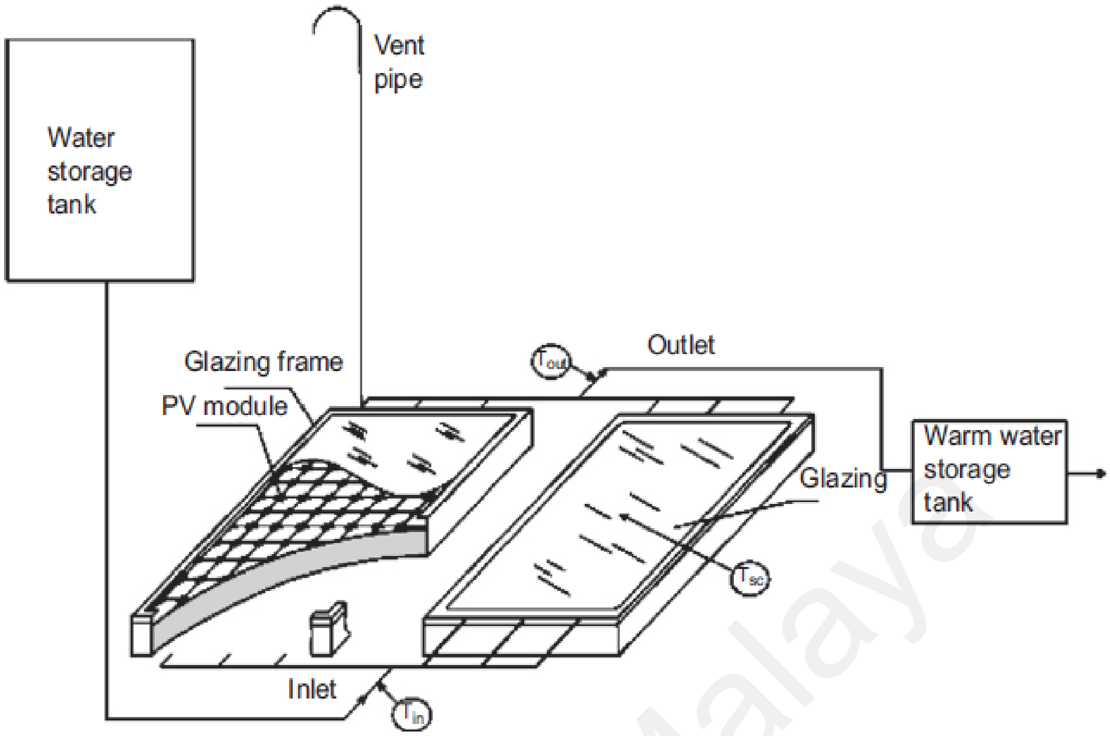

Figure 2.16: PVT water system (Erdil et al., 2008)

In terms of economic value, Agrawal and Tiwari (2010) conducted a study to evaluate the performance of BIPVT air system using different types of cell materials including monocrystalline silicon, polycrystalline silicon, ribbon silicon, amorphous silicon, CdTe and CIGS. Though it is known that monocrystalline silicon PV have high efficiency and suitable for generating electricity for residence in a building, this study demonstrated that amorphous silicon BIPVT system is more suitable and low cost for New Delhi climate. The result is presented in table 2.1 below.

Table 2.1: Summary of the annual outputs, overall efficiencies and annualized cost of power generation for BIPVT system under New Delhi climate (Agrawal & Tiwari, 2010)

PV technology	Electrical output from BIPVT (kWh)	Thermal output from BIPVT (kWh)	Overall thermal efficiency of BIPVT system (%)	Overall exergy efficiency of BIPVT system (%)	Annualized cost of BIPVT (US$)	Cost per unit power generation for BIPVT system (US$/kWh)	Cost per unit power generation for BIPV system (US$/kWh)	Reduction in cost (%)
c-Si	15131	16764	51.99	14.91	1931.03	0.1190	0.1338	12.44
p-Si	13141	17535	47.88	13.19	1641.01	0.1143	0.1309	14.51
r-Si	11179	18306	43.84	11.50	1487.35	0.1189	0.1395	17.35
a-Si	6066	20615	33.54	7.13	785.66	0.1009	0.1416	19.77
CdTe	7958	19845	37.41	8.75	1128.83	0.1182	0.1416	19.77
CIGS	9578	19074	40.65	10.13	2928.94	0.2654	0.3195	20.41

The advantage of solar PVT air heating system was further investigated by Bala et al. (2003), which was applied in drying the pineapple. Hot air was flowed throughout the tunnel using two dc fans operated by a flat plate solar module. Solar tunnel built for this application has a loading capacity up to 150 kg of pineapple and can protect the product from dust, insects and rain. Thus the dried pineapple produced is high in quality. During the study, air temperature at the outlet varied from 34.1 to 64.0 °C. It was concluded that drying time can be reduced by using this system compared to directly using sun to dry the products.

Nagano et al., (2003) constructed a new thermal-photovoltaic (PV) hybrid exterior wall boards that incorporated PV cells. The setup of the research can be seen in Figure 2.17. Air had been used as a cooling fluid for PV panel while they evaluated the exergy, electrical power generating ability and the solar heat collection capacity during winter season. Several conclusions were made throughout this research where it was found that the collected thermal energy does not increase linearly in proportion to the height of the wallboard; this relationship is especially apparent at low air flow rates where the effect of increased wallboard height is much smaller.

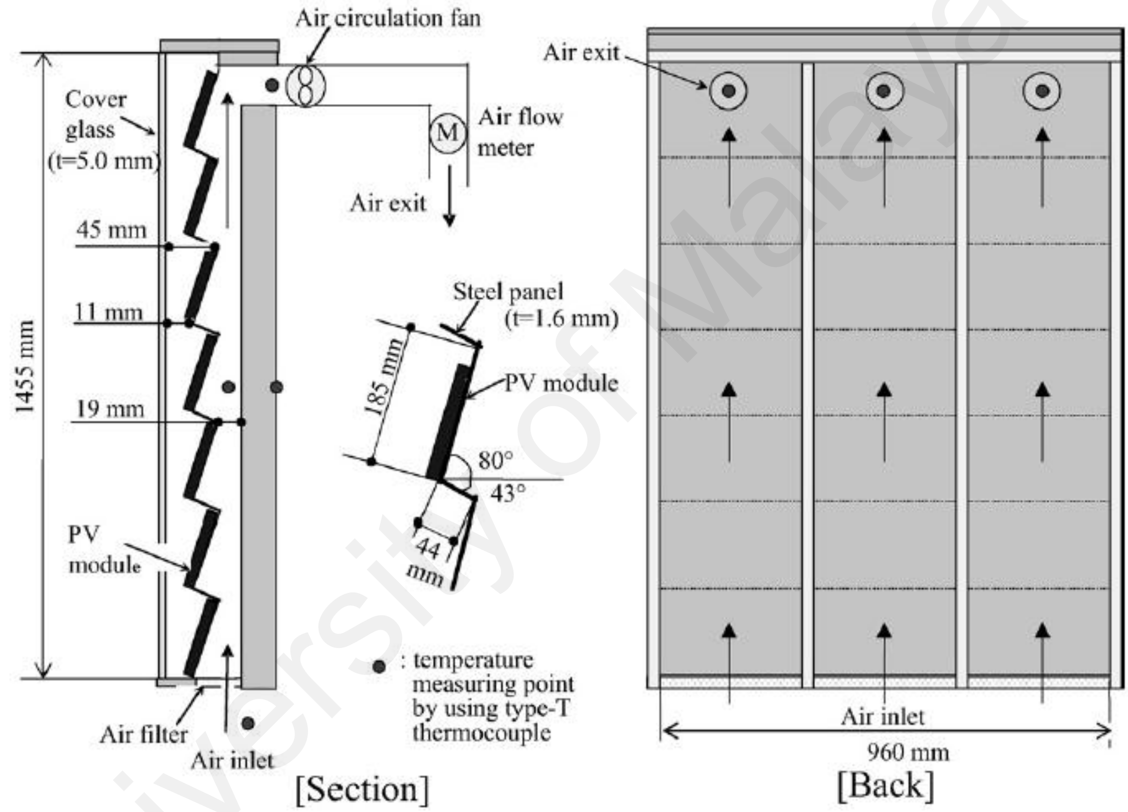

Figure 2.17: Schematic diagram of a thermal-PV hybrid wall board (Nagano et al., 2003).

Touafek et al (2013) proposed a new type of hybrid collectors for air heating as can be seen in Figure 2.18. Development of the hybrid PV/T air collector has been done after conducting a numerical study through numerical modeling where The Runge-Kutta order 4 method has been applied to solve the mathematical equation. From experiment, it has been claimed that the proposed design has given a good thermal and electric performance compared to the traditional hybrid collectors. Air has been chosen in this study since it is the easiest and cheapest way to remove heat from PV module.

Galvanized iron has been used as an absorber for the proposed design. The useful thermal power extracted from experiment is about 290 W while thermal efficiency is around 48%.

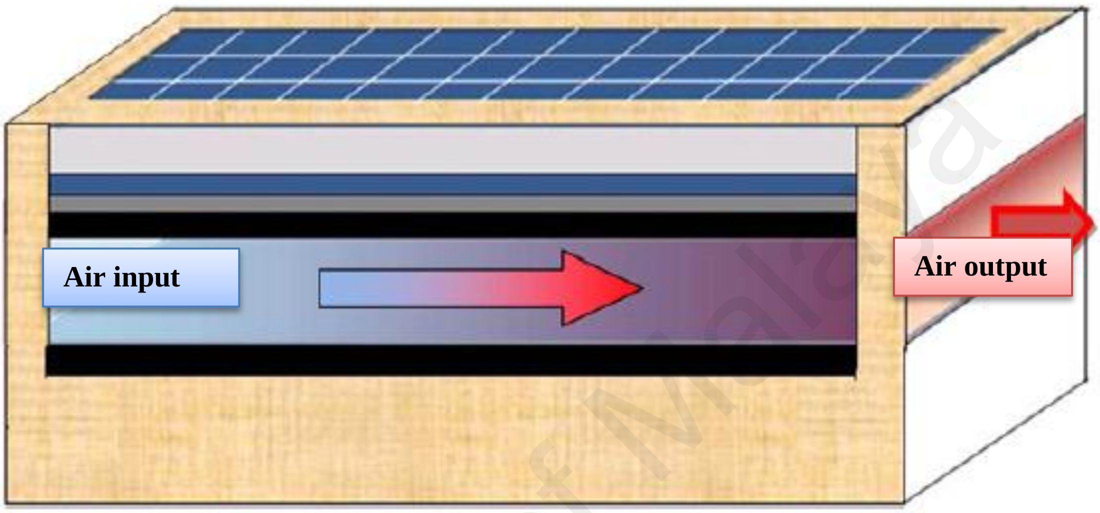

Figure 2.18: Schematic diagrams of new hybrid collector for domestic air heating (Touafek et al., 2013).

Yang & Athienitis (2012) developed a prototype of open loop air-based building integrated photovoltaic thermal BIPV/T system with a single inlet where numerical modelling has been validated by experimental procedure which has been carried out in a full scale solar simulator. On the other hand, the enhancement of BIPV/T system with multiple inlets and other means of heat transfer are studied through simulations. From experiment, it can be seen that thermal efficiency of the BIPV/T system decrease as the wind speed increased. From simulation, the two-inlet design increases thermal efficiency by up to 5% and increase electrical efficiency a little bit. It is also observed that peak temperature of the PV module is reduced when using two inlet BIPV/T system. In order to increase thermal efficiency especially during winter time, wire mesh and vertical glazed solar air collector has been added to the system. Schematic diagram of the two-inlet BIPV/T system connected in series with glazed air collector packed with wire mesh can be seen in Figure 2.19.

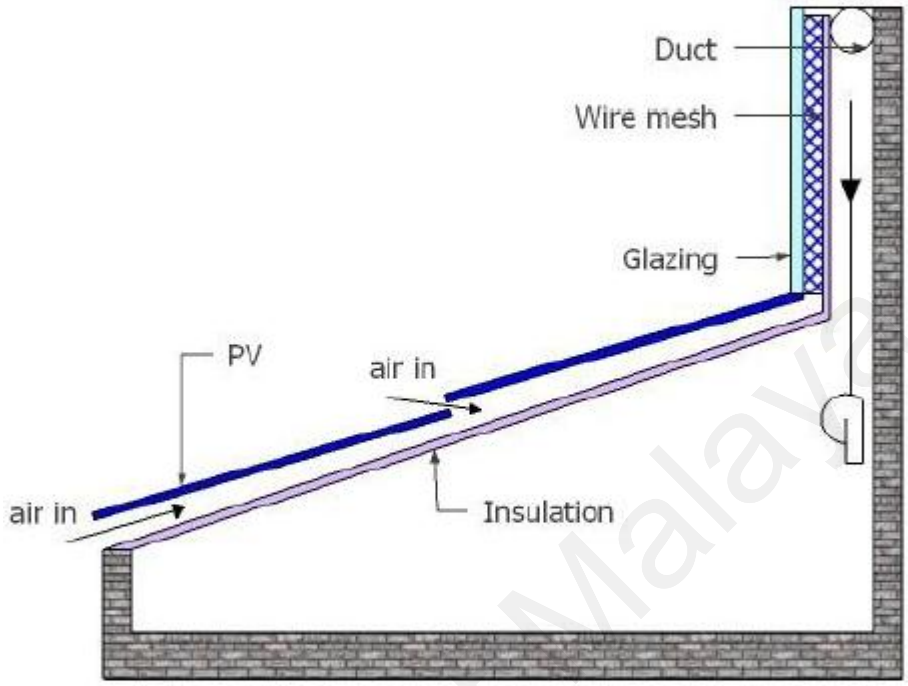

Figure 2.19: Schematic diagram of the two-inlet BIPV/T system connected in series with glazed air collector packed with wire mesh (Yang & Athienitis, 2012)

A novel study on performance of PVT air collector with different configurations has been conducted by Dubey et al., (2009). From all configuration which are case A (Glass to glass PV module with duct), case B (Glass to glass PV module without duct), case C (Glass to tedlar PV module with duct), case D (Glass to tedlar PV module without duct), it is concluded that glass to glass PV modules with duct gives the best output where its annual average efficiency is 10.41%. Schematic of glass to glass PV module with duct and glass to tedlar PV module with duct can be seen in Figure 2.20.

