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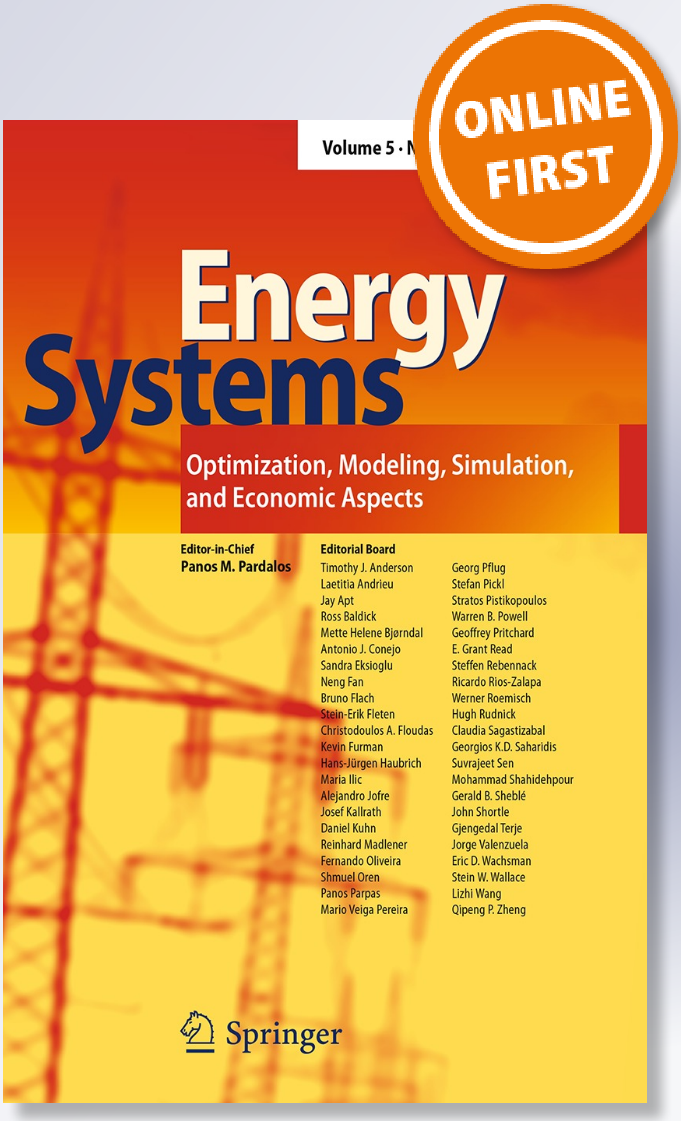

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Integrated collector storage solar water heaters: survey and recent developments

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Abstract The direct conversion of solar to thermal energy is highly efficient, more environmental friendly and economically viable. Integrated collector storage solar water heaters (ICSSWH) converts the solar radiation directly into heat at an appreciable conversion rate and in many cases using concentrating means. These systems are compact, aesthetically attractive and reasonable in construction and can reduce the environmental impact up to 40 %. They also have high collection efficiency factor and energy saving potential. Despite of many advantages, ICS solar water heaters suffer from high thermal losses in the night/overcast sky conditions. In this article, authors discuss the recently developed new and improved ICS designs and strategies used for reducing thermal losses from such devices, especially in non-collection period. The systems have been evaluated based on a followed categorization to non-concentrating, concentrating and systems with phase change materials.

Keywords Integrated collector storage solar water heaters · Phase change materials · Heat loss reducing strategy · Solar concentrator

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1 Introduction

Solar energy has tremendous potential [1,2] to fulfil the world's energy demand that is currently being accomplished by burning of fossil fuels. The efficient and exhaustive use of solar energy can reduce the intensity of global warming and climate change created by the larger and faster consumption of fossil fuels. In the recent years, various new and innovative technologies and systems have been developed that exploit the solar energy directly or indirectly and protect the environment [2–6]. However, few of these technologies have some limitations over the technologies operated by conventional fuels [7,8]. The conversion of solar energy by thermal route is highly efficient, more environmental friendly and economically viable if compared to the other routes of conversion [9–15]. The solar water heater is one of the thermal conversion technologies that convert the solar energy directly into concentrated form of heat at an appreciable conversion rate [16], has negligible global warming potential [17] and lower payback period [12]. The technology is suitable to provide hot water adequately for both domestic and industrial sectors [18] and also contributes in protecting the environment significantly [19].

The continuous research in solar water heaters has resulted in many different new and improved systems. As per their designs and operational principles, these systems are mainly divided into the following categories: (a) thermosiphonic or passive solar water heater, where a natural (thermosiphonic) driving force circulates the water between collector and storage tank [20]; (b) forced circulation type or active solar water heaters, where external force is applied to circulate the water [14]; (c) Integrated collector storage (ICS) systems, where both absorption of solar energy and hot water storage occur in a single unit; (d) direct circulation systems, where water is directly circulated through the solar collector; and (e) indirect water heating systems, where a secondary fluid is circulated between the collector and the tank and heats the water in the tank [21,22]; and (f) hybrid system, where electric heating is provided as a backup unit for ensuring the continuous operation of the system [23]. The thermosiphon flat plat and the evacuated tubular collector systems can supply adequately hot water in domestic sector [24]. However, these systems suffer from many issues of high heat losses by conduction, convection, and radiation, leakages through joints, corrosion, extra installation space requirement and of high additional expenses because of many components [12,25–28]. At the same time, the ICS heaters are compact systems and do not require piping, separate storage tank and other components.

The ICS system is also known as built in storage system and collector cum storage system; therefore, these names are interchangeably used throughout this article. The aesthetically attractive compact structure [29] and cheaper design of the system make it more suitable for water heating by solar especially in rural areas [30]. The systems can also reduce the environmental impact up to 40 % [31]. In one of the studies, the energetic and exergetic efficiencies and energy saving potential of the system have been estimated around 32 and 23.5 and 65 %, respectively [32]. The ICS system uses the surface of the storage tank as an absorber while in the other systems separate components are employed for heating and storage of the water [33]. Despite of so many advantages, these systems could not get sufficient popularity in the society due to high heat losses in the night/overcast sky [29,34]. Therefore, a few researchers have given considerable attention and improved the performance of these systems by developing advanced systems and applying effective heat losses reducing strategies. In this article, authors present a review on the latest development and improvements in the ICS systems. Based on their heat collection and storage principles, the ICS systems are also categorized basically into non concentrating, concentrating and with phase change materials systems. Moreover, the article discusses the heat losses reducing strategies to be applied in the systems.

