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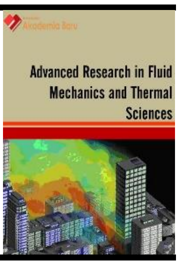

Technology Progress on Photovoltaic Thermal (PVT) Systems with Flat-Plate Water Collector Designs: A Review

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ABSTRACT

Commercial solar cells are currently less efficient in converting solar radiation into electricity. Photovoltaic (PV) performance decreases as temperature increases. Many efforts have been made to investigate and develop hybrid PV and thermal collector systems. A photovoltaic thermal (PVT) system generates both electric power and heat simultaneously. A significant amount of work has been carried out on these systems since 1970. Different PVT systems have been invented in the last 30 years. The aim of PVT systems is to improve electrical efficiency using a cooling system by reducing cell temperature, and an absorber collector takes the excess heat underneath the PV system. Then, the heat is transferred through working fluids such as water. The harvested heat is further used in low-temperature applications, including domestic hot water supply, water preheating, and space heating. This work shows the developments of the PVT systems, development of PVT systems with spectrum filters in recent research, the development and design of flat-plate water collectors in PVT systems, including various types of flat-plate solar collectors, and also a broad classification and review of published research work on the systems. The performance of PVT-based water collectors is determined by different combinations of absorption collectors and solar collectors as important elements of PVT systems. New design ideas and innovative configurations have emerged, especially when liquid as a medium of heat transfer is utilized to obtain useful heat from the back surfaces of PV panels. Various design configurations for hybrid PVT collectors are also compiled and assessed, and the emphasis is on the design performance of absorbers. The findings show that solar collector design parameters can easily affect and enhance the overall performance of PVT systems, especially electrical and thermal efficiency. The general performance of PVT systems may have benefited significantly from the extensive research conducted on this topic since the last decade. In order to develop novel PVT systems, more effort is needed in accurate modelling, exploration of novel materials, enhancement of PVT system stability, and the design of a supporting energy storage system.

Keywords:
Photovoltaic Thermal; PVT Systems; Flat-Plate Water; Collector Designs

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1. Introduction

The rapid demand of global energy is due to the increase of population and manufacturing activities [1]. Today's fossil fuels emit polluting gases in large quantities to meet energy needs, which severely damaged ecosystems. Global warming is a serious problem that threatens the survival of humans and other species. Energy crisis is a stumbling block to economic growth in many countries [2,3]. One of the most effective ways to solve this problem is to use renewable energy instead of fossil fuels [4,5]. Photovoltaic thermal (PVT) hybrid systems that consist of photovoltaic (PV) and solar thermal components generate electricity and heat [6]. The efficiency of a solar cell is proportional to the temperature of the cell, which means that the efficiency of PV is inversely proportional to the cell. As a result, it is proposed to use a solar PVT system to convert solar heat absorbed into thermal and electrical energy by Kern and Russell [7]**.** A typical theoretical study was conducted by Hendrie [8] on a thermal PV collector using a conventional thermal planning method. Several review articles have discussed the factors affecting the performance of PVT systems [9-13].

The application and development of solar energy is a promising option because solar energy is the most abundant renewable energy source and the Earth absorbs heat (1.8 × 1014 kW) in the form of heat and light [14].The use of solar energy is less harmful to the global environment because it is renewable, inexpensive, and environmentally friendly [15]. Furthermore, solar energy is easy to use and apply, as well as convenient and efficient to use solar systems in village systems, industrial processes, and houses[16]. However, the total area required to meet the demand for heat and energy is very large. Therefore, it is advisable to use solar energy for producing electric power and heating [17]. Solar radiation can be converted into four types of energies: chemical, electrical, thermal, and mechanical energy, such as water vapour and wind, as shown in Figure 1 [18,19].

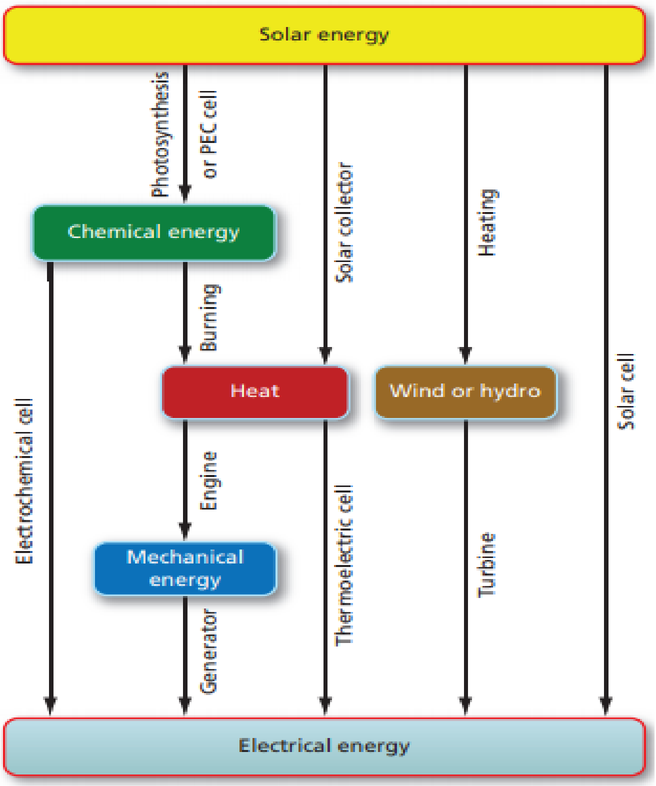


Fig. 1. Different energy conversion paths from solar energy to electrical energy [18]

Many designs have been considered to improve photoelectric performance and for that purpose, PVT collectors have been proposed. A good thermal conductivity between a heat absorption unit and a PV module can improve electrical and thermal efficiency. PVT technology has been developed in recent decades. According to a survey, each type of PVT system has its advantages, disadvantages, and applications, as shown in Table 1. Much research is needed to consistently improve their performance[20,21].

Table 1
Comparisons of different types of Flat Plat PVT systems

Type of flat plate PVT systems.	Working fluid	Advantages	Disadvantages	Applications
Air- type PVT systems	Air	Simple design and Low maintenance cost.	Low thermal performance. less applications of hot air	Heating space and the agricultural sector
Liquid-type PVT systems	Water	Large heat carrying capacity, Higher thermal and electrical efficiency than Air-type PVT system	Normal structure and higher cost	Space heating, Water heating system, Water percolation and Sea water desalination
	Stage change material	It is effectively used for thermal management of photovoltaic systems	Inserted with the PVT system	Integrated system and PV thermal management system management
Liquid-type PVT systems	Nanofluid	Fine performance. Suitable Temperature and conductivity	Limited exploration, difficult use in buldings and danger of use	Water heating system. Build an integrated system
Bifluid-based PVT systems	Air and water	High performance of thermal and electricity, hot water and hot air, excellent cooling of PV panels	compound structures, expensive and limited applications	Heating area and hot water heating system

In the mid-1970s, PV technology was directed towards the PVT system, where the problem of PV power degradation at high temperatures for PV panels began to draw attention due to its high potential for energy production. Solar technology consists of solar collectors and PV solar technology as shown in Figure 2. Hybrid PVT systems were proposed and revised by Martin Wolf [22].

2. Concept of Photovoltaic Thermal PVT

PVT absorbers are very important as the absorbers can reduce the temperature of a cell or a PV unit, collect the heat from the hot working fluid, and increase the efficiency of a PV module. Figure 3 illustrates a PVT system.

It is always useful to discuss recent developments in technology to understand the development process and to present future development trends. There are different studies describing different aspects of PVT systems, and several published audit papers from 2010 to 2019 are shown in Table 2. The purpose of this article is to provide a broad classification of PVT systems in order to discuss experimental and theoretical works of PVT systems in recent years. This paper also includes a review of the application of other PVT liquid systems with different absorption collectors. A comparative study based on the main advantages of PVT technology is also included.

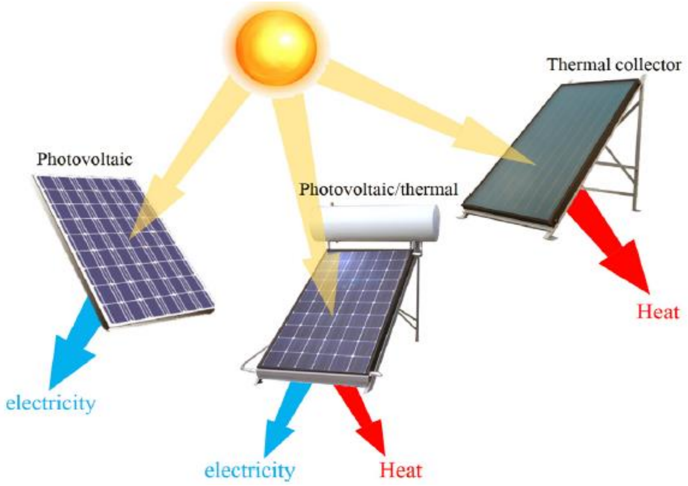


Fig. 2. Solar technologies [23]

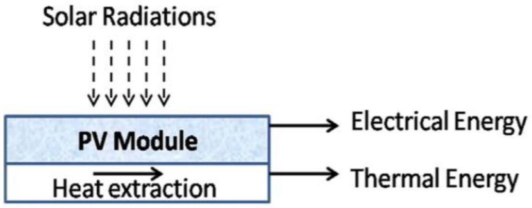


Fig. 3. Concept of PVT system

Table 2
Summary of previous reviewes articles on dealing with research and development aspects

Investigato Year	Studied System	PV Type	Method	Main Method	Performance Results
Sarhaddi *et al.*, 2010 [24]	Air based PVT system	monocrystalline silicon	Simulated and experimental	Study are thermal and electrical parameters of a typical PVT air collector	Thermal efficiency, electrical efficiency and overall energy efficiency of PVT air collector is about 17.18%, 10.01% and 45% respectively
Daghigh *et al.*, 2011 [25]	Liquid based PVT system	Summary Type of cells	Simulated and experimental	Review the refrigerant and water type PV/T collectors amongst the PVT liquid	The water based photovoltaic thermal collector systems are practically more desirable and effective than air based systems
Ghani *et al.*, 2012 [26]	A hybrid PVT water collector		Simulated	Study Effect of flow distribution on the photovoltaic performance	flow distribution was uniform, photovoltaic performance was improved by over 9% in comparison to a traditional photovoltaic (PV) collector, for poor flow performance was only improved by approximately 2%
Swapnil Dubey *et al.*, 2013 [27]	PVT water collector system	A monocrystalline and B multicrystalline	Experimental and Theoretical	testing of two different photovoltaic–thermal (PVT) modules A, B	Thermal efficiency and PV efficiency for Type A PVT module are 40.7% and 11.8%, respectively, and for Type B are 39.4% and 11.5%, respectively
Dupeyrat *et al.*, 2014 [28]	PVT solar hot water system		Experimental and simulations using TRNSYS	Study of the thermal and electrical performances of	Electrical output for equivalent roof area for the combination PVT/PV is around 12.7% in Paris, 12.6% in Lyon and10.7% in Nice

				PVT solar hot water system.	
Jicheng Zhou, 2015 [29]	PV module	polycrystalline	Simulation	Study of temperature distribution of the cell layer	highest temperature of 331.76 K near the solar cell center. The lowest temperature difference between the center and the edge is 0.68 K and the highest temperature difference between the center and corner is 1.2 K
Jee Joe Michael & Iniyan Selvarasan 2016 [30]	PVT water collector	monocrystalline	Experimental	A novel PVT collector was developed, by laminating the solar cells directly to a copper metal thermal absorber	reducing the thermal resistance by 9.93 % for effective heat transfer fromthe PV cells to the heat transfer fluid. Due to the presence of the copper sheet
Ali H.A. Al-Waeli *at el.*, 2017 [31]	Air based PVT system, PVT water collector	Summary Type of cells	Review for all method	The study will focus on the type of fluid used and its effect on the thermal and electrical efficiency of the system	Suggested that the use of nanoparticles and water as base fluid improves the overall system efficiency, more research is essential to reduce the cost and, improve the effectiveness and technical design of such systems
Jiajun Cen *et al.*, 2018 [32]	PVT water collector system	Monocrystalline,polycrystalline,bifacial monocrystalline	Experimental and theoretical model	In this experiment, three types of PV panel are used	demonstrated the capability to provide hot water of approximately 80 °C for a family of four, as well as providing excess electricity towards household applications
Jicheng Zhoua, 2018 [33]	PVT water collector	Polycrystalline silicon	Experimental and simulations using TRNSYS	We investigate the effect of multiple factors on the temperature distribution, including tube spacing, absorber materials, inlet velocity and tube row arrangement, respectively	Reducing tube spacing and using absorber materials are the most effective way to increase uniformity of temperature distribution
Neha Dimri *et al.*, 2019 [34]	PVT-TEC water collectors		Thermal model	Considering three different types of PV modules, namely opaque, semitransparent and Aluminum base and comparative between them	The results demonstrate that the daily overall electrical energy gain, daily rate of thermal energy gain and daily overall exergy gain is the highest for [Case 3] Aluminum base PVT-TEC water collector

3. Classification of PVT systems

PVT systems are largely classified according to the order of thermal extraction, working medium, and end applications. In addition, PVT systems can be classified based on the concentration of radiation. The outstanding works done in modern PVT systems are discussed in the following text. PVT is reviewed in this section with a focus on the PVT system classification as shown in Figure 4.

