Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review

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Abstract

Invention of evacuated tube heat pipe solar collectors (HPSCs) was a huge step forward towards resolving the challenges of conventional solar systems due to their unique features and advantages. This has led to their utilization in a wide range of solar applications surpassing other conventional collectors. However, relatively low thermal efficiency of heat pipe solar (HPS) systems is still the major challenge of solar industry evidenced by numerous studies conducted mainly during the last decade to improve their efficiency. To date, several review papers have been published summarizing studies relevant to utilization of HPSCs in various thermal applications. However, to the authors' knowledge, a comprehensive review which surveys and provides an overview of the studies undertaken to improve the thermal performance of HPS systems (mainly during the last decade) by implementing different strategies has not been published to date. This review paper summarizes all the proposed strategies to improve the thermal efficiency of different industrial, domestic, and innovative HPS systems. First, the concept, structure, and operational principles of HPSCs are introduced concisely. Then, novel structures and designs of HPSCs aiming to increase the thermal efficiency of the collector as the most important component of the solar system is reviewed. This is followed by a comprehensive review of various methods to store solar energy more efficiently, increase solar system's operation time, increase overall efficiency by turning the solar system into a multi-purpose system, enhance heat transmission in the solar system, and implement new solar loop and heat pipe working fluids with better heat transfer characteristics. Finally, research gaps in this field are identified and some future research trends and directions are recommended.

Keywords: Heat pipe, Solar system, Thermal performance, Efficiency improvement

Contents

1. Introduction

Solar collectors are special type of heat exchangers utilized to absorb the incoming solar energy, transform it into heat, and transfer it to the solar working fluid. The solar working fluid carries the collected solar energy either to the load or to a thermal energy storage tank to be used for daily, night time, or cloudy period demands. The thermal performance of the solar collector contributes greatly to the overall performance of a solar system and that is why solar collectors are the major components of any solar system [1]. Different types of solar collectors including flat plate solar collectors (FPSCs) [2-7], all glass evacuated tube collectors (ETCs) [8, 9], and evacuated U-tube collectors [10, 11] have been introduced and studied in past years.

FPSCs are cheap, durable, and manufactured easily, however, they are technically and economically effective only during sunny warm days [12]. Also, FPSCs are not an efficient choice for applications with high operating temperatures due to their high thermal losses. Requiring sun trackers, limited heat transfer, high hydraulic resistances, fouling on the inner surface of tubes, water freezing on cold nights, and being vulnerable to moisture and condensation are other significant drawback of FPSCs [13-15].

On the other hand, ETCs have cylindrical absorbing surfaces and because of that, they track sun passively during the day. Moreover, their maintenance costs are relatively low and unfavorable climatic conditions (e.g., cloudy, rainy) affect their performance less than that of flat plate collectors [16]. However, the possibility of overheating remains as one of the most important disadvantages of ETCs. In addition, solar working fluid flows inside the tubes and this affects the performance of the collector (e.g., freezing, glass break, and etc.) [12].

The heat pipe solar collectors (HPSCs) were invented to resolve the challenges faced by the conventional solar collectors. HPSCs comprise heat pipes (HPs) which are inserted inside the vacuum-sealed glass tubes having the advantages of both technologies [15]. Heat pipes are highly efficient thermal conductors with anti-freezing property, constant-temperature heat transfer, and high performance [17, 18]. HPSCs have significant advantages over conventional solar collectors including uniform working fluid flow, almost isothermal heat absorption, very low hydraulic thermal resistance, low heat loss and high outlet temperature, and high efficiency even in unfavorable and cold climatic conditions [19-21]. In addition, if one tube breaks, the system can continue the operation while in other solar collectors, the whole system has to be halted for repair [22]. Technical and economic advantages of HPSCs over other types of solar collectors has been recently reviewed [20].

Many studies have analyzed the performance of HPSCs and compared their performance in various applications with other types of solar collectors especially FPSCs [23-30]. In one of the most comprehensive papers in this field, Ayompe et al. [17] compared the daily, monthly, and yearly thermal performance of heat pipe and flat plate solar water heating (HPSWH and FPSWH) systems. The annual solar fraction, collector efficiency, and system efficiency of the FPSWH system were 38.6%, 46.1%, and 37.9%, respectively. These parameters had higher values of 40.2%, 60.7%, and 50.3% for the HPSWH system proving its better performance compared to the flat plate system. Zambolin and Del Col [31] also compared the thermal performance of HPSWH and FPSWH systems theoretically and experimentally following the EN 12975-2 standard. Low dependency on climatic conditions, higher efficiency, and higher outlet temperature were mentioned as the most remarkable advantages of HPSWHs over FPSWHs.

The abovementioned advantages have increased the utilization of HPSCs in various small scale commercial and residential solar applications including water heating, space heating, solar desalination, small power plants, electricity generation, and drying systems. The performance of HPSWH systems under climatic conditions of Perth, Australia was studied both theoretically and experimentally and the optimum collector size for that specific climatic conditions was obtained to be around 2 m^2 which equals to 25 vacuum tubes [32]. In a similar study, the optimum collector size for a HPSWH system operated in Iran was found to be 1.24 m^2 which equals to 15 vacuum tubes [33].

Shafieian et al. [34] reviewed the most significant recent studies on different domestic and industrial applications of HPSCs, challenges and the future research potentials in this field. However, low thermal efficiency of HPSC-based systems has been the major challenge of solar industry [35, 36]. Therefore, many studies have been conducted in recent years to develop new methods to improve the efficiency of these systems [37].

To enhance the thermal performance of HPS systems, researchers have focused mainly on changing the structure and geometry of HPSCs, solar radiation concentration, manifold chamber configuration, inclination angle, solar and HP working fluid, HP filling ratio, novel storage methods, and turning the solar system into a multi-purpose system [38-41]. In spite of all the valuable efforts, to the authors' knowledge, there is no review paper available to summarize all the strategies and methods proposed to date. Therefore, in this paper, latest strategies, methods, and designs to enhance the thermal performance of HPS systems along with their effectiveness, contribution, advantages, and disadvantages have been reviewed and discussed. Moreover, challenges and research gaps have been identified and recommendations for future research potentials have been presented. The authors hope this review paper will benefit both new and existing researchers in the field of solar thermal engineering, and more specifically in the field of heat pipe solar systems.

2. Heat pipe solar collectors: structure, principles of operation, modelling, and applications

HPSCs consist of two main components, heat pipes and vacuum-sealed glass tubes. Heat pipe is a closed container with a specific amount of working fluid (mainly water, methanol, or ethanol) that transfers heat through continuous evaporation-condensation cycle (Fig. 1). Heat pipes are inserted inside the vacuum-sealed glass tubes to form the HPSC (Fig. 2). The process of solar energy absorption and heat loss which occur in the HPSC is presented in Fig. 3. As it can be noticed, a portion of the solar radiation which strikes the glass tube is absorbed and used to vaporize the working fluid inside the heat pipes and the remainder is dissipated back into the environment. The vapor inside the heat pipes rises towards the condenser section where transfers its heat to the solar working fluid (mainly water, air, or glycol) through manifold of the HPSC, then condenses, and returns to the evaporator section, and the cycle continues [20]. As mentioned earlier, HPSCs have been utilized in various range of thermal applications and several review papers have summarized these studies comprehensively [21, 34]. Taking into account that the main focus of this review paper is to study the latest strategies, methods, and designs to enhance the performance of HPS systems and in order to avoid repetition of the previous published papers, only the most recent and remarkable studies regarding the applications and modelling of HPSCs are presented in Tables 1 and 2, respectively.

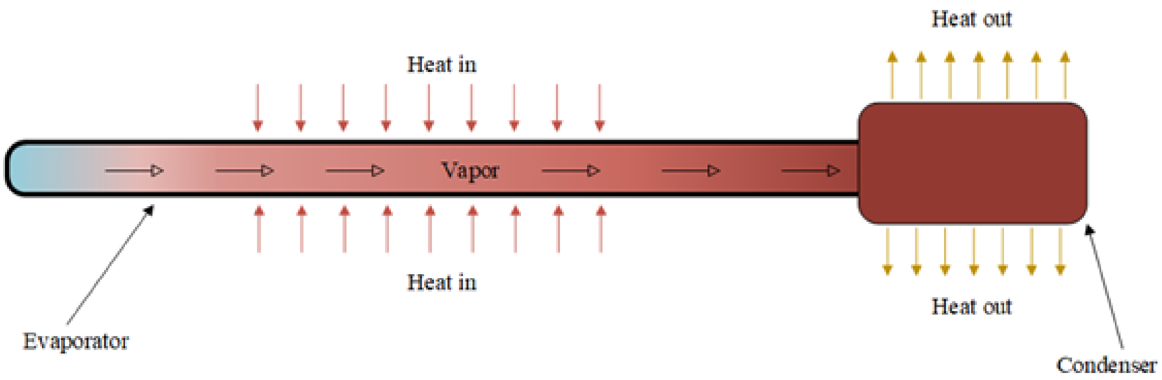

Fig.1. Schematic diagram of a heat pipe.

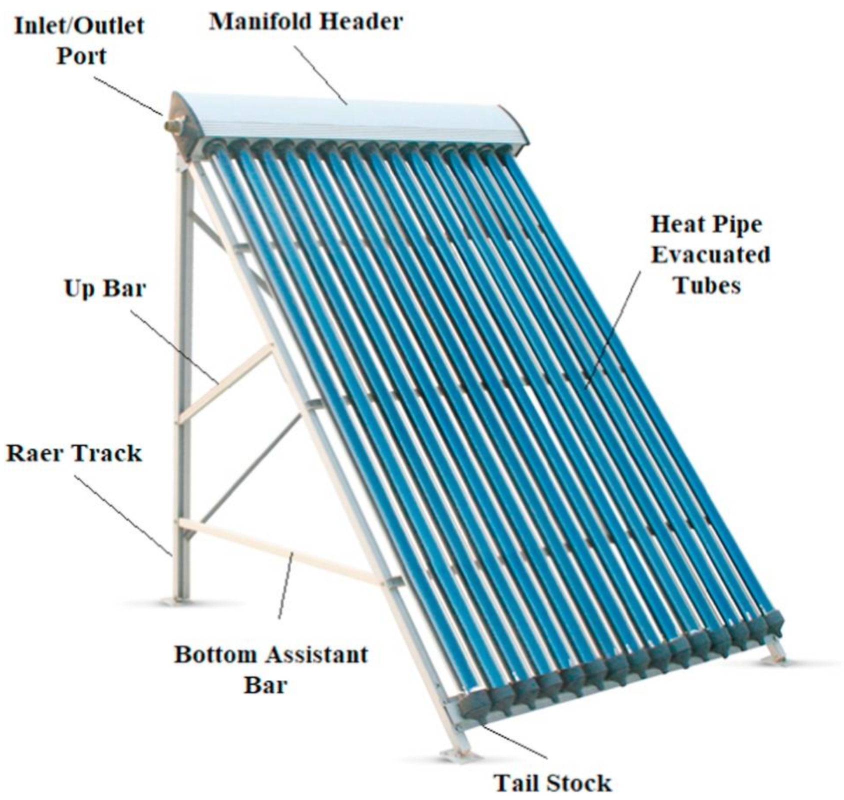

Fig. 2. Schematic diagram showing the main components of a HPSC [34].

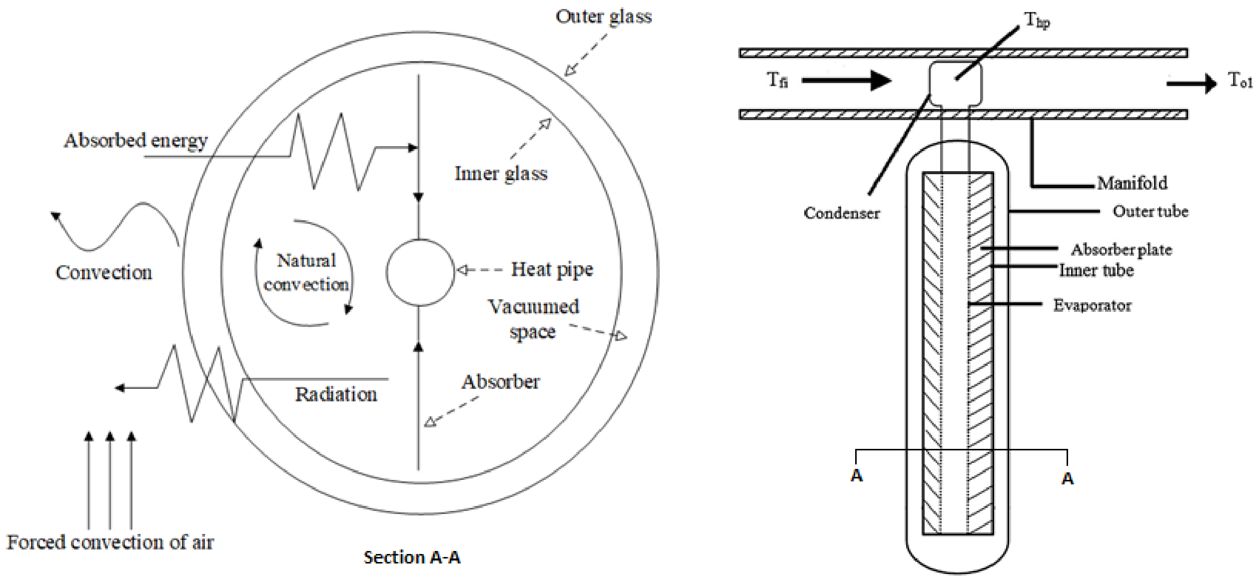

Fig. 3. Solar energy absorption, transformation, and loss in a single glass tube of a HPSC [42].

Table 1. Summary of recent studies on the application of HPSC in solar systems.

Application	Description	Source
Water heating	Design stages a HPSWH system in three European climates.	[43]
	Performance evaluation of a HPSWH system to supply the hot water demand of residential houses in summer.	[33]
	A comprehensive review on utilization of loop HPs in HPSWH systems.	[44]
	The effect of design parameters on the thermal performance of active HPSWH systems.	[45]
	A novel thermosiphon HPSWH system to reduce the overall costs of the system.	[46]
Space heating	Introducing a novel micro-heat pipe solar space heating system.	[47]
	Thermal evaluation of an integrated solar HP wall space heating system.	[48]
	Energy performance evaluation of a heat pipe water-based solar floor heating system.	[49]
Desalination	A heat pipe based solar desalination system integrated with an air bubble column humidifier.	[50]
	A heat pipe based multiple-effect diffusion solar still.	[51]
	A novel heat pipe based spiral multiple-effect diffusion solar still.	[52]
Power generation	Experimental analysis of a heat pipe based thermoelectric solar power generation system.	[53]
	Thermal performance of a heat pipe solar concentrated power plant.	[54]
	Experimental investigation on the performance of flat HP receivers in solar power plants.	[55]

Table 2. Summary of recent studies on mathematical modeling of HPS systems.

Description	Source
• A 3D CFD simulation was performed to study a new micro-heat pipe flat-plate solar air heating system.	[56]
• A three-dimensional steady-state mathematical model was developed based on thermal resistance network and finite volume methods to predict the temperature field and thermal performance of flat plate HPSCs.	[57]
• A three-dimensional numerical model was developed to analyze the heat transfer and fluid flow of a conceptual loop heat pipe solar central receiver.	[58]
• A numerical model was proposed to calculate the absorbed solar energy of HPSCs based on heat transfer processes including natural convection, radiation, forced convection, and phase change.	[59]
• Numerical algorithms were proposed to dynamically simulate the energy absorption process, thermal storage, and energy release modes of a HPSWH system with phase change materials (PCMs).	[60]
• An unsteady model was proposed to analyze a solar photovoltaic (PV)/loop HP heat pump system considering heat transfer and fluid flow processes.	[61]
• A dynamic model was proposed to analyze the thermal efficiency and coefficient of performance of a façade-based loop HPSWH system.	[62]
• A steady numerical model was developed based on thermal resistance network and effectiveness-NTU method to study a flat plate HPSC.	[42]

3. Strategies to improve the thermal performance of heat pipe solar systems

The main strategies that have been proposed to enhance the thermal performance of HPS systems have been focused on the structure of HPSCs (e.g., changing the geometry, modifying the manifold chamber configuration, inclination angle, and HP structure), new solar loop and heat pipe working fluid (e.g., new nanofluids and compositions), novel storage methods (mainly phase change materials), and turning the solar system into a multi-purpose system (applications such as water heating, space heating, electricity generation, and drying). This section covers all of these strategies comprehensively and investigates their role and efficacy in efficiency improvement of the HPS system.

