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A review of latest developments, progress, and applications of heat pipe solar collectors

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A review of latest developments, progress, and applications of heat pipe solar collectors

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Abstract

Among all the available solutions to the current high energy demand and consequent economic and environmental problems, solar energy, without any doubt, is one of the most promising and widespread solutions. However, conventional solar systems face some intractable challenges affecting their technical performance and economic feasibility. To overcome these challenges, increasing attention has been drawn towards the utilization of heat pipes, as an efficient heat transfer technology, in conventional solar systems. To the authors' knowledge, despite many valuable studies on heat pipe solar collectors (mainly during the last decade), a comprehensive review which surveys and summarizes those studies and identifies the research gaps in this field has not been published to date. This review paper provides an overview of the recent studies on heat pipe solar collectors (HPSCs), their utilization in different domestic, industrial, and innovative applications, challenges, and future research potentials. The concept and principles of HPSCs are first introduced and a review of the previous studies to improve both energy efficiency and cost effectiveness of these collectors is presented. Moreover, a concise section is dedicated to mathematical modeling to demonstrate suitable methods for simulating the performance of HPSCs. Also, the latest applications of HPSCs in water heating, desalination, space heating, and electricity generation systems are reviewed, and finally, some recommendations for future research directions, regarding both development and new applications, are made.

Keywords: Solar collector; Heat pipe; Efficiency; Applications; Progress.

Contents

1. Introduction

Availability, renewability, great potential, and being environment friendly has turned solar energy into the best possible renewable option to meet increasing energy demand. However, intractable challenges in regard to efficient collection and effective storage of this free and clean energy create serious limitations to its industrial applications. Solar energy is accessible only during daytime so it has to be absorbed, transferred, and stored efficiently. That is why solar collectors are the most important component of all solar-driven systems [1].

Fundamentally, there are three types of solar collectors: Flat Plate Solar Collectors (FPSCs), Evacuated Tube Solar Collectors (ETSCs), and Heat Pipe Solar Collectors (HPSCs). FPSCs are designed and used in a wide range of forms. Although FPSCs are durable, cheap, and manufactured easily, their application is technically and economically feasible only in sunny warm climates and/or during the summer. For instance, in cold climatic conditions, cloudy days, and windy areas, their efficiency reaches 75% in summer but drops to less than 40% when solar radiation intensity and ambient temperature are not high [2]. FPSCs are also vulnerable to moisture which affects their durability and decreases the overall efficiency of the solar energy system in which they are used [3].

Another significant drawback of FPSCs is their unsuitability for applications with high operating temperatures due to increased thermal losses and, hence, significantly decreased efficiency of the collector and the overall solar energy system. Selecting better absorbing surfaces and applying anti-reflective glass and extra insulation have been proposed to rectify these issues; however, the associated extra costs affect the economic feasibility of these systems [4]. At the same time, flat plate collectors have high hydraulic resistances [5] and should be utilized with sun trackers for a better performance which also increases their operational and maintenance costs [6].

ETSCs were introduced to address the challenges confronted by FPSCs, especially to improve their efficiency at high temperatures. In this type of collector, the space between the two layers of glass tubes is vacuumed and selective absorbers and transmitters are applied to decrease thermal losses [7]. This has significantly improved the performance of ETSCs even in cold environments with low solar radiation [8, 9]. Another key advantage of these collectors is their low maintenance cost [10]. These led to an increase in ETSCs' market share in China from 88% in 2003 [11] to 95% in 2009 [12].

Despite these proven advantages of ETSCs, the possibility of overheating remains as one of the most important drawbacks of ETSCs. For instance, while the temperature limit for domestic applications is 100 °C, these collectors can easily cross this limit. Therefore, enough working fluid should continuously be available to receive the extra thermal energy; otherwise material problems or vacuum loss occurs [2]. Another drawback of these collectors is their high initial costs [13]. Also, ETSCs should be handled with care as they are made from a special type of glass and are fragile [2].

Heat pipe solar collectors (HPSCs) which have the advantages of both evacuated tube collectors and heat pipes were introduced to overcome the limitations of FPSCs and ETSCs. HPSCs remove heat from the absorbing surface with the highest efficiency and transfer it to the working fluid with the lowest thermal and hydraulic resistances [14]. In this type of solar collector, heat pipes function by applying the latent heat instead of sensible heat and heat transfer only occurs by phase change process of the working fluid which significantly reduces temperature drop, increases heat transfer capability, and decreases the required heat transfer area and weight [11]. Also, the very high heat transfer coefficient of phase change process has turned HPSCs into highly efficient heat transfer devices [15]. Furthermore, the completely natural movement of working fluid eliminates the necessity of mechanical devices such as pumps [11]. Additionally, HPSCs control operating temperature and prevent overheating, which is a common problem in solar applications [16, 17]. Also, while the elimination of corrosion and freezing increase the operating life of HPSCs [18], they can simply be fitted in roofs or facade side of buildings due to their light weight and simple design [19].

Unique features and advantages of HPSCs have turned them into an attractive option for solar applications and drawn significant attention in recent years. To the authors' knowledge, there is no review paper available to date on HPSCs, their applications in different solar energy systems, and investigations to improve their field performance. Therefore, this paper reviews the most significant studies on: (i) heat pipe solar collectors, their types and progress; (ii) performance of HPSCs in different domestic and industrial solar systems; and (iii) innovative applications, challenges, and the future research potentials in this field. This information will be a valuable reference for those who are interested in or intend to perform research in the field of solar thermal engineering, in particular in the field of heat pipe solar collectors.

2. Structure, performance and advancements of heat pipe solar collectors (HPSCs)

This section presents details about structure of HPSCs (i.e. heat pipes and glass evacuated tubes) along with the latest studies to analyze and improve the performance of these collectors and recent advancements in this field.

2.1. Structure of HPSCs

2.1.1. Heat pipe

HPSCs include two major components: i) heat pipe, and ii) glass evacuated tube. A heat pipe is principally a sealed tube which holds a wick structure and a specific amount of fluid (e.g., water, methanol, and ethanol) inside it acting as the working fluid [10]. Fig. 1 shows the longitudinal and the cross sectional views of a typical heat pipe which demonstrate its working mechanisms including (i) evaporation, (ii) adiabatic transfer, and (iii) condensation.

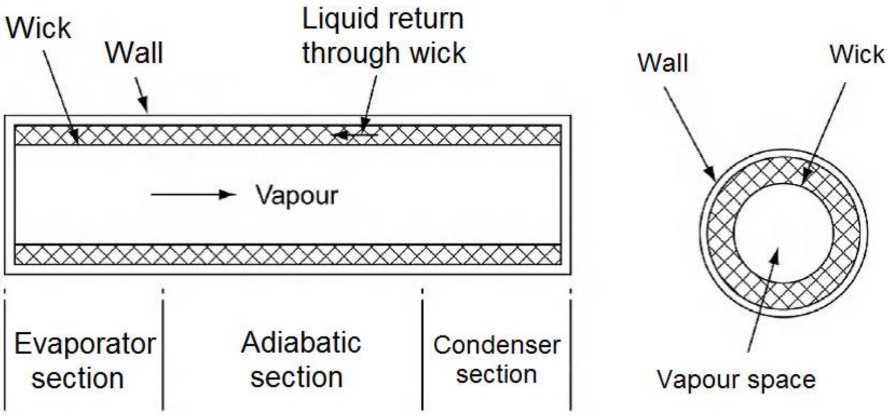


Fig. 1. Longitudinal section and cross sectional view of a typical heat pipe [20].

Heat passes through the evaporator section and provides the required thermal energy for evaporation of working liquid. Then, the vapor moves towards the adiabatic section then the condenser section, where the vapor turns into liquid by losing its thermal energy. The liquid then returns to the evaporator section via the capillary wick structure and the cycle continues [21]. The working fluid, the wick structure, and the tube are the main components of all types of heat pipes. The selection of working fluid depends greatly on the fluid properties, the compatibility with the wick and tube materials, and the operating temperature range [22]. Among all the properties of the working fluids, thermal conductivity has a significant effect on improving the thermal performance of heat pipes. Some researchers focused on increasing thermal conductivity by adding nanofluids to the base working fluid [23, 24]. A comprehensive review paper has been published summarizing the relevant studies in this field and also specifying the perspective of using nanofluids in heat pipes for further studies [25].

Since the main focus of this review is on the heat pipe solar collectors rather than the heat pipe itself, more details about the heat pipe structure, components, characteristics, modeling, design, various applications, and limitations can be found in the references presented in Table 1.

Table 1. Significant references and their content description about heat pipes.

Title	Description	Source
Design and Technology of Heat Pipes for Cooling and Heat Exchange	• Various features of heat pipes under steady state and transient working conditions • Focusing on the physical features of heat pipes • Presenting mathematical models and empirical formulas • Applications of heat pipes	[26]
An Introduction to Heat Pipes: Modeling, Testing, and Applications	• Classifications and operational fundamentals of heat pipes • Physical performance of different working fluids • Design, analyzing and manufacturing of heat pipes • Applications of heat pipes, especially for cooling	[27]
Transport Phenomena in Capillary-Porous Structures and Heat Pipes	• The principles of vapor-liquid flow motion and heat transfer • Physical descriptions of two-phase flow hydrodynamic and heat transfer	[28]
Heat Pipes Science And Technology	• Mathematical modeling of heat pipes under different operational conditions • Heat and mass transfer process in heat pipes	[29]
Heat Pipes Theory, Design and Applications	• Classifications and fundamentals of heat pipes • Design, analysis and manufacturing of heat pipes • Applications of heat pipes • Application of nanofluids in heat pipes	[20]

2.1.2. Evacuated tubes

Evacuated tubes are made of glass and once a number of them are placed in a parallel arrangement, they form the evacuated tube solar collector (ETSC). Each tube consists of one inner and one outer tube with a very small light reflection (Fig. 2). The inner tube acts as the absorbing surface, while the outer tube acts as the transparent glass to facilitate the passage of solar radiation. The space between the two concentric tubes is vacuumed to create thermal insulation [30].

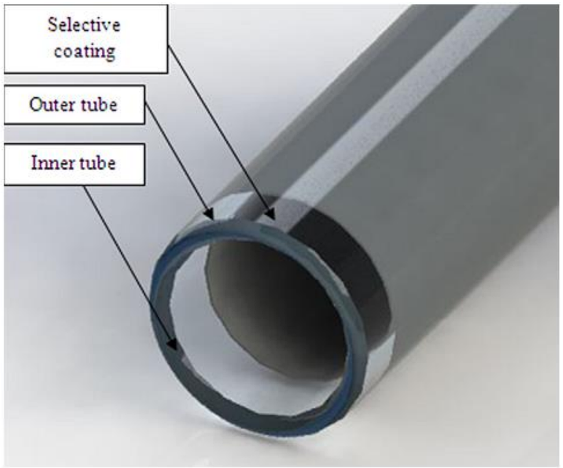


Fig. 2. A typical evacuated glass tube [31].

In contrast to FPSCs, ETSCs do not require sun trackers due to their cylindrical absorbing surface. Furthermore, the effect of low solar radiation, low ambient temperature, and high wind velocity on the performance of ETSCs is considerably less. Also the vacuumed space between the glass pipes significantly decreases both heat losses and maintenance costs [32]. These unique features of evacuated tube collectors have attracted researcher attention.

Another type of ETSCs which combines U-shape copper tubes with the evacuated glass tubes is called U-type ETC. The U-tube ETC has a simple structure and is also tolerant to high pressure [33]. Fig. 3 illustrates the U-type ETC along with its cross section view.

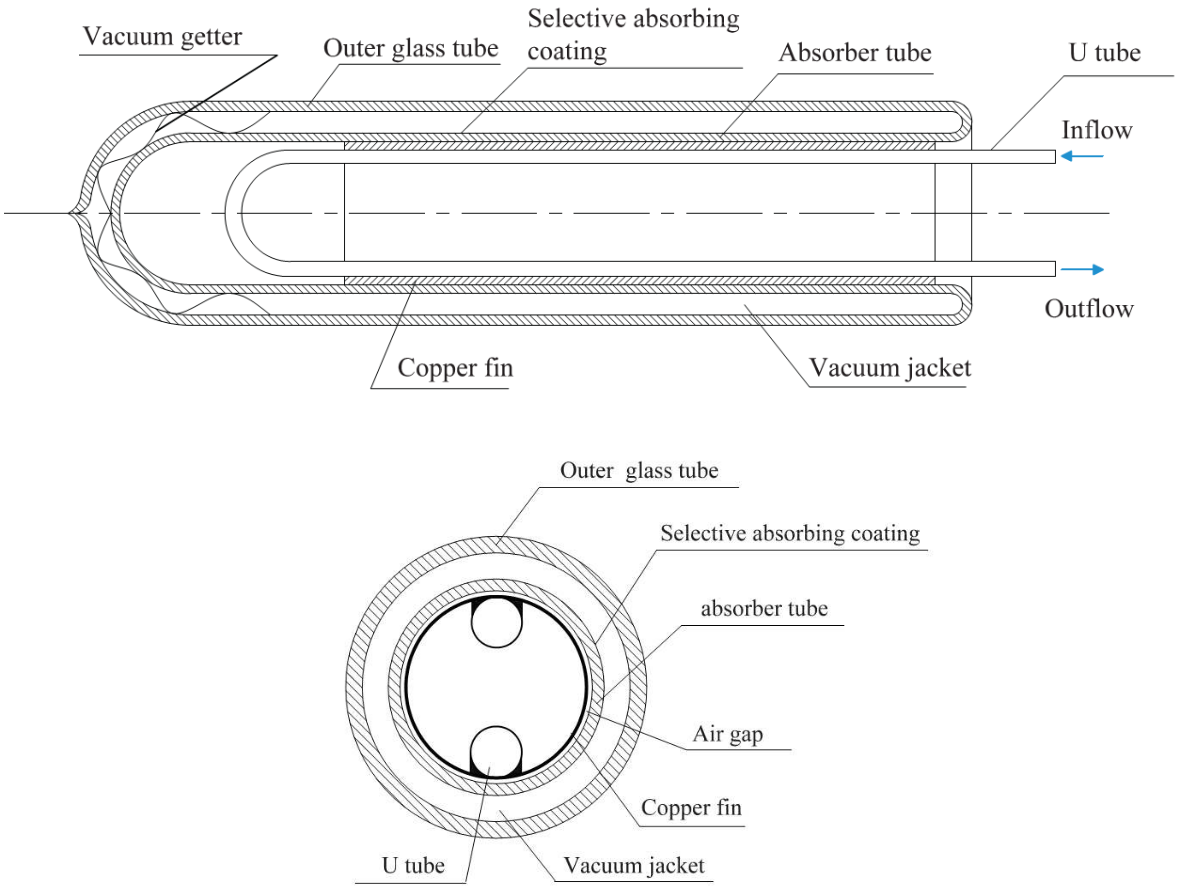


Fig. 3. U-tube ETSC with and it's cross section [34].

One of the most important design parameters of ETSCs is the shape of the absorber. Fig. 4 shows different shapes of the absorbers used in ETSCs including tube welded inside a circular fin, finned tube, U tube welded on a copper plate, and U tube welded inside a rectangular duct. According to the theoretical and experimental investigations, U-tube welded inside a circular fin shows better performance in ideal conditions compared to other three shapes. However, if parameters such as the shadow due to the adjacent tubes and the effects of the diffuse irradiation are considered, U-tube welded on a copper plate has the best thermal performance [35].

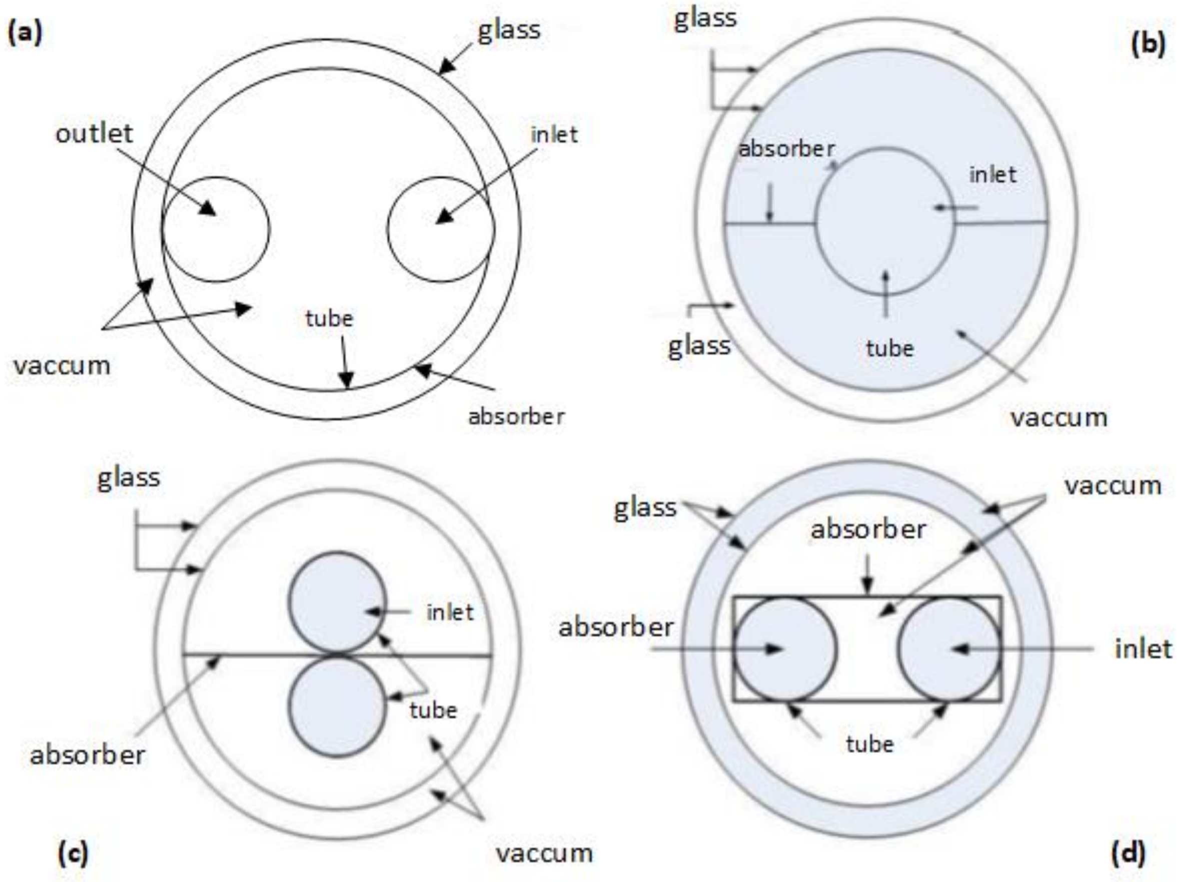


Fig. 4. (a) tube welded inside a circular fin, (b) finned tube, (c) U tube welded on a copper plate, and (d) U tube welded inside a rectangular duct [35].

Table 2 summarizes the most important and relevant studies involving ETSCs along with their description and key findings.

