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Research Article

Emerging Trends in Solar Water Heating Technologies

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Abstract: This article presents a comprehensive and detailed review focused on the design aspects of solar water heating (SWH) systems, with a particular emphasis on the technological advancements that have shaped their evolution. The first section offers an in-depth analysis of the key components integral to the functionality and efficiency of SWH systems, including the solar collector, storage tank, and heat exchanger. The review traces the development of these components, highlighting improvements in materials, configurations, and thermal efficiency. The second section explores the latest innovations in alternative refrigerant technologies, prompted by environmental and regulatory challenges, and their impact on system performance. Additionally, this section investigates cutting-edge advancements, such as enhanced absorber coatings, advanced insulation techniques, and optimized heat exchange designs, all of which contribute to significant improvements in the thermal performance, reliability, and cost-effectiveness of SWH systems. This article identifies opportunities for further research and development to advance the practical and economic viability of solar water heating technology.

Keywords: Solar Water Heating; Solar Collectors; Flat-Plate Collectors; Heat Exchanger; Heat Transfer Fluid.

1. Introduction

Solar radiation is utilized as a renewable energy source for a wide range of industrial and domestic applications. Presently, in addition to its use for space heating, air conditioning, and lighting, water heating constitutes approximately 20% of household energy consumption in the United States [1,2]. Solar-powered domestic water heating systems have demonstrated the potential to reduce water heating costs by 70–90%, positioning them as one of the most effective solutions for substantially lowering household energy usage. Over the past three decades, advancements in solar water heating technology have significantly enhanced its sustainability, efficiency, and economic feasibility [3,4].

For example, the global capacity of solar water heating (SWH) systems increased from 160 GW_{th} at the beginning of 2010 to 185 GW_{th} by the start of 2011. Although China dominates the SWH market with a capacity of 118 GW_{th}, significant growth has also been observed in regions such as the European Union, Japan, India, and Brazil. In contrast, the expansion of solar water heating in the United States remains relatively modest compared to its substantial water heating needs [5,6]. Globally, there are numerous opportunities for considerable growth in the domestic water heating market, with even greater potential for industrial applications. As of 2010, only 100 such industrial projects were in operation worldwide [7,8].

Numerous solar water heating (SWH) systems have been designed and developed to meet the specific requirements of various applications and adapt to diverse local climatic conditions. This paper will explore the historical evolution of SWH system designs over the past 30 years [9,10]. Since the 1960s, SWH technology has matured significantly, leading to the commercialization of various designs; however, there remains considerable potential for further improvements in efficiency and reliability

[11,12]. Many of these advancements have focused on addressing challenges posed by low ambient temperatures and seasonal variations in solar radiation ratios. Other design issues, such as high component costs, overheating, corrosion, and inadequate protection against freezing, have also been areas of concern [13,14]. Numerous studies have proposed solutions to these problems, including the use of different collectors, storage tanks, and working fluids tailored to specific regional and geographical conditions [15]. From the 1980s to the present, there has been growing interest in enhancing the thermal performance of SWH systems by improving absorber plate characteristics, enhancing the thermal stratification of storage tanks, optimizing design parameters, and expanding the heat-transfer area [16,17].