3.1. Structure of HPSCs

The first aspect of HPS systems that has attracted researchers' attention is the structure of HPSCs. Different components of HPSCs, including heat pipes, manifold, and absorber, as well as add-on components, such as compound parabolic concentrators (CPCs), and transmission mechanisms have been chosen to be investigated [35, 36]. Many novel designs and configurations have been proposed and their effects on the thermal performance of HPSCs have been investigated. This section summarizes the most recent studies regarding the changes in the structure of HPSCs and their consequent effects on the performance of these collectors and solar systems.

3.1.1. Changes in structure of HPSC

Rybár et al. [63] changed the inner configuration of the manifold header of a HPSC by adding metal foam structural elements (Fig. 4) and compared its performance with the conventional manifold header. The experiments showed that the new structure improved the thermal power of the collector from 85.2 to 201.8 W per square meter of the collector area and increased the performance enhancement factor from 1.14 to 3.20.

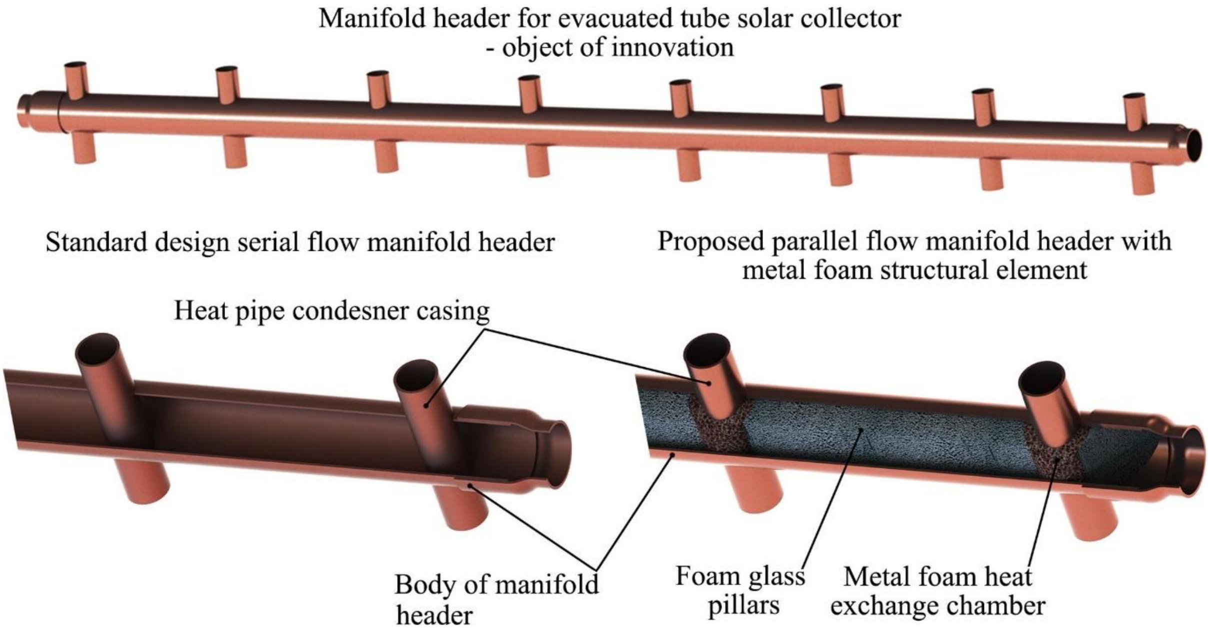

Fig. 4. The inner configuration of manifolds in conventional HPSCs and proposed header with metal foam structural element [63].

Zhang et al. [64] proposed the utilization of heat shields in the manifold header section of HPSCs (Fig. 5) and investigated its effect experimentally. Using heat shield enhanced the thermal performance of the HPSC especially at higher operational temperatures. The thermal efficiency of the solar collector equipped with heat shield reached 54.70% at high inlet temperatures which was 31.49% higher than the efficiency of a solar collector without heat shield. Also, the heat-loss coefficient reduced by 50.80% upon using heat shield in the HPSC.

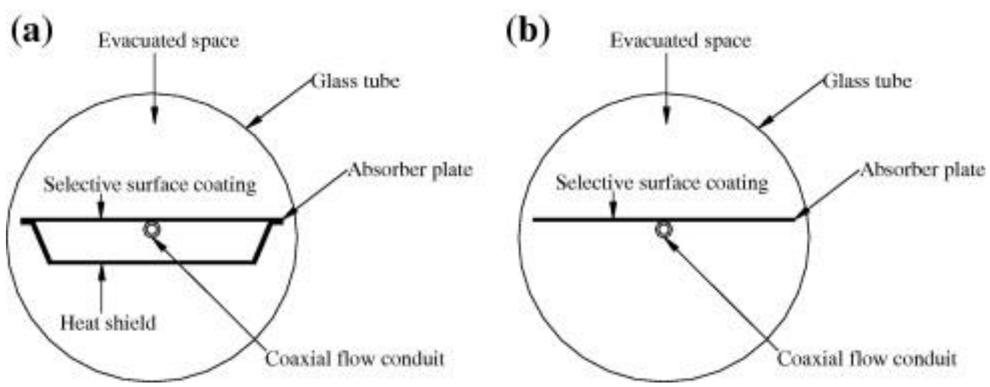

Fig. 5. Cross sectional view of HPSC's tubes: (a) with heat shield, (b) without a heat shield [64].

Azad [65] conducted comprehensive experiments to compare three flat plate HPSCs with different absorber and manifold configurations namely Types I, II, and III as are shown in Fig. 6. All solar collectors utilized two layers of 100-mesh stainless steel screen functioned as the wick structure of heat pipes. Type III had an integrated plate as the absorber surface while other collectors used mechanically bonded aluminum plates. Types I, II, and III utilized shell and tube, double-pipe, and shell and tube heat exchangers as their manifold, respectively. The results showed that Types I and III had lower production costs, however, a little leakage in one of the heat pipes could stop their functionality. Type I reached the highest thermal efficiency amongst all and design enhancement was recommended for Types II and III.

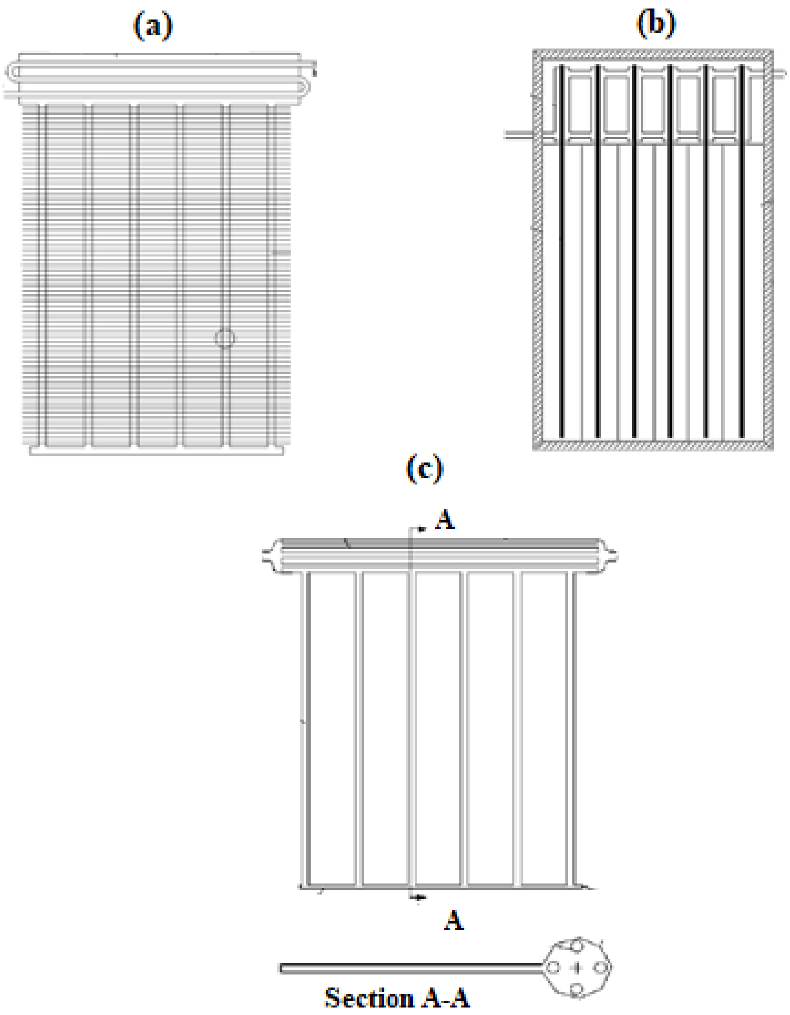

Fig. 6. Three different types of HPSCs: (a) Type I, (b) Type II, and (c) Type III [66].

Rassamakin et al. [12] proposed a new structure of flat plate HPSCs by implementing heat pipes made from aluminum alloy equipped with longitudinal grooves and wide fins (Fig. 7). The new structure was lighter and at the same time less expensive. The experimental results showed the better thermal performance of the new proposed collector in terms of heat transfer, hydraulic resistance, and thermal resistance which resulted in reaching the maximum thermal efficiency of 72%.

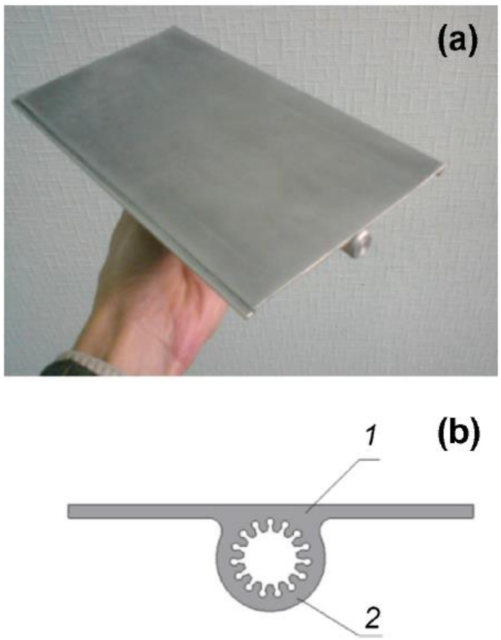

Fig. 7. The new design of finned HP: (a) outer view, (b) cross-sectional view (1- absorber, 2 grooved heat pipe [12].

Hu et al. [67] compared the performance of wickless and wire-meshed HPSCs (Fig. 8) used in a photovoltaic/thermal (PV/T) solar system at different inclination angles. The solar simulator was used to create identical climatic situations. The wickless HPSC was more sensitive to the inclination angle than the wire-meshed collector. The wire-meshed HPSC was recommended for latitudes less than 20° while the wickless HPSC had better performance at latitudes higher than 20°. The overall thermal efficiency of the wire-meshed and wickless HPSCs were 51.5% and 52.8%, respectively.

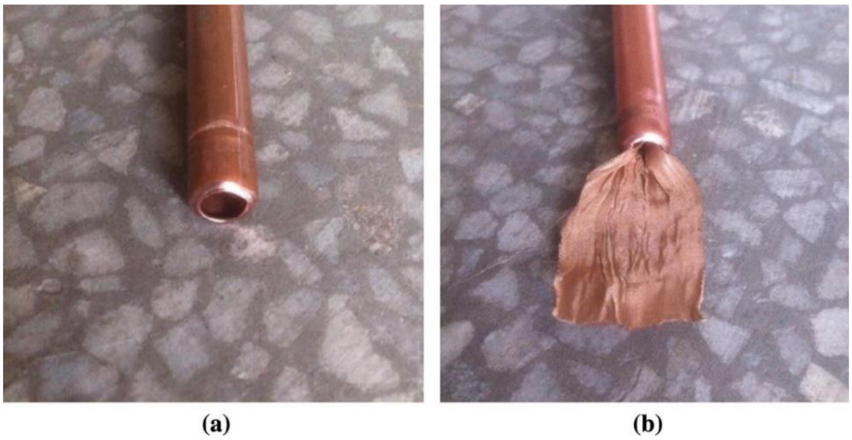

Fig. 8. Two different inner structure of HPs: (a) wickless (b) wire-meshed [67].

Wang et al. [68] designed novel flat micro-heat pipe arrays to be used in the HPSC of a solar air heating system (Fig. 9). The experimental results showed that the proposed configuration had higher thermal efficiency, higher heat transfer rate, and lower heat loss at high air flow rates compared with the conventional collectors. Table 3 summarizes the most important studies on HPSCs novel structures and their application in HPS systems along with their remarks and key findings.

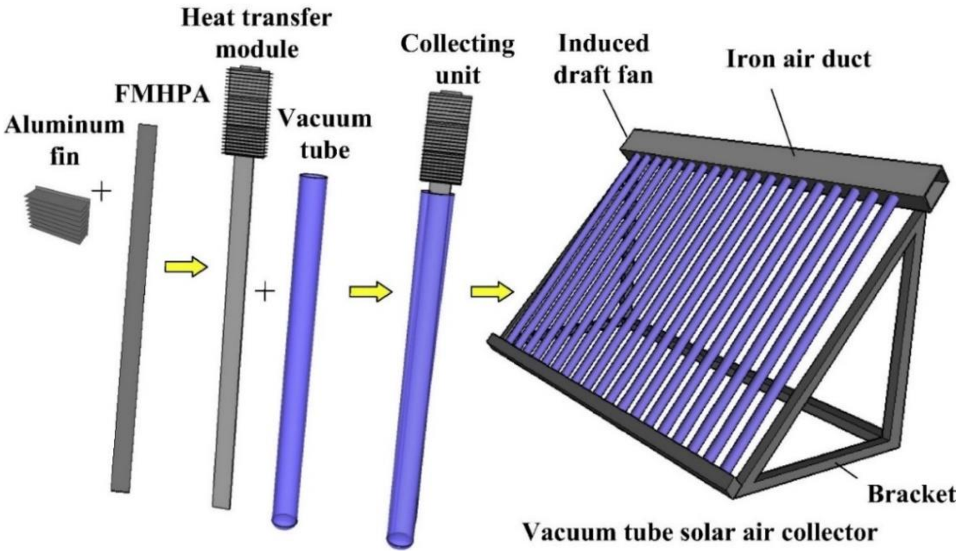

Fig. 9. The novel flat micro-heat pipe solar air collector [68].

Table 3. Summary of recent studies on novel structures of HPSCs.