Table 2. Summary of some significant studies with focus on evacuated tube solar collectors

Description(s)	Remarks and key findings	Source
Application of Al_2O_3/ water nanofluid as the solar working fluid in evacuated tube solar collectors	• At the mass flow rate of 60 L/h, collector's efficiency was 57.63%. • Efficiency had an ascending trend as the volume fraction of Al_2O_3 nanoparticles increased. • The study recommended to use Al_2O_3/water as the collector's working fluid.	[36]
Performance evaluation of an evacuated tube solar water heater under transient energy input conditions	• The effect of transient energy input on the performance of the solar collector was negligible. • Under constant values of tilt angle and energy input, the collector showed better performance in lower operation times. • Internal stratification number method was recommended for comparison of passive and active storage methods.	[37]
Transient CFD modeling of water flow inside evacuated tube solar collectors	• CFD modeling for simulating the thermal performance of evacuated tube solar collectors under different climatic and operational conditions was examined and the results were appropriate.	[38]
Investigating the effect of using carbon nanotube selective coatings used in evacuated tube solar collectors	• The carbon nanotube was proposed as an ideal solar selective coating for evacuated tube collectors as it had better absorption and lower reflection compared with common coatings.	[39]
Design and optimization of evacuated tube solar water heaters	• Design of two innovative evacuated tube solar water heaters resulted in high heat collection rates of 11 MJ/m^2.	[40]
Experimental analysis of evacuated tube solar water heaters	• The performance of evacuated tube and flat plate domestic solar water heaters was compared. • ETSCs and FPSCs solar fractions were 84% and 68%, respectively.	[41]
Effect of utilizing reflectors on the performance of ETSCs	• The utilization of reflectors increased the outlet temperature and efficiency of ETSCs by 17 ˚C and 8%, respectively.	[42]
Solar drying using an evacuated tube collector	• The optimum mass flow rate and collector area was 0.019 kg/s and 1.72 m^2, respectively. • Satisfactory performance for drying all agricultural products with optimum pick-up efficiency of 11%.	[43]

2.1.3. Assimilation of heat pipes and evacuated tubes

When the evacuated tubes and heat pipes are combined, they form the heat pipe solar collector (HPSC). The schematic of a typical HPSC with its main components is shown in Fig. 5. Also, functionality of a typical HPSCs is presented in Fig. 6 including the following phases: (1) Solar radiation passes through the glass and reaches the absorber surface and turns into heat; (2) Produced heat reaches the evaporator section of the heat pipes and vapourises the working fluid; (3) The generated vapor moves upwards towards the condenser section and transfers its heat to the solar loop working fluid through the manifold, and at the same time returns to liquid form; (4) The liquid then moves downwards to the evaporator section and the cycle continues.

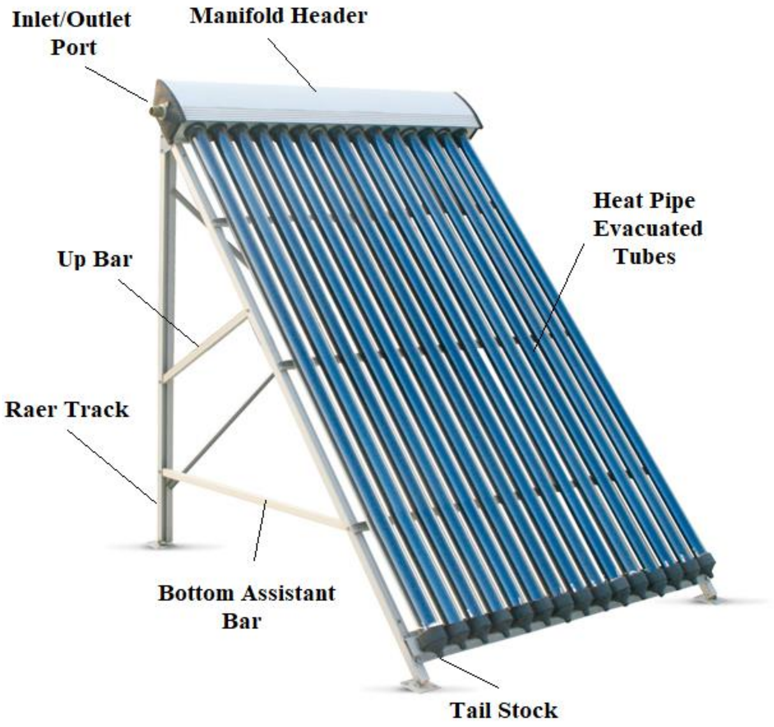


Fig. 5. Components of a HPSC.

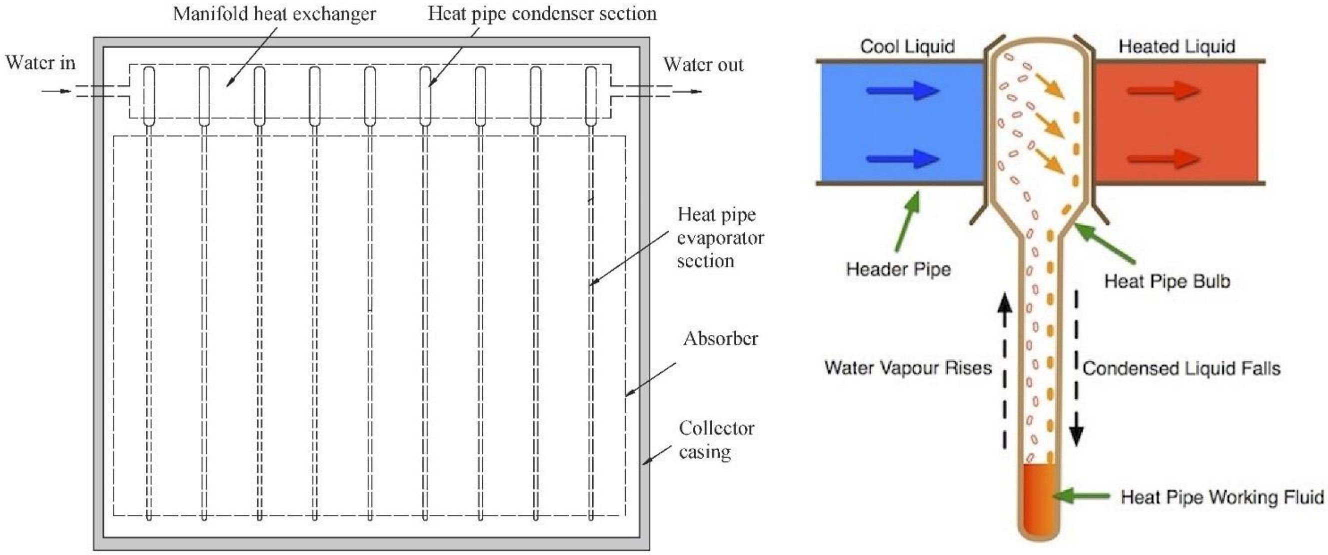


Fig. 6. Schematic to show functionality of an HPSC [44, 45].

2.2. Performance and advancement of HPSCs

Some researchers have compared the performance of HPSCs with FPSCs and ETSCs [46, 47]. For instance, one study compared the thermal performance of a 4 m^2 FPSC with a 3 m^2 HPSC in Dublin, Ireland [46]. The annual average collector and system efficiencies of the FPSC system were 46.1% and 37.9%, respectively, while these values were 60.7% and 50.3% for the HPSC. In another study, the performances of HPSCs and ETSCs under Mediterranean climatic conditions were evaluated showing 15–20% higher efficiency for the former [47]. Overall, the mentioned advantages of HPSCs in the literature can be summarised as : (i) high overall efficiency, (ii) high absorbance and heat transfer capability, (iii) resistance to freezing and low heat losses, (iv) no overheating and fast start, (v) resistance to high pressure and thermal shock, and (vi) independecy of inclination angle [48].

Compared with other sections of HPSCs, the contact thermal resistance between the absorber and the heat pipe is rather high. To resolve this issue, special extruded aluminum alloy (6060/6063) heat pipes were proposed (Fig. 7) [2]. In this novel design, the base cross-section of heat pipes was kept unchanged while wide fins and longitudinal grooves were added. In this new design, all the parts were manufactured as one entity and then grooves were created longitudinally [49]. As a result, the contact thermal resistance exists between the absorber and the heat pipe decreased significantly.

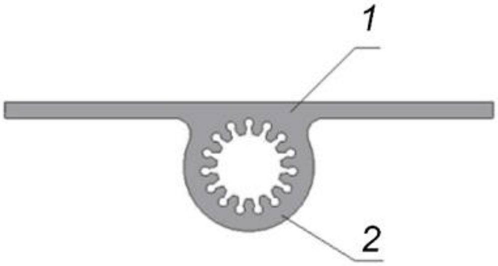


Fig. 7. The cross-sectional profile of heat pipe to reduce the contact thermal resistance [2]: 1) absorber, 2) heat pipe

In order to increase the heat transfer contact area, the use of fin arrays in the condenser section of heat pipe solar collectors was proposed (Fig. 8) [50]. According to the theoretical and experimental results, utilizing larger-diameter fins resulted in an improvement in efficiency only until the number of fins increased to 25. Overall efficiency was also increased by 4.73% when 5 fins were added, while this value was ~3.91% when the number of fins was raised from 10 to 30. Therefore, it is more advantagous to use a lower number of fins in condenser section of HPSCs.

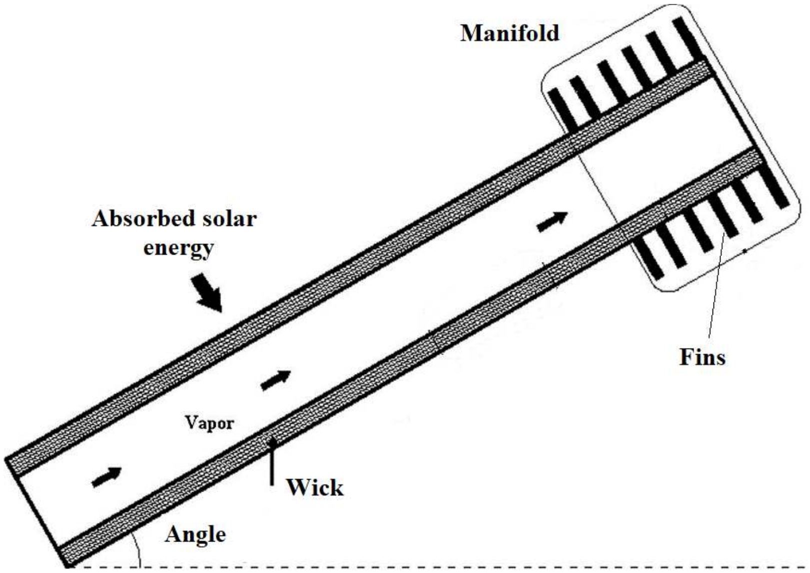


Fig. 8. Fin arrays arrangemnt for the condenser section of heat pipe solar collector [50].

In a comprehensive experimental study to verify the quality assurance of HPSCs, a 30-heat pipe collector was used and the results were analyzed according to the standard EN 12975 [19]. Based on experimental results, the following formula for determining the thermal efficiency of HPSCs was proposed [19].

$$\eta = \frac{A(\eta_0 G - a_1 \Delta T - a_2 \Delta T^2)}{AG} \tag{1}$$

where η is the thermal efficiency of solar collectors, which is defined as the thermal output of the collector devided by radiation input. ΔT (˚C) is the temperature differences between mean fluid temperature and the ambient temperature, and all other parameters including conversion factor (η_0), irradiance (G), area (A), and constant values (a_1, and a_2) are specified in the literature [19].

Another study with the aim of improving the thermal performance of HPSCs proposed inserting thermal oil inside the space between the inner surface of the evacuated tube and the heat pipe [51]. The main intention was to change the heat transfer process to convection by oil and conduction via heat pipe fin. The experimental results showed that the temperature of the heat pipe increased by 25%, which resulted in heat transfer rate improvement for the solar collector. The study also concluded that thermal oil could act as an energy storage medium, which enabled the system to work after sunset. Among all the key parameters in the efficiency of HPSCs, to date more attention has been directed to the heat pipe working fluid and its filling ratio. A comprehensive review of the application of nanofluids in HPSCs can be found in the literature [52].

Table 3 summarizes the studies in this field specifically referring to the working fluids used and the key results obtained.

Table 3. Summary of studies focused on heat pipe working fluid of HPSCs.

Working fluids	Description	Remarks and key findings	Source
Chloroform, Hexane, Methanol, Petroleum Ether, Acetone, and Ethanol	Energy and exergy performance evaluation at different solar working fluid mass flow rates	• Hexane had the worst performance at all solar working fluid velocities (2-4 m/s). • Among different working fluids, Acetone had the best energy efficiency (65%) for the mid-range velocities (2-3 m/s). • Regarding exergy efficiency, Chloroform and Acetone had the best performance in low and high velocities, respectively.	[53]
Methanol, Ammonia, Water, Acetone, and Pentane	Analyzing the performance during an operational day based on thermal resistances and critical heat flux	• From technical and economic points of view, water was the best with efficiency of 84% was the best working fluid.	[54]
R22 and R 134a	Investigating the effect of some parameters such as heat pipe working fluid, filling ratio, and tilt angle	• The best performance was obtained at 30% filling ratio for mass flow rates of 0.0051 and 0.0062 kg/s. • This optimum performance also occurred at 40% filling ratio for mass flow rates of 0.007 and 0.009 kg/s. • The optimum tilt angle at mass flow rate of 0.009 kg/s occurred at 20°.	[55]
Ethanol	Experimental evaluation of HPSCs at different heat pipe filling ratios, and tilt angles	• Collectors with ethanol concentrations of 50% and 75% had the best performance among all other concentrations.	[56]
Methanol	Measuring the temperature different locations over the heat pipes at different filling ratios	• The optimum performance occurred at 66% filling ratio • A lower temperature difference between the evaporator and the condenser resulted in better thermal performance.	[57]

2.2.1. Flat plate heat pipe solar collectors (FPHPSCs)

Flat Plate Heat Pipe Solar Collector (FPHPSC) is another type of HPSC which is less common in the market. In this type of collector, while solar radiation absorption and transmission process are identical to those in other types, their heat pipes are connected to flat plate absorbers instead of being separated tubes (Fig. 9). This results in some advantages such as functioning like a thermal-diode with heat flow in one direction only, low heat loss, and preventing over-heating [17, 58]. The most important parameters which affect the efficiency of this type of solar collector are working fluid, absorber configuration, and heat transfer rate in the manifold [59]. Therefore, most of the research activities in this field have focused on these parameters.

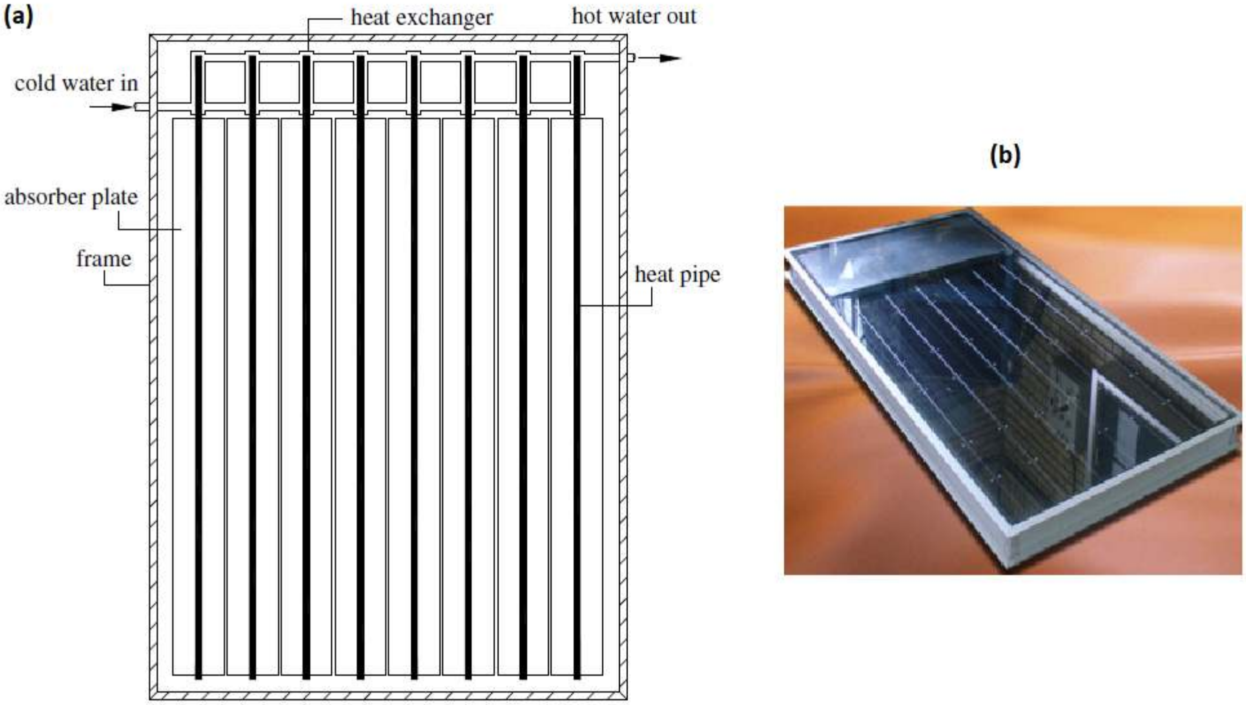


Fig. 9. A flat plate heat pipe solar collector: (a) shematic view, (b) general view [14, 60].

In a comprehensive experimental study, three different absorber and manifold configurations of flat plate heat pipe solar collectors namely Types I, II, and III were tested, comparing their performance simultaneously under similar operational and climatic conditions [60]. The heat pipes which were used in this study also had the same physical characteristics and held two layers of 100-mesh stainless steel screen as wick structure. In Type III, the absorber was an integrated plate; the other two collectors had mechanically bonded aluminum plates as their absorbers. The condenser sections of Types I, II, and III were shell and tube, double-pipe, and shell and tube, respectively (Fig. 10). In terms of production cost and ease of use, Types I and III were better than Type II; however, leakage in only one of their heat pipes could prevent the collector from functioning. Type I had the best thermal performance; however, performance improvements in Types II and III could be expected with design enhancement. Overall, all three types showed satisfactory performance and each had advantages and disadvantages.

With the same collectors, Azad [61] also studied the effect of the quantity of heat pipes and effective absorber area on the performance of HPSCs. All of the three collectors were tested at the same time based on American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 93–1986. The author concluded that increasing the number of heat pipes and the absorber area had a positive effect on the thermal efficiency of the solar collector. Also, shell and tube heat exchanger was recommended as the best configuration for collector’s manifold.