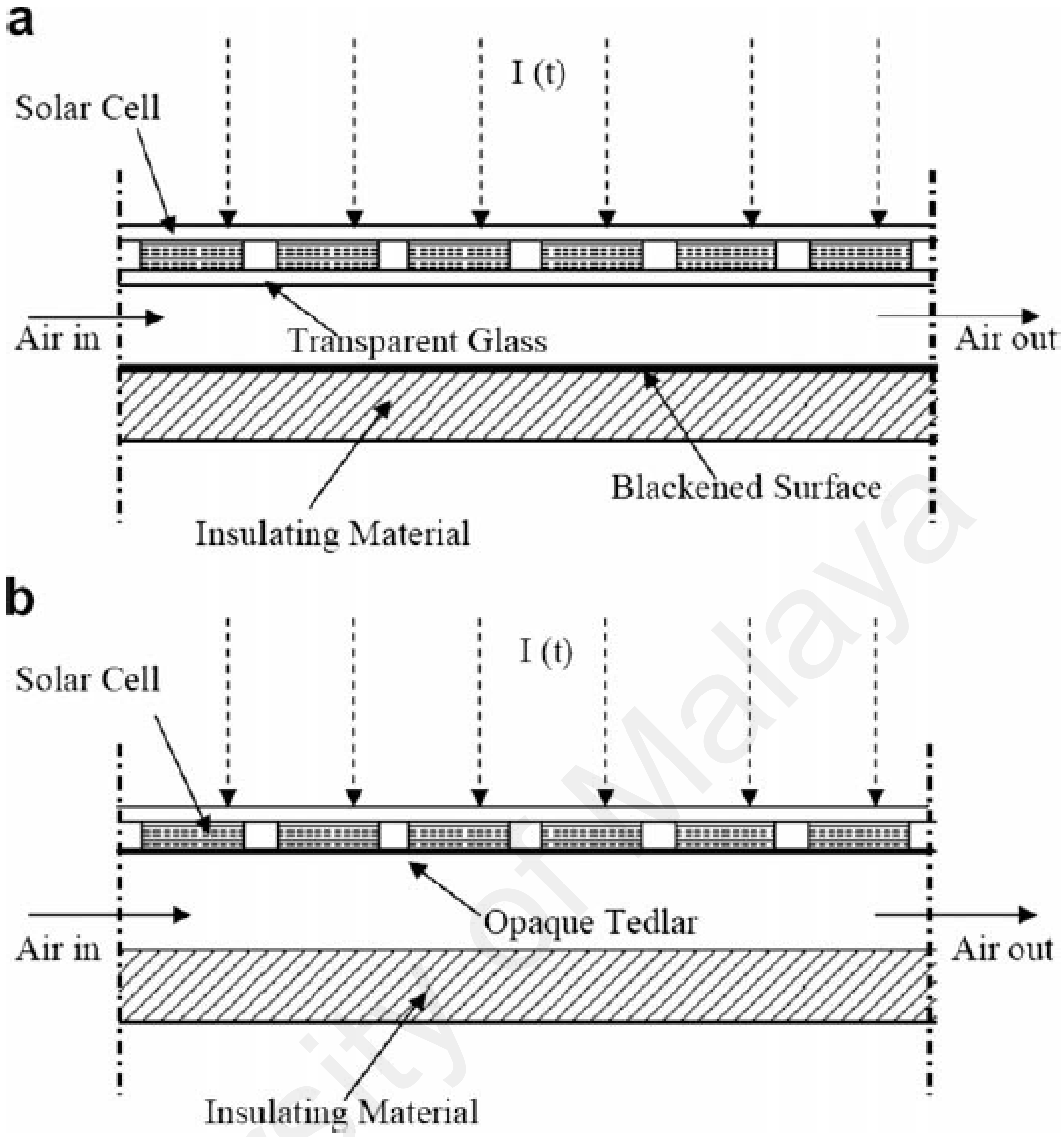

Figure 2.20: Schematic of glass to glass PV module with duct and glass to tedlar PV module with duct (Dubey et al., 2009)

Vats and Tiwari (2012) conducted and experiment to study the energy and exergy performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system using six different photovoltaic (PV) modules which are monocrystalline silicon, amorphous silicon, polycrystalline silicon, CdTe, CIS and HIT technology. From the study, it is concluded that HIT PV module will produce high electrical efficiency while amorphous silicon PV is suitable for high thermal purpose. It is also observed that maximum thermal energy and exergy efficiency is 2497 kWh and 834 kWh respectively for HIT PV module. Again, Vats et al., (2012) study the effect of various packing factor on the performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system with air duct for six different photovoltaic (PV) modules which are monocrystalline silicon, amorphous silicon, polycrystalline silicon, CdTe, CIS and HIT technology. Reducing packing factor will decrease the PV and room temperature hence increases power output. From the study, it is observed that maximum electrical and thermal output was achieved by amorphous silicon PV module with packing factor of 0.62. Anderson et al., (2009) conduct a study on BIPVT performance theoretically using a modified Hottel–Whillier model and confirm the result experimentally. It is agreed that fin efficiency, the thermal conductivity between the PV cells and their supporting structure, and the lamination method do affect the thermal and electrical output from BIPVT. It is concluded that BIPVT integrated into the building is economic rather than integrating BIPVT onto the building. Shahsavar et al., (2011) conduct a novel study on using the exhaust and ventilation air for cooling the photovoltaic panels for a building in Iran. It is concluded that electrical output increase by 10.1% and 7.2% for cooling with exhaust and ventilation air respectively. Heat extracted from PV is used for the ventilation air heating load. Same study has been conducted by Sukamongkol et al., (2010) to reduce air conditioning room energy using heat produced from PVT. A model developed from simulation has been tested experimentally to validate the performance. From the study, the highest air temperature achieved by PVT is 53.8^{o}C with 6% electrical efficiency. Agrawal and Tiwari (2010) investigate the performance of BIPVT system under cold climate in India where the heat rejected can be used for space heating. In this research, it is discussed that for the system connected in series, air with constant mass flow rate will gives better performance while constant air velocity will increase the performance of a system connected in parallel. From experiment, overall thermal efficiency is 53.7% while the exergy for electrical and thermal are 16,209 kWh and 1531 kWh, respectively.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 OVERVIEW

The methodology section comprises of two part: first; hardware and software used and the second part is experimental setup and procedure. Hardware construction and software implementation involved in this research will be discussed further in Section 3.2 and 3.3. Setting of the experiment will be further discussed in Section 3.4 while Section 3.5 will be describing the procedure to carry out research for indoor and outdoor experiment.

3.2 HARDWARE

PV module in Figure 3.1 is used to analyse the performance of PV and PVT system. For this research, the PV module SP75 manufactured by Siemens is used. The material for solar cell is monocrystalline silicon which is known to be easily affected by high temperature (Kumar & Rosen, 2011). Detailed technical specification is tabulated in Table 3.1.

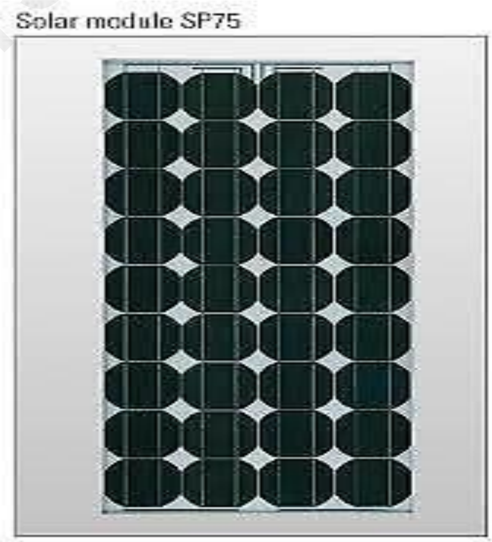

Figure 3.1: Solar module SP75

Table 3.1: SP75 specification

Electrical parameters	
Maximum power rating, Pmax [W_P]	75
Rated current, IMPP [A]	4.4
Rated voltage, VMPP [V]	17.0
Short circuit current, ISC [A]	4.8
Open circuit voltage, VOC [V]	21.7
Thermal parameters	
NOCT [^oC]	45± 2
Temp coefficient: Short circuit current	2.06mA/^oC
Temp coefficient: Open circuit voltage	-.007V/^oC
Qualification test parameters	
Temperature cycling range [^oC]	-40 to +85
Humidity freeze, Damp heat [%RH]	85
Maximum system voltage [V]	600V per UL
Wind loading PSF [N/m^2]	50[2400]
Maximum distortion [^{o}]	1.2
Hailstone impact Inches [mm]	1.0 [25]
MPH [m/s]	52 [v=23]
Weight Pounds [kg]	16.7 [7.6]

In this study, the thermal collector is made from copper due to its high heat conductivity compared to other metals. In addition, corrosion resistivity of copper is also better. However, copper is a bit heavy compared to aluminum. Copper with diameter 15mm and 22mm are welded to be in rib position as shown in Figure 3.2 below. Thermal collector is then painted black in color in order to help increase the heat transfer between PV back and pipe. Table 3.2 shows the specification of copper.

Figure 3.2: Design of thermal collector

Table 3.2: Specification of copper

Parameter	**Value**
Relative Density	8.79
Specific Heat	0.39 *kJ/kg K*

As discussed in several researches, the usage of fin between PV back and thermal collector will also increase the heat transfer. Fins that are made from aluminum has high heat capacity value. Fins used in this research can be seen in Figure 3.3 while the specification of aluminum is shown in Table 3.3.

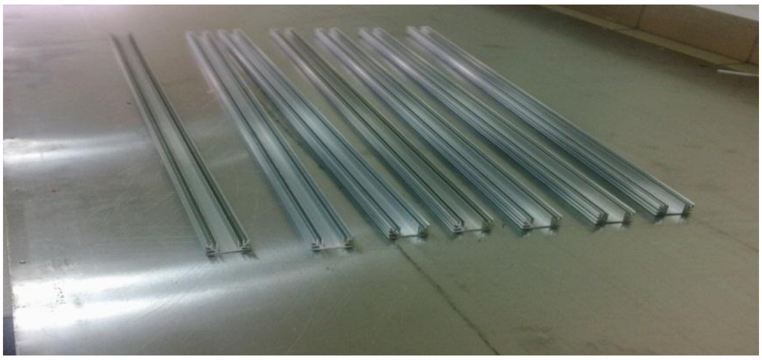

Figure 3.3: Aluminum fins

Table 3.3: Specification of aluminum

Parameter	Value
Relative Density	2.72
Specific Heat	0.436 *kJ/kg K*

Insulator made from plywood is used to trap the heat produced by PV module. BOYU air pump is used in this research to supply air flow at different speed. Air is being flowed into thermal collector at 25l/min and 50l/min. Solar simulator is built to conduct an indoor experiment for PV and PVT performance under various irradiation levels. Irradiation levels can be varied by controlling the power supply. Using power supply, irradiation level in solar simulator can be controlled by varying the output power. Pyrometer was used in this research to measure light irradiation. The angle meter or also known as inclinometer use to confirm the tilt angle of PV and PVT module. Manufactured by Starret, this angle meter offers a large, readable scale for accurate readings from 0-90^0 in any quadrant.

3.3 DATA LOGGER

Data logger in Figure 3.4 is used to capture the power output from PV and PVT. This data logger manufactured by UMPEDAC is also capable to give the reading of irradiation and temperature. This data logger is integrated with NASA 500 Version 0.2 software that can display and store the measured data. Table 3.4 shows the specification of data logger.

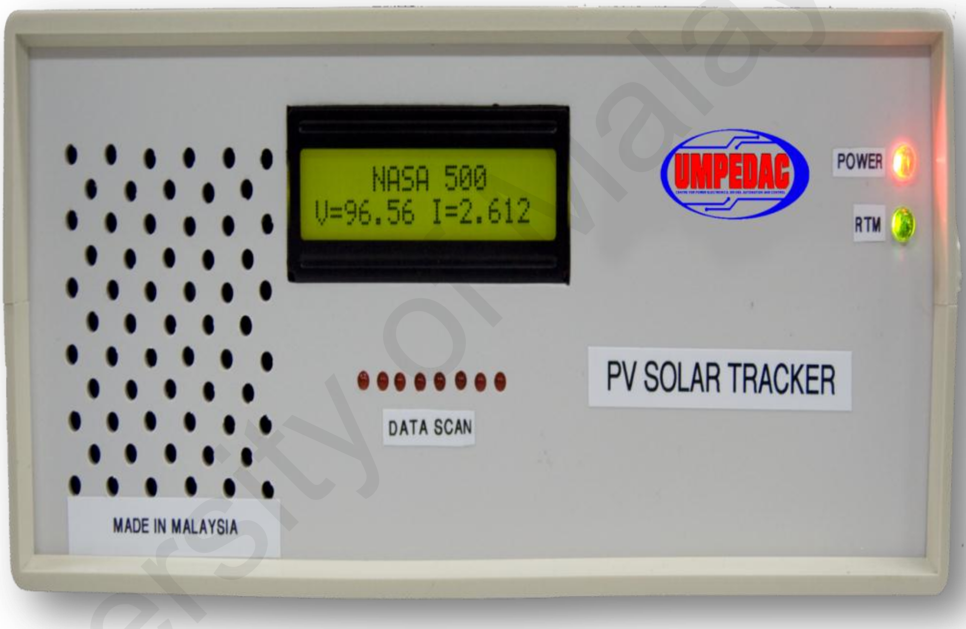

Figure 3.4: Data logger to measure power output and irradiation

Table 3.4: Specification of data logger

Dimensions:	20x22.5x8 cm
Display:	2x16 LCD
Software Version:	NASA 500 Version 0.2
Maximum Measuring Voltage:	200V DC
Maximum Measuring Current:	18A DC
Communications:	Serial (RS 232/USB)

HOBO temperature data logger has four external channels that can support the temperature sensor. In this research, temperature sensor has been placed on the back of PV, upper surface of PV, inlet pipe and outlet pipe of PVT. Ambient temperature also has been measured. PV stand is used when conducting the outdoor experiment as can be seen in Figure 3.5. Using PV stand, the angle can be changed remotely.

Figure 3.5: PV stand to support PV and PVT modules

3.4 SOFTWARE

HOBOware

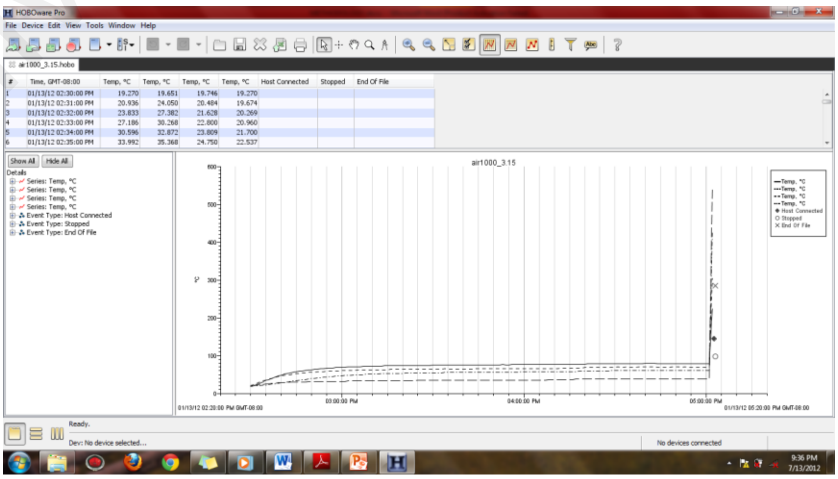

Figure 3.6: Graphical User Interface of HOBOware

This software comes with the purchase of HOBO data logger and temperature sensor. The software automatically plots the graph for temperature measurement. It is easily operated since the GUI is simple and friendly as can be seen in Figure 3.6.

NASA 500 Version 0.2

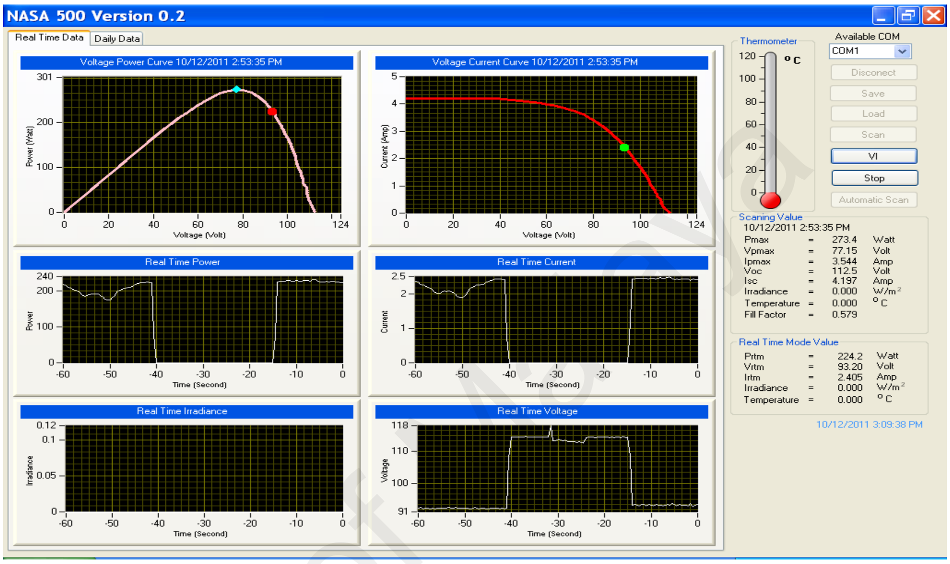

Figure 3.7: Graphical User Interface of NASA 500 Version 0.2

NASA 500 Version 0.2 can monitor PV array solar irradiation, temperature, and power, all in real time. Data collected will be stored in Excel. The GUI is simple and very friendly like in Figure 3.7.