Overview	Remarks and key findings	Schematic	Source
A novel structure of flat plate HPSC used in a SWH system was proposed by using one large integrated wickless heat pipe instead of separate heat pipes in the collector.	• The new structure had significant advantages such as high stability and low leakage. • The maximum achieved efficiency was 66%. • Higher thermal efficiencies can be reached by the proposed new structure using better thermal insulation.	Fig. 10	[69]
The effect of adding fin arrays into the condenser section of the heat pipes used in HPSCs.	• Using fin arrays in the HPSC increased its efficiency modestly. • The highest achieved efficiency was 60%. • The optimum value of mesh number was found to be 100 meshes/in for HPSCs.	Fig. 11	[70]
The effects of changing the surface radiative characteristics of the absorbers used in HPSCs on the thermal efficiency and losses.	• A direct relationship was observed between the surface emissivity and the heat loss of the HPSC. The heat loss increased by 31% as the surface emissivity increased from 0.03 to 0.12. • Changing the absorber’s characteristics have a positive effect on the HPSC’s efficiency at high-temperature applications and not in low-temperature ones.	-	[71]

The structure of a HPSC was changed by using foamed metals instead of conventional finned surfaces and oil instead of air in the evacuated glasses.	• The changes led to 25% increase in the outlet temperature of the collector. • The changes improved the heat transfer rate and caused better contact between the absorbers and heat pipes.	Fig. 12	[72]
A novel structure of flat plate HPSC was proposed by adding inner rings to the evaporator section of the heat pipes.	• Adding inner rings at 5-cm axial distances increased the outlet temperature of the collector and its efficiency by 12 °C and 12.2%, respectively.	-	[73]
The effect of changing the cross section of HPs on the thermal efficiency of flat plate HPSCs was investigated by designing three different cross section geometries including circular, semi-circular, and elliptical.	• The collector using HPs with elliptical cross section showed better performance compared to other geometries at low heat pipe filling ratios • At high heat pipe filling ratios, the collector using HPs with the semi-circular cross section showed worst performance among all geometries. • The optimum heat pipe filling ratio for the collector using HPs with elliptical cross section was about 10%.	-	[74]
The heat pipes’ physical shape was changed in the range of micro and mini sizes and its effects on the heat transfer limitations of the HPSC were studied.	• Heat transport limits of micro HPs were higher than mini HPs. • The dominant limits observed in micro HPs were capillary and entrainment limits.	-	[75]

The effect of increasing the number of HPs on the thermal performance of a HPSWH system was investigated based on ASHRAE standard 93–1986.	• The collectors with lower number of HPs showed better performance in the morning and in the afternoon compared with conventional collectors. • Further research on the design of the condenser section of the HPs was recommended for future studies to enhance the thermal efficiency of HPSCs.	Fig. 13	[30]
A new thin membrane HPSC was designed and experimented with the aim of increasing thermal efficiency with lower costs using two sheets of spot-welded stainless steel creating ribs.	• The efficiency was found to be in the range of 40%–70% which was slightly higher than that of conventional collectors. • A linear equation was obtained describing the thermal efficiency based on collector inlet and ambient temperature and also solar radiation.	Fig. 14	[76]
The effect of several structural parameters including wick structure, evaporator length, and inclination angle on the thermal efficiency of HPSCs was studied numerically.	• The solar collector with 7.3-mm thick sintered copper HPs which were filled with acetone and operated at inclination angle of 45° showed the optimum performance. • Important guidelines for efficient design of HPSCs were presented.	-	[77]
New coaxial heat pipes were designed for HPSCs which were made of two concentric tubes with refrigerant existing in the annulus volume space.	• The thermal efficiency of the collector improved by the maximum value of 67% at mass flow rate of 0.009 kg/s. • R22 and R 134a had almost similar performances as the heat pipe working fluid.	-	[78]

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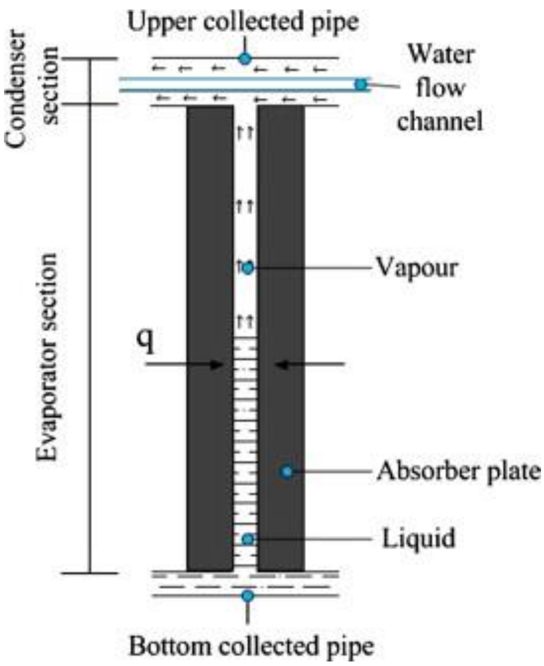

Fig. 10. The novel HPSC which uses one large integrated wickless heat pipe instead of separate heat pipes [69]

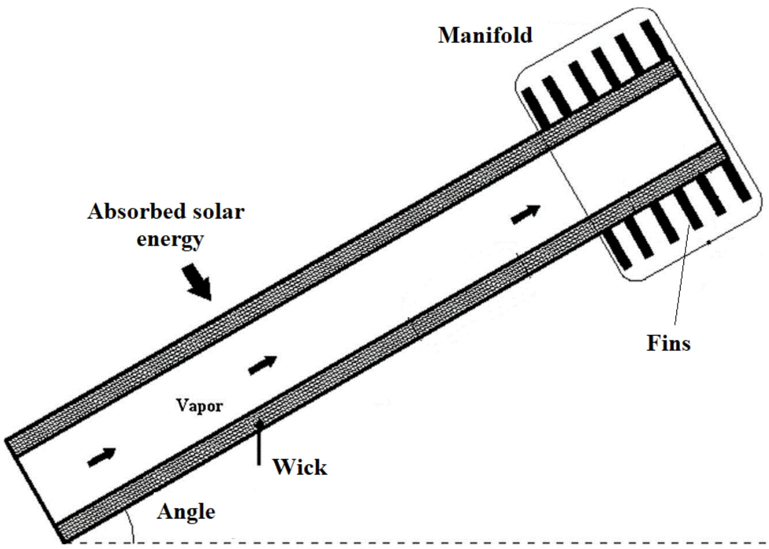

Fig. 11. The HPSC equipped with fin arrays in the condenser section [70].

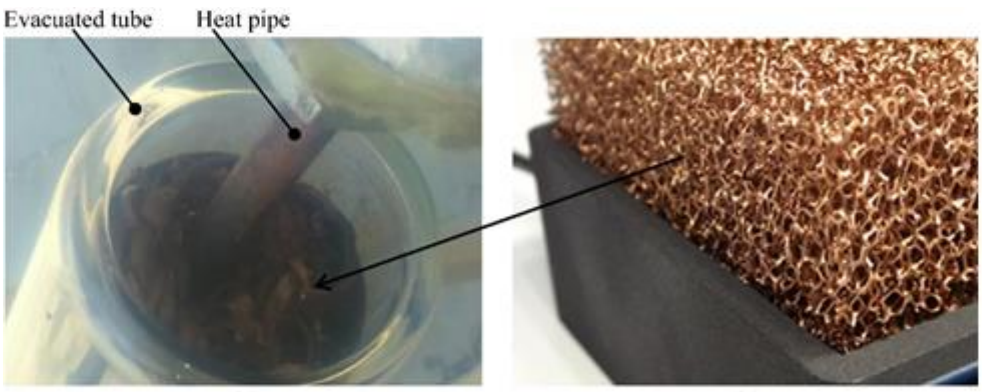

Fig. 12. The vacuum glass filled with foamed copper [72]

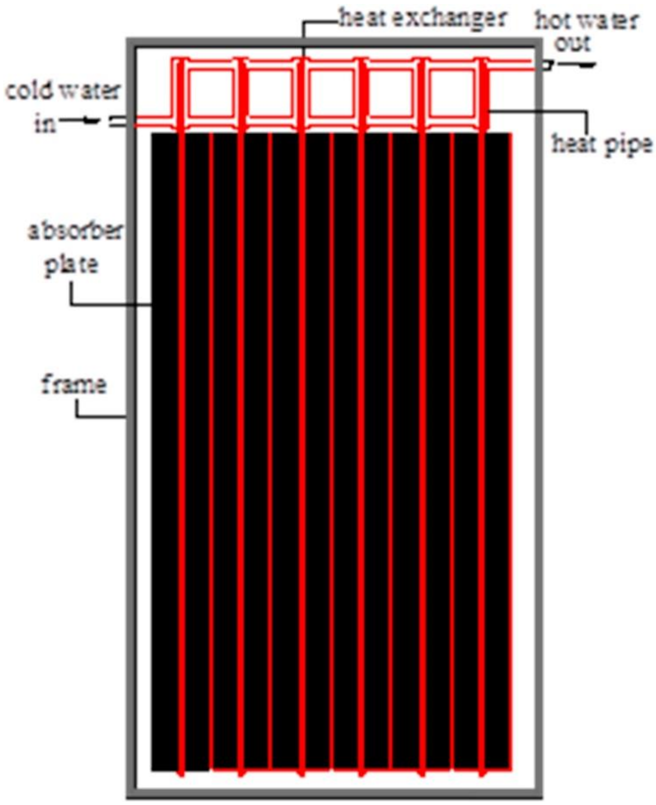

Fig. 13. Schematic diagram of HPSC used to study the effect of the number of heat pipes on the thermal performance of a HPSWH system [30]

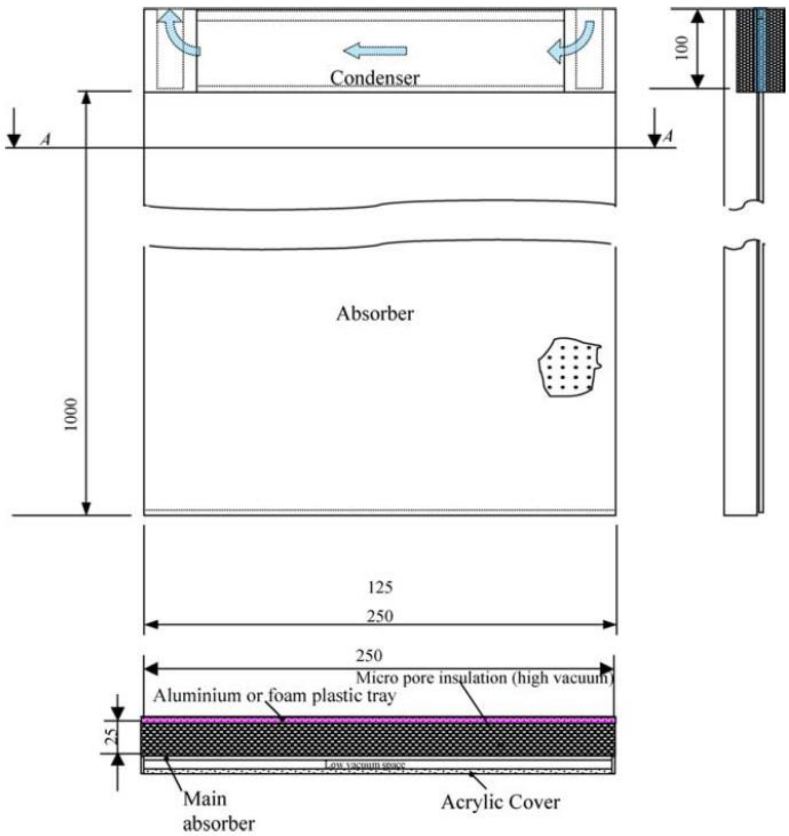

Fig. 14. Schematic diagram of the proposed thin membrane HPSC [76]

3.1.2. Assimilation of HPSCs and CPCs

Wang et al. [79] proposed the utilization of a crank rod transmission mechanism in a combination of CPCs and HPSCs to achieve a sun tracking CPC HPSC (Fig. 15). Experiments were conducted at three different working modes including fixed mode, intermittent tracking mode, and continuous tracking mode. The results showed that using the tracking mechanism increased the thermal efficiency by 30% compared to the fixed mode resulting in 1.9-2.3 times higher output energy. In addition, the thermal efficiency of the intermittent tracking mode was 3.6% higher than that of continuous tracking mode turning the intermittent tracking mode into the optimum operational mode.

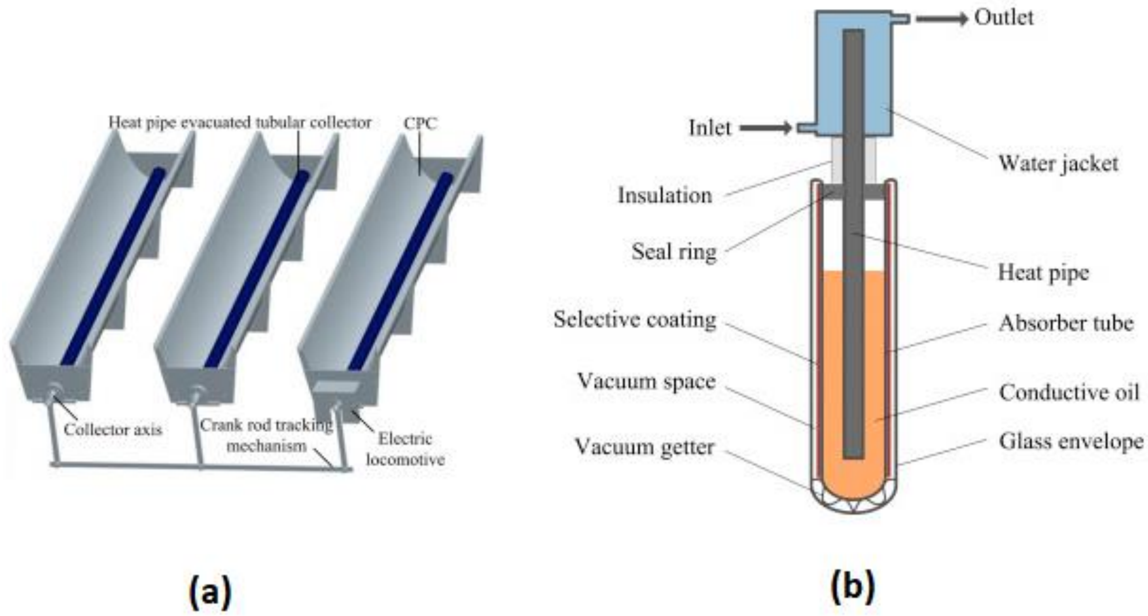

Fig. 15. (a) The sun tracking CPC HPSC, (b) a glass tube of the CPC HPSC [79].

Nkwetta et al. [80] compared the thermal performance of CPC- and conventional HPSCs in a range of operating conditions in medium temperature applications. The experimental results showed that the daily energy collection and average outlet temperature of the CPC solar collector were 25.42% and 30% higher than those of the conventional one. In another experimental study, the thermal performance of a low-concentrating ETHPSC with geometrical concentration ratio of 2.92 in solar air-conditioning systems was investigated [81]. Reaching to the optical efficiency of 79.13% proved that the combination of CPCs and HPSCs increased both thermal efficiency and flux concentration while decreased convective heat losses.

Nkwetta and Smyth [82] compared the performance of a CPC HPSC with single-sided and double-sided absorbers. Figure 16 shows the two proposed profiles of CPCs used in this study. Both collectors showed satisfactory performance to be used in solar systems for providing the heating demands of the buildings. The outlet temperature and thermal efficiency of the double-sided collector were higher than those of the single-sided one. Implementing these CPCs was recommended to decrease the required surface area of the HPSCs used in specific applications.

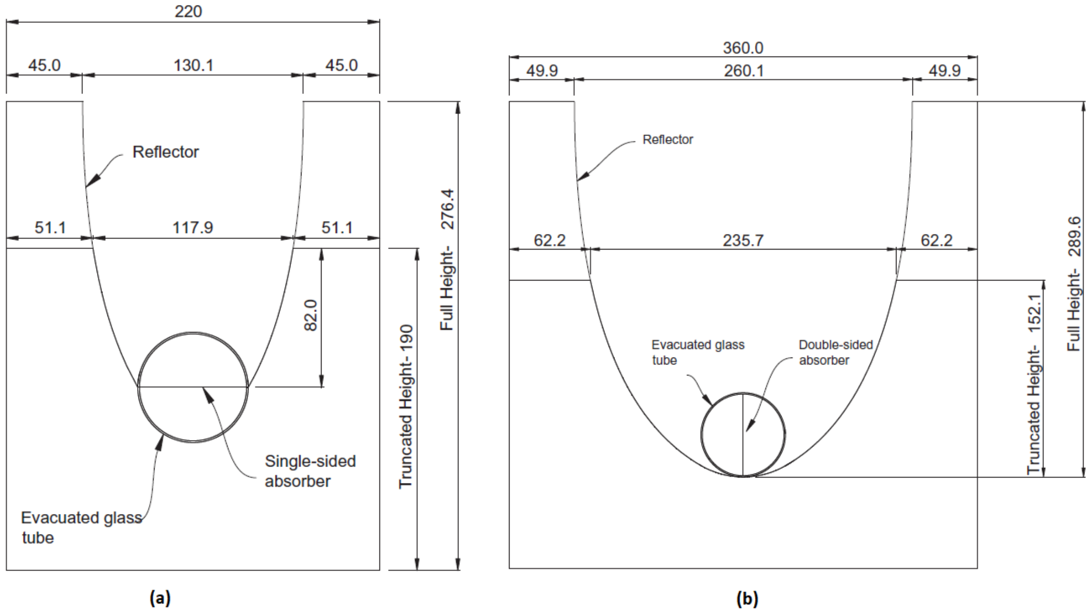

Fig. 16. (a) Single-sided and (b) double-sided absorbers used in CPC HPSCs [82].

