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Literature Review on Flat Plate Photovoltaic-Thermal (PV/T) solar Collector system

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Abstract – *The concept of combining photovoltaic panel and solar thermal collector to gain electrical & heat energy simultaneously has its own advantages over their standalone performance. Although it has received limited attention in past years, however with increasing energy demands, PVT collectors are now becoming the focused area of research. The purpose of this review is to provide the detailed theoretical study, design components of PVT solar collector module, a broad classification of various emerging technologies in it and their application in domestic, commercial and industrial areas like space heating, water heating, building integrated PVT systems etc. The review mainly focuses on different PVT absorber designs, their advantages and limitations, the heat transfer fluid used. the presented paper can be used by engineers, students working on theory and optimum design of photovoltaic thermal solar collector module.*

Key Words: **renewable energy, solar energy, hybrid collector, photovoltaic-thermal collector, PV/T**

1. INTRODUCTION

At present, worldwide energy demand is continuously increasing with an increase in technological advancements & population. The latest forecasts revealed that the world's energy consumption is increasing with an estimated growth of 48% through 2040, which is associated with the economic growth in the developed countries, as well as in developing ones (1). In the Era of Technology, electrical energy is the basic need of human mankind. However, the global fossil fuel reserves which are a prime mover of energy seem to have reached their peak production. As their consumption is increasing in a huge amount compared to their replenishment. Most of these traditional non-renewable resources are expensive in terms of production, installation, and use. These non-renewable resources have a huge contribution in increasing environmental consequences like global warming, greenhouse effect, and climate changes, etc. Therefore, newer solutions for energy production, conservation, its supply, and instantaneous environmental protection are highly insistent. Thus, finding newer & eco-friendly renewable resources are now being essential. After repeated energy crises, (in 1972, 2008) consumption of renewable energy sources are increasing by an average of 2.3%/year between 2015 and 2040 (1). Renewable energy technologies are primarily based on Wind, Hydropower, Solar, Geothermal energy sources. Among these available renewable energy sources, Solar based ones have high potential to achieve a significant development with a reduction in carbon emission and energy savings. It is one of the abundant propitious renewable energy sources. it can be exploited worldwide with unlimited availability. (3).

In order to harvest useful energy from the sun, various converting techniques exist, such as converting solar energy in the form of thermal energy (4) or electric energy (3) or exploiting it by biochemical reactions (5). Solar thermal (ST) collector converts incoming solar irradiance into heat (4). A part of solar radiation energy is harvested in the form of electrical energy by using Photovoltaic technology. However biochemical energy can be obtained from solar energy by using photosynthetic technology, these are called solar chemical fuels. The energy can be stored in them and then later converted into heat when needed (5). Effective implementation of these technologies in the last few 2-3 decades has successfully reduced hunger, desalination, improved health & ensuring sustainable development. Though there is a large scope for improving its efficiency better than the earlier one.

Solar thermal collectors collect heat from incoming solar radiation by absorption and transfer it to heat transfer fluids (HTF) flowing inside the device (4). The heat is then used for different purposes. Solar thermal collectors have high thermal efficiency by up to 80% (6). The solar thermal designs are one of the best cost-effective systems & has more demand for room heating, water heating, gas heating, and manufacturing process heating (4).

The photovoltaic cells convert diffused and concentrated solar radiations into direct current through the bombardment of photons on the photovoltaic semiconductor panel (13). There are various notable advantages of PV technology as compared to other technologies, as it operates without producing noise, harvests clean and green energy, a highly reliable system with less maintenance and it's expected life span between 20-30 years (3). Solar energy of 1.08 X 10^{18} kWh reaches the earth's surface (2). About the total 100% solar energy incident on the earth surface, there exists a 38.3% visible light, 8.7% ultraviolet and 47.4% infrared (IR) electromagnetic radiation (7). however, the photovoltaic cells respond to only a small portion of the visible solar spectrum, which is equal to or higher than the band gaps of the PV cell (11). About 80-90% solar radiation available in solar spectrum falls on the PV panel, up to 15-20 % of solar radiation is only converted into electricity, and the rest of all is either reflected back to the atmosphere or converted into heat causes an increase in the PV cell temperature (70). PV cell electrical efficiency is in the range of 10-20% depends on the solar cell types, the ambient conditions, and the cell temperature. Nowadays, the electrical efficiency of monocrystalline cells is reported around 26.7% by the best laboratory (9). This assumed effectiveness is under the standard test conditions (25°C cell temperature, 1000 W/m2 solar radiation, and air mass 1.5) (3). However, with an increase in temperature, diode circuit resistance increases exponentially results in reduced fill factor and open circuit voltage (10). Further, there is a reduction in the PV cell electrical efficiency (3). This tends to an increase in cost per unit power as these reduce global system performance. The efficiency of the crystalline silicon and amorphous silicon PV cells reduces to respectively 0.4% to 0.5% and about 0.25% with an increasing unit degree Celsius PV cell temperature ahead ambient temperature depends on the type of solar cells (8) (11) (12). Thus, to obtain optimum solar cell efficiency, an innovative cooling technique needs to be developed which will maintain cell temperature at normal operating temperature.

These can be minimized by the cooling the PV panel by using various active and passive cooling methods. Active cooling methods uses electricity to reduce heat. While the passive cooling methods reduces the heat by transferring it to water, air cooling and so on with the help of natural conduction/convection phenomenon. (13). Passive cooling methods can be classified based on the use of fluid used for cooling as like water passive, air passive, and conductive cooling techniques (14). The absorber plate as like solar water heater is used to remove heat from PV panel which can be used for heating of water or air or any fluid used. This concept of combining solar photovoltaic and Thermal system (Combined Heat and Power production) is known as Hybrid Photovoltaic/Thermal (PV/T) collector system (15). In consideration of both the heat and electricity production, a hybrid photovoltaic thermal (PV/T) collector is brought to produce at a time the electricity and thermal power. (16). Such a cogeneration technique not only improves the PV module efficiency by cooling effect but also increases overall system efficiency by waste heat recovery (17). These combination concepts can build an environment with zero-carbon industry process. This concept of cogeneration is not a new, however it has received inadequate attention. Research has been carried out on this concept in the middle of the 1970s to the early 1980s in the USA (18). Martin Wolf was the first to engineer a flat plate PV/T solar collector system & analyzed the performance of combined PV/T system for domestic applications (19).

The most significant purpose of using a PV/T collector is to enhance the electrical efficiency by cooling to the rated cell temperature. This fact limits the fluid maximum temperature, which is considerably lower than the rated cell temperature. as a result, PVT collectors limits it's use only in relatively less-temperature applications like room heating (20), domestic hot water systems (21), thermal storage (22), desalination (23), in the agricultural industry (24) and pool heating (25), etc. The electrical energy generated from the PV panel is moreover stored in batteries, which can be further used to meet the electrical loads or exported to the national grid. The lead-acid battery is the most common type of battery technology used in the PV system, due to its advanced and low-cost technology. Whereas in recent years, lithium-ion batteries acquiring market share, even if it has a higher cost (11).

The combination of these two systems provides various benefits (18) like

i. PV cell performance and hence its overall efficiency increases, as they can be uniformly cooled through the solar thermal system.
ii. It produces more energy per unit area of a module than the corresponding separate solar thermal collectors and PV modules. As there is a reduction in space utilization, it is mainly used in restricted roof space.
iii. Lower installation cost and symmetric facade appearance. As they can be easily mounted on existing roofs with minimal modifications, which can also reduce the payback period.

iv. Reduces thermal degradation of a photovoltaic panel and thermal stresses of module components hence increase the lifespan of the PV panel.

2. BASIC CONCEPT & CLASSIFICATION OF PV/T TECHNOLOGY

The solar cells work on the principle of the photovoltaic effect. The incoming photons which have a lesser amount of energy than the bandgap of the PV cells won't be absorbed by the PV cell material. These photons reach the back surface of the panel and some get absorbed while some reflected back to the front side of the panel. This absorption generates heat. Along with it, each photon which has a higher energy than the bandgap of the PV cell, generates an electron-hole pair. Due to which electricity is generated, but whole energy is not used, a part of photon energy generates heat causes increase in temperature of PV cell (50). The electrical efficiency of photovoltaic panel reduces with rise in its temperature. Thus, it is necessary to maintain PV cells to its nominal operating temperature. However, this waste heat generated can be recovered with cooling techniques that cause an improvement in electrical performance. Photovoltaic Thermal system combines conventional solar thermal collector and photovoltaic module. The working principle of the PV/T system is as shown in fig-1. A part of a solar radiation incident on the PVT system is converted into electrical energy, whereas remaining is converted into heat causing reduced in PV cell efficiency, which can be extracted to harvest thermal energy.

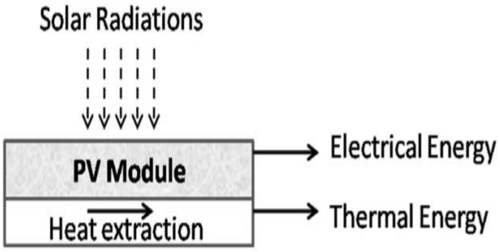


Fig-1: Concept of PVT system (26).

The PVT system can be broadly classified in several ways such as classification based on the heat transfer fluid used, mode of fluid movement, type of heat extraction, absorber exchanger arrangement and end applications. However, in the literature, depending on the PV module, PVT technology is divided into Flat Plate, Flexible and concentrated collector system as shown in fig-2 (11). PV/T solar collector system classification based on heat transfer fluid used is as like water-based, air-based, refrigerant-based, heat pipe-based, nanofluids based or phase change material based. moreover, it can also be classified according to non-concentration and concentration provisions of solar radiations.

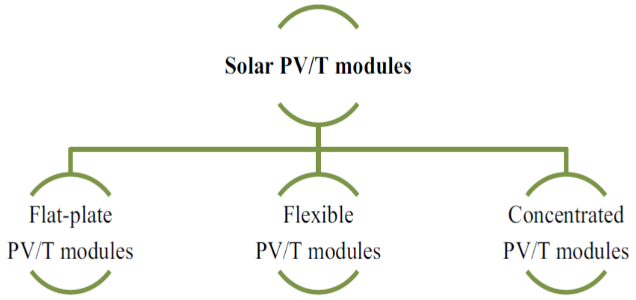


Fig-2: Classification of PV/T solar collector based on the type of PV module (11).

