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Thermal Assessment of Evacuated and Flat Plate Collector Solar Water Heater for the Enhancement of Collector Area

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Abstract

Over the past decade, India has witnessed a significant increase in the share of renewable energy sources in its energy mix, rising from 13.2% in 2010 to 24.8% in 2020, driven by governmental policies like the National Solar Mission and the Renewable Purchase Obligation (RPO). This growth has been further fueled by diminishing fossil fuel reserves, rising fuel prices, and global emissions regulations. Consequently, there has been a notable surge in the adoption of solar evacuated tube collector-based domestic water heating systems, with installations in India escalating from 1.8 million square meters in 2015 to 3.2 million square meters in 2020, reflecting increased awareness and the tangible benefits of renewable energy technologies. However, challenges persist, especially in densely populated urban areas with limited installation space due to rapid urbanization. To address this, the study proposes reducing the collector area by varying evacuated tube diameters. Comparative analysis between evacuated tube collectors and flat plate solar water heaters aims to introduce a dual absorber solar water heater capable of harnessing direct and diffused solar radiation, enhancing hot water generation and system efficiency. Findings suggest that 48mm diameter and 1800mm length tubes are optimal for evacuated tube models, while a 4m2 collector area proves excessive for a 150-litre solar water heater. Theoretical validation using MATLAB aligns with experimental results. A dual absorber-based solar water heater is proposed, potentially reducing collector area by approximately 30%. Further research is recommended to refine the capacity and efficiency of this proposed model.

Keywords: Solar Energy, Evacuated Tube Collectors, Flat Plate Collectors, Solar Water Heater

1. Introduction

India’s energy demand is escalating rapidly, driven by a burgeoning population of 1.36 billion and a fast-growing economy marked by urbanisation and industrial development. This surge in demand carries significant implications for the global energy market. The Government of India has made substantial strides in ensuring widespread access to electricity and clean cooking solutions while implementing comprehensive energy market reforms and integrating a substantial share of renewable energy into the national grid. Despite ongoing efforts to diversify energy sources, coal continues to dominate India’s energy supply landscape. However, India is committed to enhancing its energy security and sustainability through major investments in clean energy. Creating a unified national power system has been a pivotal step in improving electricity security. From 2016 to 2018, the share of solar photovoltaic (PV) and wind energy in the electricity generation mix doubled from 4% to 8%, reflecting the country’s significant progress in renewable energy integration. In addition to expanding renewable energy capacity, India has achieved notable advancements in energy efficiency. Between 2000 and 2018, energy efficiency improvements resulted in the avoidance of an additional 15% of energy demand and the reduction of 300 million tonnes of CO2 emissions. These efforts underscore India’s commitment to mitigating climate change and enhancing sustainable energy use. The government’s initiatives to improve access to electricity and clean cooking have yielded remarkable outcomes. Since 2000, 700 million people have gained access to electricity, and 80 million new liquefied petroleum gas (LPG) connections have been established to promote clean cooking. These initiatives have significantly improved the quality of life for millions of Indians and reduced the reliance on traditional biomass cooking methods, which pose health and environmental hazards [1]. Its ambitious renewable energy targets show India's focus on secure, affordable, and sustainable energy. The government aims to continue integrating variable renewable energy sources, such as solar and wind, into the national energy mix. This strategic approach supports global efforts to combat climate change and addresses local air pollution issues. India is developing a robust institutional framework to attract investments to meet the growing energy demand. This involves regulatory reforms, improving business efficiency, and creating a favourable investment climate. These measures are essential for mobilising the financial resources required to sustain the country's energy transition and infrastructure development. The implications of India's energy policies and demand trends extend beyond its borders, influencing the global energy market. India's increasing need for energy imports, particularly oil and natural gas, affects global energy prices and trade flows. Additionally, the country's expanding renewable energy sector drives demand for renewable energy technologies and equipment, impacting global markets for these products.

2. Global Scenario of Solar Water Heaters

Germany continues to lead the European Union in solar thermal capacity, holding the highest capacity despite a 12% market decline from the previous year, marking the lowest level since 2007. The country added 0.6 GW in 2013, bringing its total capacity to 12.9 GW. Meanwhile, the United States expanded its solar thermal capacity by 0.7 GW in the same year, reaching 16.7 GW, positioning it fifth globally in solar thermal capacity. Notably, 58% of the solar collectors in the U.S. are unglazed collectors. In Australia, 0.6 GW of solar thermal systems were added, with 78% being unglazed, resulting in a total capacity of 6 GW, of which 60% are unglazed.

