An extensive review on the latest developments of using oscillating heat pipe on cooling of photovoltaic thermal system

Mahyar Kargaran[1], Hamid Reza Goshayeshi[1,*], Hadi Pourpasha[2], Issa Chaer[3], Saeed Zeinali Heris[2,*]

[1]Department of Mechanical Engineering, Azad University, Mashhad Branch, Mashhad, Iran

[2]Faculty of Chemical and Petroleum Engineering, University of Tabriz, Tabriz, Iran

[3] Centre for Civil and Building Services Engineering, School of the Built Environment and Architecture, London South Bank University, London, SE1 0AA UK

Abstract

Photovoltaic -thermal (PV-T) panel is one of the major solar energy sources applied to convert the solar radiation into electrical power directly. This type of panel is considered a viable solution to guarantee energy security and to reduce greenhouse gases. On the other hand, the efficiency of PV-T modules diminishes when the temperature of module rises leading to degradation in the conversion efficiency along with the life span of a photovoltaic cell. Applying cooling techniques will lead to the decrease of the excess heat which is generated and to make life span longer simultaneously. Higher efficiency can be achieved by incorporating oscillating heat pipe (OHP) into energy systems. PV-T module thermal and electrical efficiency can be improved by using an oscillating heat pipe.

This review encourages the selection of an oscillating heat pipe and the heat transfer enhancement approach to increase energy conversion rate and the productivity corresponding to the PV-T system, as well as identifies the research gaps, future vision, and development that can be done. Firstly, the OHP-PV-T system and its performance in detail are illustrated. Then, the structure and working principles of the system are discussed, followed by a review of the work conducted in this case. The advantages of using an oscillating heat pipe as a solar panel cooling approach are then highlighted. Understanding the advanced cooling technologies mentioned above is vital for further modifications of

current PV-T panels. Moreover, using nanofluid as coolant can make a significant contribution to enhancing the total system efficiency.

Keywords: Photovoltaic system; Oscillating heat pipe; Cooling; Heat transfer

Nomenclature

A	heat transfer area (m^2)
A_c	collector aperture area (m^2)
C_p	heat capacity of flowing medium (J/kg k)
D	diameter (mm)
h	heat transfer coefficient (W $m^{-2}K^{-1}$)
I	incident solar radiation (W /m^2)
$\dot{m}$	mass flow rate
P_O	output power (W)
Q_e	Electrical energy (W)
q	heating power (W)
T	temperature (°C)
T_{rc}	reference temperature(°C)
U_L	total heat transfer coefficient (W/ m^2 k)
Greek	
α	absorptivity
β	temperature coefficient (/°C)
τ	transmittance of the material
η	efficiency (%)
Acronyms	
BIPV/T	Building-integrated photovoltaic/thermal
CNT	carbon nanotubes
LHP	loop heat pipe
OHP	oscillating heat pipe
PV	photovoltaic
PV-T	photovoltaic-thermal
PHP	pulsating heat pipe

Subscripts

a	ambient
e	electrical
I	inlet
o	overall
out	outlet
p,m	mean value of plate
th	thermal
u	useful

1. Introduction

The demand for renewable energy has a growing trend nowadays as the human population rises [1,2,3], as discharge of pollutants produced by burning fossil fuels leads to major concern due to the negative impact on the environment, namely global warming, greenhouse gases, and the depletion of the ozone layer [4,5,6]. Renewable energy sources specially the sun, have drawn the attention of many researchers around the world. The solar energy can be converted into electricity by photovoltaic (PV) modules made of silicon which is a semiconductor.

Photovoltaic thermal collectors, typically known as PV-T collectors, are power generation technologies that make it possible to carry out the conversion of solar radiation into thermal and electrical energy. A PV-T collector is a combination of photovoltaic solar cells that convert solar radiation into electricity with a solar thermal collector that transfers excess heat from the photovoltaic module to a working fluid. With the combination of electricity and heat generation within the same structure, a higher efficiency can be achieved by these technologies [7,8].

Solar Photovoltaic panels contains the solar array of a photovoltaic system which produces and delivers solar electricity for residential and commercial purposes. There are a few solar panels available with the efficiency of 19% or higher. A PV system generally consists of one or more solar panels, a solar inverter, and additional mechanical and electrical components [9]. However, the efficiency of PV modules is remarkably dependent on some factors such as ambient temperature and solar irradiance, resulting in a reduction in efficiency and reliability [10]. On the other hand, module overheating is considered a major problem that diminishes the system's efficiency dramatically. Many cooling techniques were studied in order to dissipate the heat produced by the PV module and lower the temperature of its surface. Consequently, to control the PV panel temperature within the manufacturer's operating range, it is essential to remove the generated heat from the photovoltaic panels by adapting cooling PV approaches. Cooling methods are applied to boost the efficiency of PV and PV/T panels, as displayed in Fig. 1 [11, 12, 13, 14, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27 and 28].

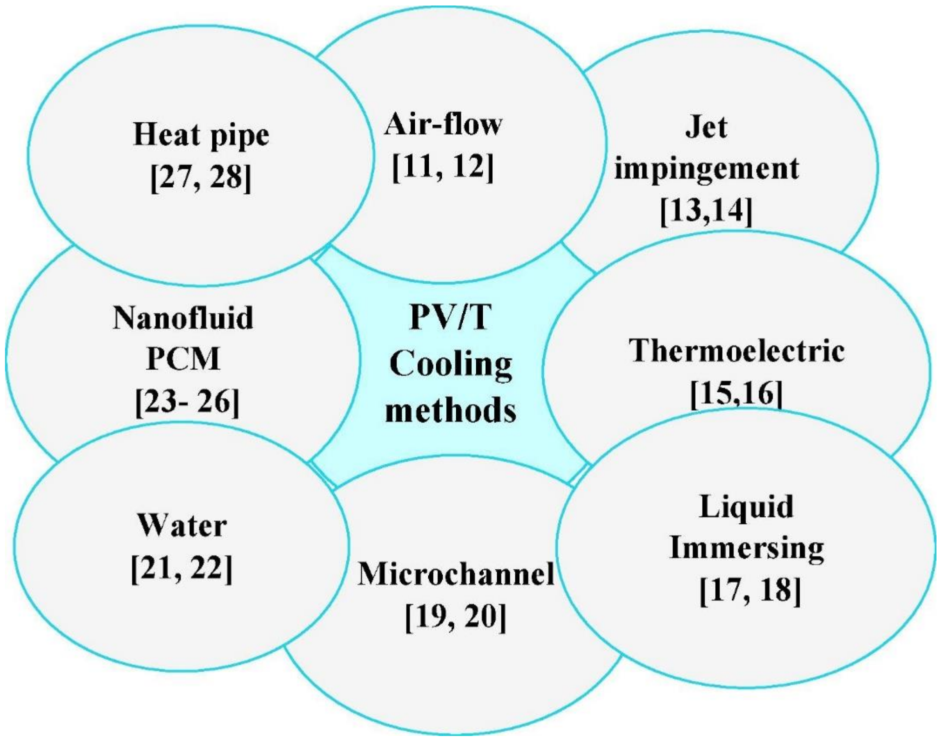


Fig. 1 Various cooling methods of PV, PV-T module

This study presents a detailed review regarding the research outcomes of the cooling approach using oscillating heat pipes (OHPs) or pulsating heat pipes (PHPs). Akachi [29], [30] proposed an OHP that consists of interconnected capillary pipes packed with a train of liquid–vapor slug-plugs [31]. Recently, using OHPs in various energy conversion systems has become a growing trend, especially in PV-T systems to dissipate heat more efficiently. In addition, applying OHPs can make a significant contribution to cooling down PV-T modules by almost 10 °C, which leads to improved PV-T performance.

2. The PV-T system's fundamental concept and operation

The solar efficiency of PV cells and modules is a parameter connected with the cells' materials and temperature. As it was mentioned earlier, to achieve a higher efficiency in a PV system, it is essential to dissipate heat from the PV surface and use it for further heat utilization. As a result, the photovoltaic thermal system, which comprises a combination of PV modules and heat extraction devices, has been introduced. This allows the cooling PV-T surface to give rise to boosted electrical efficiency and use the dissipated heat for heating purposes at the same time. Fig. 2 illustrates a whole picture of the various technologies used to convert solar energy into other forms of energy [32].

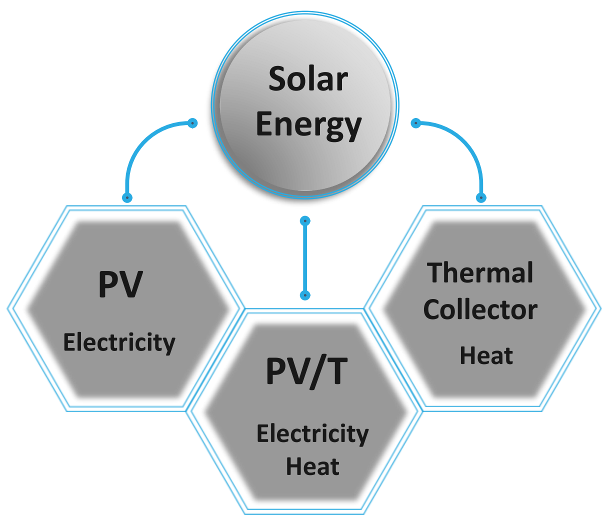


Fig. 2 A diagram of various solar conversion technologies [24].

Fig. 3. PV-T energy balance diagram PV cell performance with β [38].

The PV-T was generally discussed by Kern et al. [33]. For a PV/T module, electricity was generated by PV-T when the wavelength was between 0.6 to 0.7 μm; however, the vast majority of it was converted into heat. As reported by Zongdag et al. [34] and Zhao et al. [35], the PV-T systems have the potential to make the most use of solar irradiation in comparison with either PV system or thermal collector, thereby being considered as an attractive and effective alternative for heat and power generation. A PV-T module is fundamentally a combination of the function of a thermal collector and a PV panel. PV-T performance is measured by adding the electrical efficiency (η_e) and thermal efficiency (η_{th}), so overall efficiency is obtained as:

$$\eta_o = \eta_{th} + \eta_e \tag{1}$$

And thermal efficiency is formulated as:

$$\eta_{th} = \frac{Q_u}{I} \tag{2}$$

Where η_{th} is a ratio of the useful thermal energy, Q_u, to the overall incident irradiation, I. Fig. 3 displays the basic principle of a PV-T energy balance.