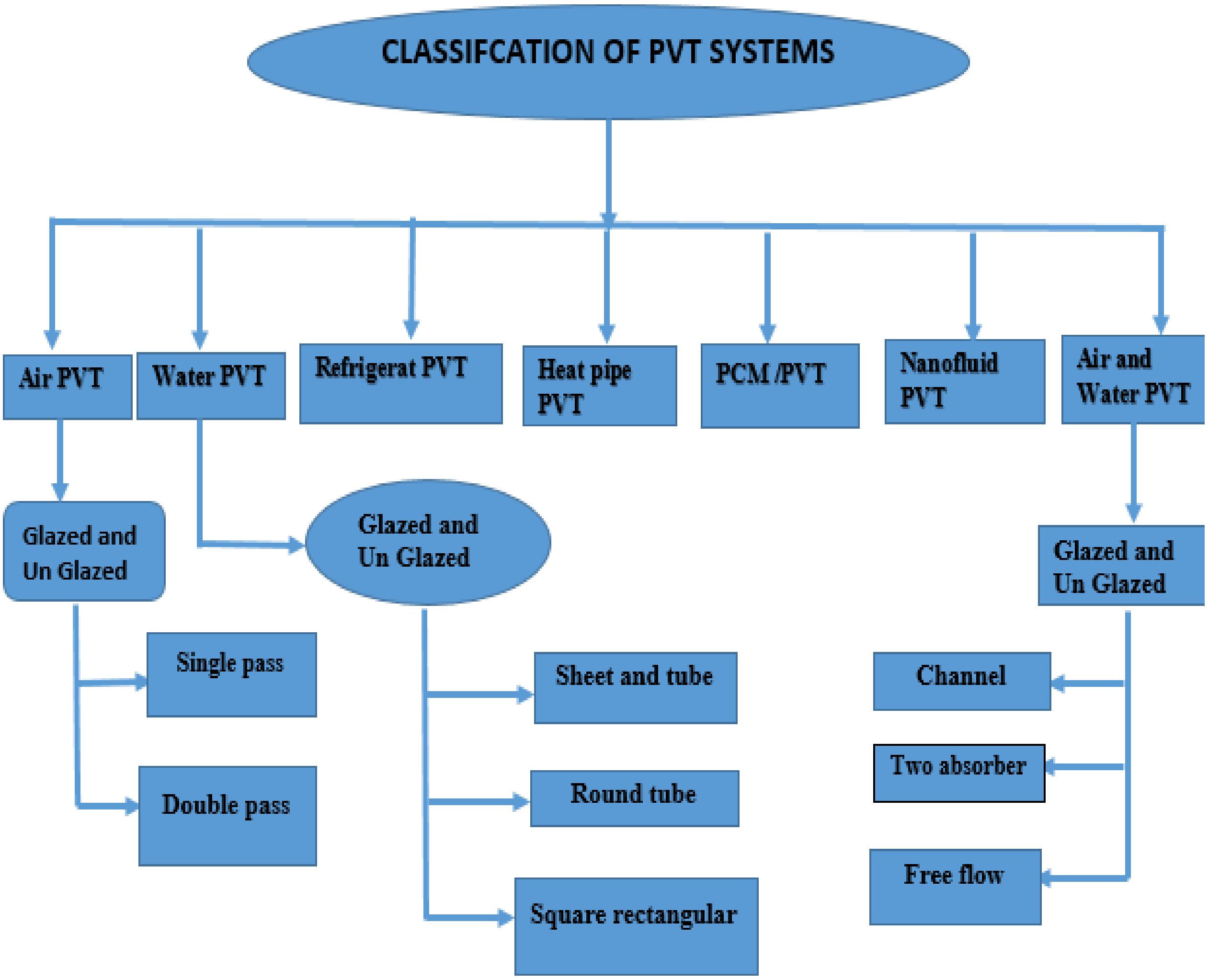


Fig. 4. Classification of PVT system

The system of the work by Martin [35] consists of the casing (C), solar cells (S), absorption (A), liquid (F), and the atmosphere. A suction device with a tube filled with liquid below the absorption sheet is considered, as shown in Figure 5. The results show that the solar cell efficiency is in the range of 9.5%–10.5%.

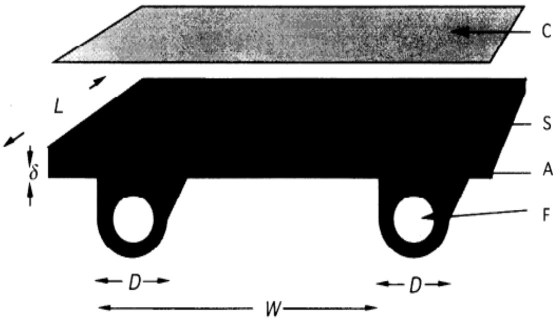
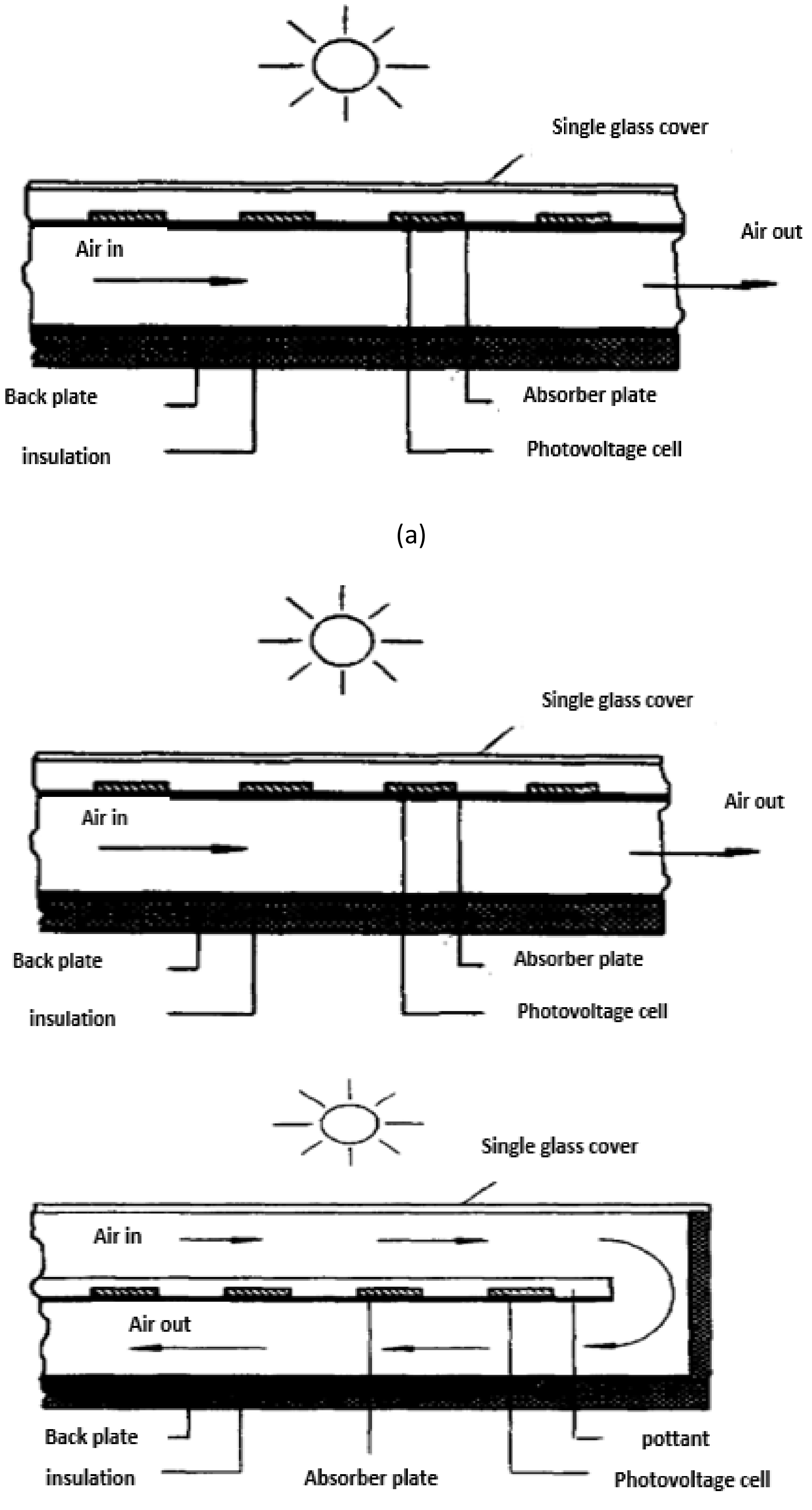


Fig. 5. Configuration of PVT hybrid system [35]

The performance of a PVT air collector was studied extensively by researchers, which was developed by Sopian *et al.*, [36] .The behavior of single- and double-pass was analysed under constant conditions. The results show that the double-pass PVT collector exhibits better behavior than the single-pass PVT collector, as shown in Figure 6.



(b)

Fig. 6. Configuration of (a) single pass and (b) double pass photovoltaic thermal solar collector [36]

Fujisawa *et al.*, [37] developed a PVT hybrid collector. The system consists of a flat solar collector heated with a monocrystalline solar cell on the substrate of a non-selective aluminum absorption plate, as shown in Figure 7. The results show the solar cell efficiency of 9.1%.

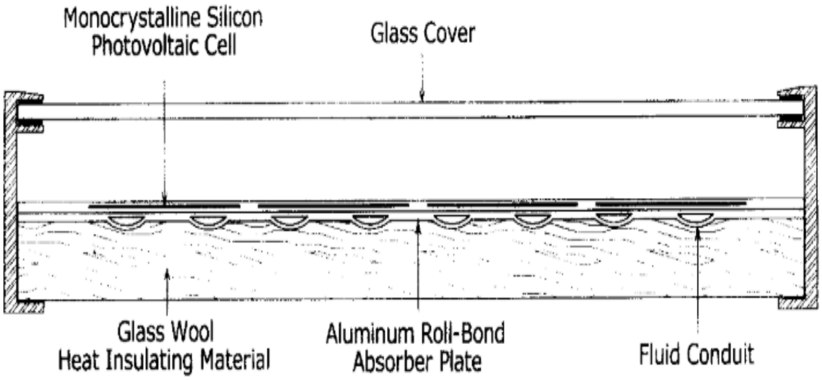
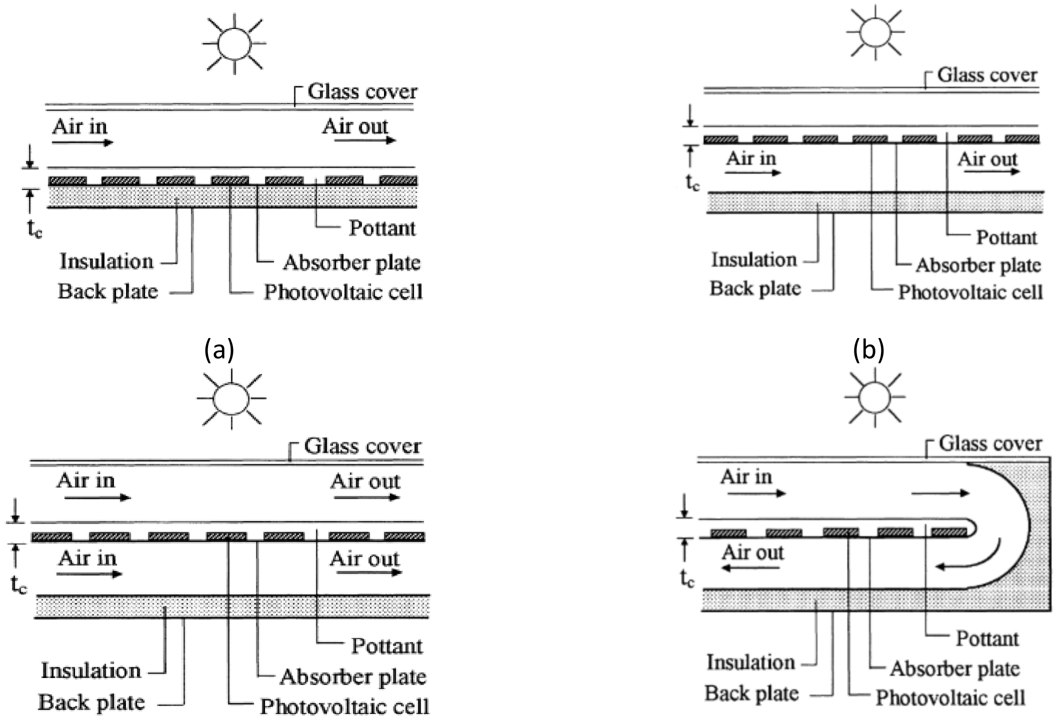


Fig. 7. Cross section of the PVT collector [37]

A comparative study for the performance of four PVT solar air collector models was conducted by Hegazy *et al.,* [38], as shown in Figure 8. For model A, air passes over the absorber, under the absorber for model B, and both sides of the absorber for model C, and model D used the double-pass method. The results show that model A of the PVT collector has the lowest overall performance, whereas model C has the highest overall performance, followed by model D and model B collectors.

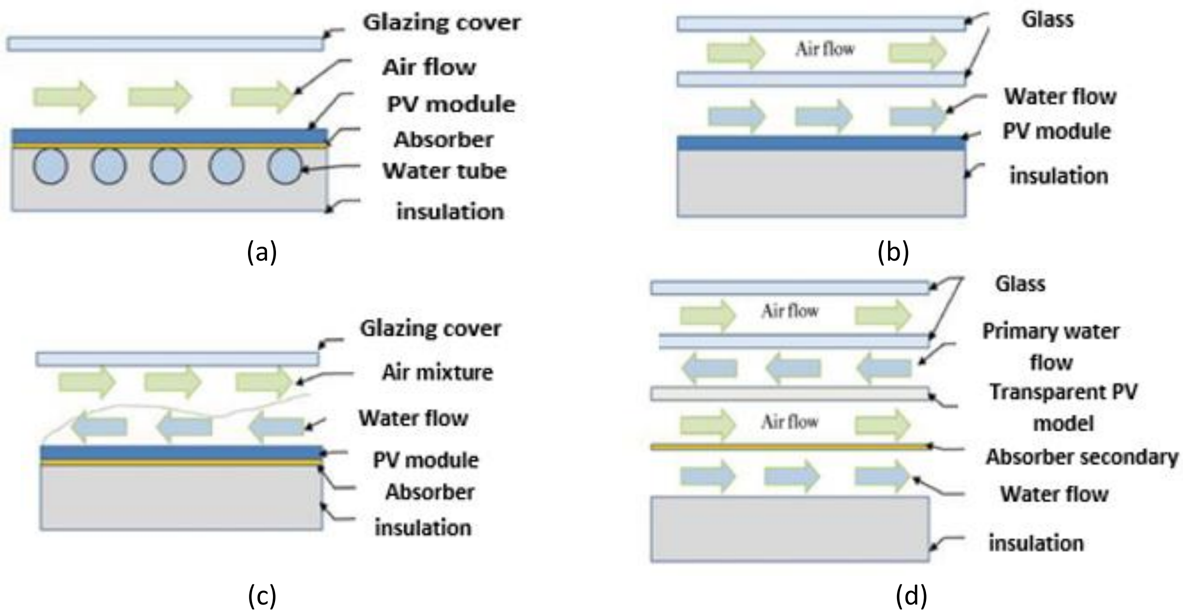


(a) (b)

(c) (d)

Fig. 8. Configuration of the various PVT models [38]

Four different design configurations of combined water and air PVT solar collector systems were developed by Zondag [39] .The design concepts can be divided into four different groups as shown in Figure 9, which are sheet and tube (A), channel (B), free flow (C), and two-absorber PVT (D) collectors, where 9 designs were evaluated for combined PV thermal collectors. From the results shown in Table 3 for thermal and electrical efficiencies, the channel below transparent PV design gives the best efficiency. Although the annual efficiency of the PV system for the sheet-and-tube design in the solar heating system is only 2%, it is easier to manufacture and this design is considered as a good alternative.