3.5 PV/ THERMAL CONFIGURATION

Before running the experiment, PVT system was design and constructed. Fin is placed between PV rear and thermal collector, and both are painted in black. The PV rear was then covered with plywood in order to trap the heat from flowing out. Parameter values of the testing are tabulated in Table 3.5. Figure 3.8 shows the schematic diagram of PVT system used in this study. The locations of the sensor and data logger are shown in Figure 3.9 and 3.10.

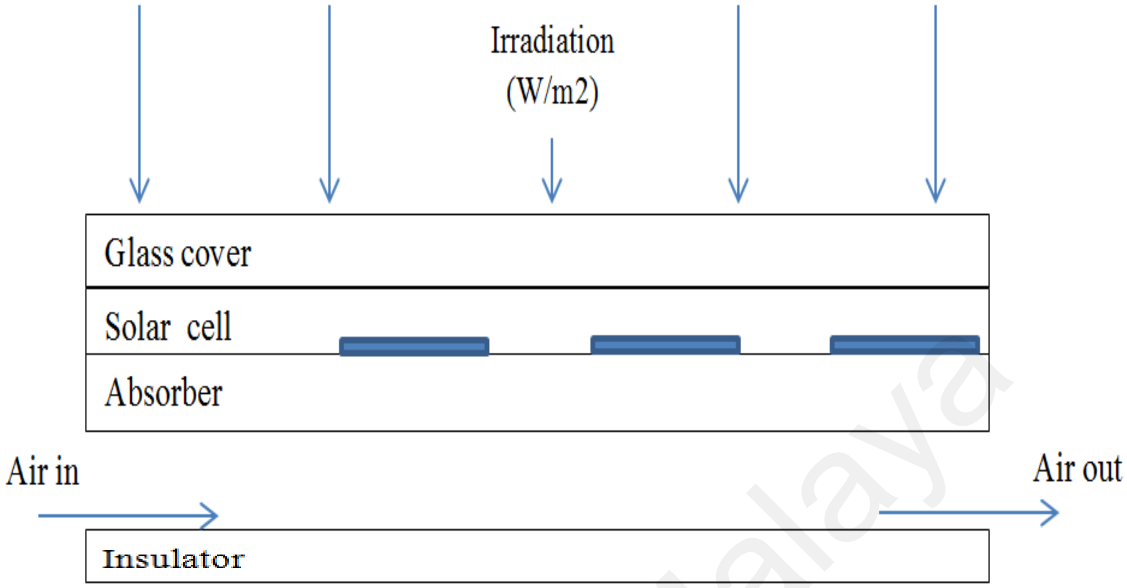

Figure 3.8: Schematic diagram of PVT system

Table 3.5: Parameter values for testing

Parameters	Value
Solar simulator	90 halogen lamp (50W), 4 fan
Module type	Siemens SP75 monocrystalline silicon
PV module area	$0.6324m^2$
I_{sc} (STC)	4.8A
V_{OC} (STC)	21.7V
Collector material	Copper
Length of thermal collector	1.0 m
Diameter of thermal collector	0.015 m
Fin length	1.0 m
Fin width	0.034 m
Specific heat for air	1.005 kJ/kg.K
Air density	1.127 kg/m^3
Air flow	25l/min, 50l/min
Angle	3.15^o, 18.15^o
Irradiation	500-1000 W/m^2
Time	150 minutes
Parameters measured	Power output, upper surface temperature, back surface temperature, inlet air temperature, outlet air temperature, ambient temperature

The experiment has been conducted in the solar simulator and the PV module used in this study is 75W mono crystalline silicon solar cell manufactured by Siemens. Solar simulator is placed in the room with controlled environment. The experiment is conducted to study the power output from PV and PVT and also total heat that can be extracted using air from PVT. Field experiment was conducted for four days.

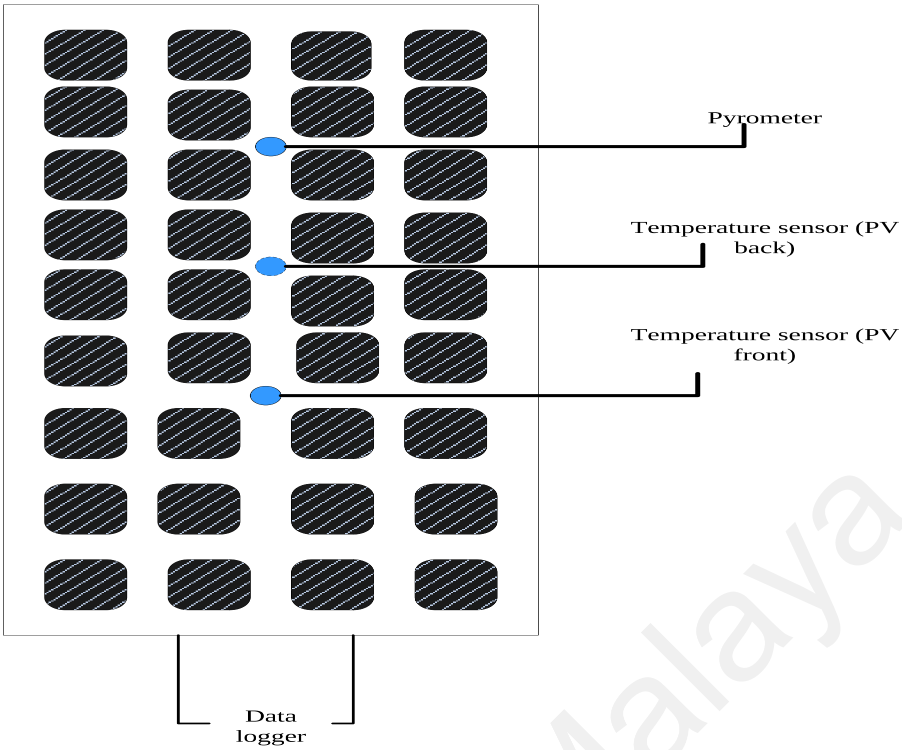

Figure 3.9: Location of temperature sensor and data logger for PV

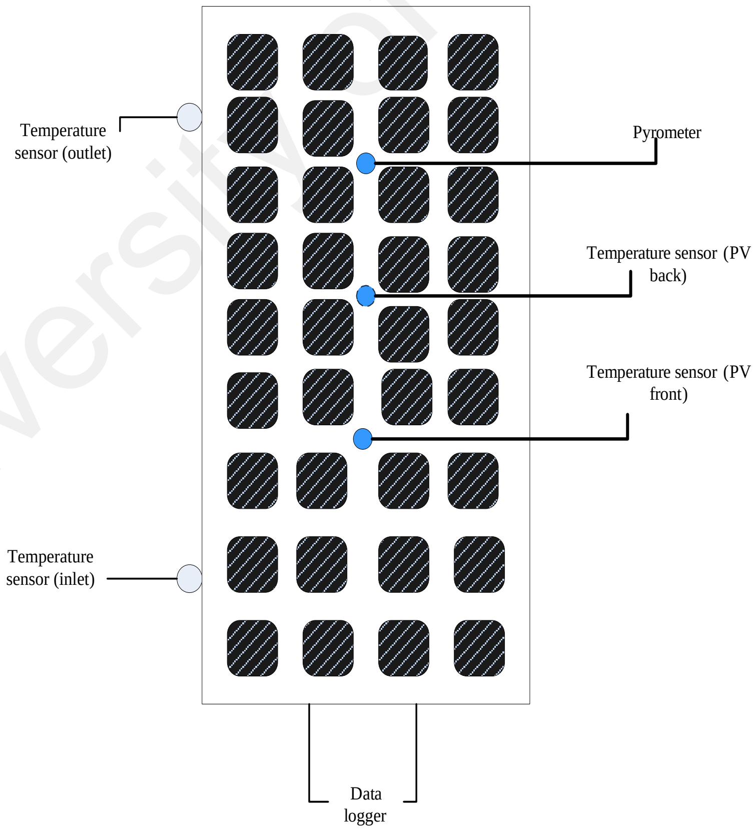

Figure 3.10: Location of temperature sensor and data logger for PVT

3.6 EXPERIMENTAL AND MEASUREMENT SYSTEMS OF THE PV/THERMAL SYSTEM

INDOOR EXPERIMENT

At first, experiments conducted were for PV module only. For phase 1, PV module has been tilted at angle 3.15°. Constant irradiation is set for 150 minutes for every irradiation level starting with 500W/m^2 until 1000W/m^2 respectively. Irradiation level is measured using Li-Cor pyrometer. During this time, voltage, current, power and module temperature are being monitored using data logger with 1-minute interval. Temperature sensor had been placed on the PV, rear of PV and also one temperature sensor to measure ambient temperature. After 150 minutes, PV module will be cooled before starting a new experiment for other constant irradiation level. Same procedures are being repeated for the next phase where PV module is tilted in the simulator at angle of 18.15°. One of the experimental setup for 18.15° tilted is shown in Figure 3.11.

For PVT, experiments begin by blowing 25 liter per minute air as a cooling fluid. The same procedure as testing PV module without thermal collector is applied. After two phases are finished, air with speed 50 liter per minute is flowed and the same procedure is repeated. Speed for the air flow is controlled using an air pump. For PVT experiments, temperature sensors are placed on the top and back surface of the PVT and also at inlet and outlet of the thermal collector. This procedure is repeated again for other angles. Experiment has been conducted in a room with controlled environment. Temperature of the room is fixed to 30°C so that it could help to slow down the PV module temperature increment.

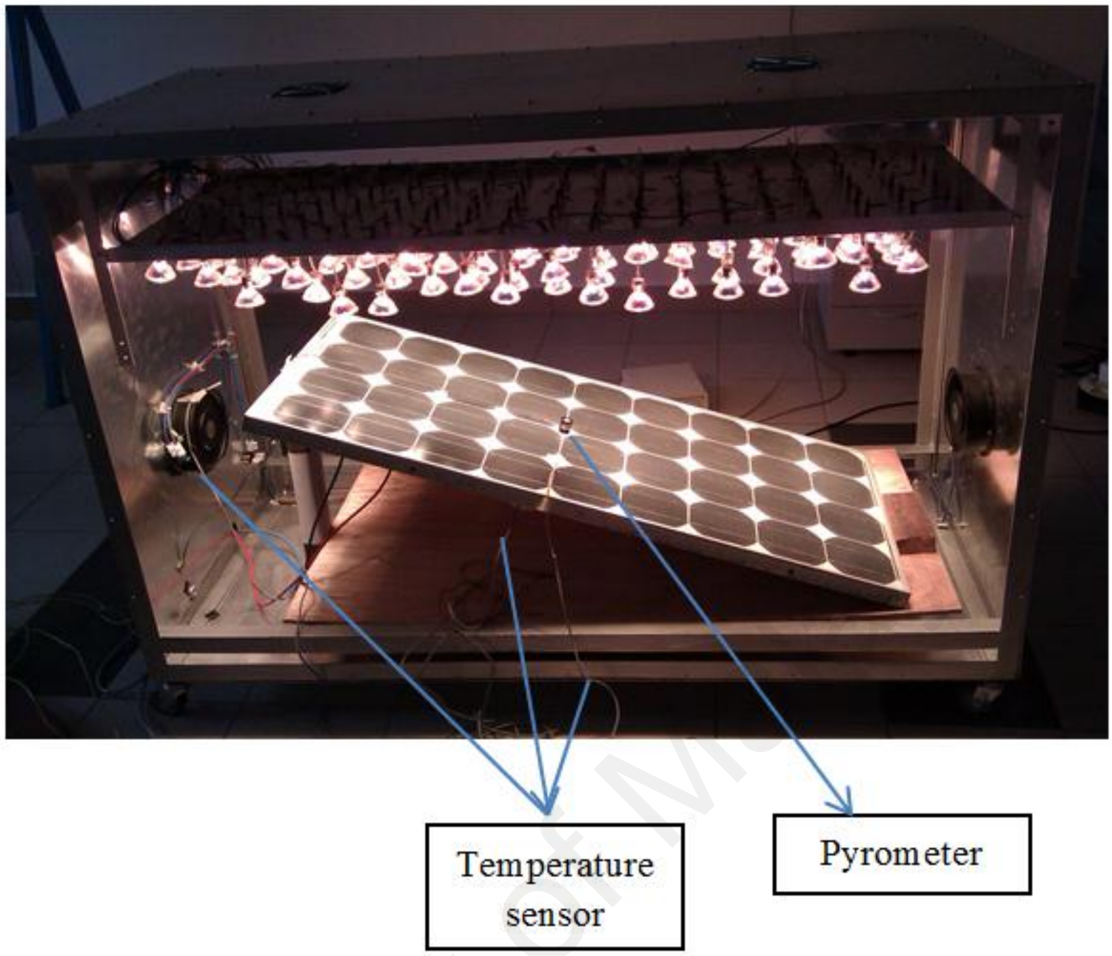

Figure 3.11: PV module tilted at 18.15° for 700W/m^2 irradiation testing at ambient temperature 30°C.

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OUTDOOR EXPERIMENT

For field testing, PV and PVT have been placed side by side on the PV stand. At first, PV and PVT were tilted at angle 3.15° facing south as can be seen in Figure 3.12. 25l/min air is given to the PVT as cooling fluid. For outdoor testing, experiment were carried out from 10 am to 4 pm. Experiments were then repeated on the next day for other angles and air speed. Outputs from the modules were connected to the data logger in order to get the power output from PV and PVT for comparison purposes. On the other hand, data such as upper surface temperature, back surface temperature, inlet air temperature, outlet air temperature, ambient temperature and irradiation were also taken. Logging interval of one minute were taken for each data from 10.00 am until 4.00 pm. During the time experiment was conducted, the ambient temperature varies between 29 - 40°C and the wind speed are 10-16km/h.

Figure 3.12: Experimental setup for outdoor testing

3.7 MATHEMATICAL MODEL

Overall performance of PV module strongly depends on the irradiation, operation temperature, working condition or weather and the module characteristics itself. As PV module absorbs and converts the solar irradiation into electrical energy, a fraction of it forms heat energy that will decrease the power output since the heat produce raises the PV temperature. Measuring electrical output from PVT system is easy since the output can be use directly to the device and storage usage is optional (Chow, 2010).

From previous study (Wolf, 1976; Kern & Russell, 1978; Cox & Raghuraman, 1985; Garg et al., 1994; Sopian et al., 2000; Hegazy, 2000; Coventry, 2005; Chow, 2010; Chow et al., 2007; Dubey & Tiwari, 2008), electrical efficiency can be described as:

$$\mu_e = \mu_r \left(1 - 0.0045(T_c - T_r)\right) \quad (3.1)$$

Where μ_e is the electrical efficiency, μ_r is the reference efficiency at T_r =25 ^{o}C and T_c is cell temperature. However, according to (Sarhaddi et al., 2010), equation (3.1) is not suitable to be used for low irradiation level since the temperature of solar cell will be equal to ambient temperature. On the other hand, this equation could not give the exact output of open circuit voltage, short circuit current, maximum power point voltage and maximum power point current for PV/T air collector.