According to [18], the paper provides a comprehensive analysis of various solar-assisted water heating systems and their market potential. Residential solar water heating, a time-tested technology, has undergone significant advancements in both scope and quality, evolving into a successful, market-ready product. Its growing adoption reflects its potential as a sustainable energy solution for modern households. Moreover, this study [19] aimed to provide a comprehensive understanding of the current economic and technical advancements in solar water heating systems, while identifying the remaining barriers hindering their widespread adoption. The study explored potential research areas to enhance system performance and establish strategic plans related to the design and installation of these systems. Furthermore, the study seeks to promote the global solar thermal market and contribute to achieving both China’s and international targets for energy conservation, renewable energy utilization, and carbon emission reduction within the building sector. In [20], a comprehensive review of solar water heating systems for both domestic and industrial applications is presented. These systems are broadly classified into two categories: passive and active solar water heating systems, each of which can operate in either direct or indirect modes. The review provides a detailed analysis of their performance, applications, and the factors influencing their selection. It is noted that active systems typically exhibit higher efficiencies, ranging from 35% to 80% greater than those of passive systems. In [21], the effective utilization of solar energy is constrained by its intermittent availability, which limits its application and efficiency in both domestic and industrial settings, particularly for water heating. Solar energy conversion into thermal energy is the most straightforward and commonly employed method, with a conversion efficiency of approximately 70%, significantly higher than solar photovoltaic systems, which achieve only 17% efficiency. Solar water heating systems are particularly well-suited for these applications due to their operational simplicity and minimal maintenance requirements. In this direction, the paper [22] investigated recent advancements in solar water heating systems, focusing on the three fundamental components that influence the system’s thermal performance. It also provides a detailed review of the development of various solar collectors used in solar water heaters, encompassing both non-concentrating collectors (such as flat plate collectors and evacuated tube collectors) and concentrating collectors (including parabolic dish reflectors and parabolic trough collectors). These collectors are analysed in terms of optical optimization, heat loss mitigation, heat recuperation improvement, and the implementation of various sun tracking mechanisms. Among the different types of collectors, the parabolic dish reflector has demonstrated the best overall performance in terms of efficiency and effectiveness.

This article makes a significant contribution to the field of solar water heating (SWH) systems by offering a comprehensive and detailed review of the design aspects that underpin their performance and development. It provides an in-depth examination of the essential components, such as the solar collector, storage tank, and heat exchanger, while tracing their evolution through advancements in materials, configurations, and thermal efficiency. Furthermore, the article addresses recent innovations in alternative refrigerant technologies, driven by environmental and regulatory demands, and assesses their influence on system performance. The exploration of cutting-edge developments, including enhanced absorber coatings, advanced insulation methods, and optimized heat exchanger designs, offers valuable insights into the improvement of thermal efficiency, reliability, and cost-effectiveness. By identifying key areas for future research and development, this article paves the way for advancing the practical and economic feasibility of SWH systems, positioning them as critical components in the pursuit of sustainable energy solutions.

2. Solar Water Heating Systems

Solar water heating systems harness solar energy, and in some cases, are supplemented by ambient energy to heat water. The first commercial SWH, named "Climax," was patented in the United States by Kemp [23]. In the early 1900s, several researchers focused on improving the design of SWH systems to enhance their durability and efficiency. The commercialization of these systems expanded significantly in the early 1960s. In the sections below, various SWH systems are reviewed and categorized according to their circulation methods and applications, with a discussion on recent design modifications [24]. These systems can be broadly classified into two categories: passive solar water heating systems and active solar water heating systems. Figure 1, illustrates line schematic of an unusual thermosyphon solar water heater.

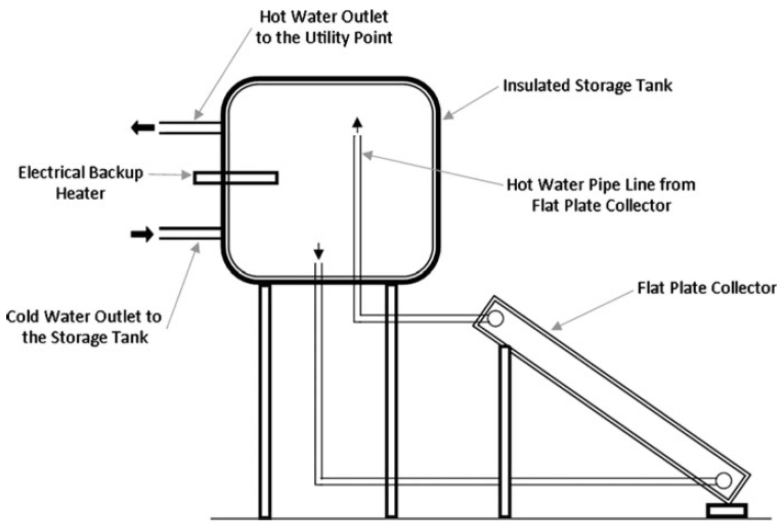

Figure 1. line schematic of an unusual thermosyphon solar water heater.