(a) (b)

(c) (d)

Fig. 9. Configuration of the various PVT system:(A) sheet- and- tube (B) channel,(C) free flow , (D) two-absorber (insulated type) [39]

Table 3
Thermal efficiency at zero reduced temperature with simulation production of electricity and corresponding electrical at zero reduced temperature for various PVT –collector design concepts [39]

Panel type	Thermal efficiency	Electrical efficiency
PV laminate	-	0.097
Sheet and tube PVT-Collector 0 cover	0.5	0.097
Sheet and tube PVT-Collector 1 cover	0.58	0.089
Sheet and tube PVT-Collector 2 cover	0.58	0.081
PVT-collector with channel above PV	0.65	0.084
PVT-collector with channel below opaque PV	0.60	0.090
PVT-collector with channel below transparent PV	0.63	0.090
Free flow PVT-collector	0.64	0.086
Two-absorber PVT-collector (insulated type)	0.66	0.085
	0.65	0.084
Thermal collector	0.83	-

A study on the performance of PVT solar water collectors was carried out by Dubey and Tiwari [40] .The system consists of a glass cover, a solar cell, tubes or flowing channels through the absorber, and also a fluid, as shown in Figure 10. The results show that the solar cell efficiency is in the range of 11.4%–11.6%.

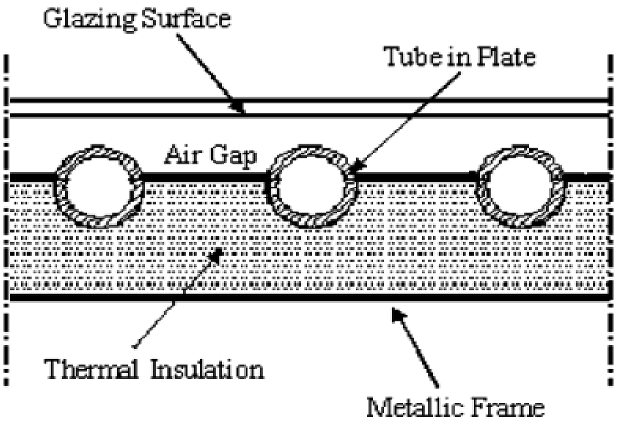


Fig. 10. Configuration of the PVT System [40]

The performance of PVT solar air collectors for three different flat-plate solar air heaters was evaluated by Alta *et al.*, [41] .Two of the systems have fins (b and c) and the other system is without fins (a), as shown in Figure 11. The results show that the heater with double-glass cover and fins (model b) is more effective, followed by model c and a.

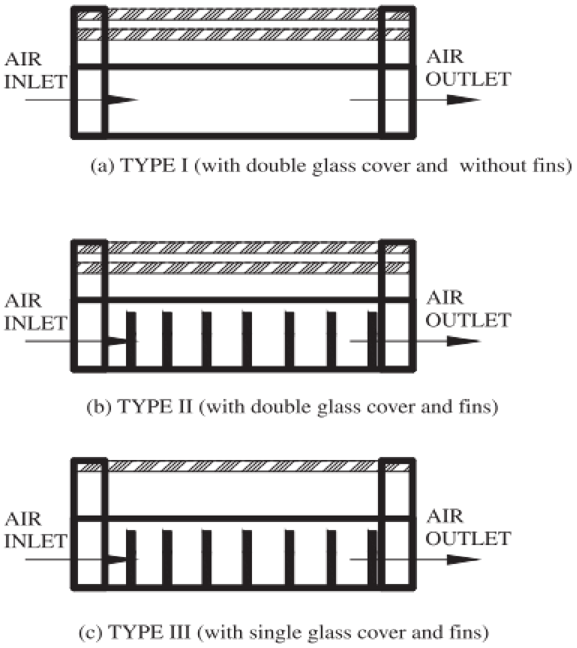
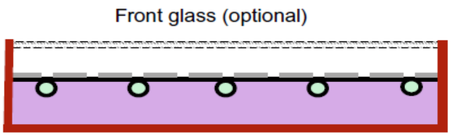
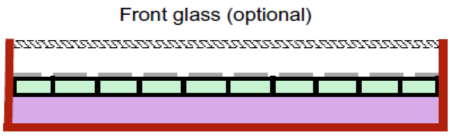


Fig. 11. Configuration of the various PVT models of (a),(b) and (c)[41]

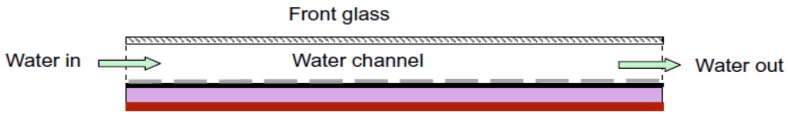
Chow [42] studied the performance of hybrid PVT water collectors with front glass, in which the design concepts can be divided into four different groups: sheet and tube (a), box channel (b), channel above PV unit (c), and channel below PV unit (d), as shown in Figure 12.



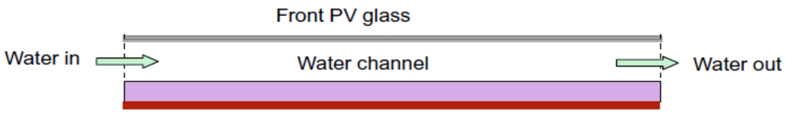
(a) Sheet-and-tube design



(b) box channel design



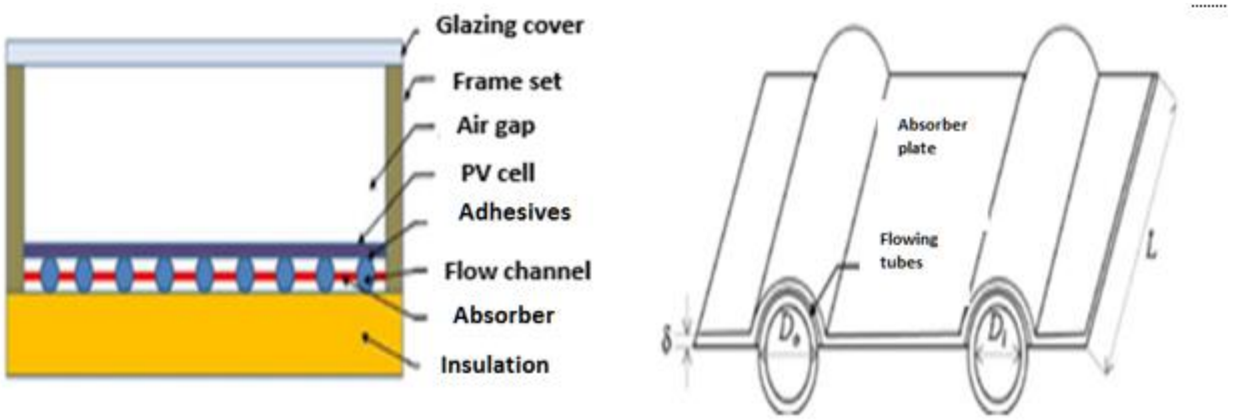
(c) Channel above PV design



(d) Channel below PV (transparent) design

Fig. 12. Configuration of the various PVT models [42]

Zhang *et al*., [43] studied the performance of PVT solar water collectors comprising several layers, namely from the top to bottom, a flat-plate thermally clear covering as the top layer, a layer of PV cells or a commercial PV lamination laid beneath the cover with a small air gap, tubes or flowing channels through the absorber and closely adhered to the PV cell layer, and also a thermally-insulated layer located right below the flow channels, as shown in Figures 13(a) and (b).



(a) (b)

Fig. 13. (a) Configuration of the PVT System (b) Schematic of flowing channels through the absorber [43]

The performance of hybrid heat pipe PVT water collectors was studied by Wu e*t al*., [44] The system consists of : (1) Solar PV modules, (2) solar PV panel, (3) thermal conductivity material, (4) heat pipe,(5) insulation material in evaporator section, (6) glass side seal, (7) glass cover, (8) insulation material in adiabatic section,(9) cooling (heated) fluid outlet pipe; (10) cooling (heated) fluid outlet header; (11) radial fins; (12) cooling (heated) fluid channel,(13) cooling (heated) fluid inlet header, and (14) cooling (heated) fluid inlet pipe and the heat pipe was made of copper as show in Figure 14. The results show that the overall thermal, electrical and exergy efficiencies of heat pipe PV/T hybrid system could reach up to 63.65%, 8.45% and 10.26%, respectively.

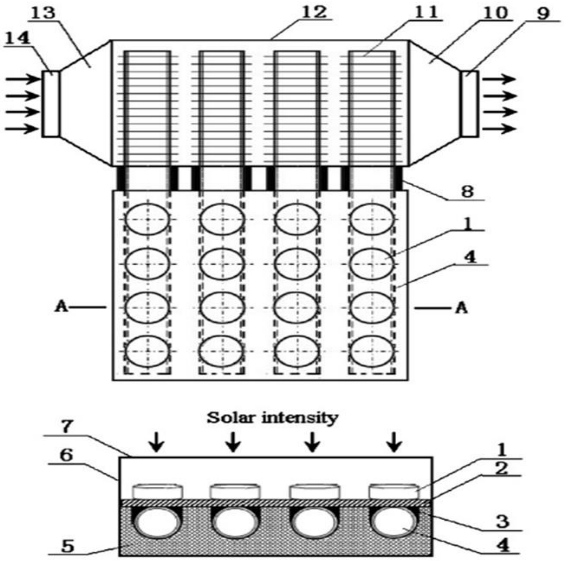


Fig. 14. Configuration of heat pipe PVT hybrid system [44]

The comparison of electrical and thermal performance of glazed and unglazed hybrid PVT water collectors was conducted by Kim and Kim [45]. Glazed PVT collectors, as shown in Figure 15, produced more heat but have slightly lower electrical yield. Meanwhile, unglazed PVT collectors, as shown in Figure 16, produced relatively less thermal energy but showed higher electrical performance.

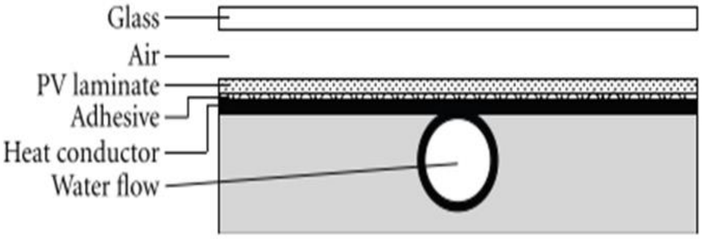


Fig. 15. Sectional view of a glazed PVT collector [45]

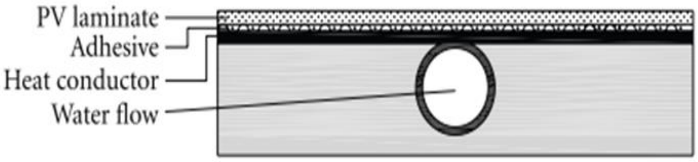


Fig. 16. Sectional view of an unglazed PVT collector [45]

A novel integration of a PVT flat-plate collector and heat pipes was designed and constructed by Gang *et al*., [46] , as shown in Figure 17. A dynamic model was developed to predict the performance of the heat pipe PVT (HP-PVT) system, and experiments were conducted to validate the simulation results. The results show that the average total first- and second-law efficiencies of the system in the test duration are 51.5% and 7.1%, respectively.

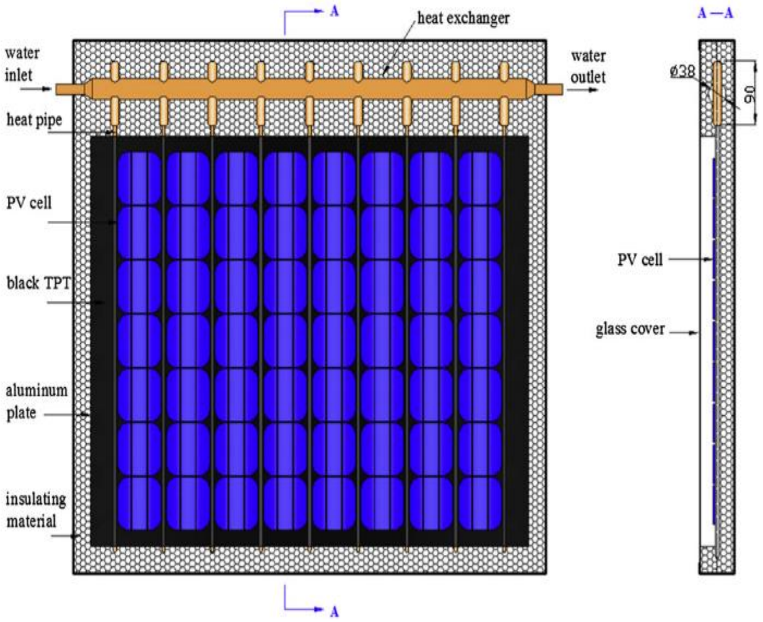


Fig. 17. The HP-PVT solar collector [46]

The implementation of heat transfer fluids in two common PVT water collector designs was investigated by Dupeyrat *et al.*, [28] , as shown in Figure 18 (a) and (b) for covered and uncovered PVT collectors, respectively. The system consists of: (1) laminated solar cells, (2) heat exchanger construction, (3) heat removal fluid, (4) a glass cover, (5) aluminum frames, (6) thermal insulation, and a (7) static air layer. The results show an additional glass cover gives a much better operating efficiency in the relevant reduced temperature range compared to non-covered collectors.

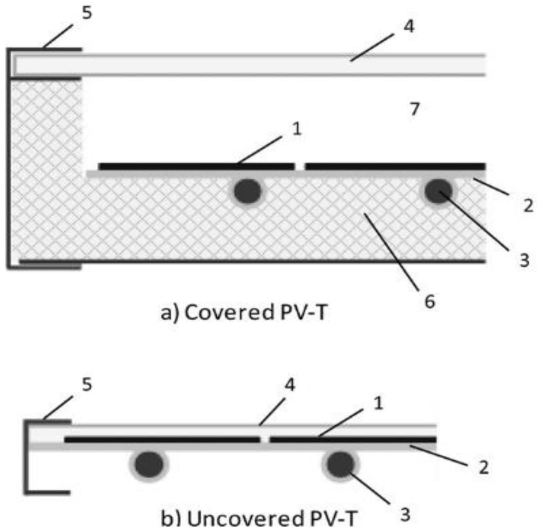


Fig. 18. Cross-sections of the two common PVT collector designs using water : (a) a covered and (b) a uncovered PVT collector[28]

A comparative study of the performance of five PVT solar air collector models was done by Shan *et al.*, [47] , as shown in Figure 19. Based on energy-balance equations, mathematical models for several PVT systems with different configurations were developed. The results show that the electrical and thermal performance is optimal in case b and case d, respectively.