Solar thermal technologies are also gaining traction in several African countries, including Egypt, Kenya, Morocco, Mozambique, Namibia, Tunisia, Zimbabwe, and South Africa, primarily for water heating. In Israel, approximately 85% of the population utilizes solar water heating systems (SWHS) for domestic use, a trend similarly observed in the Palestinian territories and Jordan. Cyprus has a remarkably high adoption rate, with about 93% of its population using domestic SWHS, and these systems are installed in 52% of the hotels.

Globally, the use of solar water collectors varies significantly across continents. Figure 8 illustrates the distribution percentages of solar thermal collectors installed in various continents, the applications of solar thermal collectors in different regions and their major contributing countries. This data underscores the diverse adoption rates and applications of solar thermal technologies worldwide, reflecting regional differences in technology uptake and implementation strategies. In summary, while Germany and the United States significantly contribute to global solar thermal capacity, other regions, such as Australia, Africa, and the Middle East, also demonstrate notable advancements in solar thermal adoption. The global landscape of solar thermal technology continues to evolve, driven by efforts to enhance energy efficiency and sustainability through renewable energy solutions [2].

As the demand for solar energy grows to meet future energy needs across various sectors, its potential to replace fossil fuels is becoming increasingly evident. This shift not only reduces the carbon footprint but also mitigates global warming. Evacuated tube solar collectors (ETSC) are pivotal in harnessing solar thermal energy for applications such as air heating, water heating, and drying in domestic and industrial contexts. This review paper provides a comprehensive overview of ETSC technology, examining factors influencing performance, including fin arrangement, integrating phase change materials, tilt angle, solar radiation, and airflow rate. The review delves into key thermal performance parameters of ETSC-based solar air heaters and dryers, such as collector efficiency, dryer efficiency, energy and exergy efficiency, thermal profile, zone temperature, relative humidity, and heat loss during operations. It thoroughly assesses the effectiveness of ETSC-based air heating systems and solar dryers, particularly for drying agricultural products. Additionally, the paper discusses ongoing research aimed at enhancing thermal performance through the integration of nanofluids and phase change materials. Furthermore, the review includes a CO2 mitigation analysis and compiles global standards for ETSC-based air heaters and dryers. It highlights the significant potential of solar air heaters (SAH) in food commodity drying when paired with appropriate drying chambers and improvements in the design of ETSC-based solar dryers. The study analyzes the work of various researchers to identify prospective research gaps and areas for future design and development. ETSC technology holds substantial promise for advancing solar thermal applications across multiple sectors. ETSC-based systems can significantly contribute to sustainable energy solutions and global carbon reduction efforts by addressing current research gaps and enhancing design efficiencies [3].

3. Experimental Setup

Although heat transfer and flow structures in single-ended tubes have been extensively studied, there is a lack of publications addressing natural convection in evacuated tubes with variable diameters. Techniques for performance enhancement, such as geometrical modifications of the absorber plate, solar selective coatings, and nano-fluids, have received significant attention for improving solar water heating systems. However, models need to evaluate the long-term performance of these systems with different collector configurations under various operating conditions. Changes in geometric configurations, such as the length and diameter of single-ended tubes, lead to stratification at the bottom of the tube—a phenomenon not yet thoroughly investigated. This gap in research opens the field to explore variable reflective coatings to enhance natural convection inside evacuated tubes, which can be modelled and analysed using computational fluid dynamics (CFD) or similar software. The practice of water heating, which can be traced back to the mid-18th century when Benjamin Waddy invented the first residential heating system, has undergone significant transformations. From the advent of electric heating to the popularity of gas geysers, the journey has brought us to the era of non-conventional solar water heating. The well-known benefits of lukewarm water for bathing, such as improved blood circulation and muscle relaxation, have further fueled the demand for efficient water heating systems. However, the mandatory installation of solar water heating systems in every household presents challenges in terms of costs and space constraints. With the Real Estate Regulatory Authority (RERA) and government support for renewable energy, the feasibility and implementation of such systems are now under scrutiny [4].

