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Research Article

Empirical Investigation and Analyzing the Thermal Efficiency of Solar Water Heaters Using Evacuated Tubes and Heat Pipes, Considering Multiple Variables and Nanofluid Applications

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ABSTRACT

The effective harnessing of solar radiation offers a promising solution to various environmental challenges, with solar water heaters serving as a prominent method for capturing and converting solar energy into thermal energy. This study evaluates the performance of an Evacuated Tube Heat Pipe Solar Collector (ETHPSC) by examining the effects of water combined with varying concentrations of multiwalled carbon nanotube (MWCNT) nanofluids as the heat pipe's working fluid through a two-step process. A series of experiments were conducted over a six-month period in Navsari, India, characterized by diverse climatic and land cover conditions that significantly influence actual evapotranspiration (AET) rates. The experiments utilized water mixed with MWCNT at concentrations of 0.1%, 0.2%, and 0.3%. The study assessed the efficiency of the solar collector, which was integrated with a compound parabolic concentrator, under varying operating conditions, including three tilt angles (25°, 35°, and 45°), three filling ratios (30%, 40%, and 50%), and three mass flow rates (0.0042, 0.0047, and 0.0056 kg/s). The findings indicate that the collector efficiency improved with the optimal weight concentration of nanofluid and with decreasing mass flow rates. Notably, the ETHPSC with a 0.2 wt.% MWCNT nanofluid, at a tilt angle of 45°, a filling ratio of 40%, and a mass flow rate of 0.0042 kg/s, achieved an efficiency of approximately 64%. The results underscore the importance of optimizing filling ratios and inclination angles to enhance system performance.

1. Introduction

Energy consumption has been driven by the growing requirement for fossil fuels in the industrial as well as civil sectors; by 2025, it is expected that oil consumption will have surpassed 120 million barrels per day. Making the switch to renewable energy sources has become crucial because of resource depletion and rising CO_2 emissions[1]. Globally, this trend is accelerating since renewable energy is more environmentally friendly and sustainable [2]. Solar energy can be captured by photo-thermal and photovoltaic techniques. Photovoltaic system converts solar radiation into electrical energy, however photo-thermal system translates solar radiation to thermal energy like

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solar water heater[3]. Market for solar water heaters has expanded significantly over the last 10years. Evacuated tube solar water heaters (ETSWHs) are more effective and have lower thermal losses in comparison with flat-plate solar water heaters [4]. A variety of usage of heat pipes as efficient heat absorbers in ETSWHs have been studied to boost their thermal performance[5] or to raise the temperature of their working fluid[6]. Without the need for capillary action or external power, heat pipes that use gravity and have condenser positioned above the evaporator may circulate the working fluid [7, 8].

Evacuated tube solar water heater performance depends on several variables like solar irradiance, tilt angle, filling ratio, mass flow rate, and working fluid of the heat pipe. Ayad et al. [9] found that solar irradiance levels, and reflector efficacy may be reduced in areas having insufficient sunlight, while aluminum reflector sheet incorporation with ETSWH framework enhances energy consumption by around 19% on average. Aluminum reflector efficiency may be influenced by size as well as geometry of ETSWH framework. Mahesh et al. [10] recommend utilizing a lower tilt angle throughout the summer season to achieve enhanced efficiency along with reduced payback periods for ETSWH performance. Safaa et al.[11] discovered that elevated temperatures can augment heat loss from the collector, however increased temperatures may enhance thermal efficiency. Variations in altitude angles might influence the operational temperature range of collector, especially in cold climate zones.

Efficiency enhancements of up to 78%. The effectiveness of ETHPSCs was investigated by Abd-Elhady et al. [12], who also emphasized the substantial influence of the working fluids employed, such as hexane, ethanol, methanol, acetone, petroleum ether, chloroform, on energy as well as exergy efficiency, as also reported by Ersoz [13]. Hamdi et.al [14] discovered that the heat transfer coefficient of aluminum oxide nanofluid surpasses that of the base fluid. This feature escalates with rise of Reynolds number and volume fraction. Mahbubul et al. [15] utilized single-walled carbon nanotubes as working fluids in an attempt to increase the ETHPSC's output temperature and efficiency. Promising outcomes for domestic hot water were demonstrated by Naghavi et al. [16] when they investigated nanoparticle integration with water and coupled ETHPSCs with phase transition materials for latent thermal storage.