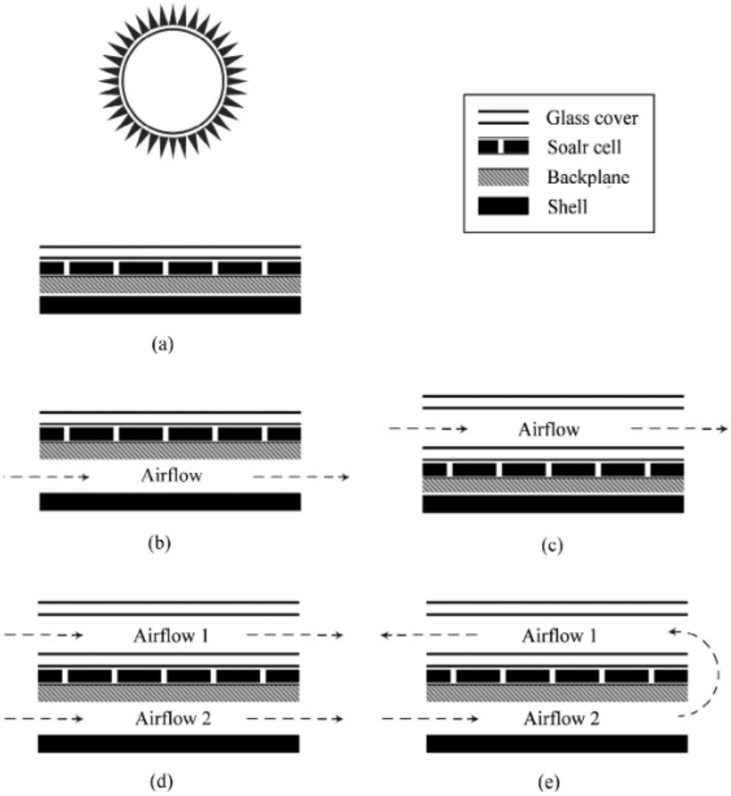


Fig. 19. Configuration of the various PVT models of a, b, c, d and f [47]

In recent years, PVT systems have used liquid as a heat transfer fluid more than air, and the most frequently used liquid is water. The cost of PVT maintenance is inexpensive for air, but PVT systems that use water as the working fluid have more stable thermal performance. Liquid-type PVT systems are more common because the systems have higher thermal power than air, as well as the highest general efficiency [48]. Herrando *et al*., [49] constructed a PVT system that consists of a PV covered section of hybrid PVT water collectors : (a) PVT collector cross-section. (b) PVT layers consists of: 1. Tempered glass (high transmittance), 2. EVA encapsulating film, 3.c-Si PV cells, 4. EVA encapsulating film, 5. Adhesive plus back-sheet Tedlar, 6. Aluminum absorber plate plus solar collector and 7. Insulating layer as shown in Figure 20. The results show that for a completely covered collector and at a flow rate of 20 L/h, 51% of the total electricity demand and 36% of the total hot water demand over a year can be achieved by the hybrid PVT system.

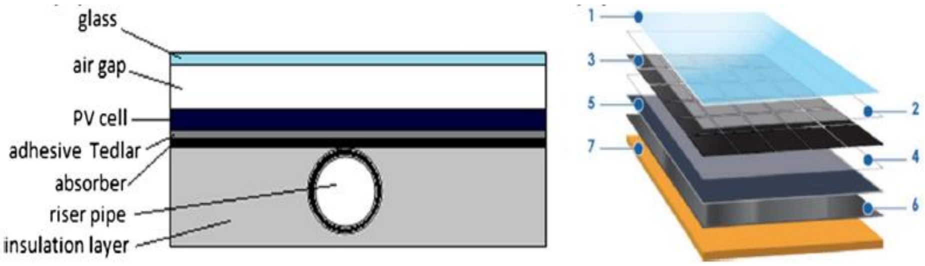


Fig. 20. Configuration of PVT hybrid system[49]

The effects of reflectors on day and night performance of a finned passive PVT system were numerically studied by Ziapour [50].The cross-section of the PVT system using reflectors is shown schematically in Figure 21. It consists of a glazed cover, a PV module, a flat-plate absorber, fins, an insulating box, a water storage tank, and two identical reflectors installed on the collector. The reflectors are two back insulating aluminum flat plates. The simulation results show that the reflectors reduced the night heat losses and increased the solar radiation rate on the absorber plate. The use of removable insulation reflectors saves extra thermal energy.

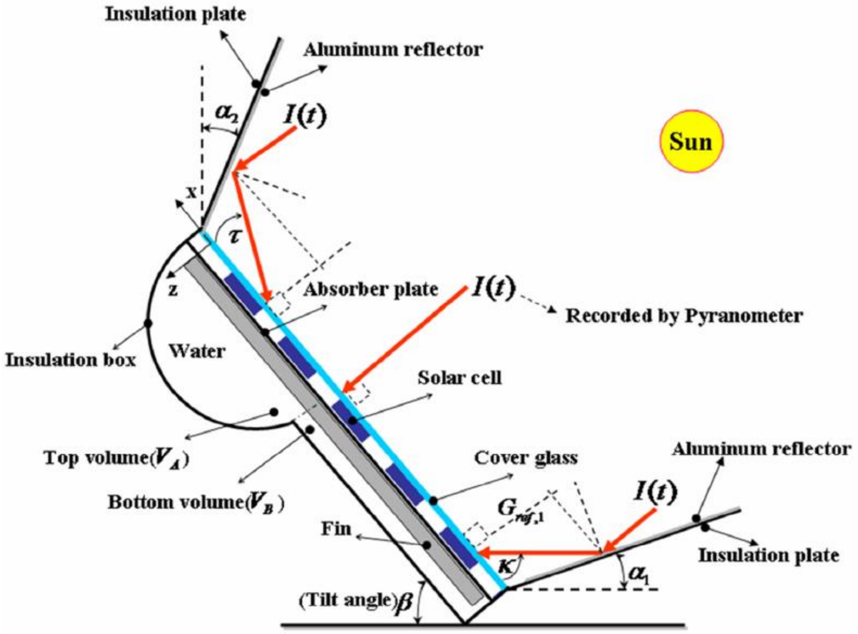


Fig. 21. Schematically presentation of the finned passive PVT system [50]

In a study, a hybrid PVT water collector was constructed by Liang *et al.*, [51]. The collector consists of a liquid, as well as sheet-and-tube connected in series, as shown in Figure 22. The water tubes are made of copper. The results show that the electricity efficiency (ηel) increased from 15.46% to 15.75% and T decreased from 32.92 to 22.68 °C when the mass flow rate increased from 0.1 to 0.5 kg/s.

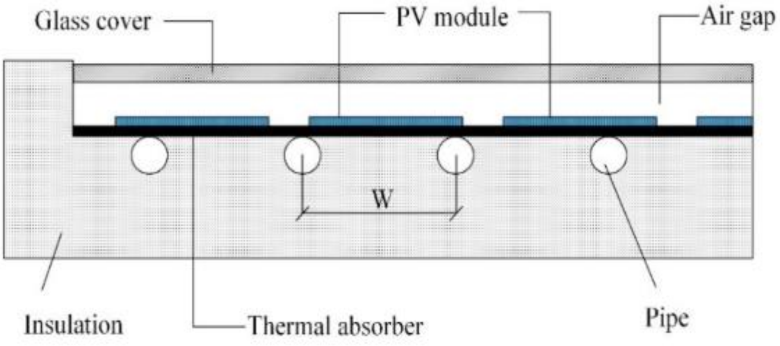


Fig. 22. Front view of sheet and tube hybrid photovoltaic thermal (PVT) water collectors [51]

Khan *et al.*, [52] constructed a hybrid PVT water collector for four types PCM, as shown in Figure 23. Flat-plate collectors are the most investigated solar heating collectors because these collectors operate in mid and low temperature range, and small industries and domestic applications more commonly utilise this technology. It is also easier, in terms of design, to manufacture the collectors and the resulting thermal efficiency is quite satisfactory. The results show that flat-plate solar air heaters with PCM have thermal efficiency of 22%–96%.

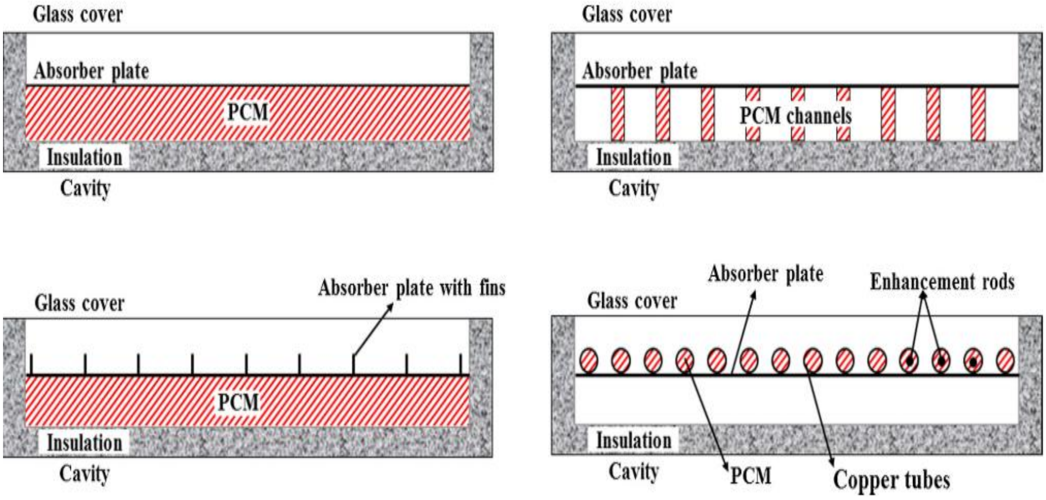


Fig. 23. Categorized concepts of solar air heating collector designs with PCM [52]

4. Beam Split PVT System (BSPVT)

In beam-splitting PVT (BSPVT) systems, the incoming solar radiations are split into two components: the useful and the undesirable radiations for photo electricity. The most commonly used solar cell materials are unable to convert the entire terrestrial solar spectrum into electricity. A solar cell responds to photons having energy equal to the band gap of the solar cell material. The photons with higher or lower energy than the band gap of the solar cell material cause losses in the PV system. Thus, it is strongly desirable to filter the incoming solar radiations by any means and to allow only the useful part of the solar spectrum to fall on the solar cell. This will reduce the operating temperature of the solar cell and thereby improves its electrical efficiency. Theoretical designs of such different filters viz. band pass filters, band stop filters, and edge filters were documented by Alagarsamy *et al*., [53].

Appels *et al*., [54] invented a high-concentration spectrum splitting solar collector with a new practical implementation of spectrum splitting for solar cells. The device has a prism-like body with a smaller device that absorbs less photons and increases the efficiency, as shown in Figure 24. The practical optical efficiency of the device was calculated using available materials, in which the calculated practical optical efficiency was 66%.

Imenes and Mills [55] published a paper in 2004 and reviewed the application of spectral beam splitting approach in PV applications. The scheme in Figure 25 represents an overview of the development of solar concentric beam splitting technology.

Mojiri *et al*., [56] presented a comprehensive review of the application of beam splitting in solar technology. Cost is the main obstacle in applying these systems for real applications. Many researchers are currently focusing on the development of a PVT system using selective liquids for spectral filtration and heat absorption. Selective liquid spectrum filters are an economical alternative to existing filters. Recent research on the use of liquids as spectral filters is discussed in the following text. Huang *et al*., [57] examined the performance of heterogeneous solar cells (organic solar cells, P3HT: PCBM) for PVT applications using spectral filtration techniques. The theoretical form of this investigation as shown in Figure 26. Researchers argue that the use of low bandgap polymers can improve this figure by up to 40%.

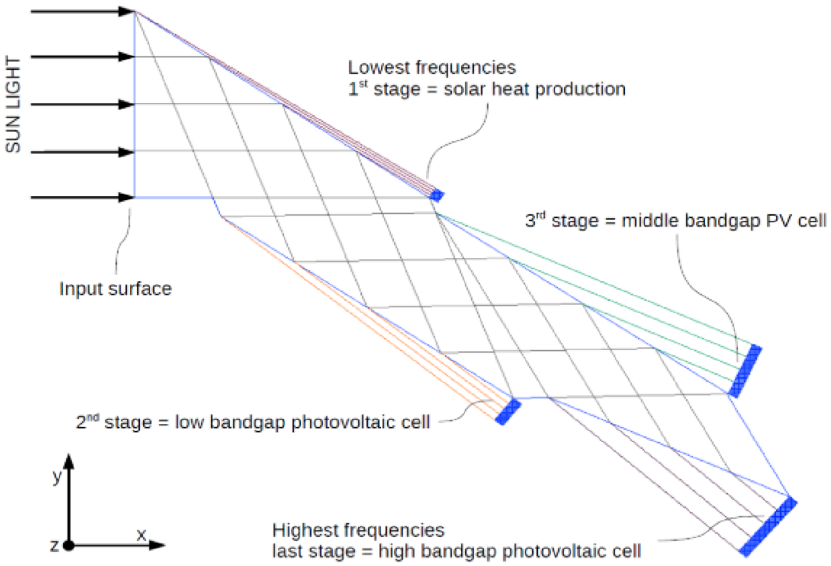


Fig. 24. Device splitting solar collector [54]

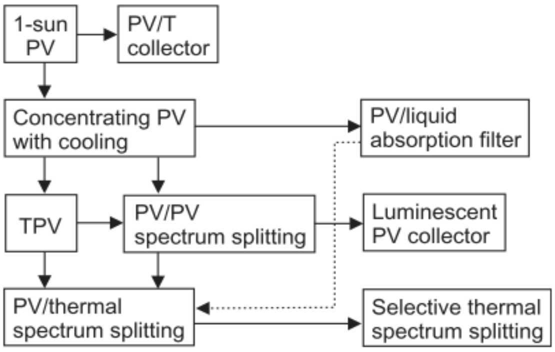


Fig. 25. An outline of the development of solar concentrating beam splitting systems[55]

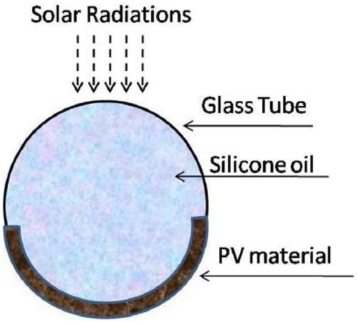
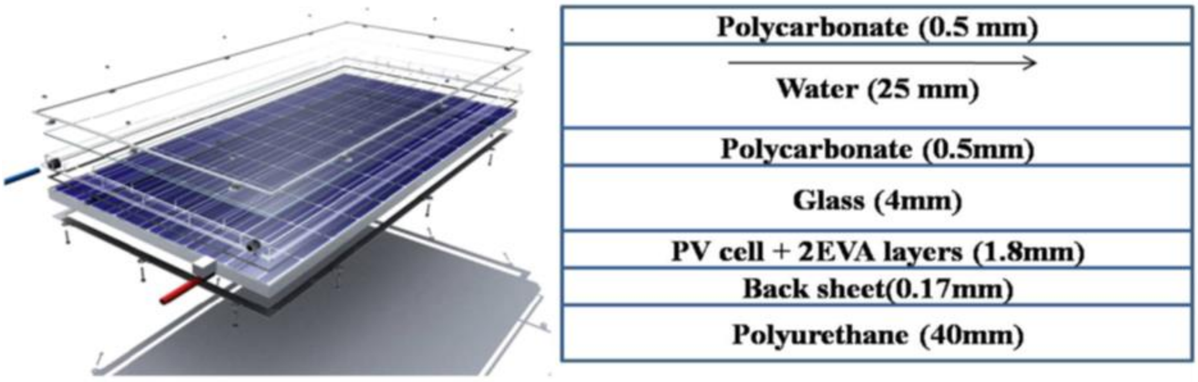


Fig. 26. Ray diagram in the tube with and without silicone oil [57]

Rosa-Clot *et al.*, [58] used water as a spectrophotometer for BSPVT. As shown in Figure 27, in one unit of the plate, a 25mm water layer is maintained on the PV module using a polycarbonate glass case.



