Journal of Engineering, Project, and Production Management
2024, 14(1), 0002

Experimental Investigation and CFD Analysis of Different Diameter Evacuated Tube Solar Water Heater

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Selected paper from 2022 International Conference on Embracing Industry 4.0 Technologies for Sustainable Growth Engineering Management
Received June 28, 2022; revised November 26, 2022; accepted February 28, 2023

Abstract: The share of renewable energy share in India's energy mix of India has been increasing recently owing to the promotion and implementation of various government policies that promote the use of renewable sources of energy, depleting fossil fuel levels, increasing fuel prices, and stringent laws for emission reduction worldwide. The increase in the use of solar-evacuated-tube-collector-based domestic water heating is the result of this transition from conventional to non-conventional sources of energy. The recent urban agglomeration is challenging to install these solar water heaters in every household because the roof space is limited. Space reduction can be achieved by reducing the collector area by varying the diameter of the evacuated tubes. This study used a single tube and tank arrangement model with a fixed inclination to achieve a thermosyphon effect in a solar water heating system with three different diameter configurations of 48 mm, 54 mm, and 72 mm, with a tube measuring 1800 mm in length. Thermal assessment of the thermosyphon-based evacuated tube-solar water heater using the ANSYS CFD simulation software involves measuring the temperature at three different positions in the tank to study the thermosyphon initialization. This study signifies that the 72-mm-diameter evacuated tube is more capable of initializing the thermosyphon effect in the system. Nevertheless, the final temperature of the system is better achieved in the 48-mm-diameter evacuated tube.

Keywords: Solar energy, evacuated tube collectors, CFD simulation.

DOI 10.32738/JEPPM-2024-0002

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1. Introduction

With the COVID-19 pandemic outbreak in India, the country witnessed the migration of people falling under lower-income groups or those working their livelihood on daily wages to rural areas. This caused a substantial financial loss to metro cities due to the unavailability of skill-based labor. Based on the data of 2019 and 2020 quarter-on-quarter data, renewable electricity additions were 11% less, and the solar PV installations decreased by 17% year-on-year basis. As the pandemic resides in metro cities, there was a sudden increase in energy consumption in all sectors, such as transport and power consumption (IEA, 2020).

In India, coal dominates the primary energy consumption, accounting for 55% of the total energy mix, with the share of renewable energy declining by 3% in the year 2020. The lockdown in March 2020 in major cities of India further triggered the sluggish transition from conventional to non-conventional energy sources, in addition to the high installation costs and unavailability of labor for installation.

After the COVID-19 pandemic, the residents of metro cities experienced a transition in primary energy consumption, with citizens keen on following a sustainable energy consumption approach and its utilization. This article focuses on hot water generation for domestic use using a solar evacuated tube water heating system. Although the sun is a never-ending source of energy, the technology to harvest and transform it into a usable form is expensive. The energy source is diffused in nature and requires technology to trap its heat and convert it into a usable form in a very cost-effective and efficient manner. With the global enlightenment toward climate change, society is keen to look for alternative forms of energy. The seventh sustainable goal of clean and affordable energy is not far from being possible if we see a paradigm shift in our energy consumption patterns soon. The cost of energy consumption has significantly increased, because of which the consumers are shifting toward a solar water heating system. Factors responsible for the increased demand for solar water heaters (SWHs) include the reduced price of components, government subsidies, and policy interventions. Solar technology jobs involve technicians (77%), experts (10%), engineers and others with advanced degrees (9%), and marketing and administrative personnel (3%) (Sharma, 2021).

The sale of domestic SWHs has increased owing to the migration of the population to urban areas, improvement in the standard of living of the urban population, increasing electricity rates, and depletion of fossil fuels. Various government schemes to promote the use of SWHs and decrease the prices of SWH systems act as stimuli for growing the business for the installation of the SWH system. However, the installation of domestic SWH systems has become challenging because of space constraints. A typical 100-liter domestic solar water heater will occupy a projected area of approximately 1.2 sq.m. (Islam et al., 2012). To save money on gas and electricity, homeowners can generate hot water from the sun for domestic use.

Common solar sources for generating hot water include flat plate collectors and evacuated tube collectors (ETCs). ETCs are occasionally more expensive, but they significantly increase the water temperature over the ambient temperature. In his work, Dileep (2020) reported that ETCs worked better on overcast, wet, windy, and occasionally snowy days, depending on the installation. The overall area occupied by the entire apparatus is a critical issue that arises for mainstreaming the evacuated SWHs for domestic use. Mumbai is a metropolitan city in India with a population density of more than 25000 persons/sq.km, where most of the population resides in apartments. A typical apartment consists of seven levels and approximately 28 units. Therefore, to accommodate warm water in 28 flats, the same number of ETC-SWHs will have to be installed on the terrace of the same apartment where there is an appropriate amount of solar radiation (Dileep et al., 2020). The main problem arises as an evacuated tube-based SWH occupies more square feet and cannot be installed in bulk for domestic use. ETC-based SWH collector area is directly proportional to the diameter and length of the evacuated tubes. The space occupied by the domestic SWH can be reduced by changing various parameters such as the number of evacuated tubes; varying diameters of 48 mm, 54 mm, and 72 mm; length of evacuated tubes; inclination angle; and storage tank capacity.

Recent advances in the field of testing and experimentation of domestic SWHs include the study conducted by Shitzer et. al. to analyze thermosyphon flow within flat plate solar collectors composed of galvanized steel tubes. Their study inferred that; the water flow rate is directly dependent on the solar insolation incident on the collector surface (Shitzer et al., 1979). Celentano and Kirchner developed a 'Once-through' flow-type thermosyphon system that consists of minimal components and uses less space without affecting the efficiency of the system (Celentano and Kirchner, 1988). Several reports have discussed the simulation of domestic SWHs such as the study by Huang et. al., which identified a semi-empirical correlation of design and operating parameters affecting the performance of domestic SWHs (Huang, 1991).