2 A brief history of integrated collector storage solar water heaters

The first ICS solar water heater was demonstrated in late 18th century in the southwest of the USA. The water in the ICS tank type systems were placed out at a few farms and ranches for warming. These systems reportedly produced sufficient hot water on clear days [35]. In 1891, Kemp [36] patented the first commercially manufactured system the "Climax" with an idea to implement it as an ICS solar water heater. In this system, a metal tank was placed within a wooden box and the top part of the box was covered by a glass cover. The system produced hot water up to 38.8 °C in sunny days. In 1895, Brooks and Congers, two Pasadena businessmen bought the rights from Clarence to manufacture and sell it in California [37]. Further in 1902, Walker [38] proposed that the tank to be installed in the focal zone of a concentrating mirror. The system was also fitted with a standby gas fired heater.

The first commercial ICS solar water heater had four oval shaped cylindrical vessels with the flattened surface facing the sun. The size and shape of the vessel had significant effect on the solar energy collection [39]. Further, Haskell proposed a replacement of tubular tanks, placed inside the hot case of commercialized ICS system, by a flat tank for achieving larger collector area per unit volume of the tank. The tank was fitted with spacer elements and fins for achieving better heat removal from the absorbing panel [39]. In 1936, a closed and exposed single tank was studied in detail at the Agricultural Experimental station at the University of California in the US [40]. In the early 1950s, a closed pipe ICS solar water heating system was commercialized and marketed in Japan. The concept was further improved by introducing cylindrical vessels (a combined collector and storage tank), which is still used in many commercial designs [41]. Later on many researchers have shown their interests in this area and designed, developed and analysed many improved ICS systems in different parts of the world [28,34,42–46]. A few ICS designs based on the literature have been discussed by Smyth et al. [35], Frid et al. [47] and Devanarayanan and Murugavel [48]. Muneer et al. [49] have also compared the thermal performance of two different designs of built-in storage water heaters.

3 Categorization of integrated collector storage solar water heaters

The continuous research on ICS solar water heaters has led to many new, improved and innovative designs. The performance of these systems individually depends on their energy collection and storage methods. In the following subsections, a variety of ICS solar water heaters are reviewed and classified in terms of their energy collection and storage principles, with a discussion on the designs and modifications in recent years. These systems can be broadly categorized as (a) non-concentrating ICS solar water heater; (b) concentrating ICS solar water heater; and (c) ICS systems with phase change materials. The main reason of keeping the third category separately is the high heat storage capacity in the form of latent heat and producing hot water almost at constant temperature even at night.

3.1 Non-concentrating ICSSWH

3.1.1 Flat plate integrated collector storage (FPICS)

The flat plate integrated collector storage (FPICS) systems are characterized by integrating the collection of the solar energy using flat plate collector with the storage of hot water in one unit [50]. These systems are affordable and require less installation space [51,52]. Gertzos et al. have investigated the FPICS systems in direct and in indirect heating modes. In the direct heating mode, water is heated directly through the collector in the storage tank. While in the indirect heating mode, the service water passes through a serpentine tube immersed in the stored water [53]. Al-Khalifajy et al. [54] have analyzed the performance of an indirect ICS solar water heater with various heat exchanger designs. Results have indicated that a single row HX of 10.8 m length for both the elliptical and type B tube gives higher outlet water temperature, better thermal efficiency and lower initial and operational costs.

Also, the tilt of the collector had negligible effect on the design of the heat exchanger. Khalifa and Jabbar [51] have assessed the performance of a system consisting six copper tubes of 80mm outer diameter connected in series, which act as an absorber as well as a storage tank. The single glazed collector of dimensions 0.90 m by 1.80 m has been built from aluminum frame and tilted at 45°. The absorber has been placed at three centimeter below the cover. The system has performed much better than the conventional ones in terms of instantaneous efficiency, heat removal factor and collection efficiency factor. Recently, Borello et al. [55] have discussed an innovative solar water heating device consisted four cylindrical pipes. In this device, the panel absorbs the solar energy and raise the hot water towards the outlet pipe by convection and made it available at the domestic net whenever it is required. Taheri et al. [56] have constructed a simple and low cost compact solar water heater (CSWH) with an effective collector area of 0.67 m^2. The collector-cum storage water tank, size of $1.45 \times 0.56 \times 0.17$ m, was constructed from galvanized sheet of 0.0015 m thick. The system has been analyzed in natural and forced convection modes of water flow and with different collector orientations. The mean daily efficiencies for the collector orientation toward south, 10° east–south and 10° west–south have been estimated to be 73.45, 70.32 and 76.28 %, respectively. Garg et al. [57] have presented a nomogram, for ICS solar water heater, based on a method proposed by Hobson and Norton [58]. The nomogram has summarized three general non-dimensional parameters that enable designers to predict the systems' performance graphically for selected parameters and environmental conditions. Moreover, Commerford et al. [59] have developed a straightforward framework for identifying key design parameters for a site-built integrated collector storage solar water heater (ICSSWH) under uncertainty. Gertzos, and Caouris [53] have studied the flow fields and heat transfer in a recirculated type flat plate ICS solar water heater using a three-dimensional CFD model. Further, they have optimized the position and size of the recirculation ports, the arrangement and the size of the interconnecting fins [60].

Hazami et al. [61] fabricated an FPICS system with a collector surface area of 5 m^2 resting on a steel support tilted at 45° that raised the water temperature up to 50 °C. The storage character of the system has provided the necessary heat to maintain the temperature of the tapped water at an optimal value. Sopian et al. [62] have designed a non-metallic unglazed solar water heater with a water storage capacity of 3,29 L (see Fig. 1). The system has been fabricated from fiberglass reinforced polyester (GFRP) using a special resin composition of good thermal conductivity and absorptivity. In this heater, nineteen unglazed half elliptical collector tubes of absorptivity 0.95, and a collector 3 mm thick absorber sizing of 1.4 × 1.8 m have been used. The performance tests of the system, with and without night draining of the hot water, have indicated that the system could achieve 45 % efficiency for 635 W/m^2 solar radiation and 31 °C ambient temperature.

3.1.2 Tank/box type ICS system

Garg [34] has designed and tested a rectangular tank type improved built in storage solar water heater at the Central Arid Zone Research Institute, Jodhpur. The test results indicated that the system achieved sufficiently high efficiency up to 70 % and supplied about 90 L hot water at the temperature between 50 and 60 °C and between 60 and 75 °C in winter and in summer respectively. Further, Chauhan and Kadambi have tested a collector-cum-storage solar water heater, storage capacity of 70 L, in the following four modes of operation: (a) water circulated using a small pump; (b) natural convection conditions; (c) water draw-offs taking place when the water was at around 50–60 °C; and (d) water continuously pass the absorber plate with flow rates of 38, 60, and 75.9 kg/h. The highest system's efficiency, around 71.8 %, has been measured in continuous water flow at a steady water flow rate of 75.9 kg/h. The system has also performed in the desirable temperature and the efficiency range in the other three modes of operation [63]. Kumar and Rosen have reported a tank type ICS system with a corrugated absorber surface (see Fig. 2) that exhibits higher operating temperature for longer period but lower efficiency. The corrugated surface leads to a higher characteristic length for convective heat transfer from the absorber to the water and it also increases the surface area exposed to the Sun [50].

