Investigation of Performance Parameters Affecting the Efficiency of Solar Water Heater: A Review

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ABSTRACT

The need for installation of Solar Water heater is increasing in society because of several factors such as rapid urbanization, government interventions, low cost of installations, and environment-friendly application acting as a direct replacement to fossil fuels. During the past few years, the research and development associated with the technological enhancement of the utilization of solar energy have increased exponentially. However, there are various challenges involved in the selection of proper solar technology to provide a high-performance energy harvesting application for domestic water heating requirements. There is a wide literature available on various performance parameters required to develop an efficient Solar Water Heating System. This paper investigates a state-of-the-art review of the performance parameters affecting the efficiency of Solar Water Heaters by component-wise analysis of parameters divided broadly into the design, operational and external parameters. The technological advancements in solar water heaters are classified based on performance parameters and the paper summarizes the possibility of combining different performance parameters to achieve more efficient and cost-effective solar water heaters for the society as future scope of the review for researchers working in the similar domain.

Keywords: Solar Water Heating System, Performance parameters, Solar Efficiency, Flat Plate Collector, Evacuated Tube Collector, Phase Change Materials, Nanoparticles

1. Introduction

Global climate change has resulted to hunt for non-conventional energy sources in place of conventional fossil fuel-based energy sources. As per the Indian context and with the government favoring the use of renewable energy, the utilization of solar energy has increased by leaps and bounds. Solar technologies can be grouped into two broad domains, Solar Photovoltaic (SPV) which generates electricity, Solar Thermal (ST) which produces heat directly from the energy of the Sun and new technology which involves both generations of electricity and process heat which is Solar Photovoltaic and Thermal (SPV/T). All these choices have their advantages and disadvantages touted in the literature. To achieve higher solar contribution by selecting the best solar technology, one has to study the dominant factor responsible for altering the efficiency of the system [1]. Even though Solar energy is available in abundance, the technology required to harness the power of the Sun is costly.

The residential sector has an 80% share of Solar Water Heating (SWH) systems, the commercial sector which includes hotels, hospitals, others have 6%, 3%, 5% respectively and the industrial sector contains a 6% share of SWH systems. The percentage of share data shows that the residential sector is
one of the largest sectors among commercial and industrial sectors for India. The residential sector is also the largest sector for the whole of the world, with China dominating at 10% of the total global share of SWH systems [2]. About 31.3 gigawatts-thermal (GWh) of glazed (including flat plate and vacuum tube technology) and unglazed solar collectors are being added globally in 2019 and by year’s end about 479 GWh in operation [3]. With the announcement of National Solar Mission by the Government of India, there is increase in the number of SWHS deployment across India. The phase wise target is set to achieve 20 million sq. m area of solar water heater installations by the financial year 2021-22 [4].

This data illustrates that the global trend is towards installing a greater number of SWH systems for residential heating, however, the efficiency of the system proves a major setback among manufacturers. In recent times, there have been increased technological advancements by researchers to improve the efficiency of the system.

This review paper discusses different performance parameters affecting the efficiency of the SWH system. Section 2 presents an overview of components associated with a domestic SWH system. There are two types of SWH systems typically installed in residential applications, namely Flat Plate Collector Solar Water Heater (FPCSWH) and Evacuated Tube Collector Solar Water Heater (ETCSWH). Section 3 provides the recent advancements made to increase the efficiency of the SWH system by bifurcating the system into components being segregated into different parameters. Section 4 is dedicated to the discussion and future scope of this review, which will be helpful for the researchers actively involved in improving the efficiency of the SWH system.