For thermal analysis of PV/T, equations are taken from (Vokas et al., 2006). Energy balance on the surface of flat plate PV module is:

[Useful energy] = [Energy absorbed] – [Lost energy]

Energy used from PV module to heat up the fluid in the thermal collector is calculated from equation (3.2) (Zogou and Stapountzis, 2011):

$$Q = m\, C_p\, (\Delta T) \quad (3.2)$$

Where Q is the heat collected, *m* is the mass flow rate of fluid, C_p is the specific heat of fluid and ΔT is the temperature difference between inlet and outlet of pipe. From the equation (3.2), when we modified it into (3.3):

$$Q\left(\frac{1}{\Delta T}\right) = mC_p \tag{3.3}$$

Note that from this relationship, ΔT is inversely proportional with mass flow rate and specific heat capacity of fluid. In this study, mass flow rate is controlled by air pump and is kept constant during experiment. It is significant to understand that the amount of heat transferred to air is important rather than losing it to the ambience.

Thermal efficiency of the system can be calculated using:

$$\mu_{th} = \frac{Q}{G \times A_c} \tag{3.4}$$

Where μ_{th} is the thermal efficiency, Q is the heat collected, G is the irradiation level and A_c is the area of thermal collector.

Overall system efficiency is the total of μ_{th} and μ_e:

$$\mu_{overall} = \mu_{th} + \mu_e \tag{3.5}$$

Where μ_{th} is the thermal efficiency and μ_e is the electrical efficiency.

3.7.1 UNCERTAINTY ANALYSIS

Uncertainty or error analysis is needed in order to confirm the experimental data. An error can occur due to the improper experiment setup and normally due to human error while taking the measurement (Jin et al., 2010). There are two types of error which are systematic and random error. Systematic error is an error that occurs from constant value and can be minimized by calibrating the device use in experiment while random error cannot be removed as it happen due to imprecision (Janjai et al., 2009). Basic error equation can be expressed as (Schenck and Hawks, 1979).

$$x_{act} = x_m \pm \delta x_{act} \tag{3.6}$$

As can be seen in equation 3.6, x_{act} is actual value while x_m is mean value of measured data and δx_{act} is the error value.

Every sensor and data logger used in this study has its own limitation or error when reading data. In order to get a precise and accurate measurement, calculations to compute the error need to be carried out.

Error in mass flow rate, $\dot{m}$ can be calculated from equation (3.7) which the value of the air density can be neglected since it is constant.

$$\delta\dot{m} = \left[\frac{\delta A}{A} + \frac{\delta V}{V}\right] m \tag{3.7}$$

Error in electrical efficiency can be calculated by equation (3.8):

$$\delta\%_{el} = \frac{(\delta V_m + V_m)(\delta I_m + I_m)}{(\delta A_c + A_c)(\delta G + G)} \tag{3.8}$$

Where $\delta\%_{el}$the error of electrical efficiency, G is the irradiation level exposed, A_c is the area of PV module, while V_m and I_m is the voltage and current maximum produced by PV module respectively.

Error in thermal efficiency can be calculated by equation (3.9). Specific heat value for air can be neglected since it is constant.

$$\delta\%_{th} = \frac{(\delta\dot{m}+\dot{m})(\delta\Delta T+\Delta T)}{(\delta A_c+A_c)(\delta G+G)} \tag{3.9}$$

Where $\delta\%_{th}$the error of thermal efficiency, G is the irradiation level exposed, A_c is the area of thermal collector and ΔT is the temperature difference between inlet and outlet of pipe.

CHAPTER 4: RESULT AND DISCUSSION

4.1 OVERVIEW

In this chapter, details on the experimental results and discussion will be further explained. Results include graphs and tables of difference angle, air speed and irradiation level. The comparative study between indoor and outdoor experimental result will also be discussed below in Section 4.2 and 4.3 respectively. Section 4.4 shows the calculation for error analysis in both experiments.

4.2 INDOOR EXPERIMENT

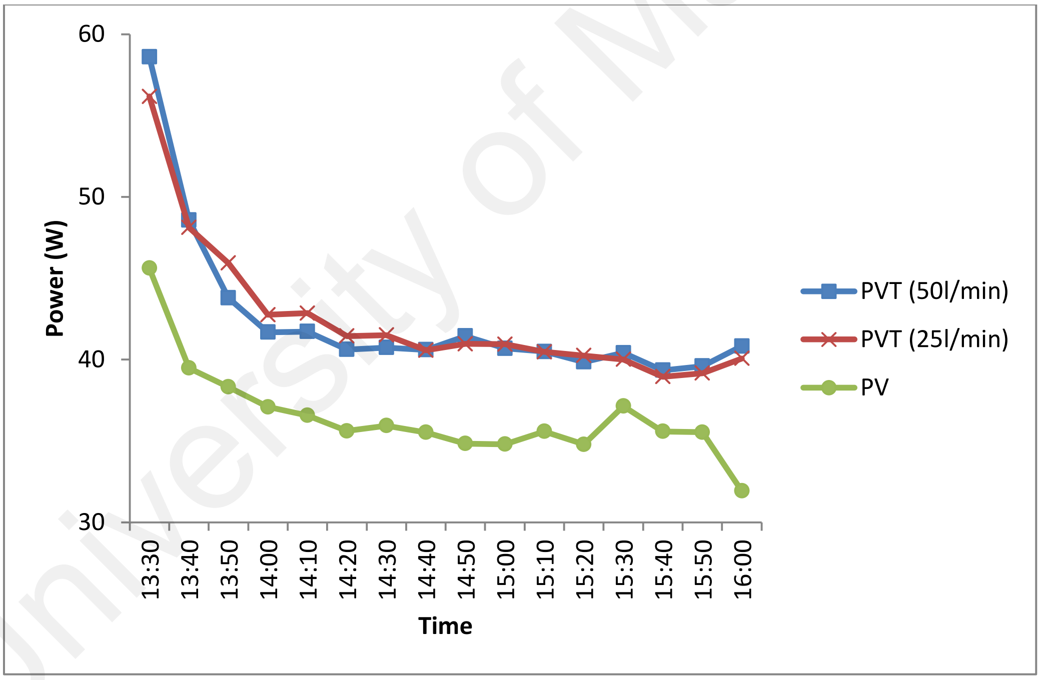


Figure 4.1: Power output (W) at irradiation 1000 W/m^2 at angle 3.15°

When PV and PVT are exposed to maximum irradiation and tilt at angle 3.15°, it can be seen that PV power output was low compared to power output from PVT for 25 and 50 l/min air flow respectively. Figure 4.1 exhibited that maximum powers captured were 58.5W, 56W and 45.1W respectively for PVT with 50l/min air, PVT with 25l/min air and PV only. Power output decreases after some time due to PV module temperature increment. Varying the air flow speed resulted in 2W power difference. Ambient temperature in the room is maintained at 30°C.

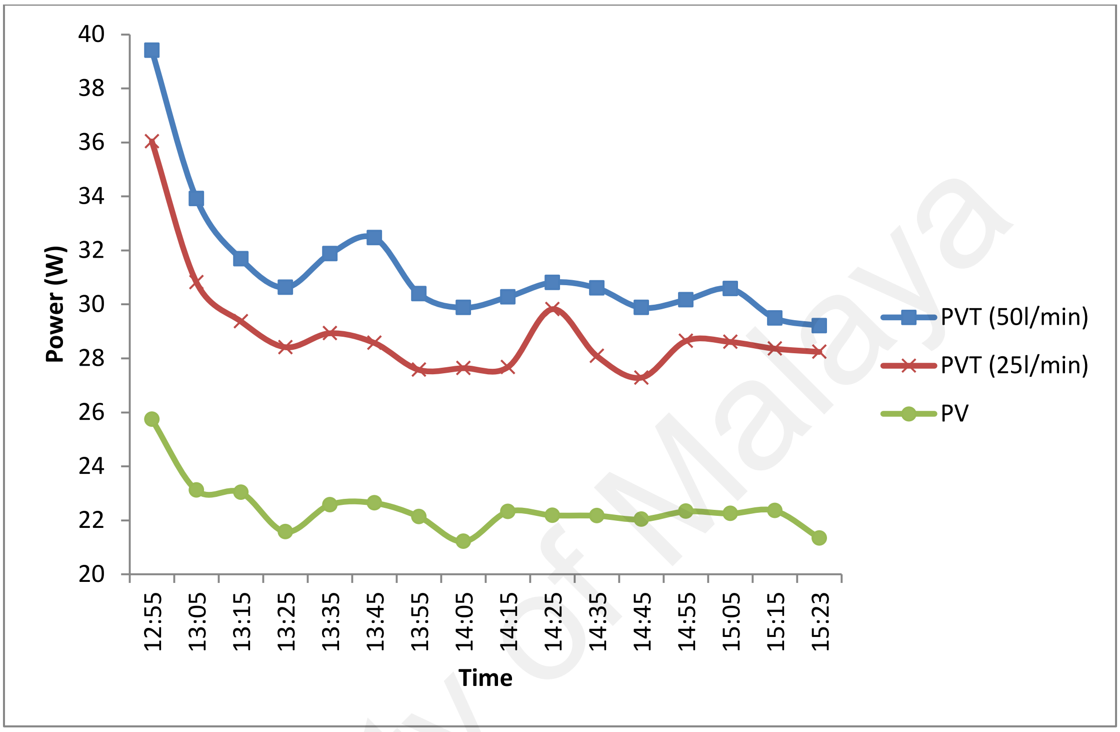


Figure 4.2: Power output (W) at irradiation 1000 W/m^2 at angle 18.15°

All modules were also tested at angle 18.15° with irradiation level at 1000 W/m^2. For PVT with 50l/min air, PVT 25l/min air and PV, the maximum powers were 39W, 36W and 25.7W respectively as can be seen in Figure 4.2. Like before, power output decreases after being exposed to constant irradiation for some time. Ambient temperature in the room is maintained at 30°C.

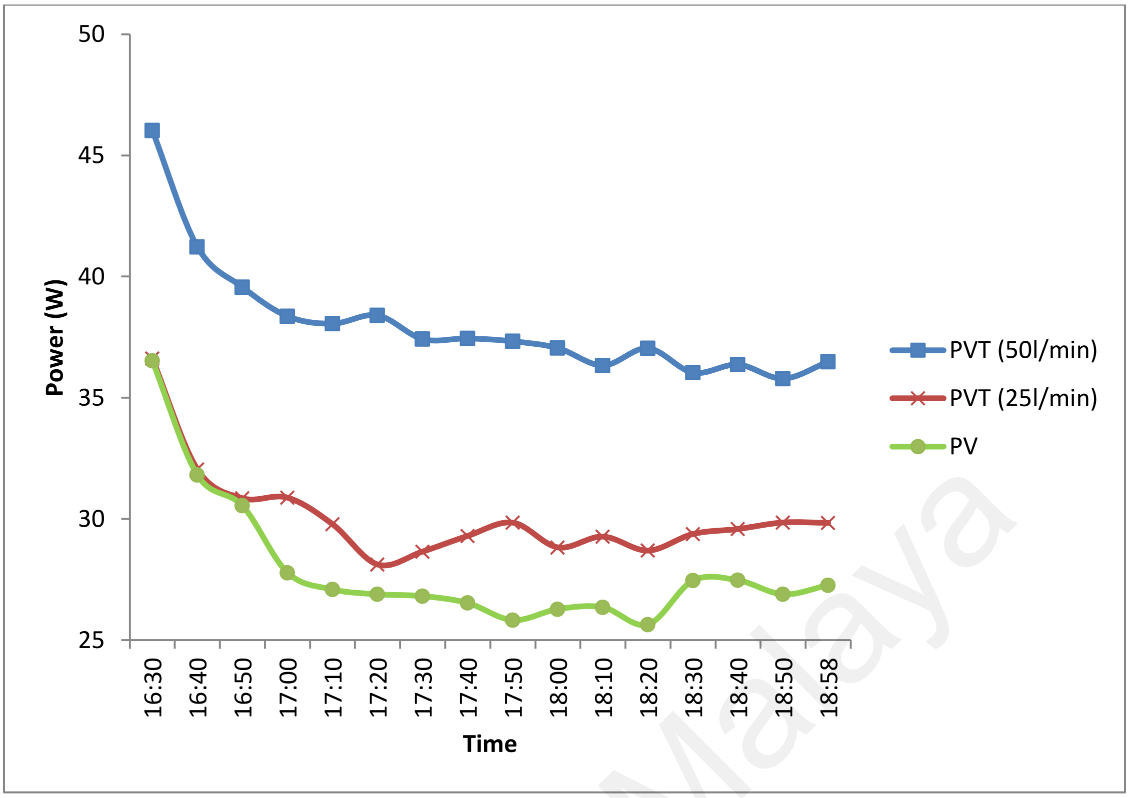


Figure 4.3: Power output (W) at irradiation 800 W/m^2 at angle 3.15°

All modules were also tested under constant irradiation 800 W/m^2 at angle 3.15° as shown in Figure 4.3. Compared to 1000 W/m^2, power output for this testing was slightly low as the performance of modules also depends on the irradiation given. For PVT with 50l/min air, PVT 25l/min air and PV only, maximum powers were 46W, 37W and 36W respectively.

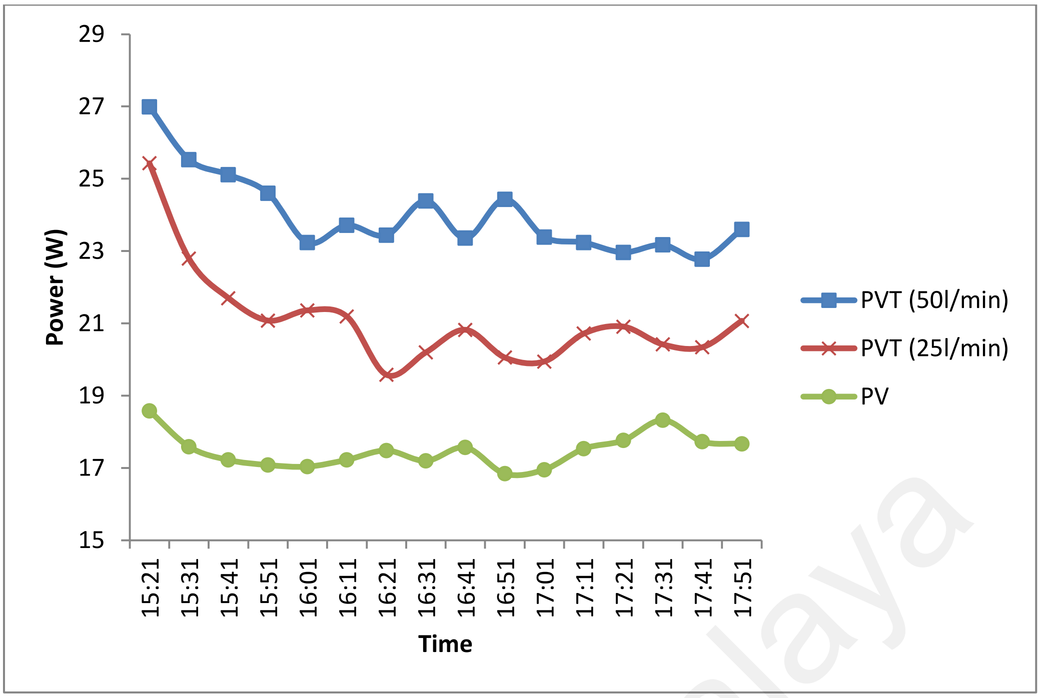


Figure 4.4: Power output (W) at irradiation 800 W/m^2 at angle 18.15°

At similar 800 W/m^2 constant irradiation level, modules were tested with similar irradiation but different angle which is 18.15°. Maximum powers captured were 27W, 25W and 19W respectively for PVT with 50l/min air, PVT 25l/min air and PV only. The power output difference for PV and PVT at this time was greater which was around 6W. Graph can be seen in Figure 4.4.