There are two equations to calculate Q_u:

$$Q_u = \dot{m}C_P(T_{out} - T_i) \tag{3}$$

$$Q_u = A_C\left[I(\alpha\tau) - U_L\left(T_{p,m} - T_a\right) - Q_e\right] \tag{4}$$

The man problem in equation (4) is to measure $T_{p,m}$, which shows the mean absorber plate temperature and hinges on different parameters such as the design of collector and working fluid property. To make a better analysis, the equations (4) was modified by the Hottel and Whillier [36] who proposed that $T_{p,m}$ can be replaced with T_i and electrical efficiency (η_e) which is formulated as:

$$\eta_e = \frac{P_O}{IA_C} \tag{5}$$

Where P_O is output power. It was mentioned earlier, the electrical efficiency, which can be obtained from equation (6) [37], diminishes with the rise of the module temperature.

$$\eta_e = \eta_{rc}\left[1 - \beta_{PV}(T_{PV} - T_{rc})\right] \tag{6}$$

And the produced electrical energy is expressed as:

$$Q_e = P_O = \eta_e I A_C \quad (7)$$

Crystalline silicon PV cells are the most common solar cells, representing a vast majority of market including Mono-crystalline (also called single- crystalline), Poly-crystalline silicon cells and Thin- film which is categorized into various groups with different performance mentioned in table 1 [38].Crystalline cells are made of high-purity silicon ,various thickness ranged from 150 to200 μm ,on the other hand, Thin- film produced by depositing one or several layer of PV material on to a substrate, thickness ranged from of 0.3 to 2 μm .

Table 1 Performance of PV cells with β [38].

Cell type	**Temperature coefficient(β) (percent / degree centigrade)**	**Cell performance (percent)**
Mono-crystalline	**-0.4 to -0.5**	**12.5-15**
Poly-crystalline silicon	**-0.4 to -0.5**	**11-14**
Amorphous-Si(a-Si)	**-o.35 to -0.38**	**11-13**
Cadmium Telluride (CdTe)	**-0.25**	**9-12**
Copper Indium Gallium Selenide (CIGS)	**-0.32 to -0.36**	**10-13**
Dye-sensitized (TiO2)	**-0.25**	**11-15**

3.Classification of photovoltaic thermal system

In response to different environmental condition and economic outlook, photovoltaic thermal collectors (PV-T) fall into many categories. In terms of structure, the PV-T collectors can be categorized as non- concentrated and concentrate type. Another classification also can be made regarding coolant which is air-biased, water-based, refrigerant -based and heat pipe PV-T collectors [39].

3.1 Air-based PV-T collector

The most commonly used method in order to cool down PV-T module is flowing air [40]. Generally ,an air-based PV-T system contains a PV panel , insulation ,and one or more glass covers on the top .There are different types of air-based PV-T models which can be delivered from the top, bottom , or both sides of panel :1- conventional air-based PV-T system ;2- double-pass with inlet air from channel located above a PV panel;3- single-pass parallel PV-T system;4- single-pass with a channel situated a above PV panel , and double pass accompanied with inlet air from channel above a PV-T panel [41]. Air-based PV-T collectors in comparison with conventional solar panel have achieved notable improvement in terms of harnessing both electrical and thermal energy. Fudholi et al [42] in an experimental research could achieve the overall efficiency of 66.73% which was much higher than the 10.7% of PV-T panel alone. This type of model is used when hot air and space heating are demanded. On the other hand, because of the fact that the thermal density of air is low, the efficiency could reduce when a great deal of thermal energy needs to be transferred.

3.2 Water-based PV-T collector

In water-based PV-T systems water is used as coolant. Normally, they comprise solar panel, insulation, absorber collector, and glass cover. Water-based collectors fall into three categories: natural flow, hybrid system, and forced flow [43]. The most popular type is forced flow PV-T system due to controlled rate of water which leads to boost the electrical efficiency. There are various types of absorber shown in Fig.4.

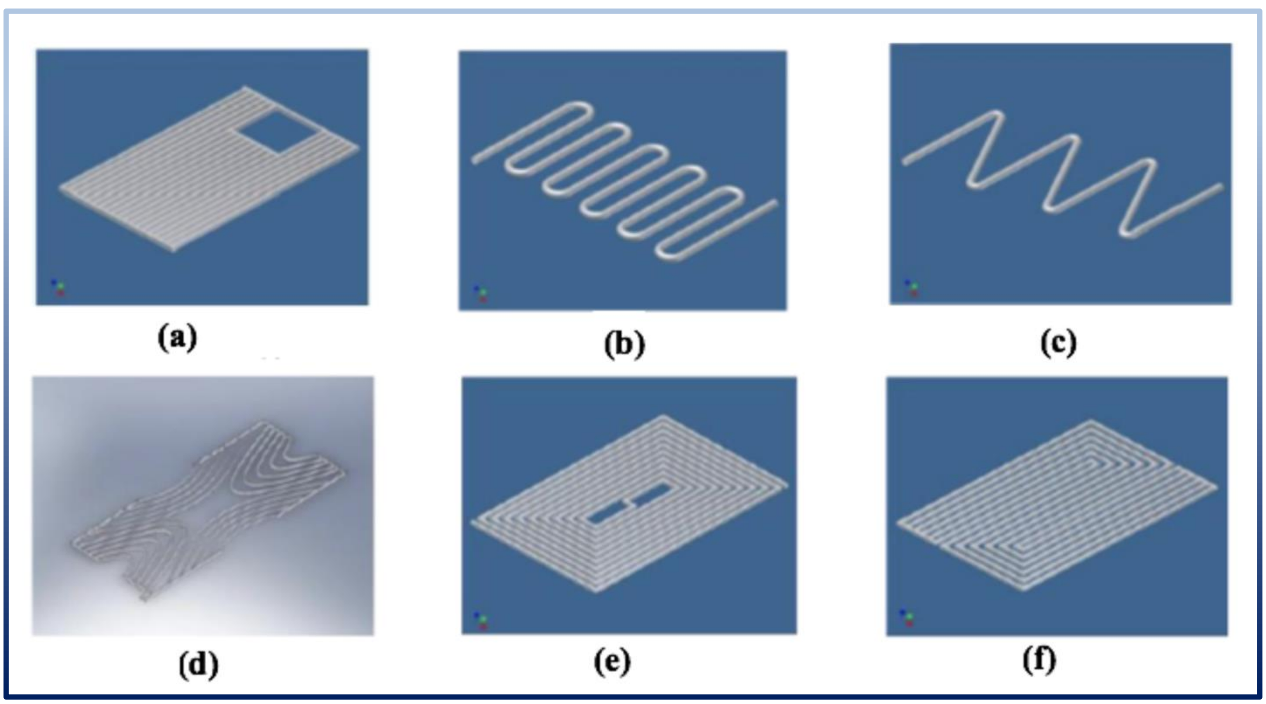


Fig.4 Common absorbers design in water-based PVT collector, (a) Direct flow, (b)Oscillatory flow, (c)Serpentine flow, (d)Parallel flow, (e) Spiral flow, (f)Web flow [44]

Since the thermal conductivity of water is more than air, water-based PV-T systems have more efficiency.

3.3 Refrigerant-based PV-T collector

Recently, refrigerant-based PV-T collector has drawn a lot of attention. In 2013, Huan-Lian Tsai [45] published a study on refrigerant-based PV-T accompanied with a heat pump water heating system and R-134a was used as coolant, while the power for heat pump was supplied by PV-T model. Since the refrigerant usually evaporates at the low temperature, the PV cells would highly likely be maintained at the same temperature which leads to dramatic improvement in terms of electrical efficiency.

3.4 Heat pipe PV-T collector

High efficiency in heat transfer makes heat pipe heat a popular device used in waste heat recovery systems. Thermal energy can be transmitted from considerable distance through a small section without any outside power. A typical heat pipe, shown in Fig. 4a, contains three segments namely, evaporation, heat insulation (adiabatic) and condensation segment.

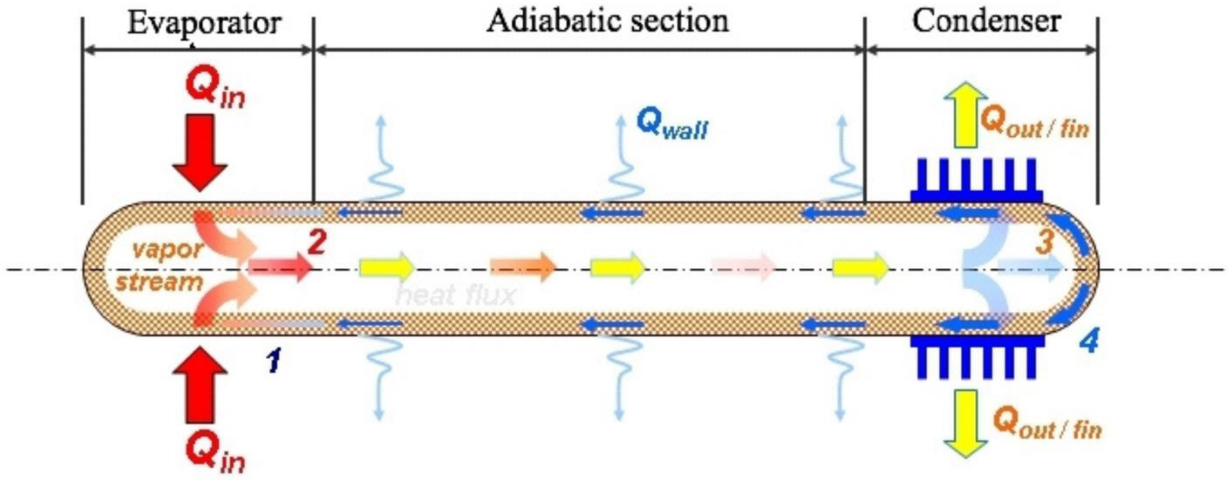


Fig. 4 A conventional heat pipe [46]

Although PV-T system has higher efficiency, freezing water in the system can cause failure. Heat pipe PV-T collectors are recommended as an effective solution, having significant benefit in terms of dissipating thermal energy from PV-T collectors. The heat pipe photovoltaic system can be categorized into three forms based on the construction of the heat pipe: integral, loop, and oscillating heat pipe Photovoltaic thermal systems [47]. Fig. 5 illustrates a concise overview of integral heat pipe PV-T collector (HP- PV-T) which has significant advantages such as resistance against freezing, lower pumping power, and greater efficiency. In HP- PV-T collectors, the temperature of water becomes higher when receiving heat from sun; thereafter, it flows to the storage tank and begins a new cycle after passing via the heat pipe condenser [48].