Furthermore, certain design rules were interpreted toward the improvement of the efficiency of domestic SWHs. This study used a simple measuring device discussed by Bannerot et. al. to account for general characteristics, which are essential for a measuring device (Bannerot et al., 1992). On this basis, variations in the tube diameter were adjusted with the storage tank's inner diameter to fix the volume flow rate of the set to 25 liters. In a study conducted by Mehmet Esen and Hikmet Esen and Esen (2005) on a two-phased closed thermosyphon SWH, the thermal performance was enhanced because of the thermosyphon effect by using refrigerants R-134a, R407C, and R410A.

2. Experimental Setup

Although the heat transfer and flow structure in a single-ended tube have been widely investigated, no studies have correlated the natural convection in evacuated tubes of variable diameter. Techniques such as geometrical modifications of the absorber plate, use of solar-selective coatings, and nanofluids have been given special attention for the performance enhancement of SWH systems. However, there is a need to model a system to evaluate the long-term performance of these systems with different collector configurations under different operating conditions. It has been observed that the change in geometric configurations, such as the length and diameter of the single-ended tube, results in stratification at the bottom of the tube, which has not yet been addressed by the research community. This makes the field open to providing a variable reflective coating to enhance the natural convection inside the evacuated tube, which can be modeled and analyzed using CFD or software alike.

Water heating has been known to civilization since the mid-18th century when the invention of first residential heating was invented by Benjamin Waddy (Soni et al., 2019). Since then, water heating methods have changed from electric heating to gas geysers to non-conventional solar water heating. Luke-warm water for bathing has been proven to be effective as it improves blood circulation and relaxes the muscles. However, there are associated costs and space constraints if SWH installations are made compulsory for every household. With the Real Estate Regulatory Authority (RERA) in place and the government promoting the use of renewable energy sources, a few questions have arisen (Ashish, 2020).

According to the preliminary research, there are several factors that people would consider before they invest in such a water heating solution. The most important reasons are as follows:

- The cost associated with installing such a system
- The lack of terrace space available in their residential complex/building.

Among these reasons, the problem of lack of space is generally overlooked by major companies, because available space to install such systems is a subjective concern, and it is difficult to derive a generalized value for the same. However, the lack of available space is a concern that must be addressed. Even if a family/person could potentially invest in solar water heating systems, they would not be able to do so if adequate space was unavailable. This problem becomes even more serious when we consider densely populated cities such as Mumbai and Delhi. In the major housing colonies of these cities, terrace space is limited, and shared by many families. On average, a household of four members has a hot water requirement of 25 liters/person/day at 60° for bathing purposes. Therefore, the total hot water requirement is 100 liters/day/person. In the present study, the ETC-SWH system was manufactured by considering a hot water requirement of 25 liters/person/day. The experiment comprised a comparison between the variable diameters of 48 mm, 54 mm, and 74 mm, with a variation in the length of 1800 mm and 2100 mm. The experiments were performed under clear-sky conditions for comparison purposes.

2.1. Layout of the Experimental Setup and Measurements

The ETC-SWH system comprises a horizontal storage tank (25-liters volume), evacuated tubes, thermal insulation, and a frame. The frame is designed to support two setups with different configurations for comparison purposes. An inlet port positioned at the top end on one side of the storage tank supplies water to the ETC-SWH. Similarly, an outlet port situated at the bottom end on the opposite side of the tank facilitates water discharge. Here, the positions of the inlet and outlet are given less priority because the analysis does not involve stratification in the tank. Fig. 1 depicts the experimental setup used in this study. The storage tank is made of mild steel with glass wool for thermal insulation. A single evacuated tube is connected to the storage tank with a 30° inclination in the horizontal direction, which receives the solar irradiation. The tube is equipped with a reflector at the bottom to enhance the effect of solar irradiation on the bottom side of the tube. Evacuated tubes are made using borosilicate glass to enable the collector to withstand high temperatures. Rubber pads support the bottom ends of the evacuated tubes. Commercially available SWH systems adopt such inlet-outlet port positioning to favor the thermal stratification phenomenon. Polyurethane foam insulation (0.05-m thick) is provided throughout the circumference of the tank, which helps to minimize heat leakage. Table 1 presents the geometric details of the experimental setup. An industrial standard digital solar power meter was used to measure the incident solar radiation, with a nominal accuracy of 5 W/m^2.

2.2. Components of Experimental Setup

2.2.1. Evacuated tubes

An active SWH works on the principle of the thermosyphon effect. A thermosyphon effect is caused by natural convection incorporated owing to density difference and buoyancy. The ideal shape for inculcating the thermosyphon effect is an open tube-like structure that is capable of heating and includes natural convection to push the hot fluid to a receiver (storage tank) at the top. An evacuated tube is a structure made up of borosilicate glass that closely resembles a Dewar flask. It has concentric tubes with a vacuum in between and has a sealed top end. Owing to the strong borosilicate material, the evacuated tubes are capable of withstanding chemical and mechanical stresses. The evacuated tubes are directly exposed to solar radiation, which causes working fluid (usually water) to heat to a temperature approximately equal to 90°C. The outer glass tube is made transparent to absorb thermal radiation with minimum reflectivity, and the inner tube is selectively coated from the outside using absorbing materials such as aluminum nitride and copper nitride to trap the heat and reflect a negligible amount of radiation. The space between two concentric tubes is made a vacuum to minimize the heat loss caused by conduction and convection. The vacuum in the annular space allows absorption of infrared radiation by the tube; hence, SWHs equipped with ETCs can provide hot water under overcast conditions. Vacuum insulation is useful for minimizing the effects of external parameters like wind, cloud cover, and albedo on the performance of domestic SWHs. The storage tank provides articulation to the evacuated tubes at the top of the tube, which is inserted at an optimum distance to initialize the thermosyphon effect in the system. During the vacuum process, a barium getter is inserted at the outer tube's base, which absorbs all the dissolved gases present in the air, such as CO, CO_2, H_2O, O_2, and H_2, which are gassed out during the operation of an SWH and storage of hot working fluid. The bottom of the tube becomes hazy white if the vacuum between the inner and outer tubes breaks. The optimum inclination angle for the evacuated tube is assumed to be 30°–45° with the horizontal to achieve the best possible scenario for initializing the thermosyphon effect.