A. Components of Experimental Setup

1) Evacuated Tube solar water heater: An active solar water heater operates based on the thermosyphon effect, which arises from natural convection caused by differences in density and buoyancy. The optimal shape for maximizing the thermosyphon impact is an open tube-like structure that heats up and uses natural convection to move the hot fluid to a receiver or storage tank at the top. An evacuated tube, typically made of borosilicate glass similar to a Dewar flask, consists of concentric tubes with a vacuum in between and a sealed top end. This robust material enables the tubes to endure chemical and mechanical stresses.

Exposed directly to solar radiation, the evacuated tubes heat the working fluid (usually water) to around 90°C. The outer transparent glass tube maximises thermal radiation absorption while minimising reflectivity. The inner tube's outer surface is selectively coated with absorbing materials like aluminium ni- tride or copper nitrite, which help trap heat and reflect minimal radiation. The vacuum between the concentric tubes minimises heat loss through conduction and convection, allowing the tubes to absorb infrared radiation. This feature enables solar water heaters with evacuated tube collectors to provide hot water even in cloudy conditions. Vacuum insulation effectively reduces the impact of external factors such as wind, cloud cover, and albedo on the performance of domestic solar water heaters.

The storage tank is connected to the evacuated tubes at the top and inserted at an optimal distance to initiate the thermosyphon effect. During the vacuum creation process, a barium getter is placed at the base of the outer tube to absorb dissolved gases like CO, CO2, H2O, O2, and H2, which are released during the operation of the solar water heater and the storage of hot fluid. If the vacuum between the inner and outer tubes is compromised, the bottom of the tube turns hazy white. The ideal inclination angle for the evacuated tube is between 30° and 45° with the horizontal, ensuring optimal conditions for the thermosyphon effect.

B. Experimental Procedure

The thermosyphon effect is the primary working principle of an evacuated tube solar water heater (ETCSWH). Inci- dent solar radiation is absorbed by the collector's evacuated tubes and then transferred to the working fluid (water) via conduction and convection. Positioned at a 30-degree incline and operating as a non-pressurized system, the ETCSWH creates a temperature gradient due to solar radiation, which enables the working fluid to circulate from the tube to the storage tank, accumulating hot water. This natural circulation process is known as the thermosyphon effect. However, several challenges arise during installation, including wind velocity, the purity of the working fluid, tube scaling, and the tracking mechanism of solar panels. Experiments were conducted from 10:00 AM to 5:00 PM on bright sunny days in October 2023, January 2024, and March 2024.

During the system's charging phase (static mode), with no inflow or outflow from the tank, data were collected from 10:00 AM to 3:00 PM at intervals of 15-20 minutes. There is also a provision for discharging (dynamic mode) the hot water at the end of the day. The collected data were then analyzed numerically and validated experimentally. This study focuses on comparing the thermal performance of the ETCSWH.

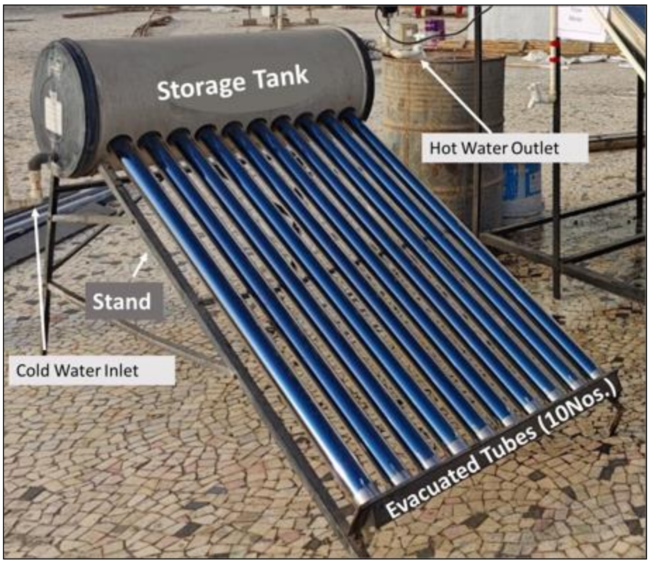

Fig 1: ETC Based SWH experiment setup

The experimentation is carried out year-round. However, a typical result for experimentation carried out on the bright sunny day of 1st October 2023 till March 2024 and observations obtained are shown in Fig. 2. The temperature of the collectors can be calculated using the energy balance equation [5],

$$\dot{m}C_p\frac{\partial T_f}{\partial t} + U_L A_c[(T_f - \Delta T) - T_a] = A_c I_T \tau\alpha \tag{1}$$

