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Harnessing Solar Energy: An Experimental Study on Development and Performance Evaluation of a Thermosyphon-Based Evacuated Tube Solar Water Heater

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Abstract

The conservation of energy is pivotal for socio-economic progress, necessitating eco-friendly energy sources like solar power. Consequently, solar thermal systems are evolving into highly energy-efficient designs. Recent investigations have assessed the performance of two types of evacuated water tube thermosyphons: one with an external heat pipe condenser and one with an internal heat pipe condenser. Additionally, research has evaluated water-in-glass evacuated tube solar water heaters through experimental measurements and a thermosyphon circulation simulation model. This study aims to manufacture cost-effective prototypes of evacuated tube solar water heaters (ETSWHs) with heat-pipe absorbers using local materials. The ETSWH utilizes the thermosyphon effect and natural convection heat transfer to provide hot water from solar energy, employing evacuated glass tubes with a selective coating mounted on a collector panel. Following the completion of the design phase using SolidWorks and accompanying theoretical calculations, comprehensive flow and thermal simulations were performed to evaluate the system's performance under diverse weather conditions. Experimental results indicated a temperature rise from 23°C to 37.5°C and an efficiency of 44.92%. The system's affordability and efficiency make it ideal for off-grid water heating, offering a cost-effective alternative to boilers.

Keywords: Solar thermal systems, Evacuated tube solar water heater (ETSWH), Thermosyphon effect, Cost effective alternative

1. Introduction

Minimizing energy consumption and greenhouse gas emissions is vital for addressing climate change [1]. Solar water heating is a well-established technology, widely recognized for its potential to reduce energy consumption and greenhouse gas emissions [2]. The rising demand for sustainable energy solutions has prompted extensive research into solar water heating systems. Among these, thermosyphon systems have gained significant attention due to their simplicity and efficiency in harnessing solar energy. Early research by Duffie et al. introduced the fundamentals of solar thermal systems [3], emphasizing the viability of thermosyphon designs in residential applications. Building on this, Kalogirou explored the efficiency of these systems under various climatic conditions [4], noting that while they are effective in sunny regions, performance drops significantly in areas with lower solar irradiance. The numerical evaluations of thermosyphon systems indicate that parameters such as filling ratio and inclination angle critically influence thermal performance, underscoring the importance of precise design and simulation in optimizing these systems [5]. The integration of energy conservation equations in finite-difference form has been a common approach in modeling thermosyphon systems, allowing for a detailed analysis of heat transfer fluid flow and system behavior under different solar insolation levels [6]. Despite extensive research, gaps remain, particularly in optimizing thermosyphon systems for diverse climates. Yu Mei Lu et al. has identified the need for optimizing material selection and system design to enhance the thermal efficiency of thermosyphon solar water heaters, especially in regions with varying climatic conditions [7]. For example, issues with thermal stratification in storage tanks and material durability under different environmental stresses are common challenges that have not been fully addressed. Similarly, Despite the recognized potential of thermosyphon solar water heaters, achieving cost-effectiveness remains a significant challenge [8]. Collectively, these findings support the development of an efficient and cost-effective solar water heater.

This study focuses on optimizing the cost-effective efficiency of thermosyphon solar water heaters, which operate through natural convection to circulate water. The research also aims to enhance thermal performance under varying climatic conditions, particularly addressing heat loss and fluctuations in solar radiation. Through a combination of experimental testing and theoretical modeling, various design configurations and materials are evaluated for improved heat retention and system efficiency.

2. Methodology

A solar water heater operating on the thermosyphon principle uses natural convection to circulate water without the need for a pump. The system comprises evacuated glass tubes as solar collectors, a storage tank, and connecting pipes. Solar energy heats the water in the tubes, reducing its density, allowing the heated water to rise and displace cooler water from the tank, creating a continuous circulation loop. The design parameters, including tube dimensions, number of tubes, and optimal tilt angle, were determined through energy balance calculations, utilizing local materials for cost-effectiveness. The calculation for our ETSWT given below:

2.1. Tilt angle calculation

To optimize the solar collector's exposure to solar radiation, the tilt angle was calculated using a series of mathematical relationships. In case of Bangladesh, spring & fall equinox and date of September 15, 2023. The declination angle was calculated using the following equation,

$$\delta = 23.45^0 \sin[\frac{360}{365}(d - 81)] \quad 1)$$

Here, d represents the day of the year. The value for the declination angle comes to 2.61° using the day of the year as 257. The expression for hour angle calculation is,

$$H = 15°[\text{Local solar time} - 12] \quad 2)$$

Using local solar time of 13:00, the hour angle (H) was calculated as 15°. The altitude angle (AL) was then determined using the following equation,

$$\sin(AL) = \cos(L)\cos(\delta)\cos(H) + \sin(L)\sin(\delta) \quad 3)$$

Here, L is the latitude, δ is the declination, and H is the hour angle. For Dhaka, Bangladesh's latitude angle is 23.81º, using the declination angle from equation (1) and hour angle from equation (2) the altitude angle results in 64.31º. Zenith Angle (Z) is complementary to altitude angle (AL) which turns out to be 25.69º. The azimuth angle (Z) was calculated using,

$$\frac{\sin(AL)+\sin(L)-\sin(\delta)}{\cos(AL)\cos(L)} \quad 4)$$

Using the value of declination angle from equation (1) and the latitude angle of Dhaka, the tilt angle came as 21.2º. When the plane is rotated about East West axis, the continuous adjustment tilt angle of the surface is,

$$\tan\beta = \tan(Z).\ |\cos(Az)| \quad 5)$$

Using the value of zenith angle (Z=25.69º) and azimuth angle (Az) from equation (4) the value for tilt angle came to 21.12º which is close to 23º which is typically used in Bangladesh.

2.2. Thermo-hydraulic calculation and energy balance

The thermo-hydraulic calculations and energy balance were performed using the equations provided by Andar et al[9] . The radiation heat transfer coefficient between the inner and outer tubes $(h_{0,i})$ and it was found to be 5.475 $\frac{W}{m^2K}$. Then using v=0.8m/s, the forced convection heat transfer coefficient $(h_{t,\omega ind})$ on the outer tube was calculated and found to be 8.74 $\frac{W}{m^2K}$. After this, the overall heat loss coefficient (U_t) was calculated using,

$$U_t = \frac{1}{A_i}\left(\frac{1}{h_{0,i}A_i} + \frac{1}{h_{t,\omega ind}A_0}\right)^{-1} \quad 6)$$

Using calculated values of inner surface area (A_i) and outer surface area ($A_{o)}$ of the tube and the computed value, the overall heat loss coefficient from equation (6) was 4.771 $\frac{W}{m^2K}$. Heat loss for only one tube,

$$Q_{loss} = U_tA_i(T_{t,i} - T_a) \quad 7)$$

Using values of A_i , inner surface temperature of tube $T_{t,i}$, T_a as 26º which is ambient temperature and U_t from equation (6) , the heat loss came as 0.704 W. Then it was calculated for N number of tubes.

Radiation rate (minimum value) on 15th September from Matlab calculation was R =295.1949 $\frac{W}{m^2K}$.

$$\text{Total input radiation energy} = RA_iN \quad 8)$$

Heat gained by water:

$$Q_g = mC_p(T_{w,o}\text{-}T_{w,i}) \quad 9)$$

Here,

$T_{w,i}$=Inlet water temperature=23º

$T_{w,o}$=Outlet water temperature=49º

C_p=Heat capacity of water=4186 $\frac{Kj}{Kg.K}$

m=mass flow rate of water=2.14x10^{-4} *kg/s*

From energy balance:

$$RA_iN - NQ_{loss} = Q_g = mC_p(T_{w,o}\text{-}T_{w,i}) \quad 10)$$

Using values from equation (7)(8)(9) the tube number is 7.99 ≈ 8.