Moreover, they have designed a two sections system coupling a storage tank with an extended storage unit (see Fig. 3). The first section collects incoming solar radiation and the second insulated section stores the hot water. A volume ratio of 7/3 between first and second sections has produced the hot water at sufficiently temperature with highest efficiency [64]. Recently, Saleh has fabricated a rectangular tank (1 × 1 × 0.03 m) using reasonably cheap construction materials available locally. In this system, the water temperature in the tank has reached up to 60 °C and higher in partly cloudy, sunny/showers and sunny/clear sky conditions during the three days out of four days of testing. However, the system has produced hot water at comparatively lower temper-

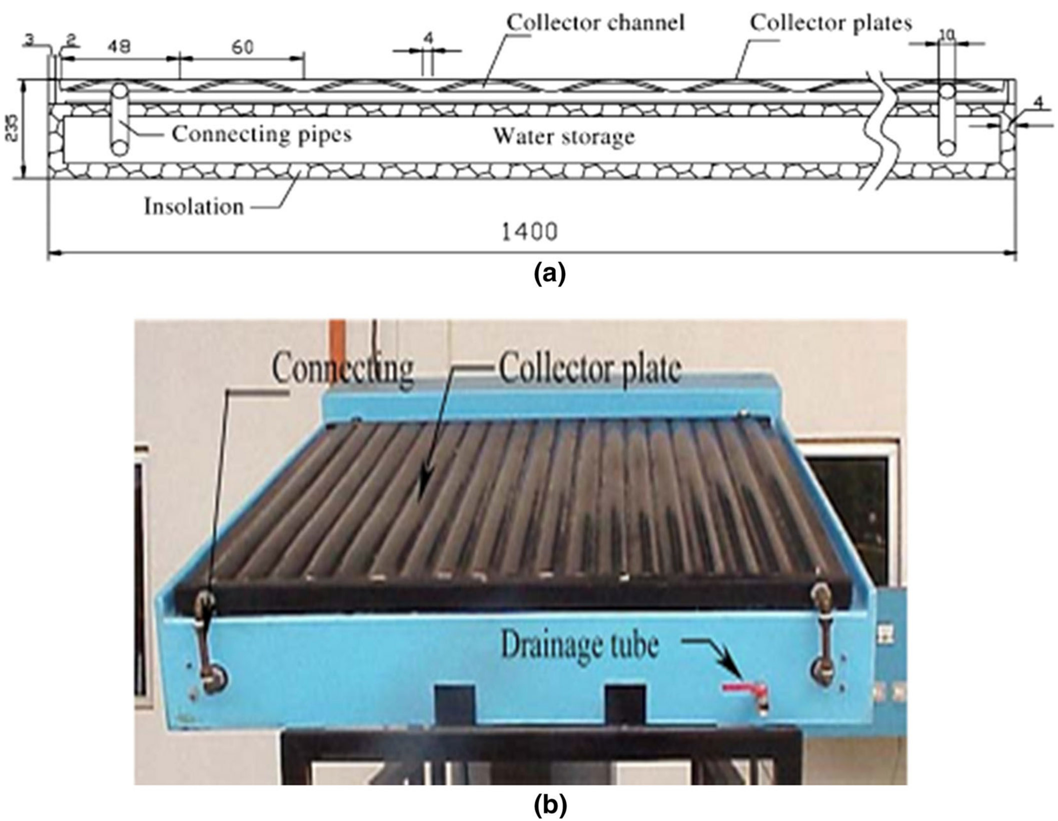


Fig. 1 **a** Cross-section of the system, **b** photograph of the system [62]

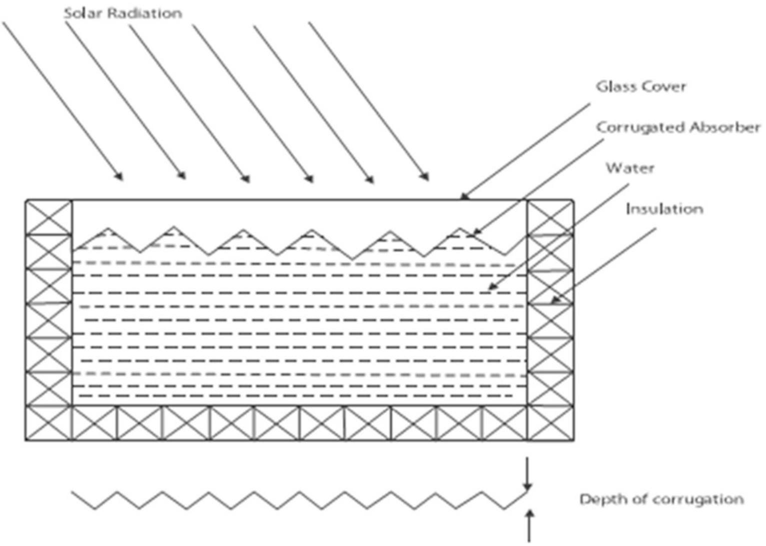


Fig. 2 Cross-section of rectangular solar water heater with corrugated surface [50]

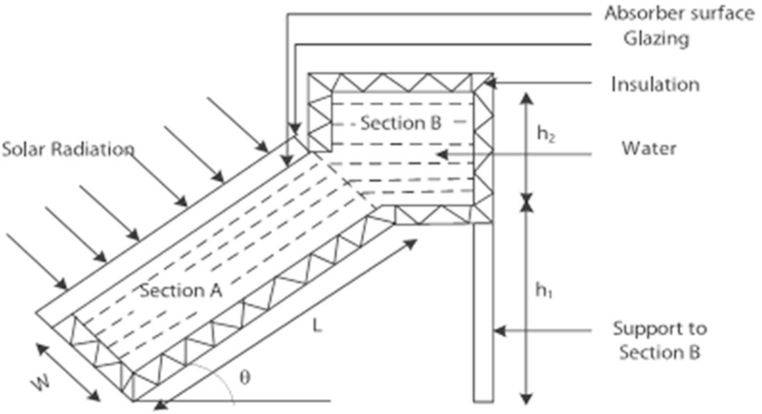


Fig. 3 Cross-sectional view a two sections ICS solar water heater [64]

ature than the imported solar water heaters [65]. Mohsen and Akash [66] have tested a box type ICS solar water heater with single glazing and observed a temperature rise by 30 °C in the tank water. Further, Mohsen et al. [26] have reported a similar type of system, suitable for supplying hot water for 24 h. The thermal performance of the system has been assessed for three different tank depths (i.e. 5, 10 and 15 cm) with single and double glazing. For a 10 cm tank's depth, the system has yielded the hot water at a higher temperature, up to 68 °C, than the other depths. Also, the system with double glazing exhibits higher potency of retaining the water temperature high in the night.