2.2.2. Storage tank

This study compared three different diameters evacuated tubes with different diameters based on the initialization of the thermosiphon effect and parameters affecting the efficiency of an SWH. To compare the three different evacuated tubes, the working fluid's volume flow rate was kept constant. The storage tanks were fabricated based on the principle of maintaining a constant volume flow rate and fixing the working fluid capacity at 25 liters in all three different evacuated tubes. During the charging cycle (daytime), the storage tank stores the hot water by allowing thermal stratification from dawn to dusk. During the discharging cycle, the storage tank should be able to maintain the temperature by not allowing the transfer from the water to the surrounding during nighttime.

The storage tank consists of two tanks: an inner tank that stores hot water and an outer tank that provides mechanical strength. The gap between the inner and outer tanks was filled with highly insulating material such as rock wool or mineral wool, which consists of an outer tank with a diameter of 300 mm and an inner tank to hold 25 liters of water. Polyurethane foam was used as an insulating medium, and we observed that the storage tank could withhold the water temperature until the next day, with a drop in temperature limited to 6° on an average. The tank had an opening for a cold water inlet at one end and a hot water outlet for domestic use on the other side of the tank. The tank was supported by a frame that also supported the lower end of the evacuated tube.

2.2.3. Insulation in the storage tank

Heat transfer in the storage tank is central to the design of SWHs. A thermal gradient exists in the operation of the SWH during the charging and discharging cycles. The ambient temperature during the day is on an average of 32°C, and at night, it can well go below 26°C. Hence, insulation has a crucial function in the design of storage tanks. Because of this temperature gradient, heat transfer is inevitable and thermal insulation provides a barrier to this temperature gradient. A material with low thermal conductivity was selected as the thermal insulator in between the two concentric tanks inhibited in the storage tank.

From a wide range of insulation materials, a proper thermal insulator was selected based on initial cost, robustness, conductivity effectiveness, and durability; the insulating material's thickness was determined based on the concept of the critical thickness of insulation. An increase in the insulating material's thickness increases the outer tank material cost; hence, in the current setup, we used thermal insulation with low thermal conductivity; additionally, low-thickness polyurethane foam was used in the current setup as it is readily available at low cost, has good thermal insulating properties, and can withstand the operating temperature of domestic SWHs, which is limited to 90°C.

2.2.4. Mounting frame

The mounting frame is composed of a number of metallic angles or plates, on which a number of units such as a storage tank, manifold box, tubes, etc. are mounted. In this experimental setup, the mounting frame was designed to house two storage tanks with different capacities to compare the different configurations of the evacuated tubes.

2.2.5. Temperature sensor

The selection and positioning of the temperature sensors depend on the various thermal zones created in the SWH setup. The thermosyphon effect causes laminar-turbulent convection currents in the evacuated tube and thermal stratification in the tank. For temperature zone measurement, the thermocouple position was determined. Three thermocouples were placed on the top, middle, and bottom of the tank, and the thermocouple position was correlated with thermal stratification zones in the storage tank. Two thermocouples were placed in the evacuated tubes to monitor the temperature rise during the charging cycle and how temperature reduced during the discharging cycle. As the system's operating temperature is limited to 90°C, a K-type thermocouple was used as it provides a wide temperature range. K-type thermocouples offer very rugged operation and can provide accurate results without being affected by environmental conditions. They are inexpensive and have a fast response time. Fig. 2 shows the actual position and attachment of sensors on the tank's side of the tank.

Table 1. Evacuated tubes used with different configuration

Parameter	ETC1	ETC2	ETC3	ETC4
Diameter	48	54	72	48
Length	1800	1800	1800	2100

Five K-type thermocouples were connected for temperature measurement at various locations within the ETC-SWH. Fig. 2 shows the arrangement of the thermocouple positioned diametrically within the storage tank to determine the temperature distribution during the experiment. The nominal accuracy of temperature measurement was 0.5°C. A conventional measuring bucket with a level indicator and stopwatch was used to estimate the water discharge through the outlet tap.

Fig. 1. Experiment setup

Fig. 2. Location of the thermocouple

2.3. Experimental Procedure

The principal function of ETCs is the thermosyphon effect. The incident solar irradiation on the evacuated tubes of the collector is absorbed and transferred to the working fluid (water) by conduction and convection. As the ETC-SWH is inclined at 30° and is a non-pressurized system, there exists a temperature gradient owing to solar irradiation which facilitates re-circulation of the working fluid from the tube to the storage tank. This results in the accumulation of hot water in the tank. This effect is known as the thermosyphon effect. However, several challenges occur during installation, such as wind velocity, purity of the working fluid, scaling of tubes, and tracking mechanism of solar panels. The experiments were conducted from 10:00 to 17:00 h on bright sunny days in October 2020, January 2021, and March 2021.

The charging of the system (static mode) when no inflow or outflow from the tank was recorded from 10 am to 3 pm, and readings were recorded at intervals of 15–20 min. There was a provision for discharging hot water (dynamic mode) at the end of the day. The results obtained were noted for further analysis using computational fluid dynamics in the ANSYS software. Hence, in this study, the experimentation work limited itself to the initialization of the thermosyphon effect and did not perform the overall thermal performance calculation of the ETC-SWH.

The experiment was conducted year-round. A typical result for experimentation conducted on the bright sunny day of March 1, 2021, and the observations obtained are shown in Fig. 3. The collector temperature was calculated using the energy balance equation, Eq. (1):

$$mCp\frac{\partial Tf}{\partial t} + UAc[(Tf - \Delta T)] = \frac{Ac}{T}\,\tau\alpha \qquad (1)$$

Based on the above equation and data obtained from direct beam radiation using a solar power meter, we computed the incident radiation on the system, temperature of the collectors at various locations, and useful energy.