2.3. Mechanical design calculation

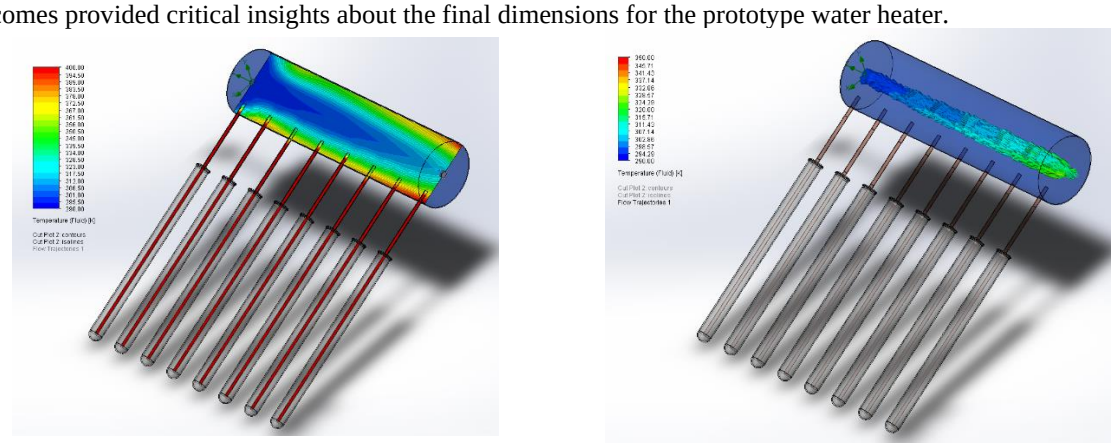
The mechanical design of the solar water heater is grounded in Barlow's Formula and is expressed as:

$$P = \frac{2ts}{D.FS} \quad 11)$$

For storage tanks and copper tubes, allowable pressure depends on parameters like thickness t, material stress S, diameter D, and safety factor FS. In the storage tank, with a larger diameter (0.254 m) and a safety factor 1, the pressure limit is 535.43 KPa. Meanwhile, the copper tube, with a smaller diameter (0.008 m) and a safety factor 3, supports a higher pressure of 2775 KPa. This comparison highlights how varying dimensions, material properties, and safety factors influence the pressure limits in different applications.

2.3. Simulation

SolidWorks Flow Simulation was performed to evaluate the flow rate, pressure, and temperature distributions of the working fluids at the outlet by applying specified inlet parameters which is shown in Fig. 1. The simulation outcomes provided critical insights about the final dimensions for the prototype water heater.



(a) (b)

Fig. 1. Thermal and Flow Simulation of the solar water heater (a) Fluid Temperature Contour, (b) Flow Trajectory in 3D view.

3. Experimental Setup:

The experimental procedures were meticulously planned and executed for maximum efficiency and precision. Key components included an 8mm copper tube with a thermal conductivity of 398 W/mK, chosen for its commercial advantages as an efficient heat absorber. To enhance heat absorption, the tube was coated with inexpensive black paint. The copper tubes were encased in borosilicate glass, known for its strength and heat resistance. The entire setup was designed in SolidWorks, as shown in Fig. 2, facilitating the creation of accurate 3D models and 2D drawings for precise manufacturing. The stainless-steel tank, formed by bending a steel plate and welded using TIG welding for clean, high-quality joints, was essential. Holes were drilled to fit the copper

tubes, with threaded caps at both ends for pressure testing. The tubes were cut, welded, and sealed securely with TIG welding, and borosilicate glass was attached using cork sheets for insulation and stability.



Fig. 2. Designing and manufacturing steps for the evacuated tube solar water heater.