3. FLAT PLATE PHOTOVOLTAIC THERMAL (PV/T) SOLAR COLLECTOR: DESIGN OVERVIEW

The flat plate photovoltaic thermal solar collector consists of different component layers as shown in fig-3. The flat plate PV/T collector consists of a PV panel, heat-absorbing and exchanger surface, the flow channel, heat transfer medium, and storage provision if essential (8). The performance of the collector is affected by each one of these components. Hence it is necessary to optimize their performance.

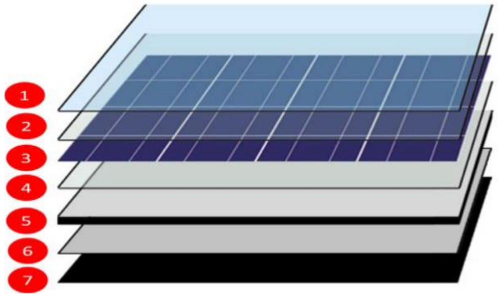


Fig-3: Schematic representation of a flat plate PVT collector module: Glazing cover (1); EVA-encapsulate (2); Solar PV cells (3); EVA encapsulate (4); TPT back sheet (5); Thermal absorber (6); Thermal insulation (7) (11).

1. Glazing Cover – Tempered glass is used as transparent glass cover for creating an air gap which increases thermal resistance, to reduce losses due to radiation and convection in the PV module. It has up to 95% of a

solar absorption coefficient (13). But it increases the optical losses (reflection, absorption) (17) Tempered glass is provided to give mechanical strength to the overall structure. As it has iron salts with limestone content makes it 5 times tougher than normal glass and used as protection against outer conditions (13). Other materials such as transparent plastic which probably increases optical efficiency could have also been chosen instead of glass. However, their material properties, like sensitive to high temperatures and UV rays, as well as limited water tightness limits their application in PV-thermal System.

Adding the top glazed covers one over one would probably improve the thermal insulation of flat plate collector design. although, each cover creates an additional reflection, which decreases electrical yield (18). However, the electrical and thermal performance can be improved by using anti-reflective coating (ARC) or low e coating and PV cells with low-temperature coefficients (26). The use of low e-coating like TiO2, a porous silicon layer, silicon nitride over glass cover reduces radiation losses. It increases thermal efficiency with the cost of lower electrical efficiency (35). While by the application of ARC, double steady-state anti-reflective coated iron glass cover has a transmission coefficient of more than 94%, which is closer to the absorption factor of conventional solar thermal collector (95%).

2. PV Cells Encapsulants – PV cell encapsulants are basically thermoplastic material which binds all the different layers with electrical insulation (8). Encapsulant materials should be such that it can bear with the thermal expansion of the different layers without any fatigue failure and cracking to the PV module and interconnections. The three most common elastomeric polymers widely used as encapsulants for PV cell laminations are ethylene vinyl acetate (EVA), polyvinyl butyral (PVB) and silicone (27). EVA is mostly used as it has elastomeric and thermoplastic properties and have very low thermal expansion coefficient, good transparency, lustrous, low-temperature robustness, crack resistance and better waterproofing properties and provides resistance to UV radiation (13). However, a specific increase in temperature of PV panel degrades ethylene-vinyl acetate layer (EVA) (28). mechanical properties of EVA lose at 130-140°C, as a result, it delaminates the PV module (29). Continuous exposure of PV panel above 50°C causes browning and discoloration of EVA sheets (13). This reduces optical transmissibility and formation of hot spots on the PV module (28). Silicone resins are very expensive than others, but it is very stable due to its negligible corrosion and UV degradation properties and has very high-temperature resistance between -55°C to 200°C (50). BIPV modules use them. Robustness, tenacity and elasticity properties enhance PVB to encapsulate safety glasses and are widely used in BIPV applications. But it has various site limitations. It is sensitive to moisture and environmental conditions. If this problem is solved, then PVB might be a good substitution for EVA.

3. The photovoltaic panel is an arrangement of solar cells in series or parallel connection for the generation of electricity. A series connection is provided to add cell voltage, while the parallel connection is provided to increase current. Currently, silicon-based PV technology has the highest global market share up to 93% (9). Because silicon is available in abundant quantity over the globe and is relatively cheaper than the existing PV technologies. Monocrystalline (mono-Si) and polycrystalline (poly-Si) silicon solar cells are most commonly used for solar photovoltaic panel generation which has average efficiencies of about 19.8% and 18.7% respectively. Both cells have a different crystalline structure. The mono-crystalline cells have high electrical efficiency compared to poly-Si cells, due to less crystalline defects. But it is comparatively expensive to manufacture. However typical crystalline silicon cell absorbs an incident solar radiation up to about 300-1100 nm range wavelength of the solar spectrum because of the bandgap of thin-film silicon (8). The second issue with these is with rise in temperature of PV module, electrical efficiency reduces by 0.45% per degree Celsius (13). Absorption factor of a silicon crystalline photovoltaic module is 74% which reduces its electrical efficiency (13). Pure silicon reflects about 30% of the incoming solar radiance (9). Anti-reflective coatings (ARC) like silicon nitride are laminated above the photovoltaic solar panel to increase the absorption factor with reduction in reflection losses and hence increases its electrical efficiency (50). The overall efficiency of the PV/T collector can be improved by using other type of solar cells like the HJT or amorphous silicon cells. Amorphous silicon cells have a higher absorption factor due to its black surface. Thermal annealing of amorphous silicon cells improves its electrical efficiency of the PVT module by 10%. They demonstrate stable long-term operation at high temperatures. HJT has a very low-temperature coefficient compared to conventional silicon cells, due to which it was shown that it has 2% higher electrical efficiency than conventional ones. However, they are economically not feasible at the present price compared to crystalline silicon solar cells (6).

4. Back sheet – It is a composite-layer film mainly used as a covering foil at the backside of the PV module. Polyvinyl fluoride (PVF) polymer or Tedlar Polyester Tedlar (TPT) is mostly used due to its weather-resistant, good hydrolytic stability, high dielectric

strength, and protection from physical damages and excellent adhesion to EVA (30, 13). Higher reflective Tedlar layer reflects incident light to the non-active layer of the photovoltaic cell which results in increased generated current, but in case of photovoltaic/thermal system, this tends to high reflection losses hence reduction in usable heat (13).

5. Absorber-Exchanger – Waste heat recovery from the PV panel is done by using absorber - exchanger technology. Thus, it is also called a 'heat extraction unit'. There are different configurations for thermal absorber designs such as sheet and tube absorber, flat box channel absorber, roll bond heat exchanger, a rectangular channel with or without grooves or fins, heat pipes, extruded heat exchanger etc being developed for heat extraction from the PV module (11). Different configurations of absorber based on literature are discussed in subsequent sections.

4. INTEGRATION METHODS FOR PV/T COLLECTORS

The PV panel and thermal absorber can be attached by various thermal integration methods such as a chemical adhesive bond or by mechanical means. The materials used and proportions of the bond strongly influence the conduction of heat between PVT module layers. Proper integration between PV panel and absorber is highly insistent because it directly influences the thermal efficiency of PVT module. The improper attachment adds more thermal resistance due to poor thermal contact between the PV panel and absorber, which will reduce the thermal efficiency up to 30%, as proper heat is not extracted from PV panel. It influences the overall heat loss coefficient and heat removal factor (F_R), and hence the PV/T module performance (29). It was shown that the poor thermal contact between the PV layer and the thermal absorber for an unglazed PVT module led to a temperature gradient of about 15°C between the PV panel and absorber (50). Also, the integrating material should have a tendency to withstand system temperature variation between high and low as well as expansion occurred due to high temperature (8). Various methods used are direct contact, thermal adhesive, mechanical fixing & direct lamination. In direct contact, the heat transfer fluid is in direct contact with the heat-affected area of the PV panel, though it has several restrictions together with poor thermal efficiency, surface failures at high pressure, freezing risk, etc. (11). It has limited applications especially used for water-based cooling. Thermal adhesives are widely used for integration purpose. It involves silicone gel, butyl adhesive, or mucilage glue, etc. which are widely used. Thermal adhesives should have high thermal conductivity, low electrical conductivity, good elongation properties, and extreme operating temperatures. Silicone gel has high thermal conductivity and high electrical resistance. Mechanical fixing is a very common method. However, it has many limitations. It cannot eliminate air bubbles completely which increases thermal resistance, while direct lamination is the most advanced method. Whole package lamination is carried out by a single adhesive layer, which reduces thermal resistance allows an increase in heat transfer. EVA is basically used for integration purposes under the PV vacuum lamination chamber (11).

5. PERFORMANCE OF FLAT-PLATE PV/T COLLECTOR

From the first law of thermodynamics, the overall efficiency is the ratio of useful heat output and electrical output to the incoming solar irradiance incident on the module's aperture area. Thus, the overall efficiency of a PVT collector module is the sum of the collector's electrical efficiency η_{pv} and the thermal efficiency η_{th}.
Overall Efficiency:

$$\eta_o = \eta_{pv} + \eta_{th} \tag{5.1}$$

Electrical Efficiency: the solar PV module efficiency is given by the following equation 3.2.

$$\eta_{pv} = P_{max} / P_{in} = (I_{max} \times V_{max}) / (G_t \times A_c) \tag{5.2}$$

Where, I_{max} and V_{max} are the current and voltage for the peak power, corresponding to solar intensity G_t and A_c is the solar PV module aperture area. However, the fundamental equation representing the electrical efficiency as a function of cell temperature is given by the equation 3.3. (7)

$$\eta_{pv} = \eta_n \left[1 - \beta_{pv} (T_{pv} - 25°) + \gamma \log_{10} G_T\right] \tag{5.3}$$

Where β_{pv} is the temperature coefficient of the PV cell and T_{PV} is the PV module temperature w.r.t. time. η_n is the nominal efficiency of the module generally given by the manufacturer; however, it can be calculated by the following equation under standard operating conditions. (25°C cell temperature and 1000 W/m^2 solar irradiance)

$$\eta_n = P_n / (G_t \times A_c) \tag{5.4}$$

Thermal Efficiency: thermal efficiency is the ratio of useful heat output Q_{th} through the working fluid to the solar irradiance striking on the PVT module. It is given by the following equation 3.5.

$$\eta_{th} = Q_{th} / G_t \times A_c = \rho V_c \times (T_{out} - T_{in}) / G_t \times A_c \qquad (5.5)$$

6. CLASSIFICATION OF FLAT-PLATE PV/T SOLAR COLLECTOR TECHNOLOGY

Flat plate PV/T collector can be broadly classified according to the type of heat transfer fluid (HTF) used, glazing, medium of heat extraction, absorber-exchanger design, etc. A broad classification of flat plate PVT collector done on the basis of literature is shown in Fig-4.