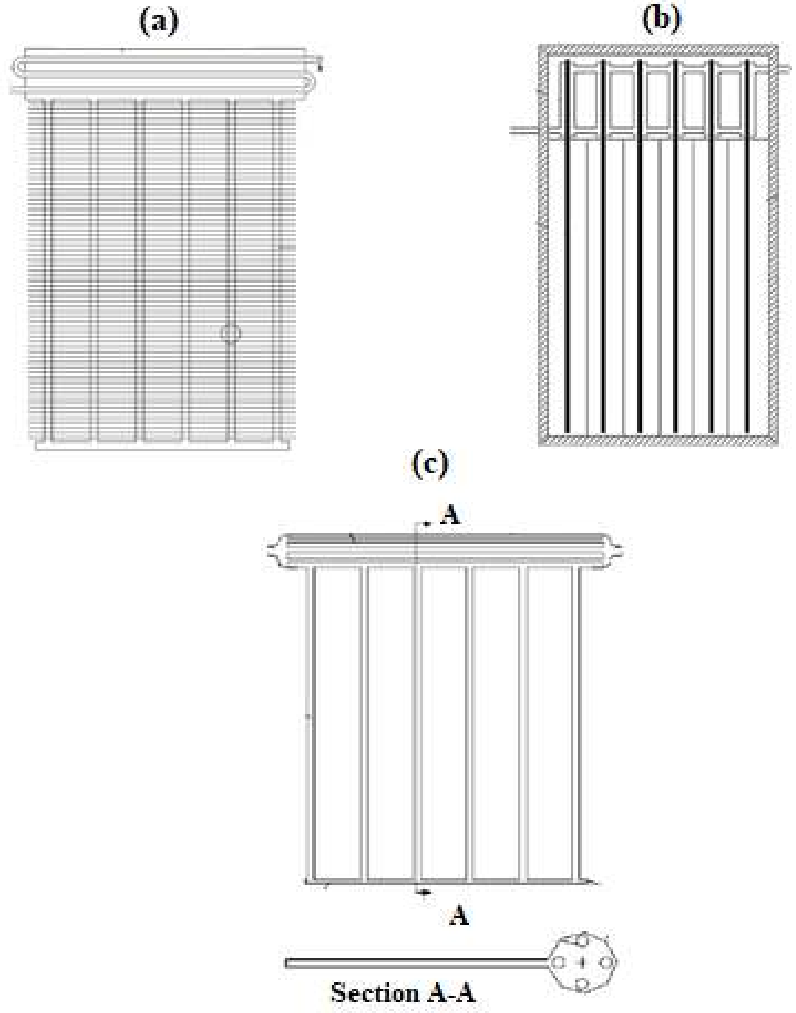


Fig. 10. Three different types of heat pipe solar collectors used by Azad: (a) Type I, (b) Type II, and (c) Type III [60].

In another experimental study, the thermal behavior of different working fluids in an FPHPSC was compared: R410A performed better compared with R407c and R-134a and resulted in the maximum thermal efficiency of ~59% [62]. Wei et al. [63] also proposed the utilization of continuous heat pipes in a new design of FPHPSC, where two horizontally linked pipes were used on two ends of the collector and one pipe was considered for returning the working fluid from the upper collected pipe to the bottom one (Fig. 11). Cold water flowed inside a pipe located in the center of the upper channel and acted as a heat exchanger. Also, the working fluid (Ethanol), which was vaporized by solar energy, flowed into the vertical pipe and then entered the upper channel. Inside the upper channel, heat was transferred to cold water flowing inside the middle pipe. Liquefied ethanol then returned to the evaporator section through the return pipe. This configuration increased the thermal efficiency to 66% resulted in the temperature increase of 250 L of water by 25 ˚C.

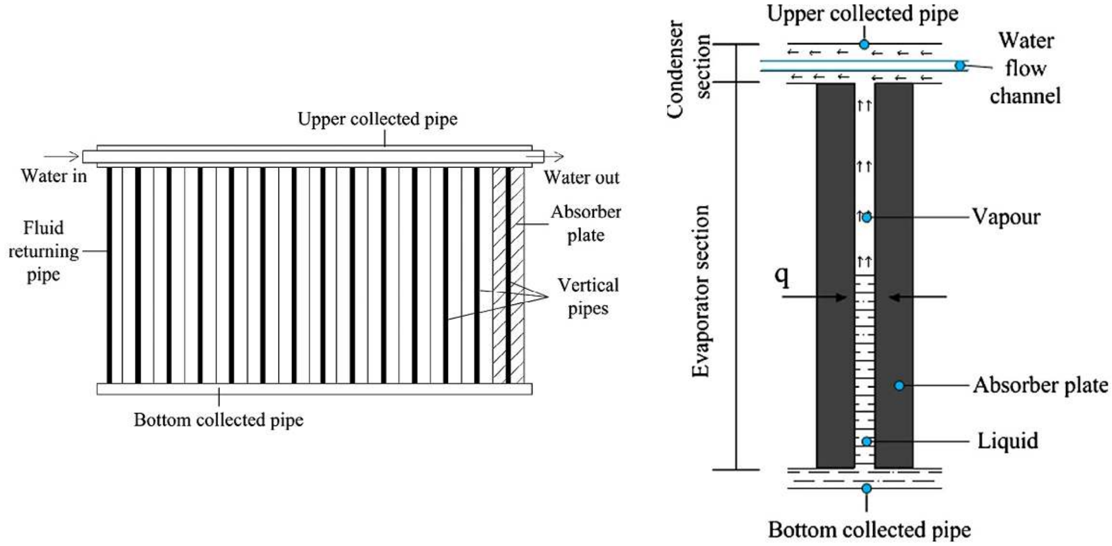


Fig. 11. The FPHPSC with continuous heat pipes proposed by Wei et al. [63].

Heat pipe cross section geometry, as an important parameter for FPHPSC performance, has also been investigated by different researchers [64, 65]. In one of these studies, three different cross section geometries being circular, elliptical and semi-circular (Fig. 12) with different working fluid filling ratios of 10%, 20%, and 35% were investigated [64]. At low working fluid filling ratios, the elliptical cross section had the best performance among all geometries, while at higher fluid filling ratios, the semi-circular cross section performed better. Also, the solar collectors with circular and elliptical cross sections had their best performance at filling ratios of 10% and 20%, respectively.

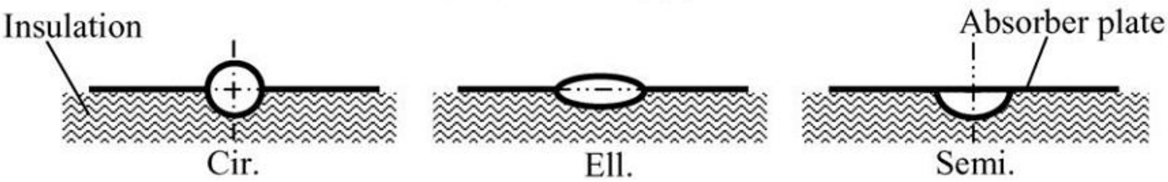


Fig.12. Cross sections of various prototype FPHPSCs investigated by Hussein et al. [64].

In another study aiming to reach higher efficiencies and lower costs, a new design for flat plate solar collectors was proposed [65]. In this novel design, the frame that contained the absorber surface was connected to a reservoir at the bottom and a condenser at the top. Two corrugated plates were welded to create mini-channels to act as heat pipes (Fig. 13) which had been previously analyzed mathematically [66]. The experimental results showed that the proposed design had a satisfactory thermal efficiency of 40–70%.

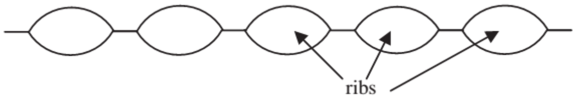


Fig. 13. The cross section of the heat pipe proposed by Riffat et al. [65].

2.2.2. Concentrated Heat Pipe Solar Collector (CHPSC)

Concentrated Heat Pipe Solar Collector (CHPSC) is another type of HPSC which is composed of compound parabolic reflectors, vacuum tubes, and heat pipes as shown in Fig. 14 [67]. Fig. 15 compares the radiation distribution over a ETHPSC and a CHPSC and shows that in addition to the beam radiation, CHPSCs benefit from a portion of diffuse radiation. That is how solar energy is concentrated on and absorbed by the heat pipes. CHPSCs with high concentrating ratios can reach high temperature levels which makes them suitable for applications such as solar power plants and desalination [68].

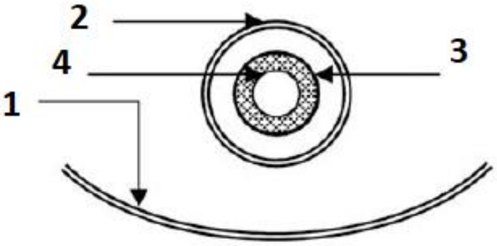


Fig. 14. Simplified scheme of a CHPSC: (1) Reflector, (2) Evacuated glass tube, (3) Heat pipe, and (4) Wick structure inside heat pipe [67].

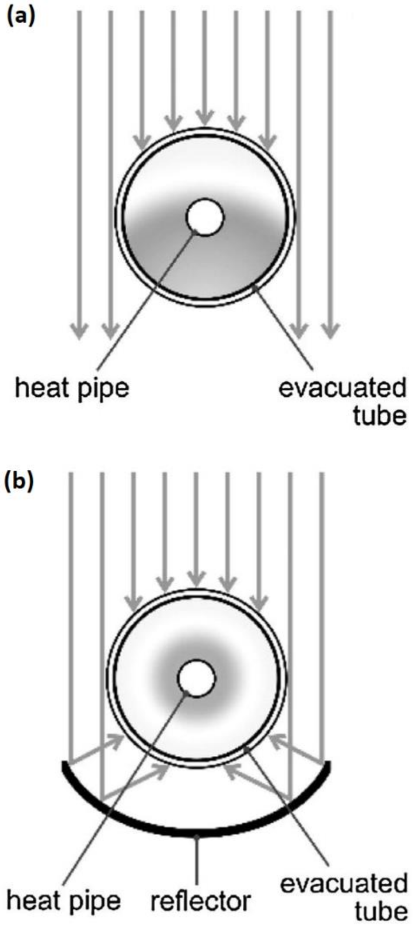


Fig. 15. Radiation distribution over a ETHPSC and a CHPSC [68].

Nkwetta and Smyth [69] proposed two innovative profiles (Fig. 16) for CHPSCs and compared them under specified conditions based on different parameters such as collection efficiency, energy collection rate, and temperatures. One of the profiles (Fig. 16a) had single-sided absorber (SSA) while the other one (Fig. 16b) had double-sided absorber (DSA). The results showed that both types are suitable for buildings' heating applications and have a great potential for cooling applications due to higher temperature and efficiency. In addition, the analysis for medium-high temperature range applications indicated that the SSA collector was more suitable for single-effect solar cooling and air-conditioning systems while DSA performed better for double-effect ones.

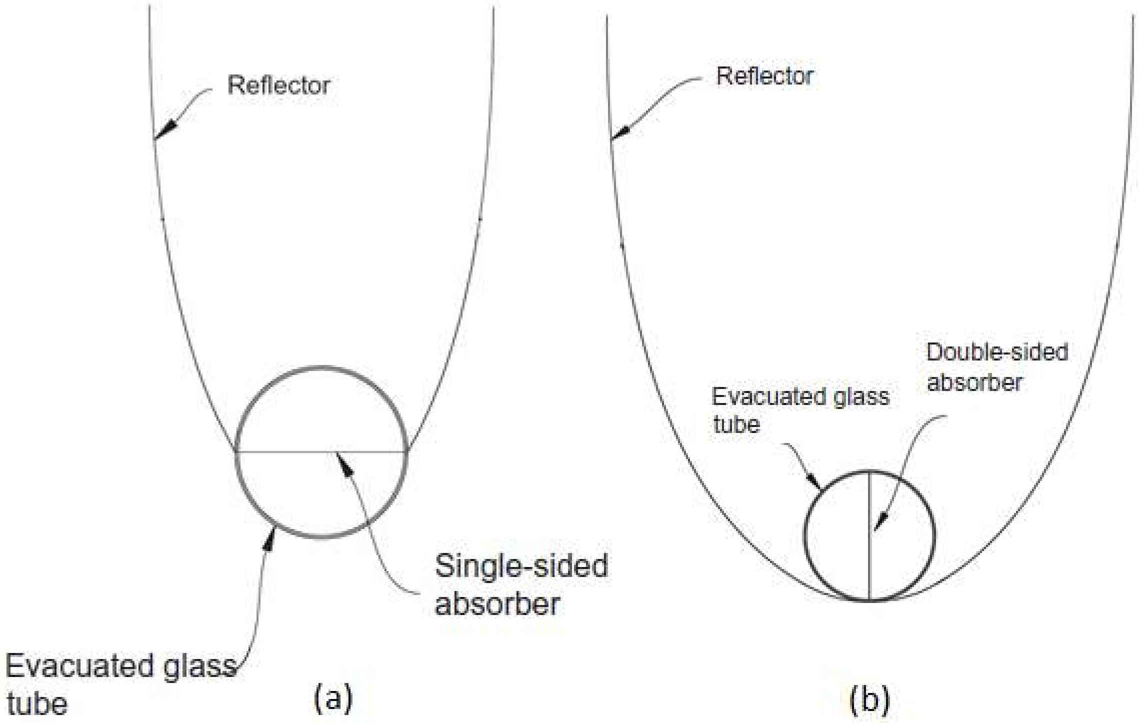


Fig. 16. Profiles for CHPSCs: (a) single-sided absorber, (b) double-sided absorber [69].

Wang et al. [70] designed a crank rod transmission mechanism and proposed a sun-tracking CHPSC to increase the compatibility of a high number of these collectors to the buildings (Fig.

17). The energy collection of the proposed CHPSC array was 1.9-2.3 times more than conventional collectors.

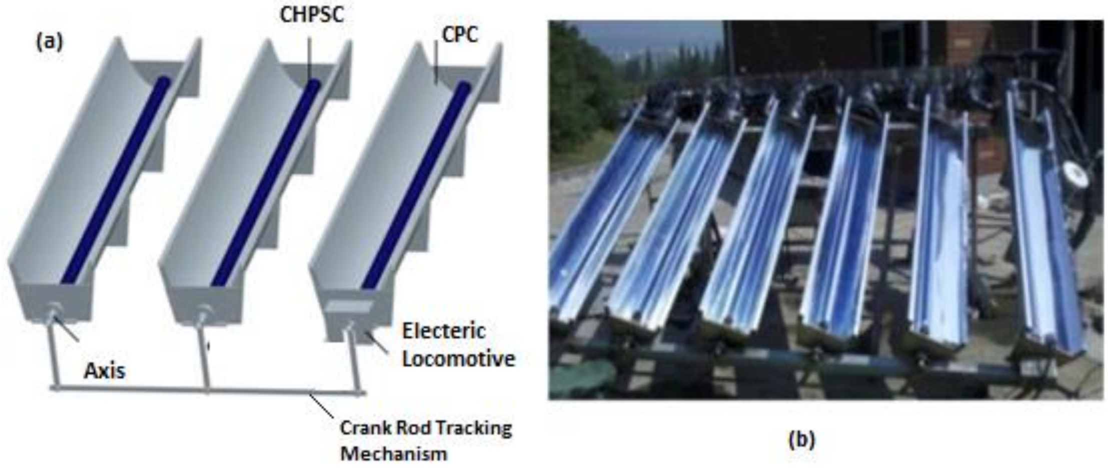


Fig. 17. The sun-tracking CHPSC: (a) schematic view, (b) general view [70]

Several studies have been conducted to enhance the thermal performance of HPSCs in various applications by adding CPCs. In an experimental study, Zhao et al. [71] investigated the heat transfer performance of combination of HPSCs and compound parabolic concentrators (CPC). Obtained results indicated that this combination improved the heat-collecting efficiency compared to conventional HPSCs. El Fadar et al. [67] developed a mathematical model and studied the performance of a CHPSC used in an adsorption refrigerating system and also investigated the effect of various parameters on the cooling efficiency of the system. Based on the obtained data, CHPSCs were highly recommended for this application.

Chamsaard et al. [72] designed, fabricated, and investigated the performance of a HPSC equipped with CPC collectors based on ISO 9806-1 both theoretically and experimentally. The results showed that the maximum obtained efficiency of the collector reached 78%. In addition, the results from the mathematical model showed that the average produced energy is 3,433.87 kWh/year. In order to reach a reasonable efficiency in solar adsorption systems, Aghbalou et al. [73] proposed the application of CHPSCs as a new solar generator. The results of the developed heat and mass transfer model indicated that the maximum nominal coefficient of performance reached 14.37% with the new combination.

3. Mathematical modeling

This section presents the equations and references required to develop a mathematical model applicable to both HPSCs and FPHPSCs. The heat transfer process inside these collectors is divided into three stages. The first stage involves the absorbtion of solar energy and turning it into thermal energy. The second stage involves transmitting thermal energy by heat pipes, followed by the last stage which is transferring thermal energy to the solar working fluid. Sections 3.1, 3.2, and 3.3 describe each stage.

3.1. Absorbing solar energy

The solar radiation which passes through the external glass is either absorbed by the coated surface of the absorbers (to vaporize the heat pipe working fluid) or dissipated back into the environment (mainly because of the temperature difference between the absorbers and ambient). This process is shown in Fig. 18 for both HPSCs and FPHPSCs and can mathematically be described by the thermal energy balance Eq. (2) [74]

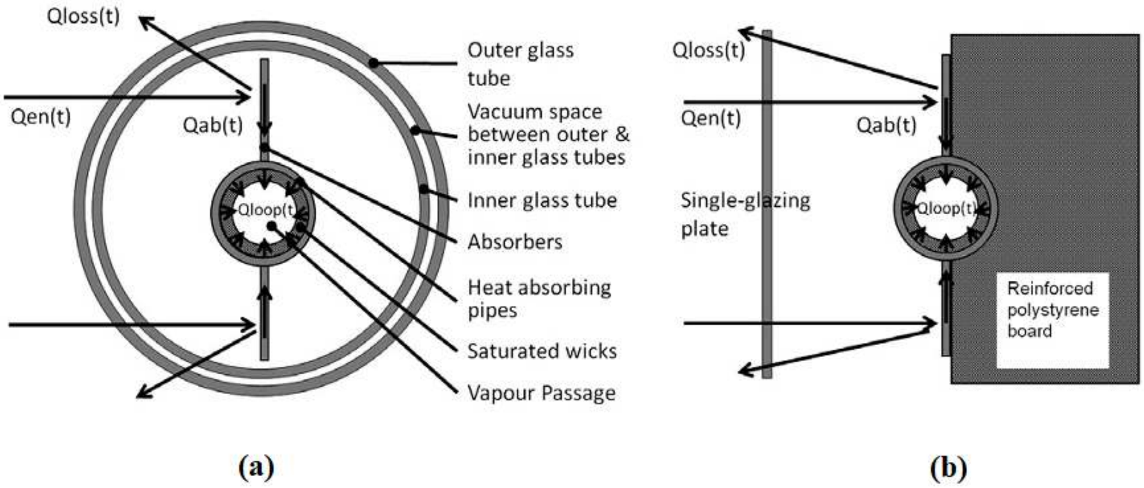


Fig. 18. Schematic of heat transfer process for: (a) HPSCs and (b) and FPHPSCs [74].

$$Q_{ab} = Q_{en} - Q_{loss} \tag{2}$$

where Q_{loss} (W) is the thermal energy dissipated back into the environment, Q_{ab} (W) is the absorbed thermal energy by the coated surface, and Q_{en} (W) is the penetrating solar energy through the glass cover. The latter can be determined from Eq. (3) and (4) for HPSCs and FPHPSCs, respectively [65].

$$Q_{en} = \tau_{go}\tau_{gi}\alpha_c A_{ab} N_{hp} I \tag{3}$$

$$Q_{en} = \tau_g \alpha_c A_{ab} N_{hp} I \tag{4}$$

where I (W/m^2) is the overall solar radiation, A_{ab} is the absorber area, N_{hp} is the number of heat pipes. τ_{go}, τ_{gi}, τ_g, α_c are the transmittance of outer glass, inner glass, flat plate glass, and absorptivity, respectively. The value of all these parameters can be found in the literature [65]. In Eq. (2), Q_{loss} (W) can be calculated from Eq. (5) and (6) for HPSCs and FPHPSCs [75, 76]:

$$Q_{loss} = \frac{T_{ab} - T_{amb}}{R_{ab-gi} + R_{gi} + R_{gi-go} + R_{go} + R_{go-amb}} \quad (5)$$

$$Q_{loss} = \frac{T_{ab} - T_{amb}}{R_{ab-g} + R_g + R_{g-amb} + R_b} \quad (6)$$

where R (K/W) is the thermal resistance and subscripts ‘ab’, ‘gi’, ‘go’, ‘b’, and ‘amb’ represent absorber, inner glass, outer glass, backboard insulation, and ambient, respectively. The equations to determine all the thermal resistances can be found in literature [74].