2. Types of Solar Water Heating System for Residential Application

2.1 Flat Plate Collector Solar Water Heating System

Flat Plate Collector comprises an insulated metallic box covered on the top with a glass sheet. Inside there are blackened metallic absorber (selectively coated) sheets with built-in channels or riser tubes to carry water. The absorber absorbs the solar radiation and transfers the heat to the flowing water. A typical layout of a flat plate collector solar water heating system is shown in Fig. 1.
2.2 Evacuated Tube Collector Solar Water Heating System
Evacuated Tube Collector (ETC) as the name suggests comprises concentric glass tubes separated by a spacer at the end of the inner tube which has U shape at the end as shown in Fig. 2. The mouth of both tubes is closed and the space inside the two tubes is evacuated to minimize the effect of radiation heat loss. ETC is highly efficient with excellent absorption over 93% and minimum emittance less than 6% as the tubes are round and sun rays strike the tubes at right angles thus minimizing reflection. In some cases, the evacuated tubes are provided with parabolic reflectors at the bottom to enhance the utilization of solar energy. The entire system is controlled and monitored by an automatic control panel. There is no scaling in the glass tubes thus suitable for areas with hard water, which is one drawback of the FPCS WH system.

With the government promoting the use of Solar thermal technologies, countries like China have increased the production capacity to supply this global surge in demand of the ETC's.

![Fig. 2. A Typical Layout of evacuated tube solar water heater [6]](image)

3. Performance Parameters Affecting the Efficiency of Solar Water Heating System
The performance of the solar water heating system can be classified into three broad parameters, first design parameters which comprise the basic components required to serve the purpose of heating and the enhancements in the efficiency caused by alterations in the geometry, design, and external features. The second parameter which affects the performance of the SWH system is operational parameters comprising a working fluid, type of flow inside the system, use of internal modifications in the system which include heat pipe and inserts. The third parameter is the external parameter is related to the climatic conditions, inclination, solar irradiation, and wind speed which also affects the performance of the SWH System.

3.1 Design Parameters

3.1.1 Tank
As far as the solar energy system is concerned, from the lower temperature section of the water storage tank, solar radiation heats the cold water circulating through the collectors, where it becomes the hot water and returns to the storage tank. If the hot water is allowed to mix with the cold water in the tank, the supplied temperature to the load is lowered and it degrades the useful quality of energy. Also, because of mixing, the whole water temperature in the tank tends to the even, the amount of energy collected may be decreased if the collector inlet fluid temperature is higher than the unmixed
storage temperature. Therefore, to get the maximum efficiency of stored energy, thermal stratification technology is introduced [7]. The efficiency of the SWH system is directly proportional to the volume of the storage tank and has a negligible effect on the configuration either horizontal or vertical [8].

A study conducted by Muhammad Nadheeb concluded that the SWH system that involves Phase Change Material PCM as thermal energy storage has formed thermal stratification inside the tank. This condition is represented by the Richardson number parameter, where the average value of Richardson numbers during the experiment was greater than 0.615 [9]. A design space approach is applied by Indrajeet Jadhav, to optimize the solar water-heating system which mainly focuses on two major decision variables, the solar collector area, and the storage tank volume, to reduce capital investment. A thermocline tank offers benefits like the uniformity of the output temperature and reduction in thermal losses from the solar collector, through the establishment of thermal stratification. It is observed from the study that the solar collector area requirement and the overall capital investment can be reduced by 57% and 28%, by optimally integrating a thermocline tank [10]. Dileep Karuthedath reported by carrying out a 3D transient CFD analysis using Ansys software, that with an increase of fluid-flow during discharge, the stratified layers disorient and lead to rapid mixing, which eventually results in an earlier drop in the outlet water temperature [11].

3.1.2 Manifold

The manifold is that part of the SWH system that is placed in the storage tank and it is a link between the evacuated tubes and tank to maintain stratification in the storage tank. The principal function of a manifold is to channelize the flow and reduce the additional pumping power required to circulate the working fluid. There are two types of design models followed by researchers while designing a manifold namely, bifurcation type and conservative type manifolds. A comprehensive review of basic geometries on manifold designs is discussed by O. K. Siddiqui et al. and recommend the bifurcation type model for achieving better performance. They have also provided future work directions related to analyzing temperature-dependent parameters like viscosity, density, etc. and to develop complex geometries on manifold designs. [12] While designing manifold, the Reynolds number of the inlet flow, Richardson Number, Biot Number (to calculate heat loss from the tank), Darcy Number (permeability of the porous manifold), location of the baffle, and the thickness of the porous tube is to be considered [13]. G. L. Harding and Yin Zhiqiang in their study showed that with no extra pumping power proper manifold design is capable to transfer the heat from the absorber pipes to the main header pipe from the manifold [14].