In another study, the thermal performance of CPC HPSCs was compared to that of the conventional ones [83]. Figure 17 shows the proposed CPC profile used in the solar collector. Based on the obtained results, the thermal efficiency of the HPSC increased by 2.57% by utilizing the proposed CPCs. Also, the designed CPC-HPSCs was recommended for medium temperature applications as it improved collection efficiency and decreased response time.

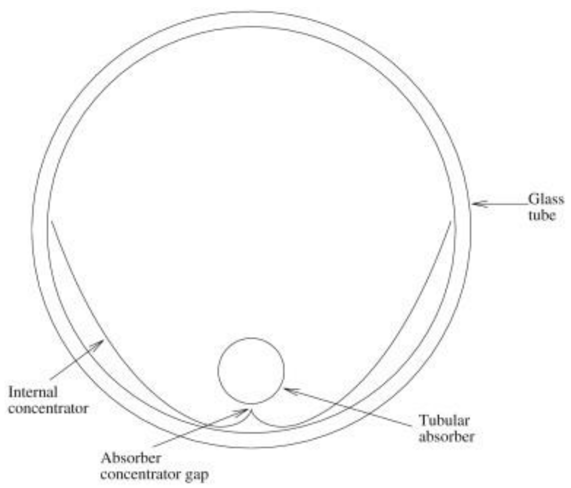

Fig. 17. The absorber profile of a CPC HPSC [83].

Xu et al. [84] proposed the new combination of CPCs with closed-end pulsating HPSCs and studied its performance experimentally. The main aim of the new design was to enhance solar radiation intensity and also to reduce the heat losses. Higher evaporation temperature increased the overall thermal resistance which affected the thermal efficiency of the collector negatively. Thermal resistance of the absorption process was 0.26 °C/W and the system reached the efficiencies up to 50% when solar radiation was around 800 W/m^2.

El Fadar et al. [85] proposed utilization of CPCs in heat pipe solar absorption cooling systems. A theoretical model was developed based on energy balance, heat and mass transfer, and thermodynamic of the processes to study the performance of the proposed system and then its results were validated by experimental data. The two major contributing factors to the thermal performance of the system were collector's width and absorber outer radius and the optimum performance of the system (COP=0.18) occurred at collector's width and absorber outer radius of 70 cm and 14.5 cm, respectively. Overall, the novel proposed system showed better performance compared to conventional systems.

Chamsaard et al. [86] studied the performance of CPC and HPSC combination in a solar water heating system according to standard ISO 9806–1. The maximum thermal efficiency of the proposed system with the collector surface area of 2.61 m^2 reached 78% leading to production of 3,433.87 kWh energy per year. The main advantage of the system was stated to be its capability to supply hot water over a period without changing the direction of the CPCs to track the sun. In a similar study, Pradhan et al. [87] evaluated the thermal performance of non-imaging CPC HPSCs at different tilt angles.

Zhao et al. [88] compared the performance of HPSCs with and without CPCs and the experimental results indicated that the CPC HPSCs have higher thermal efficiency compared with conventional HPSCs. Aghbalou et al. [89] proposed the utilization of CPC and HPSC combination as a new solar generator of a solar cooling system. A mathematical model based on heat and mass transfer processes was developed and its results showed that the proposed combination improved the maximum nominal coefficient of performance to14.37%.

3.2. Working fluids

Working fluid is considered as one of the most important factors which contribute to the performance of HPSCs determining whether the solar collector is effective in the operation [38]. It has been proved that enhancing the working fluid properties can improve the thermal and economic performance of HPSCs in HPS systems up to 50% and 28%, respectively [90]. Water is the common working fluid used in HPSCs due to its moderate vapour pressure, compatibility with copper, and high latent heat of vaporization [91]. However, water's heat transfer rate is low under low solar radiations, low ambient temperatures, and in cold winters leading to overall poor thermal performance of the solar system [92]. Therefore, significant efforts have been made in recent years to find alternative fluids to act as HP and solar loop working fluid, including various nanofluids and solutions, aiming to enhance the thermal performance of heat transfer fluid.

3.2.1. Nanofluids

Nanofluids are solid-liquid composite substances which include solid particles, rods, tubes, and fibres in nanometer scale suspended in various base fluids. These nanoparticles can be pure metals (e.g., Cu, Fe, and Au), metal oxides (e.g, Al_2O_3, TiO_2, and CuO), Nitrides (e.g, SiN and AlN), Carbides (e.g., TiC and SiC), and various sorts of carbon (graphite, diamond, and single and multi-wall carbon nanotubes (MWCNTs)). There are different categories of base fluids such as water, glycol, and ethylene [20]. Theoretical and experimental investigations have proved that the thermal properties of nanofluids are higher than those of pure fluids. For instance, thermal conductivity of MWCNT-water nanofluid with volumetric concentration of

1%, is 40% higher than pure water [20, 93]. In addition, the turbulence of the working fluid increases due to the Brownian motion of nanoparticles in base fluid resulting in higher heat transfer capability. To acquire more information about nanofluids, their applications, and challenges, referring to the review paper published by Saidur et al. [94] is recommended. Overall, nanofluids are the promising technology which have the potential of replacing the conventional fluids in HPS thermal systems [95]. Hence, this section reviews the recent studies regarding the application of nanofluids as the working fluid of HPs and solar working fluids in HPS systems.

Iranmanesh et al. [96] used graphene nanoplatelets (GNP)/distilled water nanofluid, at various concentrations ranging from 0.025 to 0.1 wt%, as the working fluid of a HPSC used in a SWH system. GNP nanosheets were added to the base fluid and ultrasonication method was used to prepare a homogeneous and stable nanofluid. First the thermal and physical properties of the prepared nanofluids such as viscosity, specific heat capacity, thermal conductivity, and stability were studied. Then, the thermal performance of the HPSWH system was studied experimentally at various water mass flow rates. The results showed that using nanofluid increased the thermal efficiency of the system up to 90.7%. Also, higher collector outlet temperature and thermal energy gain were achieved by increasing the concentration of nanoparticles.

Mahbubul et al. [97] compared the thermal performance of a HPS absorption cooling system when pure water and Carbon Nanotube (CNT)-water nanofluid was used as the working fluid. The experimental results revealed that using nanofluid with CNT concentration of 0.2 vol% improved the thermal efficiency from 56.7% (i.e. for pure water) to 66%. In addition, by considering x as T_i-T_a/G, the equation y= -183.4x+65.4 was reported to relate the collector efficiency (y) to collector inlet temperature (T_i), ambient temperature (T_a), and solar radiation (G). Ozsoy and Corumlu [98] conducted long term experiments to study the feasibility of using silver-water nanofluid as the working fluid of HPSCs used for commercial applications. A two-step electrochemical method including silver ions dispersion using electrolysis method and silver ions reduction using Tannic acid was applied to prepare the silver-water nanofluid at the concentration of 20 ppm. The nanofluid heat transfer properties were measured over a year as the stability of nanofluids may vary over time. The experimental results indicated that the thermal efficiency of the HPSC significantly increased by 20.7-40% when it was charged with nanofluid instead of pure water.

Zhao et al. [99] compared the performance of a HPSC charged with pure water and graphene-water nanofluid used in a SWH system at various concentrations of graphene nanoplatelets. By implementing a two-step method, graphene nanoparticles were added to the base fluid using a magnetic stirrer followed by PVP addition under ultrasonic oscillation conditions. The stability of the prepared nanofluid was investigated by continuous measurement of the thermal conductivity and viscosity. Experimental results under input heating conditions of 30-60 W showed that using graphene-water nanofluid with the concentration of 0.05 wt% increased the thermal efficiency of the HPSC by 10.7-15.1%. The most significant previous studies regarding the application of nanofluids as the HP and solar loop working fluids of HPS systems are summarized in Table 4. In addition, Table 5 summarizes the nanoparticles used to fabricate the nanofluids along with the thermo-physical properties of the produced nanofluid and their effects.

Table 4. Summary of recent studies on the application of nanofluids in as the HP and solar loop working fluids of HPS systems.

Overview	Working fluid(s)	Remarks and key findings	Source
Studying the effect of using CeO_2-water nanofluid as the solar working fluid of a HPSC on its thermal efficiency. The CeO2 nanoparticles with mean diameter of 25 nm were used to prepare nanofluids with volume concentrations of 0.015 to 0.035%. A two-step preparation method including adding CeO_2 nanoparticles to the base fluid and then using ultrasonic homogenizer for one and half hour.	CeO_2/water	• The maximum heat transfer rate occurred at 0.017 kg/s.m^2 mass flux rate of 0.035 vol.% nanofluid. • Compared to previous studies, the maximum heat transfer rate of the collector with CeO_2-water nanofluid was 34% more than that of previous collectors with other nanofluids. • CeO_2-water was highly recommended as an efficient solar working fluid with good thermal properties.	[100]
Experimental thermal performance evaluation of a FPHPSC using CNT-water nanofluids with volume concentrations of 0.15%, 0.45%, 0.60% and 1% in a SWH system at various tilt angles.	CNT-water Pure water	• The collector with nanofluid showed better performance at different conditions compared to the collector with pure water. • There was a direct relation between the thermal efficiency of the HPSC and nanofluid's CNT volume concentration. • Maximum thermal efficiency of 73% was obtained for nanofluid volume concentration of 0.60%	[101]

The nanofluid was prepared by immersion of CNTs in sulfuric acid and nitric acid following by treating in ultrasound bath for 2 hours.			
Experimental thermal performance evaluation of a FPHPSC with V-type absorbers using various working fluids and nanofluids utilized in a SWH system.	Methanol Ethanol DI water TiO_2- water	• Among all the working fluids, TiO_2- water showed the best performance. Significant rise (more than 15%) was observed in the thermal efficiency by using TiO_2- water nanofluid. • V-type FPHPSC was an efficient option for domestic SWH applications.	[102]
An experimental investigation to determine the thermal efficiency of a HPSC using (SWCNT-water) nanofluid as the solar working fluid with volume concentrations of 0.05-0.2% at flow rates of 0.008-0.025 kg/s. The nanofluid was prepared by adding nanoparticles to base fluid followed by adding Sodium Dodecyl Sulfate surfactants and sonication using a high pressure ultrasonic homogenizer.	SWCNT-water Pure water	• The maximum thermal efficiency was 93.43% occurred at SWCNTs concentration and mass flow rate of 0.2 vol.% and 0.025 kg/s, respectively. • Increasing the concentration of SWCNTs in nanofluid increased the collector efficiency significantly. • SWCNT-water nanofluid was highly recommended as an efficient solar working fluid.	[103]

Analyzing the thermal performance of a thermosyphon HPSC under real operational conditions with various working fluids.	Distilled water Al_2O_3-water Al_2O_3-water-surfactant water-surfactant	• Water-surfactant showed the best performance by increasing the thermal efficiency by 45.23% followed by Al_2O_3-water by 15.24% enhancement in thermal efficiency.	[104]
Preparation of a novel nanofluid by combining oxidized MWCNTs with hydroxyl radicals and using it as the working fluid of a HPSC. MWCNTs were dissolved in distilled water followed by a 2-hour dispersion using ultrasonic unit.	Oxidized MWCNT-hydroxyl radicals	• The oxidized MWCNT nanofluids showed better thermal performance compared to MWCNT nanofluids in terms of operating temperature range and absorbed energy. • The thermal conductivity of the oxidized MWCNT nanofluid with the volume concentration of 0.1% was 12.6% more than when distilled water was used as the working fluid.	[105]
Experimental study to analyze the effect of nanofluids on the thermal efficiency of a ETHPSC used in a SWH system. The concentration of TiO_2 in nanofluid and the size of nanoparticles were 0.3 vol.% and 30-50nm, respectively.	Pure water TiO_2-water	• The collector efficiency was 58 % when it was operated by pure water and reached 73 % by using the nanofluid.	[106]

Experimental thermal performance evaluation of a FPHPSC using nanofluids in a SWH system The size and concentration of TiO_2 nanoparticle were 40 nm and 80 ml/l, respectively.	Propanol TiO_2-water Pure water	• The collector with TiO_2-water nanofluid showed better performance at different conditions compared with the collector with pure water. • Using nanofluid improved the thermal conductivity and convective heat transfer coefficient of the working fluid.	[107]
Analysing the utilization of nanofluids as the solar working fluid in ETHPSCs with the particle size of 30–50 nm, concentration of 0.3 vol.%, and fixed mass flow rate of 2.7 l/min. Dispersion of nanopowder into the base fluid was done using the two-step method.	TiO_2-water Pure water	• Comparing the thermal performance of the collectors using water and nanofluid showed 16.75% higher thermal efficiency with the latter.	[108]
Comparison of the thermal performance of a FPHPSC with and without CNT-water nanofluids	Pure water CNT-water	• Using nanofluid improved the thermal performance of the system at different conditions compared to the pure water. • The optimum tilt angle was 50°.	[109]

A similar study to [108] but to investigate the impact of CNT volume concentration in the range of 1–3% with the particle size of 20–30 nm.	TiO_2-water Pure water	• The maximum thermal efficiency increase was 42% using 2 vol.% concentration of TiO_2-water nanofluid.	[110]
Experimental performance evaluation of a HPSWH system using Magnesium oxide (MgO)-water as the solar working fluid.	MgO-water	• The performance of the solar system was better with nanofluid at all concentrations. • Increasing the concentration of nanofluid had a positive effect on the performance of the solar system.	[111]
Thermal performance comparison of HPSCs with three different working fluids at different coolant mass flow rates and tilt angles.	Pure water Water-surfactant (2-ethyl-hexanol) CNT-water	• The collector with water-surfactant had the highest thermal efficiency followed by CNT-water and pure water, respectively.	[112]

Table 5. A summary of nanoparticles used to fabricate nanofluids along with the thermo-physical properties and effects.

Nanoparticle	**Basefluid**	**Concentration (vol. %)**	**Temperature (°C)**	**Thermal Conductivity (W/mK)**	**Heat capacity (kj/kgK)**	**Effect**	**Reference**
Graphene nanoplatelets	Distilled water	0.1	30	0.77	3.65	Maximum thermal efficiency of 90.7%	[96]
Carbon Nanotube	Water	0.2	30	0.65	3.25	Thermal efficiency increase from 56.7% to 66%	[97]
Silver	Water	0.02	30	1.05	-	Thermal efficiency increase by 20.7-40%	[98]
CeO_2	Water	0.035 vol	18	0.6539	4.17	Thermal efficiency increase of 34%	[100]
Single Walled Carbon Nanotubes	Water	0.2	30	0.65	3.15	The maximum thermal efficiency of 93.43%	[28]
Oxidized multiwall carbon nanotube	Hydroxyl radicals	0.1	40	0.65	-	Thermal conductivity increase of 12.6%	[105]
Al_2O_3	Water	0.2	30	-	-	Thermal efficiency enhancement of 15.24%	[104]
CuO	Water	0.1	30	-	-	The coil heat transfer increase of 39%	[113]

3.2.2. Other working fluids

Ersoz [38] used six various working fluids (i.e., acetone, hexane, ethanol, petroleum ether, methanol, and chloroform) and studied their effect on the thermal performance of a heat pipe solar air heating system under climatic conditions of Turkey. By changing the air velocity in the range of 2-4 m/s, acetone and chloroform showed the best energy and exergy performance among all the working fluids. It is worth noting that further studies regarding the investigation of this air heating system under different heat pipe filling ratios, pipe diameters, inclination angles, and materials efficiency seems necessary to improve the energy efficiency of the system to higher values. Arab and Abbas [90] studied the application of pentane, acetone, ammonia, methanol, and water in HPSCs theoretically and experimentally with the aim of improving their performance in a concentric SWH system. It was found that water had the best performance among all other working fluids.