(a) (b)

Fig. 27. TESPI system (a) packed unit (b) various layer [58]

Concentrating PVT system is described by Jiang *et al.*, [59], which contains a concentrator, a spectral beam splitting filter, an evacuated collector tube, and solar cell components, as shown in Figure 28. A non-dimensional optical model with the focal length of the concentrator as the characteristic length was developed to analyses the properties of the concentrating system using a beam splitting filter. It is shown that by using the filter, the heat load of the cell can be reduced by 20.7%, up to 10.5% of the total incident solar energy can be recovered by the receiver, and the overall optical efficiency in theory is approximately 0.764.

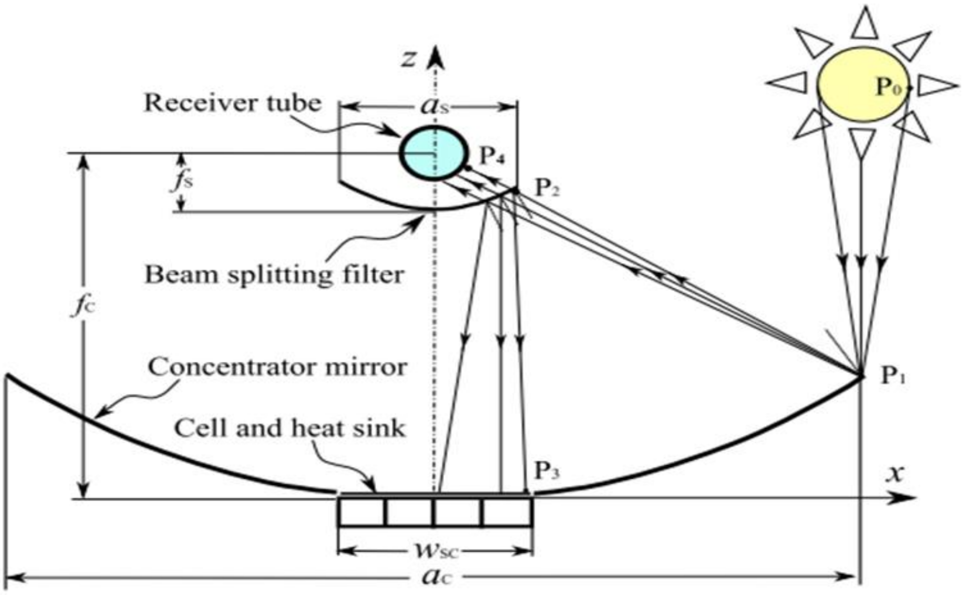


Fig. 28. Schematic diagram of the concentrating beam splitting solar system [59]

Several researchers for liquid-based BSPVT systems have reported different theoretical arguments. However, there is no trading system yet. Figure 29 presents another idea of a BSPVT system using a liquid spectrum filter studied by Joshi and Double [60]. Liquid-based BSPVT systems have not been commercialized yet. Focused research is required to bring BSPVT systems into reality.

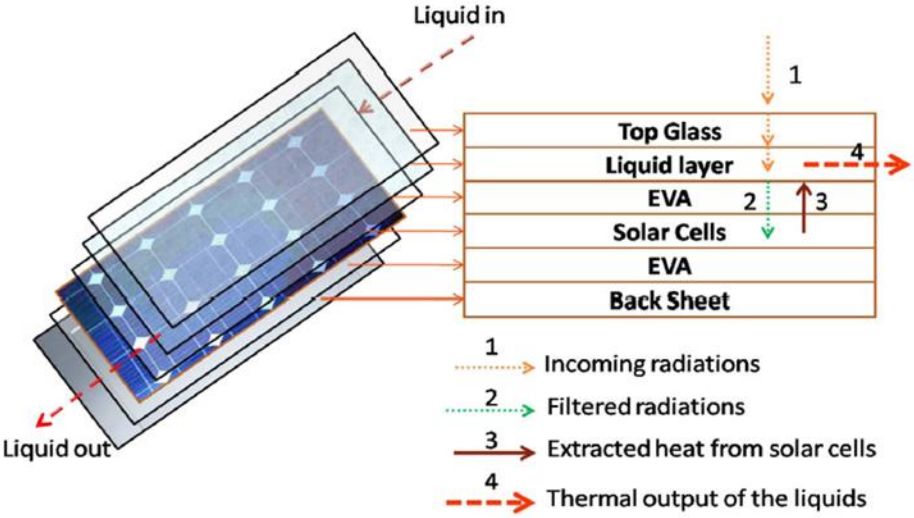


Fig. 29. Single laminated BSPVT system with liquid spectrum filters [60]

5.Development of Design of Flat Plate Water Collector in PVT System

Ibrahim *et al*., [61] constructed a hybrid PVT water collector with absorbers in the shape of round and rectangular hollow tubes placed precisely under a PV cell with a metallic bond, as shown in Figure 30. This would assure a zero gap or no gaps among the tubes and the cell, where heat transfer can be achieved accurately. The discussion of the results shows that the electric output of the hybrid PVT collector is significantly higher than that of a thermoelectric collector.

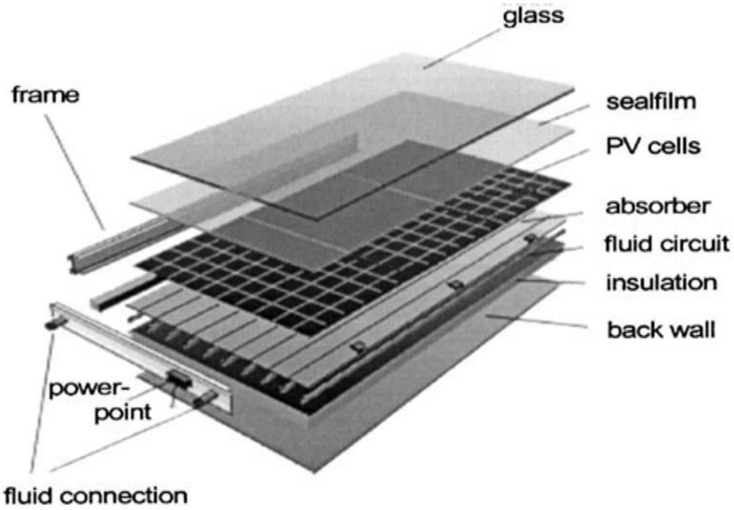


Fig. 30. Construction of the photovoltaic-hybrid collector PVT [61]

Many studies have also focused on different types of absorption designs, such as the study by Ibrahim *et al*., [62] The performance of PVT-based water collectors is determined by different combinations of absorption collectors, as shown in Figure 31. The results are shown in Figure 32 and 33 for the thermal and cell efficiencies of various absorber collectors, respectively.

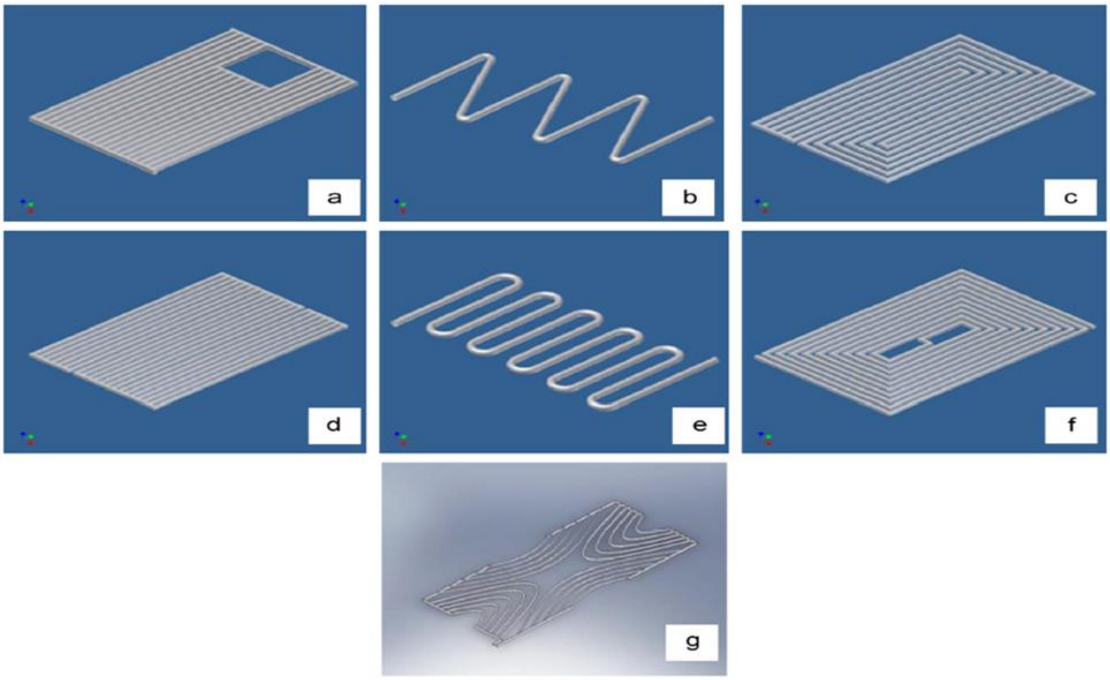


Fig. 31. (a)Direct flow design,(b)serpentine flow design,(c)parallel–serpentine flow design,(d)modified serpentine–parallel flow design,(e)oscillatory flow design,(f) spiral flow design,(g)web flow design [62]

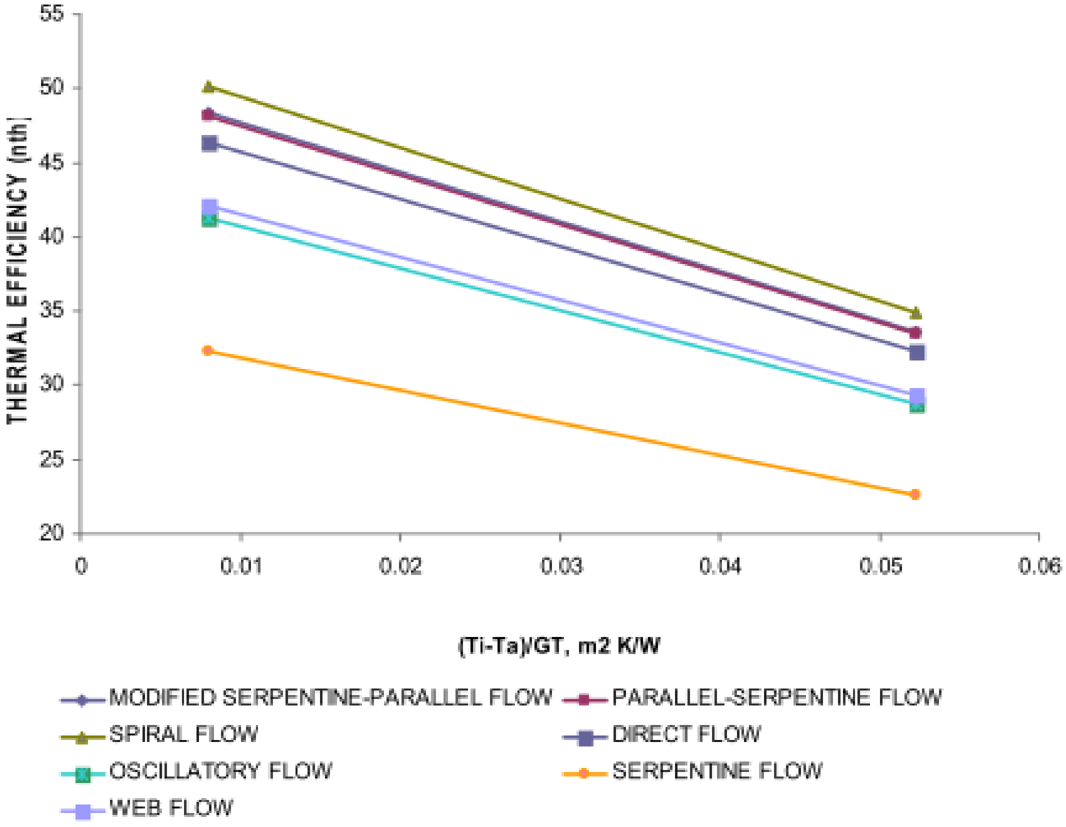


Fig. 32. Thermal efficiency of various absorber collectors [62]

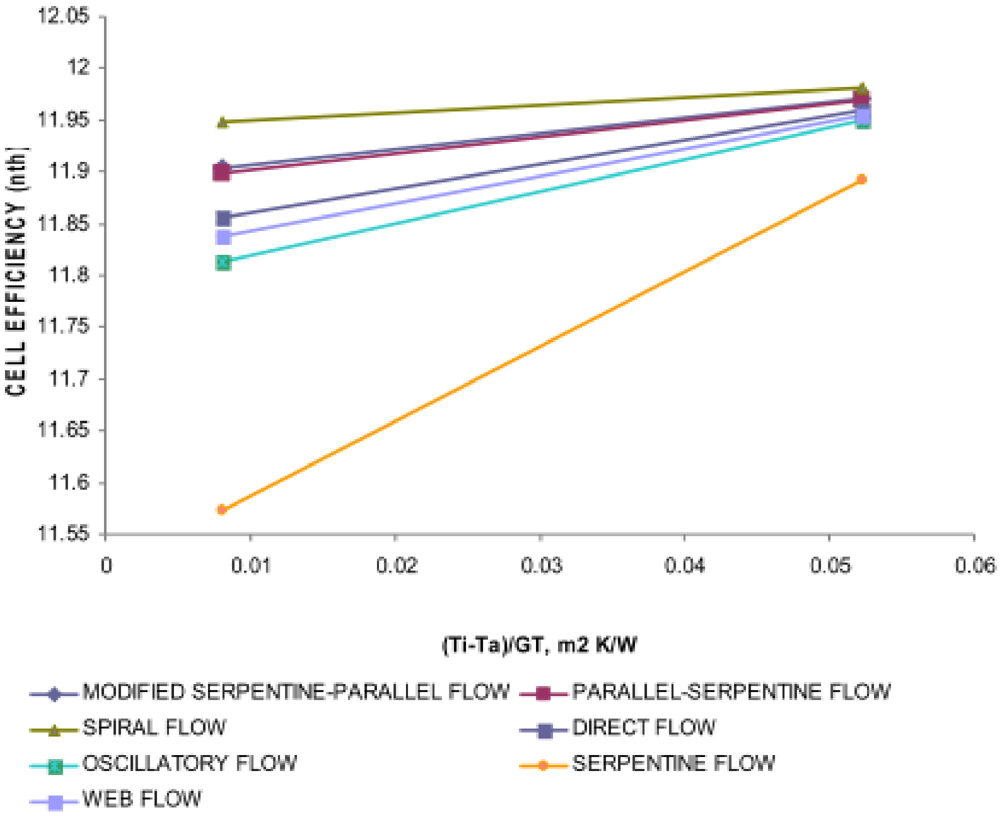


Fig. 33. Cell efficiency of various absorber collectors [62]

Two PVT collectors were designed and fabricated by Ibrahim *et al.*, [63] . The first designed collector has spiral flow and the second designed collector is a single-pass rectangular tunnel absorber, as shown in Figure 34 and 35, respectively. The results show that the spiral flow design is the best design with the highest thermal and cell efficiencies.