6.1. Based on Glazing

Flat plate PVT collector can be classified into two types, based on the presence or absence of the external cover glass which influences its performance (34).

1. Unglazed
2. Glazed

Unglazed PVT collectors doesn't have air gap present above the collector module, i.e., it has direct contact among the cover glass and EVA encapsulated PV array. The heat losses are significant unglazed collectors result in high electrical efficiency at the cost of reduced thermal efficiency. The fluid temperature is basically influenced by ambient temperature, wind speed, etc. Unglazed PVT collectors are basically used in water pre-heating systems with additional heating devices such as heat pumps etc.

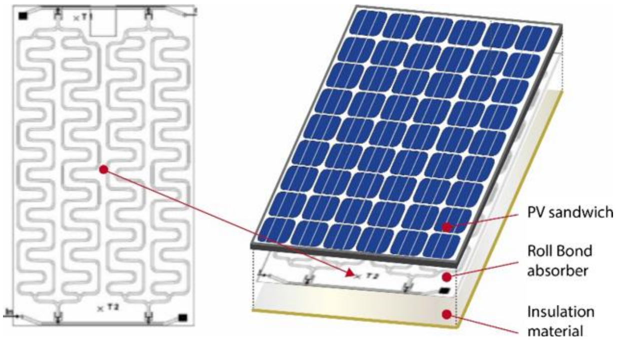


Fig – 5: Uncovered water-based roll bond PV/T Collector.

Glazed PVT collectors are provided with an air gap between the transparent cover glass and collector module, which allows a reduction in thermal losses and an increase in optical losses. This results in considerably high thermal efficiency at the cost of low electrical efficiency; however, it increases the overall efficiency of PVT collector (31).

In order to optimize the balance between thermal & electrical efficiency, several experiments and numerical investigations have been carried out for the optimum number of glazing layers. (31). A comparative investigation has been carried out in the literature (32) to compare the performance of uncovered and covered sheet and tube PVT collector, a conventional PV module and covered sheet and tube ST collector. Thermal efficiencies of 43.51% and 65.31% have been reported, for the covered PVT collector and ST collector respectively.

Sheet and tube PVT collectors were investigated with zero, one, and two covers in the literature (33). The results concluded that designs with more than two covers doesn't seem to have a realistic application since the electrical efficiency reduces too much. The single cover sheet-and-tube PVT collectors were preferred over the remaining two sheet tube designs beyond the critical point, as it collects more heat than double glass (18). With an increase in more than one number of covers, the electrical performance decreases. However, with decrease in the number of covers, the thermal performance reduces gradually (18).

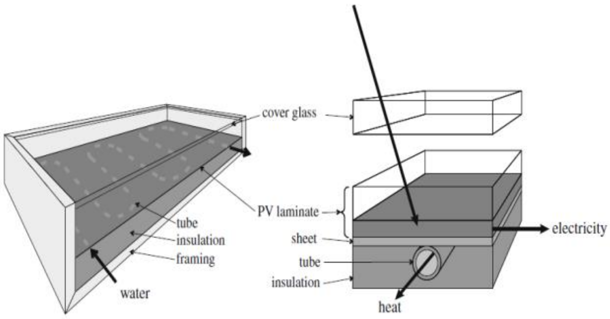


Fig – 6: Single glazed water-based sheet & tube PVT Collector.

The experimental investigation was carried out to study the performance of an uncovered water-based system. The mathematical model was created to simulate this typology of PVT collector and for energy yield estimation. The roll bond absorber was mechanically integrated with an array of PV cells connected in series as shown in Fig-5. The numerical & experimental investigation have been carried out for two years in three different cities in Italy. During simulation, parameters like the real angle of incidence of the solar radiation on the surface and the thermal inertia of the system spectral efficiency, the efficiency loss due to temperature, were considered. the maximum thermal and electrical efficiency recorded was 20–25% and 10–12% respectively for the mass flow rate of 0.055 kg/s (26) (34).

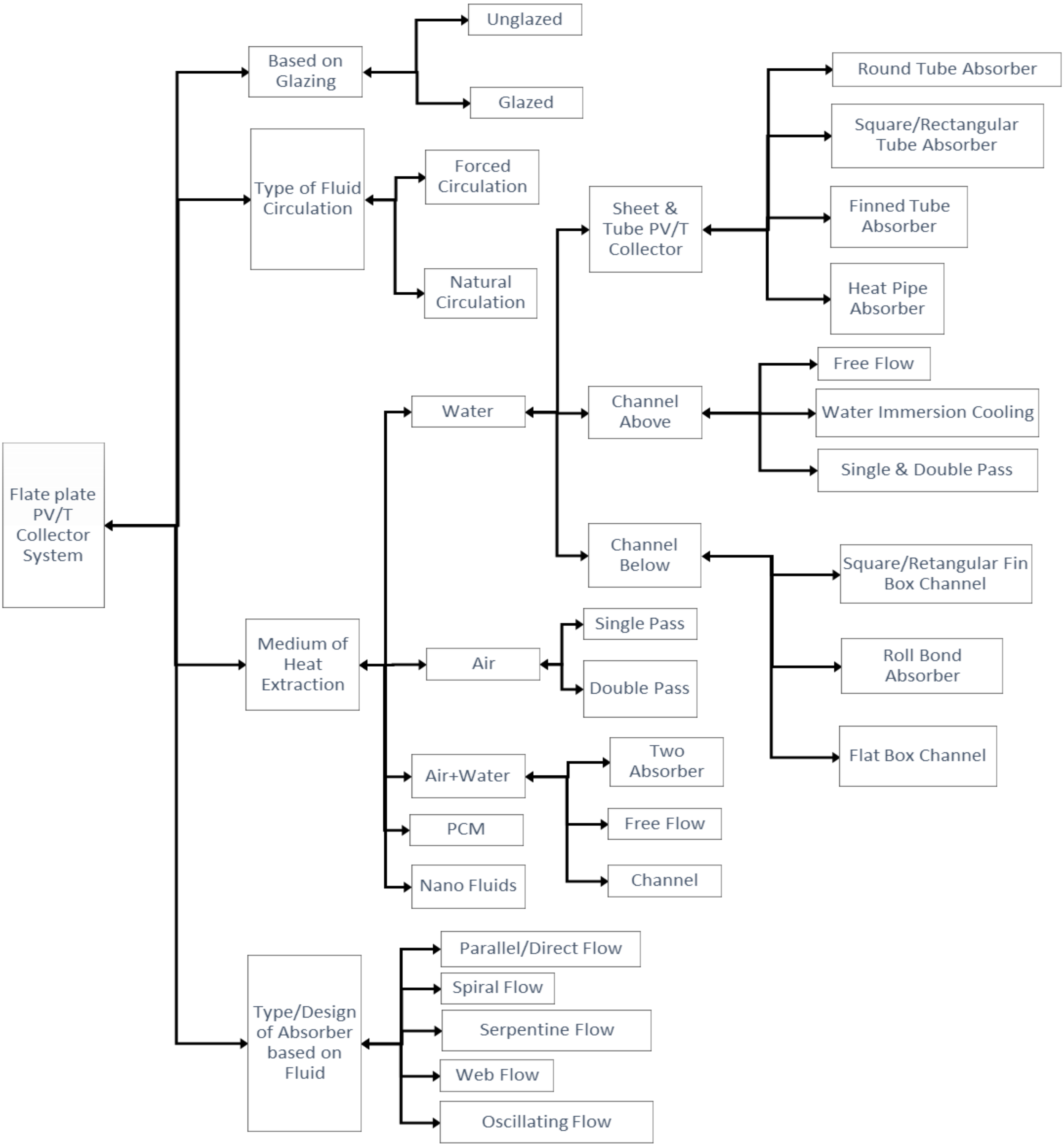


Fig – 4: Broad classification of Flat-plate PV/T Collector.

The performance of a water based single glazed PVT system is analyzed in the literature (35). The module comprises of PV laminates integrated with an absorber plate and water tubes as an exchanger to extract the heat from the PV module (Fig -6) (26). Water is pumped by using pumps. It was shown that annual thermal & electrical efficiencies of a covered S&T PVT collector recorded was about 15% lesser than the stand-alone solar thermal water heater collector system and a conventional PV module. The electrical efficiency is reduced due to rise in fluid temperature throughout a day. This is minimized by forced circulation with an optimum size of the storage tank. Hence the fluid temperature & storage tank size plays significant role in the design of PVT collector. Whereas the thermal efficiency of the PVT collector reduced compared to conventional thermal collectors is due to the higher emissivity of the absorber and lower absorption factor by the conversion into electrical energy.

The performance of a single glazed flat plate PVT system with the selective absorber is investigated in the literature (36). The investigations were paid attention on the methods of integrating PV cells to the absorber plate to minimize the thermal contact resistance. An optimized design was identified using a 2-D modeling approach, and the prototype was experimentally investigated. It has been recommended in the literature that, a single packed lamination of glazing, PV cell, and absorber plate minimizes the thermal resistance between the layers of PVT module (26).

(A) (B)

Fig – 7: Hybrid solar Photovoltaic/Thermal (PV/T) systems - (A) cooled by forced water circulation (B) cooled by forced air circulation [(44), (45)]

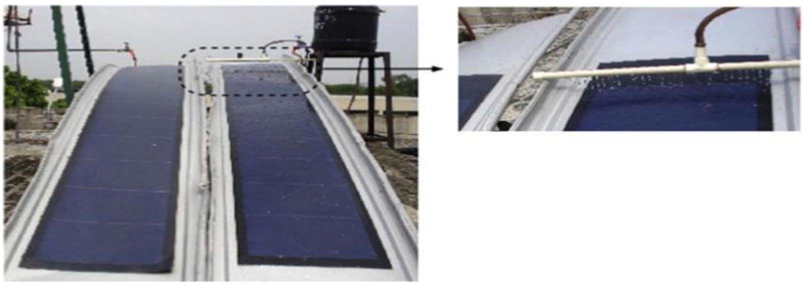


Fig - 8: Direct water spray-based PVT module (42) (44).