3.1.3 Collector

A collector is that component of the SWH system which receives solar radiation in the form of heat. The function of a collector is to collect maximum heat from solar radiation and pass it on to the working fluid with minimum loss. An experimental study concluded by assessing the performance of double glazed solar flat plate water heated with different geometries of absorber plates like flat plate, v-grooved and square pulse, that the thermal efficiency of double glazed flat absorber plate is higher [15]. Reinforced cement concrete (RCC) based collector slabs with embedded aluminum pipes can provide hot water between 38°C to 58°C during winter season [16].

A flat plate collector with a modified pattern of tubes carrying the working fluid is compared in two different modes namely serpentine and zig-zag arrangements in an experimental study conducted by Maram et al. and concluded that the zig-zag arrangement of the tubes gives efficiency more than compared to conventional and serpentine flow [17]. There are two parameters by which the
performance of a collector can be tested, first the collector efficiency factor and second the overall heat transfer coefficients [18]. A spherical solar collector reported by Mahmoud Ahmed Elhefnawy, et al. claims to have the collector efficiency factor of about 0.924 and overall heat transfer coefficient as 7.8 W/m²°C [19]. A Concentrated Solar Power (CSP) setup incorporating a linear Fresnel Lens concentrating the solar radiation to an absorber can provide a temp of about 255°C [20]. The performance of an absorber is affected by dust accumulation and wind velocity, which is inversely proportional to the absorber efficiency factor [21].

3.1.4 Integrated Design

As per the review conducted by Ramkishore el. al., Integrated collector storage solar water heater (ICSSWH) systems are compact type, cost-effective, aesthetically attractive, and environmentally friendly. It has all the components like collector, absorber, and storage integrated with one compact assembly as shown in Fig. 3. There are several designs of ICSSWH with the inclusion of PCM, reflective coating on absorbers, double cylindrical tank designs but these modifications in the design proves to be costly. The review suggests with a double cylindrical storage tank using thermal diode might improve the overall thermal performance significantly [22]. Based on the insulation coverage strategy, proposed by [23], parabolic trough collector with insulated tanks performs better in term of retention of useful heat as compared to ICSSWH.

Fig. 3. Exploded view of Heater Assembly of a typical ICSSWH [24]

Anis Messaouda proposed a novel Integrated Collector Storage using a vacuum between double-glazing covers and studied the effects of reflectivity, vacuum, and night insulation on the system performance and found out that the daily efficiency reaches 58.62% and the loss coefficient decreases to 1.68W/Km2 [25]. In a recent development at Ulster University by Mervyn Smyth the design of a horizontal cylindrical ICSSWH prototype that has a double vessel, thermal diode features (to enhance heat retention during non-collection periods) achieved efficiency over 55% by incorporating a liquid-vapor phase change material (PCM) with a very low-pressure annular cavity[26]. It is seen from the literature that ICSSWH has a limitation of heat loss during night time in the form of radiation loss, which can be addressed by implementing new technologically advanced design incorporating insulated storage tanks, double cylindrical tanks using diodes and absorber with evacuated space between the glass cover.