3.2. Thermal resistance network of heat pipes

Fig. 19 depicts the thermal resistance network, which exists in a wicked heat pipe. The overall thermal resistance of a heat pipe is the summation of all the thermal resistances [56]:

$$R = R_h + R_{f,h} + R_{w,h} + R_{wi,e} + R_{i,e} + R_v + R_{i,c} + R_{wi,c} + R_{w,c} + R_{f,c} + R_c \quad (7)$$

where R_h (K/W) and R_c (K/W) are the convective thermal resistances of the outer surfaces of the evaporator and the condenser, $R_{i.e}$ (K/W) and $R_{i.c}$ (K/W) are the evaporation and the condensation thermal resistances of the heat pipe, and R_v (K/W) is vapour-liquid resistance. $R_{w,h}$ (K/W) and $R_{wi,e}$ (K/W) are the conductive wall and wick resistances of the evaporator and $R_{w,c}$ (K/W) and $R_{wi,c}$ (K/W) are the conductive wall and wick resistances of the condenser. $R_{f.h}$ (K/W) and $R_{f.c}$ (K/W) are the residual thermal resistances that are negligible in terms of quantitative values. The equations to determine these thermal resistances can be found in the literature [16, 77].

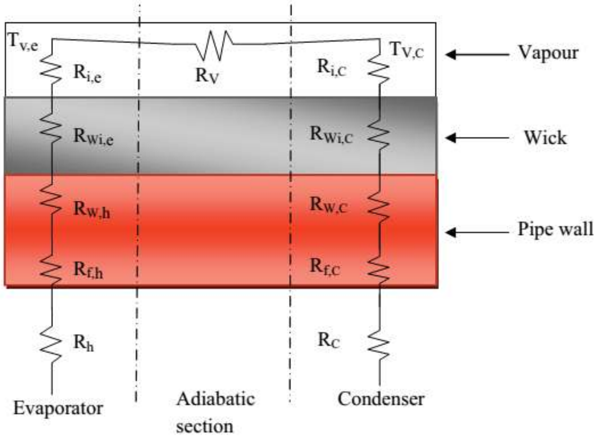


Fig. 19. Thermal resistance network of heat pipes [29].

3.3. Heat transfer process inside the manifold

In an HPSC comprising a number of heat pipes, the cooling fluid reaches the first heat pipe with the highest temperature difference. After receiving its therml energy, the temperature of the cooling fluid rises and at the same time it moves towards the next heat pipe. Therefore, the inlet cooling fluid temperature of each heat pipe is the outlet water temperature of the previous one (Fig. 20).

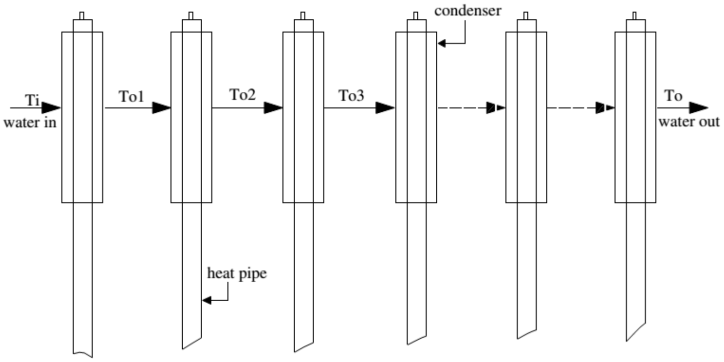


Fig. 20. Cooling fluid flow inside the manifold section of HPSCs [14].

Taking into account the fact that the condensation process inside the condenser section of heat pipes occurs at almost a constant temperature, the effectiveness-NTU (Number of Transfer Units) method can be used as follows [78]:

$$\varepsilon_n = 1 - e^{-(NTU)_{cn}} \tag{8}$$

or

$$\varepsilon_n = \frac{T_{o,n} - T_{i,n}}{T_{c,n} - T_{i,n}} \tag{9}$$

where T (˚C) is the temperature of the cooling fluid, ε is the effectiveness, and subscripts i, o, c, and n represent inlet, outlet, condenser, and number of heat pipe in series.

In Eq. (8), NTU_{cn} can be obtained from Eq. (10) [78]:

$$NTU = \frac{A_c U_c}{\dot{m} C_p} \tag{10}$$

where U_c (W/m^2 ˚C) is the overall heat transfer coefficient of the condenser section, A (m^2) is the heat transfer area, and $\dot{m}$ (kg/s) and C_p (Kj/Kg ˚C) are the mass flow rate and heat capacity of the cooling fluid. The literature also provides the comprehensive equations and references to determine the the forced convective heat transfer coefficients, the overall heat transfer coefficient, and conducting Nusselt analysis [14, 78-80].

Overall, Eq. (8) may be rewritten in the form of Eq. (11), which determines the outlet temperature of each heat pipe inside the manifold:

$$T_{o,n} = T_{i,n} + \varepsilon_n (T_{c,n} - T_{i,n}) \tag{11}$$

3.4. Other mathematical models

A three-dimensional steady-state numerical model based on finite volume method was proposed by Zhang et al. [81] to study flat plate heat pipe solar collectors. The thermal resistance networks were used to model the two-phase closed thermosyphon process inside heat pipes. The mathematical model was able to predict the temperature field of the collector as well as the absorber plate and glass cover temperature. Fiaschi and Manfrida [82] considered various heat transfer processes, e.g., forced convection, natural convection, radiation, and phase transition, and developed a steady-state mathematical model to evaluate the absorbed solar energy of HPSCs. The model was based on estimating the angle between the solar radiation and the absorbing surface, absorbed energy, and shading.

Naghavi et al. [83] combined several algorithms to dynamically model a heat pipe solar water heating system integrated with phase change material acting as a latent heat thermal energy storage. The mathematical model included heat absorption process, storage and release modes of the system. Brahim et al. [50] used the unsteady state thermal network algorithm, that was originally adapted by Corliss [84], to study the transient performance of a flat plate heat pipe solar collector by dividing the system into interconnected isothermal nodes.

The law of energy conservation along with the first law of thermodynamics was used by Li and Sun [85] to mathematically model the transient long-term working conditions of a PV/loop heat pipe heat pump water heating system. Zhang et al. [86] integrated energy balance phenomena occurring in different parts of the system including unsteady process of solar radiation, fluid flow, heat transfer, and PV electricity generation to develop a mathematical model to investigate the performance of a solar PV/loop heat pipe heat pump system.

4. Applications of heat pipe solar collectors

This section describes utilizations of heat pipe solar collectors in different applications including domestic water heating, desalination, space heating, and power generation, along with the latest studies to analyze and improve the performance of these systems.

4.1. Application of heat pipe solar collectors for in domestic water heating

4.1.1. Background

The first and the most common application of any type of solar heating system is domestic hot water preparation [87]. The reason for this popularity lies in the simple processes of water heating systems. Based on heat transfer process and working fluid circulation, solar water heating systems can be classified into different categories such as direct and indirect or passive and active. Direct systems transfer heat to water directly inside the solar collector while indirect systems use a medium working fluid to receive the solar thermal energy and transfer it to water through an external heat exchanger. Solar working fluid circulates naturally by natural convection in passive systems (thermosyphon systems) while in active systems, the working fluid is circulated via a pump. Each category has its own advantages and disadvantages and its hot water production efficiency. The performance of each system depends greatly on the type and size as well as hot water consumption pattern and climatic conditions [3]. Sections 4.1.2 and 4.1.3 review different types of heat pipe solar domestic water heating systems and recent studies regarding their design and performance improvement.

4.1.2. Thermosyphon systems (passive systems)

Thermosyphon systems are the simplest available configuration in terms of process, components, and control with no need for external power (electrical supply) due to the fact that they do not have any pumps or complicated control systems [88]. The temperature difference causes buoyancy forces which act as the circulation forcing power of the system [89]. Passive solar water heating systems have lower maintenance costs and longer service life than active systems [3]. On the other hand, their performance relies extensively on sunshine. Also, since water is circulated by buoyancy forces, larger pipe sizes should be considered to reduce head loss through the piping system. Also, the storage tank of these systems should be placed above the collector (e.g., on the roof) and requires insulation to avoid the possibility of freezing during winter. Heat loss is also a sensitive issue in these systems and reverse flow can occur at night, which results in heat loss from the solar collector to the environment [90].

Studies in the field of thermosyphon heat pipe water heaters (THPWH) have been limited mainly due to the abovementioned drawbacks. The combination of heat pipe solar collectors and storage tanks has resulted in different design configurations. The first type of THPWHs is a compact model with a pressurized tank (Fig. 21) in which the heat sources of the storage tank are the condenser sections of the heat pipes located inside the tank [91].

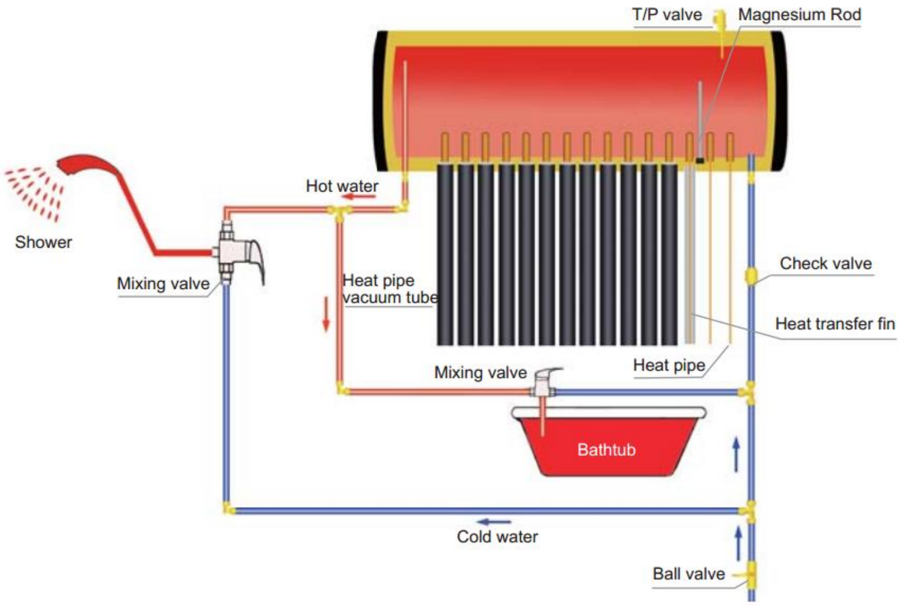


Fig. 21. A THPWH system with a pressurized tank [91].

With the hypothesis that well designed thermosyphon systems could reduce the overall costs of solar water heating systems, Redpath et al. [92] proposed and experimentally studied the separation of heat pipe solar collectors and storage tanks (Fig. 22). Their experimental results (collected over one year) showed that instead of conventional thermosiphon systems, this proposed configuration should be used in climatic conditions similar to UK. They also concluded that the application of heat pipe solar collectors in thermosyphon systems improves performance and reduced overall costs [93].

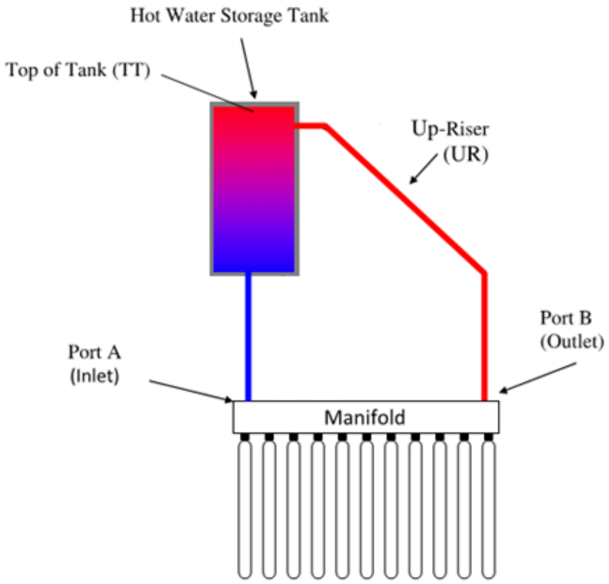


Fig. 22. The separated THPWH [93].

Pulsating Heat Pipe (PHP) is a member of heat pipe family made of a long capillary tube. This long tube is bent into several turns and filled partially with a working fluid. Significant advantages of PHPs such as flexibility, high thermal conductivity and heat transfer capacity, fast responding, and simple structure have attracted researchers to apply them in solar applications [94]. In two separate studies aiming to use heat pipe solar collectors in thermosyphon solar water heaters, utilization of loop heat pipes was proposed [95, 96]. The overall thermal process of a loop heat pipe is similar to that of ordinary heat pipes; however, in the former the working fluid passes through a loop rather than a reciprocal movement between evaporator and condenser. In the proposed configuration, a water storage tank was placed behind the collector and the condenser section of heat pipes was inserted inside it (Fig. 23). Despite the suitability of this configuration for a wide range of operational conditions and efficiencies up to 60%, its slow response time necessitates further improvements and more efficient design.

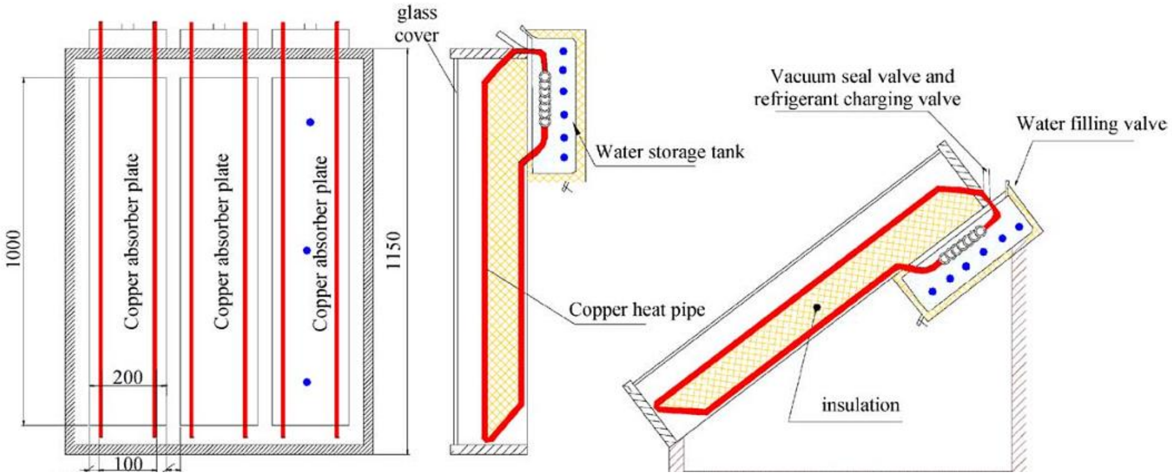


Fig. 23. Loop thermosyphon heat pipe solar water heater [95].

Arab et al. [97] used extra-long PHPs in a thermosyphon solar water heating system and carried out four different experiments including conventional thermosyphon cycle, PHPs with filling ratio of 30%, 50%, and 70%. The results showed that to reach a specified temperature, the operating time of the system with filling ratio of 70% is half of the regular system. In addition, the maximum efficiency of the former system is 53.79% while this value is 31%-36% for the latter one.

4.1.3. Active solar water heating systems

In active solar water heating systems, pumps are used as a main driving force to move the solar working fluid, which gives more flexibility in choosing the locations and the configurations of the system components. For instance, the distance between the solar collector and the storage tank can be increased in this type of system and the solar collector can be located on the roof, walls, or ground while the storage tank can be located inside the building [98]. Fig. 24 shows the schematic of an active solar water heating system.

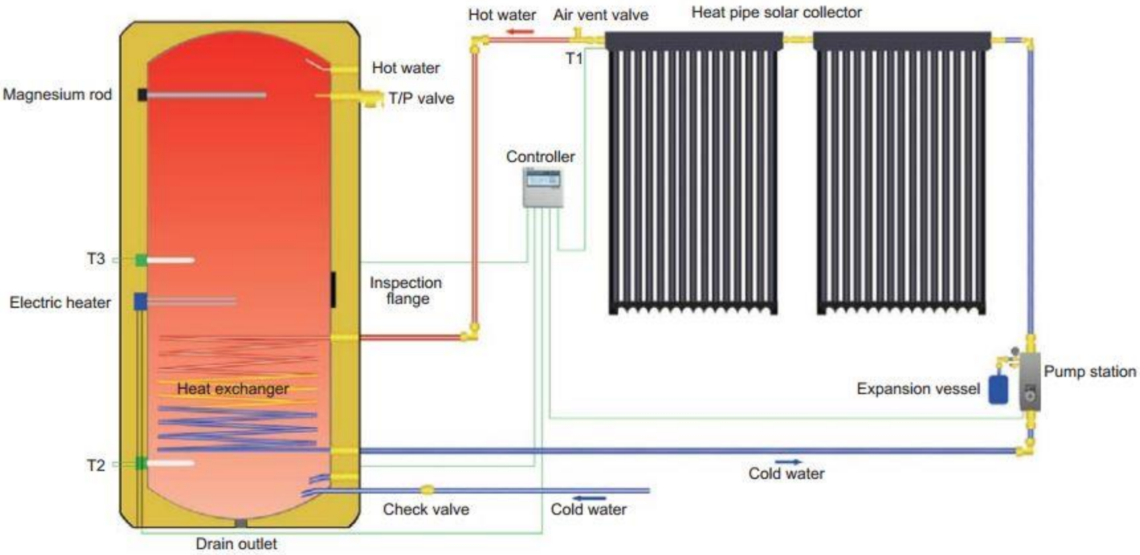


Fig. 24. The schematic of an active solar water heating system [98].

Du et al. [99] conducted a theoretical and experimental study to analyse the performance of active heat pipe solar water heaters focusing on the effect of design parameters (e.g., incidence angle and absorber area) on the system's instantaneous efficiency. They presented Eq. (12) for calculating the instantaneous efficiency (η_a) which provides a good reference to estimate the thermal performance of a heat pipe solar water heating system.

$$\eta_a = 0.603 - 0.299\frac{(T_m - T_a)}{G_t} - 0.0219\frac{(T_m - T_a)^2}{G_t} \tag{12}$$

where G_t (W/m^2) is the solar radiation intensity, T_a (°C) is the ambient temperature, and T_m (°C) is the working fluid average temperature. They also presented Eq. (13) for calculating the pressure drop (Pa) inside the manifold, which is another important parameter for designing active solar water heating systems.

$$\Delta p = 51838m^2 + 1807m \tag{13}$$

where m (kg/s) is the mass flow rate of working fluid.