Patel et al. [114] prepared eleven working fluids to study the effect of using them in closed loop pulsating HPs of a solar water heating system. Deionized water, acetone, methanol, and ethanol were used as pure fluids while the mixture of water with ethanol, methanol, and acetone were used as binary fluids and sodium dodecyl sulphate was the surfactant. The filling ratio of HPs and the concentration range of solutions were 50% and 30-100 ppm, respectively. Comparing the experimental results indicated that acetone was the best pure working fluid followed by methanol, ethanol, and water. For binary fluid, water-acetone led to better performance compared with water-ethanol and water-methanol. Also, water-acetone concentrations of 45 ppm and 60 ppm showed better performance compared to 30 ppm and 100 ppm ones.

Jahanbakhsh et al. [115] prepared mixtures of water and ethanol with different volume fractions and investigated their performance as the working fluid of HPSCs. Solutions with 50 and 75 vol.% ethanol showed the maximum heat transfer rate resulting in the thermal efficiency of

52%. In a similar study, Guo et al. [92] conducted several experiments to investigate the effect of water-ethanol solution with different volume ratios on the performance of HPSCs at low solar radiations. The heat pipes with 40 vol.% ethanol showed the best performance in terms of Start-up speed and heat transfer rate.

Kabeel et al. [78] investigated the effect of filling ratio of two types of refrigerants (i.e. R22 and R134a) on the thermal efficiency of a HPSC used in a solar air heating system. The filling ratio and air mass flow rates in this study ranged from 30% to 60% and 0.0051 to 0.009 kg/s, respectively. The results demonstrated that the filling ratio of 30% for mass flow rate of 0.0051 and 0.0062 kg/s and filling ratio of 40% for mass flow rate of 0.007 and 0.009 kg/s resulted in the optimum thermal performance. In addition, two refrigerants showed almost similar thermal performances.

Hussein et al. [74] analyzed the influence of different distilled water filling ratios (i.e. 10%, 20% and 35%) on the thermal performance of a flat plate HPSC with different pipes cross sections. The results showed that the wickless heat pipe solar collector with circular cross section had its best performance at filling ratio of 20%, while this value was 10% for elliptical cross section. The filling ratio of 20% did not show a good performance in the solar collector with the semi-circular cross section.

Esen and Esen [116] experimentally investigated the effect of various working fluids (i.e. R134a, R407C, and R410A) on thermal performance of a two-phase closed thermosyphon solar water heating system. R410A had the best performance under clear sky climatic conditions. Esen [117] also studied the application of R-134a, R-407C, and R-22 as the working fluid of a HPSC used in a solar cooking system. R-407C had the best performance in terms of efficiency and cooking time of different raw materials (e.g., rice, potato, and chicken).

Joo and Kwak [118] used indoor apparatus to create similar conditions to compare the performance of HPSCs with different heat pipe working fluids. The studied working fluids were methyl acetate, flutec-pp9, water, and ethanol. The experimental results indicated that the values of heat removal factor at the incidence angle of 40° were 0.6636, 0.6572, 0.6147, and 0.525 for water, methyl acetate, ethanol, and flutec-pp9, respectively, turning water into the working fluid with highest thermal efficiency and fastest response performance.

3.3. Storage methods

Intermittent and periodic nature of solar radiation emphasizes the crucial role of thermal energy storage in solar systems. Thermal energy storage conserves energy, reduces peak load, and fills the gap between demand and supply by storing extra thermal energy during sunshine hours and releasing this energy whenever needed (e.g., low solar radiation, night time, peak load) [119, 120]. Thermal energy in solar systems is stored in the form of sensible heat, latent heat, or a combination of both. However, the main focus of researchers in HPS systems, in all range of applications, has been on the latent form of storage [121]. This is mainly due to the advantage of this method to store and release thermal energy in peculiar isothermal processes (phase change processes) with high capacity of heat transfer [122]. This section reviews the recent studies regarding the novel PCMs and heat exchanger configurations and designs used in HPS systems.

Naghavi et al. [60] proposed a novel configuration by filling the manifold of a HPSC with PCMs to act as a latent heat thermal energy storage. The stored heat was then used to increase the temperature of water by transferring the energy through a finned heat exchanger pipe located in the storage tank (Fig. 18). The theoretical analysis showed that the thermal efficiency of the proposed system was higher than that of a similar conventional one without PCM storage tank. In addition, the proposed system's sensitivity to water extraction was lower than that of a conventional system. The authors recommended the new configuration to be coupled with the conventional HPSWH systems enabling the operation at low solar radiations and night time.

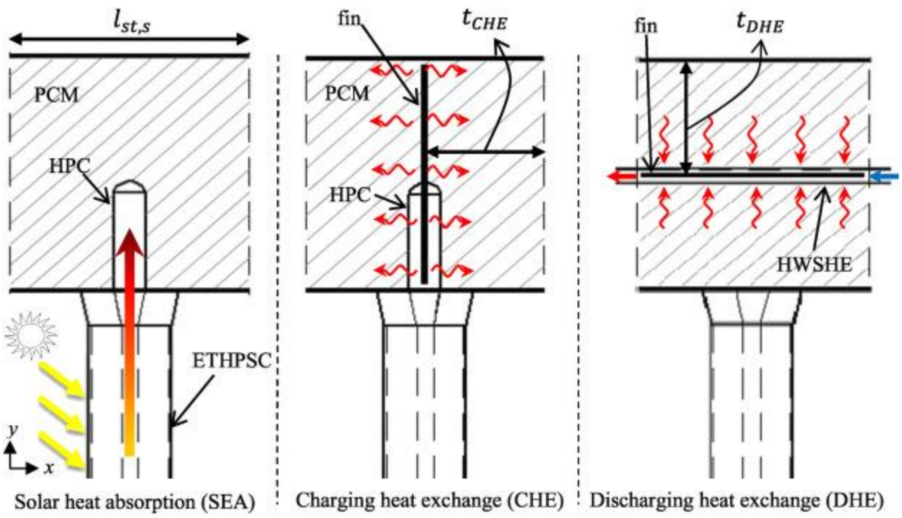

Fig. 18. Heat transfer process in a HPSC uses PCMs as the latent heat energy storage [60].

Wang et al. [68] proposed a novel storage method by using PCMs in the flat micro-heat pipe arrays of a solar air heating system. In their proposed design (Fig. 19), lauric acid, that is actually a fatty acid, was used as the storage material. The thermal efficiency of the collector was investigated experimentally based on charging and discharging time at various air flow rates. The collector showed better performance at higher mass flow rates leading to shorter charging and discharging times. The cumulative heat transfer during the discharge process was in the range of 4210 to 4300 kJ.

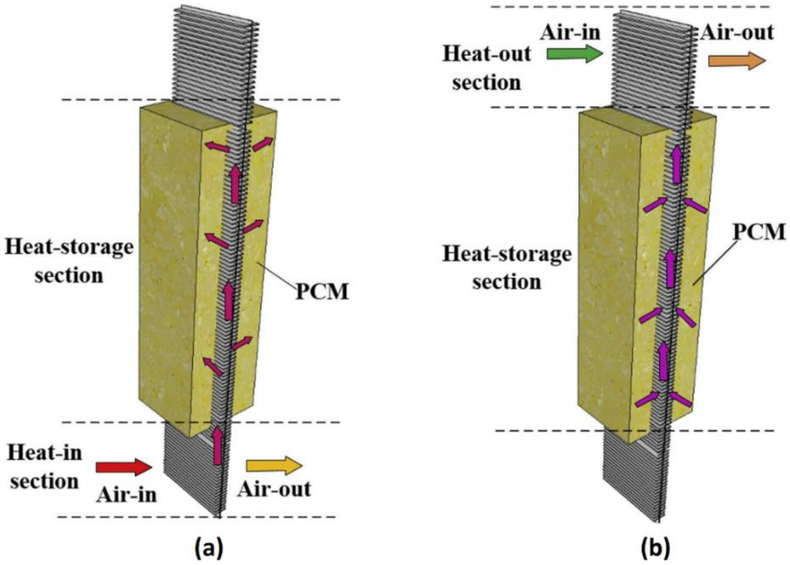

Fig. 19. Application of PCMs in the flat micro-heat pipe arrays of a solar air heating system: (a) charging working principle, (b) discharging working principle [68].

Wang et al. [123] introduced a novel type of integrated collector storage HPSCs used in solar air heating systems comprising flat micro-heat pipe arrays and PCMs (Fig. 20). The heat transfer characteristics of the proposed system was studied experimentally and the results indicated that the charging efficiency varied in the range of 56.6–65.5% and the discharging efficiency was 91.6%. Moreover, increasing the flow rate from 100 m^3/h to 150 and 200 m^3/h increased the heat extraction by 10% and 26% while decreasing the heat extraction time by 8% and 20%, respectively.

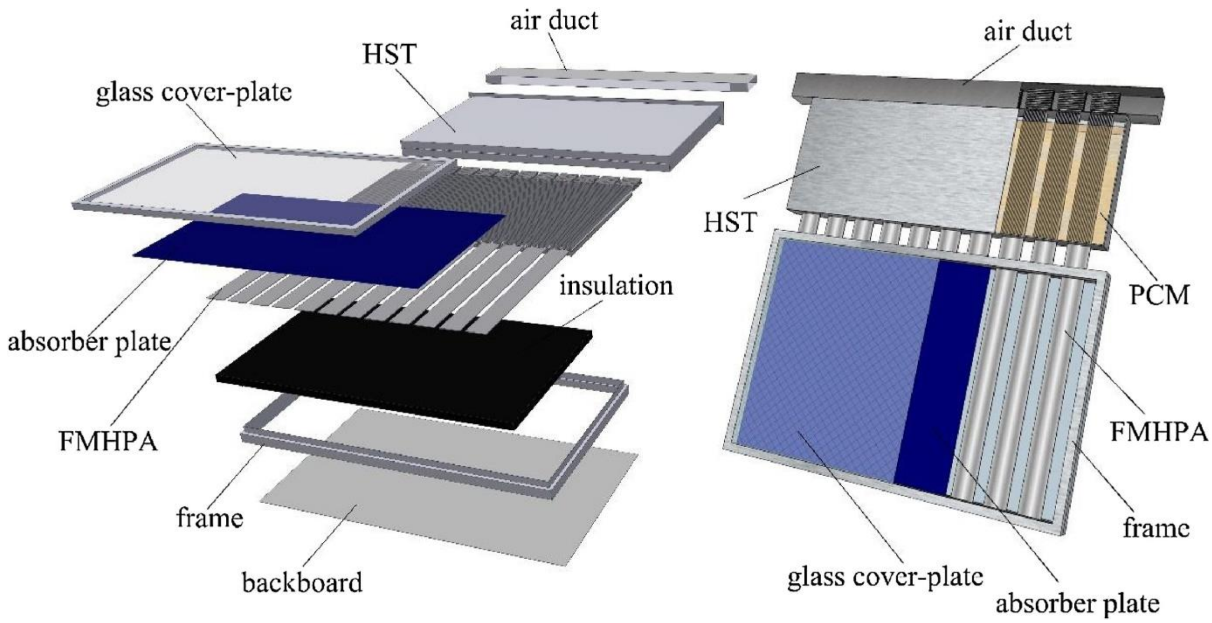

Fig. 20. Utilization of PCMs in flat micro-heat pipe array solar air heating system [123].

Li and Zhai [121] proposed the utilization of composite PCMs in a HPSC designed for mid-temperature applications (Fig. 21). The PCM used in this study was made of expanded graphite and erythritol. The experimental and theoretical results indicated that the composite of 3 wt% expanded graphite was the optimum PCM for this system leading to the storage efficiency of 40.17% for mid-temperature application.

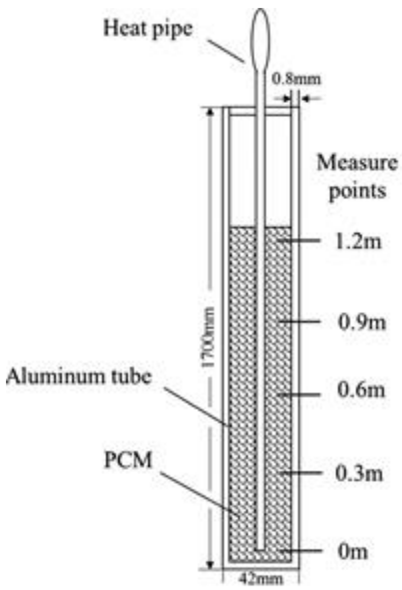

Fig. 21. The composite PCMs used in a HPSC [121].

During the charging process of conventional heat pipe solar collector/storage systems, the solar radiation only reaches the exposed area of the glass tubes resulting in uneven heating of the PCM (Fig. 22a). To resolve this issue, Felinski and Sekret [124] proposed the novel concept of using PCM (Paraffin) in a CPC HPSC to act as the solar thermal energy storage (Fig. 22b). The results indicated that the new configuration improved the temperature distribution in the PCM. In addition, the average and the maximum charging efficiency of the new system were, respectively, 31-36%, and 40- 49% higher than those of the conventional systems.

Faegh and Shafii [125] introduced a novel HP solar still system using HPSCs and PCMs to increase the operating hours of the system even after sunset (Fig. 23). The proposed system had a tank which was filled with paraffin to act as the cooling unit. During the day, the condensation heat of the vaporized water was transferred to the storage tank and turned into potable water. By decreasing the solar radiation in the evening, the storage tank acted as the evaporator using the heat pipes located inside the PCM tank to transfer heat to the saline water. The experiments showed that the overall efficiency of the system improved significantly and fresh water production rate increased by 6.555 L/m^2 per day. The most significant previous studies on new storage methods in HPS systems are summarized in Table 6.

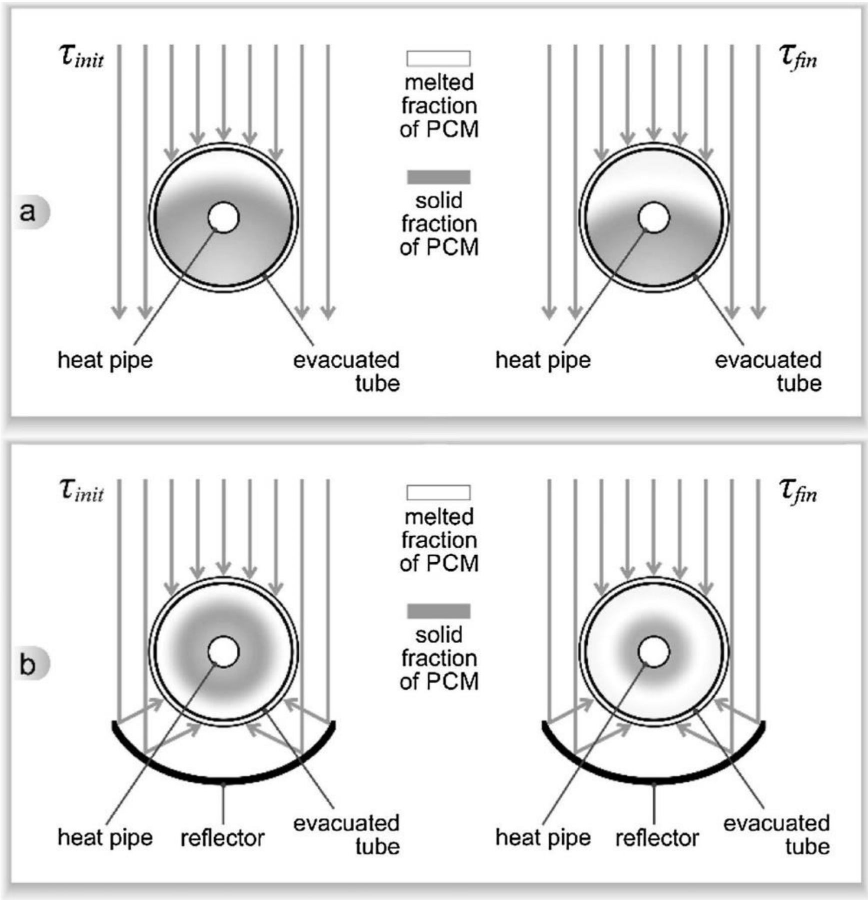

Fig. 22. The PCM melting process in a HPSC: (a) without CPCs, (b) with CPCs [124].