6.2. Based on heat transfer fluid used

PV/T collectors can be classified based on the heat transfer fluid used as water-based, air-based, refrigerant-based, heat pipe-based, nanofluids based or phase change material based.

6.2.1. Air

Air due to its less viscosity gives an advantage of a low-pressure drop inflow. Air is easily available for using it as a cooling medium in a low operating temperature where there is a possibility of water freezing. The most important features of air-based systems are the lower maintenance, minimal use of material and cost-effective in contrast to the liquid-based PVT systems. Air-based PV/T collectors have wide applications especially in room air heating (37), ventilation and drying of agricultural products. Air-based hybrid PV/T system is mostly studied due to their ease in construction, low operating cost and can be efficiently incorporated into buildings (38). The PV module is placed on one of the top surface steel box channels. The fan is powered to achieve forced circulation of air under the PV module as shown in fig-7B. The heat from the PV panel is extracted by air via convection. However, air does not show a superior heat transfer property due to lower density; specific heat and thermal conductivity. The outcomes obtained are 41% and 8% the maximum thermal and electrical efficiencies respectively (39) (40).

6.2.2. Water

Water based PV/T collector systems are the most widely studied PVT systems, because of its superior overall efficiency than that of air-based systems and it allows more uniform cooling of the PV cells throughout a life cycle (41). Water-based PV/T solar collector system is widely accepted since it has the potential of a replacement of household conventional solar water heating system. Numerous researches have been carried out in the field of enhancing the efficiency of PVT water collector systems using newer cooling techniques. Water spray cooling is the fundamental technique in which water is sprinkled on the top surface area of the PV module by using a fan and centrifugal pump to reduce the PV panel temperature as shown in fig-8 (42). In the last decade, various newer back panel provisions were designed & developed so as to enhance the heat extraction from the PV panel.

6.2.3. Refrigerants

Refrigerants plays a major role in the field of refrigeration and air conditioning. However, due to its efficient heat extraction property, several researches were focused on the use of refrigerants in PVT technology. In this technology, the evaporator coil is placed at the bottom side of PV cell, through which low-pressure low-temperature refrigerants are passed so as give cooling effect to the PV panel, which led to an increase in overall efficiency of PV/T collector (42). Though, it has some limitations such as the possibility of refrigerant leakage causing greenhouse effects and reduced electrical performance due to active cooling. The electrical and thermal efficiencies attained by this method are 12% and 50% respectively (43).

6.2.4. Phase change material

Phase change materials comes under the concept of conductive passive cooling techniques. The heat is accumulated during the melting phase of PCM i.e., endothermic process takes place, hence it can be also called as a latent heat storage material (44). During heat is supplied to the phase change materials (PCMs), they undergo sensible heating until they reach to its melting point, and later absorbs a huge amount of energy in the form of latent heat, which changes its phase from solid to liquid. But when the thermal energy input is not available the liquid PCM liberates the accumulated energy and converts to its original phase. (i.e., they accumulate or liberate a huge amount of heat in the process of melting and freezing process without change in temperature). Thus, due to its thermal benefits, PCM's are widely used in heat exchanger devices. The combination of PVT and PCMs to extract and to recover waste heat, have attracted many researchers (46). Several kinds of research have done on the use of PCMs in PVT collector. It was shown that, by the application of PCM for cooling of PV panel, the temperature of the PV panel reduces significantly, by which the life of PV panel increases by 30% (47). PCMs are mainly classified into three types named as an organic, inorganic and eutectic types. paraffins and no paraffins are the organic materials used as PCMs. Inorganic materials are hydrated salts and metals, whereas eutectics are the permutations of more than one material. Each PCMs have its own merits and demerits. The choice of material depends on various parameters such as thermal conductivity, latent heat of fusion, toxicity, corrosiveness and chemical stability (22). Though PCMs has many advantages than water and air, the literature is constrained to the air and water as a working medium in the upcoming sections.

6.2.5. Nanofluids

The recent development in hybrid PV/T collector has been concentrated on an increasing the electrical and thermal performances, several types of research have been carried out to employ an efficient nanofluids in solar technologies, which introduced a new concept of Nanofluids based PVT system. (48) (49). Basically, nanofluids are simply a common working fluid with homogeneously suspended nanoparticles of metals or metal oxides in the micrometer or nanometer scale (1-100 nm). Thus, the thermal conductivity of these normal fluids can be increased by dispersing the nanoparticles in it, which results in reduced operational cost and enhanced overall efficiencies of a system. Nanofluids have a superior thermal property than conventional fluids such as water, water-glycol solution, and oil. It has a good thermal property such as superior thermal conductivity and heat capacity and having a flexible property (by varying the nanoparticles concentration). Nanofluids can be used in a higher heat transfer rates in engineering applications.

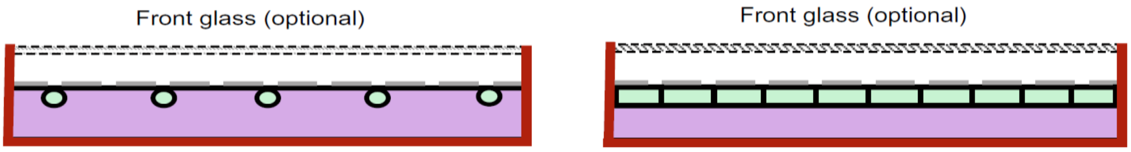
6.3. Based on Cooling channel (Absorber – Exchanger design)

Flat plate PVT collector can be classified based on the absorber-exchanger design as follows (50).

1. Sheet and Tube PV/T collector
2. Channel Above PV/T collector
3. Channel Below PV/T collector
4. Heat pipe

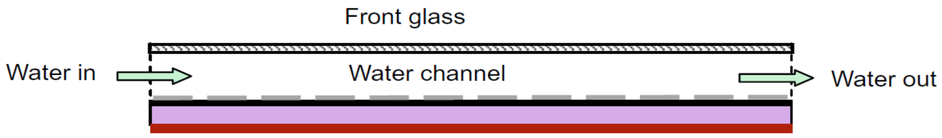
6.3.1. Sheet and Tube PVT Collector design

The sheet-and-tube thermal absorber is the most widely studied exchanger design with the use of working fluid like water or water-glycol mixtures & with parallel copper tubes (15), which also dominates the most commercially-available solar thermal collectors, mainly for domestic hot water systems, since it has only 2% less relative efficiency than standalone PV and solar thermal collector (18). As shown in figure 9 (a). It comprised of a PV module that is integrated with a thin metal sheet as an absorber made up of metal plate (copper, aluminum or stainless steel) with different integrating techniques as previously mentioned in the section 4. The heat exchanger metal tubes or polyethylene tube mats are bounded to the rear side of the plate using different welding techniques to remove thermal energy from the PV module. This heat is further used for domestic water heating. The amount of heat removed from the PV panel, and thus the overall efficiency, depends on the collector fin effectiveness and the tube bonding superiority linking the PV module and the sheet beneath the module (51). Thus, in order to optimize the design of these collectors, several researchers have made major efforts by paying attention to these design aspects (15).

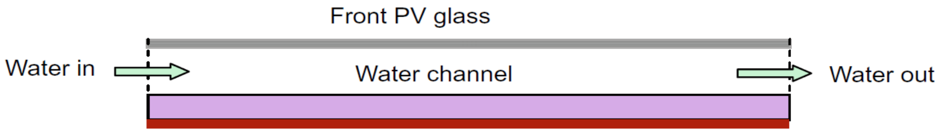


(a) Sheet-and-tube design

(b) box channel design



(c) Channel above PV design



(d) Channel below PV (transparent) design

Fig - 9: Different types of PVT solar Collectors (33).

The fluid flow pattern also plays a major role in the uniform cooling of a PV panel and temperature of outgoing fluid from exchanger. Thus, the tubing arrangement should be optimized to a maximum heat transfer area and different operating conditions. Different channel configurations such as parallel tubes, heat pipe, fin-tube, and coil tube as demonstrated in figure 10 (11). The sheet and tube design are one of the most dominating absorber designs, as it is inexpensive, easy to fabricate, accumulates a lesser amount of water capacity, has a higher-pressure bearing capacity (52). However, due to its complex structure, it limits in large scale building projects, since it adds a lot of weight of grouped metal tube arrangement (11).

The thermal model was developed and solved using MATLAB for the liquid-based PVT collector considering both the thermal resistance due the inherent characteristics of different layers and contact resistance between the layers. Also, the heat producing due to the inner series resistance is taken into consideration. The aim of this model was to provide an explicit estimation of the temperature deviation of different layers of the PVT module and to determine the fluid output temperature under constant solar radiation variation and ambient climatic conditions. It was then compared with the model developed in the literature (53), in which author did not take into account the above considerations. The results obtained are evaluated with the experimental investigation. It was examined that the errors related with the developed model were lessen due to the above considerations. The present study concluded some noteworthy observations that the PV cell temperature is highest amongst other PVT layers. Surface thermal contact resistance between the absorber and tedlar greatly influences the outlet water temperature and the ohmic resistance greatly reduces electrical efficiency under hot climate conditions (7).

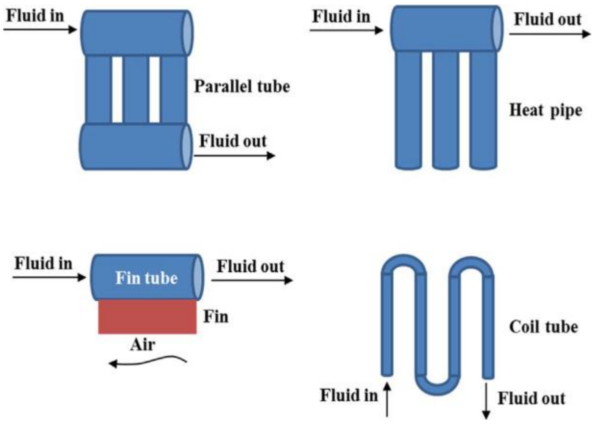


Fig - 10: Different tubes arrangements on the basis of the sheet-and-tube structures (11).

Novel flat plate sheet & tube collector along with the all-potential improvements (low emissivity coating & anti-reflective, thermal contact resistances between various PVT layers) have been studied and developed a 2D model using Finite Volume Method (FVM) (17). In this paper, the detailed 2D model results are then authenticated with the experimental outcomes from the literature (54) (55). This model allows the investigation and understanding of the impact of a newer future modifications in novel PVT collectors with respect to the conventional PVT solar collector (sheet & tube thermal absorber - exchanger). It was shown that the anti-reflective coating enhances both the electrical as well thermal efficiency. While with the use of low e coating, the thermal efficiency is improved with the reduction in electrical efficiency.