Ayompe and Duffy [100] set up an experimental rig and comprehensively investigated the thermal performance of a heat pipe solar water heater system under the climatic conditions of Dublin, Ireland. Their rig included a 3 m^2 heat pipe collector, a 300 L water storage tank, and a 3 KW electrical heater, and was studied over a year. The experimental results indicated that the average daily collected energy, system efficiency, and solar fraction were 20.4 MJ/d, 52.0%, and 33.8%, respectively. In a similar study focusing on the extracted water temperature from the storage tank, the thermal performance of a heat pipe solar water heater was evaluated in Spain showing that the required water temperature had a direct effect on system efficiency. Specifically, increasing the extracted water temperature from the tank reduced the stored energy, increased the required solar radiation, and decreased the discharged hot water volume. For instance, at solar radiation of 8000 Wh/m^2d, increasing the tank water temperature from 40°C to 80°C decreased the stored energy by 1000 Wh/m^2d [101].

By considering a hot water consumption pattern, one study investigated the performance of a heat pipe solar water heater to meet the hot water demand of residential houses in Sannandaj, Iran [102]. First, a mathematical model was developed and based on the obtained theoretical results, a rig with a 2 m^2 absorber area and a 150 L storage tank was built and experimentally tested. A collector maximum outlet temperature of 64 °C and exergetic efficiency of 5.4% were reported in this study. The results also showed that hot water consumption and system efficiency are directly related and investigating a solar heating system without hot water discharge could not provide a comprehensive understanding of its performance. Based on the obtained results, Eq. (14) was proposed, relating the efficiency (y) to environmental and functional conditions.

$$y = 9404.2x^3 - 160.65x^2 - 4.8676x + 0.3435 \tag{14}$$

In Eq. (14), x represents $(T_{w,i} - T_{amb})/G$, where $T_{w,i}$ (˚C) is working fluid inlet temperature, T_{amb} (˚C) is the ambient temperature, and G (W/m^2) is the solar radiation intensity.

Naghavi et al. [83] used phase change materials (PCMs) inside the manifold section of a heat pipe solar collector to act as a latent heat thermal energy storage (LHTES) of the system. In their proposed configuration (Fig. 25), while inlet cold water received a fraction of the absorbed thermal energy to increase its temperature, the extra amount of thermal energy was stored in PCMs. Theoretical results showed that for almost all mass flow rates in the range 50-80 L/h, the thermal efficiency of the proposed system was higher than that of conventional ones. Although this proposed configuration enabled the solar water heating system to operate efficiently during low-radiation periods and at night, the effect of parameters such as collector area and draw-off schedule on the performance of the system needed further investigation and optimization.

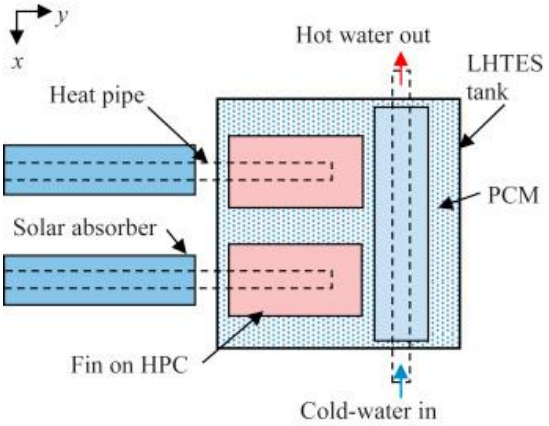


Fig. 25. Application of PCM materials inside the manifold section of a HPSC [83].

With the aim of increasing the absorbed heat and reducing heat loss, Felinski and Sekret [103] placed paraffin inside the evacuated glasses of ETHPSCs to act as PCM. The experimental results indicated that using PCM adds the capability of heat recovery from the stored heat inside it which increases the absorbed energy by 45-79% compared to conventional ETHPSCs. The most significant previous studies regarding the concept of evacuated tube heat pipe solar collector/ storage (ETHPSC/S) are summarized in Table 4, however, this field has a high potential for further researches.

Table 4. Summary of recent studies involving evacuated tube heat pipe solar collector/storage systems

Overview	PCM Material	Remarks and key findings	Source
Investigating the experimental performance of a solar water heating system equipped with ETHPSC/S	Tritriacontane and Erythritol	• Efficiency increase of 26% compared with conventional ETHPSCs	[104]
Experimental analysis of a solar collector/storage heating system for mid-temperature applications	Composite of Erythritol and expanded Graphite	• The best material for mid-temperature applications is the composite PCM with 97 wt% erythritol and 3 wt% expanded graphite. • The most suitable types of HPSC to be integrated with storage unit are 58 and 47-mm diameter evacuated tubes	[105]
Thermal analysis of domestic hot water system equipped with ETHPSC/S	Paraffin	• The increase of the annual solar fraction by 20.5% and the temperature of hot water inside the tank compared with conventional HPWH systems.	[106]
Review of using PCM in solar water heating systems including HPWH systems.	Various materials and composites	• Application of PCM for FPCs has been studied extensively and further research is needed for HPSCs and CPC collectors.	[107]

		• The energy capacity of a SWH system increases significantly by using PCM. • Further research for large-scale applications is required.	
Developing a numerical model to simulate the thermal performance of HPs integrated with PCM	Cu-0.3Si	• Variable thermal input was considered to create a precise boundary condition exists in solar applications • The parametric analysis of the effect of the heat transfer rate and PCM enclosure height was carried out. • Increasing the height to diameter of the PCM enclosure increased melting of PCM and decreased HP bottom wall temperature.	[108]
Experimental analysis of a heat pipe solar collector/storage heating system equipped with CPC.	Paraffin	• Using CPC increased the PCM temperature on the shaded side of HPSC. • Application of CPC promoted the average charging efficiency and the maximum charging efficiency by 5% and 9%, respectively.	[68]

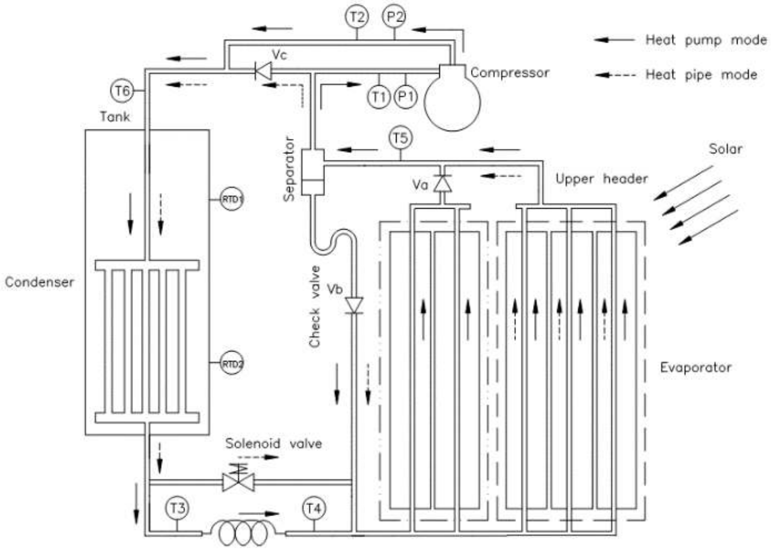
Due to layout convenience, solar water heaters are usually installed on the roofs, which involves using long pipeline. This increases heat losses and the overall cost of the system, especially in multi-story buildings [109]. To address this issue, solar thermal facades have recently attracted researchers' attention as a new and high potential configuration which integrates solar collectors with buildings. Higher solar energy absorption, shorter required pipeline and smaller heat losses, along with using dead spaces in buildings are the main advantages of these systems [110]. It is worth noting that to avoid pipes freezing during winter, Loop Heat Pipes (LHPs) are used instead of conventional heat pipes systems to transfer thermal energy from the outside to the inside of the buildings.

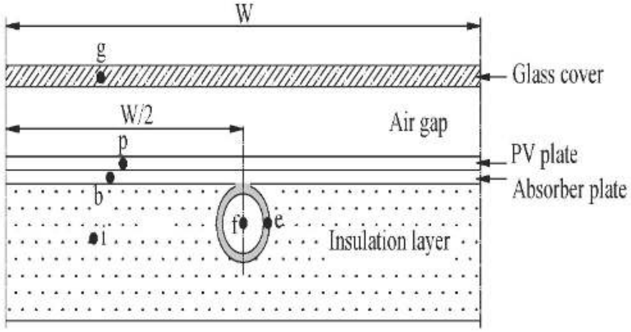
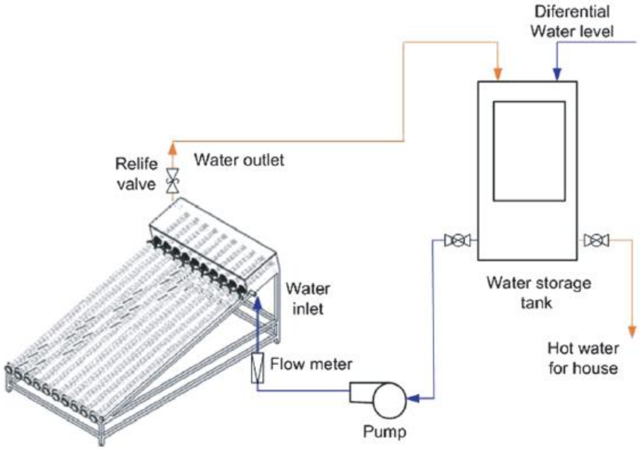
O'Hegarty et al. [111] reviewed and analyzed solar thermal facades, their components, novel facade systems, and their available markets. Li and Sun [112] combined LHPs, solar energy, and heat pump technology and proposed a novel PV/loop heat pipe heat pump water heating system working in three various modes including PV-LHP, solar/air source heat pump, and air source heat pump. The law of energy conservation along with the first law of thermodynamics was used to mathematically model the transient long-term performance of the system. The developed model was validated with experimental data and the effects of operating and structural parameters were investigated. With the aim of reducing the manufacturing cost of LHPs for commercial applications such as solar water heating and power generation, Huang et al. [113] designed and tested a novel evaporator. The results showed that the production cost brought down dramatically by the proposed design.

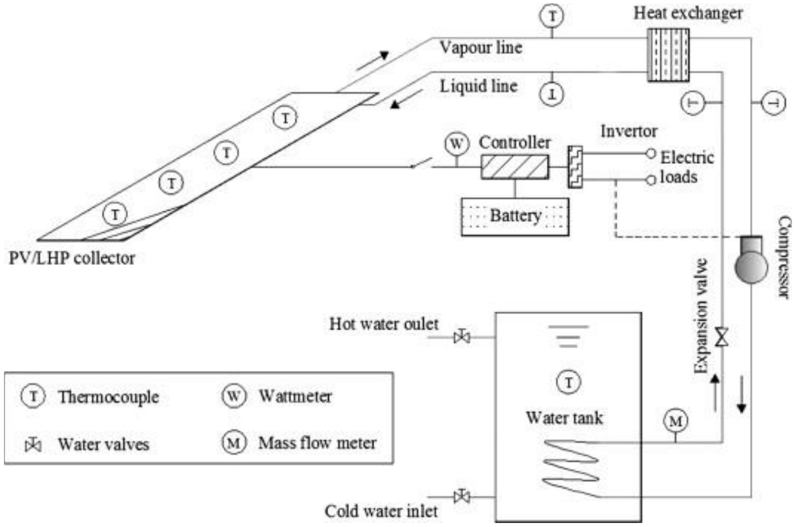
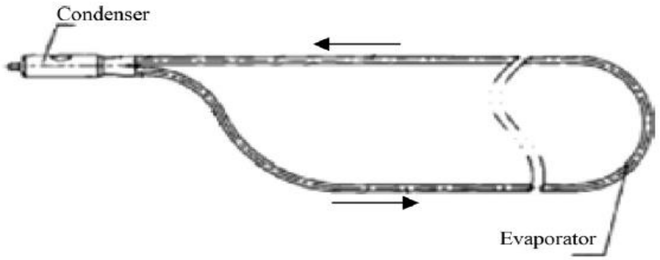
Wang and Yang [109] reviewed the application of LHPs in solar water heating systems by focusing mainly on technical background of the technology and important researches in that field. Technical and economic analysis of a novel LHP solar thermal façade system used in residential buildings of three typical European climates was conducted by Zhang et al. [114]. The sensitivity of the proposed system was evaluated by investigating the overall building socio-energy performance and developing a business model. The multidisciplinary research, which included several financial indexes such as the modified internal rate of return method, net present value, and payback period, can contribute to the early stage design and the strategic decisions for building renovations.

Table 5 summarizes significant previous studies in the field of facade-based solar water heating systems which are mainly based on LHP systems.

Table 5. Summary of recent studies involving LHP facade-based solar water heating systems

Overview	Remarks and key findings	Schematic	Source
Introduction of a solar heat pump water heating system equipped with heat pipes that operated in heat-pump mode when solar radiation was low and in heat-pipe mode without electricity consumption when solar radiation was high.	• Maximum Coefficient of Performance (COP) of the hybrid-mode system was 3.32. • The COP decreased as water temperature exceeded 30 ˚C.		[115]
Introduction of a novel solar LHP facade-based heat pump heating system. Inside the loop heat pipes, vapor goes up and enters upper water tank. Refrigerant receives thermal energy from heat pipe working fluid, passes through the compressor, enters the primary water tank which acts as the condenser and finally passes through the expansion valve.	• The average thermal efficiency of the LHP module was 71%. • The system reached maximum temperature of 58 °C. • Further optimization was recommended.	See Fig. 26	[116, 117]

Two types of glass cover (i.e. single and double glass) were used for facade-integrated solar water heaters. Generated vapor moves towards a flat plate heat exchanger acting as the condenser. Thermal energy is delivered to the flowing water which comes from a storage tank.	• The double glass system showed better performance (48.8 % efficiency) compared with the single glazed one (36% efficiency). • The proposed configuration was efficient and could face the challenges of solar facade-integrated systems such as pipe freezing.	See Fig. 27	[74, 118, 119]
A novel facade-integrated heat pipe thermal/photovoltaic system was investigated theoretically and experimentally. The annual performance of the system in Hong Kong was recorded and evaluated.	• The annual thermal and electrical efficiency of the system were 35% and 10%, respectively. • The total electricity which was saved was 315 kWh/year per unit facade surface area.		[45]
A closed-loop oscillating heat-pipe solar water heater was studied. R-134a with filling ratio of 50% was used as the working fluid of the heat pipe.	• Optimum thermal efficiency of 76% was achieved. • The proposed system showed significant advantages such as corrosion-free operation and simple construction.		[120]

A novel solar photovoltaic/LHP heat pump system for hot water generation was introduced.	• The proposed system displayed 3–5% higher exergetic efficiency compared with the conventional solar collectors. • 40 °C was the daily temperature increase of water inside the tank.		[121, 122]
A novel LHP design for variable installations of solar domestic water heating systems was introduced	• Increased installation flexibility. • Increased operational capability even in low inclination angles.		[123]

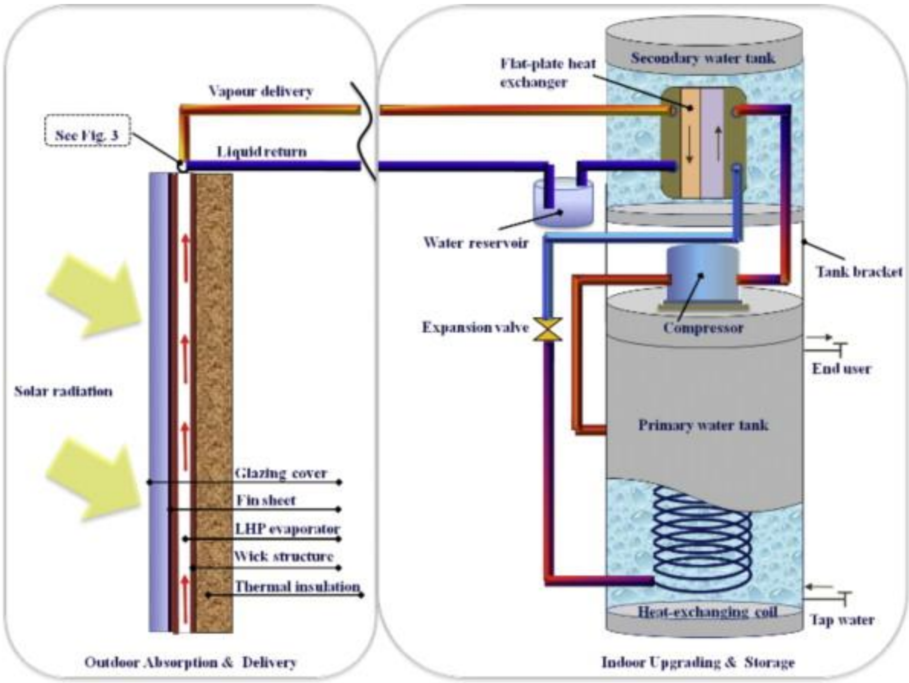


Fig. 26. A solar LHP facade-based heat pump heating system [116, 117].

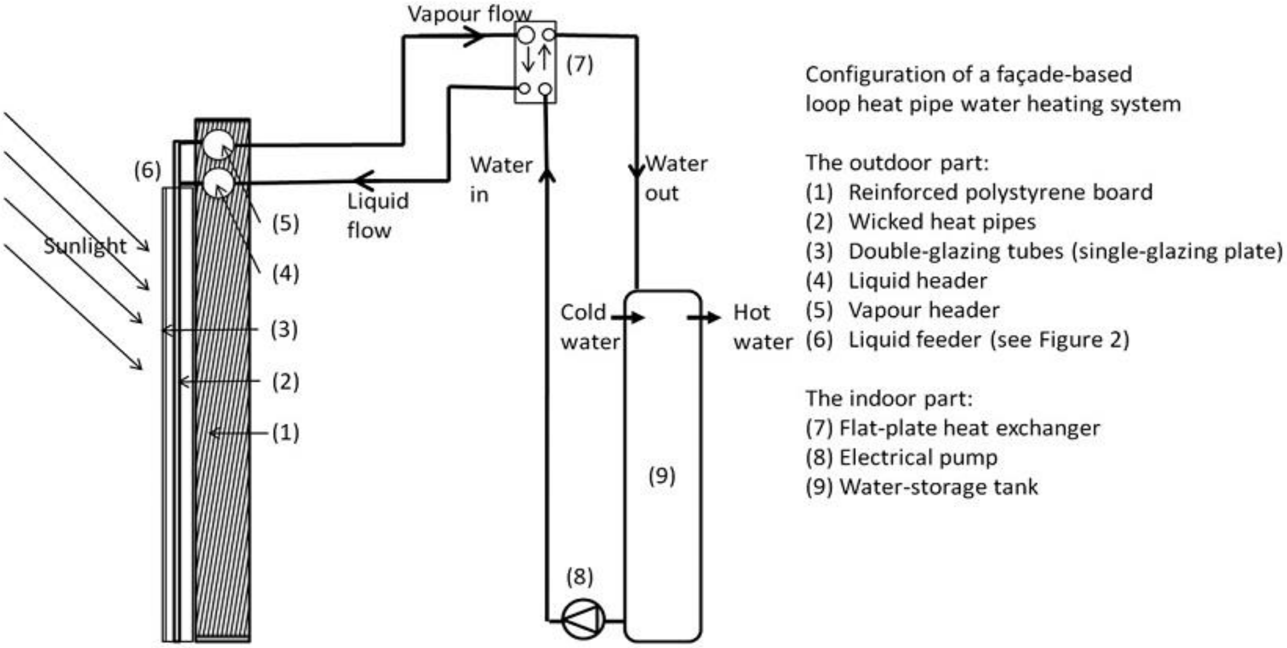


Fig. 27. A facade-integrated solar water heater [74].