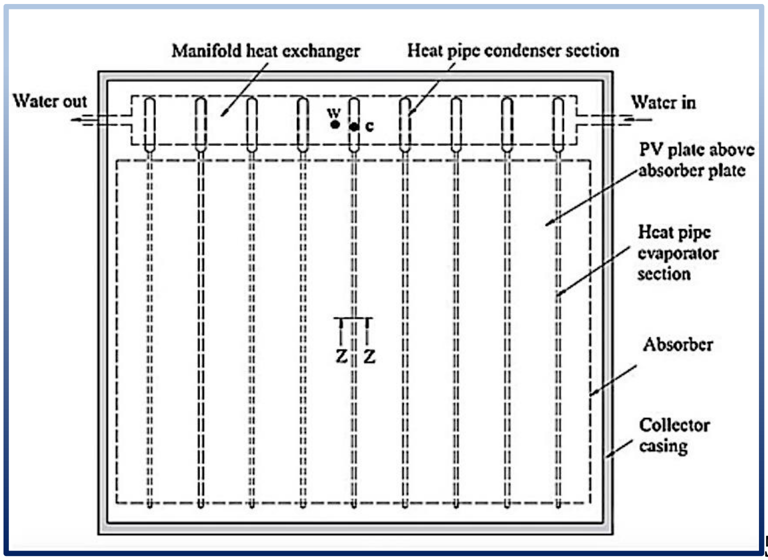


Fig. 5 Schematic of HP-PV-T [48]

In comparison to the integral heat pipe, the LHP has flexible installation and heat can transfer over a long distance. The evaporator place is behind the absorber, and the working condition of each is affected by the ratio of the vapor and liquid. The condenser is placed into the water tank or manufactured to act as a heat exchanger. Fig.6 illustrates schematic of loop heat pipe photovoltaic thermal system.

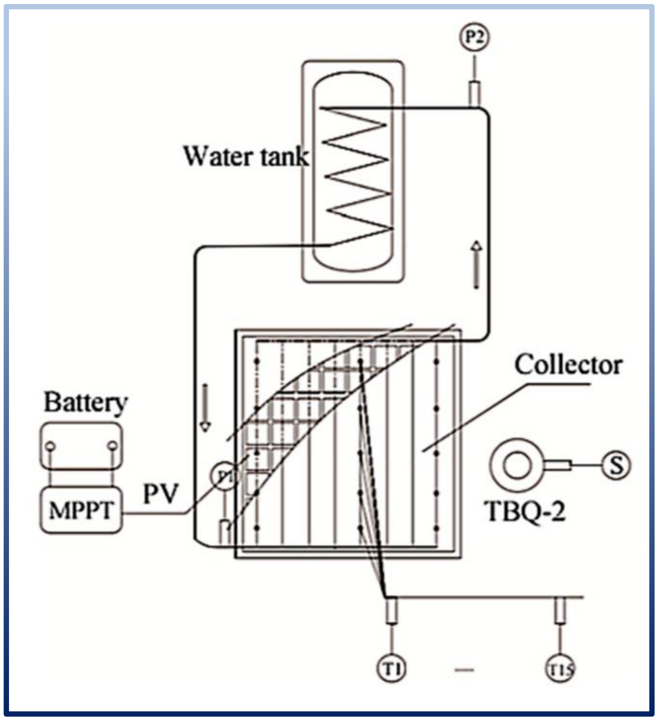


Fig. 6 Diagram of LHP-PV-T [49]

4. Oscillating heat pipe in photovoltaic and photovoltaic thermal systems

oscillating heat pipes (OHPs), also known as pulsating heat pipes (PHPs), contain a long, twisted capillary tube as shown in Fig 7, and its inside diameter must be sufficiently small to permit the formation of liquid and vapour plugs in the OHP. [50,51]. Regarding working principle, heat that travels through the evaporator area, gives rise to generate vapor, expand bubbles and build up the pressure, which excites the pulsation action of liquid-vapor plugs and slugs inside the OHP. Consequently, there is a temperature gradient between the evaporator and the condenser area, leading to heat transfer [52]. The evaporation area can be attached to the collector, and the condensation area acts as heat exchanger exposed to water or air. Furthermore, oscillating heat pipe enjoys the considerable benefits of simple structure, small volume, minimal cost, considerable heat transmission, and flexible shape [54].

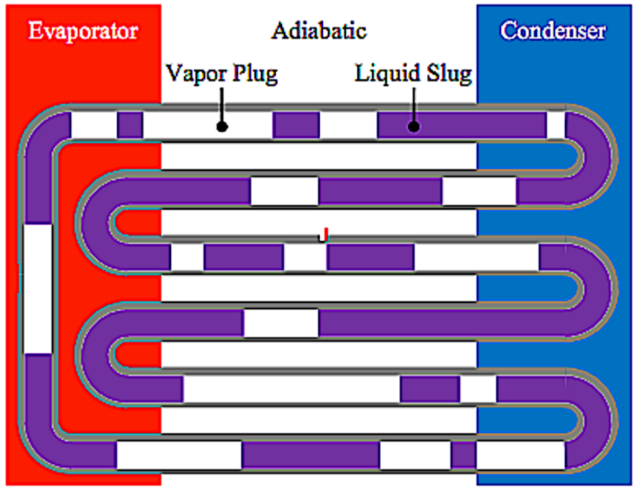
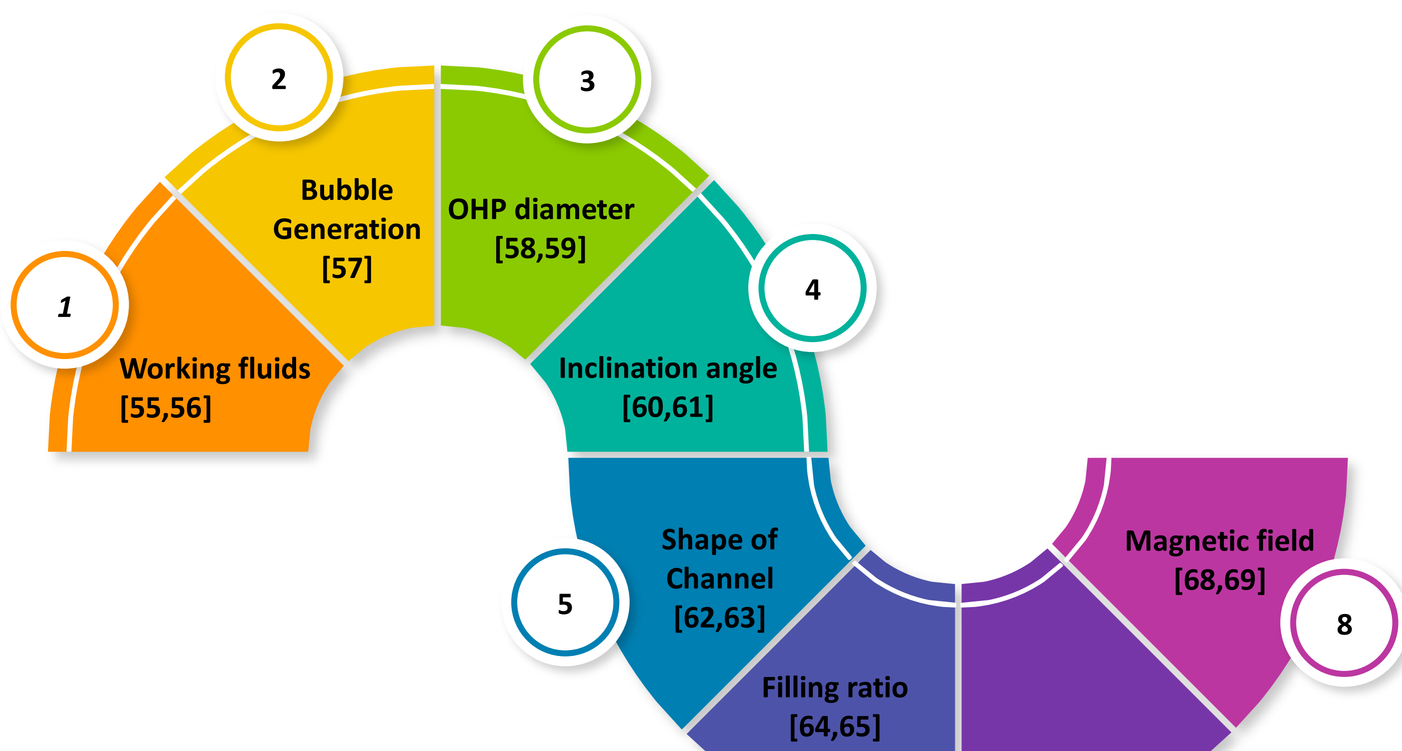


Fig. 7 Schematic of an OHP [54]

Several researches which have been widely conducted in recent years demonstrated the remarkable thermal performance of OHPs. Many factors affect OHPs performance and most important ones are mentioned in Fig.8.



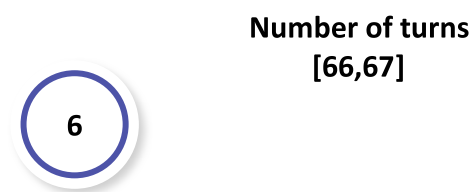


Fig. 8 Contributing factors influence OHPs performance.

For the first time, in 2010, Liang-dong [70] used OHP-BIPV-T for residential purposes, as displayed in Fig.9. The system comprises OHP, headers, finned tube, graphite conductive layer, metal frame, PV laminate module and insulations.