Dharuman et al. [67] have constructed an ICS system, with an absorber area of 1.3 m^2 and a water storage capacity of 170 L, at 30 % lower cost. The tests results indicated that the system supplied adequate hot water, between 45 and 50 °C, in the early morning for bathing and cleaning in the domestic sector. The daytime collection efficiency and overall efficiency of the system have been observed to be 60 and 40 %, respectively. Garnier et al. [68] have studied the temperature stratification in a rectangular-shaped box type ICS solar water heater. Further, Garnier and Currie [69] have predicted the stratification time and the water temperature, at different distances from the bottom, in the rectangular shape ICS box type solar water heater applying a macro model previously developed by Currie et al. [70].

3.1.3 *Triangular ICS system*

Ecevit et al. [71] have proposed a triangular ICS solar water heater. The trapezoidal design has enhanced the heat transfer between the absorber surface and the water, and also exhibited better overall performance compared to a rectangular design. The triangular cross-section also helps in getting higher solar gain and better natural convection and eventually a higher water temperature [72]. The theoretical detail of similar systems can be seen in [72,73]. Soponronnarit et al. [74] have compared the performance of a triangular system with rectangular design of the system. Both systems were tested experimentally under identical operating conditions. The triangular system performed more efficiently and had lower night heat losses.

3.1.4 *Trapezoidal ICS system*

Cruz et al. [75] have studied the performance of a trapezoidal-shaped solar water heater, with an optimal collector tilted at 45°, illustrated in Fig. 4, in Mediterranean Europe or regions of similar latitude (40–45 north). The trapezoidal cross-section has induced thermal stratification in the stored water, and provided sufficient energy storage to meet typical daily hot-water demands. The system yielded an energy savings between 30 and 70 % and hot water at 31 °C for a radiation value of 600 W/m^2. Recently, Tarhan et al. [76] have investigated the effect of PCM inclusion, in the storage tank, on the temperature distribution in three trapezoidal systems.

3.2 Concentrating ICSSWH

A solar water heater with higher solar collection efficiency and least heat losses is always preferred. A concentrating type solar water heater can collect higher solar energy than a non-concentrating heater. The concentrator designs in solar collector for low to medium concentrations can be flat or curved, line-axis or line-focus (circular, parabolic or compound parabolic) reflectors, symmetrical or asymmetrical. This section discusses all concentrating type ICS solar water heaters available in the literature.

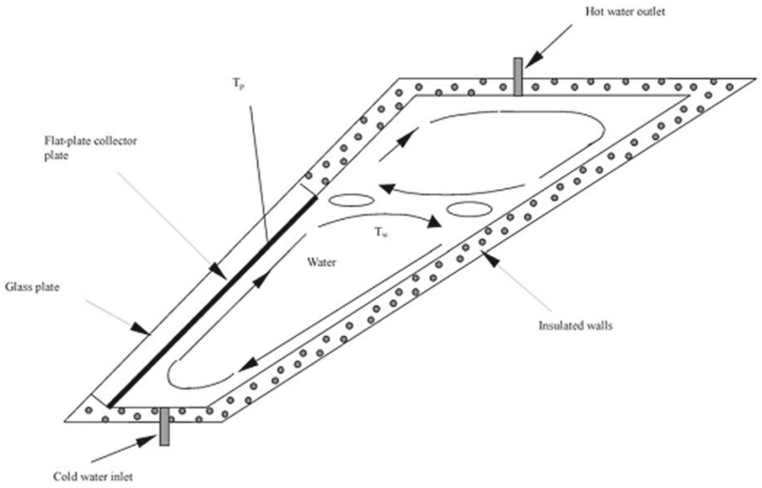


Fig. 4 Cross-sectional representation of a trapezoidal-shaped ICS solar water heater [75]

3.2.1 Compound parabolic concentrating type

The CPC have been found more suitable for solar thermal applications requiring fluid temperatures over 50 °C [77]. The high collection efficiency and less thermal losses make them suitable for high temperature applications. Therefore, the potential of solar collectors with compound parabolic concentrators has been exploited for the ICS solar water heaters application. The potential of CPC as collectors of solar energy was firstly pointed out by Winston [78].Various designs of ICS-CPC systems have been constructed and tested in the recent years. The performance of the systems has been assessed and compared in terms of the temperature variation in stored water, mean daily efficiency and heat losses during overcast sky condition and at night [79]. Saroja et al. [80] have indicated that the wall and the fluid temperatures in the system increase with solar flux, the buildup factor and the ratio of transmission for short wave and long wave radiation. A CPC ICS system has been developed using cusp type geometry (see Fig. 5) [29] that is truncated equal to the acceptance angle of the fully developed cusp to collect maximum solar radiation. A prototype has been constructed from medium density fibers wood (18 mm thick) using an optimized model out of three different selected collector configurations.

Tripanagnostopoulos et al. [81] have designed few CPC-ICS systems consisting two cylindrical storage tanks connected in series. The absorbers and the tanks are horizontally incorporated in a stationary asymmetric CPC mirror. Direct absorption of most incoming solar radiation [82] and suppression of thermal losses by the inverted surface absorbers and two inverted cylindrical surfaces [81] have enhanced the operation of the CPC-ICS systems significantly. Souliotis and Tripanagnostopoulos [24] have tested the performances of two systems of different absorbing surfaces and with storage tanks similar to ICS-2 system [83]. One system was painted matt black and other was selective. The systems have also been assessed with single and double

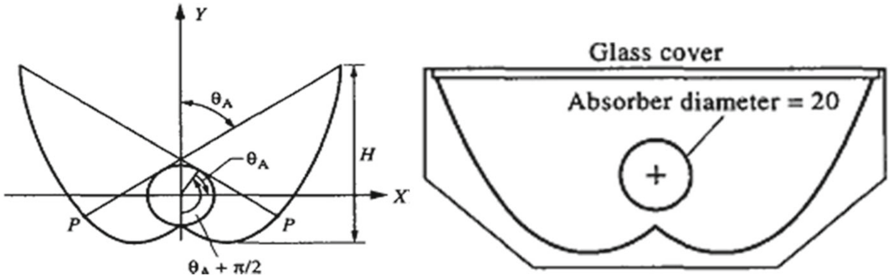


Fig. 5 **a** Fully developed cusp; **b** final collector [29]

Fig. 6 Experimental CPC ICS models mounted at the test field [87]

transparent covers for different values of transmissivity and reflectivity [24]. Moreover, assessment of a system that is consisted of a cylindrical horizontal tank, mounted in a stationary symmetrical CPC reflector, has confirmed the most promising water heating and heat retaining capabilities [84]. A similar system with cylindrical water storage tank placed inside a CPC reflector has been studied by artificial neural network (ANN) and TRNSYS software [85]. Souliotis et al. [86] have studied a heat retaining ICS vessel consisting two concentric cylinders mounted horizontally in a stationary truncated asymmetric CPC reflector trough. The absorbing outer vessel surface has been covered with a selective absorber film and partially exposed to solar radiation. The remaining vessel surface area (including the vessel ends) has been thermally insulated for improving heat retaining capability at night. The experimental results has indicated that the ICS system is equally effective for the day and night operations. Further, three similar types of CPC-ICS models have been designed, fabricated and tested outdoor side by side [87], shown in Fig. 6. The experimental results have proved that the systems perform effectively during their daily operation but the the performance perishes at night. Out of the three systems, one system is found to be the most promising regarding its thermal performance.