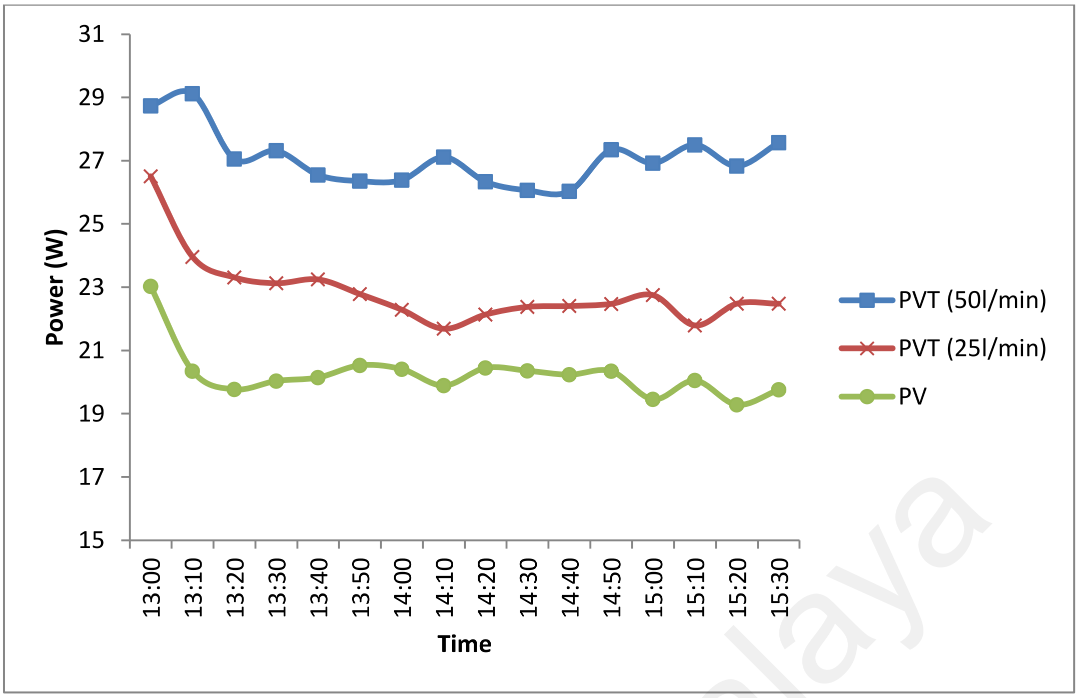


Figure 4.5: Power output (W) at irradiation 600 W/m^2 at angle 3.15°

When given constant 600 W/m^2 irradiation level, as it is expected that power output will be slightly low compared to 1000 W/m^2 and 800 W/m^2 irradiation level. Figure 4.5 shows the maximum powers captured; 29W, 27W and 23W respectively for PVT with 50l/min air, PVT 25l/min air and PV only.

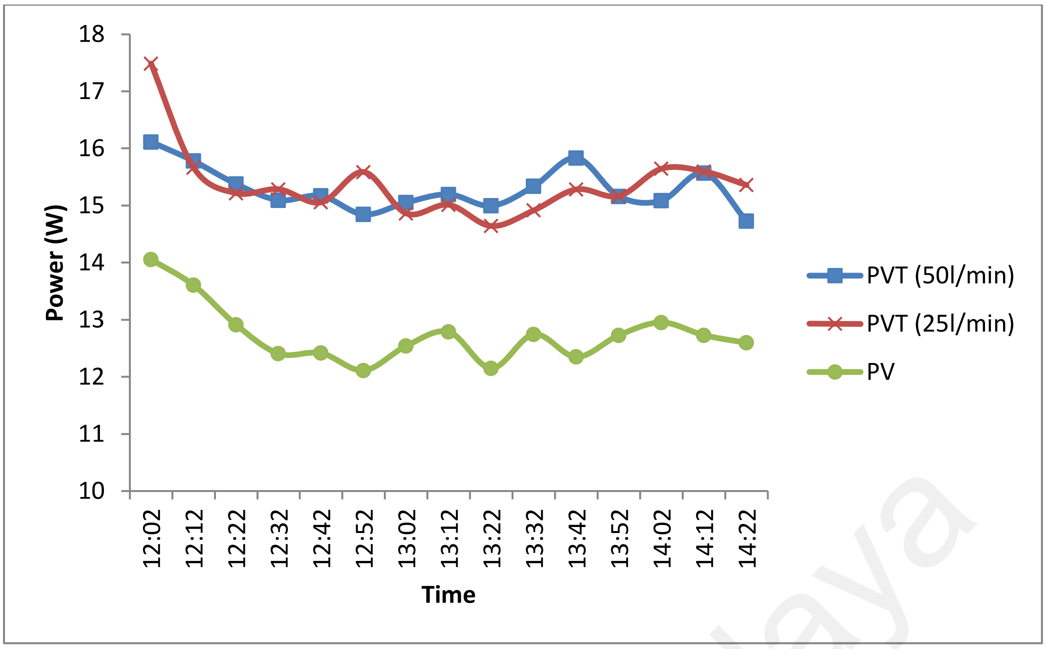


Figure 4.6: Power output (W) at irradiation 600 W/m^2 at angle 18.15°

At angle 18.15°, power output was very low compared to other testing which were 17W, 16W and 14W for PVT with 50l/min air, PVT 25l/min air and PV only respectively. The decrement of power output was slow compared to when modules were exposed to 1000 W/m^2 and 800 W/m^2 irradiation level. Figure 4.6 displays that power output varies when thermal collector is flowed with different air speed. Around 4-7W more power can be collected by PVT compared to PV only.

Table 4.1: Air temperature (◦C) for 25l/min flow

Irradiation (W/m^2) / Angle (◦)	3.15◦		18.15◦	
	T_{in}	T_{PVT}	T_{in}	T_{PVT}
600	25.008	44.2	25.008	45.4
800	25.2685	53.7	25.008	48.0
1000	27.092	62.0	26.571	53.8

Table 4.1 shows the highest air temperature measured for 25l/min at the outlet of the thermal collector (T_{PVT}) at different constant irradiation level and angle. There is a small difference in temperature value for every angle but obvious differences when we change the irradiation level. At angle 3.15° and 1000 W/m^2 irradiation, 62◦C of air temperature was measured at the end of the experiment while the same angle with 600 W/m^2 irradiation recorded 44°C only. When the speed of air flow changed to 50l/min, the air temperature measured decreased compared to 25l/min air flow as can be seen in Table 4.2. When given 1000 W/m^2 irradiation at angle 3.15°, air temperature as high as 60°C was achieved in this study. Higher temperature value was measured at the outlet of the thermal collector as the irradiation level increased. Only a slight difference in temperature rise was detected after changing the flow rate of air. This situation shows that for a small system, flow rate of air is not necessary since it only gives small temperature difference. Furthermore, high flow rate pump requires more power consumption.

Table 4.2: Air temperature (out) for 50l/min flow

Irradiation (W/m^2) / Angle (°)	3.15°		18.15°	
	T_{in}	T_{PVT}	T_{in}	T_{PVT}
600	22.924	42.09	23.966	41.356
800	23.966	46.449	25.529	47.711
1000	25.008	60.786	25.008	53.221

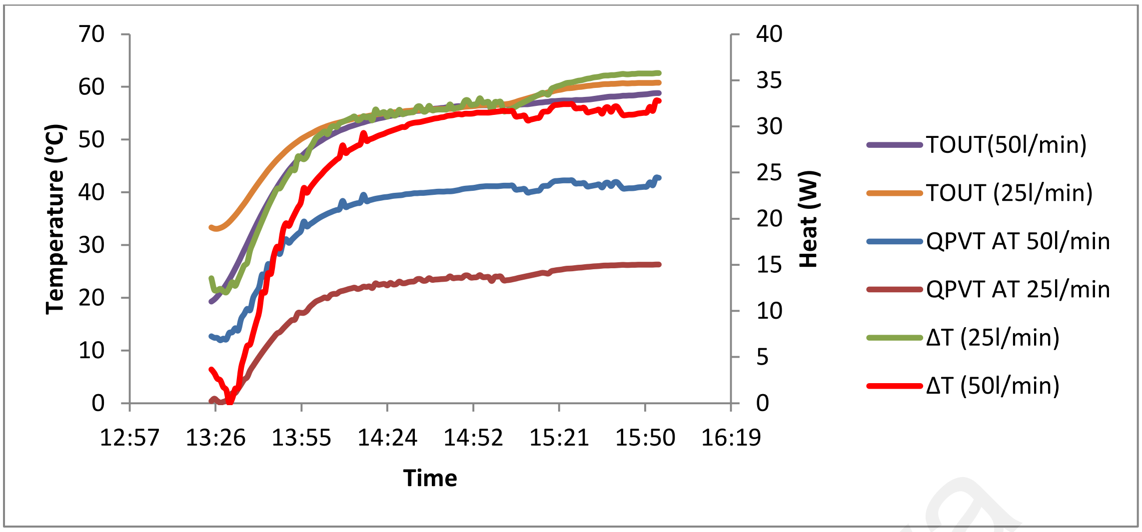


Figure 4.7: Heat (W) and temperature (^{o}C) at irradiation 1000 W/m^{2} at angle 3.15°

Figure 4.7 shows the graph for heat output from PVT and temperature rise value for 25l/min and 50l/min air speed. It can be seen that more heat is produced when the air speed increases. Highest temperature is measured at 60°C for 50l/min air flow and 62°C for 25l/min air flow. The total of 1645.051W and 2929.111W heat was produced at the end of the experiment for 25l/min and 50l/min air flow respectively.

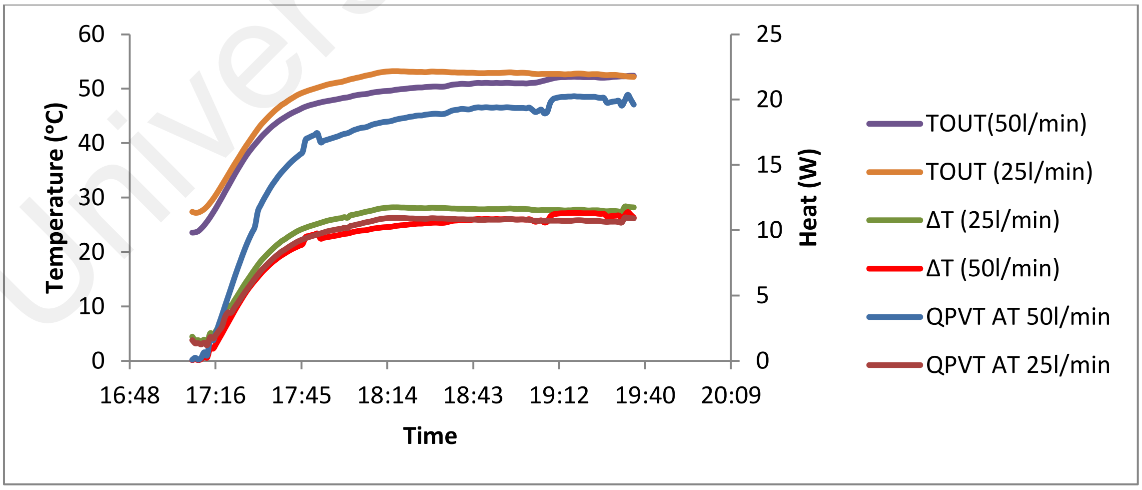


Figure 4.8: Heat (W) and temperature (^{o}C) at irradiation 1000 W/m^{2} at angle 18.15°

A total of 1202.154W and 2082.864W heat output was collected for 25l/min and 50l/min air speed respectively when angle is changed to 18.15˚. This is less by an average of 20% than the angle before. Figure 4.8 shows Heat (W) and temperature (°C) at irradiation 1000 W/m^2 at angle 18.15º.

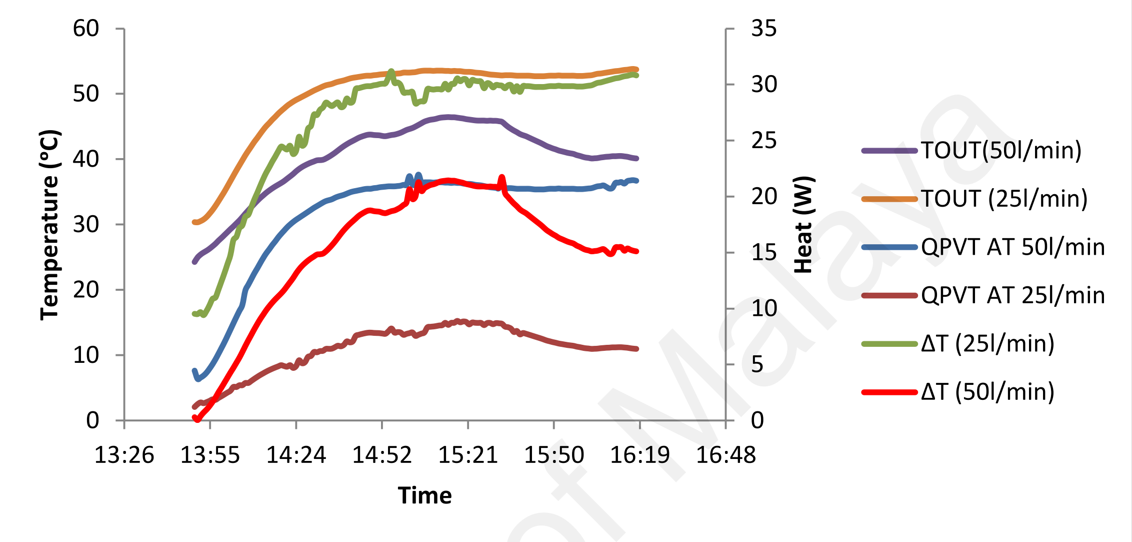


Figure 4.9: Heat (W) and temperature (^{o}C) at irradiation 800 W/m^2 at angle 3.15°

For constant 800 W/m^2 irradiation level at angle 3.15°, 843.0554W and 1551.66W heat energy were produced by the PVT system for 25l/min and 50l/min air speed respectively as in Figure 4.9. This value is 45% less than when irradiation level is 1000 W/m^2 at the same angle. More heat was collected when PVT uses 50l/min of air which mean temperature of PV cell also decreases, thus giving better power output compared to 25l/min air flow. Temperature and mass flow rate of fluid influences the amount of heat collected. It is also noted that temperature difference between air inlet and outlet decreases as mass flow rate and irradiation level increases.