Three PVT water collectors were designed and compared in terms of thermal performance before fabricating into prototypes by Sopian *et al.*, [64]. The designed collectors have direct, parallel, and split flow, as shown in Figure 36, 37, and 38, respectively. The results show that the split flow design of PVT collector has better performance compared to direct and parallel flow.

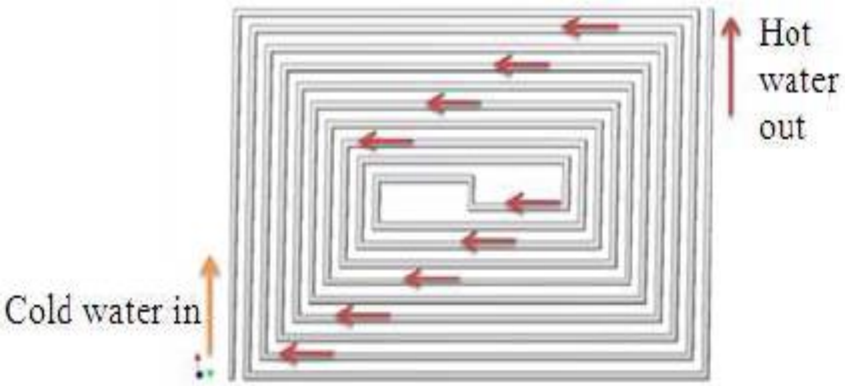


Fig. 34. The design of spiral flow absorber collectors [63]

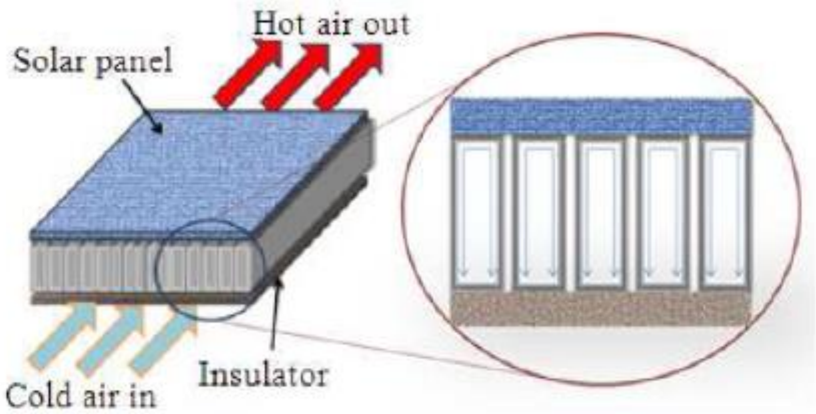


Fig. 35. The design single pass rectangular tunnel absorber collectors [63]

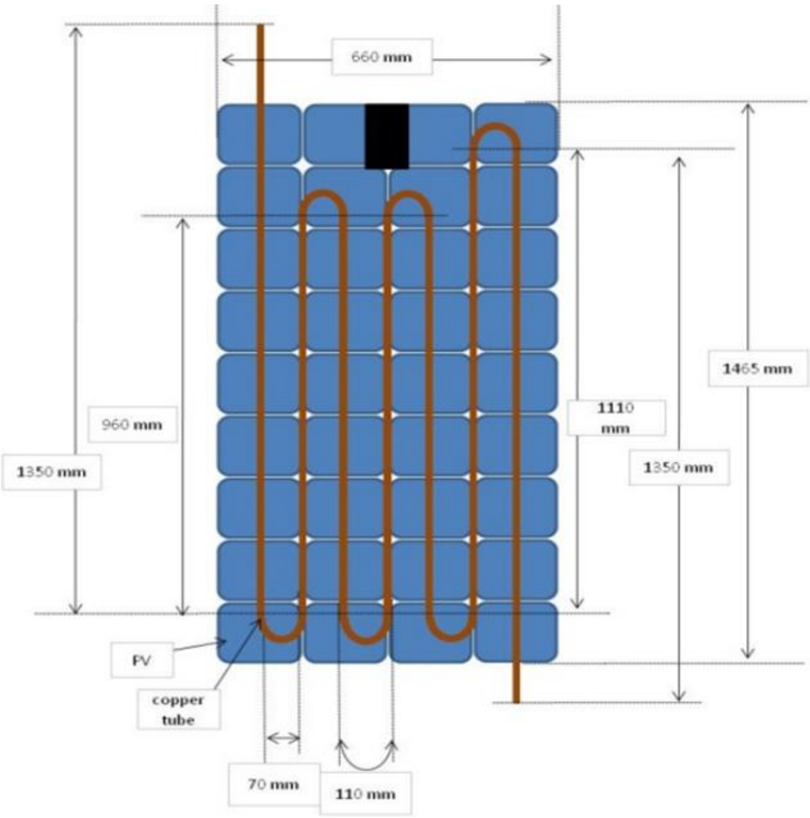


Fig. 36. Schematic of Direct flow PVT [64]

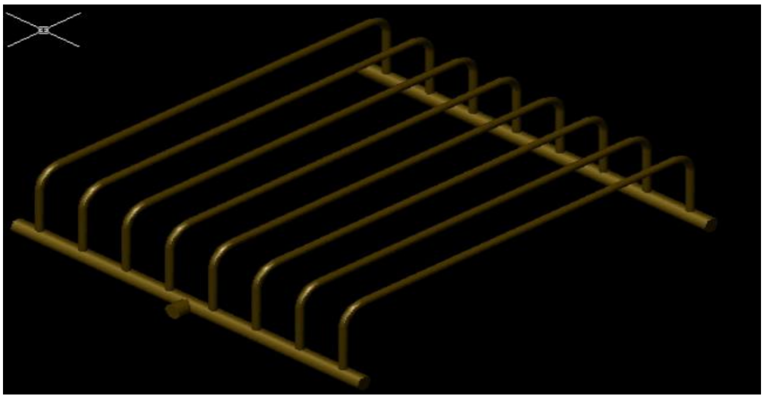


Fig. 37. 3D view of Parallel flow PVT [64]

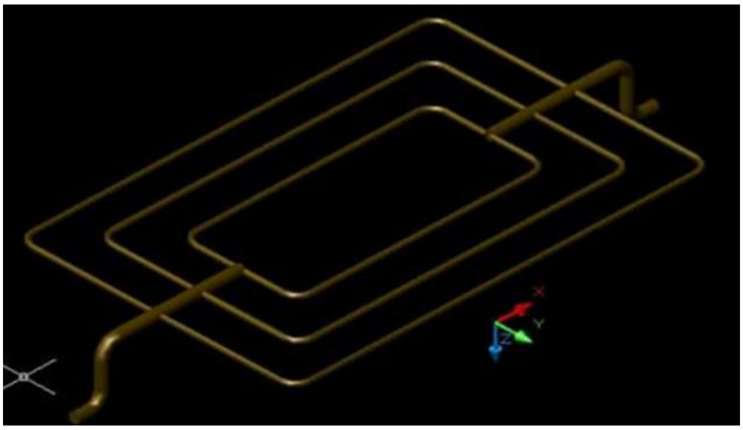


Fig. 38. 3D view of Split flow PVT [64]

A liquid-based PVT thermal collector is usually designed with a metal plate and a fluid channel absorber fitted to the back surface of a PV panel, as shown in Figure 39. The fluid passes through the parallel- and series-connected pipes to effectively transfer heat between the working liquid to the PV unit for reducing the temperature of the PV unit [65]. The test results indicated that the daily thermal efficiency could reach approximately 40% when the initial water temperature in the system is similar to the daily mean ambient temperature.

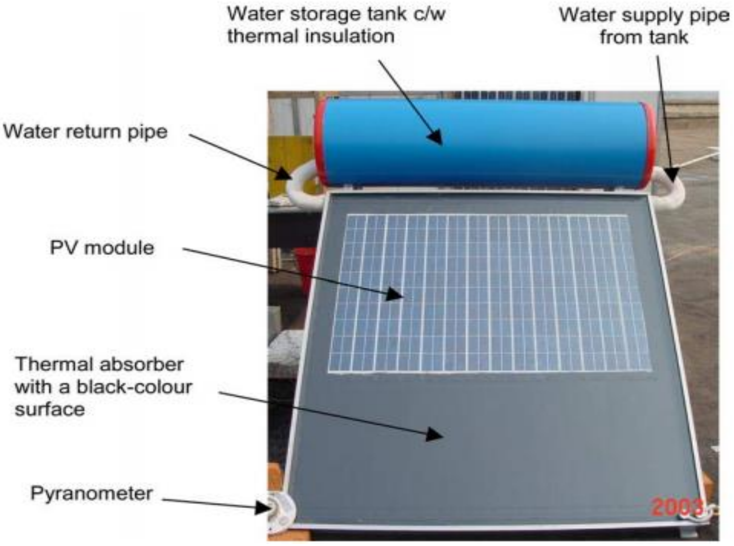


Fig. 39. System hybrid PVT water collector [65]

An accurate dynamic model was developed to investigate the performance of individual glass panels and pipe collectors. The front view of the water-heating PVT collector is shown in Figure 40. The study highlights the importance of establishing good thermal conductivity between absorption panels, water pipes, and solar cells [14].The results show that, the electricity efficiency (η_{el}) increases from 8.3 % to 8.9 %.

Modelling, validation, and simulation of the model by Ibrahim [66] are presented using theoretical data and comparative study of seven different absorber tubes, as shown in Figure 31. Simulation was performed to determine the best design that provides high total efficiency. The simulation results show that the best design is the spiral flow design with the highest thermal efficiency of 50.12%, with the corresponding cell efficiency of 14.98%. The variations of thermal and cell efficiencies for seven different absorber tubes for PVT collectors are shown in Figures 41 and 42, respectively. Modelling and validation of the model configurations of a serpentine absorber collector were carried out by Rosli *et al.*, [64] to determine the highest thermal efficiency of PVT.

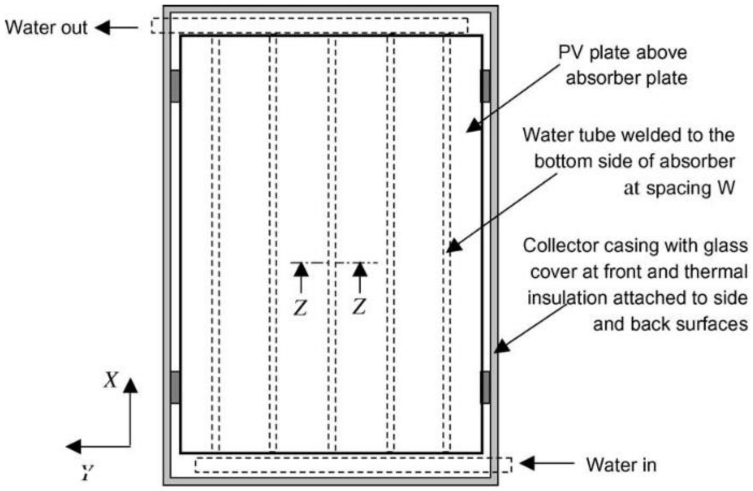


Fig. 40. Front view of PVT water collector [14]

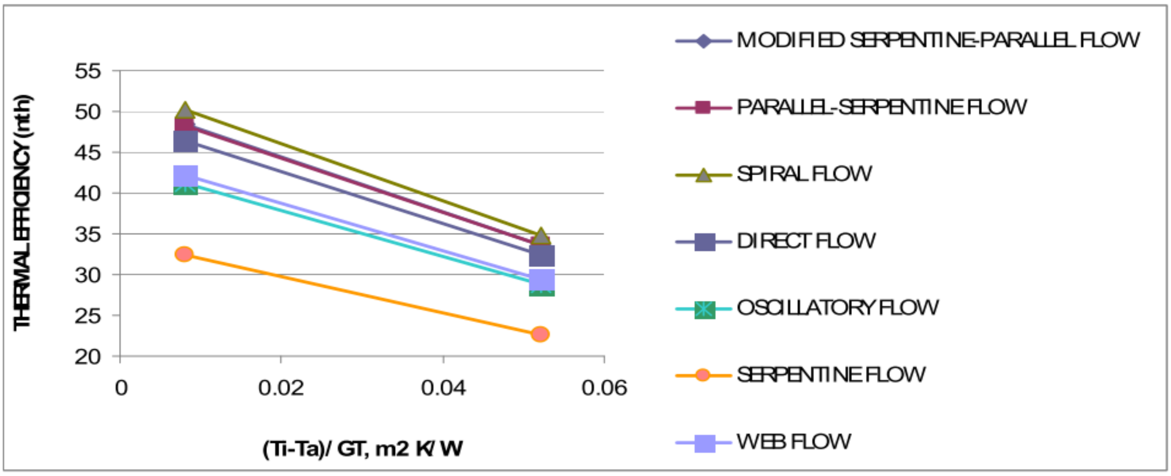


Fig. 41. Variation of thermal efficiency of various PVT water collectors [66]

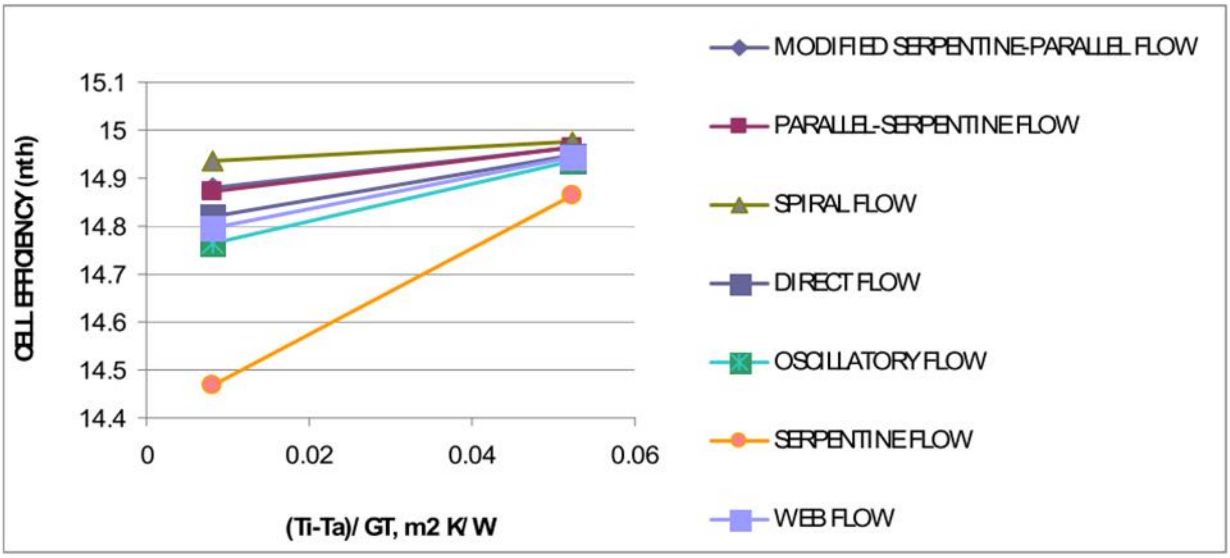


Fig. 42. Variation of cell efficiency of various PVT water collectors [66]

Modelling and validation of the model configurations of a serpentine absorber collector were carried out by Rosli *et al*., [67] to determine the highest thermal efficiency of PVT. The simulation was performed for four configurations of the serpentine tube. The results show that the best design achieved 50% of thermal efficiency at zero reduced temperature, as shown in Figure 43.