Xu et al. [124] introduced a novel combination of compound parabolic concentrators (CPC) with closed-end PHPs in a solar water heating system (Fig. 28). The extracted results from a built prototype with PHPs' filling ratio of 40% was used to analyze the thermal efficiency and the operating characteristics of the system. The overall efficiency of the system was 50% which is promising in comparison to conventional PHP solar collectors.

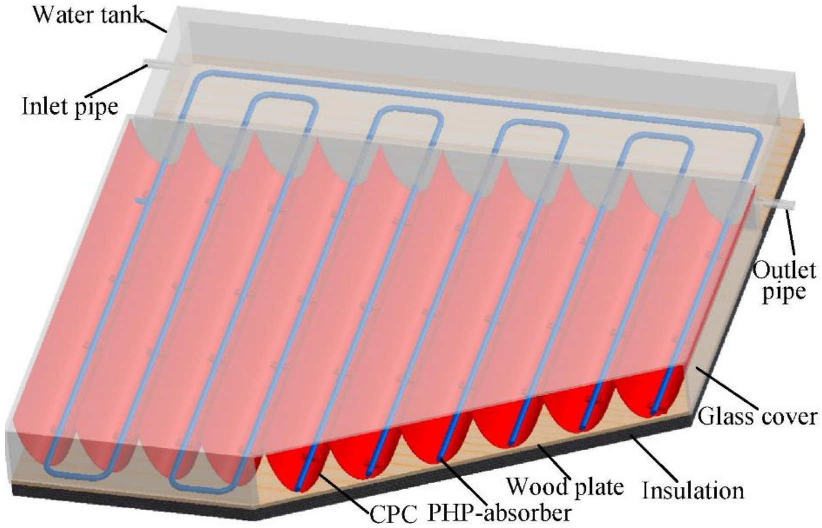


Fig. 28. a solar water heating system equipped with CPCs and PHPs [124].

In another study, the effect of different physical and operational parameters of closed-end PHPs used in a flat plate solar water heater was investigated experimentally [125]. These parameters included the length of heat pipe's evaporator, inclination angle, filling ratio, and flow rate. According to the obtained results, the effect of evaporator length was negligible, and regardless of this parameter, the optimum filling ratio of heat pipes and tilt angle were 30% and 20°. Similar investigations were carried out by Rittidech and Wannapakne [126], Rittidech et al. [127], Nguyen et al. [128], and Yang et al. [129].

In a semi-experimental study, the behavior of PHPs in a flat plate solar water heater was investigated using a two-layer artificial neural network method and genetic algorithm [130]. The study focused on various parameters such as filling ratio, solar radiation, evaporator length, inlet water, outlet water, and inclination angles. After validating the results of the developed neural network model with experiments, it was used along with a continuous genetic algorithm to optimize the thermal efficiency of the system. Based on the results, the optimum values of filling ratio, evaporator length, and inclination angle were 56.94 %, 1.08 m, and 25° which resulted in optimum thermal efficiency of 61.4 %. At the end, neural network and genetic algorithm were recommended as proper methods to predict and optimize the performance of these systems.

4.2. Application of heat pipe solar collectors for desalination

The survival and health of human beings relies greatly on adequate access to fresh water resources. However, the ratio of potable water resources to unhealthy and salt water resources on earth is about 0.026. Population and industry growth and high water consumption have made the situation worse during the last few decades and this has turned water shortage to a global threat [131]. Many researchers have tried to solve this issue by proposing different desalination methods; however, most of the previous proposed systems have been either inefficient or energy intensive. Also, most of the proposed desalination systems could not be justified on environmental grounds in terms of pollution and waste disposal [132]. Therefore, the application of free and clean solar energy in desalination systems by proposing new and efficient combinations seems promising [133]. Furthermore, because of significant benefits in terms of energy and environment, these solar energy-based desalination systems can be applied in remote and isolated areas with low access to urban facilities [134].

Taking into account the great advantages of HPSCs, several researchers have tried to apply them in desalination systems in recent years. The simplest design of heat pipe solar stills included a square basin of 0.4 m length with a 35° inclined glass cover as shown in Fig. 29 [135]. The absorbed solar energy was transferred to the saline water through condensers of the heat pipes located inside the basin. The water vaporized rose up towards the condenser and turned into fresh water. Although the performance of the proposed heat pipe-based desalination system was much better than previous types of solar still systems, its fresh water production rate (1.02 kg/m^2h) was not satisfactory.

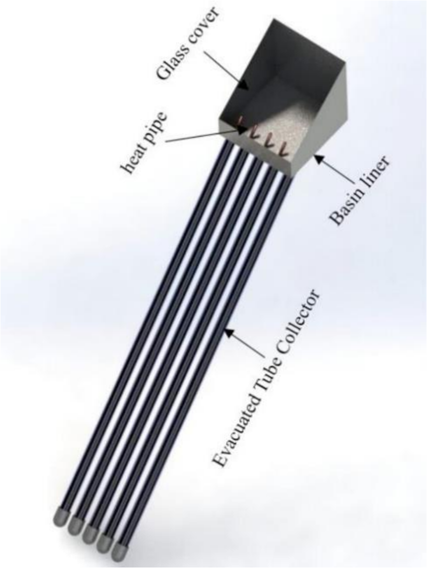


Fig. 29. The schematic of a simple heat pipe solar still [135].

To improve the performance of heat pipe solar stills, the utilization of parabolic reflectors for more efficient absorption of solar radiation was proposed [136]. The specific configuration of the desalination basin and the condenser section for this set up is shown in Fig. 30. The dimensions of the basin and maintenance costs are reduced and the fresh water production rate improves. Hence, the proposed configuration was suggested to be analyzed in larger desalination scales [136].

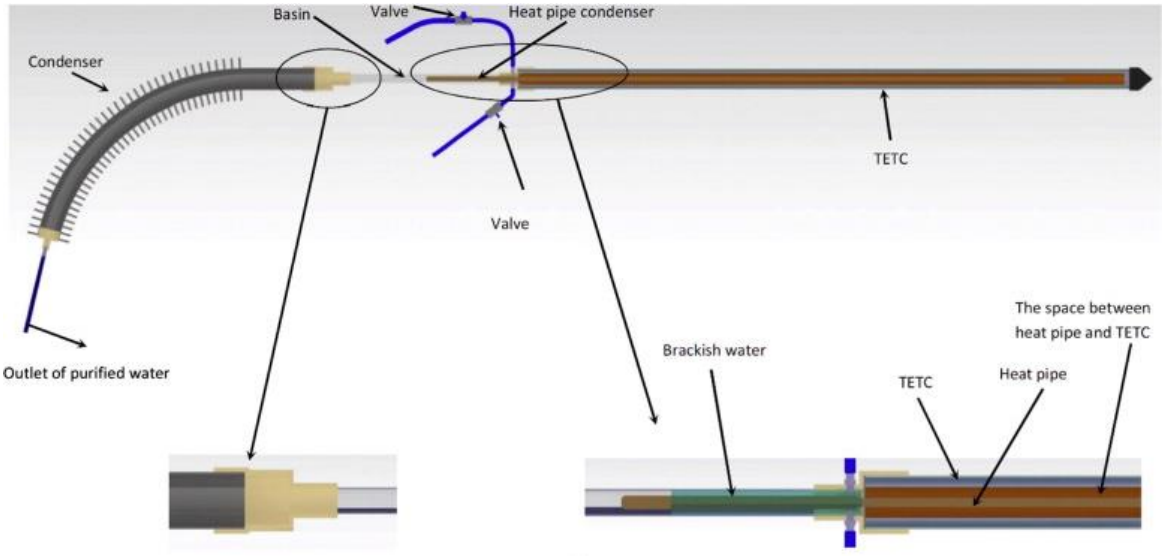


Fig. 30. Details of the proposed heat pipe solar still with utilization of parabolic reflectors [136].

Aiming to increase the operating hours of solar stills even after sunset, the application of phase change materials in heat pipe solar stills, to store condensation heat and use it during night, was proposed (Fig. 31) [137]. The overall process was very similar to conventional solar stills except that it had a tank filled with Paraffin, i.e. PCM tank, which acted as the cooling unit. During the daytime, vaporized water transfers its condensation heat to Paraffin and turns into fresh water. In the evening and as the solar radiation decreases, the PCM acts as the evaporator and begins to transfer stored energy to the saline water through the heat pipes placed inside the PCM tank. The evaporator sections of the heat pipes are inside the PCM tank while their condensers are located inside the saline water. The proposed system improved the overall efficiency significantly reflecting increased fresh water production rate of 6.555 L/m^{2}day [137].

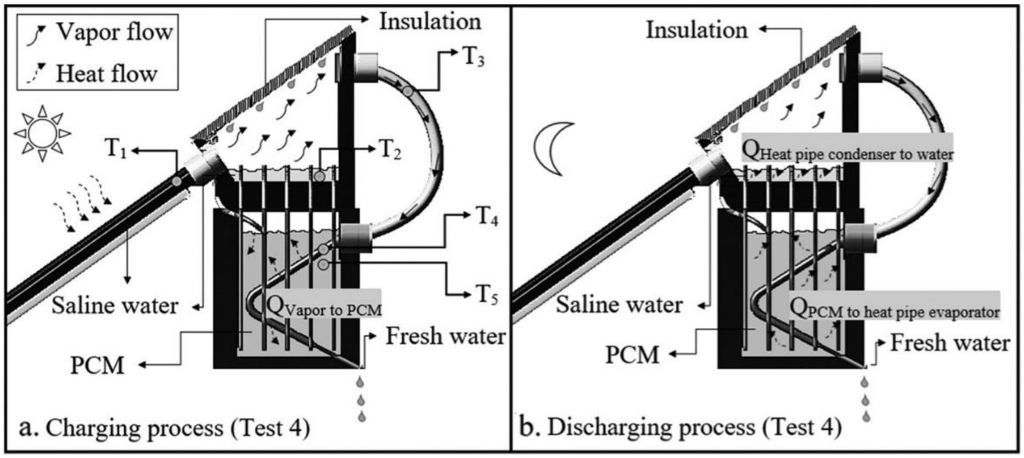


Fig. 31. Heat pipe solar still equipped with PCM condenser: (a) day time (b) night time [137].

Chong et al. [138] connected a HPSC to a multiple-effect diffusion (MD) solar still to achieve a higher temperature gradient and a higher fresh water production rate (Fig. 32). In this system, as the temperature of the sea water is increased, it starts moving towards the multiple effect diffusion unit as a result of thermosyphon effect. Both the outlet hot brine and distilled water enter a heat exchanger and transfer their extra heat to sea water. The bent shape of the wick-plate of the MD unit helps to prevent the obstruction of channels by contamination. The results indicated that on sunny days with solar radiation of 800 W/m^2, the outlet temperature of the solar collector reached 100 °C resulting in a fresh water production rate of 2.79 L/m^{2}d.

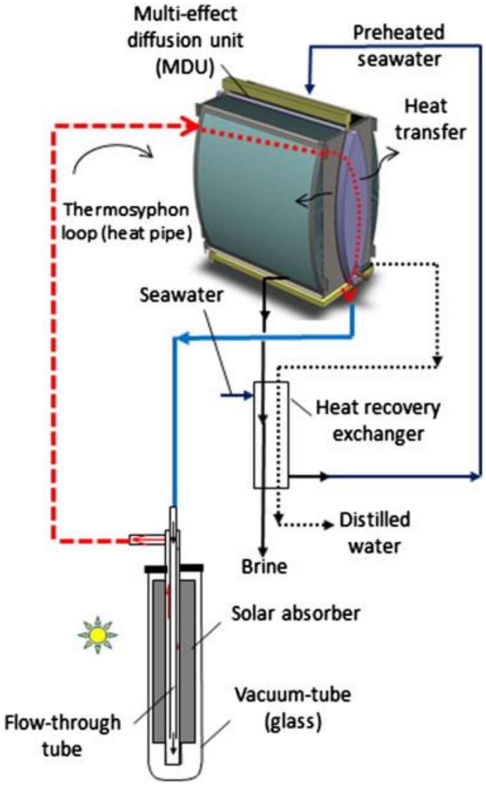


Fig. 32. Connecting HPSC to a multiple-effect diffusion unit [138].

In a similar study, HPSCs were integrated with a spiral multiple-effect diffusion unit to be used for desalination [139]. The specifications of the solar system and the heat recovery unit were the same, however, the bent shape of MD unit was replaced by a spiral. The fresh water production rate of the new configuration reached 8 L/m^{2}d, showing a significant improvement compared with the previous configuration [139].

By proposing a novel configuration, Behnam and Shafii [140] investigated the performance of a heat pipe solar air bubble column humidifier (Fig. 33). Significant advantages of HPSCs along with effective mixing and high interface area of the air bubble column humidifier were the main innovations for this study, which aimed to achieve better performance and lower cost. In the proposed system, absorbed solar energy is transferred to the humidifier by heat pipes, and at the same time, generated saturated air is extracted and blown into dehumidifier by a fan and flows over a cooling coil. Fresh water is produced by the condensation process and collected from the bottom of the dehumidifier. The overall fresh water production rate in this configuration was 6.275 L/m^{2}d. For achieving optimum performance, the height of the humidifier should be kept equal to the condenser height.

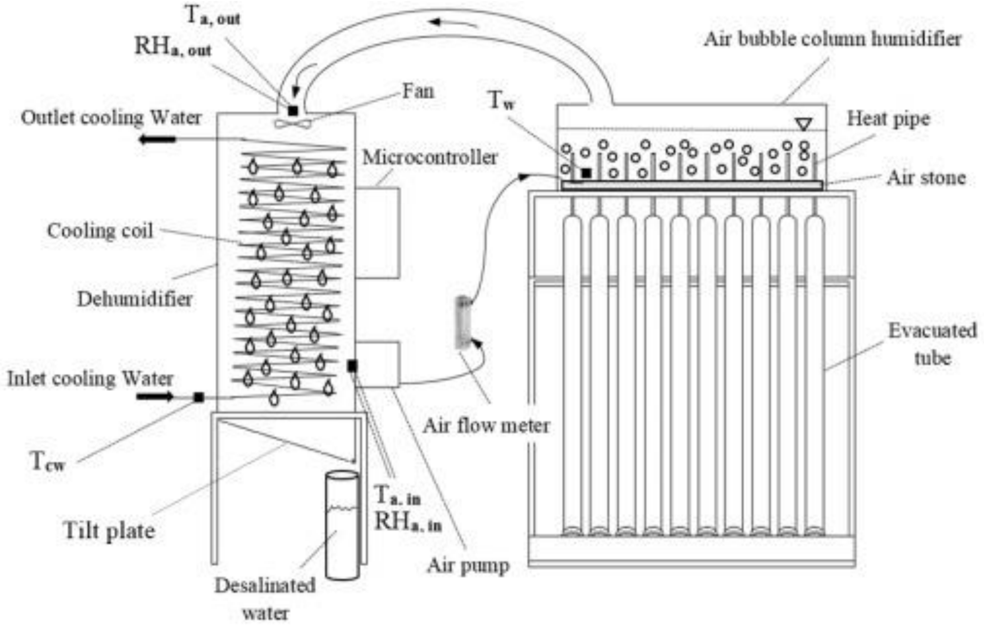


Fig. 33. Schematic of the heat pipe solar air bubble column humidifier [140].

Alwaer and Gryzagoridis [141] connected a HPSC to a storage tank equipped with an internal copper coil acting as the boiler (Fig. 34). In this system, solar working fluid circulates through the copper coil and warms the water inside the tank. The vapor that is produced directed towards the cooling system and passes the second coil, where it turns into fresh water by transferring its heat to the cold water inside the storage tank. Although the initial experiments were encouraging, they did not reach a satisfactory level, so creating a partial vacuum inside the tank to reduce the vaporization temperature was proposed.

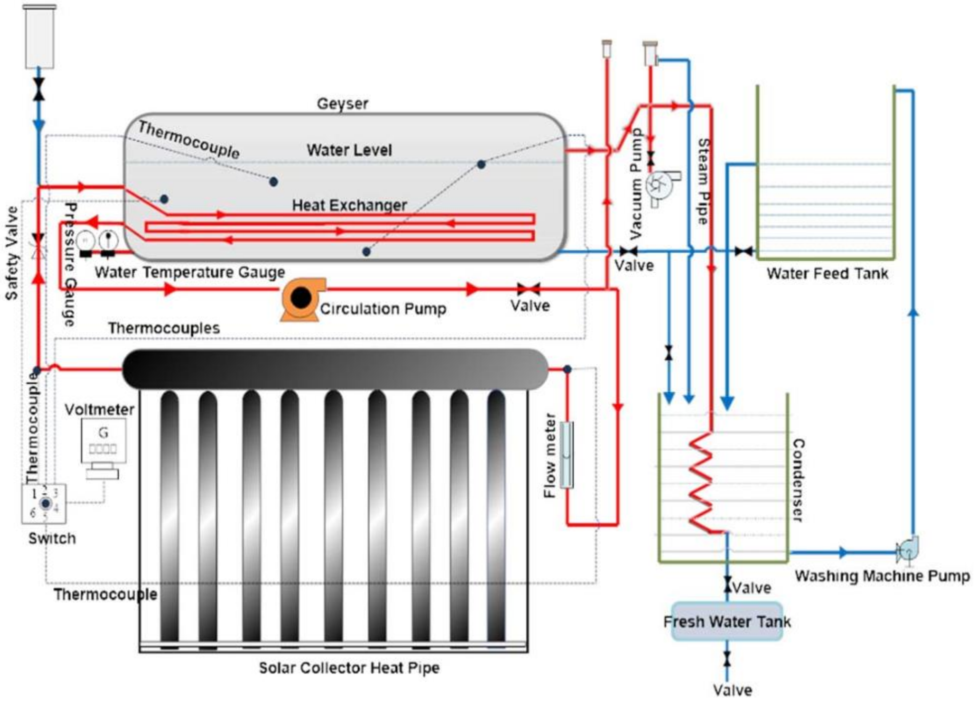


Fig. 34. HPSC coupled with a storage tank equipped with an internal copper coil [141].

Abad et al. [94] proposed the application of PHPs in the flat plate collector of a solar desalination system (Fig. 35). The experimental results of a case study in Tehran, Iran revealed that the new configuration increased the fresh water production rate as it reached up to 875 mL/m^{2}h from 12:30 PM to 1:30 PM. Other important parameters such as optimum filling ratio of the PHPs and water depth in the basin were also studied in details.

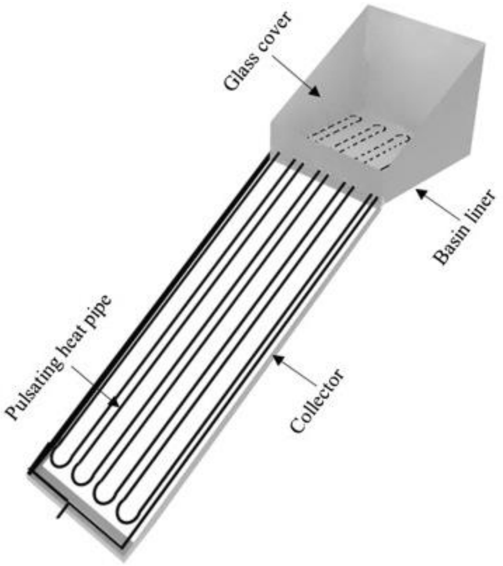


Fig. 35. Application of PHPs in a flat plate collector of a solar desalination system [94].