As the technological advancements in ICSSWH will continue all across the globe, the cost associated with the manufacturing and insemination in the market will increase in near future. The only disadvantage of this system is the bulkiness, which makes it challenging to use it in domestic applications.
3.2 Operational Parameters

3.2.1 Working Fluid

From recent studies, it is found that the working fluid can influence the performance of a solar collector significantly. Water, oil, and air are the most common working fluids used in the solar energy system, but the thermal conductivity of these fluids is relatively low [5]. Nanofluids comprise base liquid and nanomaterials that have enhanced thermophysical properties such as higher thermal conductivity, thermal diffusivity, and convective heat transfer coefficients [27] [28]. Besides improving the effectiveness of heat transfer, nanofluids also improve optical properties, transmittance, and extinction coefficient of solar collectors. By using nanomaterials, the efficiency of an FPC increase by at least 10 than a conventional FPC [29]. The most studied nanofluids as working fluids are Al2O3, Water-based CuO nanofluid, TiO2, Carbon nanotube nanofluid, Deionized water, and water-based CuO nanofluids, CO2 as working fluid having efficiency range from 35% to 61% [30].

It is seen from the literature that; nanoparticles increase the thermal performance of the SWH system as they impart high thermal conductivity to the working fluid without an increase in friction factor, so the pumping power required is also not considerably increase [31]. However, many authors have reported that the efficiency decreases as the weight fraction and material size increase and there is an optimal mass flow rate at which the efficiency of the system is maximum [32]. Another challenge associated with the nanofluid reported by several research articles is of agglomeration. Agglomeration of the nanoparticle is the assemblage of mass particles to grow from nanoscale dimensions to larger dimensions because of the presence of intermolecular forces present in the material [33]. The problem of agglomeration of nanoparticles is found less in glycol-based nanoparticles like ethylene glycol, propylene glycol and Therminol VP-1 where no agglomerations were reported [34].

3.2.2 Flow dynamics

In a thermally stratified tank, the working fluid coming from the absorber region must follow natural convection. This compromises the efficiency of the system as the heat received by solar radiation should be absorbed and transmitted quickly so that the water gets heated quickly. Nanomaterial with an appropriate base fluid is one such solution as discussed in the above section. Any alternative working fluid will have a combined effect of the SWH system. While some parameters give better advantage to other problems like agglomeration, the thermal conductivity of nanomaterial, etc. will be worth researching. The surface area and wavelength of the system plays an important role in improving the efficiency of the system [35].

There are several softwares like ANSYS CFD, Fluent, Gambit which are used to validate the results conducted. A dynamic simulation is validated with experimental analysis to find the efficiency of the system [36] The location of the inlet and outlet pipe of the system also plays an important part in improving the efficiency of system an arrangement is required for thermal stratification in the storage tank [37].

The experimental investigation of designed and developed system has been carried out for two modes i.e. mid-day charging mode and full-day charging mode. It has been observed that for considered mass flow rates, thermal efficiency of the system was varied in the range of approximately 52–62% for full-day charging mode while for mid-day charging mode, it was varied between 55 and 72%. The maximum value of thermal efficiency was approximately 72.52% at mass flow rate of 24 LPH for mid-day charging mode [38].
3.2.3 Heat Pipe

A heat pipe is a device used to transfer heat from hot source to cold source separated at a short distance. A heat pipe has working fluid contained in the pipe and the space is evacuated and sealed from both ends the heat pipe is divided into three regions namely evaporator section, adiabatic zone and condenser region as shown in Fig. 4.

![Fig. 4. Longitudinal section and cross-sectional view of a typical heat pipe [39]](image)

The working fluid comes in contact with the hot zone in the evaporator region and vaporizes to reach the other end of the tube and transfers this heat to the condenser region as shown in Fig. 5. The thermal conductivity of heat pipe can be increased 100 times depending upon the pipe material, working fluid and distance between condenser and evaporator region [40].

![Fig. 5. Evacuated tube collector with a single heat pipe [41]](image)

Using heat pipe for solar application dates back to the 1980s [42] and since then the advancements in the heat pipe technology have increased tremendously. Table 1 below summarizes the technological advancements in the materials used for heat pipes, working fluid and nanomaterials used in heat pipe for enhancement of performance parameters of SWH systems.

