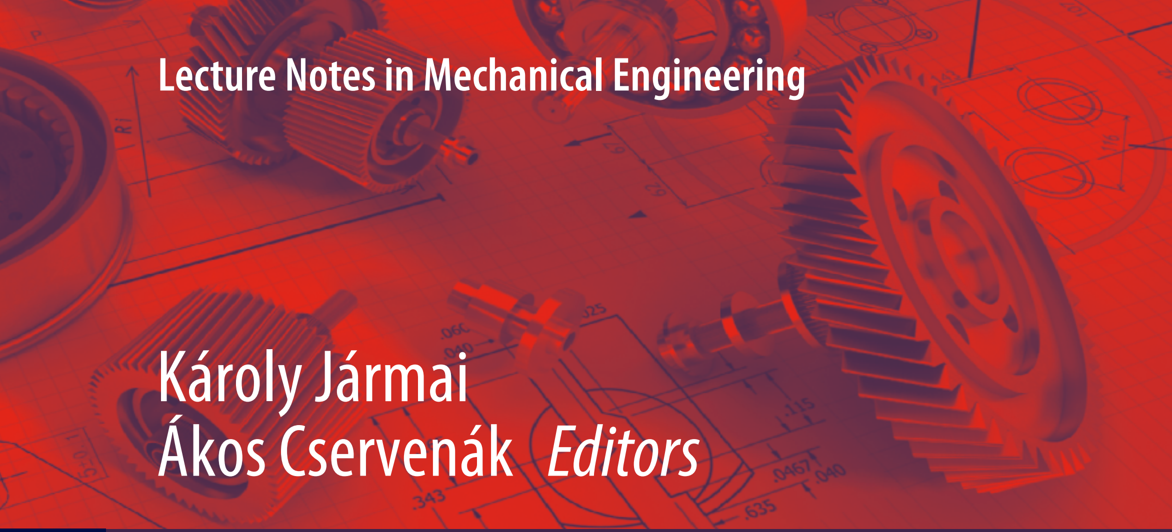

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A Literature Review of a Dual-Purpose Solar Collector

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Abstract. Solar energy is an abundance, inexpensive and clean source of energy. Using this energy source can be widely spread as the efficiency of solar systems improves. The main component of any solar thermal system is the solar collector which absorbs the incident solar radiation and converts it into heat. Solar thermal systems are categorised into two major types as air and liquid heaters. A solar air heater (SAH) is used for space heating and crop drying. A solar water heater (SWH) is used to supply hot water for domestic and industrial applications. However, air and liquid collectors are considered as a single purpose collector since the working fluid is air or liquid only. One way to enhance the performance of solar thermal systems is by combining both air and liquid heaters in one facility called dual-purpose solar collector (DPSC). This collector is basically a flat plate solar collector (FPSC) with two sections, one for air heating and the other for water heating. Therefore, it can produce hot air and hot water simultaneously. Using DPSC can attain high temperature, and high thermal performance with a reduction in cost and space. Despite many significant investigations on DPSC, no review paper has been seen. This article presents the different designs and applications of DPSC and the parameters affecting its performance. A comparison between single and dual-purpose solar collectors is also discussed. Moreover, the possibility of integrating DPSC in some automobile manufacturing processes is suggested in this article as well.

Keywords: Solar energy · Solar thermal systems · Solar heaters · Dual- purpose solar collector (DPSC) · Automobile industry

1 Introduction

Energy is getting into all sectors that deal with our daily life. It comes either from conventional sources like coal, oil and natural gas, which known as fossil fuels or from alternative sources like solar, wind, hydro, nuclear, and geothermal which known as renewable energy. Among the renewable energy sources, solar energy is an environmental- friendly,

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inexpensive, clean, and carbon- free source of energy [1]. Both light and heat are emitted from the sun and can be invested by producing electrical energy from the first and thermal energy from the latter. A photovoltaic panel (PV) is the well- known device that directly converts the emitted light from the sun into electrical energy. While a solar collector is a device that converts the radiant heat from the sun to thermal energy and transfers it to the heat transfer fluid (HTF) [2].

Solar collectors can be classified based on the required temperature of the working fluid into a concentrating and non-concentrating collector [3]. Among the non- concentrating collectors, the low- temperature flat plate solar collector (FPSC) is a widely spread collector and is commonly designed to perform as a single- purpose collector. FPSCs have been used to heat air and water individually through an absorber plate. Therefore, FPSCs can be subdivided according to the type of flowing fluid into solar air heaters and liquid heaters [4]. Solar air heater (SAH) is characterised by its very low manufacturing, maintenance, and operational costs. It has a vital role in space heating [5–7] and crop drying [8, 9]. The main drawbacks of SAH are the low thermal conductivity of air and high heat loss to the ambient [10]. Whereas solar water heater (SWH) has a distinctive importance in producing hot water for domestic, residential, and industrial applications due to its effective operation, simple design, and low maintenance cost [11].

In general, the main merits associated with FPSCs are relatively low manufacturing cost, the ability to collect incident solar radiation, and needless for sun's tracking system [12]. Whilst the major demerit is the low thermal efficiency due to the low heat delivered from the absorber plate to the circulating fluid [13]. Thus, a numerous studies and modifications [3, 14–16] have been conducted to enhance the rate of heat transfer between the absorber plate and the circulating fluid and thus increasing the thermal performance of FPSCs.

The combination of two solar thermal technologies (i.e., air and liquid heaters) in one facility called dual-purpose solar collector (DPSC) is one of the most feasible solutions to overcome the drawbacks of FPSCs. It is one of a novel avenues by which the following benefits can be obtained:

- increase the thermal performance and annual application of solar energy.
- reduce the required install area and cost.
- achieve high temperature with high heat delivery of solar thermal systems.