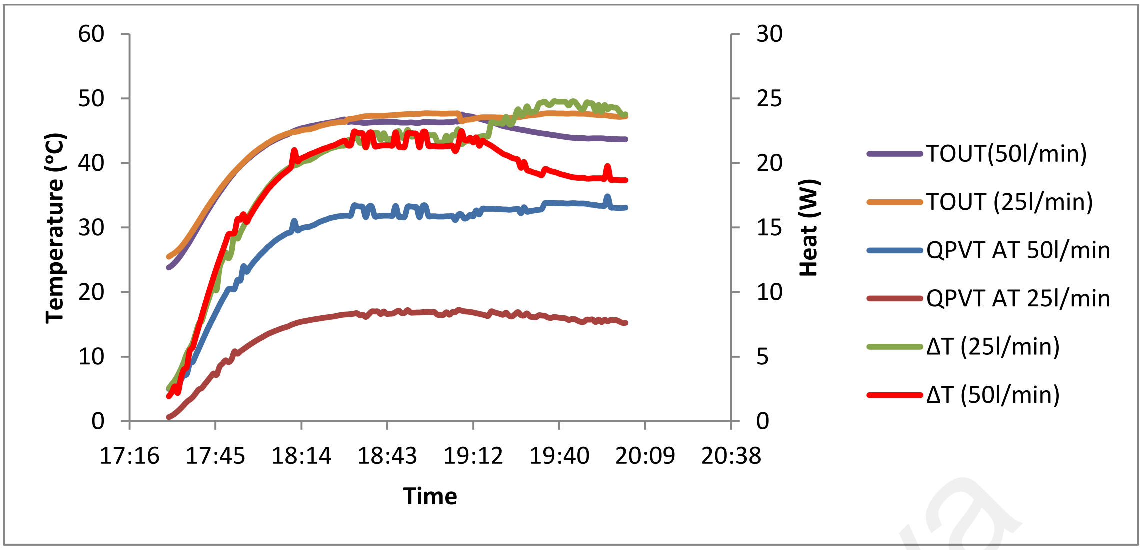


Figure 4.10: Heat (W) and temperature (°C) at irradiation 800 W/m^2 at angle 18.15°

Heat produced by PVT reduces by average 11% when tilted angle is changed from 3.15° to 18.15° for both air speeds. The highest temperature value measured were 47°C and 43°C for 25l/min and 50l/min air speed respectively as shown in Figure 4.10.

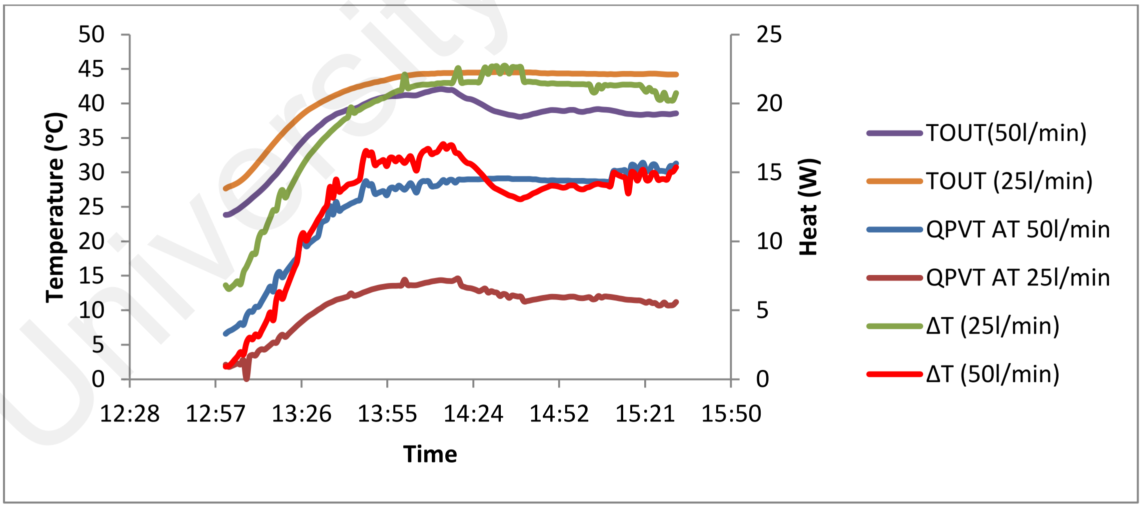


Figure 4.11: Heat (W) and temperature (°C) at irradiation 600 W/m^2 at angle 3.15°

Total heat collected decrease as the irradiation level decrease. For irradiation 600 W/m^2 at angle 3.15°, only 809.454W and 1541.5W heat were produced by our PVT system. The highest temperatures measured at the outlet of thermal collector were 42°C and

37^{o}C for 25l/min and 50l/min air speed respectively. Figure 4.11 shows the result for heat (W) and temperature (^{o}C) at irradiation 600 W/m^2 at angle 3.15°.

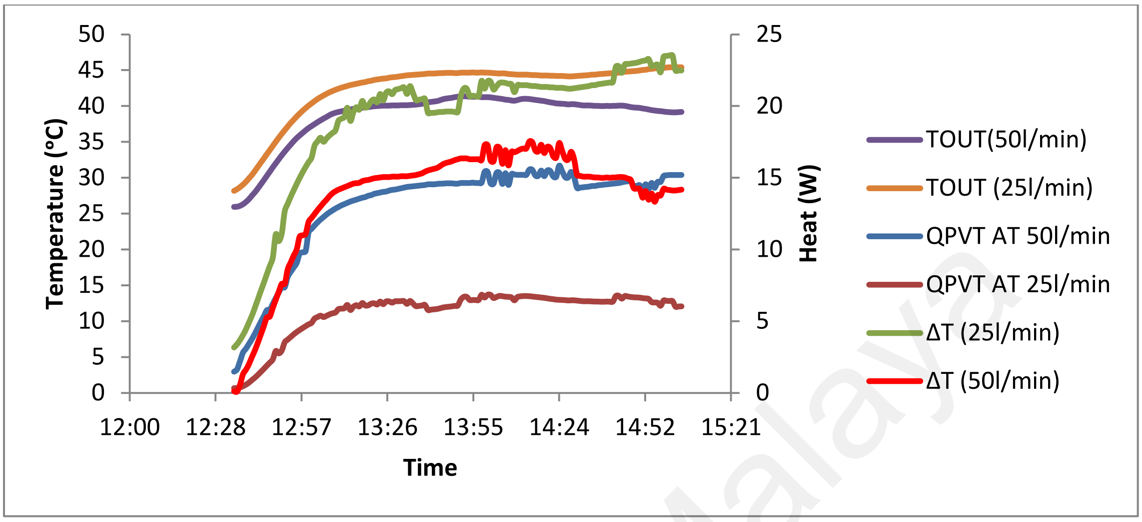


Figure 4.12: Heat (W) and temperature (^{o}C) at irradiation 600 W/m^2 at angle 18.15°

Figure 4.12 shows the graph for heat and temperature at irradiation 600 W/m^2 at angle 18.15°. Highest temperatures measured at the outlet of the thermal collector were 42^{o}C and 38^{o}C for 25l/min and 50l/min respectively. The heat generated at 18.15° with irradiation level 600 W/m^2 was 806.3W and 1661W for 25l/min and 50l/min air speed respectively.

Table 4.3: Electrical efficiency (%) of PV and PVT system

Irradiation (W/m^2) / Angle (°)/System	3.15°			18.15°		
	PV (%)	PVT_{25} (%)	PVT_{50} (%)	PV (%)	PVT_{25} (%)	PVT_{50} (%)
600	10	11	11	10	11	11
800	9	10	10	10	10	10
1000	9	9	10	10	0.10	10

Table 4.4: Thermal efficiency (%) of PVT system

Irradiation (W/m^2) / Angle (°)	3.15°		18.15°	
	PVT_{25} (%)	PVT_{50} (%)	PVT_{25} (%)	PVT_{50} (%)
600	4	10	4	10
800	4	10	4	9
1000	6	9	4	8

Table 4.3 and 4.4 show the electrical and thermal efficiency for PV module, PVT with 25l/min air flow and PVT with 50l/min air flow for all angles tested indoor using equation:

$$\mu_e = \mu_r \left(1 - 0.0045(T_c - T_r)\right) \quad (4.1)$$

and

$$\mu_{th} = \frac{Q}{G \times A_c} \quad (4.2)$$

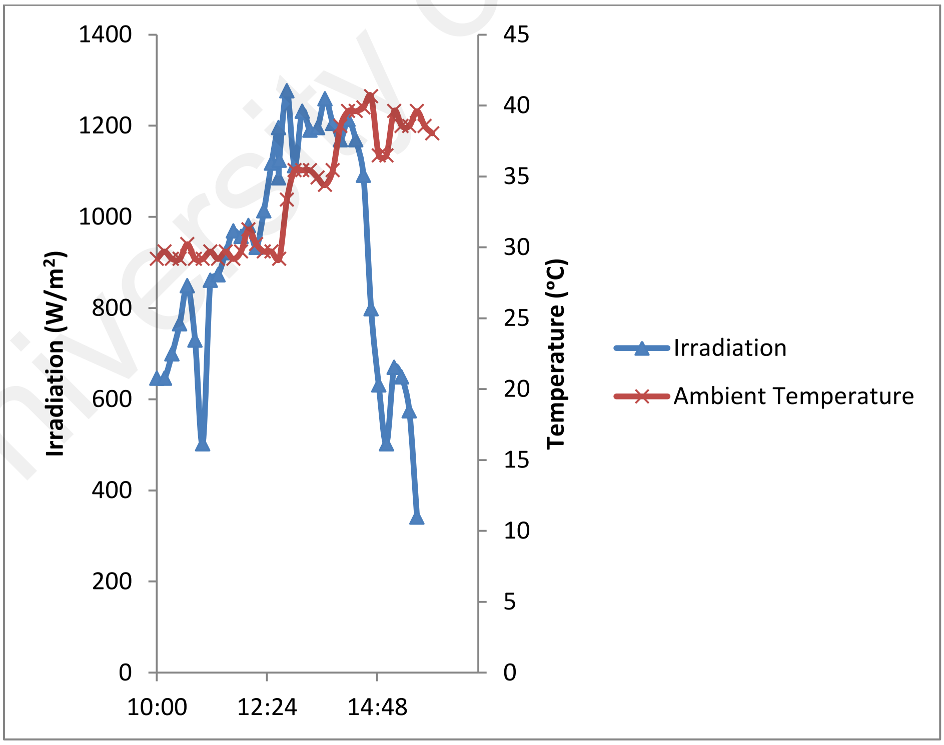
Since the PV module used in this research is small (75W), there is not much difference in efficiency for every system. It can be deduced that as irradiation level increases, the electrical efficiency decreases. This is due to the rapid increment of temperature as irradiation level increases. However, this situation serves an advantage for thermal efficiency since it will increase when irradiation level increases. Increasing the air speed for PVT only gives a feeble effect towards the system's electrical efficiency but thermal efficiency will be increasing two times greater.

4.3 OUTDOOR EXPERIMENT

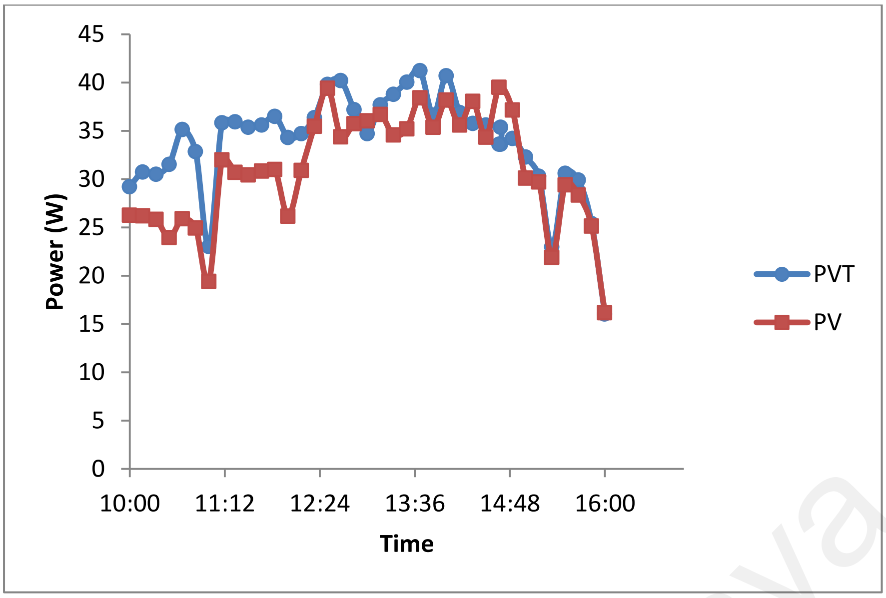
Table 4.5: Test schedule

Date	Time (Hour)	Angle (°)	Flow rate (l/min)	Average wind speed (km/h)
16-03-12	1000-1600	3.15°	25	12
29-03-12	1000-1600	18.15°	25	14
18-03-12	1000-1600	3.15°	50	13
23-03-12	1000-1600	18.15°	50	14

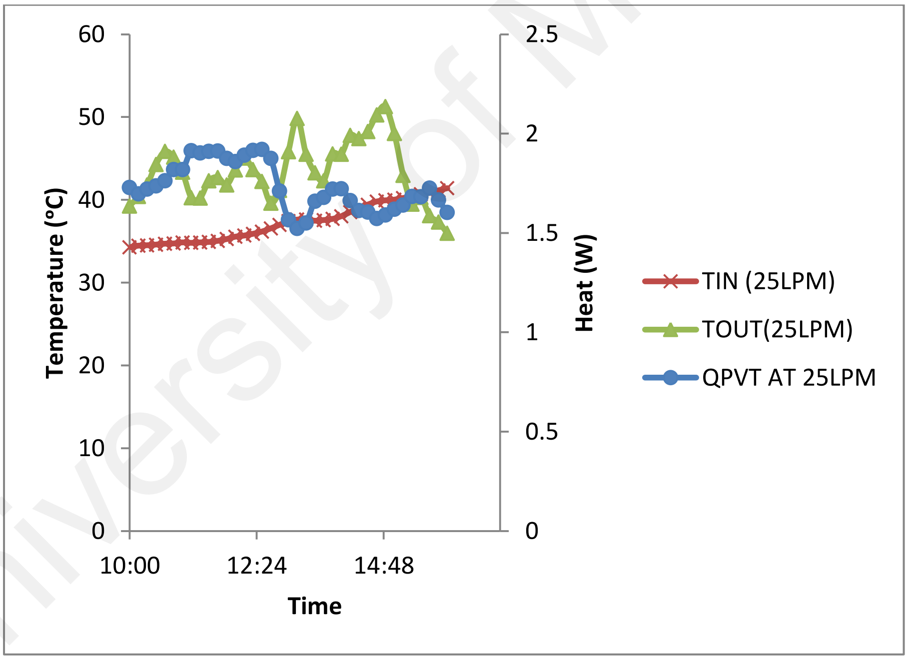
Table 4.5 shows the data collected during outdoor experiment. During these months, the weather in Malaysia is hot and humid with small amount of rainfall. Outdoor experiment will produce difference in output compared to indoor experiment due to other influence like wind and humidity.



a) The variations of solar irradiation and ambient temperature



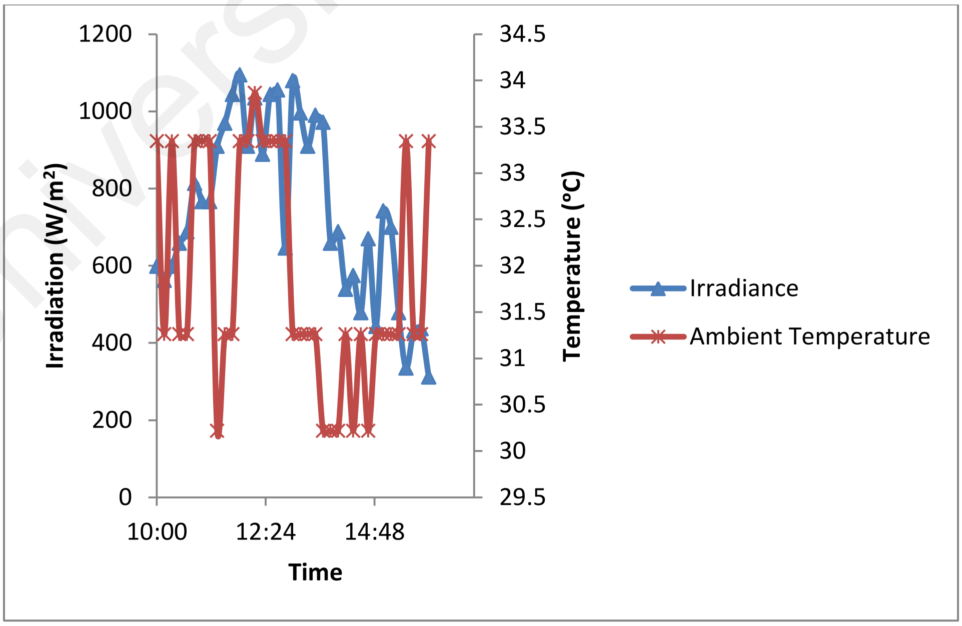
b) Daily variation of power output from PV and PVT system