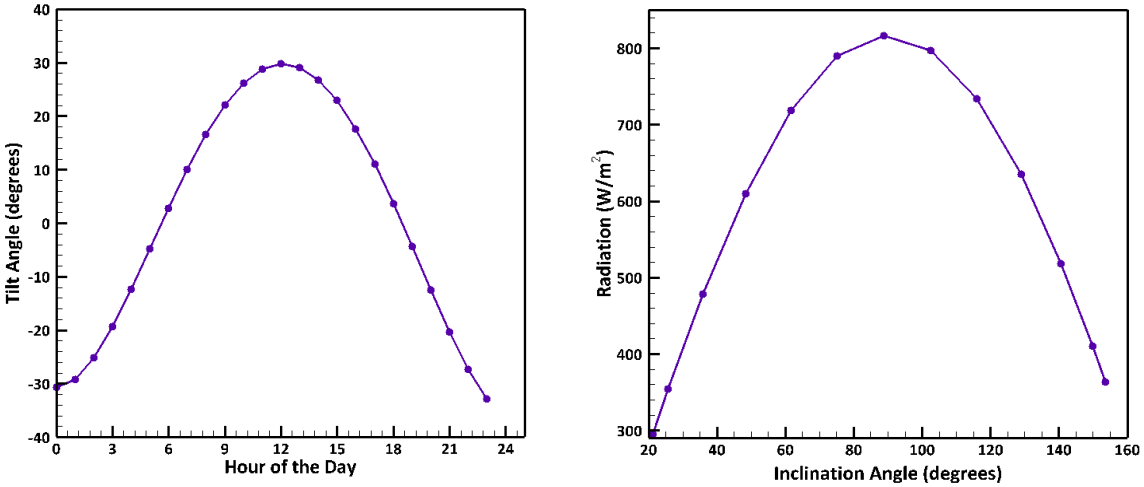
4. Result and Discussion

The simulation results, considering various parameters, along with the experimental findings, are discussed in this section. The parameters analyzed include tilt angle, radiation variation, efficiency, tube number, and temperature fluctuation. Additionally, the actual temperature rise, and bursting pressure were calculated during the experimental study. Using an average flow rate of 18 mL/min and other measurements obtained during testing, the system parameters were determined through relevant equations, and corresponding graphs were plotted. The collected data is presented in Table 1.

Table 1. Data collected at different times of a day from the corresponding graphs

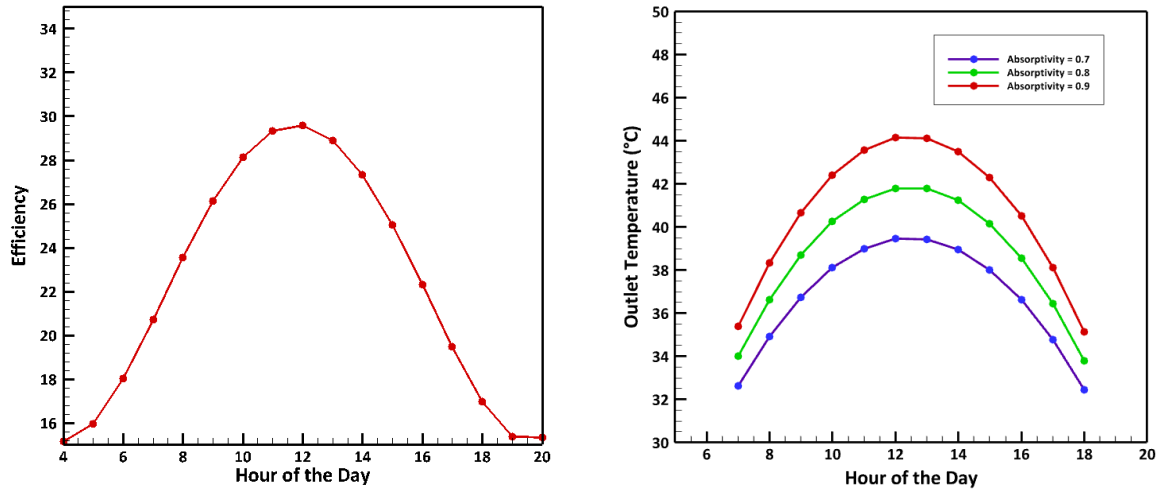
Hour of the day (h)	Tilt angle (degree)	Radiation (W/m2)	Efficiency (%)	Absorptivity	Outlet temperature (ºC)
08:00	12.3	228.9	23.6	0.7	34.9
10:00	25.3	339.4	28.1	0.75	39.2
12:00	29.6	396.1	29.4	0.8	41.9
14:00	25.9	349.1	27.2	0.85	42.4
16:00	19	278.7	22.2	0.9	40.5

The tilt angle, considering the angles of declination, hour, azimuth, altitude, and zenith, is depicted in Fig. 3(a). The graph illustrates the variation in the inclination angle throughout different hours of the day, showing that the tilt angle reaches its peak at approximately 12 pm. Consecutively, Fig. 3(b) presents the radiance variation corresponding to different inclination angles.