In term of Passive solar water heating systems rely on heat-driven convection to circulate water or heating fluid throughout the system. These systems are generally classified into two main categories: integrated collector storage (ICS) systems and thermosyphon SWH systems. Integrated collector storage solar water heaters (ICSSWH) utilize a tank that serves both as a storage unit and a solar collector. This design, commonly known as a batch SWH system, is one of the simplest forms of ICSSWH systems, in which a tank is enclosed with glass covers to function as a collector as well [25]. However, a significant drawback of this design is the pronounced heat loss, particularly during nighttime. To mitigate heat losses, various measures can be employed, such as applying selective absorber surface coatings, using insulating materials, and adding additional glazed glass covers to enhance the system's thermal efficiency.

To further enhance system efficiency, baffles were introduced in the storage tank to guide the direction of the flowing fluid. Recent study [26] implemented a baffle arrangement in their rectangular-shaped SWH system, where the baffles were positioned to divide the vessel into an inner storage volume and an outer collecting volume. Another study [27] incorporated a baffle plate in a triangular ICS system as presented Figure 2, which significantly improved system performance, particularly during non-collection periods. The results indicated that the thickness and material of the baffle had minimal influence on system performance. Building on these developments, study by [28] introduced a simple thermal diode as illustrated in Figure 3 into the ICS system to prevent reverse circulation during night-time hours.

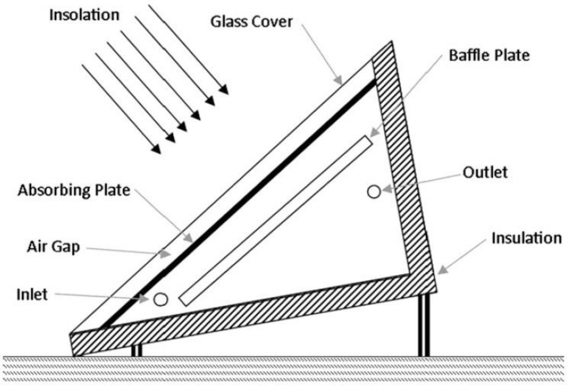

Figure 2. Triangular built-in storage water heater.

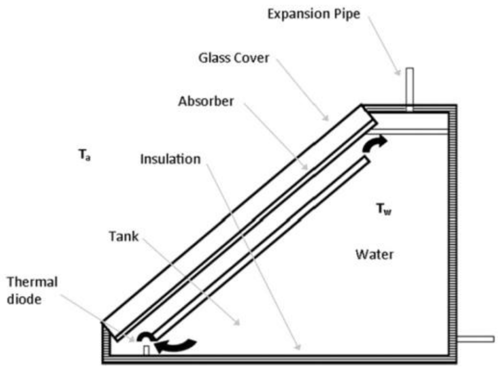

Figure 3. Integrated solar collector/storage tank.

A. Passive Solar Water Heating Systems

Thermosyphon systems became a preferred alternative to batch heaters in the late 19th century, primarily due to the latter's substantial heat loss problems, especially during non-sunlight hours. Unlike batch systems, which store and heat water in the same vessel, thermosyphon systems separate the heating and storage functions, reducing heat loss and improving overall efficiency. These systems operate without the need for mechanical pumps, making them particularly valuable in regions with limited access to electricity or where power outages are frequent. Moreover, the design of thermosyphon systems is based on the natural principle of fluid density variation, which creates circulation due to temperature differences between the hot and cold portions of the fluid. In simple terms, as the solar collector heats the fluid (usually water or another heat-transfer fluid), the heated fluid becomes less dense and rises naturally to the storage tank, which is typically positioned above the collector. Simultaneously, cooler, denser fluid from the storage tank sinks to the bottom, where it enters the collector to be heated. This process, known as natural convection, creates a continuous circulation loop, allowing the fluid to transport heat from the collector to the storage tank without the need for external energy inputs [29-31].