4.3. Application of heat pipe solar collectors for space heating

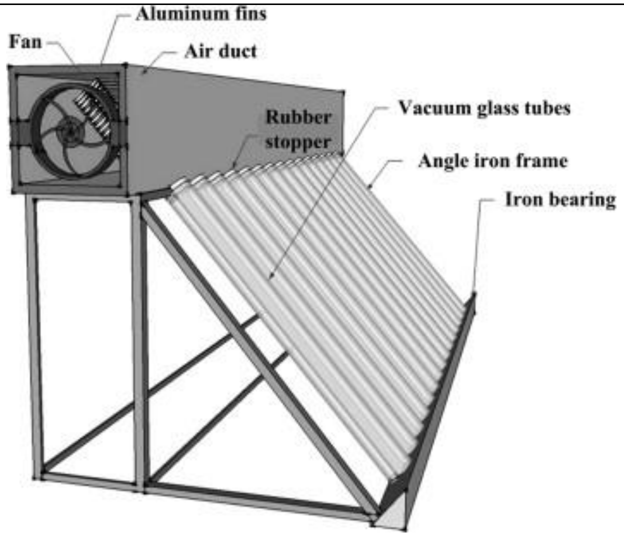
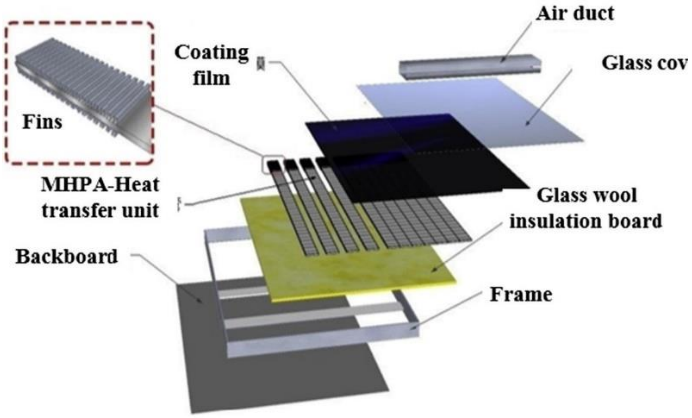
The United States Department of Energy has reported that more than half of the consumed energy in residential sector is devoted to space heating [142]. That is why the most efficient method to decrease energy consumption in regions with cold climatic conditions is to reduce space heating requirements [98]. Solar energy has been introduced as a cost-effective alternative source of energy in heating systems, instead of fossil fuels [3]. However, the application of HPSCs in space heating systems, whether air-based, water-based, or passive, is rather new and there are limited studies in this field.

The first type of Heat Pipe Solar Space Heating (HPSSH) systems use air as the main working fluid. An HPSC converts solar radiation into thermal energy and delivers it to the air, which flows by a fan [143]. Other than using fans instead of pumps and ducts instead of pipes, air-based solar collectors and water-based solar collectors are very alike [144]. Solar energy absorbed by the film coating of the vacuum tubes transfers to the evaporator section and vaporizes the heat pipe working fluid. Vapor moves towards the condenser section and transfers its heat to the flowing air. The vapor condenses and returns back to the evaporator section. Apart from space heating, air-type systems can also be used in agricultural drying and mostly operate at relatively low temperatures compared with water-based solar collectors [98].

The second type of HPSSH systems are water-based floor heaters, which are more attractive nowadays due to their significant advantages, including greater thermal comfort and more integrated heat distribution [145]. These systems are able to heat the air above ground up to the height of a normal person and are more cost effective than the conventional systems [146]. The water temperature in floor heating systems needs to be in medium or low range. This makes the floor heating system an appropriate option to be combined with solar systems [147].

The third type of HPSSH systems are passive systems where heat pipes are partially incorporated inside the building walls. It is well known that walls play an important role in the energy consumption of buildings [148]. Walls facing south absorb greater amounts of energy (northern hemisphere), especially in winter; however, the problem is the low efficiency of the energy transfer process from the outside to the inside of the buildings [149, 150]. To make the process more efficient, heat pipes can be added to walls to create a new passive solar system [151]. The evaporator section of the heat pipes is in direct contact with the solar absorbers and receives thermal energy. Generated vapor moves towards the condenser section through the adibatic section located in the insulated wall of the buildings. In the condenser section, vapor delivers the latent heat of condensation to a thermal storage tank or the ambient air [152]. Experiments have shown that the efficiency range of these systems is between 60% and 80% [142]. Table 6 summarizes the significant studies in the field of heat pipe solar space heating systems including air-based, water-based, and passive systems.

Table 6. Summary of recent studies involving heat pipe solar space heating systems

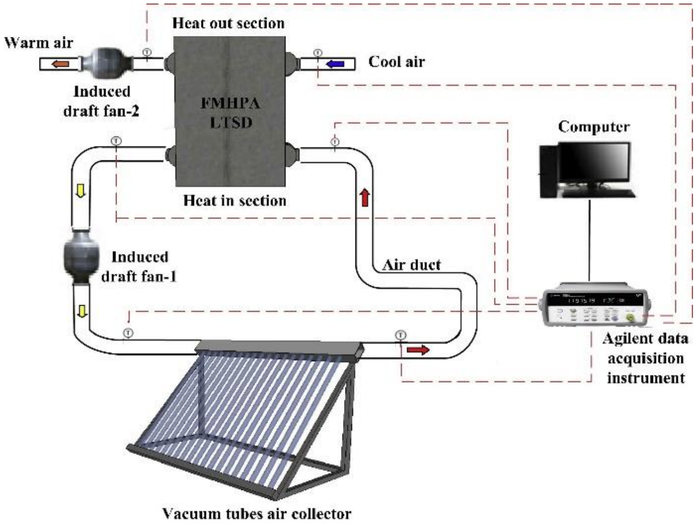
Overview	Remarks and key findings	Schematic	Source
A novel air heating system utilizing micro-heat pipe arrays as the main components of the heat collecting and transfer section.	- The maximum thermal efficiency of 73% was achieved. - The air pressure drop was less than 25 Pa when air flow rate was lower than 200 m^3/h. - The efficiency of the proposed system can be obtaind from $\eta=0.75-6.36(T_i-T_a)/I$, where T_i (°C) and T_a (°C) are the inlet and the ambient temperature and I (W/m^2) is the solar radiation.		[143]
V-shaped aluminum fins connected to the condenser section of micro-heat pipe arrays to improve heat transfer coefficient of air systems.	- The average efficiency of 69% was achieved at an air flow rate of 290 m^3/h. - The air pressure drop was less than 10.4 Pa when the air flow rate was lower than 290 m^3/h.		[153]

A new solar air collection-storage system to increase utilization hours of the system and overcome the lower heat capacity and storage capability of air compared with water.

Hot air generated by HPSC was not used directly; instead, it was directed towards a sealed storage tank filled with PCM (lauric acid) and transferred heat through flat micro-heat pipe arrays.

The other side of storage tank was connected to load duct. Cool air was blown by another fan passed the aluminum fins and absorbed thermal energy from PCM.

- The maximum achieved solar fraction was 56%.
- Higher air flow rates resulted in higher efficiencies, higher heat transfer, and short charging and discharging time.

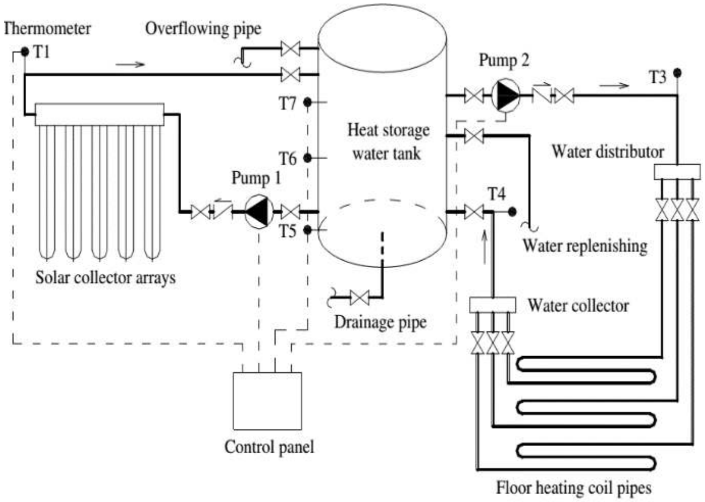


[154]

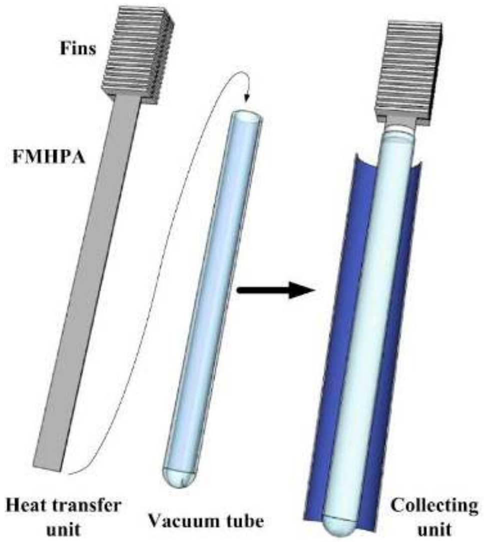
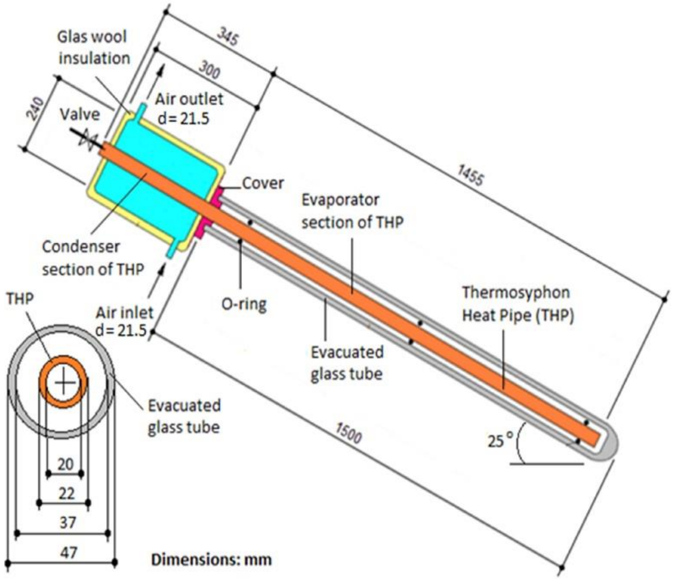
The performance of a heat pipe water-based solar floor heating system was evaluated in Shanghai, China by installing 150 m^2 of HPSCs to cover the heating demands of a building with an area of 460 m^2.

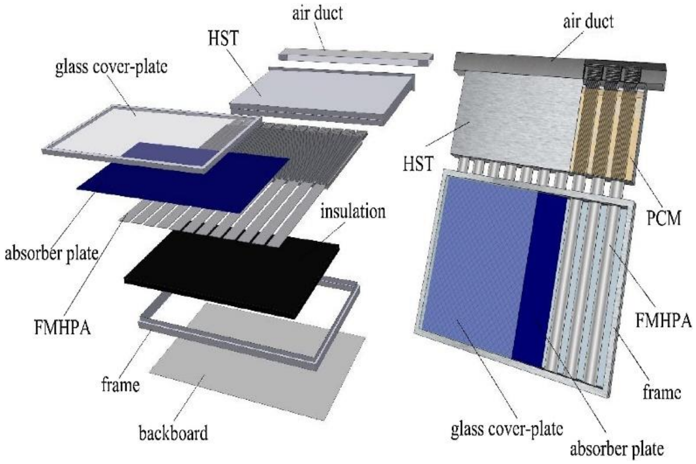
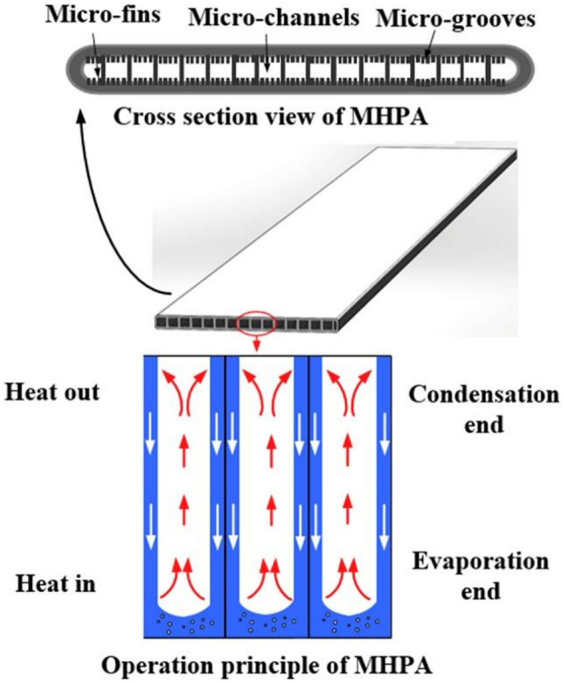
The whole system was controlled by a central control unit by defining special parameters such as temperature difference between the solar collector and the storage tank.

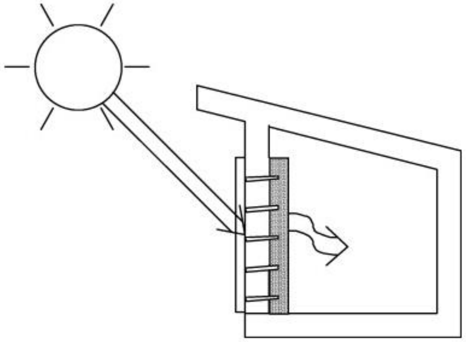
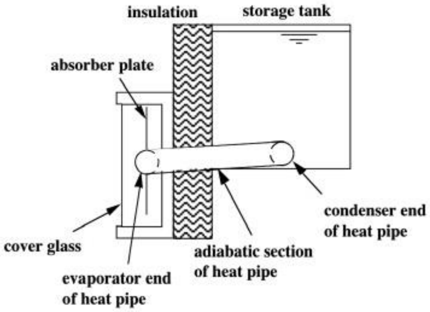
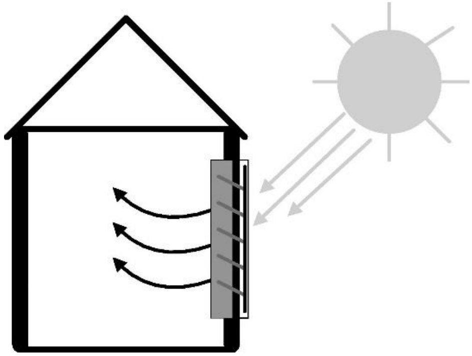
- The solar fraction and the average heating capacity of the system was 56% and 25.04 kW, respectively.
- The proposed system was able to produce sufficient thermal energy to keep indoor warm and could conserve a significant amount of energy in winter compared with conventional systems.



[147]

A novel combination of CPC solar air collectors with flat micro-heat pipe arrays was introduced. The theoretical and experimental thermal performance of the proposed system was investigated under climatic conditions of Beijing, China.	• The average and instantaneous efficiency reached 61% and 68%, respectively. • Increasing the air volume flow rate had a negative effect on the overall efficiency.		[155]
The effect of six different working fluid (i.e. Hexane, Chloroform, Methanol Petroleum Ether, Acetone, and Ethanol) on the energy and exergy performance of a heat pipe solar air heater was evaluated at different solar working fluid mass flow rates was evaluated.	• Hexane had the worst performance at all solar working fluid velocities (2-4 m/s). • Among different working fluids, Acetone had the best energy efficiency (65%) for the mid-range velocities (2-3 m/s). • Regarding exergy efficiency, Acetone and Chloroform had the best performance in low and high velocities, respectively.		[53]

The effect of integrating heat pipe solar air heating system with PCM as the latent heat storage was studied experimentally.	• The overall efficiency of the combined system during charging and discharging was 59% and 91.6%, respectively. • Increasing the flow rate of the heat transfer fluid increased heat extraction rate and decrease the heat extraction time		[156]
The thermal and energy performance of a solar air heating system equipped with micro heat pipe arrays was experimentally investigated for three different working conditions.	• The thermal efficiency was between 50% and 70%. • The proposed system reduced the daily carbon dioxide emmision by 2.13 kg. • The temperature distribution in various locations of the solar collector was analyzed.		[157]

A prototype of a heat pipe passive solar heating system was designed and constructed.	• The maximum recorded efficiency and room heat gain of the system was 83.7% and 163 W/m^2, respectively. • Further studies regarding improvement of thermal insulation and design of the frame was recommended.	  	[152]
An enhanced model for simulating heat pipe passive solar heating systems was proposed.	• The new model showed better accuracy with significant improvement in heat transfer and heat loss reduction.		[158]

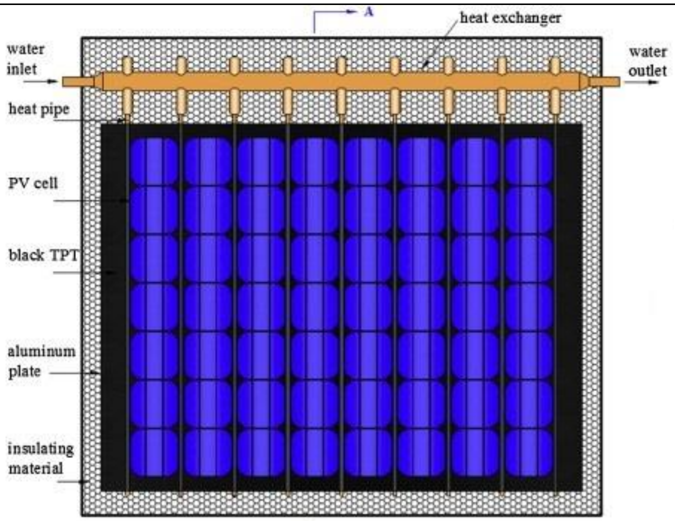
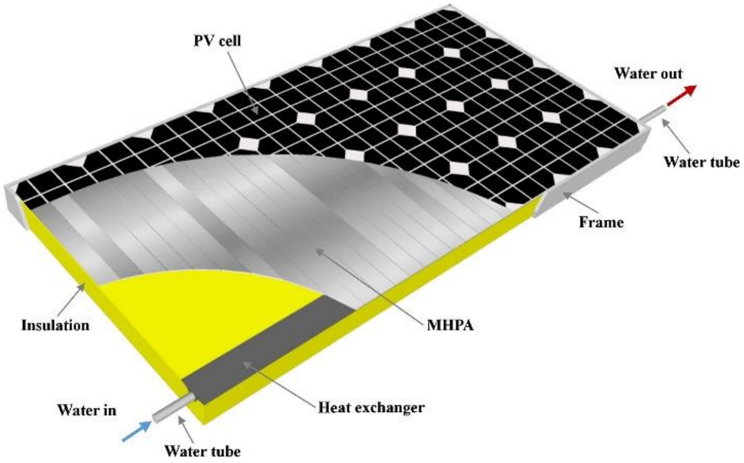
4.4. Application of heat pipe solar collectors for power generation

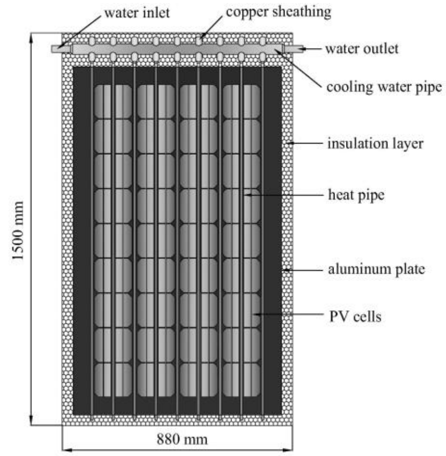
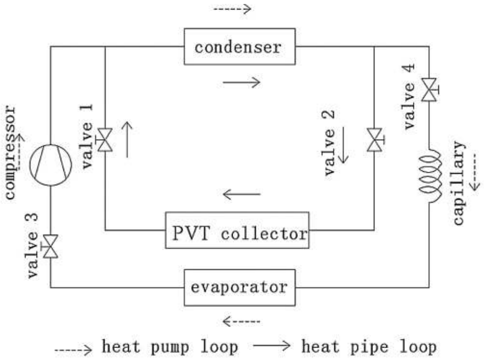
Power generation is one of the most energy intensive sectors in the world and the application of solar energy can conserve a significant amount of fossil fuels and reduce environmental consequences. The utilization of HPSCs for this application can be classified into three categories: (i) Heat pipe photovoltaic/thermal (HPPV/T) systems, (ii) Heat pipe thermoelectric generators, and (iii) High temperature solar power plants. Sections 4.4.1, 4.4.2, and 4.4.3 will look at each of these options.