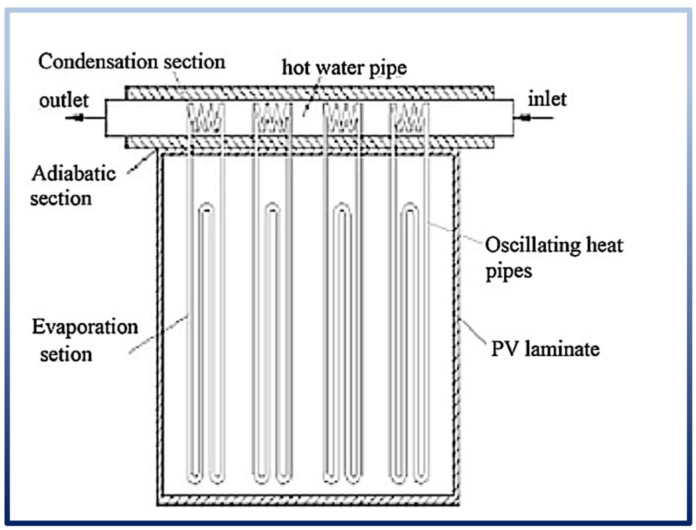


Fig. 9 Schematic of OHP-BIPV-T module [70]

Rittidech.S et al. [71] performed an experimental investigation on the performance of a solar collector by coppered closed-end oscillating heat pipe (CEOHP), Fig.10, with R134a as a coolant, demonstrating higher efficiency in terms of energy and economy. It was observed that the proposed system could the tackle corrosion and freezing problem (occurred during cold months), while it provided the efficiency of about 62%.

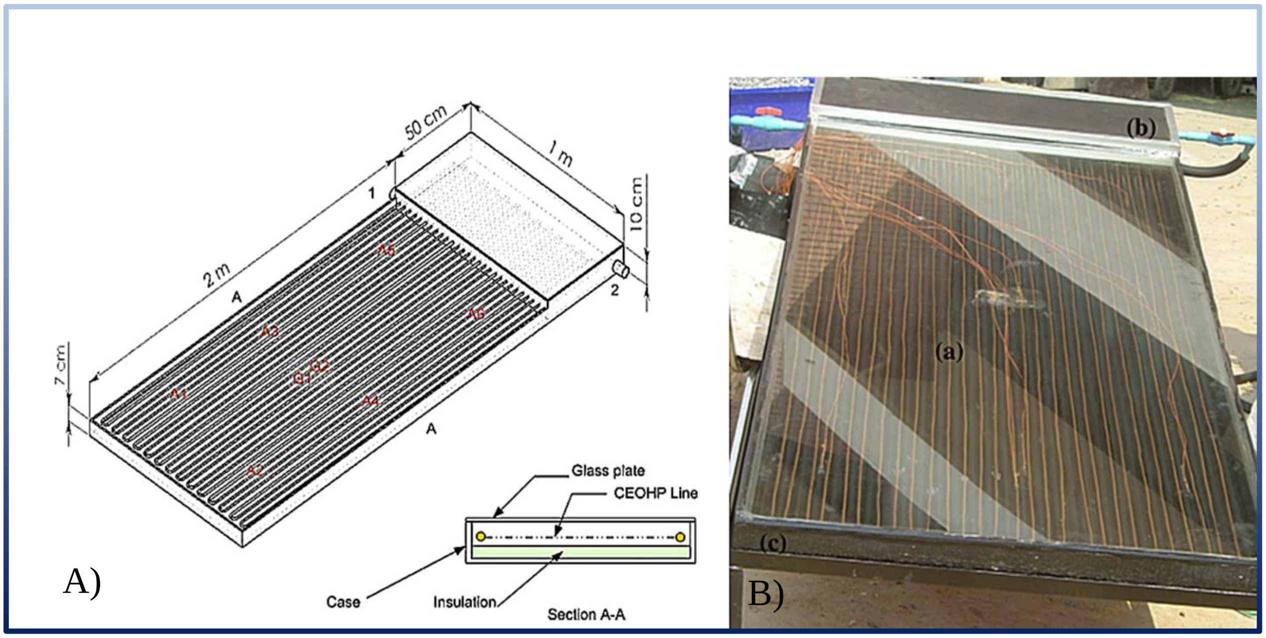


Fig. 10 A) 1. Water inlet; 2. Water outlet; B) (a) Collector; (b) Condenser water tank; (c) Frame

Nguyen et al. [72] investigated the impact of the flow rate and the filling ratio, ranged from 30% to 80%, of an OHP on the performance of solar collector, Fig.11. In order to assess the performance of the system with different filling ratios, the temperature of the absorber plate was measured. It was detected that the designed system had a good performance specially at 545 W/m^2 solar irradiation and 60% filling ratio where the efficiency exceeded 75%.

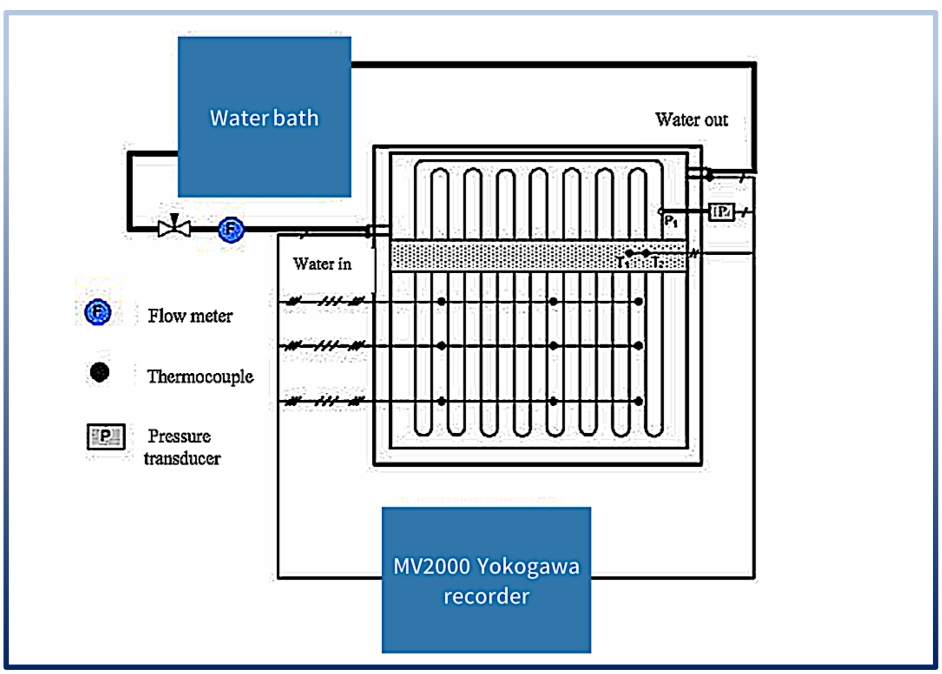


Fig. 11 Diagram of the experimental setup.

Kargarsharifabad et al. [73,74] studied on the impact of the length of evaporator, filling ratio, flow rate, and inclination angel on the efficiency of a OHP flat-plate solar collector and a multilayer perceptron neural network was also employed. It was discovered that increasing the length of the evaporator did not lead to remarkable improvement in the efficiency. Concerning the effect of the inclination angel, the system had two peaks in 20°, in which the solar heat gain was maximum, and about 45°-50° due to the optimum performance of OHPs. It was also noticed that increasing mass flow rates led to the reduction of outlet temperature. According to the theoretical study, the optimal values of the parameters were filling ratio of 56.9 %, and the inclination angle of 25.01°, and the highest thermal efficiency was observed at 61.4 %, which was 4.0 % more than in the conventional case without OHP.

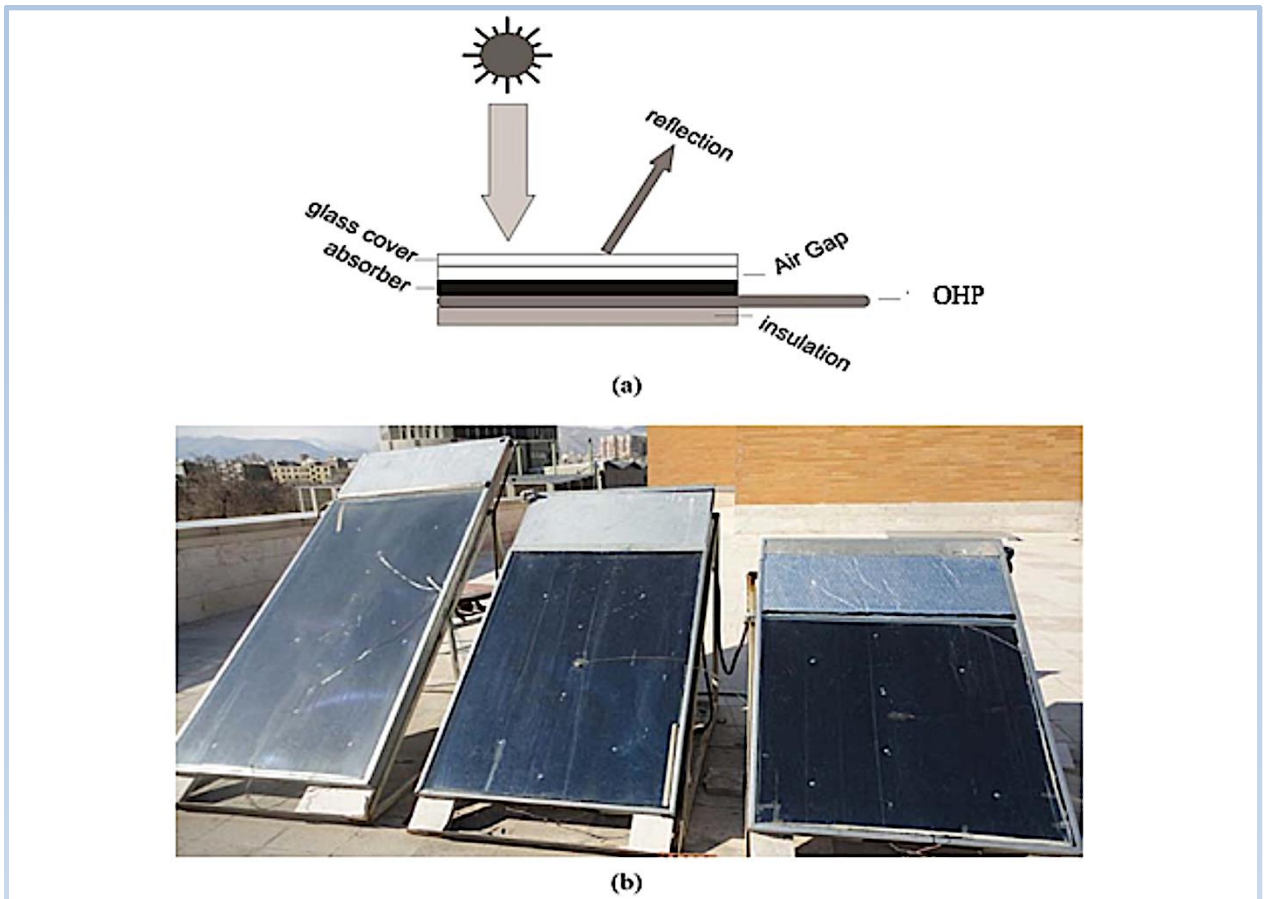


Fig. 12 (a) Schematic, (b) Experimental setup [73].