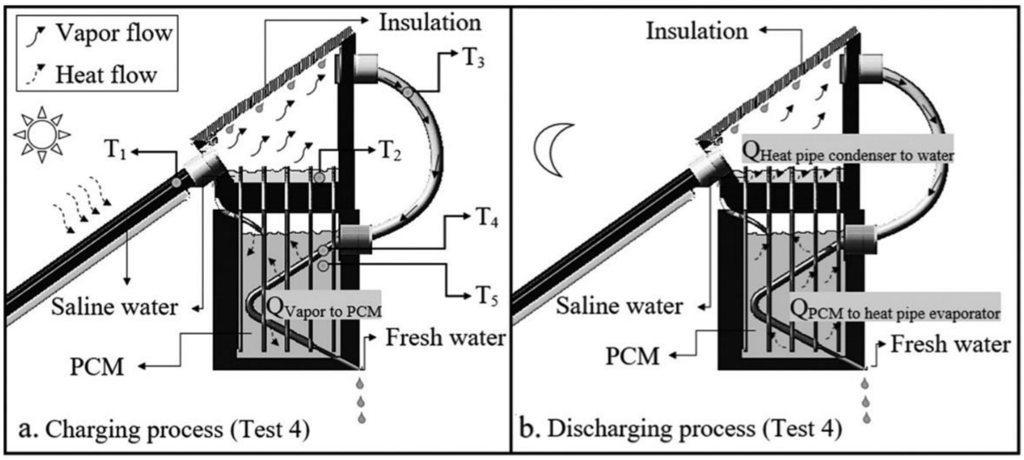

Fig. 23. Heat pipe solar still equipped with PCM condenser: (a) Charging process (b) discharging process [125].

Table 6. Summary of recent studies on new storage methods in a HPS system.

Overview	PCM Material	Remarks and key findings	Figure	Source
The effect of using PCMs in the HPSC of a solar water heating system was studied.	Technical grade paraffin	• Heat loss was delayed in the evening when solar radiation was low. • Higher hot water temperatures were achieved in the storage tank. • The annual solar fraction improved by 20.5% compared with the conventional systems without PCM storage.	-	[126]
The application of PCMs in solar thermal systems including HPWH systems was reviewed comprehensively.	Different PCMs and composites	• Application of PCM in HPSCs has a great research potential. • The thermal capacity of solar thermal systems increases considerably by using PCM. • Further research is necessary for large-scale applications.	-	[127]

Application of PCM in a new type of cylindrical HPSC was investigated experimentally.	Paraffin wax/water	• Increasing the mass fraction of PCM reduced thermal efficiency. For instance, composition of 56.7 wt% paraffin wax and 100 wt% water showed the worst performance • The HPSC filled with 25.28 wt% water showed the highest average thermal efficiency	Fig. 24	[128]
A mathematical model was developed to analyze the thermal performance of HPs with integrated PCMs used in solar applications.	Cu/0.3Si	• To simulate the performance of HP in solar applications accurately, variable thermal input and boundary conditions should be defined. • The effect of different parameters such as PCM enclosure height on the heat transfer rate of the system was investigated. • Higher height to diameter ratio of the PCM enclosure decreased HP bottom wall temperature and increased PCM melting.	-	[129]
Integration of PCMs within the HPSC of a solar water heating system was investigated.	Tritriacontane Erythritol	• The thermal efficiency improved by 26-66% depending on the mode of operation compared with the conventional collectors without PCM storage.	-	[130]

A new heat pipe solar collector/storage system was analyzed.	Commercial-grade paraffin	• The operating time of the HPSC was extended by heat recovery of the stored energy during the discharge process. • Less heat loss from both the collector and piping. • The overall amount of useful heat enhanced by 45-79%, compared with the conventional collectors without PCM storage.	Fig. 25	[131]
The integration of PCMs and HPs for different applications including solar thermal systems was reviewed.	Different PCMs and composites	• The integration of PCMs and HPs improves the thermal conductivity and overall efficiency and prevents overheating. • Using PCMs as an internal section of the HP and the integration of PCMs and HPs in low temperature solar applications were recommended for future research.	-	[132]
A compact design of HPSCs integrated with latent heat storage was proposed to be used in solar water heating systems.	Paraffin wax	• The system's thermal efficiency varied between 38–42% and 34–36% in sunny and cloudy-rainy days, respectively. • The system could partly supply the night hot-water demands • The new design improved the thermal conductivity and overall efficiency and prevented overheating.	-	[133]

A novel HPSC integrated with porous phase change materials to be used in solar air cooling and conditioning systems was introduced.	granular solid–liquid PCMs combined with RT100 and high-density polyethylene	• the whole system operated at the isothermal status with temperatures over 70 °C. • The proposed design improved the heat transfer properties, specifically thermal conductivity, in absorption and release processes. • The results were promising showing the great potential of the system for industry applications.	-	[134]

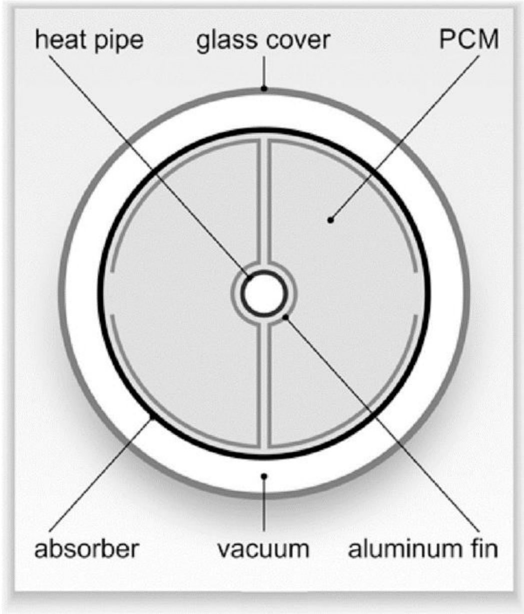

Fig. 24. Cross section of the proposed HPSC integrated with PCM [131].

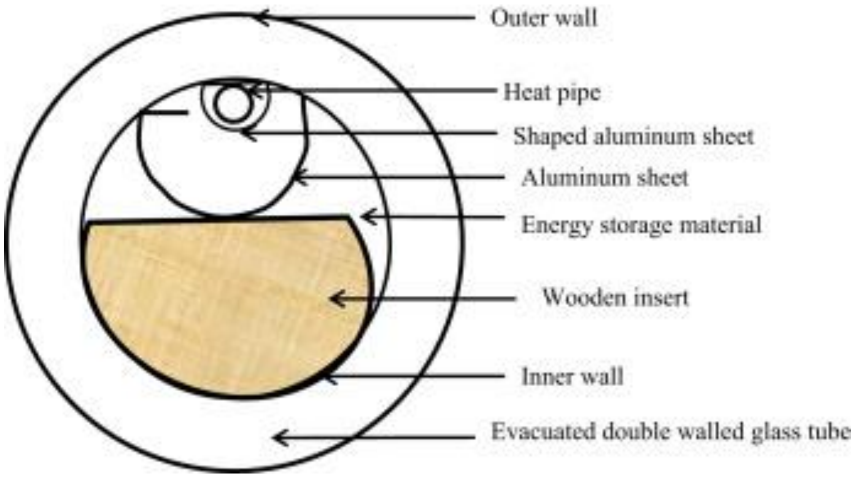

Fig. 25. Cross section of the proposed HPSC integrated with PCM [128].

Overall, the unique advantages of the PCM storage method using have attracted researchers to focus more on latent heat storage than conventional sensible one. Four main configurations have been proposed so far including using PCMs inside the manifold section of HPSCs, using PCMs as the absorber of HPs in HPSCs, filling the interior space of the vacuum glass tubes with PCMs, and finally filling a separate tank with PCMs and integrating that with a sensible storage tank. Taking the published papers so far, integrating the latent heat storage tank with the conventional sensible heat storage tanks in heat pipe solar systems seems more promising.

3.4. Multi-purpose applications

Another strategy which has been investigated widely in recent years is increasing the overall efficiency of the HPS system and HPSC at the same time. This can be achieved by turning the solar system into a double-purpose or multi-purpose system. This strategy not only results in utilization of the maximum capability of the solar system, but also reduces the inlet temperature of the HPSC which significantly increases the collector's efficiency [135]. In most of the studies in this field, solar water heating has been considered as the base application and other applications such as space heating, drying, and power generation, have been added to the system. Among all the applications, a great share of the studies has been allocated to generating electricity using PVs. This is mainly due to two reasons: first, their easy integration from technical and economic standpoint, and secondly, operating in combination with other applications decreases the PV's surface temperature which increases its photoelectric conversion efficiency dramatically [21]. This section reviews the recent studies regarding double-purpose and multi-purpose HPS systems.

With the aim of generating electricity, decreasing the air-conditioning load, and producing hot water simultaneously, Hui et al. [136] designed a novel building integrated HP/PVT system (Fig. 26). The annual thermal performance of the proposed system was investigated both theoretically and experimentally. The annual electricity generation and water heating efficiency of the system were 10% and 35%, respectively, leading to electricity saving of 315 kW h/year per square meter.

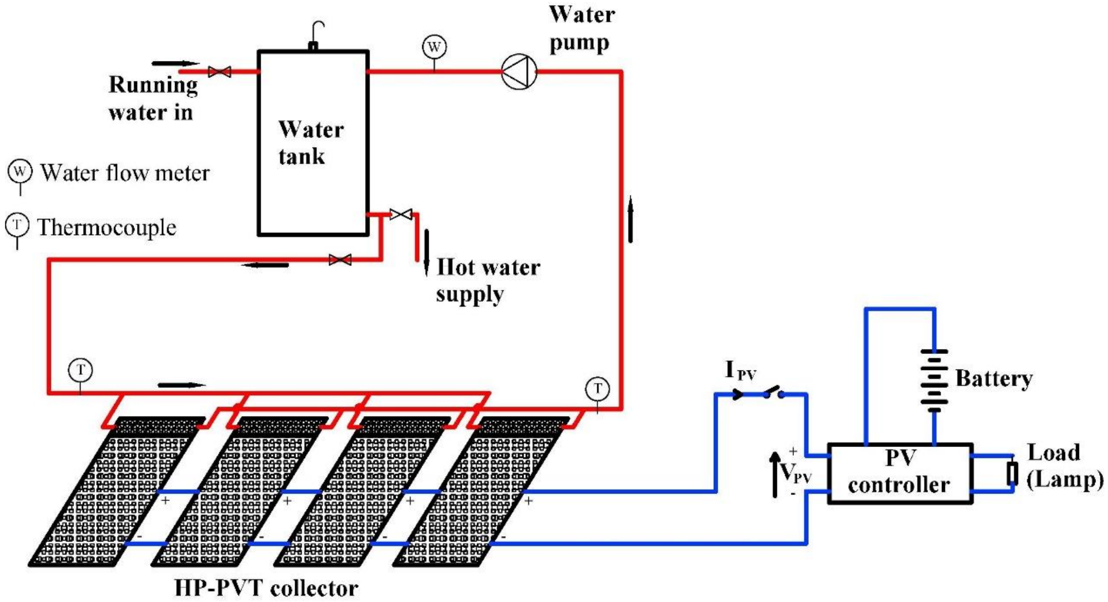

Fig. 26. Schematic diagram of a multi-purpose HPS system aiming to supply electricity, air-conditioning, and hot water [136].

Jouhara et al. [137, 138] designed a multi-purpose solar system in which the HPSC was a building envelope material. The system could generate electricity, produce hot water, and provide the required energy of a heat pump for heating and cooling of the inner space of the building (Fig. 27). The experimental results showed that the overall efficiency of the multi-purpose HP solar system was 15% higher than the standalone water heating system.

Hou et al. [139] designed a new HP solar PV-thermal system using micro heat pipe arrays to produce hot water and generate electricity, simultaneously (Fig. 28). The thermal efficiency of the proposed system was a function of seasonal temperature and reached 40% in summer and 20% in winter. The overall thermal efficiency of combined PV/T system varied between 30% and 50% throughout the year. In a similar study, the thermal performance of a crystalline silicon solar PV/T system was studied numerically (Fig. 29) [140]. The daily electrical and thermal efficiencies of the system were 7.6% and 50.7%, respectively.

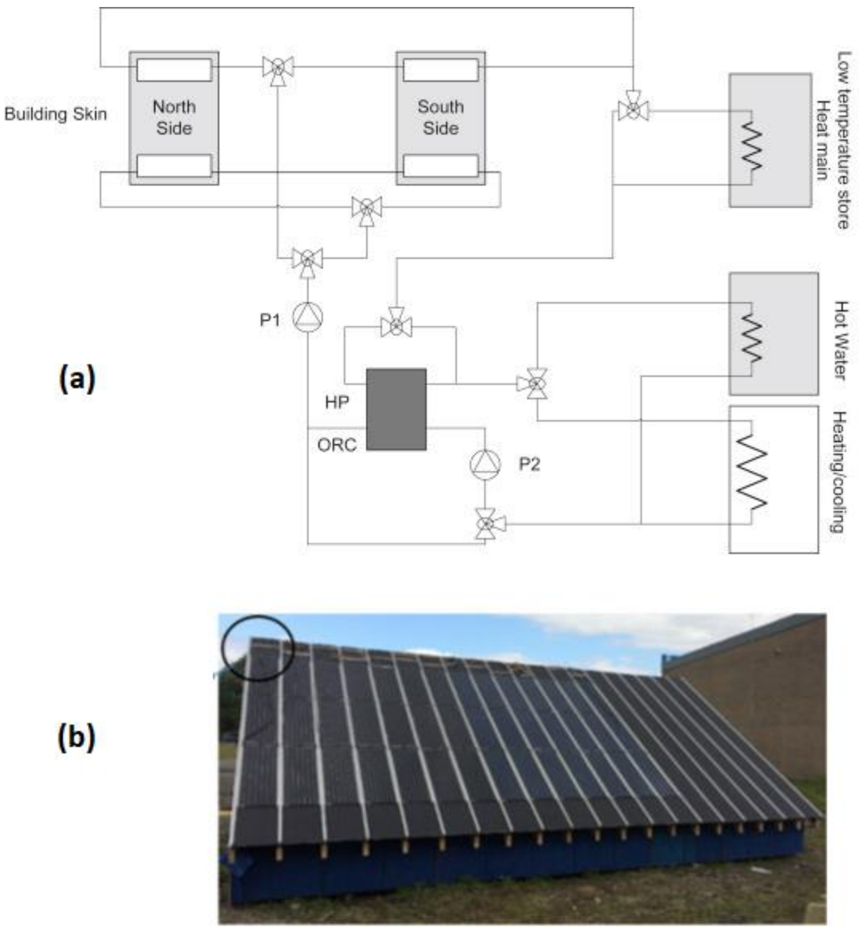

Fig. 27. (a) Schematic diagram and (b) installation of the multi-purpose HPS system with the heat pump and storage system [137].

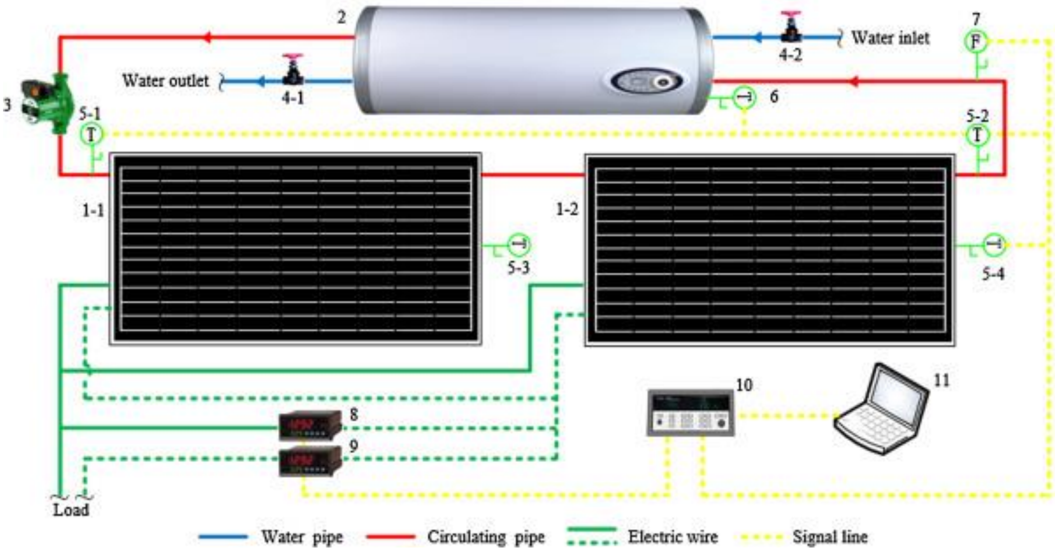

Fig. 28. Schematic diagram of the new HP solar PV-thermal system using micro heat pipe arrays [139].