A 3D model is developed and evaluated for sheet and tube PVT solar collectors considering all the corresponding optical and thermo-physical properties of all layers of PVT. The optical behavior of PVT is modeled by discrete ordinate (DO) with regards to the solar ray tracing algorithm. Again, the greenhouse effect is also taken into consideration by using a two-band radiation DO model. Consequently, this model is used to examine the effect of numerous parameters which include a number of tubes, bonding size, and pipe diameter on the performance of PVT collector and PV cell temperature distribution. It was concluded that thermal efficiency of PVT is greatly influenced by the greenhouse effect in the air gap between the glass cover and PV module. However, there is a very slight reduction in electrical efficiency. For a given total mass flow rate, the overall optical losses decrease with an increase in the number of tubes. Again, it reduces the average temperature of the module and total pump power, which in turn increases electrical efficiency, with a cost of additional mass (12).

Seven new absorber collectors design configurations are designed modeled and compared for single glazed flat plate PVT collector as shown in figure 11. These absorber collector designs are simulated using Microsoft Excel software to determine the best absorber design having the highest overall efficiency. In these simulations, the different collector designs are analyzed with the parameters such as solar radiation, water mass flow rate, and ambient temperature, for time-domain from 6.00 AM to 8.00 PM. It was concluded that the gap between adjacent hollow tubes underneath the PV module plays an important role in determining the performance of collector configuration. The thermal and electrical performance of the S&T PVT collector can be improved by keeping closer tolerance in spacing between adjacent tubing, so that heat to be generated in the PV module is absorbed and eliminated to the working fluid uniformly. The results showed that the spiral flow design confirmed the best design with the highest electrical and thermal efficiency of about 11.98% and 50.12% respectively, while the serpentine flow absorber had the lowest overall efficiency of 45% among all the absorber designs (56).

Sheet and tube PV/T water collectors with three different absorber-exchanger designs as shown in figure 11 (a, b, c). are experimentally investigated in the literature (57). The prototypes of these new absorber designs are fabricated and indoor testing is carried out at the Solar Energy Laboratory, University Kebangsaan Malaysia. The fluid inlet and outlet temperature, ambient temperature, water flow rate inside the tube, wind velocity at the collector surface, etc. are the parameters to be controlled for indoor testing. It was concluded that the PV efficiency of collectors varies significantly with respect to time, over a range of PV temperature and mass flow rates. The thermal efficiency increases with an increase in the mass flow rate of the PVT collector. For a typical 800 W/m^2 solar radiation, the Thermal efficiency of web flow absorber and direct flow absorber increased from 41.11% to 48.07% and from 46.43% to 54.13% with an increase in a mass flow rate of 0.011 Kg/s to 0.041 Kg/s respectively. While, the highest thermal efficiency observed by spiral flow absorber, which is from 45% to 54.61% with an increase in mass flow rate from 0.011 Kg/s to 0.041 Kg/s. With an increase in the mass flow rates, the temperature of the PV module decreases non-linearly at all solar radiations. For a typical 800 W/m^2 solar radiation, the PV surface temperature of the web flow absorber collector reduced from 63.34°C to 49.54°C, whereas for the direct flow and spiral flow absorbers reduced from 62.57°C to 50.32°C and 65°C to 52.4°C respectively. While, that for a constant mass flow rate, the temperature of the PV module increases with an increase in solar radiation. The results indicate that the optimum absorber design from the above three absorbers is the spiral flow absorber design. At 800 W/m^2 solar radiation and 0.041 kg/s mass flow rate, the thermal, electrical and overall efficiency of spiral flow collector design is 54.61%, 13.81%, and 68.42% respectively.

The oscillatory flow design has the lowest cell efficiency of about 11.94% compared to another absorber design (56). However, an innovative new design of oscillatory flow absorber was modeled, analyzed and simulated using MATLAB software in the literature (58). Here a dual oscillatory absorber as shown in figure 13 is designed to reduce the spacing between adjacent tubing and to obtain uniform cooling of PV cell. The results are then compared with a normal PV module. The analysis is carried out for the mass flow rates in the range of 0.01-0.049 Kg/s under solar radiation in the range of 300-1000 W/m^2. The simulation results showed that the electrical efficiency of new PVT collector is 13.13% at a mass flow rate of 0.049 Kg/s under maximum solar radiation, whereas the electrical efficiency of a normal PV module is 12.2%. The important observations obtained are discussed in Table 1. For the same PVT absorber design and normal PV module as a comparison, the CFD analysis and experimental investigation were carried out in the literature (59) under natural Malaysian weather conditions. The simulation was evaluated for determining water flow rate and heat transfer in the PV panel in ANSYS 19.2. A novel absorber is made with copper material to improve heat transfer in the PVT collector. The experimental results showed that the maximum electrical efficiency of the PVT module obtained at a mass flow rate of 6 LPM was 11.71%, while the maximum electrical efficiency of a PV panel was 10.86%. The maximum electrical power obtained from the PV module and PVT collector at a mass flow rate of 6 LPM was 51.66 W and 56.22 W respectively. The highest thermal efficiency for novel PVT collector was obtained at 5 LPM of about 59.6%, whereas average maximum heat gain obtained at 4 LPM was 496.58 W. The highest cell temperature of a novel PVT module and PV panel achieved at 2 LPM was 62.73°C and 66.95°C respectively with an average ambient temperature of 32.5°C.

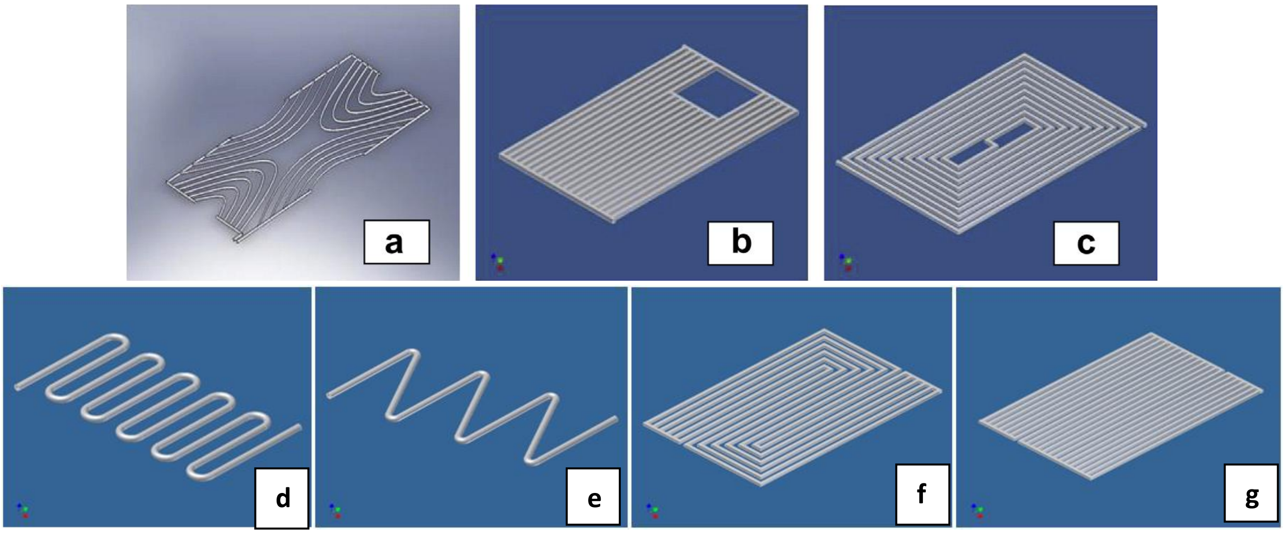


Fig - 11: (a) Web flow absorber, (b) direct flow absorber (c) spiral flow absorber (d) Oscillatory flow absorber (e) Serpentine flow absorber (f) Parallel-Serpentine flow absorber (g) Modified Serpentine-Parallel flow design (57) (56).

The simulation investigated in the literature (56) concluded that due to the less heat transfer area, the serpentine flow absorber design confirmed the lowest overall efficiency compared to the remaining absorber designs. However, in order to improve its overall performance, a novel design called serpent-direct flow absorber was designed in the literature (60). A mathematical model was developed and validated for the new design under various operating parameters in the MATLAB software. The design was created to overcome the limitations of the serpentine and direct flow absorber design investigated in (56). The new collector is a combination of serpentine flow and direct flow designs. It was observed that the novel design achieved a better thermal and electrical efficiencies compared to the conventional serpentine and direct flow absorber collector. The maximum cell efficiencies of serpent-direct flow and conventional serpentine flow absorber design were 14.8% and 14.7% respectively, while the thermal efficiencies are 52.5% and 53.5% respectively, at a water mass flow rate of 0.012 Kg/s and solar irradiance of 300 W/m^2.

The sheet and tube PVT collector using galvanized steel absorber plate and galvanized steel tubes as shown in fig-14 was studied theoretically and evaluated in the literature (61). These model results were further compared with the existing configuration studied in the literature (62), where copper serpentine absorber sheet and tube collector are experimentally studied. From the comparison, it was concluded that the thermal efficiency of a serpentine hybrid collector is lower than that of the galvanized sheet and tube PVT collector. An experimental investigation was also carried out under the meteorological conditions of Ghardaia in Algeria to validate the theoretical results. The solar radiation from 7.00 AM to 7.00 PM varied between 100 W/m2 to 1020 W/m2. They reported that the maximum electrical and thermal power generated by the proposed PV/T collector was 48W and 290W respectively. Galvanized steel is used due to its low cost compared to copper. However, due to the poor thermal properties of galvanized steel, simple galvanized steel configuration is not very interesting.

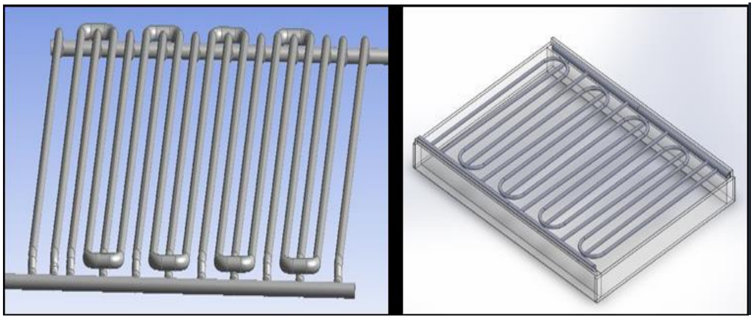


Fig - 12: (a) Front view of a serpen-direct flow design absorber (b) 3D diagram for a serpen-direct flow design absorber (60).