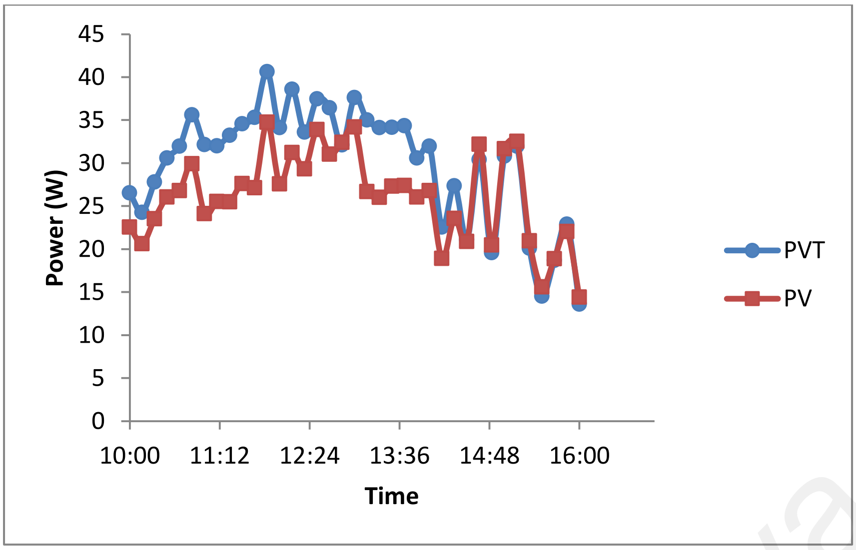
c) Variations of inlet and outlet air temperature with heat

Figure 4.13: A day test results of 25l/min air speed at angle 3.15°

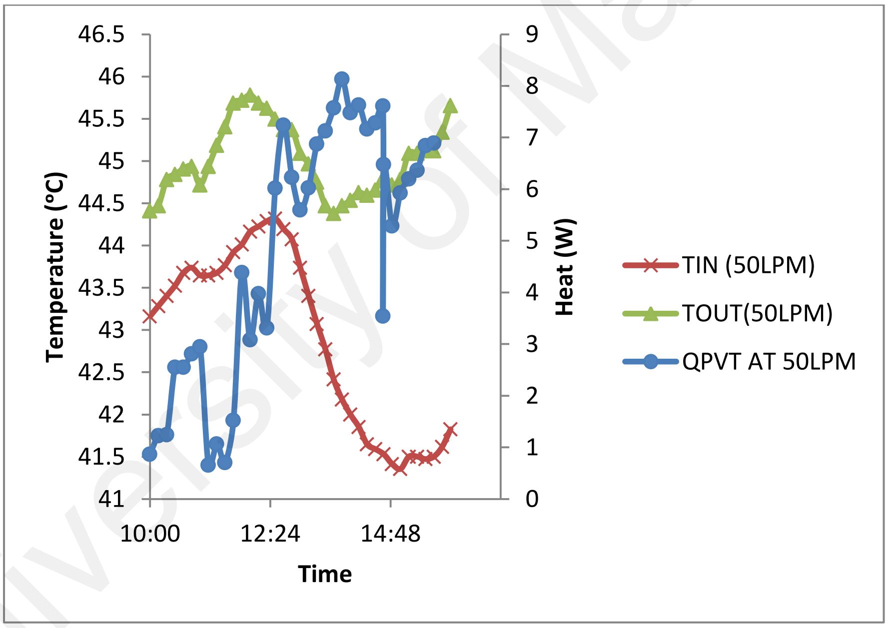
The variations of solar irradiation, ambient temperature, PV and PVT power output, heat output (Q_{PVT}), and inlet (T_{IN}) and outlet (T_{OUT}) air temperature during the test day were taken with conditions of 25l/min air speed at angle 3.15°. Maximum irradiation level and ambient temperature during the test day were 1310W/m^2 and 38.7°C respectively. For a typical day in Malaysia during March until May, wind speed ranges around 12-15km/h while humidity lies between 55-67%. From figure 4.3 (b), it can be seen that PVT system performs well than PV system in the middle of the day. Maximum power output logged for PVT and PV system are 39.08W and 38.2W respectively. Power output of PVT and PV system varies with irradiation level and ambient temperature. Variations of inlet and outlet air temperatures and heat extracted from thermal collector can be seen in figure 4.3 (c). Total heat collected during the experiment was 461.7W. In the evening, it can be seen that there was almost no difference in power output between PVT and PV system. Inlet and outlet air temperature also experienced the same. This is because the irradiation level and ambient temperature during this time were low. Due to that, module temperature decreased and heat extracted was small. Figure 4.13 shows the whole day's test results of 25l/min air speed at angle 3.15°.



a) The variations of solar irradiation and ambient temperature



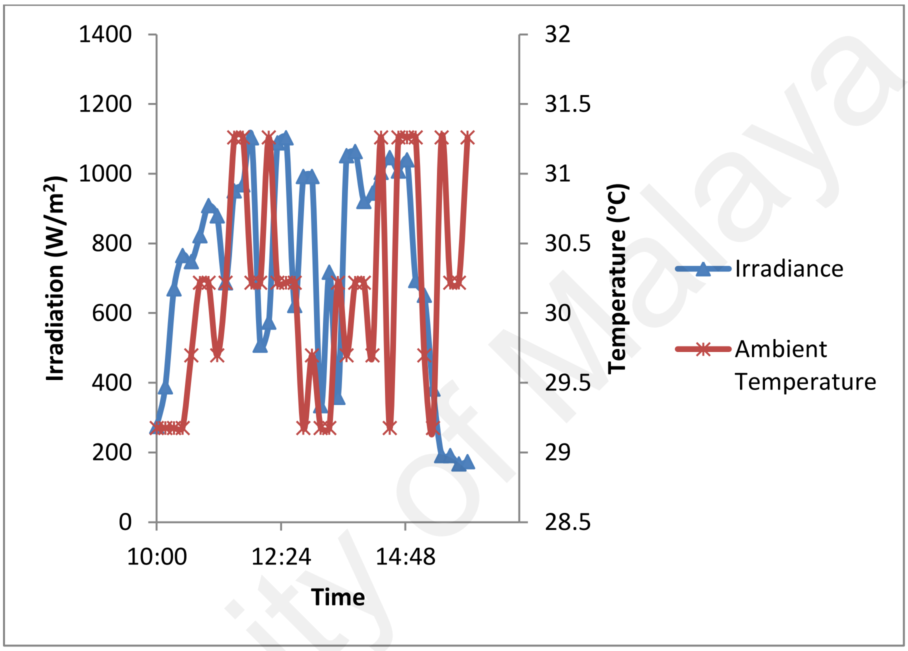
b) Daily variation of power output from PV and PVT system



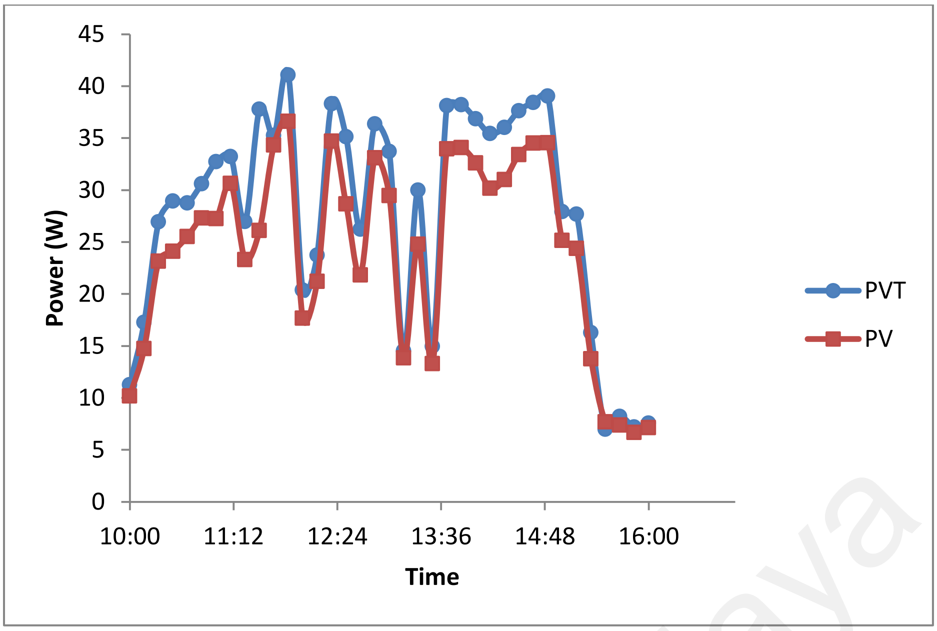
c) Variations of inlet and outlet air temperature with heat

Figure 4.14: A day test results of 50l/min air speed at angle 3.15°

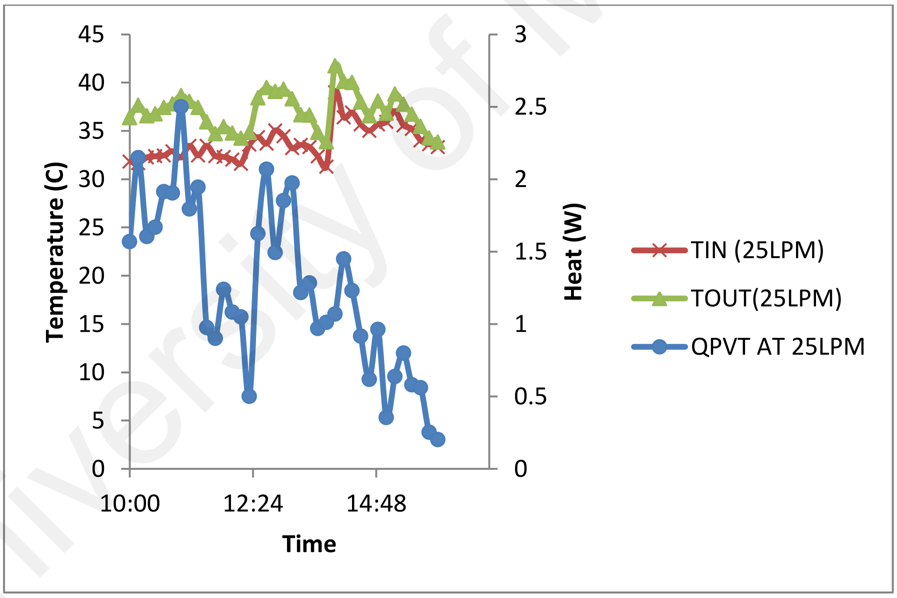
Figure 4.14 shows the variations of solar irradiation, ambient temperature, PV and PVT power output, heat output, and inlet and outlet air temperature during the test day for 50l/min air speed at angle 3.15°. Maximum irradiation level and ambient temperature during the test day were 1094W/m^2 and 34.4°C respectively. Maximum power output logged for PVT and PV system were 40W and 35.1W respectively. It is interesting to note that air mass flow rate has an influence on inlet and outlet temperature difference and the amount of heat extracted by thermal collector. However, it is only a weak influence on air temperature outlet as this is probably due to the small heat capacity of air which is only 1.005 kJ/kg.K. Total heat collected during the experiment is 721.2W.



d) The variations of solar irradiation and ambient temperature



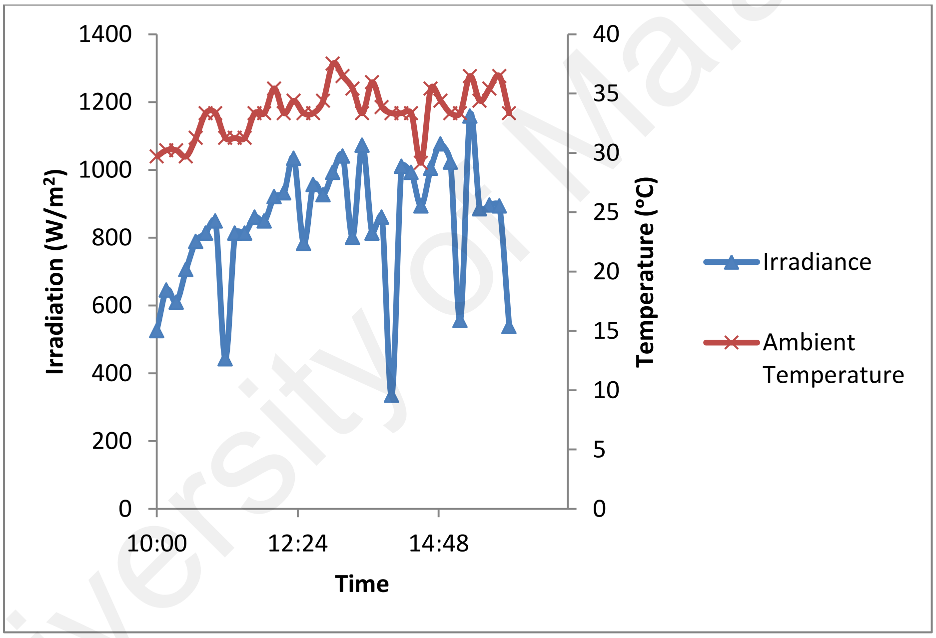
e) Daily variation of power output from PV and PVT system



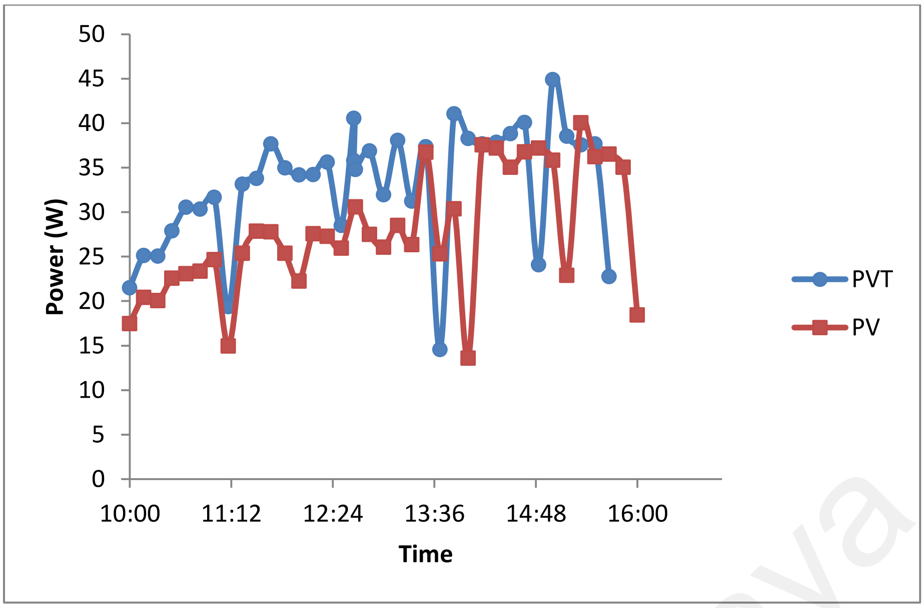
f) Variations of inlet and outlet air temperature with heat