The efficiency of the SWH was computed using Eq. (2):

$$\eta = \frac{m\,Cp\,\Delta T}{I_T\ A_C} \qquad (2)$$

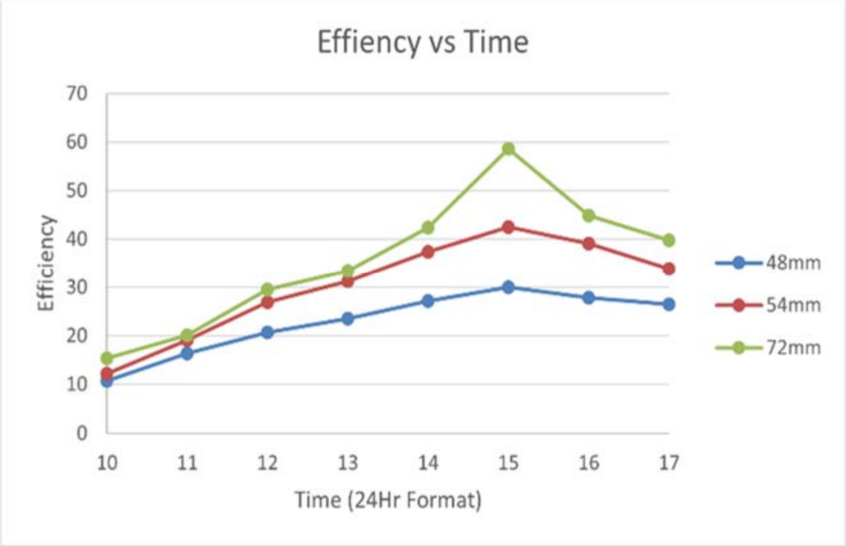

Fig. 3. Observation from experimentation

Table 2. Testing of evacuated tube collector on clear days

Sr.No	Observation	Oct 5, 2021	Jan 5, 2022	Mar 1, 2022
1	Inlet water temperature from the tank at 10.00 h (°C)	27	26	28
2	Average hot water temperature at 17.00 h (°C)	53.7	55.5	59.5
3	Total solar radiation during the test incident on evacuated tubes kWh/m^2	6.1	6.1	6.5
4	Average hot water temperature retained till next day at 9.00 h	48.9	48.9	55.4
5	Ambient temperature	31	32	34
6	Relative humidity (%) at 14.00 h	68	65	68

As can be seen, a tube with a larger diameter is more efficient than other tubes with a smaller diameter. This is because of the solar flux obstructions; additionally, tubes with larger diameters receive more solar flux radiation than tubes with smaller diameters. Another reason is the increase in the mass flow rate of the water the area increases. A relationship exists between the inclination angle and mass flow rate. The circulating mass flow rate changes according to the inclination and riser tube size (Fig. 1). At a diameter of 48 mm, for an optimum inclination angle, the driving force is smaller owing to the smaller diameter. The mass flow rate is lower, resulting in a sluggish thermosyphon effect. 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 because the peak point of the mass flow rate depends on the riser diameter. Larger riser tubes can allow a higher flow of fluid (Aung and Li, 2013). In conclusion, evacuated tube-based SWHs have widespread applications but 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 (Puthilibai et al. 2022).

3. CFD Simulation

To improve system efficiency, several design conditions such as an optimum storage tank, efficient collectors, orientation, and cost play a significant role in selecting the appropriate system for a given application. The experimental process can be too lengthy and hectic when it comes to obtaining real-time data from solar sites. Hence, simulations can be used to predict the performance of SWHs.

Table 3. The efficiency of solar water heaters

Diameter in mm	Efficiency (%)
48	30.0
54	42.54
72	58.64

In their study, Shariah et al. reported on optimizing the design parameters related to the thermosyphon effect, which improved the thermal efficiency and made the system more compact and economical. An improved multivariable optimization technique was incorporated using TRNSYS, and the same was analyzed by Abbdunnabi et al. In their analysis, the effect of weather conditions and design configuration of the collector played a significant role in improving system efficiency (Shariah and Shalabi, 1997). A similar work was conducted by Kalogirou et al. by using an analytical approach with TRNSYS; in their work, the expected energy gain from an SWH system based on the geometry showed that alteration in geometry can lead to an increase in the efficiency of the system, but this methodology should be supported by an optimization technique (Abdunnabi and Loveday, 2012). In turn, this approach could be used for energy optimization in the design phase as well as to test the existing systems to improve their performance (Mahian et al., 2013; Belessiotis and Mathioulakis, 2002).

3.1. Geometry and Mesh

The simulation of the domestic SWH was performed using ANSYS Workbench 18.1 with the fluid flow (Fluent) package for the analysis of the thermosyphon effect inculcated in the tank. A 2D model was prepared using the design modeler features. The angle between the tube and the horizontal was 30°. The geometric model is illustrated in Fig. 4.

Refinement of the mesh was performed by conducting a grid independence test, which suggested the optimum value of the elements to be 5044 to ensure the accuracy of results.