Thermosyphon systems are often classified as open-loop or closed-loop. An open-loop system directly heats water in the collector, which then flows to the storage tank for domestic use. These systems are commonly used in regions with mild winters, where freezing is not a concern, and are widely adopted in countries like Cyprus, which enjoy favorable climatic conditions for solar energy. In contrast, closed-loop systems use a heat-transfer fluid, such as an antifreeze solution, which circulates through the collector and transfers heat to the water in the storage tank via a heat exchanger. Closed-loop systems are ideal for colder climates, as they offer protection against freezing and corrosion. In terms of design and application, thermosyphon systems are simple, cost-effective, and highly durable. Their reliance on natural convection eliminates the need for mechanical components like pumps or controllers, reducing both initial costs and maintenance requirements [32-35].

B. *Active Solar Water Heating Systems*

Unlike passive systems, active solar water heating systems use one or more pumps to circulate the working fluid within the system. These active systems are generally categorized into direct circulation and indirect water heating systems. In direct, or open-loop, systems, water from the storage tank is directly circulated through the solar collector, where it is heated by solar energy. In contrast, indirect active systems circulate a heat transfer fluid through the collector, which then transfers heat to the water in the storage tank via a heat exchanger [36]. While direct systems are simpler in operation, they are more susceptible to freezing conditions and generally provide hot water at moderate temperatures (around 50–60°C).

To address freezing issues, certain design modifications have been introduced, one of which is the "drain-back" system. In this mode, a pump integrated with a differential controller circulates water from the storage tank to the solar collectors, and when the system shuts down, the water drains back to prevent freezing [3]. Many research papers have focused on the direct circulation mode of solar water heating systems, with some of the more recent investigations discussed here. In particular, the use of vacuum tube collectors for domestic water heating has been increasing, as they exhibit much higher performance than flat-plate collectors due to their low convection heat losses from the absorber. A heat transfer model to evaluate the performance of all-glass vacuum tube collectors incorporated in a direct circulation system was developed. [37]. This simplified model considers both natural circulation within individual glass tubes and forced flow circulation in the manifold header. The flow equations were derived by analyzing friction losses and buoyancy forces inside the tube. The study found good agreement between predicted and computed outlet temperatures, with deviations within 5%. This model demonstrates the effectiveness of vacuum tube collectors in enhancing system performance while maintaining accuracy in temperature predictions [38].

3. Component Designs

Over the years, significant improvements have been made to the key components of solar water heating (SWH) systems, including the collector, heat exchanger, and storage tank. These advancements have been instrumental in enhancing system efficiency and reliability. Additionally, various working fluids have been explored by researchers to optimize performance and ensure the system's functionality under a wide range of operating conditions. The following subsections provide a detailed review of the design modifications and advancements in these components, as reported in various studies.

A. Solar Collectors

Solar collectors are crucial components in solar water heating (SWH) systems, functioning as heat exchangers that transform solar energy into thermal energy, which is then transferred to the fluid circulating through the system [39]. The heat removal factor indicates how effectively the collector removes the absorbed heat and transfers it to the working fluid as following Eq. (1).

$$F_R = \frac{\dot{m}\, C_p(\mathrm{T}_{out-}\mathrm{T}_{ain})}{A_c[I_t \tau\alpha - \mathrm{U}_L\,(\mathrm{T}_{in-}\mathrm{T}_a)]} \quad (1)$$

Where:
$\dot{m}$ = Mass flow rate of the working fluid (kg/s)
C_p= Specific heat of the working fluid (J/kg·K)
T_{out} = Outlet fluid temperature (°C or K)

Since the efficiency of a SWH system is highly dependent on the performance of the solar collector, particularly the flat-plate collector, much of the research has focused on enhancing the efficiency of this component [40]. Key areas of improvement include the design of the absorber plate and the selection of glazing materials, both of which play crucial roles in determining the thermal performance of the collector.