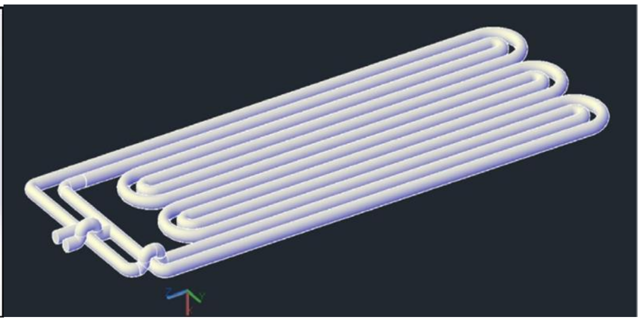


Fig - 13: Dual oscillating absorber design (58)

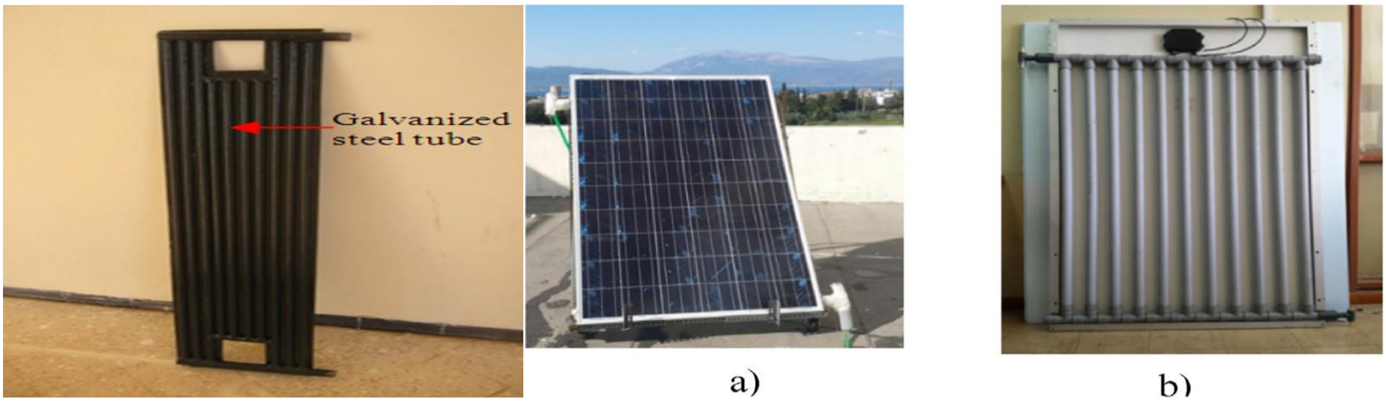


Fig - 14: Galvanized sheet and tube PVT absorber (61).

Fig - 15: PVC absorber PVT collector prototype design (1)

An extensive experimental analysis was carried out for the serpentine flow design sheet and tube PVT collector as shown in figure 12 in the literature (63). An elliptical cross-section tube is used having 8 mm and 6 mm of external and internal equivalent diameter respectively. The tube on plate configuration having a 1 mm aluminium plate glued with two serpentines is retrofitted under a standard commercial mono-crystalline panel (sharp NU-180EI). The short term Thermal dynamic numerical model was developed based on a lumped capacitance approach coupled with thermo-electrical analogy and validated with the experimental results under heavily dynamic working conditions. The results demonstrated good agreement between numerical and experimental profiles.

In order to achieve an optimal use of solar energy, improved hybrid PVT collectors with optimal performance parameters, bonding quality weight, techno-economic analysis was investigated in the literature (29) the main contribution of the literature is to develop and validate a 3D CFD-FEM model for 26 different absorber-exchanger PVT collector designs, which involves multi-physics processes (solid mechanics, fluid dynamics and heat transfer), in order to assess the thermal and electrical performances of these collectors. The different collector designs basically involve sheet and tube PVT collector and flat box PVT collector constructed with different materials (aluminium, copper, and polycarbonate and polyamide polymers with or without additives) and different sizes. It was shown that, for sheet and tube PVT collectors, the pipe diameter does not affect the thermal performance of collector design, whereas thermal and electrical performance can be improved by increasing number of tubes (i.e., heat transfer contact surface) up to 20-25 pipes, beyond which efficiencies vary asymptotically. However, for copper S&T, an increase in riser pipes increases higher initial investment with higher payback periods with a slight increase in efficiency, which is uneconomical. Whereas for aluminium S&T, lower material cost enables lower investment cost with an increasing number of pipes that outweighs the slightly worse performance due to the poor thermal conductivity of aluminium. This concludes that the aluminium S&T is an interesting alternative for copper S&T, as it reduces the weight (by 11.7%) and investment cost (by 3.7%) for the same electrical & thermal efficiency. The important observation in the case of flat box PVT collector is determined in subsequent section 3.2.3.

A low-cost water-based Photovoltaic/Thermal collector prototype was developed by using Polyvinyl Chloride (PVC) pipes as a heat exchanger as shown in figure 15. The collector prototype is as shown in fig. The aim of the literature was to develop a low cost and homemade solution, combined electricity, and domestic hot water generation. In order to assess energy, environmental and economic performance of the novel prototype, dynamic simulation was developed and validated with experimental results. The results showed that the yearly primary energy production of the proposed prototype was only 20% lower than the standard commercial PVT collector. It was concluded that the proper low cost, homemade manufacturing of PVT module can achieve good energy performance compared to that of more expensive and better engineered commercial PVT collectors (1).

6.3.2. Channel Below PV/T collector

6.3.2.1. Flat box channel type

The channel below type PV/T collector design is modeled to determine the temperature distribution over each layer of PVT design. Here, to optimize the low-cost design of absorber, galvanized iron is used instead of copper, as the galvanized iron of high quality, allows a good heat extraction with low cost compared to copper. An experimental investigation is done by using air as a working medium at the Unit of Applied Research in Renewable Energy. Prototype is as shown in figure 16. However, the theoretical results showed similar to the experimental results with less variation. The useful electrical power obtained is about 290 W while thermal efficiency is around 48%. However, total efficiency was 80% (64).

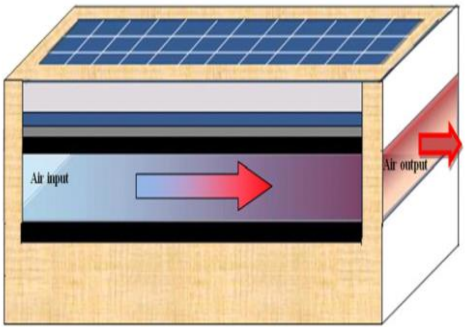


Fig - 16: A prototype of the channel below the hybrid collector for domestic air heating (64).

6.3.2.2. Rectangular/Square fin box channel

Flat box PVT collector with different materials and sizes are investigated in literature (29). The discussion for the 3D CFD-FEM simulation results as reviewed for sheet and tube PVT collector in a subsequent section is further proceed for flat box PVT collector, it was concluded that the all the designed flat box PVT collectors outperformed than the reference S&T PVT collectors (15). This was because of an increase in the heat transfer area between the absorber and the fluid. The PV module temperature distribution was seen uniform in the case of a flat box PVT collector with a reduction in cell temperature, which eliminates the effect of hot spots in the case of sheet and tube collector. In the literature, flat box PVT collector with copper, aluminium, polycarbonate and polyamide polymers with different sizes was investigated. It then concluded that all the flat box designs achieved higher optical efficiency (up to 4.8%) and lower heat loss coefficient (up to 15.7%) compared to the commercial collector taken as reference. The collector dimensions and material effects in the case of flat plate PVT collector were shown considerably small, as the thermal and electrical performance is to be maximized with an increased heat transfer surface area rather than decreasing thermal resistance. Consequently, the proposed off the shelf polymer without additives flat box PVT collector is a promising alternative to the commercial collectors. Results showed that 3×2 mm PC flat box design has better thermal and electrical efficiencies (5.9% and 2.9% higher resp.) compared to the reference cu-S&T collector. This design achieved a 15% lower heat loss coefficient and a 4% higher optical efficiency (65). Also, the design achieved the lowest payback period up to about 24.6% lower than the reference collector & reduced collector weight up to 9%.

6.3.2.3. Roll bond type heat exchanger

Roll bond absorbers already adopted for evaporators are the most suitable choice due to its higher performance for a hybrid solar collector as well than the conventional sheet and tube PVT collector. Roll bond absorbers are chosen due to many advantages, as they ensure very high thermal exchange performances, even when made of aluminium instead of costly thermal conductive copper material. Furthermore, the consolidated manufacturing processes make them extremely versatile for allowing different channel shapes and distribution. The schematic diagram of the roll-bond absorber is shown in the figure 17(b).

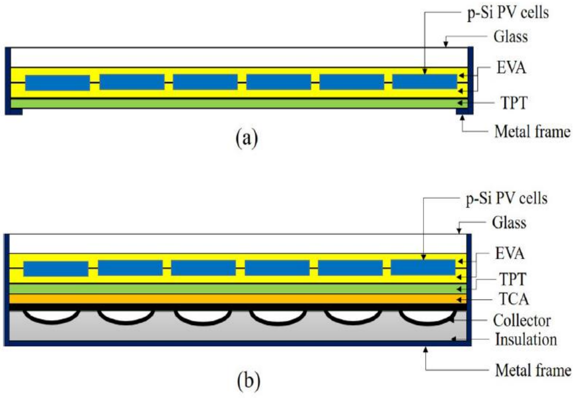


Fig - 17: Schematic diagram of (a) PV module and (b) Roll bond PV/T collector (66).

An innovative novel hybrid photovoltaic/thermal collector is modeled theoretically and validated by experimental investigation. The design consists of a single-glazed roll bond PVT collector with mono-crystalline silicon solar cells. In the literature, the harp (parallel) channel arrangement was preferred over serpentine one, because it ensures lower pressure drops and more homogeneous temperature distribution. The performance of the novel PV/T collector is then compared with the amorphous roll bond PVT collector (27).