Using the above equation and data from direct beam radiation using a solar power meter, the incident radiation on the system, temperature of the collectors at various locations and useful energy were computed. The efficiency of solar water heater is computed by using the following equation 2

$$\eta = \frac{m \cdot C_p \cdot \Delta T}{I_T \cdot A_c} \tag{2}$$

Table 1: Testing of Evacuated Tube Collector on Clear Days

S. No	Observation		Date of Test	
		Oct 1, 2023	Jan 1, 2024	Mar 8, 2024
1	Inlet water temperature from the Tank at 10.00 h (°C)	26	27	30
2	Average hot water temperature at 17.00 h	58.4	57.5	60.2
3	Total solar Radiation from 10.00 h to 17.00 h on the evacuated tubes kWh/m2	6.1	5.8	6.3
4	Average hot water retained (collected separately in insulated tank) till next day 09.00 h	42.15	45.58	54.54
5	Ambient Temperature	31	32	34
6	Relative humidity (%) at 14.00 h	68	65	68
7	Average wind speed (kph)	4.7	6.8	4.8

Table 2: Efficiency of Solar Water Heater

[6] Absorber classification in mm	Efficiency (%)
48	30.0
54	42.54
72	58.64

As we can see, a tube with a larger diameter is more efficient than other tubes with a smaller diameter. This is because of the solar flux obstructions; the tubes with larger diameters receive more solar flux radiation than tubes with smaller diameters. Another reason for that is the mass flow rate of water. It is seen that the mass flow rate increases if the area increases.

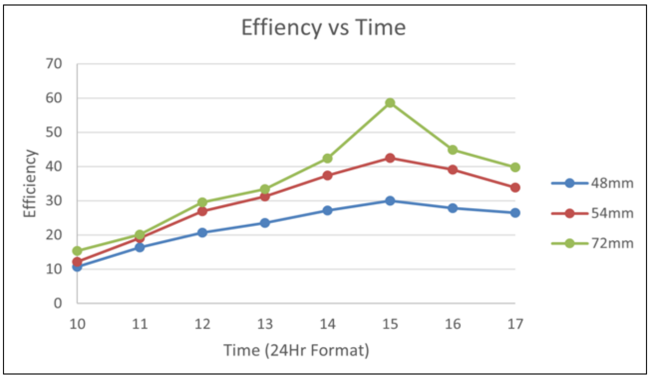

Fig 2: Observation from experimentation

At 48mm diameter, it is noticed that the driving force is lower for an optimum inclination angle due to the smaller diameter. The mass flow rate is lower, and the thermosyphon effect is sluggish. On the other hand, when the diameter of the evacuated tube is increased, the pressure gradient overcomes the optimum inclination, and the higher driving pressure increases the mass flow rate. However, the heat flux is reduced as the mass flow rate is at the peak point, depending on the riser diameter. It is noticeable that larger riser tubes allow higher fluid flow [6]. Conclusively, one can say that evacuated tube-based solar water heaters have widespread applications. Still, they are affected by an inherent problem caused by the stagnation zone that has evolved at the base of each tube's interior walls, which needs to be addressed by creating turbulence in that zone [7].
In order to compare the above results with flat plate collector, the following experiments based on flat plate collector are carried out which is explained in the next section.

1) Flat Plate Collector Solar Water Heater (FPCSWH):
Flat plate solar energy collectors are one of the oldest and most successful applications of solar energy utilisation. They are usually constructed from transparent glazing material, collector absorber plates on which coating material is applied, insulators, sealant and frame. The harvesting of solar radiation to produce useful heat energy using the flat plate collector is a function of good knowledge of the design procedure and proper material selection, which is very important for the optimum performance of these collectors. Thus, this study examines from the viewpoint of design analysis and material selection for the effective and efficient functioning of flat plate solar collectors after production [8].
Flat-plate solar thermal collectors are usually made up of a flat metallic plate, painted black on the side that faces the sun to maximize the absorption of solar radiation incident on it (thereby acting as heat collector) and insulated on the underside and edges to prevent/reduce heat losses as shown in Figure. On top of and parallel to the collector absorber plate is mounted one or more transparent glazing covers, which allows transmission of short-wave solar radiation to the collector absorber plate but is opaque to long-wave solar radiation. The transparent glazing cover is usually 25-35mm from the collector absorber plate. Provision is made to remove the heat energy retained on the collector absorber plate by circulating air through an air space above the collector plate or water through tubes soldered to the collector absorber plate. The following subheadings examine the basic components of flat plate solar thermal collectors [9].