Moreover, Tripanagnostopoulos and Souliotis [88] have analyzed the performance of four CPC systems, of equal volume, constructed from the same materials; and a cylindrical water storage tank has been mounted differently in a symmetric CPC or in an involute reflector trough. Further, they have analyzed the systems with truncated symmetric CPC reflectors, two with 90° and other two with 60° of acceptance angle. Half of the assessed systems have been constructed with one fourth thermally insulated cylindrical storage tanks and half of them without insulated tanks. These systems have been tested with involute reflectors at 180° acceptance angle. The results showed that CPC reflectors contribute to efficient operation of systems day and night, while involute reflectors mainly to the water heat preservation during night [89]. Few more systems consisted of single cylindrical horizontal water storage tanks, placed inside a stationary truncated asymmetric CPC reflector troughs of different design, have also been analyzed experimentally. The systems with asymmetric CPC reflectors have demonstrated almost the same mean daily efficiency as of the system with the symmetric CPC reflectors [90]. A CPC-ICS system with a selective absorbing surface and a reflector of high reflectance performs closely to FPTU systems has been demonstrated by Tripanagnostopoulos et al. [83].

Smyth et al. [91] have designed and developed a system with the heat retaining storage vessel mounted within a concentrating cusp reflector supported by a novel exo-skeleton framework. The CPC collector has been produced from the plastic substrate using the exo-skeleton design attains an optical efficiency approximately 65%. The system with an operating efficiency between 55 and 35 % also has the potential to displace 1,534 MJ of energy used for water heating in a domestic dwelling in the UK. The system is found to be economically viable and can compete with traditional water heaters. Recently, Helal et al. [92] have designed and built a system, composed of three parabolic branches at the National School of Engineers of Gabes. The system has verified comparable performance with the currently available solar water heaters in the international market. Additionally, a similar system, as shown in Fig. 7, has been assessed for satisfying the hot water need of a family of four persons [93]. A comparative analysis has proclaimed the lowest thermal loss coefficient per aperture area and a better thermal efficiency of the system compared to two other CPC systems.

Smyth et al. [94] have designed a novel ICS vessel using inner sleeve concept. The operation of the system under energy collection and non-collection periods is demonstrated in Fig. 8. Thermal buoyancy leads to natural circulation within the vessel(s) during collection periods. A water layer near to the exterior surface is get heated that leads to step up the hot water and passes through the perforated inner sleeve into the inner store. Further, two prototypes (A and B) (see Fig. 9) have been fabricated applying the same inner sleeve concept. The inner sleeves have been made of unplastised-polyvinylchloride (uPVC). The vessels have been positioned at the focal point of a truncated modified concentrating cusp reflector that is produced using an exo-skeleton structure to support a specular silver reflective film of 0.96 solar reflectance adhered to a 1 mm thick poly styrene substrate sheet. The systems have been experimentally tested under Northern Irish climatic conditions. The results have indicated that the system B produces water at the higher temperature whiles the system A exhibits better heat retention capability because of lower U$_{avg}$ [95].

Chaabane et al. [96] have studied a system with a cylindrical water storage tank, equipped with radial fins of rectangular profile, properly mounted in the CPC reflector. The system has been found effective during the day and obtained higher water

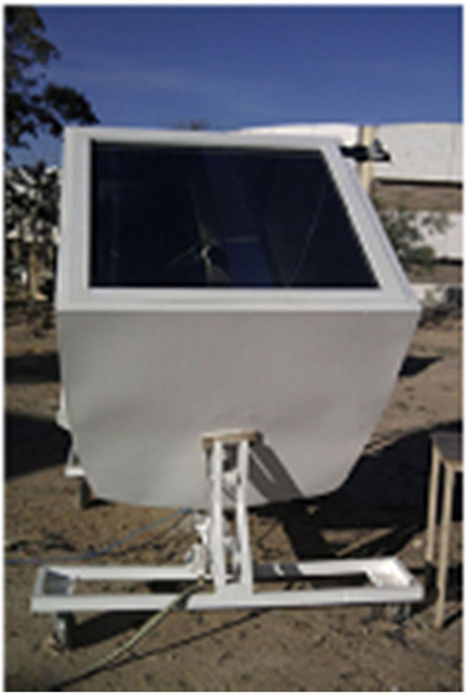


Fig. 7 An ICS-CPC prototype based on three parabolic branches design [93]

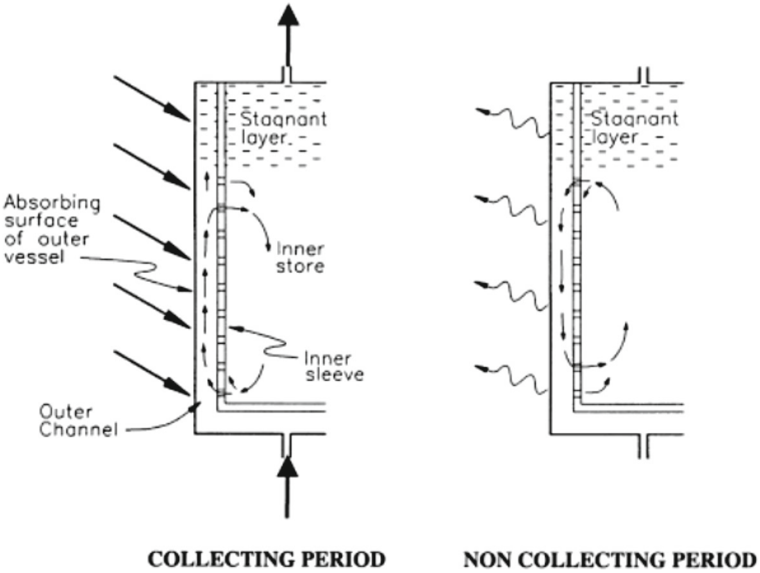


Fig. 8 Operating principle of an ICS inner sleeve solar water heater [94]