- Absorber Plate Design: The absorber plate is the most critical part of the solar collector, as it is responsible for capturing solar radiation and converting it into heat. Traditionally, absorber plates are made from materials with high thermal conductivity, such as copper or aluminum, to ensure efficient heat transfer. Recent research has focused on optimizing the geometry and surface properties of the absorber plate to improve its absorption efficiency. **Selective coatings** on absorber plates have gained popularity, as they can enhance the ability of the plate to absorb solar energy while minimizing thermal radiation losses. For example, black chrome or black nickel coatings have been shown to significantly improve heat absorption without increasing heat loss to the surrounding environment.
- Glazing Material: Glazing is used to cover the absorber plate, creating a transparent barrier that allows solar radiation to pass through while minimizing heat loss from the collector. The choice of glazing material can have a substantial impact on the system's performance. Glass is the most commonly used glazing material due to its high transparency and durability. Recent innovations have focused on using low-iron glass, which has minimal impurities and allows more sunlight to pass through. Multi-layer glazing, where multiple panes of glass are separated by air or inert

gas, is another technique that has been employed to reduce convection and conductive heat losses from the collector.

- Collector Insulation and Heat Loss Reduction: Reducing heat loss from the collector is another critical factor in improving overall efficiency. Insulating the sides and back of the collector helps prevent heat dissipation to the surrounding environment. Modern designs use materials such as polyurethane foam or mineral wool for insulation due to their low thermal conductivity. Additionally, efforts to reduce convection heat losses within the collector have led to the development of sealed or vacuum collectors, where the air inside the collector is replaced with inert gases or a vacuum is created to minimize heat transfer through air molecules.
- Vacuum Tube Collectors: While flat-plate collectors have been the dominant technology, vacuum tube collectors have emerged as a more efficient alternative, especially in regions with lower sunlight or colder climates. These collectors use glass tubes with a vacuum between the absorber and the outer environment, which drastically reduces heat loss through conduction and convection. Vacuum tube collectors are more efficient than flat-plate collectors, especially at higher operating temperatures, making them particularly suitable for applications such as space heating or industrial processes that require higher temperatures. However, they are generally more expensive and require more complex maintenance.
- Flow Optimization: The flow of fluid through the collector also plays a critical role in determining the efficiency of heat transfer. Serpentine or parallel-flow designs in flat-plate collectors have been optimized to ensure even heating and minimize pressure drops, which can affect pump performance and overall system efficiency. Researchers have explored different flow arrangements and configurations to enhance the collector’s performance under varying operating conditions, ensuring that the working fluid maintains maximum contact with the absorber surface for optimal heat absorption.

In summary, solar collectors have seen significant advancements since their inception, with modern designs focusing on improving absorber plate efficiency, reducing heat loss through better glazing and insulation, and optimizing fluid flow for maximum energy capture. The continued innovation in materials, coatings, and design configurations has made solar collectors more effective, reliable, and adaptable to different environmental conditions, ensuring their continued use as a critical component in solar water heating systems.

i. Flat-Plate Collectors

The flat-plate collector (FPC) is the core component of a solar water heating (SWH) system and is widely used for capturing solar thermal energy, especially in regions with low ambient temperatures. Its design consists of several key elements that work together to efficiently convert solar radiation into heat [41,42]:

- Selective Coated Flat-Plate Absorber: The absorber plate is coated with a selective material that maximizes the absorption of solar energy while minimizing heat loss due to radiation. This allows the plate to effectively capture solar radiation and convert it into thermal energy.
- Transparent Cover: A transparent cover, usually made of glass, is placed above the absorber plate to reduce heat loss from the top. This cover allows sunlight to enter the collector while preventing convection and radiative heat loss from the absorber plate to the surroundings.
- Heat Transport Fluid (HTF): The heat transport fluid, which could be water or another working fluid, flows through tubes or passages attached to or integrated with the absorber plate. It absorbs the heat from the plate and transports it to the storage tank or heat exchanger.
- Tubes/Passages for HTF Flow: These tubes or channels are designed to ensure efficient heat transfer from the absorber plate to the HTF. The configuration of these passages is critical for optimizing the fluid flow and ensuring even heat distribution across the plate.
- Heat Insulating Support: Insulation is placed behind the absorber plate to minimize heat loss from the collector to the environment. Materials such as polyurethane foam or fiberglass are commonly used to provide thermal resistance, reducing conductive heat losses.