Table 3: Specification of Experimental Setup

Specification	Value
Tube inside diameter/Di	11/mm
Tube Outside diameter/D	12/mm
Collector Area/Ac	1.9/m2
Emissivity of glass/ϵg	0.88
Emissivity of absorber/ϵp	0.05
Number of glazing/N	1
Thermal conductivity of insulation/$kins$	0.04 W/mK
Thermal conductivity of plate/kab	205/ W/mK
Adhesive resistance/l/Cb	Negligible
Thickness of back insulation/Bt	0.03/m
Edge thickness/Et	0.025/m
Perimeter/P	6/m
Tube spacing/W	0.1/m
Absorber plate thickness/δab	0.0005/m
Transmittance-absorptance product/$\tau\alpha$	0.88
Collector tilt angle/β	45◦

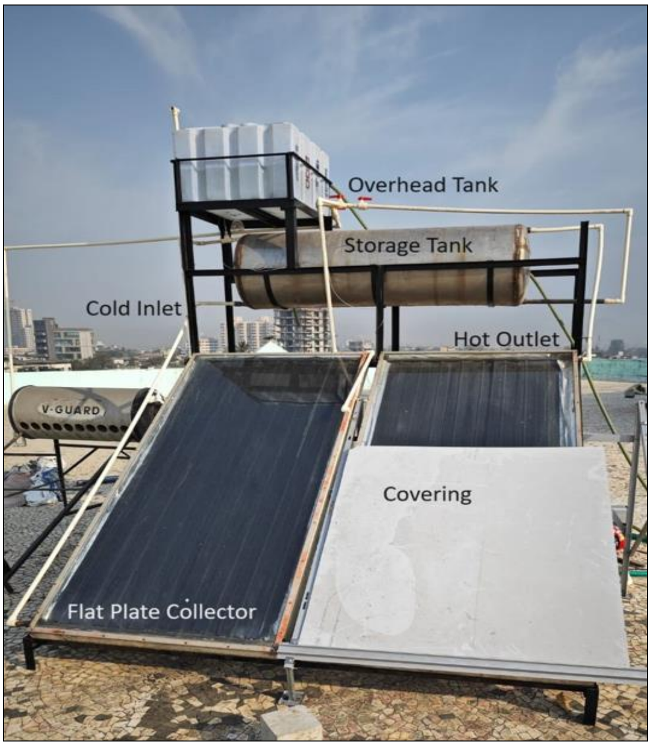

Fig 3: FPC Based SWH experiment setup

The validation of the results done using TRANSYS by Abdumnabi *et al*. provides a basis for further analysis in this project [10]. An experiment was carried out on the bright sunny day of 25th February 2024 for a flat plate collector, and the results were validated with theoretical results using

MATLAB. The methodology is to calculate the temperature of the storage tank throughout the day. Solar radiation data was obtained from the Solcast database on the day of the experiment. Three thermocouples are placed: One at the collector's inlet, one at the outlet of the collector, and one at the outlet of the storage tank. It is observed that the maximum temperature of 65°C is reached in the flat plate collector. The efficiency reaches a maximum of 75% during the time of day when the absorber receives the maximum solar radiation. The MATLAB results are close to those shown in Fig. 4 and Fig. 5 below [11].