6.3.3. Channel Above PV module

Heat transfer fluid is passed above the glass sheet of the PV module as shown in fig. 9(C). The heat absorption fluid used should have a different absorption spectrum with respect to PV in order to allow the PV module, to receive the incoming radiation. Thus, such a configuration limits the selection of heat transfer fluids. Water is the most suitable immersion fluid for heat absorption from the PV panel as it has a small overlap in absorption with the PV cell. Therefore, when water absorbs heat from the PV module the electrical efficiency increases. However, the measurements proved that the PV module covered with a water layer reduces the electrical efficiency by 4% (18). As the water reduces the transmission of infrared component of the solar radiation to the silicon cells, and due to evaporation of water, solar PV cells may get heated producing low thermal efficiency and low electrical efficiency due to the accumulation of the condensate below the top glass cover, causing additional reflection (50). The mechanical strength of the PV collector module is required to be high in order to withstand the water pressure. Due to which very thick glass cover is necessary over PV module, it results in a heavy & fragile structure of the collector (18).

In a free-flow PVT collector, fluid flows in an unrestricted manner. It eliminates the above glass cover, which in turn avoids mechanical breakage of the glass cover. Thus, it avoids the accumulation of the condensate below the top glass cover, which reduces reflection losses and material cost is reduced (18). It involves the immersion of solar cells directly into the circulating fluid. In the literature (67), Results showed that there is an 11% increase in electrical efficiency of the PV module due to submerging it into water. Such a technique is called liquid immersion cooling. PV modules are placed in large water bodies like rivers, oceans, lakes, canals, etc. For a bifacial PV module, the water layer is passed above a bifacial PV module, which has active surfaces on the top and bottom sides, Bifacial PV modules generate twice the electric energy than the conventional PV module with the same collector area. However, Due to water channel over top surface of the module, there is reduced electrical efficiency of the top surface by 10%, but the combined electrical efficiency of the bifacial PV module has increased about 40% compared to the conventional PV/T system (50).

6.3.4. Heat Pipe

The concept of heat pipe has been received major attention in the field of PVT technology for a few years due to its effective heat transfer ability with minimum losses. Heat pipes are the high heat flux transformation devices (10). They can absorb heat from the rear side of the PV module (heat source) and discharges heat to the low-temperature fluid (heat sink). A heat-driven two-phase thermodynamic cycle takes place inside the heat pipe. Heat pipes can be classified on the basis of absorber configuration such as round tubes heat pipes (RTHP) and micro-channel heat pipes (MHP). There are several kinds of research have been carried out to investigate the performance of conventional or standard RTHP systems also known as constant conductance heat pipes (CCHPs) in PV/T technology however the researches in the recent years recognized the effectiveness of MHP over conventional RTHP. MHPs are effective substitutes for the conventional round tube heat pipes due to their better heat transfer ability, low-pressure gradient, and more compact structure (68).

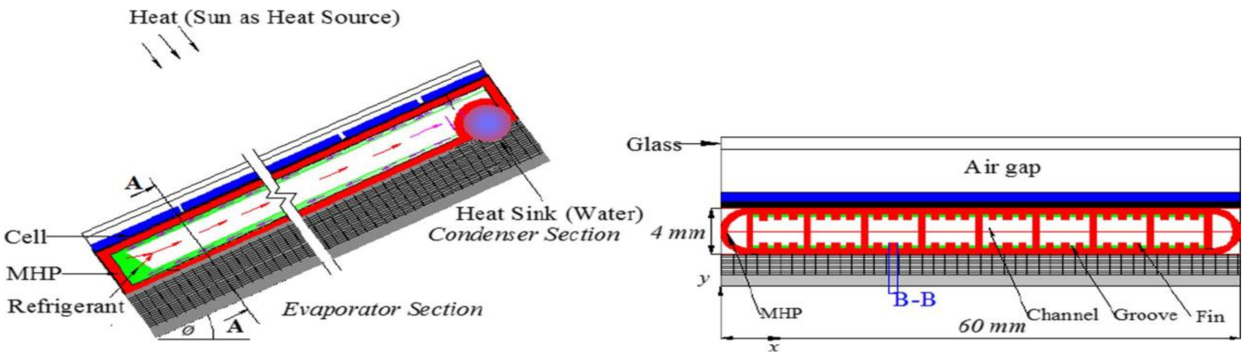


Fig - 18: Detail views of MHP-PV/T (68).

The micro-channel heat pipe is a plate heat pipe mainly used in electronics and telecommunication sector to remove a large amount of heat from electronic devices since few years however their use in a flat plate and flexible PV/T collectors have been increased since few years. The MHP works on the principle of boiling of a refrigerant at the rear end of the PV module due to heat extraction from it, and condensation of the working fluid giving latent heat in the manifold. The heat is then used for many applications such as water heating, space heating etc. There were limited studies done on the performance evaluation of the PVT collector system with MHP absorber design. The numerical and experimental studies of the proposed MHP PVT system have been carried out in the literature (68) to optimize the performance and increase in efficiency of heat pipe-based systems. Fig. shows the novel flat plate aluminium MHP absorber design having rectangular extrusions. This flat plate microchannel heat pipe has many inner micro-grooves to enhance the heat transfer as shown in fig. MHP was designed with refrigerant as working fluid to conduct heat away from the polycrystalline photovoltaic cells effectively to increase the cell performance as well as collector performance. The numerical results were agreed with the experimental data of the MHP PVT system as shown in fig-18.

7. LITERATURE REVIEW

Table 1. Literature Review on sheet & tube PVT collector

Investigator (s)	Year	Numerical or Experimental	PV Type	Glazed or Unglazed	Sheet and Tube Material & its configuration	Aim of paper	Important Remarks	Performance Results
Dudal Das, Pankaj Kalita, Anupam Dewan, Sartaj Tanweer **(7)**	2019	Both	Polycrystalline	Unglazed	Copper sheet and serpentine copper tube	Develop & validate a comprehensive thermal model for a hybrid S&T PVT considering thermal contact resistance and ohmic heat generation.	• PV cell temperature is highest than other PVT layers (310.56 K – 330.86 K) • Tedlar & absorber thermal contact resistance influences outlet temperature. • Ohmic resistance reduces electrical efficiency, crucial under hot climatic condition. • The developed model can be used for any kind of fluid with known thermo-physical properties. • Dynamic model developed considered most of the operating parameters except relative humidity and wind speed.	RMS temperature T_{wo} : 3.75K, T_G: 1.36 K, T_{PV}: 2.71K Expt. Results $\eta_e = 12.24\text{-}13.02\% \pm 2.18\%$ $\eta_{th} = 18.46\text{-}41.83\% \pm 2.29\%$ Overall Energy efficiency 19.1-28.9 ± 4.47% Overall Exergy efficiency 8.89-10.03 ± 4.47%
Oussama Rejeb, Leon Gaillard, Stephanie Giroux-Julien, Abdelmajid Jemni, et. Al. **(17)**	2020	Numerical	-	Glazed	-	Develop & validate the 2D model for novel PVT collector with optimum enhancements (Optical coatings, Thermal contact resistance between different PVT layers)	• The addition of Anti-reflective coating on the PV module increases overall PVT efficiency. • The addition of low e coating increases thermal efficiency but reduces the electrical efficiency. • Conductive heat transfer between different layers is enhanced.	For Novel PVT S&T module with ARC and low e coating, for zero loss $\eta_e = 14.25\ \%$ & $\eta_{th} = 67\ \%$ For Novel PVT S&T module with ARC and low e coating, with simple or advanced encapsulation by package lamination Mfg. process $\eta_e = 15.10\ \%$ & $\eta_{th} = 71\ \%$
Seyed Reza Maadi, Meysam Khatibi, Ehsan Ebrahimnia-Bajestan, **(12)**	2019	Numerical	Polycrystalline	Glazed	Copper sheet and parallel copper tubes with copper bonding	Develop & evaluate the 3D model of PVT incorporating solar ray tracing, heat transfer and fluid flow in a glazed collector	• Thermal efficiency increases, while electrical efficiency reduces slightly with the greenhouse effect at low solar irradiation. • Electrical efficiency is increased by increasing the number of tubes and bonding contact areas.	At solar irradiance of 300 W/m², due to the greenhouse effect, η_{th} increased by 12%. For given mass flow rate, A thermal optical loss decreases by 15.8%, 29.4%, 31.8% and 34% with an increase in a number of tubes from 5 to 10, 16, 20 and 25 respectively.

K. Touafek, A. Khelifa, M. Adouane **(61)**	2014	Both	-	Unglazed	Galvanized steel sheet and tube Bonded with weld	Numerical and experimental investigation of galvanized steel sheet and tube. & its comparison with the existing copper serpentine absorber PVT collector.	• The thermal efficiency of copper serpentine PVT collector is less than the thermal efficiency of the galvanized steel sheet and tube collector. • The inlet temperature of heat transfer fluid greatly influences the change in temperature of each PVT layer.	Inlet fluid temperature T_{wi} = 20°C Outlet fluid temperature T_{wo} = 40°C Thermal Power = 290 Wp Electrical Power = 48 W
Maria Herrando, Alba Ramos, Ignacio Zabalza, Christon N. Markides **(29)**	2019	Numerical	Both	unglazed	Copper sheet and copper tubes, D = 8 mm, n = 9 D = 6 mm, n = 9 D = 10 mm, n = 9 D = 8 mm, n = 12 D = 10 mm, n =12 D = 8 mm, n = 18 Aluminium sheet and aluminium tubes D = 8 mm, n = 9 D = 10 mm, n = 9 D = 8 mm, n = 12 D = 10 mm, n =12	Develop 3D CFD-FEM and analyze the performance of sheet and tube having different absorber - exchanger materials & size.	• Pipe diameter does not have an important effect on the thermal efficiency of the collector design. • An increase in a number of riser tubes increases the thermal & electrical efficiency of collector design up to about 20-25 pipes. • For the same size, Copper S&T performs better than aluminium S&T due to its high thermal conductivity. • Slightly increase in thermal & electrical efficiency of copper and aluminium S&T does not compensate for their higher initial investment cost. • Aluminium S&T is a prominent alternative to the conventional copper S&T having less payback period and less initial investment cost for the same thermal & electrical efficiency.	• For copper S&T at same operating conditions η_{th} = 65.9 % for n = 9 η_{th} = 67.4 % for n = 18 • For aluminium S&T at same operating conditions for n = 9 & D = 8 mm η_{th} = 65.1% Optimum design considering η_e, η_{th}, F_R, U_L, PBT. • For copper S&T w.r.t. reference cu-S&T n = 12 D = 8 mm PBT = + 2.6% (relative) relative % $\begin{cases} \eta_e = +0.8\ \% \\ \eta_{th} = +1.1\ \% \end{cases}$ • For aluminium S&T w.r.t. reference cu-S&T n = 12 D = 8 mm relative % $\begin{cases} \text{PBT} = -4\% \\ \text{Weight} = -11.7\% \end{cases}$