Kim et al. [75] integrated a novel U type OHP made of 'U' shaped evaporator and double U type which had the circular finned water tube inside condenser to increase heat transfer area in two solar collectors, Fig. 13. Results demonstrated that in the case of 903.7 W/m, solar irradiance, the heat which was accumulated by the double U type solar collector was 544.9 W/m^2, and for U type solar collector was 431.9 W/m^2. Consequently, achieved efficiency of 61.3% for U type and 46.8% for Double U type with the rate of 2 kg/min water flow was also reported.

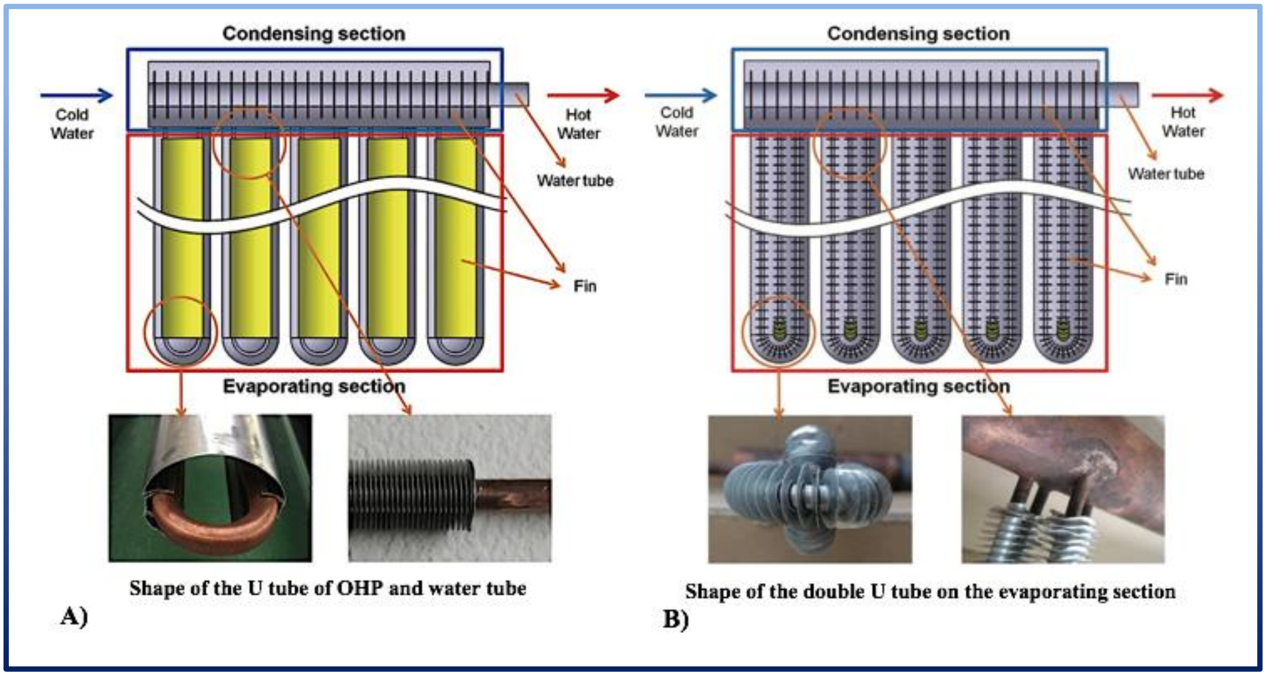


Fig. 13 A) Internal shape of U type solar collector, B) Internal shape of Double U type solar collector [75].

Sang et al. [76] were suggested to apply an oscillating heat pipe in an evacuated solar collector. It was noted that by considering low cost, flexibility, and high performance of the OHP, suggested system was promising. Such an evacuated tubular solar collector (ETC) enjoying aperture of 1.770 × 0.658 m^2 converted solar energy into heat more than 225.63 kcal/ hm^2. The working fluids applied in the study were R-142b, R-134a and Ethyl Alcohol, while the highest efficiency was achieved with ethanol.

Balotaki et al. [77] proposed a PV-T system with OHP shown in Fig. 14. It was found that the short-circuit current witnessed a moderate increase and open-circuit voltage experienced reduction with the rise of PV, leading to reduce the PV efficiency, while maximum efficiency occurred at the filling ratio of 45%, and the inclination angle of 30° when mass flow rate was 0.05 kg/s.

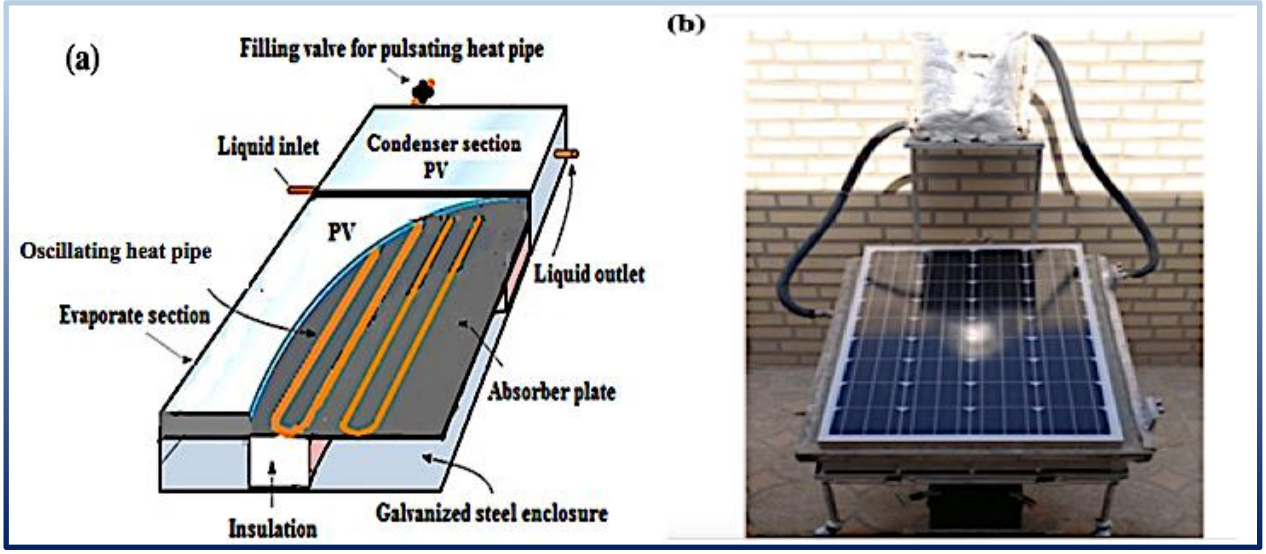


Fig. 14 (a) Schematic of OHP-PV-T, (b) Experimental setup [77].

Alizadeh et al. [78] numerically investigated the cooling of photovoltaic by applying a single turn OHP, illustrated in Fig. 15,16. Furthermore, a copper fin with the size the OHP also was used to compare the performance of system with OHP and copper and a finite-difference method was implemented. It was discovered that a PV panel included the OHP can have around 18% improvement in terms of producing electricity.

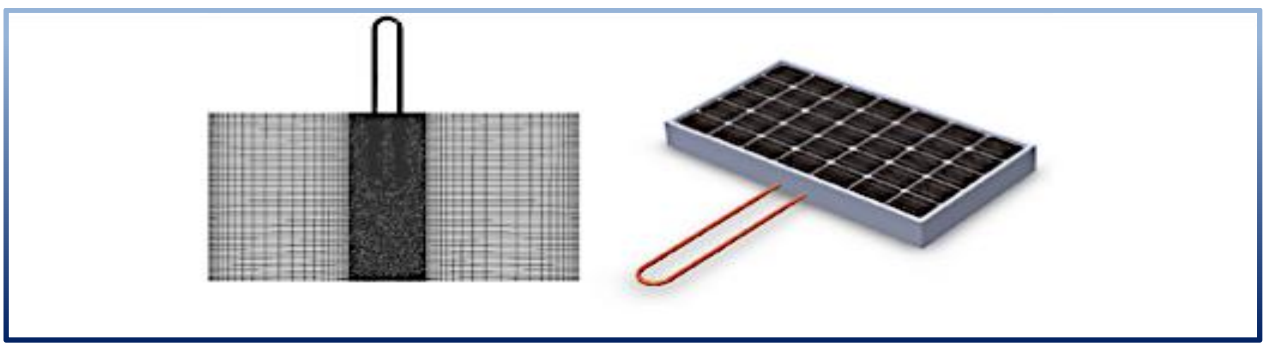


Fig. 15 Three-dimensional model OHP-PV-T [78].