This hybrid collector is mainly a FPSC with two sections, one for air heating and the other for liquid heating, therefore it generates hot air and hot liquid simultaneously. Moreover, DPSC can also perform as a single- purpose collector according to the requirements.

The concept of dual- purpose collector is not limited on combining two thermal technologies in one device, it can also be obtained by combining another two solar technologies (i.e., solar thermal and PV technologies) in one device called photovoltaic/thermal (PV/T) collector. This dual function collector recovers the accumulated heat in PV module to produce thermal energy for low and medium temperature applications and ensure high electrical efficiency of PV module as well [17]. Thus, PV/T collector has the advantage of generating both thermal and electrical energy simultaneously with a high overall efficiency [18]. Depending on the coolant used in PV/T collector, two main categories such as PV/T air and PV/T water can be noticed with a brief description [19].

In spite of many types of research, no review study on DPSC is seen. The objective of this article is to present the various works that have been carried out for DPSC concerning different designs and operational parameters. This paper hopefully assists researchers in having state of the art review of recent works in this field. Besides, it presents a new trend for incorporating DPSC with the different automobile industrial processes such as parts washing, paint drying, and corrosion protection.

2 Overview of Different Design Approaches

Based on the previously published literature, a researcher can observe that the dual function concept in solar energy systems includes a combination of any two different solar technologies in one device. Figure 1 shows the classification of dual- function collectors. The studies on DPSC are sought in the following subsections.

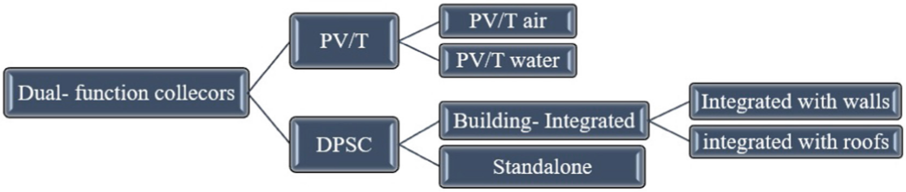


Fig. 1. The classification of dual- function collectors.

2.1 A Standalone DPSC

In this section, we referred to DPSC, which is installed and operated independently as a standalone. The first design and study of such a collector was carried out by Assari et al. [20]. The collector consists of water pipes in the top section which used for heating water and a V- shaped air channels in the bottom which used for air heating (see Fig. 2). The DPSC was investigated theoretically and experimentally as a single (i.e., air and water) and combined collector. Tests were carried out according to the American Association of Thermal Engineering (ASHRAE93–77) standards [21]. Good agreement between the calculated and experimental results was obtained. They observed an increase in the outlet air temperature by 20% after 4 p.m., which means that DPSC can be used after sunset. Also, they deduced that this collector could attain high temperature and high heat delivery with a 50% reduction in space and cost.

The same DPSC designed by Assari et al. [20] was further studied by Assari et al. [22]. They examined three types of air channel (i.e., straight fin, triangular fin, and without fin). They developed a mathematical model based on effectiveness- NTU method to calculate the outlet air and water temperatures, heat delivery, and heat exchange effectiveness. Parameters (solar radiation, inlet water temperature, airflow rate, and geometry of air

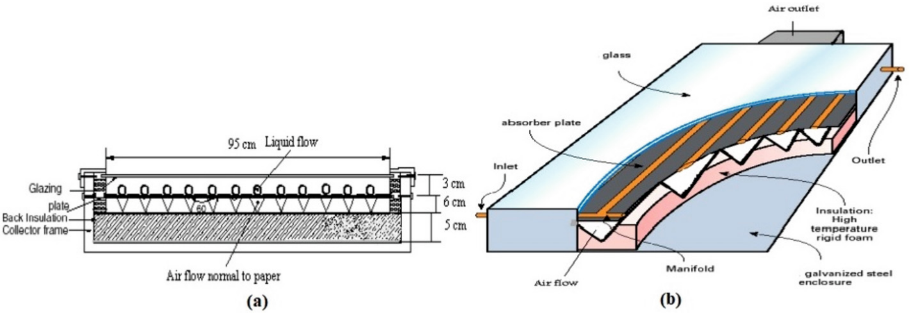


Fig. 2. The design details of DPSC: (a) the cross- sectional view (b) the schematic layout [20].

channel) were adopted to analyse the performance of DPSC. Increasing the inlet water temperature caused a decrease in both heat delivery and thermal efficiency in water section, while it caused an increase in both heat delivery and thermal efficiency in air section. Further, increasing airflow rate caused an increase in heat delivery and decrease in heat exchange effectiveness for various air channel geometry.

In a related context, the energy and exergy analysis of the same DPSC designed by Assari et al. [22] was further studied by Assari et al. [23]. In the water section, increasing the inlet water temperature increased up to 60 °C led to an increase in the exergy efficiency and a decrease in the energy efficiency, whereas both of these efficiencies are decreased as the inlet water temperature increased above 60 °C. In air section, increasing airflow rate and inlet water temperature led to an increase in both energy and exergy efficiencies for all types of air passages.

Energy and exergy analysis of DPSC with triangle air channel geometry was further studied by Jafari et al. [24]. Effectiveness- NTU method was used for analysis under a variety of inlet water temperature and airflow rate. They gained the same results presented in Ref. [23] with a conclusion that DPSC with triangle air passage has better energy and exergy efficiency than single purpose collector.

Ma et al. [25] modified a conventional solar water heater by adjusting the interior air gap of the collector to construct DPSC. They also bended the absorber fins as L-shape to increase the heat transfer in air section (see Fig. 3). Experiments have been conducted to investigate the thermal performance of the collector in both air and water heating modes. The experimental results showed that the average water heating efficiency was 50% and the daily mean and instantaneous efficiencies in air heating mode reached 52% and 55%, respectively. Theoretical results revealed an increase in the efficiency of the L-shape air channel accompanied with a decrease in outlet air temperature when the airflow rate increased.