Table 1 Summary of studies focused on heat pipe

| Material of Heat Pipe | Copper [43], Stainless Steel, Aluminum |
|----------------------|---------------------------------------|
| Working fluid        | Chloroform, Hexane, Methanol, Petroleum Ether, Acetone, and Ethanol, Ammonia, Pentane, R22, R134a [44] |
| Nanomaterial as       | Carbon nanotubes with water, Water based CuO, Propanol and (TiO$_2$ + DI De Ionized) |
Due to several advantages of using Heat Pipe Solar Collectors like high overall efficiency, capability to absorb solar radiation higher than conventional and high heat transfer, quick start operation and minimal effect of inclination angle [49]. Also, the cost of manufacturing is coming down as there are more players entering to fabricate technologically advanced design, configuration and specific to operation products.

### 3.2.4 Inserts

In the previous section, the use of heat pipe increases the efficiency of the SWH system, but the cost of the system also increases. As the stratification in the storage tank is essential to get a higher temperature at the outlet, the absorbers are so designed that there must be natural convection in the absorber region of the water heater. However, to increase the heat transfer rate in the absorber section, evacuated tubes are incorporated with inserts. The role of inserts is to inculcate near turbulent flow inside the tubes so that there is an increase in the heat transfer rate. It is proved that Nusselt number, a measure of convective heat transfer increases with the augmentation of inserts a thermosyphon type solar water heater [50].

Research interest among researchers is gaining momentum as the installation of inserts is easy, cost-effective, and can be fabricated in various shapes and sizes. The technological advancements in this field can be seen from the increase in the number of research publications for the past decade. Few of the important include the inserts such as twisted tape [51] [52], nanofluid with twisted tape [53] are metallic strips twisted to give swirl effect to the flow which causes an enhancement in heat transfer rate, square and V-cut twisted tape [54] is another variation in twisted tapes where additional boundary layer separation is induced because of sudden change on the flow profile, helical screw tape inserts [53], wire coil inserts [55] [56] [57] which do not reduce the volume flow rate inside the tube keeping the capacity of the SWH system intact.

### 3.3 External Parameters

#### 3.3.1 Solar Intensity

Nearly 58% of the geographical area in India has global solar radiation of more than 5kWhr/m2/day, and such zones are called “Solar Hotspots” of India [58]. In the places where the solar intensity is higher and the average ambient temperature is higher, are the potential places to install SWH systems. Higher solar intensity yields a greater rate of heat absorption by the collector and by a working fluid. This is because of the decrease in ambient temperature, the heat transfer rate from the outer surface of the glass tube to the working fluid decreases when the ambient temperature is less. This implies that the SWH system works on the principle of the difference of temperature which causes the neat heat to transfer from solar energy to the working fluid. Hence in many research articles, we find that the significance of ambient temperature is very important at high solar intensity regions and the study becomes insignificant at low ambient temperature zones [59].

The solar radiation is also blocked by scaling on the inside and dust accumulation [60] on the outside of the absorber glass cover for FPC and tubes of ETC's. The instantaneous efficiency drops by approximately 63% because of the formation of a 3.7mm scale inside the collector [61]. Scaling is one factor that makes ETC's more popular than FPC's for domestic Solar Water Heating. There are two forms of solar absorbers, focusing and non-focusing. The focusing type of absorbers concentrates the solar energy at a single point (circular Fresnel lens) or along a line (linear Fresnel
lens) to collect the incident and diffuse solar radiation falling onto the absorbers [62]. Fresnel lens is being used in Solar water heating, Concentrated Solar Power (CSP) for cooking, on PV panels, etc. and one such novel approach uses a Thermo Electric Generator (TEG) with the help of Fresnel lens to achieve higher efficiency in water heating [63].