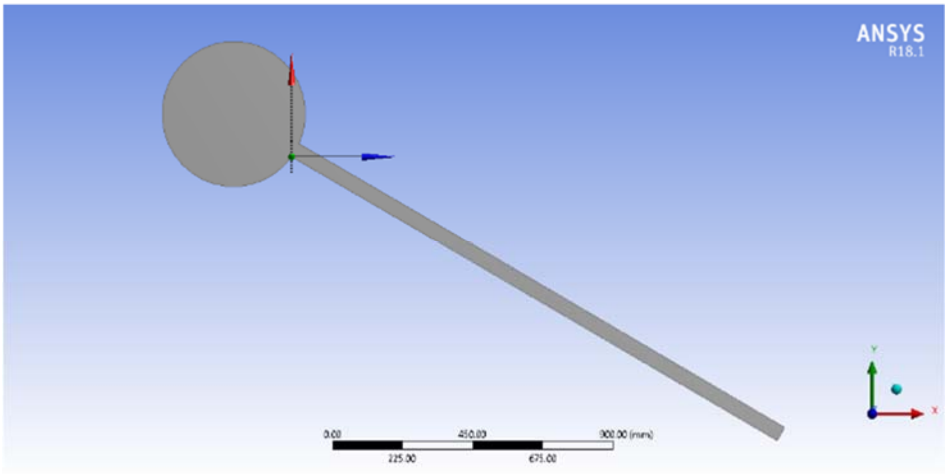

Fig. 4. Geometry of the model

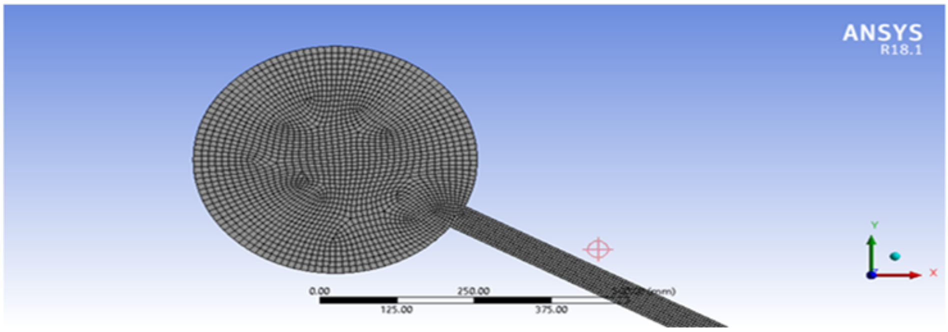

Fig. 5. Refinement in the mesh

3.2. Governing Equation

The Fluent package was used, which is a feature of ANSYS®. The simulation was carried out using the finite volume method, which discretizes the governing equation. The major assumptions in the current analysis were as follows:

- Thermophysical properties of the fluid, except density, are constant.
- Boussinesq approximation accounts for the natural convection inside the evacuated tubes.
- Viscous dissipation is negligible.
- No heat loss occurs through the bottom ends of the evacuated tubes.

Using these assumptions, the default governing equations of continuity, momentum, and energy were used.

3.3. Boundary Conditions

In this study, the computational domain was simulated in accordance with the experimental setup. The fluid domain is a 2D plane that resembles an integrated assembly of solar evacuated tubes and a thermal storage tank. The dimensions of the evacuated solar tube are varied as 48, 54, and 72 mm, whereas the tank diameter was fixed at a volume capacity of 25 liters. The length of the tube was fixed at 1800 mm for all three configurations to 1800mm. The computational domain was simulated for a single tube and single tank arrangement to reduce the computational time.

The top surface of the evacuated tube was assumed to have a constant radiation flux, which imposed a temperature of 350 K. The setup was studied for the charging cycle, which considers that the fluid is initially at a temperature of 300 K and eventually becomes heated because of the thermosyphon effect. The final temperature in this simulation was approximated to be achieved in 1000 time steps.

4. Results and Discussion

4.1. Experimental Results

The actual setup included a comparison of different diameter evacuated tubes with different diameters of 48, 54, and 72 mm and a fixed length of 1800 mm. The water heater's performance was evaluated on clear sunny days at a fixed volume flow rate of 25 liters. The results obtained from experimentation suggested that the average hot water temperature retained till 17.00 h was 59.5 °C. The efficiency comparison showed that the 72-mm diameter tube had the highest overall efficiency. The average temperature retained by the system was almost similar in all three tubes because the surface area increases as the diameter is increased, causing higher heat transfer during the discharging cycle. External parameters had a negligible effect on the thermal performance of the system.

4.2. CFD Analysis Results

During the charging mode of the SWH simulation using CFD analysis, the results obtained were similar to those obtained during the experiment. Fig. 6. shows the temperature profile of the 48-mm diameter tube.

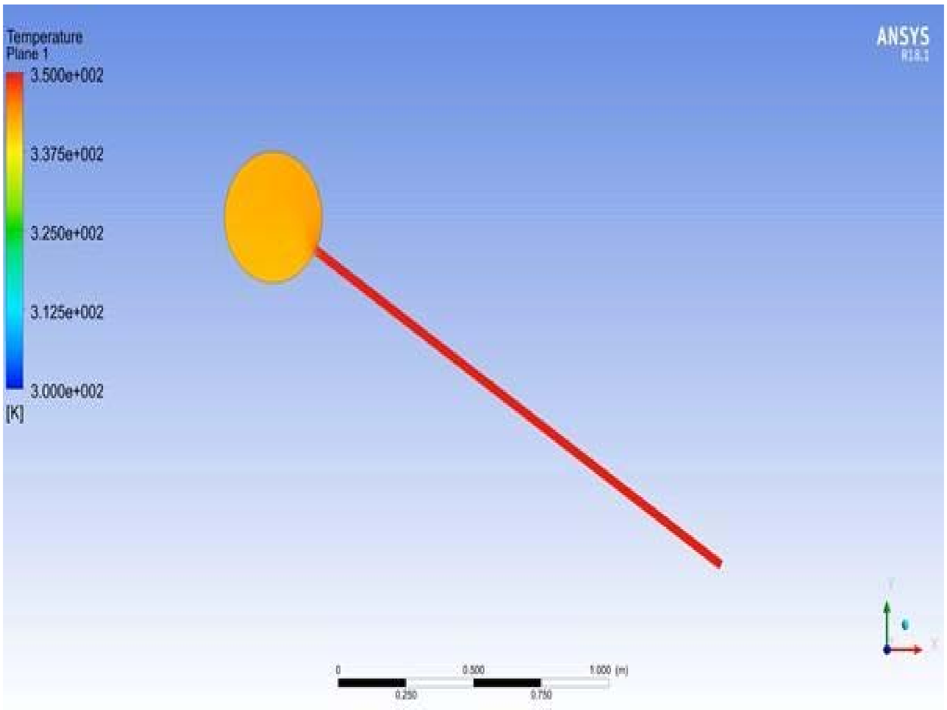

Fig. 6. Temperature profile along the length of the tube

To evaluate the effect of thermosyphon effect and thermal stratification in the thermal storage tank, the model was simulated with points located in a manner similar to that of the experiment. The location of points replicates the position of the thermocouple as Point 1 represents the middle, Point 2 represents the top, and Point 3 represents the bottom of the tank. Fig. 7 shows the arrangement of the thermocouple in the tank. The simulation correlates the phenomenon of temperature rise by virtue of density difference.