Another different design of DPSC was fabricated by Venkatesh and Christraj [26]. The novelty in their design is by replacing the storage tank of water heater with a riser tubes and header which are fitted in the bottom of air heater (see Fig. 4). The experimental tests have been carried out for load and no-load conditions for different air and water flow rates. Two scenarios were adopted in experiments: (i) both the water and air heaters are combined together to act as a multipurpose solar air heater (MPSAH), and (ii) both the water and air heaters are combined together to act as a multipurpose solar water

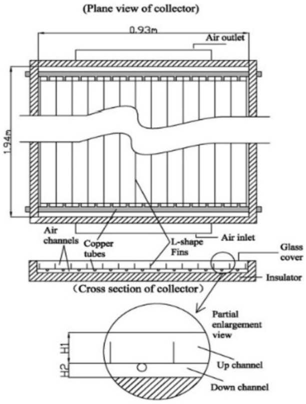


Fig. 3. Schematic of the dual function solar collector [25].

heater (MPSWH). The results of MPSAH for no load condition showed a maximum temperature of the stagnant air of 88 °C when the ambient temperature was 37 °C. For load condition, the maximum efficiency and maximum temperature difference between outlet and inlet air temperature were 85% and 39.6 °C, respectively. While the results of MPSWH for load condition, showed a maximum efficiency and maximum outlet water temperature of 67.69% and 79 °C, respectively. The novelty made by the authors increased the performance of the system as compared with a conventional collector.

Incorporating a porous medium with DPSC was a new trend adopted by Arun Venu et al. [27]. They added a matrix of the porous medium below the absorber plate (see Fig. 5). The modified DPSC was analysed numerically using ANSYS 13 software. The simulation results show that for a solar irradiance of 1000 W/m^2, the temperature difference between outlet and inlet air reached 68 °C and 24.7 °C in the lower and upper channels, respectively. Also, an increase of 11.1 °C was obtained for the water temperature. Water heat gain decreased as the inlet water temperature increased. Whereas air heat delivery increased as air flow rate increased. The thermal efficiency of the collector was enhanced due to the presence of porous matrix which enhanced the heat delivery.

One of the valuable usage of DPSC is by coupling it with a drying system to preserve the agricultural products. Solar dryer characterised by several benefits and received a lot of investigations and developments [28, 29]. The technology of solar drying is simple and can be easily adopted to domestic sector [30]. In this context, Mohajer et al. [31] presented a new hybrid system which combines the same DPSC designed by Assari et al. [22] with a domestic scale solar dryer. In their study, the outlet hot air from DPSC was applied to an indirect forced convection solar dryer. Furthermore, the outlet hot water from DPSC can be: (i) supplied for domestic usages, (ii) used as phase change material (PCM) to continue drying process during night or off- sunshine period. The results revealed the ability of the system to be used as a solar dryer and provide domestic consumptive hot water as well.

Nematollahi et al. [32] used a vertical water storage tank instead of a horizontal one with the same DPSC designed by Assari et al. [22]. The height difference between

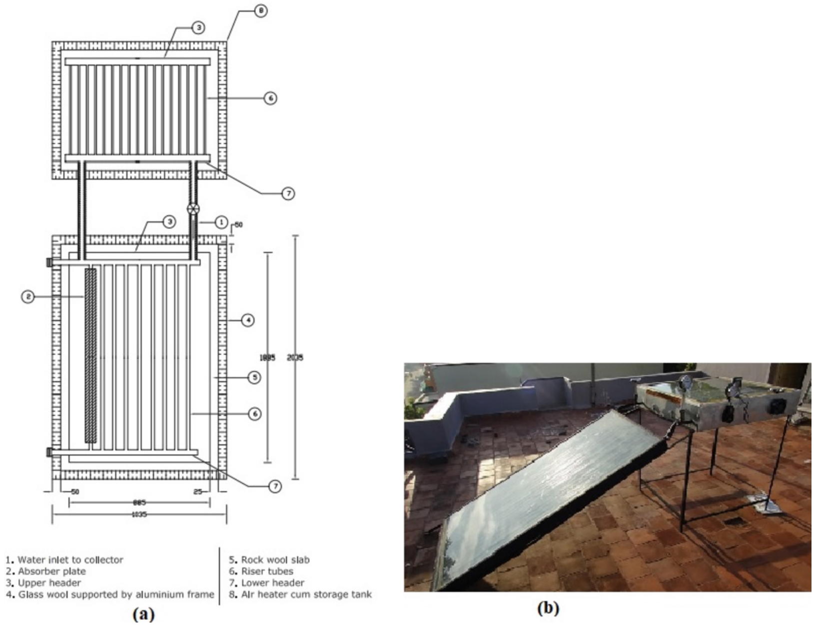


Fig. 4. A (a) Schematic layout of typical solar water heater cum air heater with storage tank. (b) Pictorial representation of multipurpose solar heating system [26].