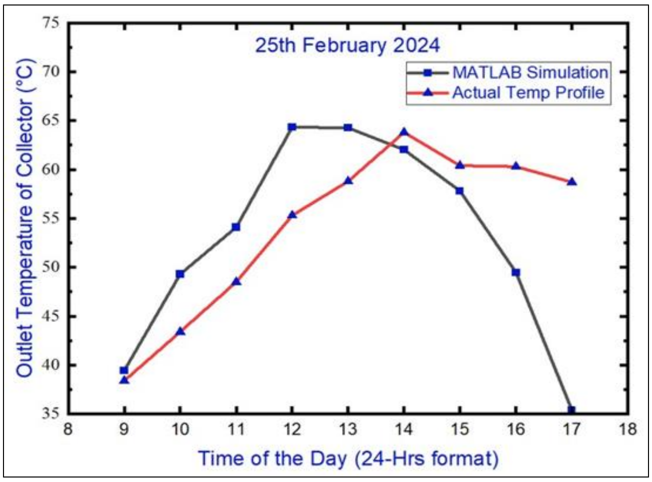

Fig 4: FPC Based SWH experiment setup

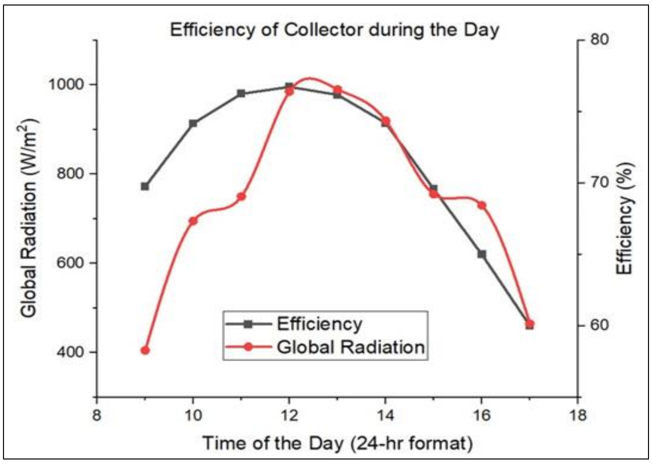

Fig 5: FPC Based SWH experiment setup

4. Results and Discussion

Based on the observations for the ETC-based SWH, it is conclusive that a 48-mm diameter tube is more effective at generating hot water at any given condition. 72 mm diameter evacuated tube gives a maximum efficiency of 58.64%, which is less than the Flat plate collector for the same setup due to the stagnation zone at the lower side of the tube, as discussed in the article [12, 13]. The experiment conducted on the Flat plate collectors reveals that the maximum temperature is reached at 2 pm of approximately 65°C with a maximum efficiency of 75%. Further experiments can be carried out to determine the minimum area required by the flat plate collector to maintain similar temperature and efficiency values so that the capacity of the flat plate collector can be enhanced by using a dual absorber on top of the flat plate collector which can utilise the direct solar radiation and thereby increase the volume of water heated during the day as shown in the proposed model below. Research can also be conducted to determine the optimum space between the two collectors and to study the effect of wind speed on the heat transfer between the fluids. Research related to the use of nanofluid can also be conducted to increase the efficiency of dual absorber-based solar water heaters (DASWH) further.

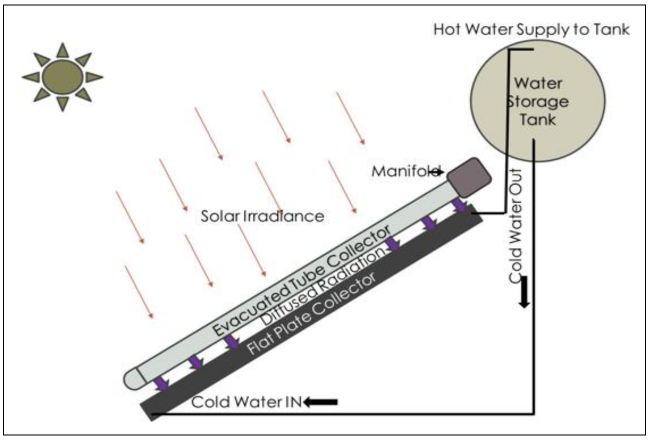

Fig 6: Proposed model of a DASWH

5. Conclusion

Recent urban agglomeration has reduced space for installing new solar water heaters in place of conventional water heaters. This study focuses on comparing evacuated tube solar water heaters and flat plate solar water heaters to find an optimum collector area to propose a dual collector-based solar water heater design. The results show that for a fixed mass flow rate, the flat plate collector of 4m^2 area is oversized, and an optimum collector area is to be found out by further research. The factors responsible for the thermosyphon effect are collector tilt, direction of the collector and wind velocity. Amongst 48mm, 54mm, and 72mm diameter tubes, the 48mm tube is more effective for hot water generation. In contrast, a stagnation region exists at the lower end of the 72mm diameter tube. An increase in the diameter of the evacuated tube creates a thermal stagnation zone at the bottom of the tubes, which directly affects the system's efficiency. Further studies can find the optimum space between the two collectors and study the effect of wind speed on the heat transfer between the fluids. A feasibility study of nanofluid can also be conducted to increase further the efficiency of dual absorber-based solar water heaters (DASWH).

6. Acknowledgment

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