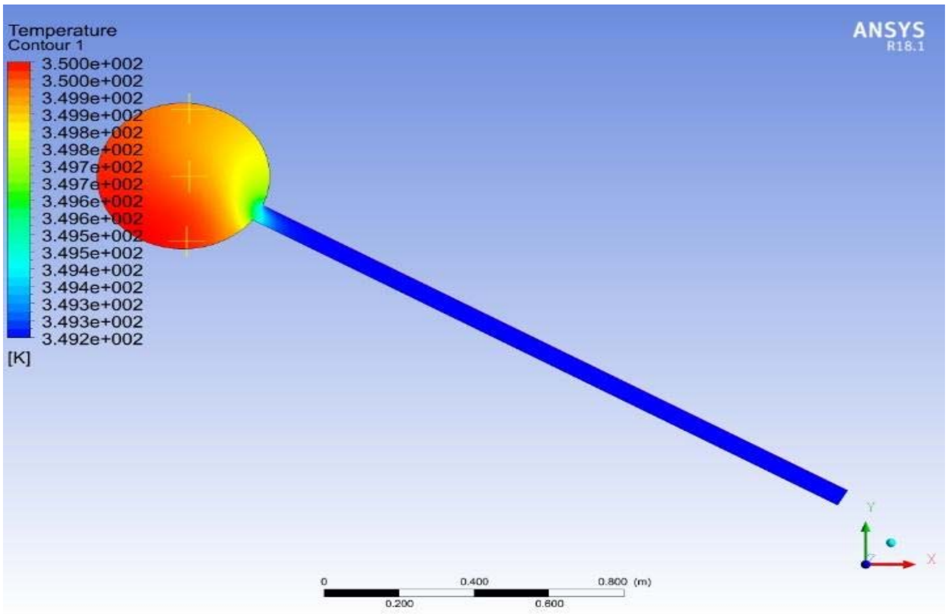

Fig. 7. Location of external points resembling the location of thermocouples

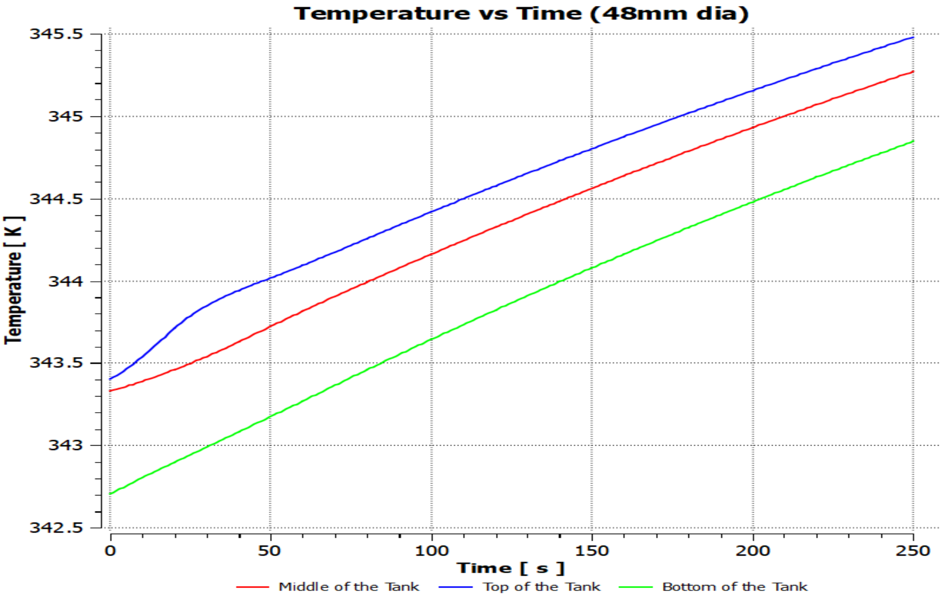

Fig. 8. Temperature profile for the 48-mm diameter tube

The final temperature was better achieved in the tube with 48-mm diameter; however, the tube with 72-mm diameter could reach the final temperature instantly. Fig. 8 shows variations in the middle, top, and bottom parts of the tank for the tube with 48-mm tube diameter; Fig. 9 for that with 54-mm diameter; and Fig. 10 for that with 72-mm diameter.

The simulation results were also obtained to study the variation in the density by virtue of turbulence eddy dissipation (Fig. 11), which indicates the rate at which energy cascades from large to small eddies within the inertial subrange. This energy is eventually converted to internal thermal energy in the viscous subrange (Borque et al., 2016).

4.3. Future Scope

The work presented in this article shows the thermosyphon effect in initializing the natural convection to raise the water temperature from 27°C to approximately 58°C. The efficiency increased as the diameter increased; however, a further increase in the diameter of the evacuated tube caused the efficiency to drop which might be because of the creation of a thermal stagnation zone at the bottom of the tube that restricts eddy formation and thereby ceases the thermosyphon effect. Further progress in CFD analysis related to the study of the stagnation zone can be performed, and various measures can be suggested to overcome this thermal stagnation zone and improve the efficiency by at least 5%–10%.