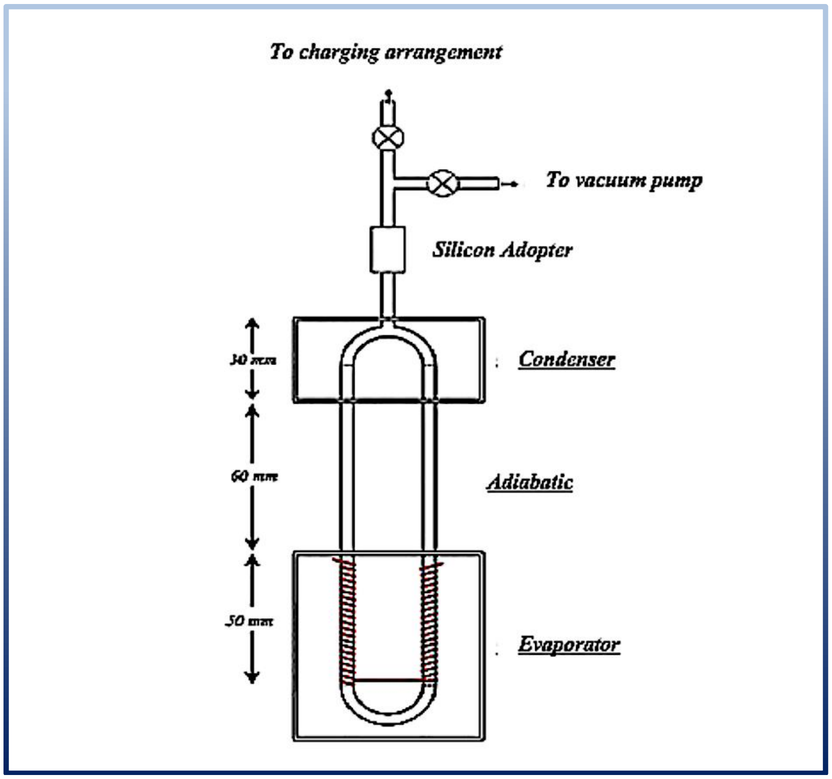


Fig. 16 Schematic diagram of OHP [78].

Roslan and Hassim [79] connected an oscillating heat pipe on the back plate of a PV panel, Fig. 17. The addition of oscillating heat pipe led to 50 °C reduction of cell temperature and boosted up to 19.45% electrical efficiency and 8.025% produced energy.

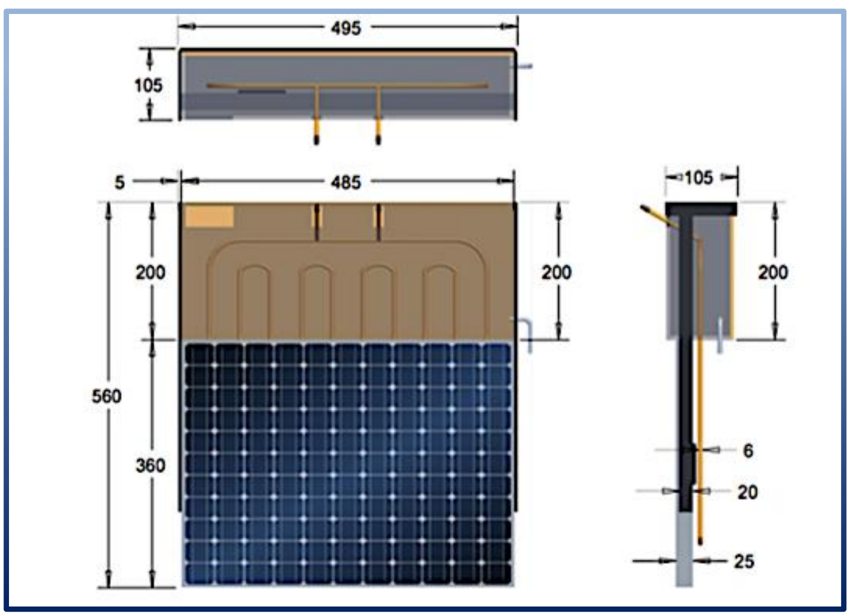


Fig. 17 Drawing of the designed system [79].

Aref et al. [80] designed PV-T system equipped with a dual-diameter oscillating heat pipe, displayed in Fig.18,19. It was reported that at 1030 W/m^2 solar irradiance, the thermal efficiency of the system with dual-diameter oscillating heat pipe with a filling ratio of 60% reached 72.4% which was higher than single-diameter.

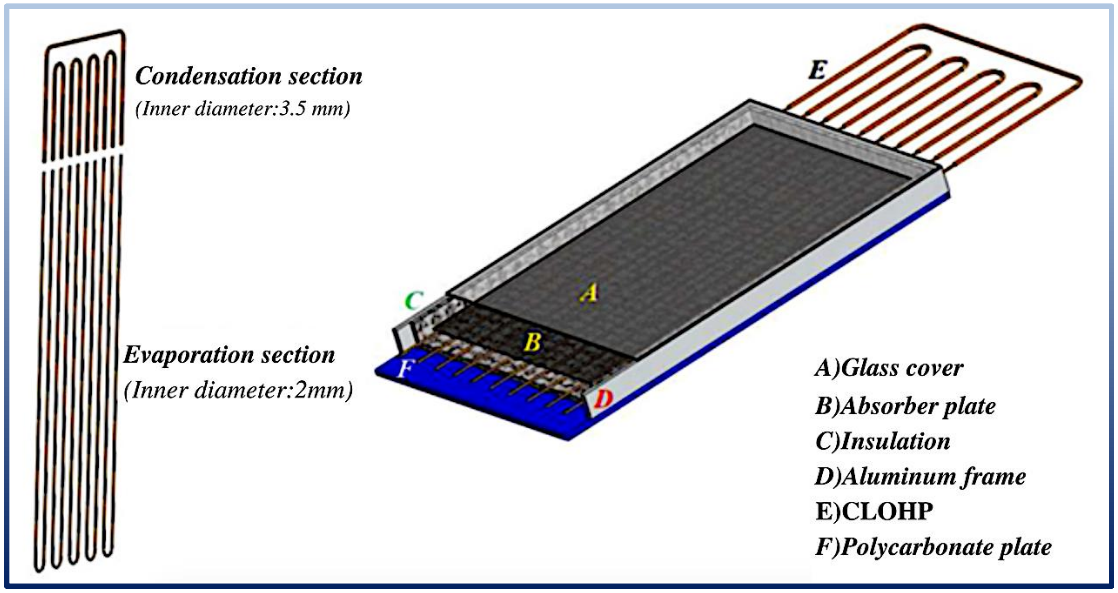


Fig. 18 Cross-sectional view of system [80].

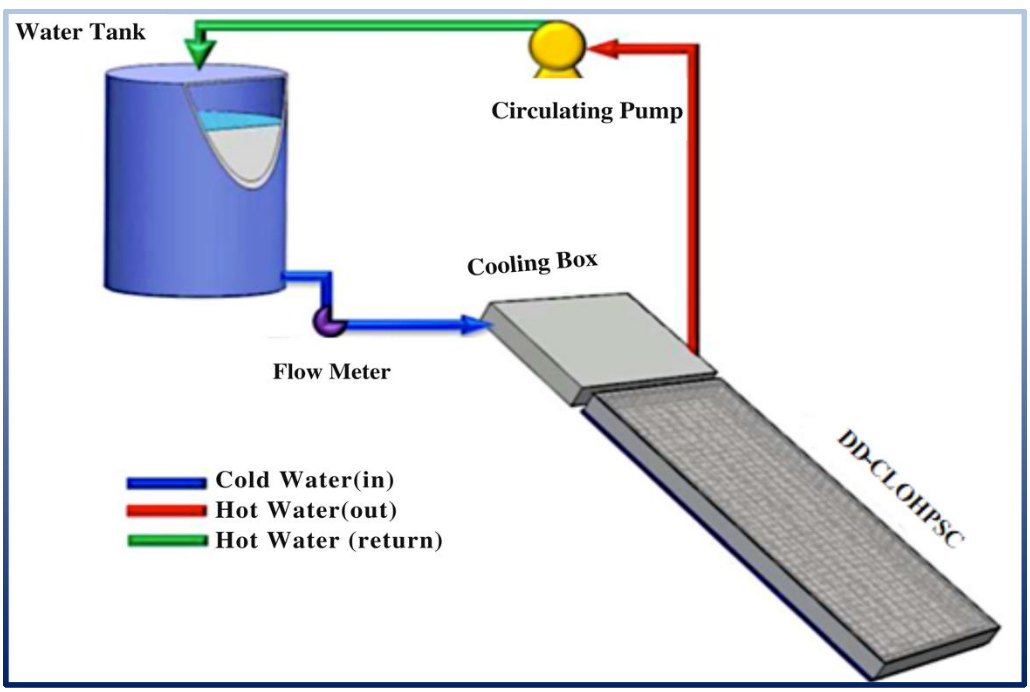


Fig. 19 Schematic of experimental system [80].

Analyzing the effect of using oscillating heat pipe (CLOHP) in PV-T system in terms of economic and thermal performance was also addressed by Alizadeh et al. [81]. The result of numerical investigations demonstrated that the efficiency was 23% which could reach 35% when the solar radiation was 1235 W/$m^2$and reduced to 13% by the reduction of solar radiation and it was also revealed that the proposed system is cost- effective and energy-efficient. Chen et al. [82] conducted an investigation on the performance of PV-T system using flower type of OHP, while the condenser section was rolled into a cylinder, as it is shown in Fig.20, and acetone was used as a working fluid. It was noticed that as the temperature of evaporator increased, thermal efficiency followed similar trend and increased to 50%.