- Protective Casing: A casing encloses all components of the collector, ensuring protection from environmental factors like dust, moisture, and physical damage. The casing also helps maintain the structural integrity of the collector and enhances its durability.

Flat-plate collectors are efficient in harnessing solar energy for domestic and industrial heating purposes and are commonly employed due to their relatively simple design, cost-effectiveness, and ability to perform well in a variety of climatic conditions [43]. The useful energy gain from a flat-plate collector is the amount of solar energy that is absorbed and converted into heat, minus the losses due to heat dissipation to the surroundings as following Eq. (2).

$$Q_u = A_c F_R [I_t \tau\alpha - \cup_L (T_{in-} T_a)] \quad (2)$$

Where:
Q_u = Useful energy gain (W)
A_c = Collector area (m²)
F_R= Heat removal factor (dimensionless).
I_t= Total incident solar radiation on the collector (W/m²)
τ = Transmissivity of the cover material (dimensionless)
α= Absorptivity of the absorber plate (dimensionless)
$\cup_L$= Overall heat loss coefficient (W/m²·K)
T_{in-}= Inlet fluid temperature (°C or K)
T_a= Ambient temperature (°C or K)

ii. Evacuated Tube Collectors (ETC)

Evacuated tube collectors (ETC) have been commercially available for more than two decades. These collectors offer superior performance in producing higher temperatures compared to flat-plate collectors, particularly in colder climates or regions with lower solar radiation [44,45]. However, their adoption has been limited due to the higher initial costs associated with the technology. ETCs are composed of several key components:

- Evacuated Tubes: The core element of ETCs is the evacuated glass tubes, which typically employ a glass-glass seal. These tubes create a vacuum that effectively minimizes heat losses due to convection and conduction. The vacuum acts as an insulating layer, significantly reducing thermal losses, even in low ambient temperatures.
- Copper Heat Pipes: Copper heat pipes are used within the evacuated tubes for rapid heat transfer. These heat pipes contain a working fluid that evaporates upon heating and efficiently transfers thermal energy to the heat exchanger or fluid flowing through the collector system.
- Aluminum Casing: The ETC system is enclosed in an aluminum casing, which ensures durability and structural integrity. The casing protects the tubes from environmental damage and maintains the alignment and stability of the overall system.

The primary advantage of ETCs is their ability to reduce heat losses due to convection and radiation, making them highly efficient in capturing and retaining heat in a wide range of conditions. However, despite their higher thermal performance, the high upfront costs of installation make ETCs less competitive compared to flat-plate collectors for some applications. Nonetheless, they are an attractive option for high-temperature applications and regions requiring more advanced heat capture capabilities.

iii. Compound Parabolic Concentrators (CPC)

Flat-plate collectors and evacuated tube collectors are commonly used in solar thermal applications to provide low to intermediate temperatures, typically in the range of 20°C to 120°C. However, to achieve higher temperatures beyond this range, concentrators or reflectors must be employed to intensify the solar radiation incident on the absorber. One of the most effective devices for this purpose is the compound parabolic concentrator (CPC), which is a type of non-imaging solar concentrator capable of reflecting a large proportion of incident radiation onto the absorber, significantly enhancing the system's ability to achieve higher temperatures [46,47].

CPCs are designed to collect and focus both direct and diffuse solar radiation. Their non-imaging nature allows them to reflect and concentrate radiation from a wide range of angles, which makes them more versatile than traditional imaging concentrators that require precise solar tracking. The most common design of a CPC is Winston's CPC, illustrated in Figure 7. In this design, the lower sections of the reflector (BA and BC) are circular, while the upper sections (AE and CD) are parabolic. This combination of circular and parabolic sections helps focus and concentrate the incoming solar radiation more effectively onto the absorber surface.