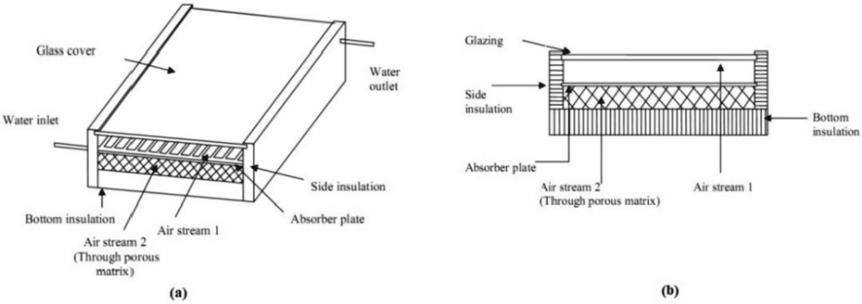


Fig. 5. DPSC with porous matrix (a) Schematic diagram. (b) Cross sectional view [27].

the inlet and outlet ports of the vertical storage tank can ensure that the temperature of the water entering collector does not alter greatly. Hence, the heat losses from collector is decreased and the thermal efficiency is increased. The average results revealed that the dual-purpose collector has a significant higher efficiency than for single purpose collector. However, the average temperature of water inside the tank was equal to 65.2 °C which can be used at night or off- sunshine hours.

The effect of inner parameters (insulation thickness, upper and lower air channels height, and diameter and number of copper tubes) on the performance of DPSC was studied by Ma et al. [33]. They developed a dynamic model which is based on a finite difference method to optimise the structure parameters. Experiments were conducted for water and air heating modes under a different air mass flow rate, different inlet water temperature, and environment conditions. However, the efficiency in air heating mode was increased as the insulation thickness increased whereas it was slightly affected as the inner diameter and number of copper tubes increased. In water heating mode, the efficiency has a maximum value of 62.5% when the inner diameter is fixed at 0.008m and for this diameter the efficiency increased remarkably as the number of tubes increased until 8.

Velmurugan et al. [34] introduced another design configuration of DPSC. They fabricated a dual function solar heating system (DFSHS) by connecting SWH, SAH, and heat exchanger in series (see Fig. 6). The system can operate in water heating (WH) mode or air heating (AH) mode, depending on the requirements in different seasons. Experiments were carried out for the two modes under different water flow rate. The maximum outlet temperature and efficiency for WH mode were 74 °C and 73.68%, respectively. Whereas, in AH mode, the maximum recorded efficiency was 69.18%.

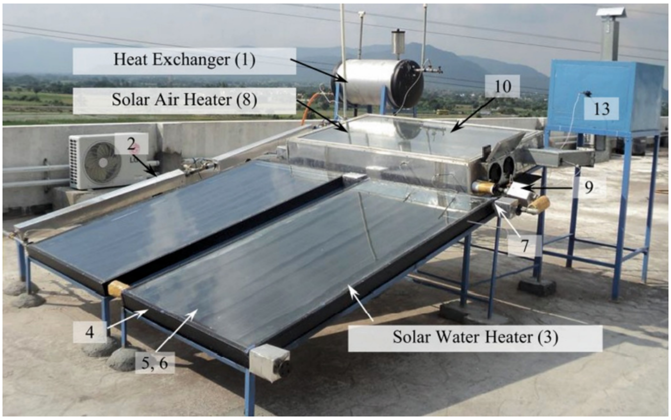
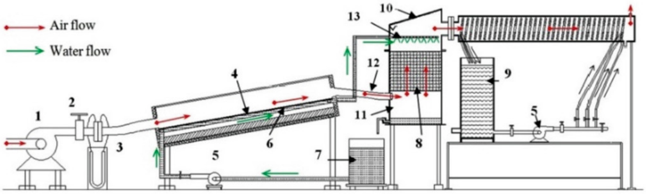


Fig. 6. Photograph of DFSHS experimental apparatus [34].

Zhang et al. [35] modified DPSC from a conventional liquid collector. The collector consists of 8 copper water tubes and two (top and bottom) diagonal arranged air channels. Experiments were carried out for three different operating modes: (A) air heating, (B) water heating and (C) air- water compound heating. In mode A, the average efficiency was 50% at a constant air flow rate of 0.024 kg/s. In mode B, the average thermal efficiency was 51.4% at a constant water flow rate of 0.13 kg/s. In mode C, experiments were conducted at constant air flow rate of 0.024 kg/s and for a variety of water flow rate. An average efficiency of 73.4% was obtained which is higher than that of mode A and B. On the contrary, the maximum temperature rise and the temperature difference of mode C are lower than that of mode A and B.

Regarding the developments in desalination technologies, researchers observed that integrating different solar collectors with humidification dehumidification desalination (HDH) system can enhance the freshwater production [36]. In this context, the effect of integrating DPSC with HDH system was experimentally studied by Rajaseenivasan and Srithar [36]. The system consists of three major parts: (i) DPSC, (ii) humidifier and (iii) dehumidifier (see Fig. 7). The DPSC supplies hot water and hot air to the humidification chamber in which the two fluids were mixed in a direct contact counter flow pattern by means of a packing material. Then, the humid air is directed to the dehumidification chamber for condensation in which, both humid air and cooling water are mixed in an indirect contact counterflow pattern. It was found that freshwater productivity can be increased by increasing the air, water, and cooling water flow rates. Also, it can be increased by increasing the outlet air temperature, which was occurred by using a convex and concave semi-circular turbulators in the air section of DPSC. The overall efficiency of the system was 68% for the absorber with a concave turbulator.



Schematic diagram of HDH system with dual purpose collector. (1) Blower, (2) flow control valve, (3) orifice arrangement, (4) absorber plate, (5) pump, (6) riser tube arrangement, (7) feed water tank, (8) packed bed, (9) cooling water tank, (10) condensing cover, (11) humidification chamber, (12) hot air inlet, (13) hot water spray pipe.

Fig. 7. Schematic diagram of HDH system with dual-purpose collector [36].

DPSC with rectangular air channels was designed and investigated by Kavoosi and Saidi [37]. The experimental results showed that the thermal efficiency of air heater, water heater and DPSC were 45%, 20% and 60%, respectively. In addition, an increment of 11% in the air heater efficiency with rectangular passages was observed as it compared to a single V-corrugated and flat plate air heaters.