Figure 4.15: A whole day test results of 25l/min air speed at angle 18.15°

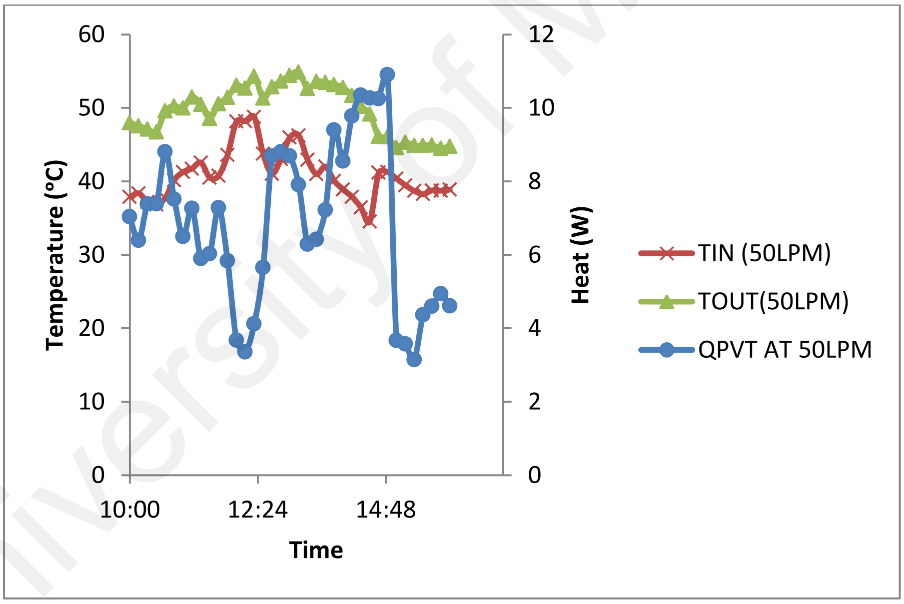
Figure 4.15 shows the variations of solar irradiation, ambient temperature, PV and PVT power output, heat output, and inlet and outlet air temperature during the test day for 25l/min air speed at angle 18.15°. Maximum irradiation level and ambient temperature during the test day were 1040.34W/m^2 and 33.34°C respectively. Average wind speed and humidity level during the test day were 14km/h and 62% respectively. Malaysia's warm and humid equatorial climate has various characteristics throughout the day. Formation of clouds creates patches in the sky resulting in obstruction for sunlight. Due to that, solar irradiation level is not constant and the intensity of the incoming solar irradiation is from the combination of direct sun, clear sky portion and cloudy portion. Maximum power output logged for PVT and PV systems were 41.08W and 38.84W respectively. Total heat extracted from the experiment was 452.8W. The small amount of heat extracted during this testing was probably due to low irradiation level and ambient temperature thus the module temperature did not increase too much.



g) The variations of solar irradiation and ambient temperature



h) Daily variation of power output from PV and PVT system



(r) Variations of inlet and outlet air temperature with heat

Figure 4.16: A whole day's test results of 50l/min air speed at angle 18.15°

Figure 4.16 shows the variations of solar irradiation, ambient temperature, PV and PVT temperature for 50l/min air speed at angle 18.15°. As the air temperature difference between inlet and outlet increased, heat extracted also increased. Again, it is evident that mass flow rate of air will influence the amount of heat extracted from module's rear to the thermal collector, power output, heat output, and inlet and outlet air temperature during the test day for 25l/min air speed at angle 18.15°. Maximum irradiation level and ambient temperature during the test day were 1224.32W/m^2 and 36.47°C respectively. Maximum power output logged for PVT and PV system were 45.78W and 39.94W respectively. Total heat extracted from the experiment was 2052.1W. It can be seen that in the afternoon, there were vast differences of outlet and inlet air. It is important to note that there are obvious fluctuations in the graph provided. This is due to ambient conditions and tolerance. Uncertainty analysis will be further explained in section 4.4.

Table 4.6: Electrical efficiency (%) of PV and PVT system

Angle (°) / System	3.15°				18.15°			
	PV_{25} (%)	PVT_{25} (%)	PV_{50} (%)	PVT_{50} (%)	PV_{25} (%)	PVT_{25} (%)	PV_{50} (%)	PVT_{50} (%)
	10.1	10.2	10.2	10.3	10.4	10.5	10.0	10.1

Table 4.7: Thermal efficiency (%) of PVT system

Angle (°) / System	3.15°		18.15°	
	PVT_{25} (%)	PVT_{50} (%)	PVT_{25} (%)	PVT_{50} (%)
	4	6	5	6

Table 4.6 shows the electrical efficiency of PV and PVT system while Table 4.7 shows the thermal efficiency of PVT system for outdoor testing. Similar to indoor testing, there is not much difference in electrical efficiency for every system since the PV module used is too small. Compared to indoor testing, low thermal efficiency has been achieved for outdoor testing. This is due to the variation of irradiation level where it is not constant like during indoor testing. In addition, wind speed can also influence cell temperature thus causing the heat extraction from PVT to be low.

4.4 UNCERTAINTY ANALYSIS CALCULATION

As discussed in mathematical equation section, uncertainty analysis needs to be conducted in order to get a precise and accurate experiment measurement. Differentiation between measured values and actual values can be used to measure error as expressed in equation (4.3):

$$x_{act} = x_m \pm \delta x_{act} \tag{4.3}$$

For each of the measured variables mentioned in the experimental setup, the uncertainty of each device or instrument used has been tabulated in table 4.8. All the values in the table are obtained from the relevant data sheet. From the flow meter data sheet, the uncertainty of air velocity is said to be ±5%. During experiment, the flow meter has been mounted not according to the data sheet. Ergo, the uncertainty is set to ±15% in order to allow for the non- ideal placement (Bambrook & Sproul, 2012).

Table 4.8: Summary for uncertainties.

Parameter	**Uncertainty**
Irradiance (Pyrometer)	±2%
Area	±2%
Temperature sensor	±0.5%
Velocity (Air pump)	±15%
Voltage MPP	±0.8%
Current MPP	±0.65%

Error of mass flow rate can be calculated using equation (4.4):

$$\delta\dot{m} = \left[\frac{\delta A}{A} + \frac{\delta V}{V}\right] m \tag{4.4}$$

$$\delta\dot{m} = \left[\frac{\pm 2\%}{0.26} + \frac{\pm 15\%}{0.00319}\right] 0.00069$$

$$\delta\dot{m} = 0.032\ {}^{kg}/_{s}$$

From equation, mass density of the fluid can be neglected as it is a constant value. Small error is calculated for mass flow rate which is 0.032kg/s.

From experiment, error for electrical efficiency can be calculated using equation (4.5):

$$\delta\%_{el} = \frac{(\delta V_m + V_m)(\delta I_m + I_m)}{(\delta A_c + A_c)(\delta G + G)} \tag{4.5}$$

$$\delta\%_{el} = \frac{(\pm 8\% + 21.1)(\pm 0.65\% + 3.3)}{(\pm 2\% + 0.63)(\pm 2\% + 1000)}$$

$$\delta\%_{el} = 11\%$$

By plugging in all the measured value and its uncertainties, error for electrical efficiency lies between ranges 7.3-11%.

From experiment, error for thermal efficiency is computed as equation (4.6):

$$\delta\%_{th} = \frac{(\delta\dot{m} + \dot{m})(\delta\Delta T + \Delta T)}{(\delta A_c + A_c)(\delta G + G)} \tag{4.6}$$

$$\delta\%_{th} = \frac{(0.032 + 0.00069)(\pm 0.5\% + 32)}{(\pm 2\% + 0.26)(\pm 2\% + 1000)}$$

$$\delta\%_{th} = 0.38\%$$

In the equation, it can be seen that specific heat value for air can be neglected since it is constant. From calculation, error for thermal efficiency lies between ranges 0.27-0.38%.

It can be seen that error for electrical efficiency is higher compared to error for thermal efficiency. The reason behind this is because of the smaller error by mass flow rate compared to error value of MPP current and voltage respectively. It is important to note that in order to get more precise measurement, device or instrument with high precision can be used in the experiment.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 OVERVIEW

In this last chapter, conclusion and recommendation are described briefly. Achievement from the research done is presented in section 5.2 while recommendation for future research in section 5.3.

5.2 CONCLUSION

In this research, indoor and outdoor performances of PV and PVT air system had been investigated. Temperature of PV module increases when it absorbs solar irradiation, which in turn affects the efficiency of PV module. Applying heat recovery unit with flowing fluid on PV module can help to solve this undesirable effect. Design of thermal collector is proposed in this study while other parameters like irradiation, mass flow rate and type of coolant have been taken into account in order to investigate the performance of PVT air system. From the study, it can be concluded that:

- Electrical efficiency of PVT air system has a small difference compared to PV module.
- High efficiency of PV and PVT cannot be achieved due to the low specific heat value of air.
- Power output of PV and PVT decrease rapidly as temperature increases.
- Thermal efficiency of PVT air system increases as module temperature and irradiation level increase.
- Increasing mass flow rate of air can help in increasing the electrical efficiency but will produce only a slight difference.
- As PV is widely known as a clean renewable energy source, the addition of thermal collector will add more advantages to user.

- Small electrical and thermal efficiency value had been drawn from this research as the system used is small.
- Results from indoor and outdoor experiments are different due to other influences such as various irradiation level, wind, cloud form and humidity that cannot be simulated in the solar simulator used during indoor experiment.

5.3 RECOMMENDATION

i. For future testing, the PVT system should be bigger to capture more heat and power output.

ii. Various designs of thermal collectors should be tested to compare the thermal efficiency between the designs.

iii. Design of thermal collector can be improved by placing thin metal sheet to increase the heat transfer between PV rear and pipe.

iv. For future experiment, instead of just measuring the temperature, hot air from pipe outlet can be used for other purposes like drying crops in a box.

v. Heat loss from the system should be reduced in order to increase thermal efficiency.

vi. Use different types of coolant such as water as it is an abundant source thanks to the Malaysian climate. In addition, the heat capacity of water is four times higher than air which is better to capture heat from PV module.

vii. Use device or instrument with high precision to minimize error in measurement.

APPENDICES

Appendix A Relevant publications

Journal Articles

1. V.V Tyagi; N.A.A Rahim; N.A. Rahim; J. Selvaraj.; "Progress in Solar PV Technology: Research and Achievement", submitted to Renewable and Sustainable Energy Review; status: accepted on 23 Sep 2012.

Conference Paper

1. V.V Tyagi; N.A.A Rahim; N.A. Rahim; J. Selvaraj.; "Solar PV/T air system: An indoor experimental validation", in Sustainable Future Energy 2012 and 10th SEE Forum (Brunei Darussalam)
2. V.V Tyagi; N.A.A Rahim; N.A. Rahim; J. Selvaraj.; "Outdoor Performance Of Solar PV/T Air System", in Power and Energy Conversion Symposium (PECS 2012, Melaka, Malaysia)

Appendix B Figure of equipment used in the experiment

Figure B1 Plywood applied as insulator

Figure B2 BOYU air pump

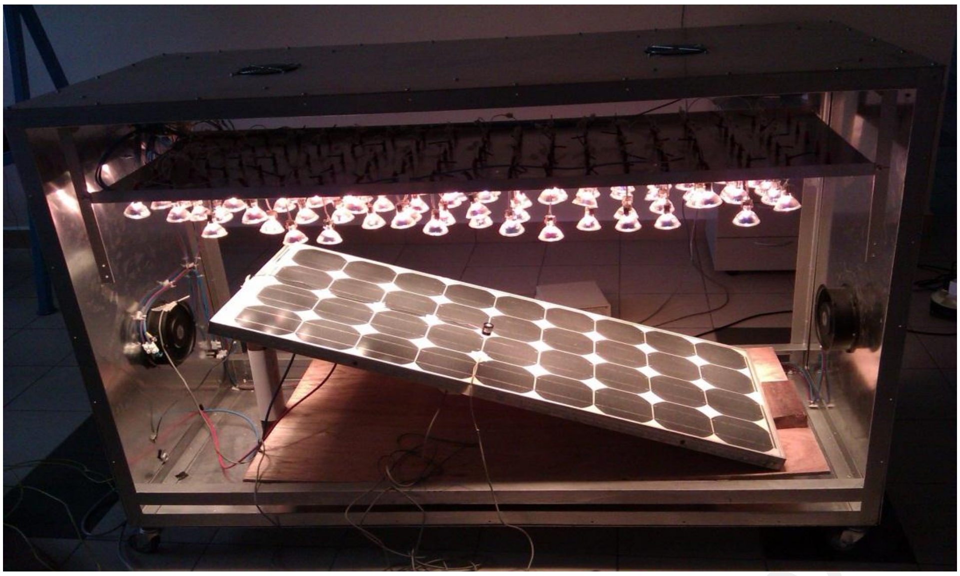


Figure B3 Solar simulator

Figure B4 SORENSEN DC power supply

Figure B5 LICOR pyrometer

Figure B6 Angle meter

Figure B7 HOBO temperature sensor and data logger

Appendix C Specifications of equipment used in the experiment

Table C1 Specification of solar simulator

EQUIPPED WITH	90 HALOGEN LAMP (50W) 4 FAN
DIMENSION (cm)	L:160 W:70 H:100
CASING	ALUMINUM
IRRADIATION (W/m^2)	0-1000
POWER SUPPLY	DC POWER SUPPLY

Table C2 Specification of SORENSEN DC power supply

Parameter	**Value**
Manufacturer	AMETEK
Voltage	0-600V
Current	0-25A
Dimension	48.3x64.7x13.3 cm
Weight	36 kg
Operating temperature	0-50°C
Cooling unit	Internal fans; vents on sides and rear

Table C3 LICOR pyrometer specifications

Parameter	Description
Response Time	10 μs
Operating Temperature	-40 to +65 °C
Size	2.38 cm dia x 2.54 cm H
Weight	28 g
Sensitivity	± 2%
Light Spectrum Waveband	400 to 1100 nm
Detector:	High stability silicon photovoltaic detector (blue enhanced)

Table C4 HOBO temperature sensor

Probe dimensions:	0.9 x 5.8 cm
Housing:	Copper-plated sensor tip
Range:	-40° to 50°C (-40° to 122°F) in water or soil, -40° to 100°C (-40° to 212°F) in air
Operating Range:	sensor tip and cable immersion in fresh water up to +50°C (122°F) for 1 year

Table C5 Specification of HOBO data logger

Dimensions:	58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)
Weight:	46 g (1.6 oz)
Memory:	64K bytes (43,000 12-bit measurements)
Battery life:	1 year typical use
Humidity range:	0 to 95% RH, non-condensing
Operating temperature:	Logging: -20° to 70°C (-4° to 158°F); 0 to 95% RH (non-condensing) Launch/readout: 0° to 50°C (32° to 122°F), per USB specification
Operating range:	-20 to 70°C (-4° to 158°F)
Time accuracy:	± 1 minute per month at 25°C (77°F)
Sample Rate:	1 second to 18 hours, user selectable
Resolution:	0.6 mV
Accuracy (logger only):	± 2 mV ± 2.5% of absolute reading; ± 2 mV ± 1% of reading for logger-powered sensors
Analog channels:	0 to 2.5 Vdc (w/CABLE-2.5-STEREO); 0 to 5 Vdc (w/CABLE-ADAP5); 0 to 10 Vdc (w/ CABLE-ADAP10); 4-20 mA (w/CABLE-4-20MA)

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