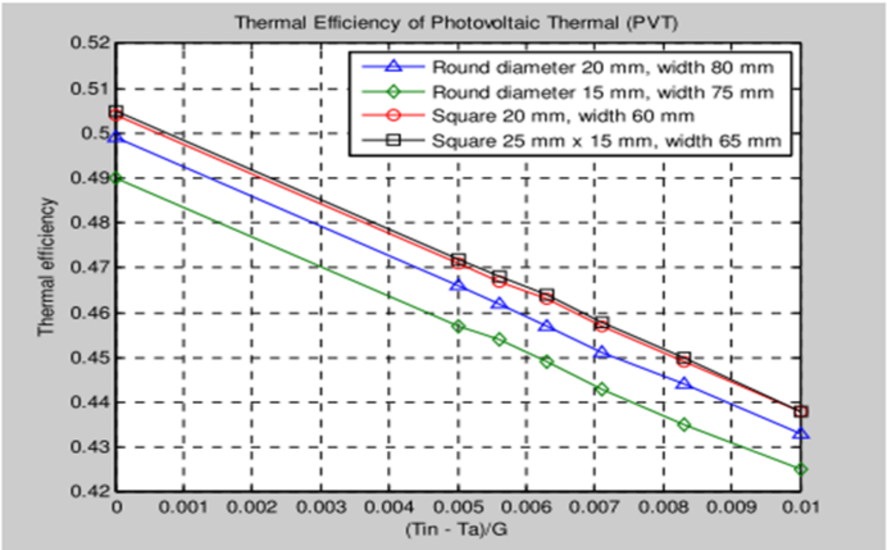


Fig. 43. Thermal efficiency of the PVT[67]

Fudholi *et al*., [68] evaluated the electrical and thermal performance of three designs of PVT water collectors, as shown in Figure 44. The results show that the thermal efficiencies for the web flow absorber, the direct flow absorber, and the spiral flow absorber are 48.07%, 54.13%, and 68.42%, respectively. Meanwhile, the PV efficiencies for the web flow absorber, the direct flow absorber, and the spiral flow absorber are 12.37%, 12.69%, and 13.81%, respectively.

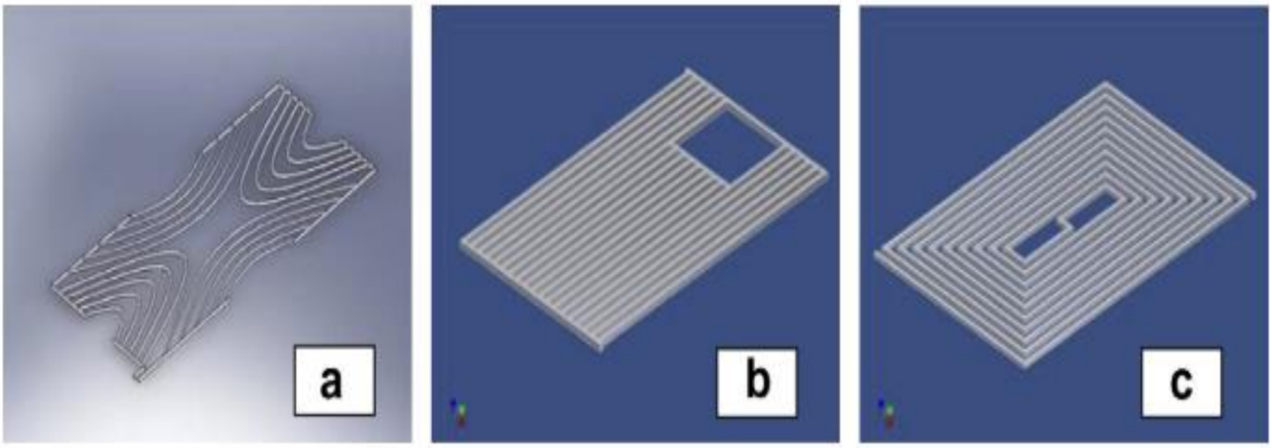
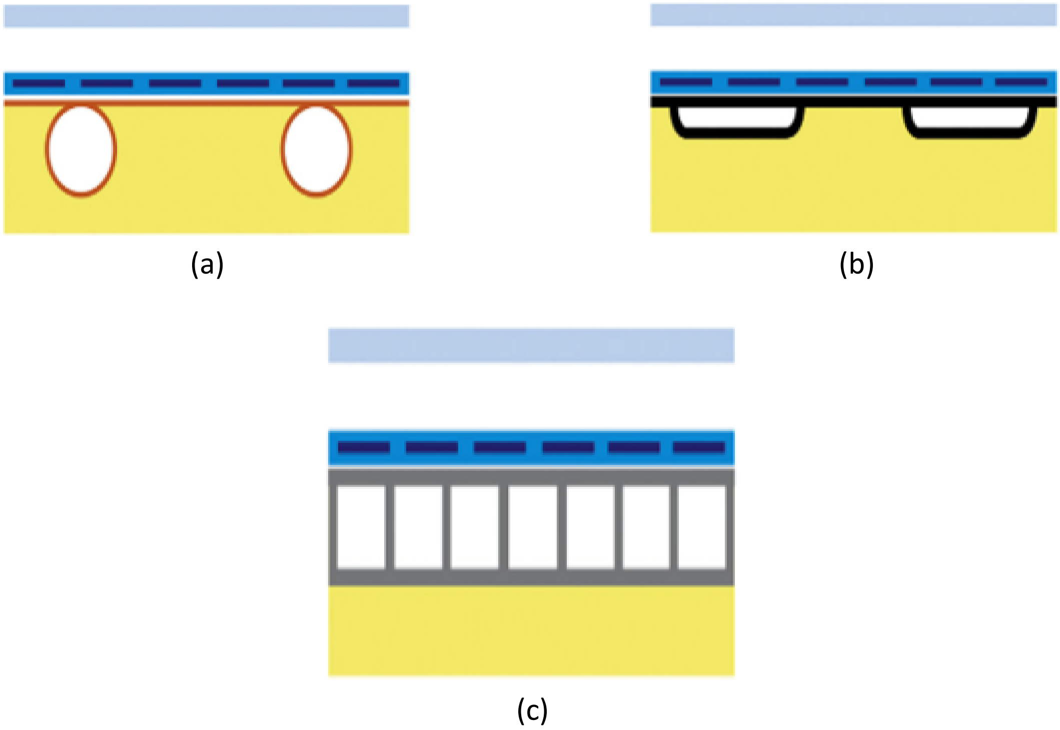


Fig. 44. (a) Web flow absorber (b) direct flow absorber and (c) spiral flow absorber [68]

Aste *et al*., [69] analysed the performance of flat-plate PVT water collectors with the most commonly used thermal absorbers. The thermal absorber designs can be classified into three groups: sheet-and-tube (A), roll-bond (B), and box channel (C) absorbers, as shown in Figure 45. The most commonly manufactured absorber is the sheet-and-tube type.



(a) (b)

(c)

Fig. 45. Thermal absorber classification (a)sheet and tube,(b) roll bond and (c) box channel [69]

Analytical calculation for heat removal factor (FR) on each design of PVT water collectors for four different designs was conducted by Rosli [70] . The designs consist of a square tube with 20 mm diameter (A), a round tube with 15 mm diameter (B), a rectangular hydraulic tube with 18.7 mm diameter (C), and a round tube with 20 mm diameter (D), as shown in Figure 46. The results show that design D has the highest heat removal factor, followed by designs B, C, and A.

Fig. 46. Serpentine collector absorber of a PVT system:(from left),(A) square tube with 20 mm diameter,(B) round tube with 15 mm diameter,(C) rectangle tube hydraulic with 18.7 mm diameter,(D) round tube with 20 mm diameter [70]

A study on the performance of PVT with rectangular tube absorber design placed under the PV was carried out by Shamani [71] ,as shown in Figure 47. The PV efficiency is between 10.35% and 11.5%, whereas the thermal efficiency is between 43.7% and 54.3%.

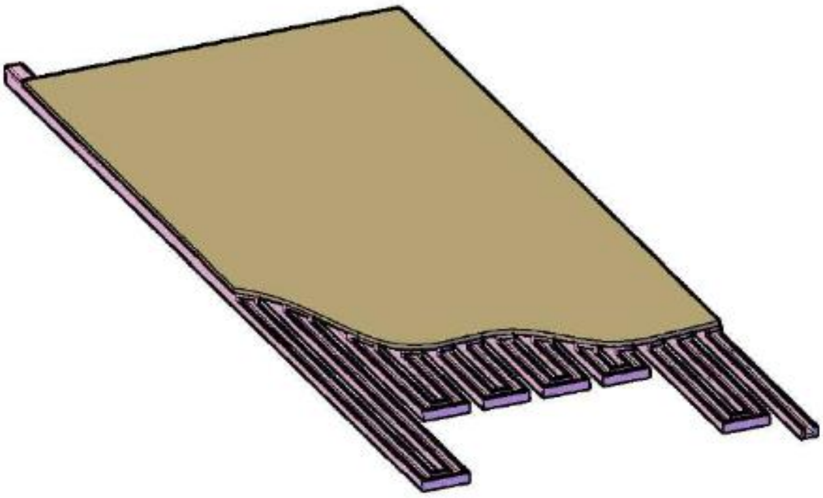
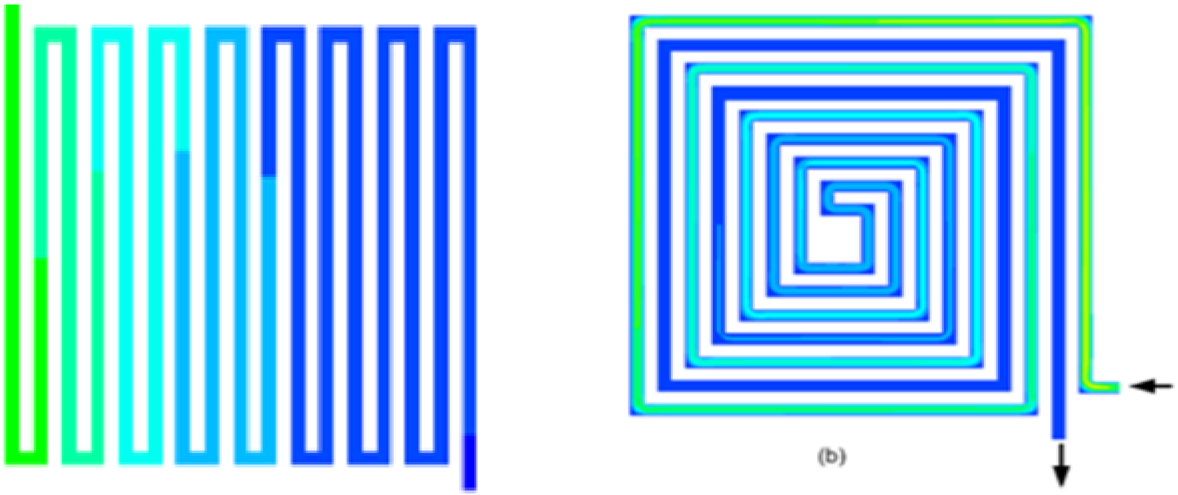


Fig. 47. The rectangular tube absorber collector of a PVT system [71]

A comprehensive numerical model for three-dimensional (3D) computational fluid dynamics (CFD) was developed by Said *et al.*, [72]. Using Fluent 14.5. The proposed study was performed to evaluate the performance of a cell with serpentine and helical flow channels, as described in Figures 48 (a) and (b). The model was verified using one of the experimental results available in previous studies. The results show a good agreement for the comparison between the numerical model and the reported experimental data. Furthermore, the pressure distribution for the serpentine channel design is higher than the pressure distribution for the helical channel design due to higher velocity distribution values at the helical channel.



(a) (b)

Fig. 48. (a) Serpentine, (b)Helical water Absorber design for PVT Collector [72]

The 3D dimension of the hybrid PVT water collector in the CFD program was performed by Shamani [73]. The simultaneous use of new ellipse design of absorber as shown in Figure 49. The results shown that new ellipse absorber collector generates a combined PVT efficiency of 74.3% with electrical efficiency of 13.78%.