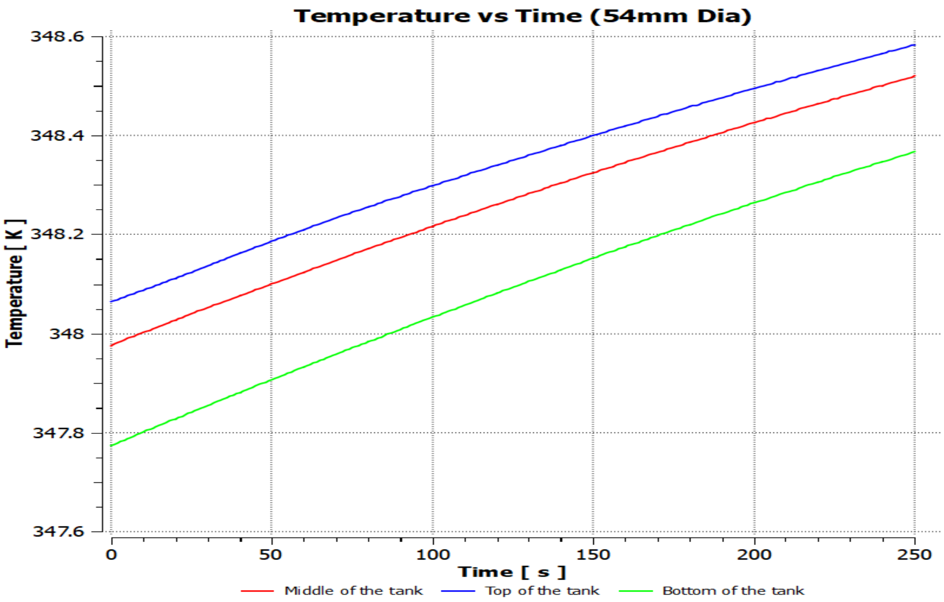

Fig. 9. Temperature profile for the 54-mm diameter tube

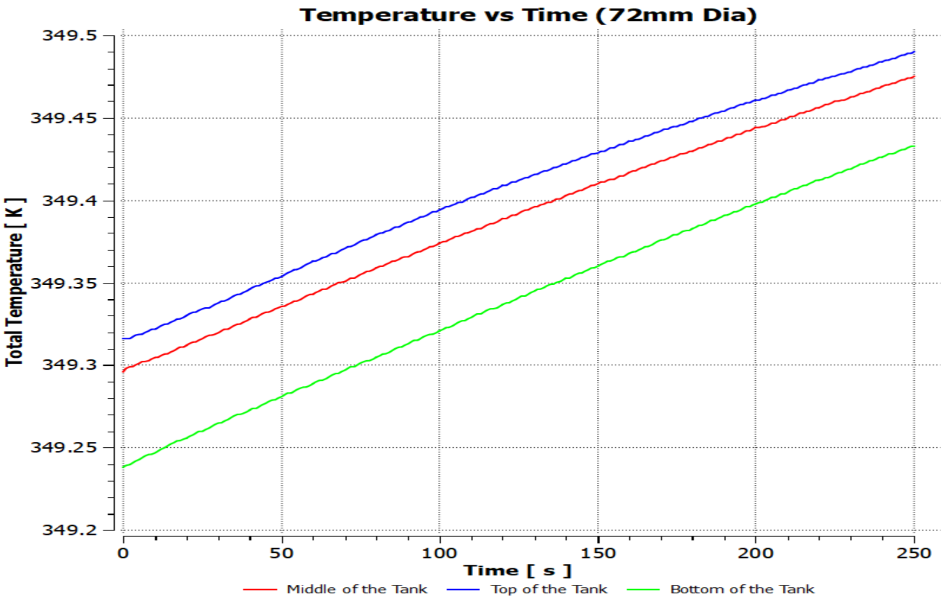

Fig. 10. Temperature profile for the 72-mm diameter tube

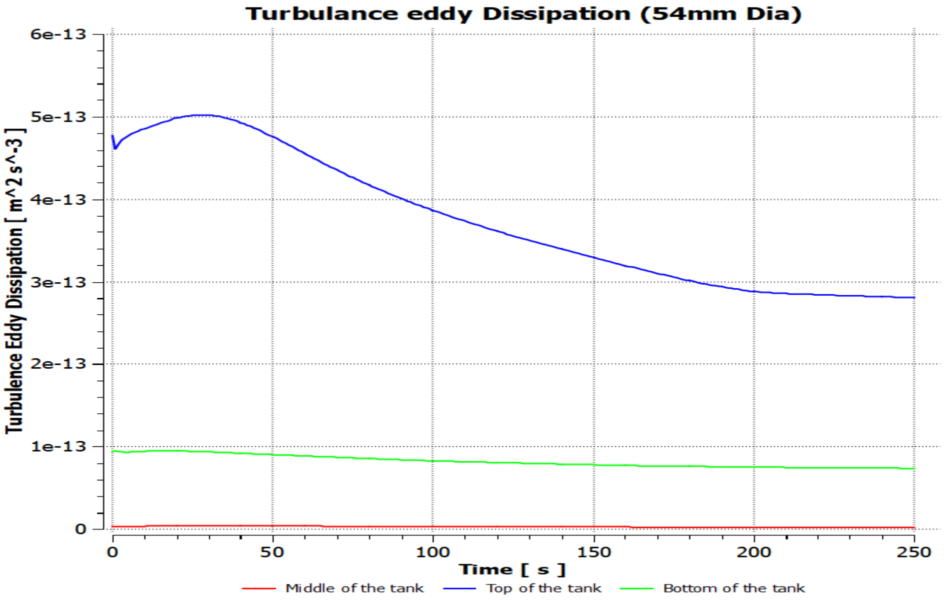

Fig. 11. Turbulence eddy dissipation

5. Conclusion

Recent urban agglomeration has resulted in reduced space for the installation of new SWHs instead of conventional water heaters. This study focuses on the feasibility of reducing the projected area of SWHs by altering the tube diameter and length of the tube for a fixed capacity usage without affecting the system's efficiency. The experimental results agree with the CFD results; however, the challenge is to develop a 100-liter capacity model and validate it with the experimental results. This study puts forth a baseline for implementing Industry 4.0 with a sensor-based model to inculcate real-time data for analysis. Our results indicate that the 48-mm diameter tube is effective in sustaining the temperature achieved during the day, whereas the 72-mm diameter tube is quick in terms of achieving higher temperatures in a short duration owing to the turbulence eddy distribution. Further study is required in terms of data acquisition from the experimental model and the real-time effects of various parameters on the efficiency of domestic SWHs. An increase in the diameter of the evacuated tube creates a thermal stagnation zone at the bottom of the evacuated tubes, which directly affects the efficiency of the system. Advanced CFD analysis can be conducted to understand this formation of the thermal stagnation zone and thereby improve the efficiency by 5%-10%.

Acknowledgments

This work was supported by the Renewable Energy Lab, Department of Mechanical Engineering, Vidyavardhini's College of Engineering & Technology, by providing the facility to carry out experimentation work and the Computer Center for providing the license version of ANSYS 18.1.

Institutional Review Board Statement

Not applicable.

References

Ashish R. (2020). Maharashtra Makes Solar Panels Must for All New Buildings. *Real Estate News, Economic Times.* Retrieved from https://realty.economictimes.indiatimes.com/news/rregulatory/Maharashtra-makes-solar-panels-must-for-all-new-buildings/50739581. on March 13, 2022.

Aung, N. Z., and Li, S. (2013). Numerical Investigation on Effect of Riser Diameter and Inclination on System Parameters in a Two-Phase Closed Loop Thermosyphon Solar Water Heater. *Energy Conversion and Management,* 75, 25–35, doi: 10.1016/J.ENCONMAN.2013.06.001.

Bannerot, R. B., Tu, Y. W., Scott, A., Placke, G., and Poche, T. (1992). A Simple Device for Monitoring Flow Rates in Thermosyphon Solar Water Heaters. *Journal of Solar Energy Engineering*, 114(1), 47–52, doi: 10.1115/1.2929981.

Belessiotis, V., and Mathioulakis, E. (2002). Analytical Approach of Thermosyphon Solar Domestic Hot Water System Performance. *Solar Energy*, 72 (4), 307–15. doi: 10.1016/S0038-092X(02)00011-7.