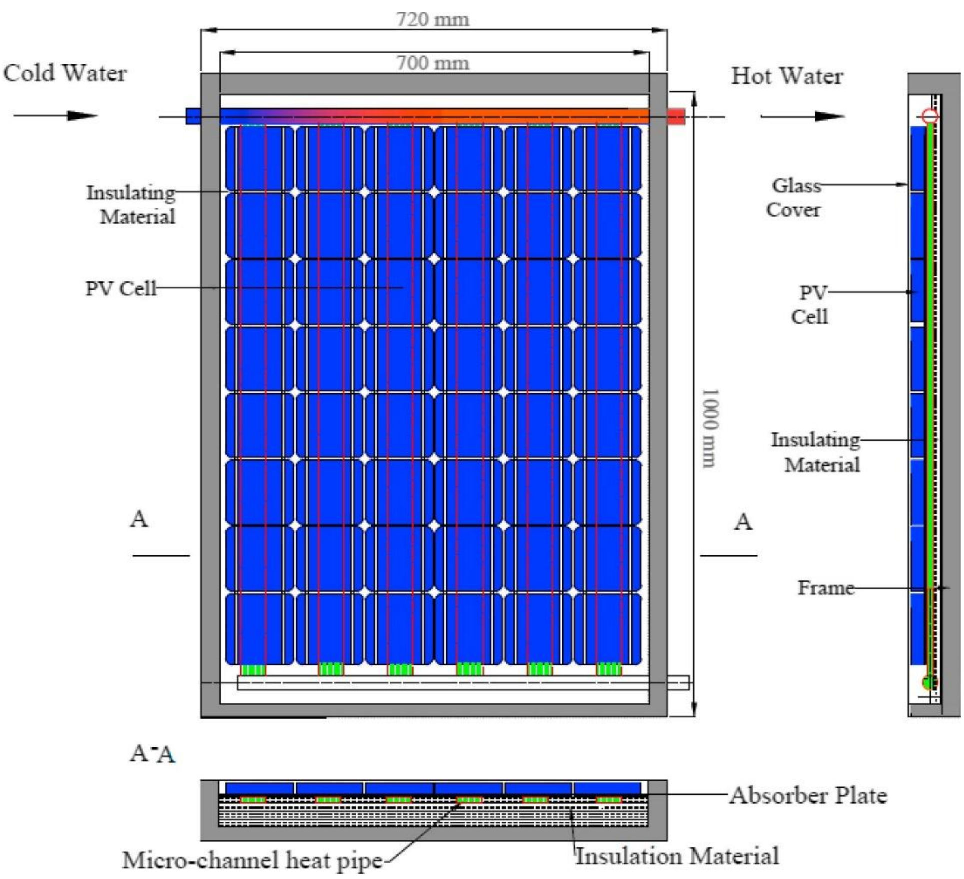

Fig. 29. Schematic diagram of the new HP solar PV-thermal system using crystalline silicon PV units [140].

Nájera-Trejo et al. [141] studied the economic feasibility of using ETHP solar collectors in a double purpose domestic hot water heating and radiant floor heating system (Fig. 30). To analyze the system under real thermal load, a two floor house was modelled theoretically. The thermal analysis of the designed system was carried out using TRNSYS software while Microsoft Excel was used for technical and economic analysis. The optimum number and storage tank volume of the proposed double purpose system were 8 and 40 L/m^2 leading to the payback period of approximately 11 years.

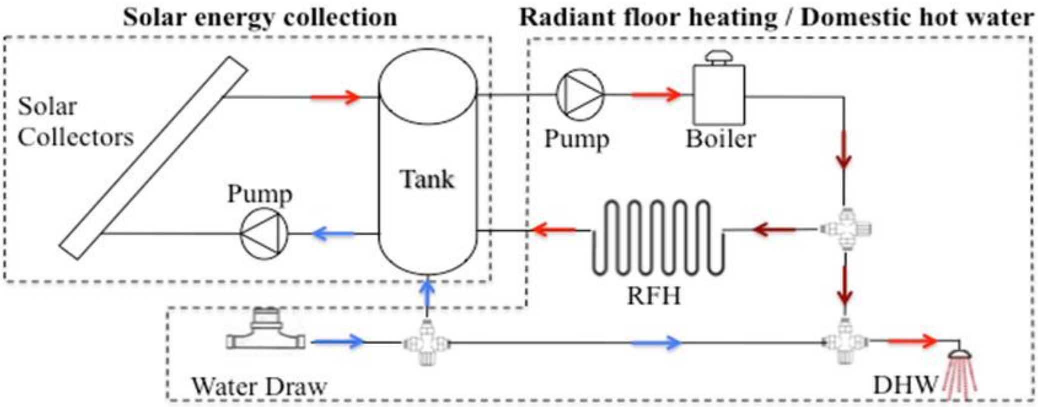

Fig. 30. Schematic diagram of the novel double-purpose domestic hot water heating and radiant floor heating system [141]

In two similar studies, a multi-purpose heating-drying system consisting of a HPSC to provide the required energy for domestic water heating unit as well as a dryer was introduced (Fig. 31) [135, 142]. The theoretical and experimental results indicated that the overall efficiency of the system was enhanced when it was operating under multi-purpose mode. In addition, the inlet air temperature of the dryer was the most important parameter contributing to the performance of the system. However, the proposed system needed further economic study to provide insights into its industrial-scale application.

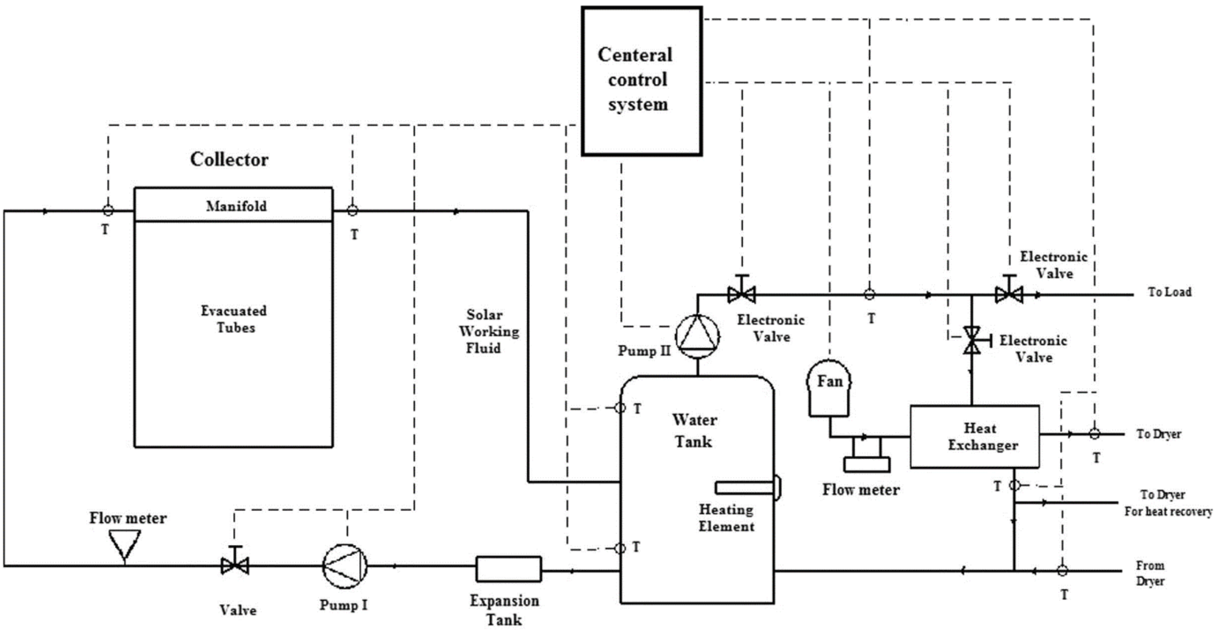

Fig. 31. Schematic diagram of the novel multi-purpose heating-drying system [135].

Chen et al. [143] studied a combined HP solar PV/T heat pump system to produce hot water and generate electricity at the same time (Fig. 32). First, an optimization study was performed to find the optimum number of HPs and heat pump capacity, and then, the effect of several parameters such as PV packing factor, water temperature in condenser, ambient temperature, and solar radiation on thermal performance of the system was analyzed at six different working modes. It was found that higher values of PV backboard absorptivity, ambient temperature, and solar radiation had a positive impact on the coefficient of performance while increasing PV packing factor, heat pipe pitch, and water temperature in condenser affected the coefficient of performance negatively. The most significant recent studies to turn the HPS system into a double-purpose or multi-purpose system are summarized in Table 7.

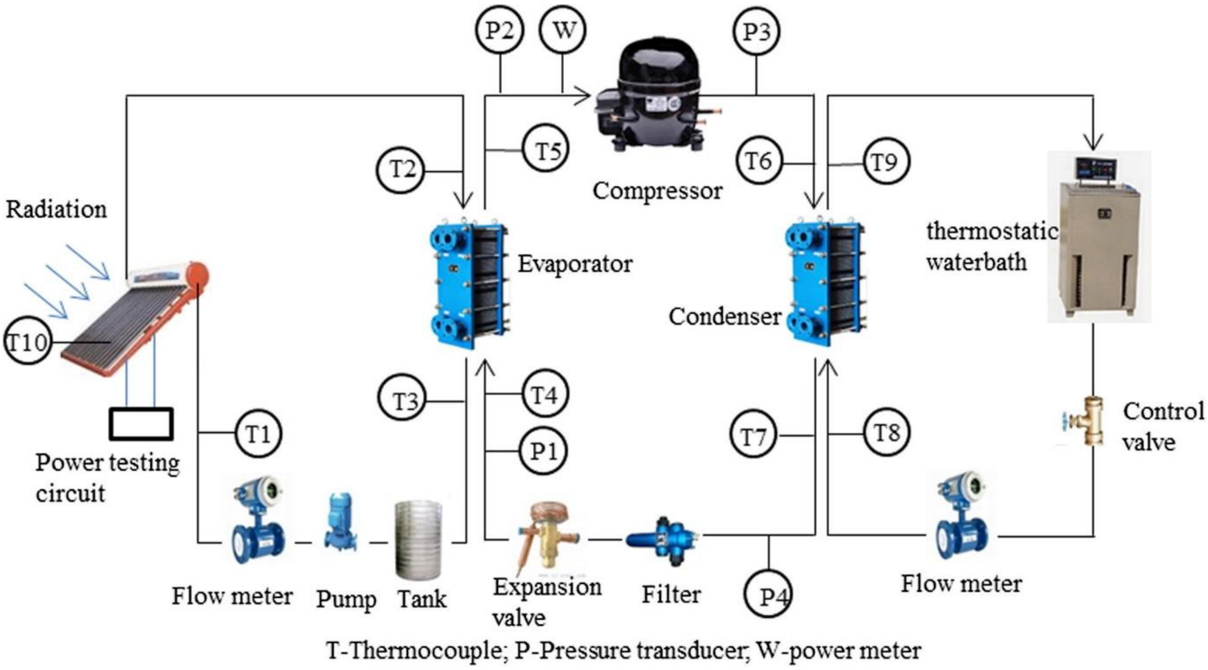

Fig. 32. Schematic diagram of the novel HPS PV/T heat pump system [143].

Table 7. Summary of recent studies to turn the HPS system into a double-purpose or multi-purpose system.

Overview	Remarks and key findings	Figure	Source
Application of annular thermoelectric generators in HPSCs to produce hot water and generate electricity simultaneously was proposed.	• The exergy efficiency and power output of the proposed system were 0.40% and 0.52% higher than conventional systems. • The proposed system enhanced heat transfer characteristics and thermal insulation and provided insights into designing industrial scale systems.	Fig. 33	[144]
A new hybrid system comprising photovoltaics, HPs, and thermoelectric generator was proposed.	• The proposed configuration enhanced the performance of PV cells and overall output power. • The system was specifically efficient and recommended for regions with hot climatic conditions	Fig. 34	[145]
A combined water heating and power generation system by incorporation of HPSCs and thermo-electric generators (TGs) was analyzed.	• A mathematical model was proposed to optimize the design and operating parameters of the system. • The thermal and electrical efficiency of the system reached 55% and above 1%, respectively, at solar radiation and water temperature of above 600 W/m^2 and 45 °C.	-	[146]

Combination of concentrating thermoelectric generator with the micro-channel HPSC was investigated.	• The effect of various parameters such as absorbing coating area, ambient temperature, concentration ratios, and wind speed on the thermal performance of the system was analyzed. • To have the optimum performance, all contributing parameters should be optimized together. • Heat transfer performance of the system was better than conventional systems.	Fig. 35	[147]
A combined HP solar water heating and thermoelectric power generation system was analyzed theoretically and experimentally.	• The temperature difference across the TG reached 75 °C at heat flux of 50,000 W/m^2 leading to the hot water temperature of up to 80 °C. • The proposed system is applicable for domestic or industrial applications.	-	[148]
A new efficient and low-cost heat pipe solar system to provide electric power and heat simultaneously was designed, built, and tested.	• The output electrical power, collector efficiency, and electrical efficiency were 64.80 W, 47.54%, and 1.59%, respectively. • The proposed system was economic and practical and it was recommended for commercial production.	-	[149]
The incorporation of finned HPSCs and TGs to produce hot water and generate electricity was proposed.	• The influence of main operational, physical, and environmental parameters, such as TG length, number of TGs, cooling water temperature, and solar irradiation, on the conversion efficiency and maximum power output was analyzed.	-	[150]

	• An analytical model was proposed to study the performance and to optimize the design and operating parameters of the system.		
A new heat pipe PV/T system was proposed to supply thermal and electrical energy.	• The impact of various parameters, including PV cell covering factor, space of heat pipes, absorptive coatings material, and water flow rate, on the system performance was analyzed. • One of the main advantages of the proposed system was the ability to operate in cold regions without the freezing problem. • The average energy and exergy efficiency of the system were 51.5% and 7.1%, respectively.	-	[151]
A novel PV loop HP/solar assisted air source heat pump was designed and tested to produce domestic hot water and generate electricity.	• The overall photo-thermal efficiency of the new system was higher than that of the conventional ones. • The monthly average power consumption per liter of hot water, the monthly average COP, and annual solar heating ratio were 0.009 kW h/L, 3.10, and 57.8%, respectively.	-	[152]
A building-integrated hybrid system was suggested by incorporating solar PV cells and HPSCs	• The first and second laws of thermodynamics were applied to study the effect of relevant parameters, such as packing factor of solar cell, water mass flow	Fig. 36	[153]

	rate, inlet water temperature, and heat loss coefficient, on the overall thermal performance of the system. • The energy, exergy, and electrical efficiencies of the hybrid system were 63.65%,10.26%, and 8.45%, respectively.		
The tilt angle and tank volume which are among the key parameters of a hybrid heat pipe PV/T solar system were optimized.	• Increasing the tank volume initially decreased the electricity and hot water generation and then increased them. • The system having the tank volume of 80 L reached the highest efficiency of 67.5%. • Details of the optimized tilt angle and orientation based on the simulated model were presented. The average annual hybrid efficiency and heat collection were 4.37% and 2328.16 MJ.	-	[154]
The combination of TGs and HPSCs to form a solar water heating and thermoelectric power generation system was studied experimentally.	• The highest output power of the system was around 16 W which occurred at mid-day. • Further improvements were recommended regarding the storage tank and water circulation energy loss restriction.	-	[155]