(a) (b)

Fig. 3. (a) Tilt angle variation with the hours of the day (b) Radiation variation with inclination angles keeping tilt angle constant for a day.



(a) (b)

Fig. 4. (a) Efficiency variation with hour of the day keeping tilt angle constant for a day (b) Outlet temperature variation with different absorptivity of inner tube for a day.

Fig. 4(a) illustrates the system's efficiency throughout the day at a constant tilt angle, peaking at 30% around 12 pm and gradually decreasing after that. Absorptivity values of 0.7, 0.8, and 0.9 were analyzed, considering various factors. Fig. 4(b) shows the outlet temperature for these absorptivity values at different times, with a maximum of approximately 44°C at 12 pm.

Following the manufacturing process and final leakage testing, the thermal performance of the prototype was evaluated over three consecutive days, as depicted in Fig. 5. From Table 2, it can be seen that for day one, with an inlet water temperature of 23°C, the outlet temperature reached 37.5°C, resulting in a temperature increase of 14.5°C. This outcome aligns closely with our calculated predictions and demonstrates the effectiveness of the solar water heater thermosyphon prototype. Additionally, a pressure test was conducted along with thermal performance testing which is shown in Fig. 6, confirming that the system can withstand an allowable bursting pressure of 50 psi. The overall performance of the prototype achieved an efficiency of 44.92%, indicating a satisfactory level of efficiency.

Table 2. Data Collection and Visualization of Experimental Analysis

Date and Time: 15 September 2023, 1 PM Weather: Partly Cloudy Temperature: 29.5°C Inlet Temperature: 23°C Outlet Temperatures: 37.5°C	Date and Time: 16 September 2023, 1 PM Weather: Partly Cloudy Temperature: 30.0°C Inlet Temperature: 21.4°C Outlet Temperatures: 36.5°C

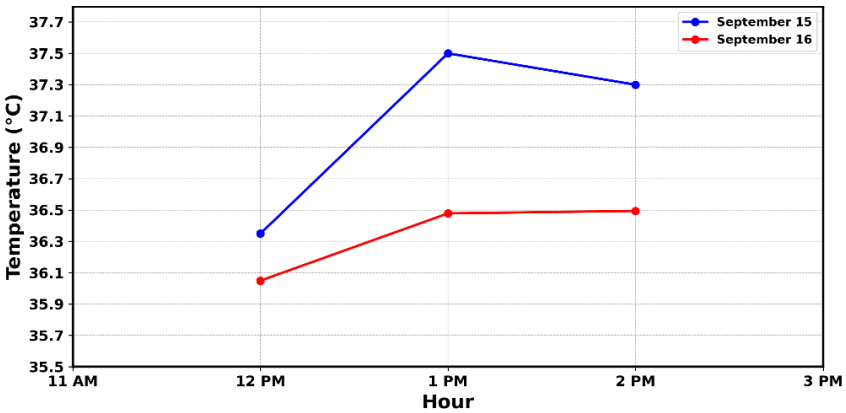


Fig. 5. Experimental hourly average outlet temperature variation for two days.



(a) (b)

Fig. 6. (a) Thermal performance testing and (b) burst pressure testing of the evacuated tube solar water heater

5. Conclusion

Despite certain limitations, efforts have been made to enhance the performance of a thermosyphon through innovative design and the integration of a natural circulation system. The key findings from the project can be described as:

- Various parameters, such as tilt angle, radiation variability, efficiency, tube count, and temperature fluctuations, were analyzed from the simulation data to optimize the design.
- The current prototype achieved an average overall efficiency of 44.92%. The system can withstand an allowable bursting pressure of 50 psi. Experimentally, the system resulted in an average temperature increase of 14.5°C, with an inlet water temperature of 23°C and an outlet temperature of 37.5°C.
- The objective is to improve efficiency and scalability to a 150-liter capacity while ensuring cost-effectiveness.

To further improve performance, additional features such as an actuator system could be incorporated to manually adjust the orientation of the tubes based on the sun's position throughout the day, enhancing solar capture. Furthermore, integrating sensors and probes to monitor and regulate temperature, pressure, and flow within the system would enhance operational control. Therefore, the thermosyphon system has the potential to become a cost-effective alternative to traditional water heaters for both commercial and household use.

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