Another refined design of DPSC was adopted by More and Pote [38]. It consists of horizontal copper tubes instead of parallel ones mounted on the top of an absorber plate and a triangle air channel connected to the bottom of the absorber. The maximum experimental and theoretical efficiencies were 72.4% and 68.81%, respectively and the maximum temperature in the horizontal storage tank was 50 °C at noon. Besides, the heat losses in DPSC were 20%, while for a conventional flat plate collector are about 33–50% [39]. Furthermore, the results revealed that the efficiency of DPSC always higher than 50% during the whole day.

A detailed mathematical model for DPSC was developed by Shemelin and Matsuka [40] to simulate two different designs of a dual air/water solar collector (DAWC) (see Fig. 8). The model was simulated in TRNSYS 17 software and it was experimentally validated. Good agreement between the simulated and experimental results were obtained. Therefore, the model was further used to analyse the performance of three DAWC for three houses from three different locations with different energy performance level for each. The results revealed that DAWC is more efficient for buildings with high heat energy consumption and performs better in cold and moderate climates than in warm climates.

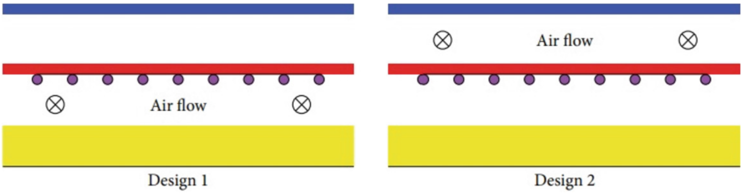


Fig. 8. The DAWC designs considered [40].

A simulation analysis based on computational fluid dynamics (CFD) was studied by Shandal et al. [41]. COMSOL Multiphysics 5.4 software was used to model and simulate the DPSC by considering it consists of four domains: water tubes (A), absorber plate (B), triangular fins (C), and air channel (D) (see Fig. 9). The model was validated against the experimental results and good convergence was observed. Thus, it was further used to study the thermal behaviour of water and air inside the DPSC during Winter, Spring and Summer for different fluid flow rates and water inlet temperatures. As an expected, the outlet air temperature decreased as the air velocity increased. The efficiency increased as the water flow rate increased, whereas it decreased as inlet water temperature increased.

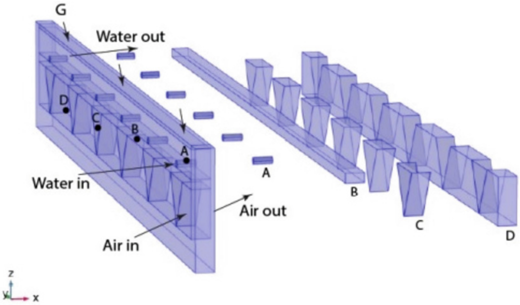


Fig. 9. The domains of the simulated DPSC [41].

Somwanshi and Sarkar [42] developed a new collector known as dual-purpose cum-storage air-water heater (DCS- AWH). It consists of an upper air heating section and lower water heating section which are separated by an absorber plate (see Fig. 10). Both the outlet water and air temperatures were computed theoretically based on a simple mathematical model and compared with an experimental values. The model was further utilised to analyse the effect of covering the collector during the night and the effect of air flow rate on water and air temperatures. It was found that about 19.9% of the heat delivered to the air and water was conserved by using the cover. Also, the collector performed well at a low airflow rate rather than at a heigh one. The maximum water and air temperatures in winter and summer were 56 °C, 50 °C and 89.6 °C, 81.1 °C, respectively. Finally, the average thermal efficiency of the system was 5.5% and 24.6% higher than that found in Ref. [32] and [38], respectively.

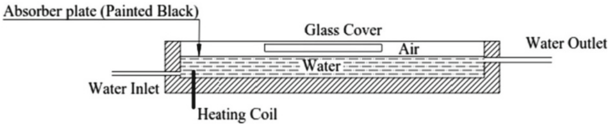


Fig. 10. Cross-section view of DCS- AWH [42].

Recently, Kumar et al. [43] experimentally investigate a novel hybrid DFSC. They used a pressurised shot- blasting technique for roughening the inner surface of air channel and the absorber plate of water heater to enhance thermal performance. Moreover, solar glycol (SG) with multi-walled carbon nanotube (MWCNT)-based nanofluids with two-volume percentages (0.1 vol% and 0.2 vol%) were tested to further improve the convective heat transfer coefficient. The water and air heaters were tested separately under a variety of air and water flow rates. In the air heater test, the maximum difference between the outlet and inlet air temperatures was 25 °C, the heat transfer rate recorded 452W, and thermal efficiency attained 33.2%. In the water heater test, the maximum difference between the outlet and inlet water temperatures was 18.32 °C, the heat transfer rate recorded 680W, and thermal efficiency attained 51.03%. for the 0.2 vol% SG/MWCNT-based nanofluid.

Harvesting solar energy and producing both hot water and hot air are not the unique function of DPSC. It can serve as heat collection during daytime and cold collection (rejecting heat) during night as was indicated by Miao et al. [44]. They innovated a new design, in which the single-pane glass cover of a conventional FPSC was replaced by a double-pane polycarbonate cover (see Fig. 11).

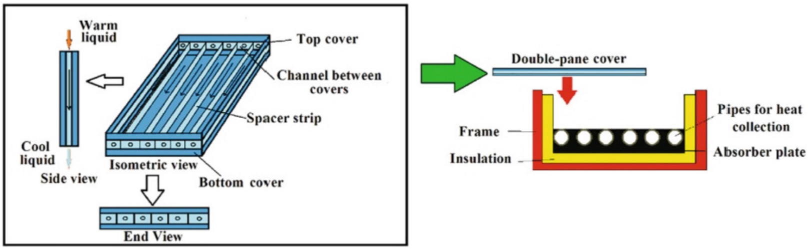


Fig. 11. Design of DPSC for heat and cold collection [44].