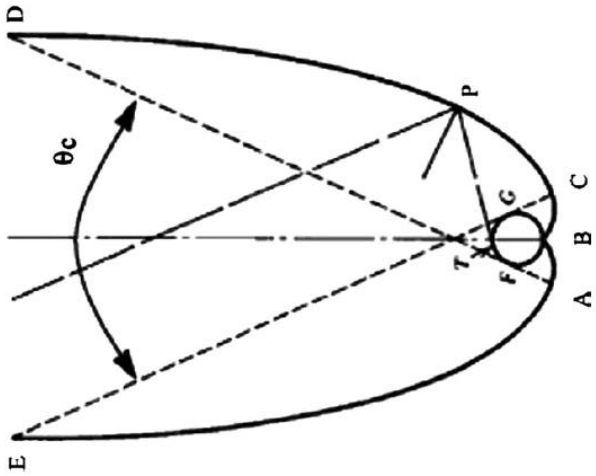

Figure 7. Schematic illustration of a CPC collector [47].

CPCs are particularly useful in applications where higher operating temperatures are required, such as in industrial processes or advanced solar power generation systems. By concentrating solar radiation, CPCs can achieve higher energy efficiencies and temperatures, making them a critical component in high-performance solar thermal systems.

B. Storage Tank

The storage tank is a crucial component of a solar water heating (SWH) system, playing a significant role in determining the system's overall performance. Its primary function is to store the collected solar thermal energy, ensuring the availability of hot water at the desired temperature for end-users. The efficiency of the SWH system is heavily influenced by the design, construction, and insulation of the storage tank, as it must minimize heat loss while maintaining the desired temperature for extended periods. Moreover, storage tanks are typically constructed from materials such as steel, concrete, plastic, fiberglass, or a combination thereof, depending on the specific application and environmental conditions. Steel tanks, often lined with corrosion-resistant materials, are widely used due to their durability and ability to withstand high pressure and temperatures. In contrast, fiberglass and plastic tanks offer the advantage of being lightweight, corrosion-resistant, and easier to handle, although they may not be suitable for higher temperature applications [48].

In addition to construction materials, the insulation of the storage tank is critical to reduce heat loss and maintain thermal efficiency. Materials such as polyurethane foam or fiberglass insulation are commonly used to minimize conductive and convective heat transfer from the tank to the surrounding environment. In this direction, the design of the storage tank also impacts system performance, as factors such as thermal stratification—the layering of water by temperature—can influence the efficiency of heat exchange. Proper tank design ensures that hot water is drawn from the top, where the water is at its highest temperature, while cooler water is replaced at the bottom for reheating. This stratification helps maintain optimal water temperatures and enhances the overall efficiency of the SWH system [49].

C. Heat Exchanger

In indirect solar water heating (SWH) systems, a heat exchanger (HX) is employed to transfer the solar heat absorbed by the working fluid to the storage tank. Heat exchangers are typically made from highly conductive materials such as aluminum, stainless steel, cast iron, copper, steel, and bronze. Among these, copper is the most commonly used material in SWH systems due to its excellent thermal conductivity and resistance to corrosion. Various configurations of heat exchangers have been developed to optimize the heat transfer process in indirect water heating storage tanks. The most common configurations include the immersed coil-in-tank, shell-and-tube, and mantle heat exchanger designs [50].

In the coil-in-tank heat exchanger configuration, several loops of tubing, made of either single or double walls, are immersed in the storage tank. This design allows for efficient heat transfer from the working fluid in the coil to the water in the tank. Study [51] conducted a detailed study on several coil-in-tank HX configurations, analyzing the behavior of a novel stratified tank (Tank A) and two standard tanks (Tanks B and C). The novel stratified storage tank (Tank A) was designed to test the effect of an improved inner storage design and was compared with the more traditional designs of Tanks B and C. In Tank B, the HX coil was arranged upward from the bottom to the top of the tank, whereas in Tank C, the coil was arranged similarly but included a U-turn to extend downward back toward the bottom of the tank. Figure 10, presents sketch structure of Tanks A, B, and C.