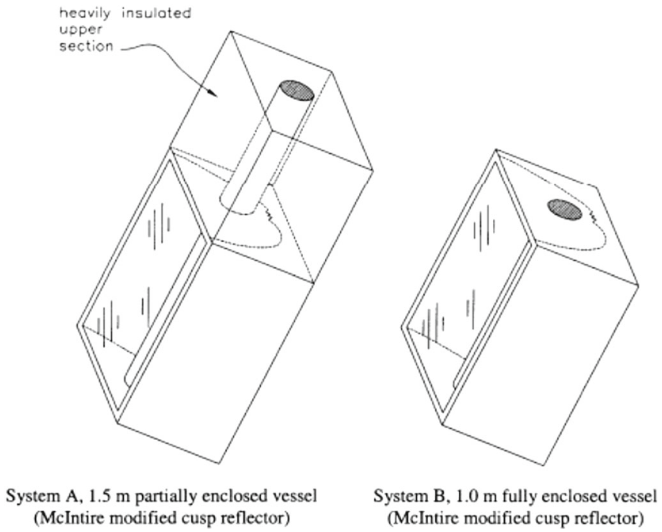


Fig. 9 Developed prototypes using inner sleeve design [95]

temperature for longer period, but of higher thermal losses. However, an increase in the fins' depth leads to higher water temperature and minimize the thermal losses.

3.2.2 Pyramid type system with concentrator

Kumar et al. [97] have fabricated and tested a truncated pyramid geometry based multipurpose solar device. The device has also been tested as a solar water heater. The system has been constructed by a glazed surface size of 50 × 50 cm, selected as per the Indian SBCs, and a black painted aluminum plate size of 32.6 × 32.6 cm as absorber placed at a depth of 49.2 cm. The glazing surface has been kept horizontal with a variable slant for adjusting angular tilt to the base of the proposed model to receive maximum insolation. As a solar hot water system, the maximum efficiency of the device has been estimated to be 54 %. The day-time and average night-time heat-loss coefficients have been determined to be 5.7 and, 3.74 W/m^{2}°C, respectively.

3.3 ICS systems with phase change materials

The introduction of phase change materials (PCMs) to utilise the latent heat stored in it during the melting process is one of the most repeatedly proposed techniques in solar water heating systems. The higher heat storage capacity in the form of latent heat and isothermal behaviour, during the melting process, of PCM [98] successfully extends the operational period of domestic solar water heaters [21], [99], [100]. The PCM stores extra thermal energy in the form of latent heat during the daytime by changing its phase and releases this thermal energy to heat the water when it is extracted from the system to meet the demands of hot water in the night or during the overcast sky conditions. Cold water enters in to the system extracts stored latent heat from the

PCM and changes the phase of the PCM. The PCM-integrated solar collector can also eliminate the need of conventional storage tanks thus reducing the cost and space. Other advantages of using the PCM as storage medium over conventional SDHW systems are: (a) the reduction in the collector's maximum temperature during stagnation that minimize the problem of severe reduction in solar collector's life time expectancy [21]; and (b) enhances the useful efficiency by reducing the significant heat losses when the solar collector is at its highest temperature [101]. Therefore, inclusion of a PCM can partially recover the temperature of the water and leads to extending the effective operational time of the system [102]. The performance of the PCM solar water heater varies with PCMs and it is not necessary that the use of every PCM will deliver a significant benefit [103]. Hence, the selection of material and its position in the system are crucial and need to be decided very carefully so that the system can produce hot water in the desirable temperature range [104]. Chaabane et al. [105] recently presented computational results, validated by experimental data in the literature. They proposed to integrate a phase change material (PCM) directly in the collector and to study its effect on the ICSSWH thermal performance. 3D CFD models were developed and series of numerical simulations were conducted for two kind (myristic acid and RT42-graphite) and three radiuses ($R = 0.2$ m, $R = 0.25$ m and $R = 0.3$ m) of this PCM layer. Rabin et al. has used a salt-hydrate PCM in an ICS solar collector that yields a collection performance of approximately 66 % during the winter in Beer-Sheva, Israel. However, the use of such a system was limited to space and soil heating greenhouses applications in arid areas [106]. Eames and Griffiths have predicted the collection and retention of heat in the rectangular cross section solar collector/storage systems filled with water and various concentrations of PCM slurries of a 65 °C phase change temperature. The slurry system collects heat less effectively than the system filled with water. The storage of heat at a higher temperature in the PCM slurry allows higher solar saving fractions [107]. Tarhan et al. have tested three trapezoidal built in storage solar water heaters, one with myristic acid, one with lauric acid and one with water. The lauric acid has been placed in a storage unit that acts as a baffle plate, while myristic acid has been stored in a storage unit that acts as an absorbing plate. The tests results have indicated that the use of lauric acid stabilizes the temperature and reduces the volume of the water tank but it is found very effective for retaining the water temperature at night. The system with myristic acid has been found quite effective in retaining the water temperature in the night since it solidified at 51–52 °C temperatures and acts as a thermal barrier [76]. Koca et al. have studied a flat plate solar collector with a PCM stored in a storage tank that is located under the collector. A special heat transfer fluid has been used to transfer heat from collector to the PCM. The average net energy and exergy efficiencies of the system have been observed approximately 45 and 2.2 %, respectively [108]. Moreover, several other composites of compressed expanded natural graphite (CENG) and the PCMs (e.g. paraffin, stearic acid, sodium acetate trihydrate and pentaglycerin) have also been elaborated to be placed directly inside a flat plate solar collector in order to replace the traditional copper-based solar absorber [109].

4 Heat losses reducing strategies for ICS solar water heaters

The high heat loss from the storage tank to the surroundings is seen as one of the major drawbacks of the ICS solar water heaters. The heat losses in these systems exist because the surface area of the storage tank is intentionally exposed to the Sun for absorbing solar radiation. In particular, the heat losses are highest at night and during overcast conditions with low ambient temperature. The water temperature drops substantially in the night due to the losses and this drop is seen larger especially in the winter nights [29]. Hence, the most of the research work has been focused on the heat retaining strategies for establishing efficient operations in the ICS solar water heaters t by reducing the heat losses. A few of the strategies discussed in the recent literature are summarized in the following subsections.