In the heat collection mode, water or other liquid gets heated as it flows in the copper tubes embedded in the absorber plate, while in the cold collection mode, water or other liquid rejects heat to the outside by radiation and/or convection as it flows in the channels between the two panes. The experimental results indicated that this collector has higher cooling and heating capacity than uncovered collectors, which in turn lowers the energy consumption of Heating, Ventilation, and Air Conditioning (HVAC) systems.

2.2 Building- Integrated DPSC

Utilisation of DPSC is not limited to a standalone collector only, but also can be used as building- integrated collector. The reason behind using such a collector is summer overheating which is a common problem in temperate climates that appears with passive space heating designs such as trombe-wall, composite Trombe- Michel wall and PV-Trombe wall [45]. Building- integrated collector is widely used in building sector since it reduces building energy consumption and provides space heating in winter, water heating and lowers the cooling load in summer as well.

Ji et al. [46, 47] proposed building- integrated dual function solar collector which operated with natural circulation of water (see Fig. 12). The newly designed collector was examined experimentally and numerically under water heating mode. The results showed that the daily cooling load of a test room with collector is 2% lower than that without collector on a typical summer day. On winter, the mean indoor air temperature was up to 24.7 °C while the mean ambient temperature was 4.8 °C. Moreover, the numerical model can give an accurate prediction of system performance.

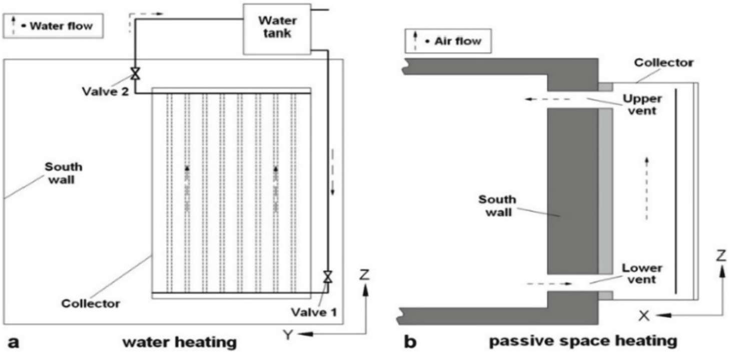


Fig. 12. Schematic diagram of the building- integrated dual function solar collector: (a) water heating circuit, (b) section view of passive space heating [46].

The effect of DFSC on the cooling load of a building in summer was investigated by Jie et al. [48]. The collector mounted on the south façade of the building and operated in water heating mode with natural circulation. The results obtained from the developed numerical model was much more agreeable with the experimental results. Therefore, the model was used to predict the cooling load of a room with and without the collector. The simulation results showed that the cooling load of a room with the collector is 2.05% lower than that without the collector. Moreover, the DFSC can enhance the thermal environment of the building and provide domestic hot water in summer without overheating problems caused by other conventional passive solar heating systems.

A hybrid solar system composed of two DPSCs was presented by Zhi et al. [49] to heat a solar demonstration building. One of the DFSCs performed as a Trombe wall and provided passive space heating. Whereas the other performed as a solar air heater and provided active space heating. The results revealed that the strategy of passive solar heating for southern rooms and active solar heating for northern rooms could maintain the average indoor temperature at 17 °C. TRNSYS 17 simulation software was used to predict the solar fraction. It was observed that solar fraction of the hybrid system is low for low irradiance areas and vice versa.

The mismatch between the conventional solar collector and the tile roof of a traditional building in appearance motivated some researchers to propose a novel DPSC which has a good match with the local special feature building culture. Luo et al. [50] proposed a novel tile- shaped DPSC in which the glass cover was further covered by Polymeric Methyl Methacrylate (PMMA) covers to enhance the aesthetical view and minimise the heat loss (see Fig. 13). The collector was experimentally tested and compared with DPSC without PMMA covers and with DPSC has a semicircle covers. The daily thermal efficiency of the tile- shaped collector when it was operated in water heating mode varied from 54% to 61.8%. While it varied from 44.7% to 59.2% and from 35.5% to 67.4% for the DPSC with semicircle covers and DPSC without PMMA covers, respectively.

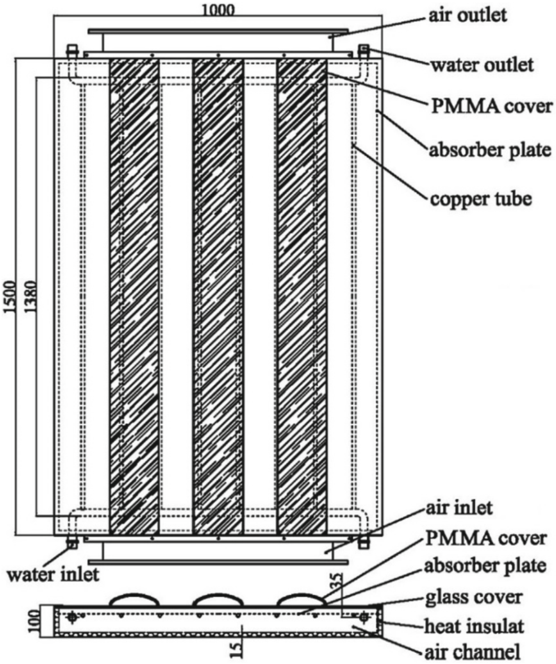


Fig. 13. Schematic of the tile-shaped dual-function solar collector [51].