Borque, P., Luke, E., and Kollias, P. (2016). On the Unified Estimation of Turbulence Eddy Dissipation Rate Using Doppler Cloud Radars and Lidars. *Journal of Geophysical Research: Atmospheres,* 121 (10), 5972–89. doi: 10.1002/2015JD024543.

Celentano, R. and R. Kirchner. (1988). An Experimental Study of a once-through Thermosiphon System. *Journal of Solar Energy Engineering,* (110:2 (2): 90–97. doi: 10.1115/1.3268250.

Dileep, K., Raj, A., Dishnu, D., Saleel, A., Srinivas, M., and Jayaraj, S. (2020) Computational Fluid Dynamic Analysis on Solar Water Heater: Role of Thermal Stratification and Mixing on Dynamic Mode of Operation. *Thermal Science* 24: 1461–72. doi: 10.2298/TSCI190601419D.

Esen, M., & Esen, H. (2005). Experimental Investigation of a Two-Phase Closed Thermosyphon Solar Water Heater. *Solar Energy* 79 (5),459–68. doi: 10.1016/J.SOLENER.2005.01.001.

Huang, B J. (1991). A Performance Test Method of Solar Thermosyphon Systems. Retrieved from http://www.asme.org/terms/Terms_Use.cfm. on March 13, 2022.

Islam, M. R., Sumathy, K. K. S. U., and Khan, S. U. (2013). Solar Water Heating Systems and Their Market Trends. *Renewable and Sustainable Energy Reviews 17 (2013) 1-25.* doi: 10.1016/j.rser.2012.09.011.

Abdunnabi, M. J. R., and Loveday, D. L. (2012) Optimization of Thermosyphon Solar Water Heaters Using TRNSYS. Part2: Parametric Study Using a Modified TRNSYS Model. *Proceedings of the International Conference on Future Environment and Energy (28), 154-160.*

Mahian, O., Kianifar, A., Kalogirou, S. A., Pop, I., and Wongwises, S. (2013). A Review of the Applications of Nanofluids in Solar Energy. *International Journal of Heat and Mass Transfer*. doi: 10.1016/j.ijheatmasstransfer.2012.10.037.

Puthilibai, G., B. Prabhu, V. Vinodkumar, Raviteja Surakasi, B. Kannadasan, Shailendra Kumar Bohidar, and Ram Subbiah. (2022). Study on the Impact of Twisted Tapes on the Water Temperature Enhancement in Solar Water Heater. *Materials Today: Proceedings*. doi: 10.1016/J.MATPR.2022.02.459.

IEA (2020). Renewables. Retrieved from. https://www.iea.org/reports/renewables-2020 on June 21, 2022.

Shariah, A. and Shalabi, B. (1997). Optimal Design for a Thermosyphon Solar Water Heater. *Renewable Energy* 11 (3): 351–61. doi: 10.1016/S0960-1481(97)00005-0.

Sharma, N. (2021). Akshay Kranti Report. *IREDA.*

Shitzer, A., Kalmanoviz, D., Zvirin, Y., and Grossman, G. (1979). Experiments with a Flat Plate Solar Water Heating System in Thermosyphonic Flow. *Solar Energy* 22 (1): 27–35. doi: 10.1016/0038-092X(79)90056-2.

Soni, V. K., Shrivastava, R. L., Untawale, S. P., and Shrivastava, K. (2019). Performance Analysis and Optimization of Fresnel Lens Concentrated Solar Water Heater. *Journal of Solar Energy Engineering, Transactions of the ASME* 141 (3). doi: 10.1115/1.4041846.

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