Adnan Ibrahim, M.Y. Othman, M.H. Ruslan, M.A. Alghoul, M. Yahya, Zaharim and K. Sopian **(56)**	2009	Numerical	Polycrystalline	Single glazed	Copper Sheet and a copper tube with different collector design – direct flow, oscillatory flow, serpentine flow, web-flow, spiral flow, parallel-serpentine flow, modified serpentine-parallel flow	Performance investigation of different absorber designs and to determine the best absorber design based on highest overall efficiency.	• It is advisable to perform simulation at the early stage of design, to enable justification for the correct design configuration of any design proposed. • Gap or spacing between adjacent tubing beneath the PV module plays an important role in determining the performance of the PVT module. • With the reduction in spacing between tubing, the overall efficiency increases.	1) Direct Flow design T_{wo} obtained 30.3°C 2) Oscillatory Flow design T_{wo} = 29.9°C Cell efficiency = 11.94 % (Lowest among all) 3) Serpentine flow design T_{wo} = 28.8°C Total efficiency = 45% (Lowest among all) 4) Web flow design T_{wo} = 29.5°C 5) Spiral flow design T_{wo} = 31°C Total efficiency = 68% (Highest among all) Cell efficiency = 11.98 % (Highest among all) 6) Parallel-Serpentine flow. T_{wo} = 30.5°C 7) Modified Serpentine-Parallel flow design T_{wo} = 30.7°C
Giovanni Barone, Annamaria Buonomano, Cesare Forzano, Adolfo Palombo, Orestis Panagopoulos **(1)**	2019	Both	Polycrystalline	Single glazed	Polyvinyl Chloride (PVC) pipes as tubes for Novel PVT collector design. Bonded by a commercial glue and then sealed by Teflon tape	Design and development of low-cost prototype of water-based PVT collector, experimental and dynamic simulation model investigation to access the energy, economic and environmental performance under different parameters.	• The proposed model was able to achieve a low initial cost with home-made manufacturing. • It was able to return primary energy savings compared to that of more expensive and better engineered commercial PVT design.	During winter season, Electrical efficiency = 18% During Summer season, Electrical efficiency = 16%

Ahmad Fudholi, Kamaruzzaman Sopian, Mohammad H. Yazdi, Mohd Hafidz Ruslan, Adnan Ibrahim, Hussein A. Kazem **(57)**	2013	Experimental	Polycrystalline	Single glazed	Round hollow tubes for web flow design & rectangular hollow tubes for direct and spiral flow design – Stainless Steel Bonded with tungsten inert gas welding method.	Investigating the performance of the three absorber designs of PVT water collector – Web flow, Direct flow, and Spiral flow	• PV efficiency of collector varies significantly with respect to time, under different PV temperature and mass flow rates. • The thermal efficiency increases with an increase in the mass flow rate of the PVT collector. • With an increase in the mass flow rates, the temperature of the PV module decreases non-linearly at all solar radiations. • for a constant mass flow rate, the temperature of PV module increases with an increase in solar radiation	At mass flow rate 0.041 Kg/s For web Flow design, $\eta_e = 12.37$ % $\eta_{th} = 48.07$% $\eta_o = 60.44$% For direct flow design, $\eta_e = 12.69$ % $\eta_{th} = 54.13$% $\eta_o = 66.82$ % For spiral flow design, $\eta_e = 13.81$ % $\eta_{th} = 54.61$% $\eta_o = 68.42$ %

Table 2. Literature Review on Channel below (flat box) PVT collector

Investigator (s)	Year	Numerical or Experimental	PV Type	Glazed or Unglazed	channel Material & its configuration	Aim of paper	Important Remarks	Performance Results
Khaled Touafek, Mourad Haddadi, Ali Malek (64)	2013	Both	Monocrystalline	unglazed	Galvanized steel channel and air as working medium	Numerical modeling and simulation of a new design of hybrid collectors for air heating, & experimental validation	• Electrical performances of PV modules deteriorate significantly with an increase in its temperature. • The natural circulation of air is the easiest and cheapest way to remove this heat and consequently increase efficiency.	$\eta_{th} = 48$ % $\eta_o = 80$ %

Table 3. Literature Review on Rectangular/Square with grooves Flat box PVT collector.

<table>
<tr><th>Investigator (s)</th><th>Year</th><th>Numerical or Experimental</th><th>PV Type</th><th>Glazed or Unglazed</th><th>Flat box absorber Material & its configuration</th><th>Aim of paper</th><th>Important Remarks</th><th>Performance Results</th></tr>
<tr><td>Maria Hernando, Alba Ramos, Ignacio Zabalza, Christon N. Markides (15)</td><td>2018</td><td>Numerical</td><td>Both</td><td>unglazed</td><td>Copper channels: 3×2mm, 10×10mm
Aluminium channels: 3×2mm, 10×10mm, 20×10mm
Polycarbonate: 3×2mm, 6×4mm, 10×10mm
Polyamide: 10×10mm, 20×10mm, 40×10mm
Polymers with additives :
PA90-15: 10×10mm
PA30-33: 3×2mm, 6×4mm, 40×10mm, 10×10mm, 20×10mm.</td><td>Develop a 3D CFD-FEM and analyze the performance of flat box PVT collector having different absorber - exchanger materials & size.</td><td>• All flat box PVT collectors outperformed than the Cu S&T reference PVT collectors, due to increase in heat transfer area between the absorber and the fluid.
• The PV module temperature distribution was seen uniform in the case of a flat box PVT collector with a reduction in cell temperature, which eliminates the effect of hot spots in the case of sheet and tube collector.
• The collector dimensions and material effects in the case of flat plate PVT collector were shown considerably small, as the thermal and electrical performance is to be maximized with an increased heat transfer surface area rather than decreasing thermal resistance.</td><td>
<table>
<tr><th>City</th><th>Polymeric flat-box PVT</th><th>Benchmark PVT</th></tr>
<tr><td rowspan="2">Athens, Greece
Vp = 50 L/H</td><td>%th,cov 61.3</td><td>%th,cov 60.1</td></tr>
<tr><td>%e,cov 64.4</td><td>%e,cov 64.4</td></tr>
<tr><td rowspan="2">London, UK
Vp = 30L/H</td><td>%th,cov 29.3</td><td>%th,cov 28.5</td></tr>
<tr><td>%e,cov 65.6</td><td>%e,cov 65.5</td></tr>
<tr><td rowspan="2">Zaragoza, Spain
Vp = 65 L/H</td><td>%th,cov 45.3</td><td>%th,cov 45.3</td></tr>
<tr><td>%e,cov 66.5</td><td>%e,cov 66.3</td></tr>
</table>
</td></tr>
<tr><td>Oussama Rejeb, Leon Gaillard, Stephanie Giroux-Julien, Chaouki Ghenai, Abdelmajid Jemni, et. Al. (17)</td><td>2019</td><td>Numerical</td><td>-</td><td>Glazed</td><td>-</td><td>Develop & validate a 2D model for novel PVT collector with optimum enhancements
(Optical coatings, Thermal contact resistance between different PVT layers)</td><td>• The addition of Anti-reflective coating on the PV module increases overall PVT efficiency.
• The addition of low e coating increases thermal efficiency but reduces the electrical efficiency.
• Conductive heat transfer between different layers is enhanced.
• Channel heat exchanger PVT collectors outperformed than the Cu S&T reference PVT collectors, due to increase in heat transfer area between the absorber and the fluid.
• The advanced channeled PVT design with optical coatings operates at higher fluid temperatures and lower photovoltaic cell temperature.</td><td>For Novel PVT advanced channelled module
$\eta_e = 15.40$ %
$\eta_{th} = 73$ %
Tpv = 51.98°C to 51.82°C
Two = 48°C</td></tr>
</table>

Table 4. Literature Review on Roll bond absorber type PVT collector.

Investigator (s)	Year	Numerical or Experimental	PV Type	Glazed or Unglazed	channel Material & its configuration	Aim of paper	Important Remarks	Performance Results
Alessandro Miglioli (27)	2017	Both	Mono-crystalline	Glazed	Aluminium roll bond absorber	Design, modeling, and optimization of a roll bond hybrid photovoltaic-thermal collector. Comparison with	• The electrical yield of the system employed with the monocrystalline solar cell was higher than that of the system employed with amorphous ones. However, the thermal yield of amorphous is higher than a mono-crystalline system. • The thermal efficiency of the PVT collector was lower than conventional ST collector. • The thermal expansion of different PVT layers is a critical issue. It should be considered during simulation.	η_e = 16.60 % Electrical Power = 31.5 W T_{max} = 70 – 80 °C

8. CONCLUSIONS

This paper represents a literature review of flat plate photovoltaic thermal solar collector. A comprehensive study has been carried out by reviewing several literatures from problem statement to final product output of several prototypes. As the, the electrical efficiency of photovoltaic panel reduced with increase in temperature. To cope up with this issue, the root causes & their solutions are discussed in subsequent sections. the electrical efficiency is improved by cooling photovoltaic panel by different means like active or passive cooling as discussed, the extracted heat by passive cooling can be used for different applications. This concept of generating electricity and heated fluid medium by combining photovoltaic & thermal technologies called as cogeneration techniques.

Further in the section 3, the design philosophy of PVT system is discussed by taking into consideration different components of PVT systems, its effects on the performance & present solutions. It can be concluded that, each and every component plays a major role in the performance of PVT collector. Based on this literature, an optimum collector design can be evaluated. The integration techniques of PV panel & thermal absorber also play a major role in thermal exchange among them.

In the section 4, the different PVT prototypes based on their working philosophy, design parameters & different governing parameters, a broad classification has been carried out in the figure 4. Again, a detailed discussion on this design philosophies is being carried out in subsequent sections. It is then concluded that, single glazed, spiral flow sheet and tube heat exchanger design absorber is the best design in case of improving overall efficiency of PVT collector. Further overall efficiency can be increased by using an anti-reflective coating above the glazing, with the use of advanced photovoltaic cells like mono-crystalline silicone cells at the present scenario.

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