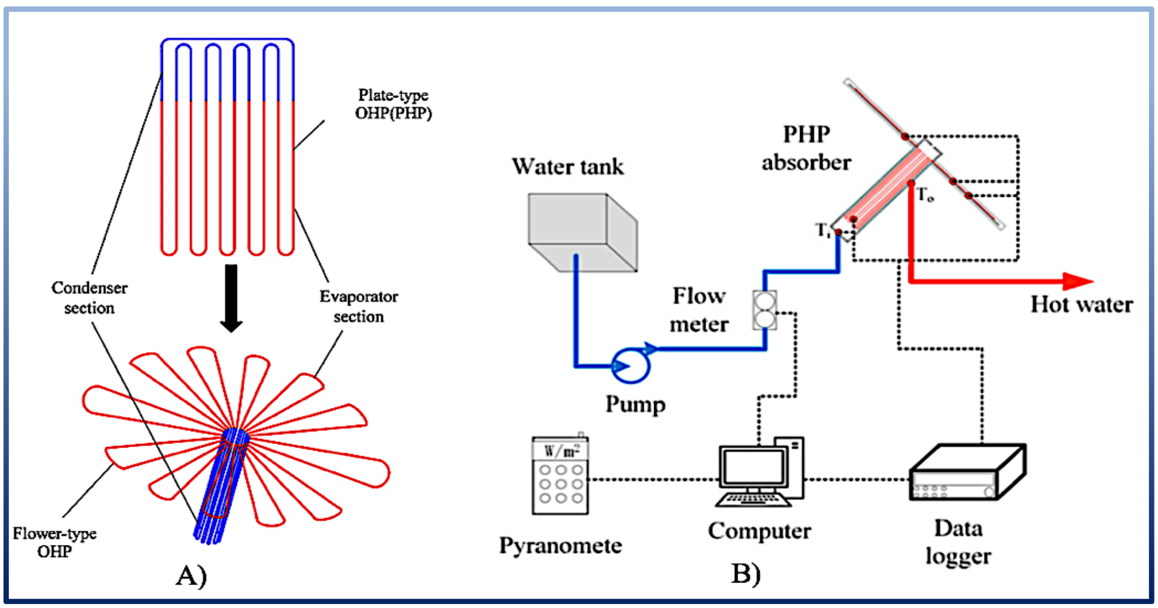


Fig. 20 A). Flower type of OHP **B).** Schematic of the experimental setup [82].

5. Concentered oscillating heat pipe PV-T system

Concentrated photovoltaic (CPV) system makes a contribution to focus the direct solar radiation on the photovoltaic module. In comparison with common PV-T system, concentered PV-T system are more fairly efficient. The mirrors applied in the heat pipe PV-T system are commonly Fresnel lens, matrix concentrators, compound parabolic concentrators and dish concentrators to name a few [83-85].

Xu et al. [86] performed experimental investigation on a collector equipped with a compound parabolic concentrator with OHP (Fig.21). It was observed that owing to the rise of the evaporation temperature thermal efficiency of the system increased and at 800 W/m^2 solar irradiance, the design showed more than 50% efficiency.

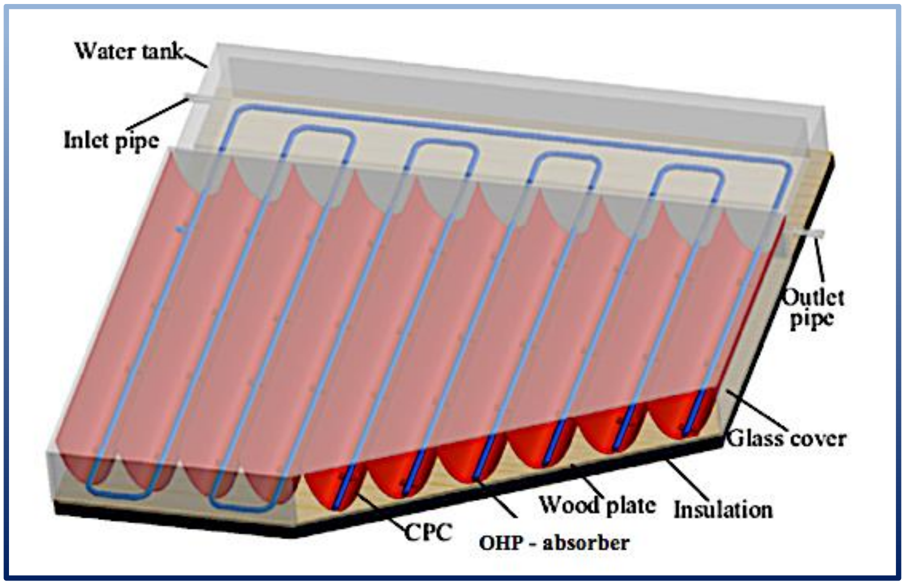
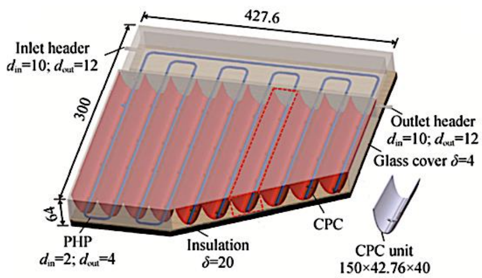
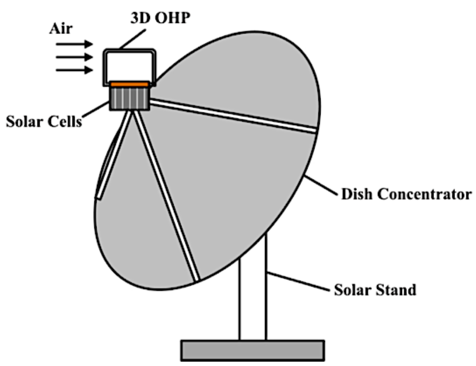
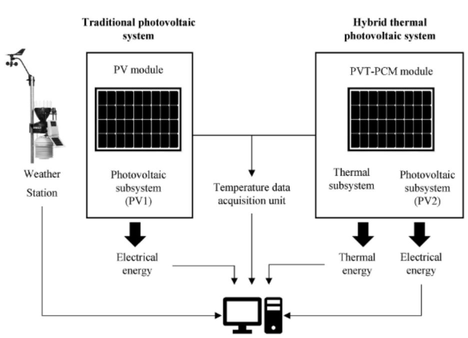


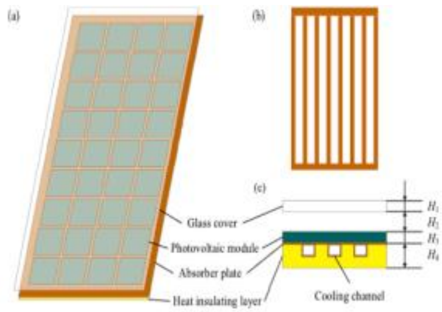
Fig. 21 Schematic of the system [86].

Some researches on concentered PV-T system have been carried out experimentally and theoretically, and the results are mentioned in Table 2.

- **Table 2** Investigations on concentered photovoltaic collector (CPV)system

Researcher	System	Method /Performance
Geng, Wenguang et al. [87] 2012		♦ Numerical and experimental study The heat pipe cooling method was used which was reliable and cost-effective and able to boost electrical efficiency.

Raj, Arun et al. [87] 2012		♦ Numerical and experimental study ♦ The heat pipe cooling method with Acetone as coolant was used. The system showed higher efficiency and could generate the maximum voltage of 22.23V.
Xu et al. [89] 2020		♦ Numerical study ♦ OHP was used as cooling method. The optimum effeminacy was achieved at angel of 45◦when was solar irradiance 1000 W/m^2 and as air speed increased, the reduction of performance was observed.
Wang, Hai et al. [90] 2020		♦ Experimental study ♦ 3D-OHP with porous structures of sintered copper particles on the evaporator and ethanol as coolant were used. The proposed structure boost OHP performance and as result enhanced the performance of the system, while the temperature of CPV remained under 57^{o}c.
Carmona et al [91] 2021		Experimental evaluation of a hybrid photovoltaic and thermal solar energy collector with integrated phase change material (PVT-PCM) in comparison with a traditional photovoltaic (PV) module

Shen et al. [92] 2021		Numerical study on the thermal performance of photovoltaic thermal (PV/T) collector with different parallel cooling channels

6. Nanofluids on oscillating heat pipe PV-T system

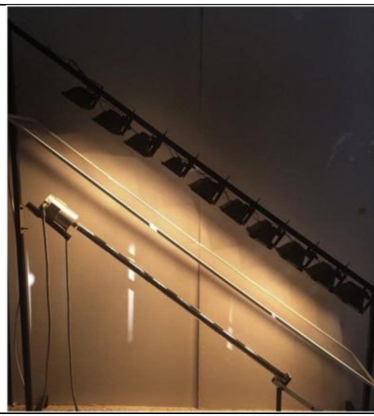
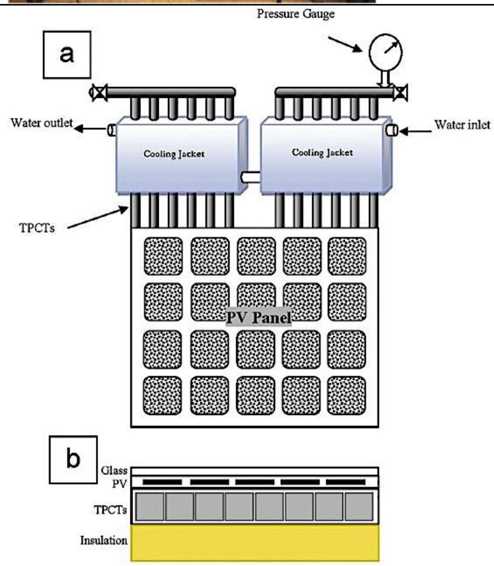
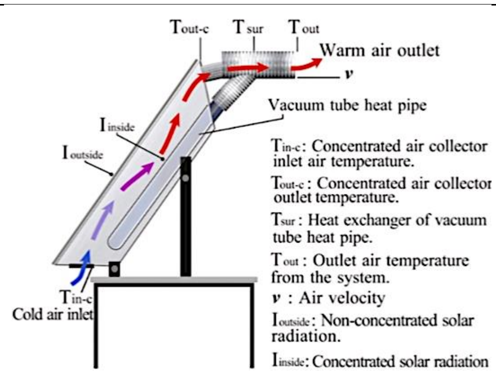
The term