4.1 Adding insulating material

Optimally addition of suitably selected thermal insulation at the non-illuminated/illuminated tank surfaces can reduce heat losses significantly in ICS solar water heaters [90]. Nayak et al. [110] have investigated the effect of different insulation thicknesses, (top and bottom) on the water temperature in the tank of a built in storage solar water heater. Different insulating materials including transparent insulation material (TIM) have extensively been used in the ICS s systems [43,111–113]. The use of TIM lowers the heat loss coefficient in the systems and eventually reduces the thermal losses from the cover while allowing solar radiation to hit the absorber [114]. The effect of different TIM configurations on the heat collection during the day and the heat retention during the night have been discussed in [115,116]. Reddy and Kaushika [116] have investigated the effective thickness of TIM applying the various combinations between the top glazing and the absorber plate. They have reported with the 10 cm sheet of TIM as the most effective configuration and system with this thickness has achieved an average solar collection and storage efficiencies in the range of 20–40 % and the water temperature in the tank between 40 and 50 °C. Moreover, Kaushika and Reddy [117] have compared the transparent honeycomb cover system with a TIM cover system with single glazing. The compound honeycomb cover system excels over other. The system has exhibited optimum performance for a honeycomb depth between 5 and 7.5 cm and aspect ratio between 15 and 20. Additional benefit in terms of solar gain and thermal storage has also been achieved by compounding the honeycomb array with an air layer of 12 mm and with a selective absorber. Chaurasia and Twidell [115] have reported the system with TIM produces hot water at higher temperature with a storage efficiency of 39.8 % compared to without TIM. Recently, Sridhar and Reddy [118] have investigated that the average heat transfer coefficient, of a system with TIM, increases from 90 to 115 $\mathrm{W/m^{2\circ}C}$ as the inclination angle increased from 10 to 50. Garg [34] has suggested an overnight insulation cover or transferring hot water in to an insulated tank for getting sufficient hot water in the early next morning. Kumar and Rosen [119] have examined that the system with a double glass cover and without night insulation cover has demonstrated the greatest thermal performance while the system with an insulating baffle plate and with a single glass cover has exhibited the lowest

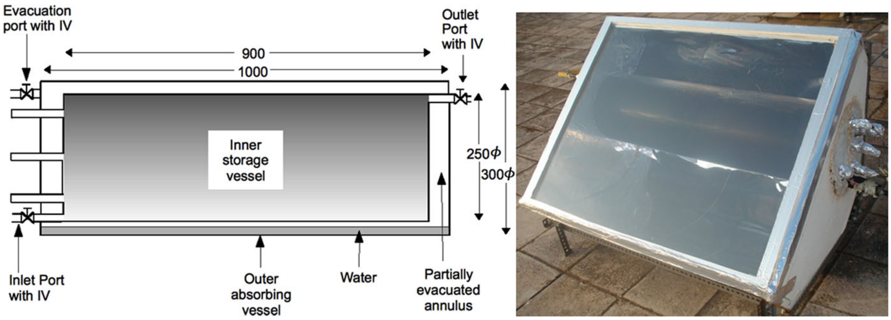


Fig. 10 The thermal diode employed in ICS systems [86]

thermal efficiency. AL-Khaffajy and Mossad [120] have optimized the upper and lower air gap spacing in a flat plate integrated collector system with double glass covers. Khalifa and Jabbar [51] have applied 40 mm thick rigid Styrofoam insulation on all sides, bottom and space between the tubes for maximizing heat retention capability of a collector cum storage system.

4.2 Thermal diode

Mohamad et al. [121] and Sopian et al. [62] have constituted a thermal diode in the ICS solar water heater for preventing reverse circulation during the night. Thermal diode have reduced the heat transfer significantly during non-illuminated period, especially when the temperature in the storage tank is high [121] and also reduces the temperature drop in the storage tank by 50 % [62]. In a CPC ICS system, an annulus between the cylinders has been partially evacuated and contained a small amount of water, which changes phase at low temperature and produce vapor, as shown in Fig. 10. This vapor in the annulus creates a thermal diode transfer mechanism from the outer absorbing surface to the inner storage vessel surface [86].

4.3 Two cylinders geometry

In the CPC ICS solar water heaters, the collector absorber also works as a storage tank. Similar to the other ICS solar water heaters designs, CPC ICS systems also suffer from high thermal losses because of the storage tank in the system cannot be insulated properly. Therefore, appropriate strategies need to be applied for minimizing the losses. Tripanagnostopoulos and Yianoulis [79] have suggested a secondary cylinder design and Kalogirou [122] has introduced a primary cylinder (110 mm diameter) in between the main cylinder and the glass. In this design [122], the cold water is introduced directly to the primary cylinder that feeds the main cylinder. The arrangement has reduced the convection currents drastically that eventually reduces the night losses. Tripanagnostopoulos and Souliotis [123] have also analyzed different configurations of a system with two tanks (see Fig. 11). Most of the combinations have efficiently elevated the water temperature and minimized the heat losses; but, one of the config-

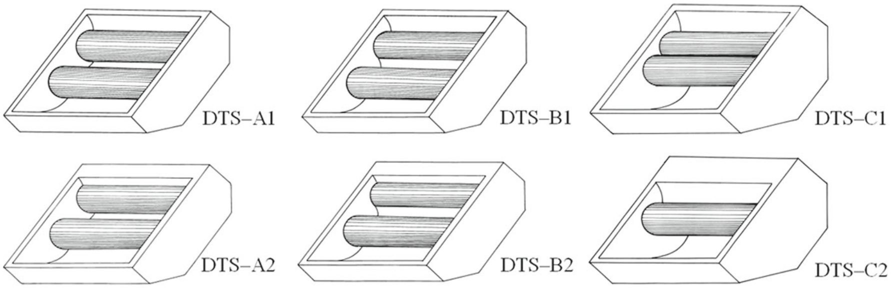


Fig. 11 Front–side views of the tested DTS systems [123]

urations (DTS-B2) had the least heat losses. Kessentini and Bouden [124] studied the effect of emissivity of the absorber, quality of reflectors and glazing, on the performance of a prototype model similar to DTS-B [125]. The absorber of low emissivity and use of a double glazing reduced the overall heat losses by 47 % and increased its daily efficiency from 18 to 25 %. The annual diurnal useful heat gain has been increased by three percent when the concentrator's reflectivity is increased from 0.75 to 0.95.

4.4 Inner sleeve arrangement

The ICS vessel with inner sleeve configuration has demonstrated the capability of heat loss mitigation. The thermal collection and retention capabilities and the stratification characteristics of such systems have been examined with seven different inner sleeve arrangements [93]. Some of the configurations have verified an increase in the heat retention ability over existing vessels. The vessel with a two third perforated inner vessel (3 mm holes) has been utilized as an inner sleeve, which has reduced the overall heat losses up to 20 % during non-collection period and also retained thirty percent more thermal energy in the upper one third part of the vessel, Smyth et al. have confirmed the better heat retention capabilities because of the lower U_{avg} value in one of the two prototypes fabricated using the inner sleeve concept (Figs. 8, 9). Moreover, the systems based on this concept have demonstrated the capabilities of collecting higher solar energy and yielding larger solar savings fraction in limited water draw-off condition [95], [126].