A new hybrid heat pipe PV/T system was proposed to supply thermal and electrical energy and tested in both spring and summer.	• The output electrical power and thermal efficiency of the proposed system improved by 5.67% and 16.35%, respectively compared with conventional systems. • The findings supported the idea of turning solar systems into multi-purpose systems for thermal energy gain efficiency enhancement.	-	[156]
A novel micro-channel HPSWH system integrated with TGs was designed to be installed as a balcony wall-mounted solar system.	• The thermal and electrical efficiency of the proposed system reached 64% and 0.67%, respectively. • The energy and exergy analysis showed that the novel integrated system had a high thermal and electrical potential and needed further research.	-	[157]
A novel PV/T loop heat pipe solar system using microchannel heat pipe evaporator integrated with PCM triple heat exchanger was proposed.	• The overall efficiency of the proposed PV/LHP system reached 67.8%. • The system has 28% higher overall efficiency compared to a conventional system.	-	[158]
The performance of a PV loop HP heat pump water heating system was optimized.	• The power consumption of the system was reduced by 55.7%. • The social-economic benefits of the system were justified for cold regions	-	[159]
An integrated solar energy collector–storage system based on the lap joint-type flat micro-heat pipe arrays was proposed.	• The maximum thermal storage and extraction efficiency were 73.8% and 97.1%. • The average thermal storage and extraction power were 623.7 W and 815.9 W.	-	[160]

A hybrid heat pipe solar-gas system was proposed to supply the energy demand of a four-member family.	• The thermal efficiency of the collector increased by 14% in August. • The thermal efficiency of the collector increased by 15.6% in October.	-	[161]
A solar HP heat pump system was proposed to provide domestic hot water and space heating.	• The system reached the maximum coefficient of performance of 6.38. • The evaporation temperature of the heat pump affected the performance and heating capacity of the system significantly. • The economic analysis of the proposed system proved its capability of being implemented in real residential scales.	Fig. 37	[162]

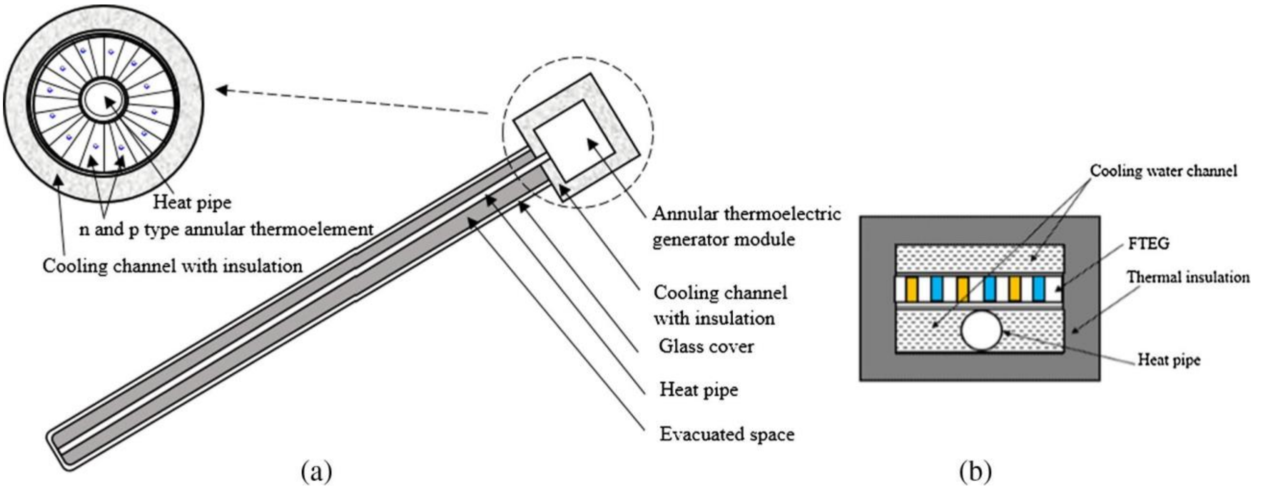

Fig. 33. (a) Application of annular TGs in a HPSC to produce hot water and generate electricity simultaneously, (b) cross section view of the solar TG [144].

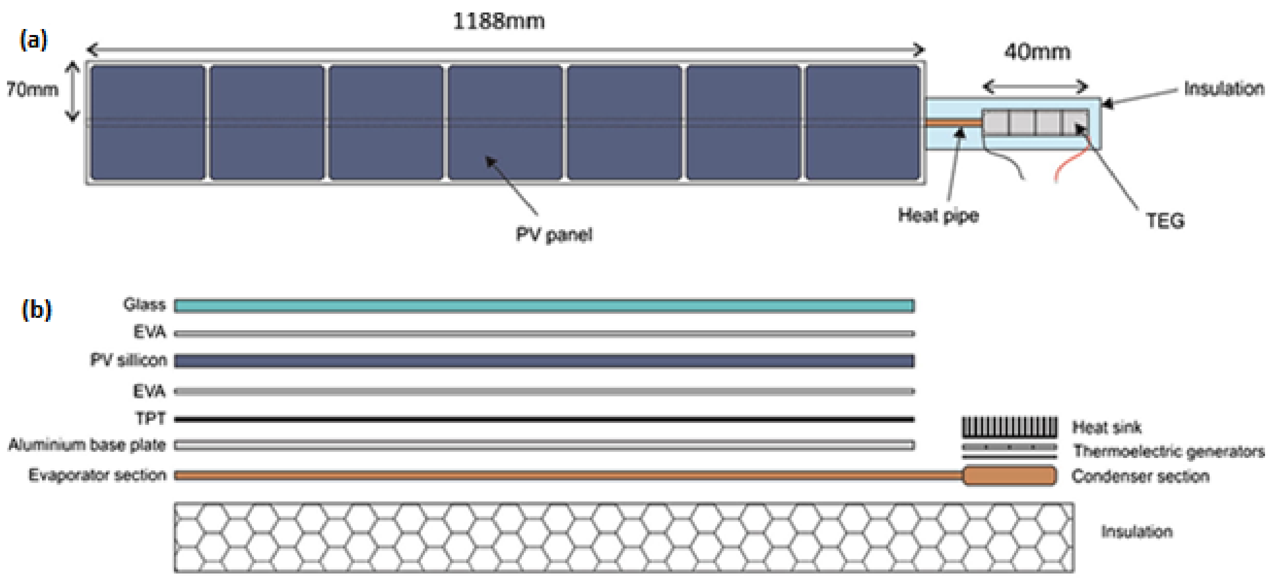

Fig. 34. HP based PVT–TG solar collector: (a) Top view, (b) Side view [145].

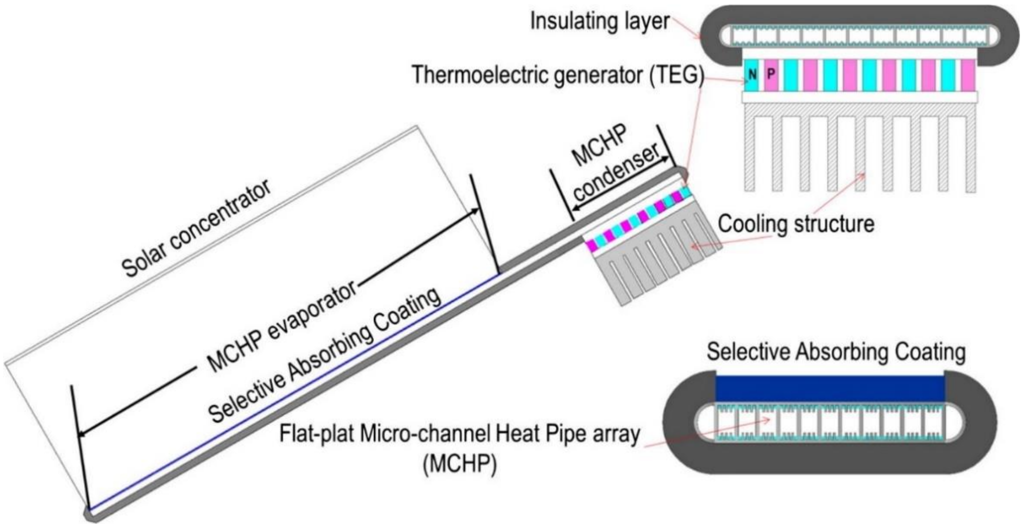

Fig. 35. Combination of concentrating TGs with a micro-channel HPSC [147]

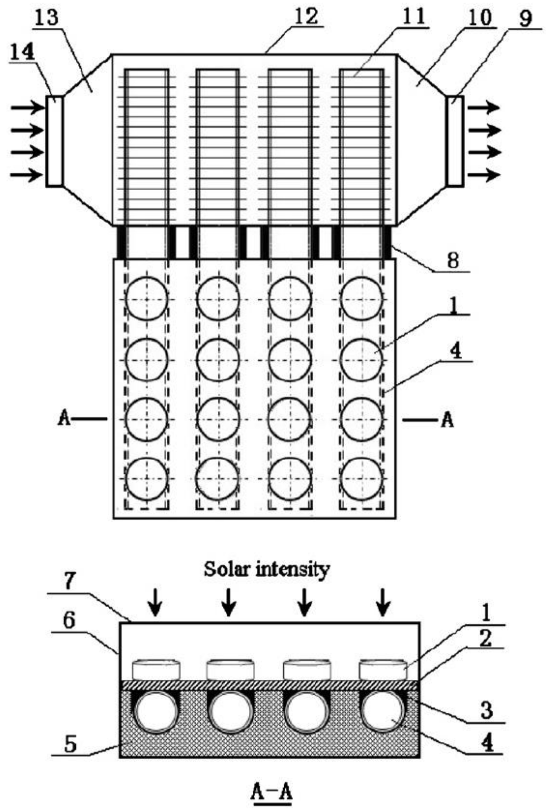

Fig. 36. The schematic diagram of the building-integrated hybrid system by the incorporation of solar PV cells and HPSCs: (1) PV modules; (2) PV panel; (3) thermal conductivity material; (4) HP; (5) evaporator section insulation; (6) glass side seal; (7) glass cover; (8) adiabatic section insulation; (9) fluid outlet; (10) fluid outlet header; (11) fins; (12) fluid channel; (13) fluid inlet header; and (14) fluid inlet pipe.[153]

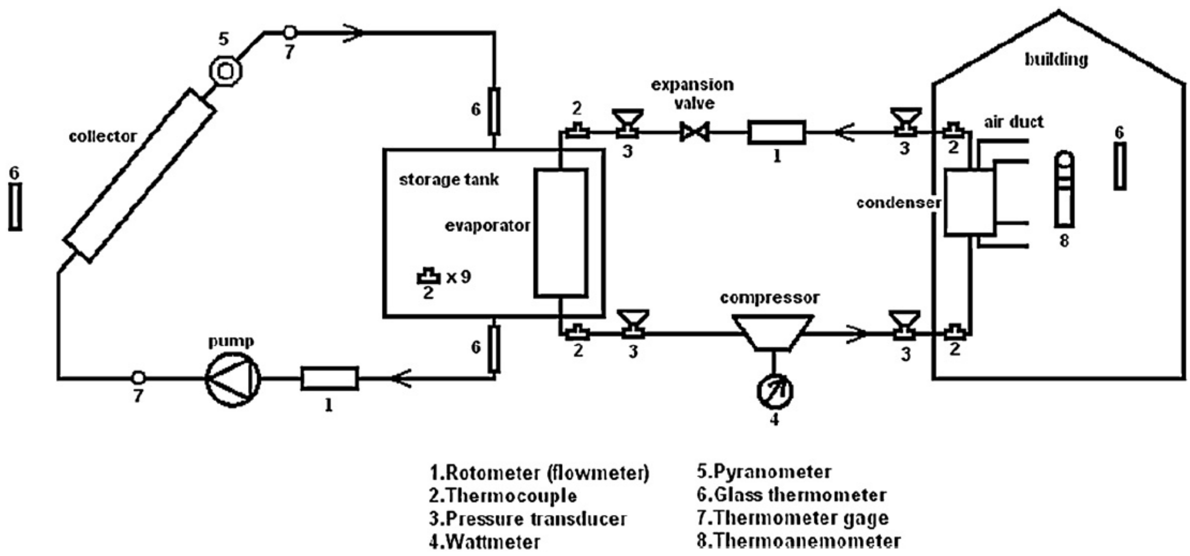

Fig. 37. Schematic diagram of the solar HP heat pump system for domestic water and space heating [162].

4. Recommendations for future research

As the utilization of HPSCs in a wide range of applications is expanding fast, the studies regarding the efficiency improvement of these systems has increased remarkably. While these studies have resulted in great achievements to date, HPS systems still have high potential regarding thermal efficiency improvement. Also, there is no doubt that the existing knowledge should expand and improve continuously. Based on the studies reviewed in this paper, several new research directions are proposed as follows:

- Limited number of studies have provided the economic analysis of their proposed designs and configurations, therefore, the economic feasibility analysis of the systems proposed previously or to be proposed in future is highly recommended especially for double-purpose and multi-purpose applications. In addition, the influences of the HPSCs size on the performance of heat pipe solar systems to investigate the feasibility of scaling these systems up needs further study.

- The studies associated with changing the structure of HPSCs have been mainly focused on the manifold header section of the collector while other components such as coating material of the absorber has remained under-researched.
- The efforts to improve the thermal performance of HPSCs by changing the working fluid has been mainly focused on the heat pipe working fluids while studies regarding the solar working fluids are very limited. Hence, utilization of new solar working fluids (especially nanofluids) and comparison of their performance can be expanded significantly.
- The future studies must be directed towards the reliability of using nanofluids in HPSCs from technical, environmental, and economic standpoint. Presenting reliable information regarding the fabrication methods and volume fractions of uniformly-dispersed nanofluids with desirable characteristics, low cost nanoparticles, and non-toxic constituents is necessary.
- Further studies should be performed to resolve the challenges faced when using nanofluids in heat pipe solar systems such as nanoparticles migration, nanofluid instability, low specific heat of nanofluids, higher pressure drop leading to greater power required for pumping, possible erosion and corrosion, high viscosity, and temperature dependency of nanofluids' thermophysical properties. Fabricating nanofluids using more than one type of nanoparticles can also be an interesting research topic.
- Regarding the thermal storage in heat pipe solar systems, the major share of studies has been devoted to latent heat storage methods. Further work is needed to analyze the sensible heat storage methods and strategies to improve their efficiency.
- It has been proven that turning the heat pipe solar system to a double-purpose or multi-purpose system increases the overall efficiency noticeably. However, the main focus of

the researchers to date has been on the integration of PV units with HPSWH systems. Incorporation of HPSWH systems with other thermal application is a great research potential which needs more attention and further investigations. Also, the base system of the multi-purpose applications has been mainly water heating systems while air-based systems seem to be another possible option with high potential.

- New studies must be directed towards finding novel strategies to improve the thermal performance of heat pipe solar systems. For instance, regulating the solar working fluid mass flow rate or adjusting the storage tank temperature with the thermal load seem to have promising research potential.

5. Conclusions

This paper comprehensively reviews recent studies regarding the proposed strategies to improve the thermal performance of HPS systems. Section 2 contains concise information about HPSCs' principles, applications, and modelling aiming to create a background knowledge for the readers. Section 3.1 reports the new designs and configurations of different components of HPSCs in HPS systems along with their effect on the thermal performance of both the collector and the system. Section 3.2 covers the studies on heat pipe and solar working fluids as one of the major contributing factors to the thermal efficiency of HPS systems. Section 3.3 summarizes the studies regarding the utilization of novel PCMs and heat exchanger compositions and designs in HPS systems. Section 4 contains a comprehensive review of recent efforts to turn a HPS system into double-purpose or multi-purpose systems aiming to increase the overall efficiency of the HPS system and HPSC at the same time. Finally, Section 4 presents existing challenges in the field and identifies research gaps and provides recommendations for future research potentials.

Conflict of interest

None declared.

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