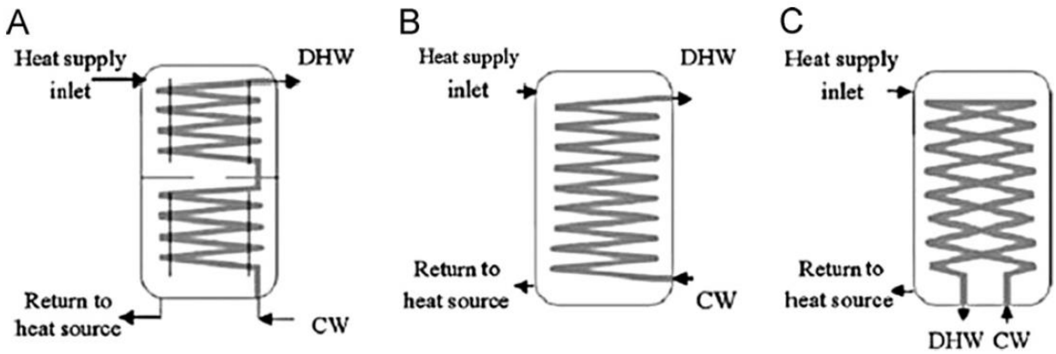

Figure 10. Sketch structure of Tanks A, B, and C.

The study concluded that the stratified tank (Tank A) was up to 32% more effective in heat transfer compared to the commercially available designs. The results confirmed that to maximize heat extraction, the immersed HX should be coiled upwards and positioned in the upper part of the tank. This design not only enhances the efficiency of heat transfer but also improves the thermal stratification within the storage tank, which contributes to the overall performance of the SWH system.

D. Heat Transfer Fluid

The heat transfer fluid (HTF) plays a crucial role in solar collector systems, particularly in solar water heating (SWH) systems. In these systems, the HTF absorbs solar energy in the collector and transfers this energy through the heat exchanger to the water stored in the tank. The properties of the HTF—such as its boiling point, freezing point, flash point, viscosity, and thermal capacity—are critical factors in selecting the appropriate working fluid for a SWH system [52,53]. For instance, in cold climates, a HTF with a low freezing point is essential to prevent the fluid from freezing, whereas in hot climates, a HTF with a high boiling point is necessary to withstand elevated temperatures.

Common heat transfer fluids used in SWH systems include:

- Air – Mainly used in air-based solar collectors where a fluid with low thermal capacity is sufficient.
- Water – Widely used for its high heat capacity and cost-effectiveness, though it requires protection against freezing in colder regions.
- Hydrocarbon oils – Used for higher temperature applications due to their higher boiling points.

- Glycol/water mixtures – Frequently used in colder climates as they offer excellent freeze protection while maintaining good heat transfer properties.
- Refrigerants/Phase-change liquids – Employed in systems where phase change is utilized for improved thermal efficiency and heat transfer.

The choice of HTF is dictated by the specific environmental conditions and performance requirements of the SWH system, with particular attention given to maintaining fluid integrity and efficiency over varying operational conditions.

4. Conclusion

Research in renewable energy has gained significant momentum since the signing of the Kyoto Protocol. Among the various renewable technologies, solar water heating (SWH) stands out as one of the most efficient methods for converting solar energy into thermal energy. As a developed and widely commercialized technology, SWH systems have demonstrated considerable potential; however, there remain opportunities for further enhancements in system performance, reliability, and efficiency. This paper presents a concise review of the key design features and technological advancements related to improving the energy efficiency and cost-effectiveness of SWH systems.

Various SWH designs have been introduced to the market, with increased adoption in tropical regions of developing countries where solar energy is abundant. Recent innovations, such as heat pump-based solar collector technology, offer promising designs that allow for the effective use of solar energy even in regions with less favorable solar conditions. The performance of heat pump-based SWH systems is influenced by several factors, including the choice of refrigerant. Due to rising environmental concerns, refrigerants with high global warming potential (GWP) have come under scrutiny, leading to their gradual phase-out. In addition to the selection of appropriate working fluids, research has increasingly focused on improving the performance of various components within the SWH system. These advancements aim to enhance system efficiency, reliability, and environmental sustainability, potentially increasing the market penetration of SWH technology and delivering both environmental and financial benefits.

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