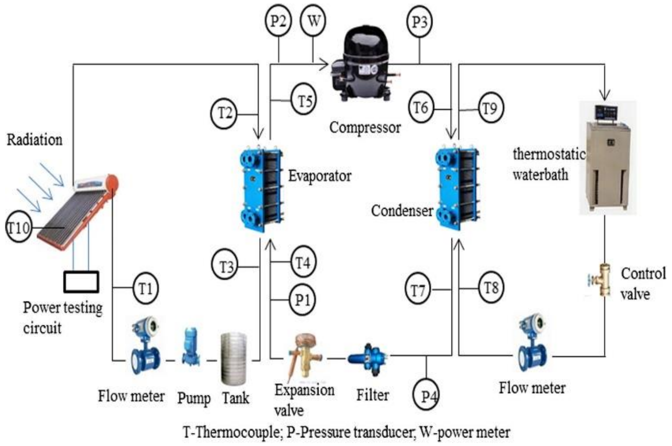
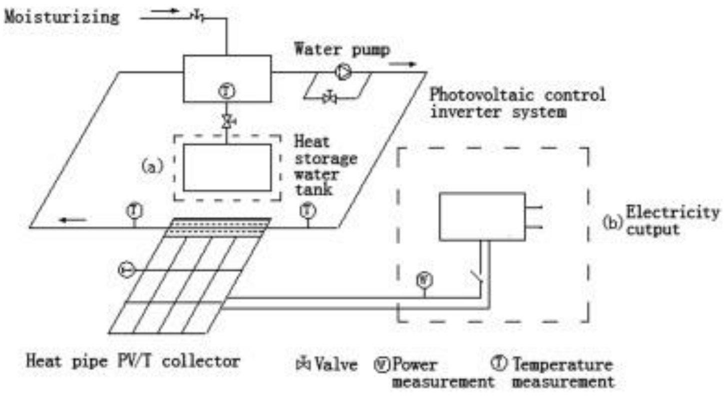
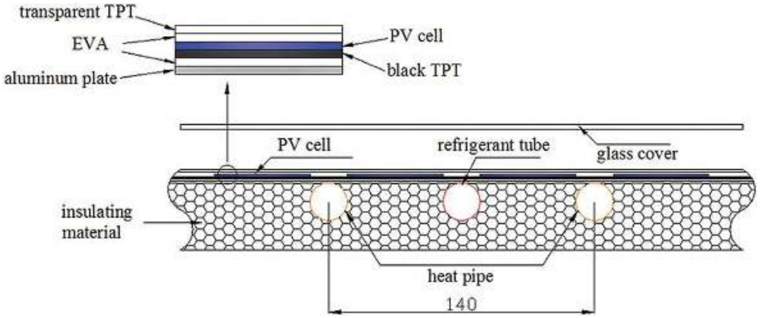
4.4.1. Heat Pipe Photovoltaic/Thermal Systems

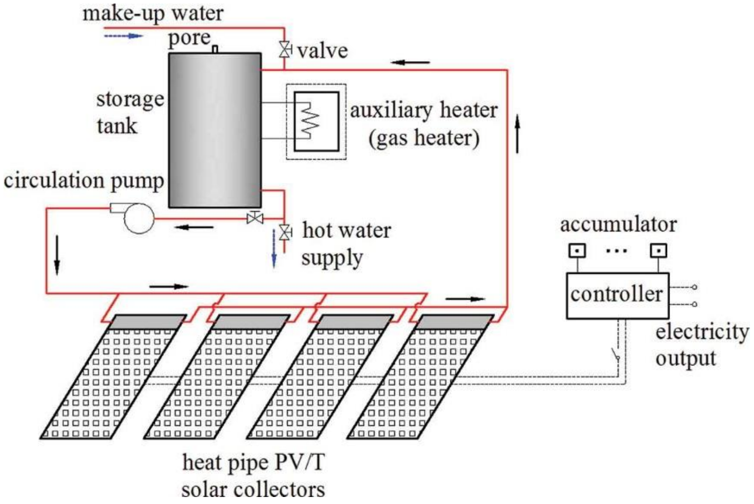
Heat Pipe Photovoltaic/Thermal (HPPV/T) systems are the combination of heat pipes with photovoltaic panels to produce thermal and electrical energy simultaneously [159]. Photovoltaic/Thermal (PV/T) modules convert a fraction of the absorbed solar energy into electricity and the other fraction into heat. Heat pipes absorb and transfer this extra heat to the solar working fluid [160]. In spite of the significant advantages of PV/T systems compared with conventional collectors [161], the combination of cylindrical-shaped heat pipes with PV modules creates several drawbacks, such as higher thermal resistance, non-uniform temperature distribution, and higher manufacturing costs [162]. Therefore, most of the studies in this field were focused on flat plate heat pipes. Table 7 presents a summary of some of the significant studies that have been conducted to date in the field of HPPV/T systems.

Table 7. Summary of significant studies in the field of HPPV/T systems.

Description(s)	Remarks and key findings	Schematic	Source
A new flat plate heat pipe PV/T panel was proposed and its performance was investigated theoretically and experimentally. Copper heat pipes were attached to an aluminum plate and water was the working fluid.	The thermal, electrical, overall, and exergy efficiency of the system were 45.7%, 10:2%, 51.5%, and 7.1%, respectively.		[163, 164]
Application of micro heat pipe arrays in PV/T modules. The main aim of the proposed configuration was to reduce the limitations of conventional heat pipes.	The optimum thermal, electrical, and overall efficiency of the module were 37.8%, 15.1%, and 50.8%, respectively. Advantages: higher contact area between the plate and the heat pipes, higher heat transfer coefficient, more reliable, lower hydraulic resistance, and lower manufacturing costs		[164]

Studied the effect of inclination angles and wick structure on the performance of heat pipe PV/T systems.	Wicked and wickless heat pipes showed their best performance at inclination angles of <20˚ and >20˚, respectively.		[165]
A novel HPSC with and without PV, as a building envelope, was studied experimentally in Cardiff, UK.	HPSC with and without PV had thermal efficiency of 64% and 50%, respectively. The combination of HPSC and PV increased the power output of PV by 15%.		[166]
Proposed a novel heat pipe PV/T system including loop heat pipe collector and heat pump.	The optimum coefficient of performance of the heat pump and the solar heating fraction were 3.10 and 57.8%, respectively.		[112]

Theoretical and experimental analysis of a heat pipe PV/T water heating system. The effect of various parameters such as PV backboard absorptivity, solar radiation, ambient temperature, and PV packing factor on thermal and photovoltaic/thermal COP was studied in detail.	Increase of solar radiation intensity and packing factor had a positive effect on the coefficient of performance, while increase ambient temperature and PV backboard absorptivity had a negative effect.		[167]
Experimental optimization of volume of storage tank and inclination angle of a heat pipe PV/T system.	The optimum tank capacity was 80 L resulting in efficiency of 67.50%. Increase of storage tank volume and temperature are inversely proportional. Smaller tank resulted in lower power generation efficiency.		[168]
Proposed a new heat pipe PV/T collector to solve freezing problem which occurs in traditional PV/T collectors. Experimentally tested the collector with and without glass cover.	The average thermal efficiency of the collector with and without glass cover were 41.30% and 37.16%, respectively. These values for PV efficiency were 9.42% and 11.51%, respectively.		[169]

Compared the daily and annual performances of a heat-pipe PV/T and water heating system.	Water heating system had higher thermal energy gain while PV/T system had higher exergy efficiency.		[170]

4.4.2. Heat pipe thermoelectric generators

In recent years and with the aim of finding efficient alternatives to PV collectors, the combination of heat pipe solar collectors and thermoelectric generators has been proposed by several researchers [171-174]. Heat that is generated from a temperature gradient can be turned into electricity by using thermoelectric generators [175]. As in the heat transfer process, free-charge carriers migrate from the hot side to the cold side (Fig. 36) resulting in voltage production which is directly related to the temperature difference. Thermoelectric generators are simple with no moving parts; they are also reliable with low maintenance costs, silent, environmentally friendly, and can start functioning even with small sources of heat [175, 176]. According to the literature [177], a typical 1m^2 PV collector can produce 132 W while this number is 160W for a heat pipe solar thermoelectric generator (HPSTG) with the same area. Consequently, a HPSTG is considered as a superior alternative to PV collectors [173].

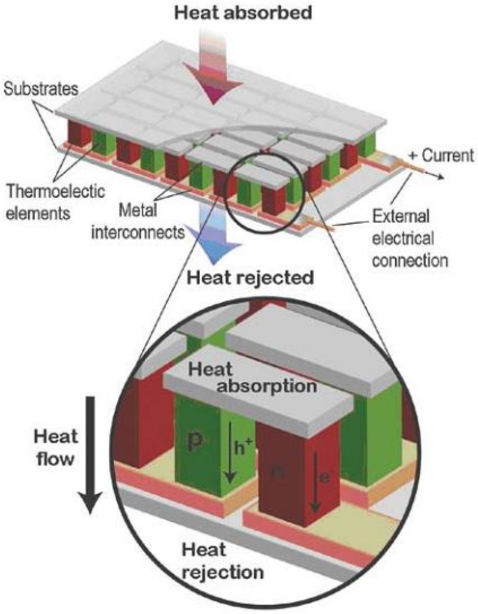


Fig. 36. Schematic of the voltage production process in a thermoelectric generator [175].

In a theoretical and experimental study, Li et al. [172] proved that a combination of thermoelectric generators with heat pipe solar collectors resulted in better efficiency, higher output power, and satisfactory performance compared with thermoelectric generators in series. The proposed system (Fig. 37) included micro-channel heat pipes and thermoelectric modules that were attached under the condenser surface of heat pipes. These modules absorbed the latent heat of condensation inside the heat pipes and created a temperature gradient.

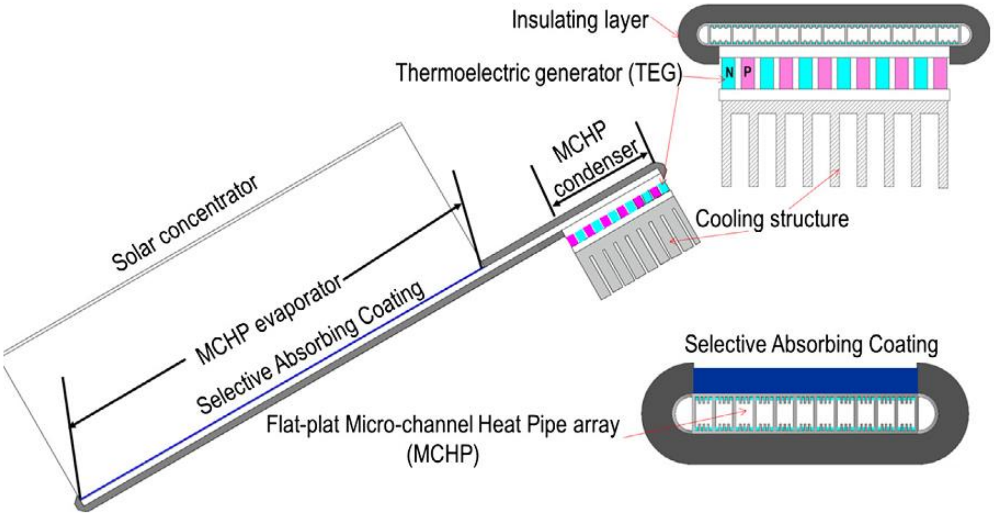


Fig. 37. Schematic diagram of the HPSTG [172].

In a similar theoretical study, a HPSTG system was modeled by considering several simplifying assumptions such as constant solar radiation [171]. According to the results, the system could reach the optimum conversion efficiency of 3.346% at solar radiation of 1000 W/m^2 [171]. Manufacturing factors such as temperature dependence of material properties and contact thermal resistance were not considered in this study and, hence, can be considered in future performance study of these systems.

With the aim of producing both hot water and electricity, Omer et al. [173] experimentally examined the performance of a new heat pipe thermoelectric solar collector. The 0.5 m^2 surface area of the solar collector was covered with a special absorbing paint and connected to a 50 L water tank. The output electrical power of the proposed system was 160 W/m^2 of absorber surface and water temperature inside the tank reached 95 ˚C. Therefore, in spite of satisfactory performance, this type of double purpose system still needed more technical improvements. In a similar study using annular thermoelectric generators instead of flat-plate ones, Manikandan and Kaushik [174] conducted an energy and exergy analysis based on the first and second laws of thermodynamics. The results indicated that by having the output power and exergy efficiencies of 1.92W and 5.02%, respectively, the proposed system showed a better performance than heat pipe flat plate thermoelectric generator.

4.4.3. High temperature applications

In order to use heat pipe solar collectors in high temperature applications such as solar power plants, various configurations have been proposed. Most of these studies used molten salt as the working fluid or heat storage material [87]. Table 8 provides a summary of these studies.

Table 8. Summary of some significant previous studies on the application of heat pipe solar collectors in high temperature applications.

Description(s)	**Remarks**	**Source**
Numerically investigated the performance of a new heat pipe solar power plant by studying the effect of some design parameters such as evaporator temperature.	• The new system can decrease the possibility of frozen molten salt. • The proposed configuration improved the daily operating duration of the solar power plant and reached 85% efficiency.	[178]
Filled the heat pipe collector of a solar power plant with sodium as the working fluid.	• Input heat and inclination angle are the most effective parameters influence on the start-up time and efficiency. • The new configuration decreased thermal stresses and stabilized system operation.	[179]
Loop heat pipes with different filling ratios were used to absorb and transfer solar energy to an Alkali thermal to electric converter.	• Operational parameters such as thermal conductivity and thermal resistance are greatly influenced by filling ratio. • The optimum filling ratio for heat pipes in this application was 32% of the evaporator volume.	[180]
Designed and introduced a high temperature heat pipe for utilization in a thermochemical solar reactor.	• While the new design improved the temperature distribution in the chamber significantly, its thermal resistance range (0.12 to 0.19 °C/W) was in the same order of magnitude of a typical heat pipe.	[181]
Proposed a high temperature heat pipe with frozen start-up improvement.	• Better start-up time at inclination angles between 0° and 45° compared with conventional heat pipes.	[182]

5. Future trends in heat pipe solar collector research and development

The use of heat pipe solar collectors in various applications is expanding fast because of their advantageous and significant characteristics compared with conventional solar collectors. Although the previous studies and efforts in this field have led to valuable achievements to date, heat pipe solar collectors have high potential regarding both development and new applications. Also, the necessity of continuous improvements in the existing knowledge is unnegotiable. Based on this literature review, the following new research directions involving HPSCs might be useful to take advantage of free and clean solar energy more efficiently and innovatively.

- There are limited research on the economic analysis of HPSCs and it is highly recommended that the economic feasibility of previous and future proposed systems should be evaluated for all different applications and configurations.
- Improving the performance of heat pipe solar collectors as the most important components of solar systems is also very important. Therefore, the application of novel working fluids (e.g., various nanofluids), investigating the effect of design parameters (e.g., pipe diameters and materials), and studying the effect of some operational parameters (e.g., working fluid mass flow rate, inclination angle, and climatic conditions), are recommended.
- Most of the previous studies in the field of heat pipe solar water heaters have not considered the consumption patterns of the location where use of such a system is proposed. More theoretical and experimental studies are required to understand the effect of water consumption patterns on the thermal performance of water heaters. Regulating the volume of extracted hot water based on the climatic conditions and the performance characteristics of the solar water heating system can lead to the optimum use of available capacity.

- Comprehensive comparisons of thermosyphon and active heat pipe solar water heating systems under different climatic conditions and consumption patterns are also needed. This would improve the understanding of these systems, resulting in a more accurate selection of system types and operational characteristics.
- Loop heat pipe facade solar systems have noteworthy technical advantages (e.g., lower piping cost) and architectural benefits (e.g., improving the aesthetic effect of the building). Hence, utilizing loop heat pipes in facade solar systems can be expanded significantly.
- The high potential and great prospective of solar energy utilization in desalination systems is well known. However, the heat pipe solar desalination systems proposed to date are mainly focused on solar stills and their performance is not yet satisfactory. Other possible configuration of heat pipe solar desalination systems have received little attention. Therefore, further studies to improve the performance of the proposed solar stills along with considering other types of desalination methods and introducing novel systems are strongly suggested.
- Studies regarding the application of heat pipe solar collectors in space heating systems including air-based, water-based, and passive system are very limited. Therefore, more studies should be conducted in this field to develop novel, more efficient, and cost-effective systems.
- The utilization of heat pipe solar collectors in solar cooling and air conditioning systems has also remained under-researched and further work is needed to provide more reliable references in this field.
- The manufacturing costs of thermoelectric generators are falling and their combination with solar energy has shown a promising future. Therefore, there is scope for more work

on heat pipe solar thermoelectric generators. Also, previous theoretical and experimental studies in this field have considered many simplifying assumptions and have reported only short-term performance. Future studies considering manufacturing parameters, such as temperature dependence of material properties and contact thermal resistance, along with long term and annual performance of heat pipe solar thermoelectric generators are highly recommended.

- The utilization of heat pipe solar collectors in novel applications needs further designs. Studies related to new applications such as hydrogen production, are in their initial stages and need more research effort.

6. Conclusion

This paper comprehensively reviews recent studies regarding HPSCs along with their utilization in different conventional and innovative solar systems. Section 2 includes the information about HPSCs' principles and design features, and covers recent significant studies which aimed to improve the thermal performance and economic feasibility of these collectors. Section 3 reports a brief modelling method for simulating HPSCs consisting of all existing processes (i.e. absorbing solar energy, transferring thermal energy through heat pipes, and heat transfer inside manifold). Section 4 contains a comprehensive review of the various applications of HPSCs including water heating (i.e. passive and active systems), desalination, space heating (i.e. air-based, water-based, and passive systems), and electricity generation (i.e. PV/T, thermoelectric generators, and solar power plants) systems. Finally, section 5 identifies challenges and research gaps along with recommendations for future research potentials are presented.

Conflict of interest

None declared.

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