He et al. [51] further studied a tile- shaped DPSC in water heating mode by using CFD. The numerical results obtained were compared with an experimental ones and reveled a good agreement. The influence of inlet water temperature, water mass flow rate, solar radiation, and ambient air temperature on thermal efficiency were also studied. The results showed that lower inlet water temperature, higher water flow rate, higher ambient air temperature and lower solar radiation enhanced the thermal efficiency of the module. Moreover, a comparative study revealed that the collector with tile-shaped cover can achieve higher efficiency than a flat plate collector does at higher temperature operation.

In the same context, Hu et al. [52] designed a novel roof type dual function solar collector named (Type 1) by using a wavelike PMMA top cover instead of the glass cover (see Fig. 14). An absorber plate divided the gap between the cover and the bottom of the collector into up and down channels. A dynamic model was developed using MATLAB software and validated experimentally. The model was adopted to predict the thermal efficiency and outlet water temperature of this collector under the same operating conditions used in Ref. [51]. The simulated results indicated that higher thermal efficiency as well as lower heat loss coefficient can be achieved with Type 1 collector. Further, it was found that the wavelike collector provided better consistency for traditional Chinese buildings than other roof-integrated solar collectors.

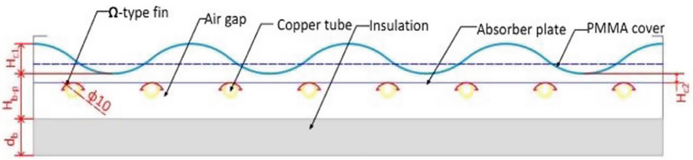


Fig. 14. Cross-sectional view of wavelike roof solar collector [52].

Ma et al. [53] tested the thermal behaviour in passive heating mode for a room integrated with DPSC (test room) and a room without DPSC (reference room). Both of the test and reference rooms were examined under a controlled and non- controlled conditions. For the non-controlled condition, the average room temperature for both rooms were 8.24 °C and 4.81 °C, respectively. For a controlled condition, the room temperature was set to 18 °C, the power consumption for both rooms were 4.322 kWh and 7.796 kWh, respectively. Moreover, the influence of the copper water tubes in DFSC and the depth of air channel on thermal efficiency were studied. An enhancement in efficiency was observed as compared with traditional passive solar air heater without water tubes.

2.3 New Trend

Apart from that, the automobile industry depends on the non- renewable energy sources (i.e., fossil fuels) and electricity for manufacturing processes of vehicles. The maximum temperature range required in different process in an automobile industry is 120 °C [16]. Among these processes, parts washing, paint drying, and corrosion protection can be accomplished by integrating solar systems to save energy [54]. In parts washing, hot water is used before the assembly process to remove debris from the parts, such as dirt, grime, and metal chips. The temperature of the washing water is between 70 °C- 90 °C and it is usually heated by electric heaters [55]. Hot air is required in paint shops to dry the painted parts. The air temperature needed for this purpose is in the range of 80 °C to 150 °C and it is usually gained by fossil fuels [55]. Phosphate coating is a pretreatment process applied to automobile parts to protect them against corrosion. In this process, the parts are immersed in a solution path of phosphate of around 90 °C.

It is worthy of being highlighted on the idea of integrating DPSC, storage tank, and an auxiliary heater in the automobile industry to reduce energy consumption and make this industry more sustainable.

3 Mathematical Model of DPSC

The useful energy Q_U and thermal efficiency η_c of DPSC are given by the following relationships [20]:

$$Q_U = (Q_U)_L + (Q_U)_a \tag{1}$$

$$\eta_c = \frac{Q_U}{AI_T} \tag{2}$$

where; A is the area of the collector, I_T is the solar radiation, and the indexes a, L are for air and liquid part, respectively.

The useful heat gain to the fluid is calculated based on the energy balance as:

$$Q_U = \dot{m}_f C_f \left(T_{fo} - T_{fi}\right) \tag{3}$$

or

$$Q_U = A_P S - Q_L \tag{4}$$

where A_P is absorber plate area, S is absorbed incident solar flux by the absorber, and Q_L is the heat loss through top, bottom and side:

$$Q_L = U_L A_P \left(T_{pm} - T_{amb}\right) \tag{5}$$

where T_{pm}, T_{amb} are the absorber and ambient temperatures, U_L is overall loss coefficient and calculated as:

$$U_L = U_t + U_b + U_e \tag{6}$$

U_t, U_b, U_e are top, back and side loss coefficient respectively. A detailed calculations for these coefficients can be found in Ref. [56].

Thermal efficiency of DPSC is expressed as [56]:

$$\eta_c = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{I_T} \tag{7}$$

Here, $\tau\alpha$ is transmittance-absorptance product of cover, F_R is the heat removal factor which is defined as the ratio of actual heat transfer to the maximum possible heat transfer and can be calculated as [56]:

$$F_R = \frac{\dot{m}C_P}{AU_L}\left[1 - e^{-\left(AU_L F' / \dot{m}C_P\right)}\right] \tag{8}$$

Here, $\dot{m}$ is the mass flow rate, C_P is the specific heat of fluid and F' is the collector efficiency factor.