3.3.2 Wind
In India, the way Solar intensity and ambient temperature vary, wind speed also varies over a wide range in a year. The average wind speeds recorded in India for the entire year lie between 7m/s to 10m/s [64]. So, it would be interesting to know how it affects the performance of the SWH system. Even though there is a lot of literature available for the parameters related to design and operations, there is very limited work done in analyzing the effect of wind speed on the performance of the SWH system. The difference between ambient temperature and collector temperature is the driving force for heat transfer to take place, and variation in the wind speed affects the ambient temperature and so is the rate of heat transfer from absorber surface to working fluid [65]. The major concern of wind velocity affecting the solar water heater is during cyclones, the model suggested by Chung et al. is to lift the structure to a suitable height depending upon wind velocity history and to provide a guide plate just behind the storage tank inclined at an angle ‘α’ with the horizontal [66]. They further investigated by experimental results and found the relationship between mean longitudinal and spanwise pressures associated with tilt angle, guide plate, and freestream turbulent intensities [67].

3.3.3 Inclination
The angle made by the absorber with the horizontal is known as the collector tilt angle and is usually denoted by ‘β’ in most of the literature. As discussed in the previous section about the importance of thermal stratification in the storage tank, collector tilt plays an important role in the stratification in the storage tank of a thermosyphon type water-in-glass SWH [68]. Bracamonte et al. suggested that the inclination angle should be equivalent to the latitude of the location so that the solar radiations are almost normal to the absorber mostly in a year.

The absorber tilt can also affect the flow regime inside the evacuated tube to develop a stagnation region if the inclination is over 45° [69]. Stagnation region is developed when there is no effect of heat transfer to cause convection currents in the fluid [70] because of which there will be no improvement in the efficiency. In the afternoon time, the incoming cold water is usually hot which try to rush into the evacuated tube because of the inclination and mixing with the already present hot water and because of this sudden turbulence the thermally stratified region breaks which are reverted in the evening [71].

4. Discussion and Future Scope
The following points are worth discussing from the literature review about the parameters that affect the thermal performance of a SWH system. Emphasis is being made to provide insights about future scope by suggesting to combine two parameters and study its effect of the overall system of domestic water heating.

- To improve the efficiency of the system, the tank should be made capable to achieve a thermal barrier between the incoming cold fluid and outgoing hot fluid known as thermal stratification. Further research related to developing prototypes with adiabatic thermal barrier materials capable of floating inside the tanks can be considered and tested prior to modeling using CFD and TRNSYS.
In places where the frequency of discharging the hot water is less, an auxiliary storage tank with PCM material can be installed which can be monitored with sensor-based technology to sense the external parameters like whether forecast to optimize the collection rate in the tank.

Complex geometries of manifold and novel collector design incorporating triangular, pentagonal collector tubes with integration of solar panels can be experimentally investigated and validated by using simulation.

Increasing the length of the evacuated tube collectors generate stagnation region which makes it inefficient and the addition of inserts results in decreased volume flow rate so further research in inserts should be taken by increasing the diameter of the tube. The variation of tube diameter along with various inserts may be studied for performance improvements.

Very less literature is available for external parameters affecting the performance parameters of SWH system. The wind velocity is inversely proportional to the efficiency so in places where the wind velocity is more than 7m/s the system can be incorporated with auxiliary air heaters and this hot air can be incorporated over the absorbers. This may open a new field of study in the design of microchannels over the absorbers for effective movement of hot air.

The salient feature of this review paper is to provide an insight to the components classified broadly into three basic performance parameters and their effect on the performance of SWH system

5. Conclusion

This paper presents an overview of recent studies on performance parameters affecting the efficiency of the Solar Water Heating System and revealed that there are three different parameters, namely design, operational and external parameters in which the components of the solar water heating systems can be classified. The potential of each component is studied in detail in this review and it is found that the efficiency of the system is influenced by varying the parameters. The paper provides some inputs related to future research in the discussion section. This review will be very useful for industries involved in installations of domestic solar water heaters, and for research organizations.

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