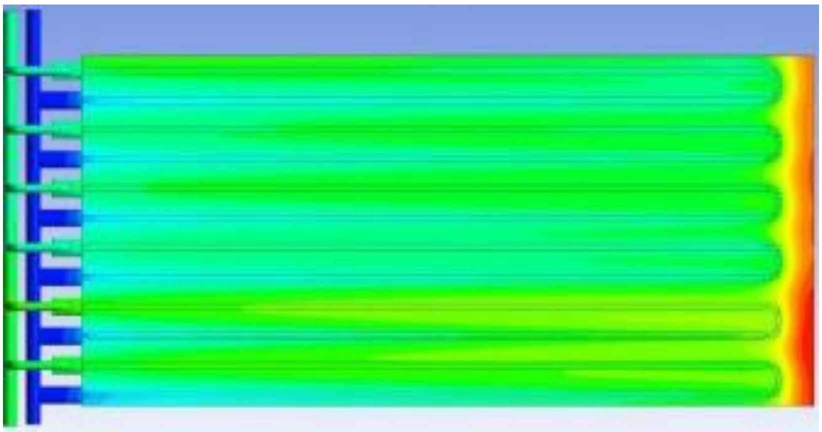


Fig. 49. New Ellipse Absorber Design for PVT Collector[73]

Three different absorber tubes were designed by Rosli [74] , which are serpentine, U-flow, and spiral designs, as shown in Figures 50, 51, and 52, respectively. The results show that the spiral absorber achieved 47.2 °C temperature difference, and followed by the U-flow and serpentine absorbers with temperature difference of 46.51 and 45.74 °C, respectively. In addition, the spiral absorber has the highest thermal efficiency of 19.74% at 0.0005 kg/s, followed by the U-flow and serpentine absorbers with thermal efficiency of 19.45% and 19.13%, respectively. At 0.005 kg/s, the spiral absorber has the highest thermal efficiency (22.96%), followed by the serpentine and U-flow absorbers (22.62% and 21.02%, respectively).

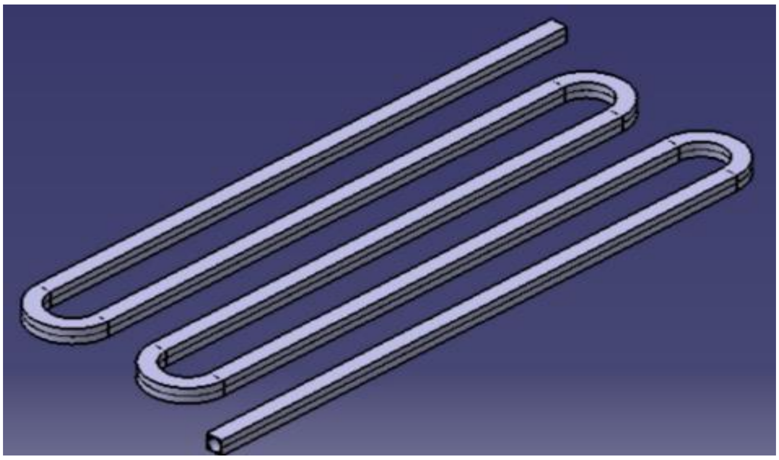


Fig. 50. Serpentine water absorber design [74]

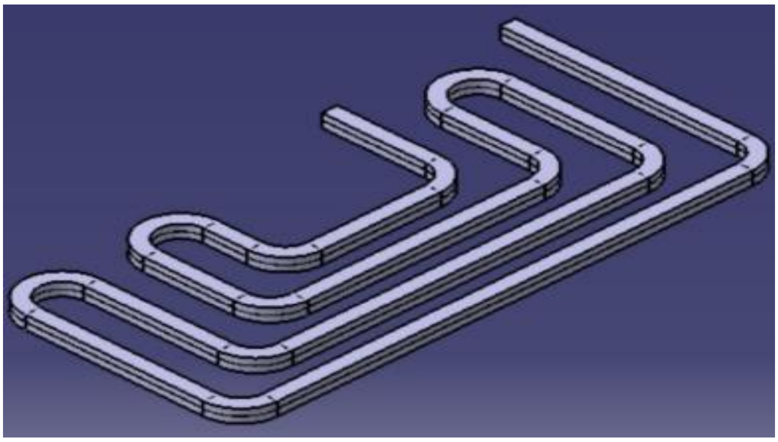


Fig. 51. U-flow water absorber design [74]

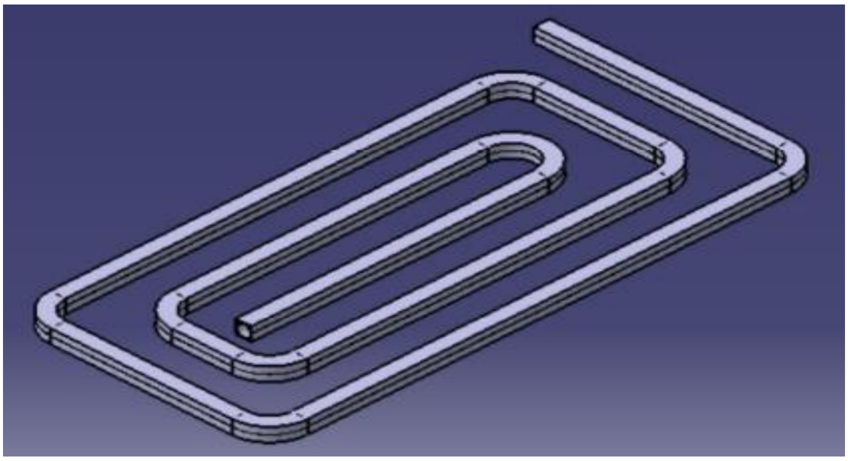


Fig. 52. Spiral water absorber design [74]

Modelling, validation, and simulation of a model were carried out by Sachit [75] using theoretical data by utilising MATLAB programme and conducted a comparative study between two different absorber tubes: a new design (serpin-direct) and serpentine flow design, as shown in Figures 53 and 54, respectively. The results indicate that the serpin-direct PVT design achieved 53% and 14.3% of thermal and electrical efficiencies, respectively, at optimum conditions of 900 W/m2 of solar radiation and 0.06 kg/s of mass flow rate**.**

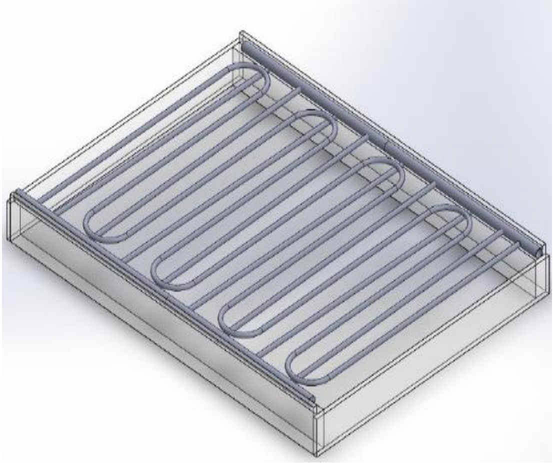


Fig. 53. Serpin- Direct Design of PVT [75]

Fig. 54. Serpentine Flow Design of PVT [75]

Two hybrid PVT designs were investigated by Al-Musawi [76] . The first system is a PV unit with copper sheet and tubes (serpentine tube) as the thermal collector (PVT module), as shown in Figure 54(a). The second system is a pure traditional unit without an external cooling system (PV module), as shown in Figure 55(b). The results show that for the first system, the electrical and thermal efficiencies are 10% and 25%, respectively.

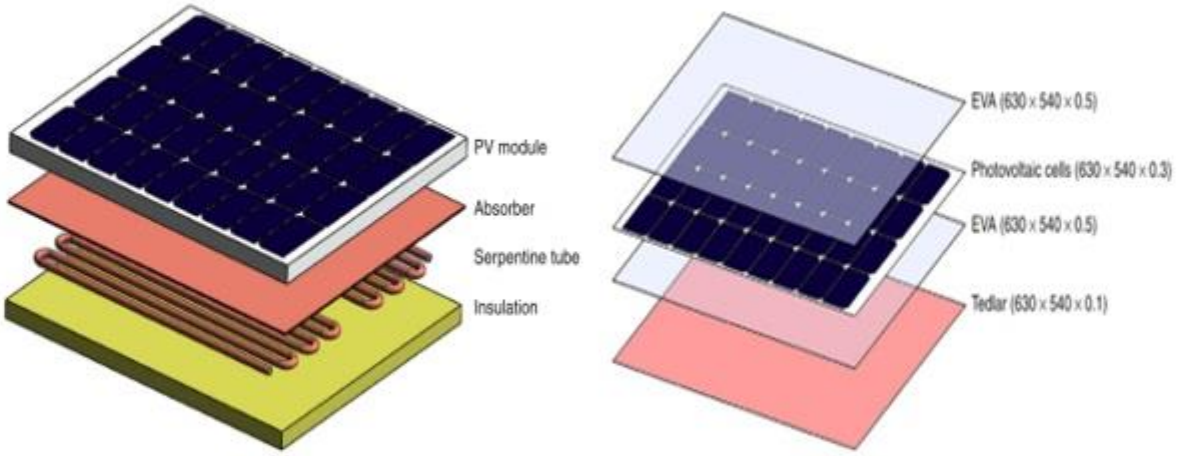


Fig. 55. (a) Serpentine Flow Design of PVT (b) Construction of PV module [76]

Jia *et al.,* [77] compared different thermal absorbers for liquid PVT systems, as shown in Table 3.

Table 3
Comparison of different types of liquid PVT systems

Thermal absorber	Advantages	Disadvantages	Performance optimization
Sheet –and- tube PVT collector	Advanced and mature technology	Weak electrical efficiency	suitable number of top covers
Channel - PVT collector	Higher- thermal efficiency	1. The structure is heavy but fragile 2. Limited choices for working fluid	Use transparent PV panels and reduce costs of transparent material
Free flow- PVT collector	1. Low reflection and cost of materials 2. The structure of the machine is better	1. Instability at rise temperatures 2. big heat loss due to evaporation	suitable working fluid
Two–absorber-PVT collector	1.best mechanical construction 2. Higher thermal efficiency	Heavy but crisp construction	Add a transparent buffer layer between the primary and secondary channels

Nine different designs were evaluated by Zondag *et al.*, [39] . The results show that the sheet-and-tube design with zero cover is the best design to improve electrical efficiency. The thermal efficiency for the uncovered collector is 52%, whereas the thermal efficiency of the single-cover sheet-and-tube design is 58%. Meanwhile, the design with the channel above PV typically has 65% thermal efficiency, as shown in Figures 56 and 57, respectively.

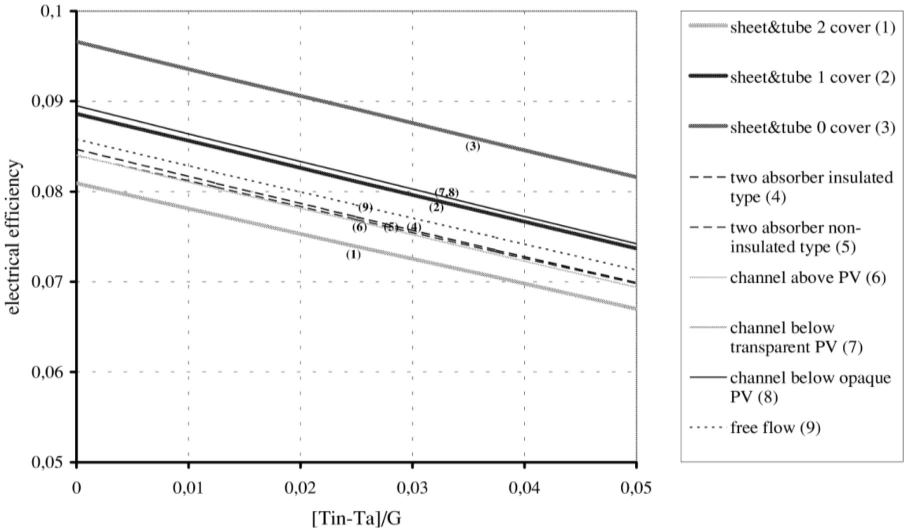


Fig. 56. Variation of Electrical efficiency for various PVT water systems [39]

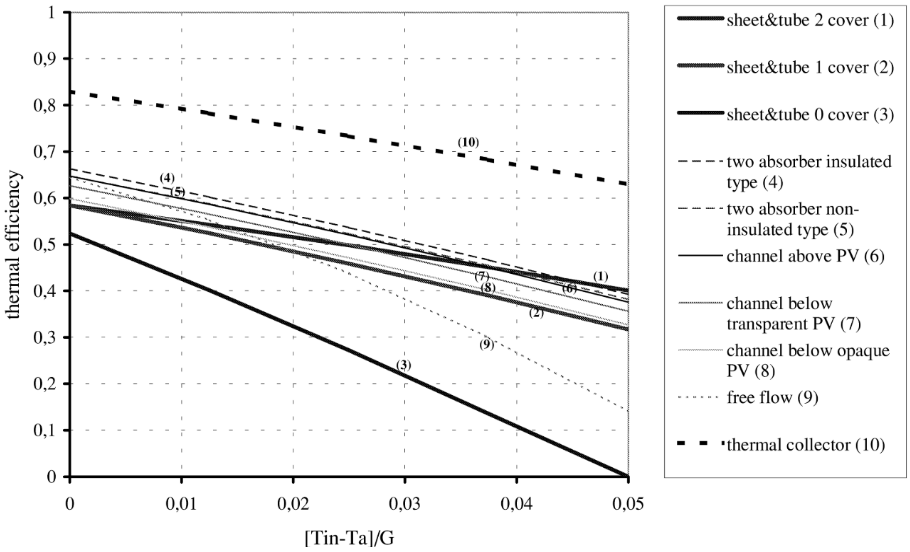


Fig. 57. Variation of Thermal efficiency for various PVT water system [39]

4. Conclusions

A number of experimental, theoretical, and review articles covering various aspects of research and development of PVT systems have been published in the literature for decades. Figure 4 shows the general category of this hybrid PVT system in current research. This work provides a comprehensive review on the development of PVT systems. The performance of PVT-based water collectors is determined based on different combinations of absorption collectors compared to other types of energy. From the literature, a number of absorber design elements have been developed, and analytically and experimentally evaluated to help improve PVT system performance, in which the sheet-and-tube absorber plate is commonly used due to its manufacturing simplicity. From the perspective of absorber design, two main elements, namely (1) water flow tube and channel configuration and (2) glazing in covered or uncovered modes, have been developed. Certain types of spiral absorber design have also achieved the highest known performance as reported in the literature, although the manufacturing cost has not been elaborated. The thermal efficiency of unglazed PVT collectors is low due to loss of heat from the top surface, but this type of collector achieved a good electrical efficiency. The above-mentioned discussions prove that absorber design, particularly its thermal and electrical efficiencies, is an important factor for PVT system performance. PVT technology can be improved through

i. Precise mathematical models.
ii. Research and development of novel materials.
iii. Improvement of the stability of a PVT system.
iv. The design of a subsidised energy storage system.

PVT technology combines the advantages of individual devices into a single system that provides water and electricity simultaneously and improves the efficiency of PV cells with heat removal. The market potential is expected to greatly increase in the effort to deal with future environmental problems.

Acknowledgement

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