Assari et al. [22] developed a mathematical model based on effectiveness- NTU method. The effectiveness is defined as heat delivery to maximum heat delivery that can transfer to fluids:

$$\varepsilon_f = \frac{\dot{m}_f C_{P,f}\left(T_{f2}\text{-}T_{f1}\right)}{\dot{m}_f C_{P,f}\left(T_{pm}\text{-}T_{f1}\right)} = \frac{T_{f2}\text{-}T_{f1}}{T_{pm}\text{-}T_{f1}} \tag{9}$$

or

$$\varepsilon_f = \frac{(T_{pm}\text{-}T_{f1}) - \exp^{\left[-\frac{h_f A_f}{\dot{m}_f C_{P,f}}\right]}(T_{pm}\text{-}T_{f1})}{(T_{pm}\text{-}T_{f1})} = 1 - \exp[-\frac{h_f A_f}{\dot{m}_f C_{P,f}}] \tag{10}$$

where T_{f2}, T_{f1} are the fluid temperatures at outlet and inlet, h_f is the convection heat coefficient, NTU is defined as:

$$NTU = \frac{h_f A_f}{\dot{m}_f C_{P,f}} \tag{11}$$

Therefore, the useful energy of collector is given as:

$$Q_u = \left(\frac{\varepsilon_f \dot{m}_f C_{P,f}}{U_L A_p + \varepsilon_f \dot{m}_f C_{P,f}}\right) A_P S - \left(\frac{\varepsilon_f \dot{m}_f C_{P,f}}{U_L A_p + \varepsilon_f \dot{m}_f C_{P,f}}\right) U_L A_p (T_{fi}\text{-}T_{amb}) \tag{12}$$

And the efficiency as:

$$\eta = \left(\frac{\varepsilon_f \dot{m}_f C_{P,f}}{U_L A_p + \varepsilon_f \dot{m}_f C_{P,f}}\right)(\tau\alpha)_{av} - \left(\frac{\varepsilon_f \dot{m}_f C_{P,f}}{U_L A_p + \varepsilon_f \dot{m}_f C_{P,f}}\right) U_L \frac{(T_{fi}\text{-}T_{amb})}{I_T} \tag{13}$$

Here, equations are for fluids (water and air) and the subscript f means fluids.

The exergy analysis of DPSC was studied by Assari et al. [23]. The exergy balance can be written as follows:

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_u = \dot{E}x_{dest} \tag{14}$$

where;

$$\dot{E}x_{heat} = \left(1 - \frac{T_o}{T_s}\right)\dot{Q}_u \tag{15}$$

where $\dot{E}x_{heat}$ is exergy due to heat, $\dot{Q}_u$, the total rate of the energy, is received by the collector absorber area from the solar radiation, and T_s is the black body temperature (6000 K). The exergy destroyed is the total entropy generated $\dot{S}_{gen}$ times the ambient temperature T_o as:

$$\dot{E}x_{dest} = T_o \dot{S}_{gen} = \dot{I} \tag{16}$$

Thus, the exergy balance for collector become:

$$\left(1 - \frac{T_o}{T_s}\right)\dot{Q}_u = \dot{m}_f C_f \left[\left(T_{fo} - T_{fi}\right) - T_o\left(\ln \frac{T_{fo}}{T_{fi}}\right)\right] \tag{17}$$

The exergy efficiency is the ratio of useful exergy to the exergy of the solar radiation:

$$\eta_{ex} = 1 - \frac{\dot{I}}{\dot{E}x_{heat}} \tag{18}$$

4 Conclusion and Future Work

Several studies have been conducted to increase the annual application of solar energy and maximise the heat delivery of solar thermal collectors. Combining both air and liquid heaters in so-called DPSC is a distinctive innovation in this field. Based on the literatures presented in this overview, the following can be deduced:

- The overall performance of DPSC is directly affected by:

  - Design aspects such as the roughness elements on the absorber plate, air channel geometry, inserting a porous medium, using PMMA covers, insulation thickness, and water tubes.
  - Operational parameters such as solar irradiance, inlet fluid temperature, fluid flow rate, and the geometry of air channel.

- When the inlet water temperature is increased, both the heat delivery and thermal efficiency in the water section of DPSC are decreased whilst in the air section of DPSC they are increased. Thus, it is preferred to utilise a vertical water storage tank rather than a horizontal one since it offers a temperature stratification between the inlet and outlet openings and keeps the temperature of water entering the collector at the initial one.
- When the airflow rate is increased, both the heat delivery, energy, and exergy efficiencies in the air section of DPSC are increased for all air passages with best results for triangle one.
- Integrating a porous matrix in the air channel of DPSC has a significant advantage to enhance thermal performance as it increases the heat transfer area.
- Using the horizontal water tubes in DPSC instead of the vertical ones has an intangible effect on the efficiency enhancement.
- Using the tile- shaped PMMA covers with DPSC has two different advantages. First, enhances the aesthetical view of the Chinese traditional buildings. Second, minimises the heat loss of DPSC and thus maximises its efficiency.
- The hot air produced in DPSC can be used to dry agricultural products in drying system, while the hot water can be used as a PCM to continue drying process through the night or off- sunshine periods.

- Integrating DPSC with a distillation system can improve the distillation productivity and reduce the desalination cost to the lowest value of 0.0257 $/kg.
- DPSC can reduce the greenhouse emission by lower the energy consumption of HVAC (Heating ventilation and air conditioning) systems like cooling towers and chillers when it used as a heat and/ or cold collection.
- Integrating DPSC with buildings has several advantages:

- In winter, it can perform as space heating and maintain the indoor air temperature higher than the ambient by 20 °C under specific conditions.
- Reduce the cooling load of a building in summer by approximately 2%.
- Hot water can be supplied normally for domestic use in both seasons.
- Save about 3.5 kW/h of the daily power consumption when the indoor temperature is controlled to be at 18 °C.

- In the automobile industry, there is a reasonable possibility to use DPSC in some manufacturing processes and reduce the dependency on conventional sources of energy.

As a summary, DPSC is not only used to supply hot air and liquid simultaneously or separately, but it also performs better than the single purpose air and water collectors with high energy savings and approximately 50% reduction in space and cost. Besides, it is an efficient device for any region, any application (i.e., domestic, agricultural, and industrial), and under any meteorological conditions.

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