4.5 Baffle structure

Parkash et al. [127] have integrated a baffle plate in an ICS solar water heater in order to control the heat losses. Expectedly, the baffle plate in the system reduced the heat losses effectively. Further, Kaushik et al. [73] have inserted an insulating baffle plate in the collector-cum storage tank that splits the tank water into two sections (see Fig. 12): the upper column and the lower column. An incoming and outgoing vent provided in the baffle plate keep the water of the two columns in contact. Smyth et al. [128] have experimentally tested an inverted absorber ICS solar water heater with various

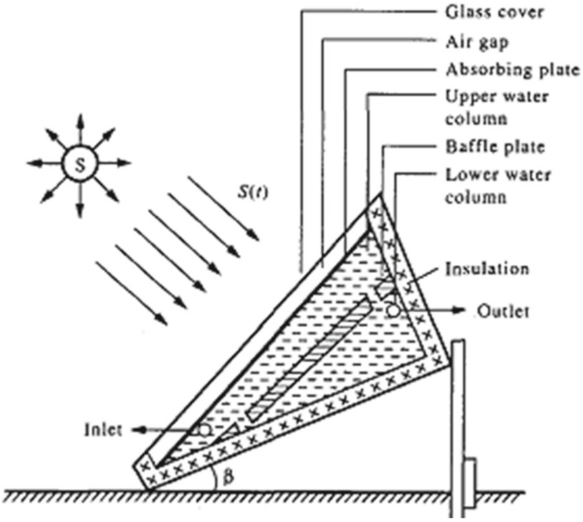


Fig. 12 Triangular built-in-storage solar water heater with baffle plate [73]

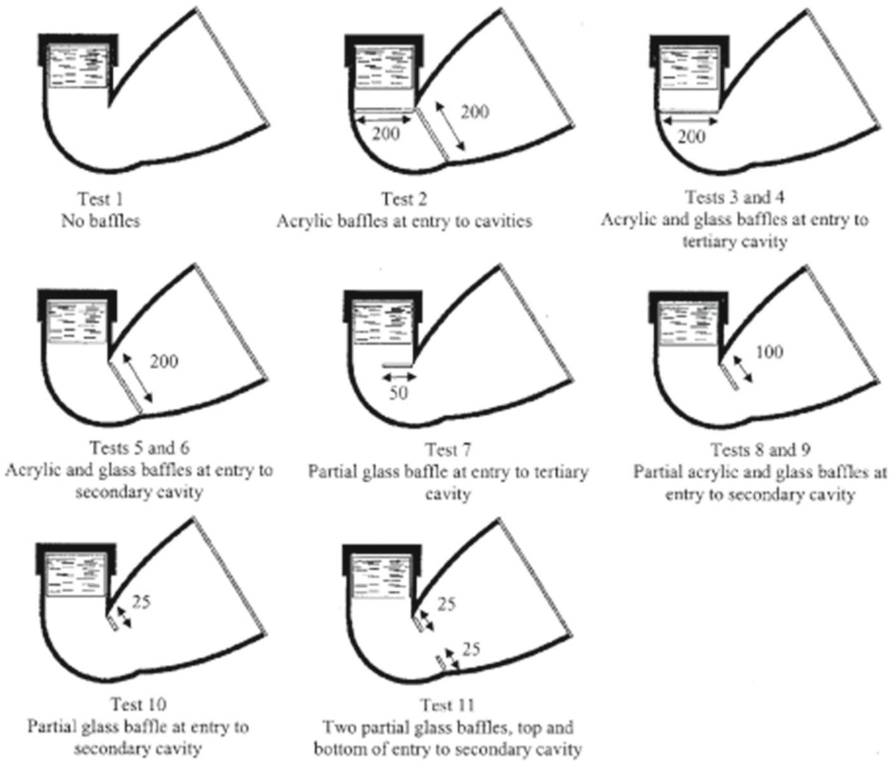
transparent glass baffles (see Fig. 13) placed at different locations within the collector cavity. Results of the study have indicated that the baffle located at the upper portion of the exit aperture in the CPC has reduced the heat losses, as a result of convection suppression, without increasing optical losses significantly. Kaptan and Kilic [129] have also investigated the performance of a built-in-storage type solar water heater made of five pipes (each of length 1.8 m and diameter of 12 cm) with a baffle plate in each pipe. Earlier, Sokolov and Vaxman [130] have a water-side baffle-plate adjacent to the absorber to direct the natural water-circulation in a trapezoidal system.

4.6 Reverse-thermosyphon prevention valve

Faiman et al. [33] have presented an ICS system with a new device "reverse-thermosyphon prevention valve" that automatically lowers the heat loss coefficient in the night (see Fig. 14). In this system, outer surface of one wall has been coated to make a solar absorber plate. One insulating has been positioned beneath and parallel to the coated surface that allows the flow of a water film, in the day time, between the two surfaces by the thermosiphonic effect. A mechanical valve is used to restrain the movement of the water film between the surfaces at night. This arrangement of the components in the system has reduced the night time heat loss coefficient of the collector aperture effectively.

5 Conclusions

Compared to other solar water heaters, the ICS heaters are compact in size and do not require expensive piping, a separate storage tank and/or other components. This article presents a concise summary of the recent research and developments in ICS



Test 1
No baffles

Test 2
Acrylic baffles at entry to cavities

Tests 3 and 4
Acrylic and glass baffles at entry to tertiary cavity

Tests 5 and 6
Acrylic and glass baffles at entry to secondary cavity

Test 7
Partial glass baffle at entry to tertiary cavity

Tests 8 and 9
Partial acrylic and glass baffles at entry to secondary cavity

Test 10
Partial glass baffle at entry to secondary cavity

Test 11
Two partial glass baffles, top and bottom of entry to secondary cavity

Fig. 13 Alternative baffle arrangements in an inverted absorber ICS solar water heater [127]

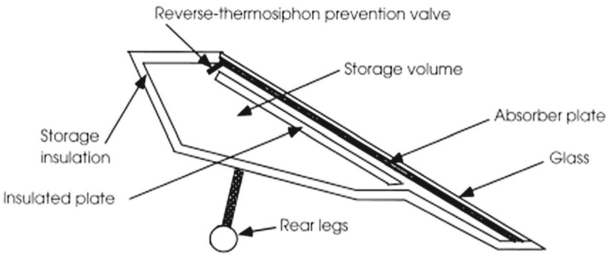


Fig. 14 Schematic vertical cross-section of a reverse-thermosiphon prevention valve [33]

solar water heaters. As for the energy collection and storage methods, these systems have been evaluated based on a categorization to non-concentrating, concentrating, and systems with PCM. Most of such devices provide adequate hot water for domestic use, but suffer from high heat losses in non-collection period. Comparatively, the concentrating systems and systems with PCM have high collection efficiency. Also, the PCM systems successfully provide the fairly hot water even in non-collection period. However, the performance of the systems with PCM varies significantly with thermo-chemical properties of the material and their designs. Authors have also discussed important heat loss reducing strategies, which improve the heat retention capability of the systems remarkably during night/overcast conditions.

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