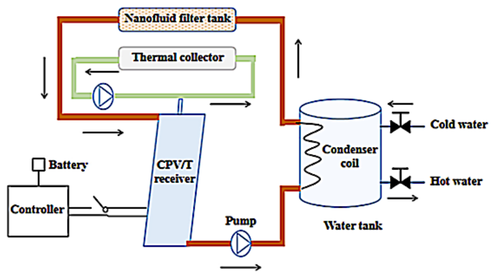
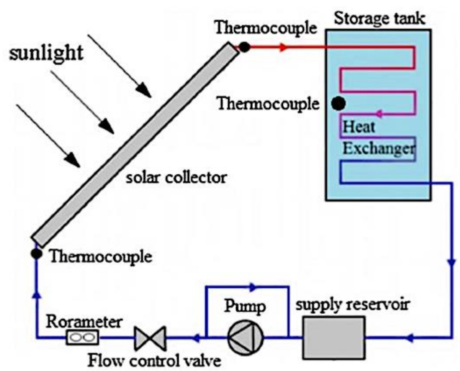
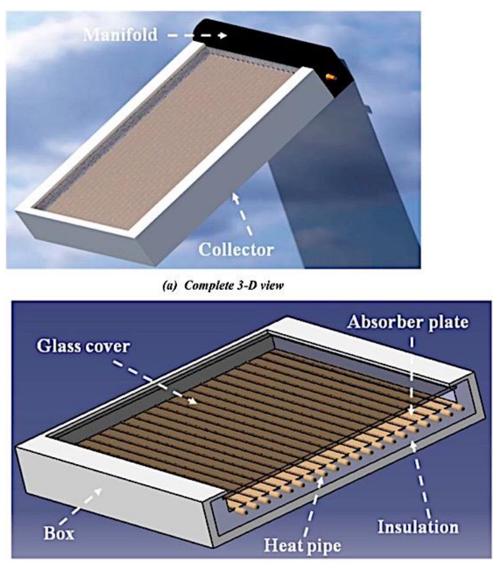
Senthil Kumar et al. [96] and Chougule et al. [97] conducted different experiments in order to investigate the effect of using a heat pipe with carbon nanotubes-water nanofluid as coolant in a solar collector. In both experiments, it was observed that the performance of the system improved significantly. The results of the latest studies on the use of nanofluid in heat pipe PV-T systems have been pursued by some other researchers, which are listed in Table 3.

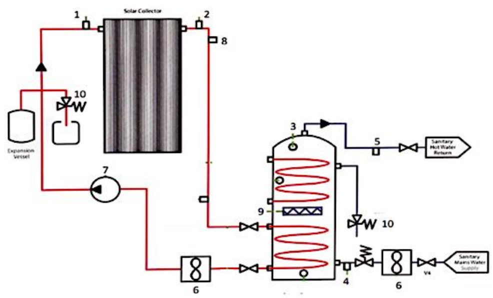
Xu et al. [106] recently published an extensive review on the application of nanofluids in OHPs, reporting that many assumptions have been put forward to gain a better understanding of improving thermal conductivity and heat transfer behavior such as Brownian motion, interfacial layering, clustering, diffusive and ballistic phonon transport. The use of nanofluids in OHPs to improve thermal performance has received a lot of attention [107,108]. Metal-based nanofluids (Ag [109] and Cu [110]), metal-oxide nanofluids (Al2O3 [111], SiO2 [112], CuO [113], TiO2 [114], Fe3O4 [115,116], and Fe2O3 [117]), and carbon-based nano-materials (diamonds [118], C60 [119], CNTs [120], graphene oxide [121], and graphene [122]) have been used in OHPs.

Most of the investigations concentrated on using nanofluid in the integral heat pipe PV-T systems and loop heat pipe PV-T systems, while investigations into the application of nanofluid in OHP-PV-T systems are quite rare.

Table 3. latest investigations on nanofluid in heat pipe PV-T systems

Researcher	Setup	Result /performance
Ozsoy et al [98]		♦ Experimental study **Heat pipe cooling with silver-water nanofluid was used, boosting the total efficiency between 20.7% and 40%** ♦
Moradgholi et al. [95] 2018		♦ Experimental study ♦ Heat pipe cooling with different concentrations of methanol and Al_2O_3 (2, 1.5, and 1 wt%) were examined and at the filling ratio of 50% and 1.5 wt%, of the nanoparticle's concentration, the system experienced 1.0 % increase in electrical energy and 27.3% in total energy average.
Kaya et al. [96] 2019		♦ Experimental study ♦ Energetic and exegetic analysis were conducted when methanol and CuO-methanol were used as working fluid in heat pipe. The system efficiency with nanofluid reached 64% and average exergy values 298 J/kg was reported.

Han et al. [97] 2020		♦ Numerical study ♦ Dynamical model of energy balance a concentrating photovoltaic-thermal system includes Ag/CoSO4-PG nanofluid and heat pipe was investigated. Overall efficiency of the system including heat pipe showed 10.4% increase.
Shafiey et al. [98] 2021		♦ Experimental study ♦ Using Al_2O_3, MgO and CuO nanofluids in heat pipe were investigated. The system efficiency improved by 9-20% and optimum efficiency of 83% was recorded for CuO nanofluid.
Allouhi et al.[99] 2021	(a) Complete 3-D view (b) Excluding the manifold	♦ Numerical study ♦ Heat pipe cooling with three different nanofluids (CuO, Al_2O_3, and TiO_2) were studied and CuO-based nanofluid had the highest enhancements in terms of the energetic and exergetic efficiencies calculated at 2.7% and 11.1%, respectively compared to water.

<table>
<tr><td>Henein et al. [100]
2022</td><td></td><td>

Experimental study
Energetic and exegetic analysis of using magnesium oxide/ multi-walled carbon nanotubes (MgO/MWCNT) hybrid nanofluid in heat pipe were carried out and an increase of 55.83% for energy efficiency and 77.14% for exergy efficiency were reported.
</td></tr>
<tr><td>Henein et al. [104] 2022</td><td>
</td><td>

Experimental study
An energetic and exegetic analysis of using magnesium oxide/multi-walled carbon nanotubes (MgO/MWCNT) hybrid nanofluid in heat pipes were carried out and an in crease of 55.83 % for energy efficiency and 77.14 % for energy efficiency was reported.
</td></tr>
<tr><td>Arifin et al. [105] 2022</td><td>
</td><td>

Numerical study • When TiO2-based PVT systems are used, an average photovoltaic temperature of 58.5 ◦C is generated, with a photovoltaic efficiency of 13.04 %.
</td></tr>
</table>

An extensive review was conducted by Recently, Xu et al. [101] regarding the application of nanofluids in OHPs, reporting many assumptions have been put forward to gain a better insight concerning improving thermal conductivity and heat transfer behavior such as Brownian motion, interfacial layering, clustering, diffusive and ballistic phonon transport and to name a few. The application of nanofluids in OHPs in order to boost their thermal performances has been extensively investigated [102, 103]. Metal-based nanofluids (Ag [104] and Cu [105]), metal-oxide nanofluids (Al_2O_3 [106], SiO_2 [107], CuO [108], TiO_2 [109], Fe_3O_4 [110,111], Fe_2O_3 [112]], etc.), and carbon-based nano- materials (diamonds [113], C60 [114], CNTs [115], graphene oxide [116] and graphene [117]) have been using in OHPs. It should be mentioned that the number of the investigations which concentrated on using nanofluid in OHP-PV-T system is quite rare.

8. Conclusions

Heat pipe photovoltaic thermal collectors (HP-PV-T) have emerged as a promising way to improve the performance of PV-T collectors. A lot of efforts have been making all around the globe to enhance the efficiency of PV-T collectors. Due to considerable advantages of OHP-PV-T collectors compare to conventional solar collectors, recently, the applications of this type of collectors have been growing considerably. In this paper, an in-depth review regarding the thermal and electrical efficiencies of OHP-PV-T collectors using different designs was carried out, which is accompanied by a comprehensive survey concerning the recent advances of the usage of nanofluids in the system in order to obtain a better insight on its mechanism and deployment in renewable energy applications. Also, the following conclusions can be derived from the present study:

- Since the condensation of OHPs has a complex structure, a complicated heat exchanger is required to achieve optimum thermal efficiency leading to push up costs and make the deign complicated.
- Nanoparticles cooling is highly effective method used to lower PV collector temperature, thereby using nanofluid and OHPs at the same time could enhance PV-T efficiency significantly.
- A lot of assumptions have been considered in prior numerical investigations which make a contribution to simplify the issue.
- Most of the studies focused on HP-PV-T systems, however, the work on OHP-PV-T is quite rare. Since the structure of OHP is more complicated, hence more study on this type should be conducted.
- Assessing the long-term effect of different parameters on most novel designs of HP- PV-T were hampered by the limitation of time and expenses, thereby, providing the condition to carry out study for long-term schemes (quarterly or annually), which lead to perform

comprehensive analyses of the performance of the system specially to comprehend the long-term stability of nanofluids, is quite essential.

- The major factors on the performance of HP- PV-T collectors have been mainly focused on the solar irradiance, mass flow rate, wind speed, to name a few. On the other hand, researches concerning the system working fluids are quite rare. Therefore, the using of new working fluids in the system and comparing their performance can be expanded considerably.
- Future research should focus on the reliability of nanofluids in OHP-PV-T in terms of technical, and environmental aspects. There is a dire need to provide reliable information on the production methods and volume fractions of nanofluids with eco-friendly components.
- More studies must be conducted on OHP-PV-T, which focus nano particles migration, nanofluids behavior including temperature dependence of thermophysical properties of nanofluids, changing nanofluid properties by using additives, erosion and corrosion probability.
- Since the vast majority of previous studies paid much more attention to latent heat storage methods on OHP-PV-T, further investigations on the effect of sensible heat storage methods on the system efficiency is required.
- The importance of economic analysis of OHP-PV-T systems has been widely ignored by the majority of studies. Hence, assessing economic evaluation is strongly suggested for future investigations, including all types of configurations.
- Studies concerning the use of OHP-PV-T in space heating systems such as air-based, water-based are quite rare. Consequently, conducting more in-detail studies is essential in order to boost efficiency of systems in terms of both economic an energy aspect.
- Three-dimensional oscillating heat pipe is a new designed of OHP with added advantages and the use of nanofluid like graphene oxide as coolant accompanied by this new type of OHP would be an innovative idea to enhance PV-T efficiency more than other applied methods discussed in this article.

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