To improve performance, researchers have added nanofluids to tubular thermosyphons. Hussain et al. [17] discussed the effectiveness of an ETSC ("Evacuated tube solar collector") utilizing nanofluids containing one-to-one, 30 nm and 50 nm-sized Ag (silver) and ZrO_2 (zirconium oxide) nanoparticles in pure water at concentrations of 1%, 3%, and 5%. It had been prepared using the two-step method. Mass flow rates of 30 and 90 L/h m^2 were employed to evaluate the ETSC. Because of the higher thermal conductivity (TC) of Ag, the results demonstrated that Ag nanofluids (5%) performed better than ZrO_2. The experimental energy analysis indicate that application of nanofluids enhanced the performance of heat pipe systems.

In an experimental investigation [18] on nanofluids application in heat pipe solar collectors, Daghigh et al. [19] tested MWCNT, CuO, as well as TiO_2 nanofluids and found that they performed 25%, 12%, and 5% better thermally than water in August and 15% and 7% better in October, respectively. In another experimental investigation on the effects of a bentonite-based nanofluid in heat pipes, Guru et al. [18] found that at 200 W of heating power as well as 5 g/s cooling water mass flow, the heat pipe efficiency increased to 37%. Sozen et al. [20] assessed the effectiveness of fly ash and alumina nanofluids in two-phase closed thermosiphon heat pipes and found that using a nanofluid instead of water at a heating power of 400 W and a cooling water flow rate of 5 g/s reduced the thermal resistance by 30.1%.

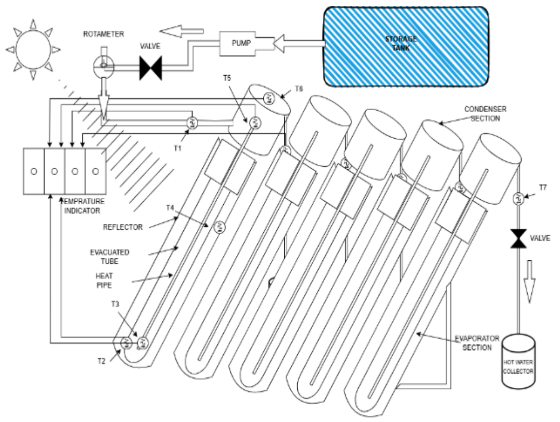

Fig. 1. Schematic of experimental setup of HPETSC

While numerous studies have confirmed that the thermal performance of heat pipe evacuated tube solar water heaters is significantly influenced by the choice of working fluid, its filling ratio, and various operational parameters, a comprehensive experimental analysis that systematically investigates the interplay between these factors is still lacking. Much of the existing literature examines these variables in isolation. Consequently, there is a distinct gap in understanding how optimizing the working fluid by varying its weight percentage, affects thermal efficiency when concurrently subjected to dynamic real-world conditions such as solar irradiance, ambient temperature, and inlet water temperature. This study, therefore, aims to address this gap by conducting a thorough experimental evaluation to determine the optimal working fluid composition, tilt angle, mass flow rate, and filling ratio for enhanced performance under a range of operational conditions.

Fig. 2. Experimental setup of HPETSC

2. Experimental Setup & Procedure

In the present study, a solar water heater with five separate evacuated tube solar collectors coupled with wickless heat pipes and linked with a storage tank were thoroughly evaluated outdoors as shown in Figure 1 & 2. Under the environmental conditions of Navsari (20.73° N, 72.96° E), India, tests were conducted. ASHRAE 93-2003 is a standard most often utilized for outdoor evaluation of glazed solar thermal collectors. Examining the overall performance of an HPETSC equipped with a parabolic trough concentrator was the goal of this investigation. To substitute the traditional solar water heater, a standalone system was established. The HPETSC model under investigation was consisted of two vacuum-sealed glass tubes. A specialized material was coated the interior of the glass tube, which is directly linked to a copper heat pipe containing a circulating HTF (heat transfer fluid). To ensure effective functioning, each condenser heat pipe unit is coupled with an evaporator heat pipe unit. The evaporator sections of the heat pipes are crucial for system performance and are incorporated into the evacuated glass tubes, which are placed at their centers. Conversely, the condenser portions are secured in place by rubber stoppers and are positioned inside the storage tank to transfer solar energy that has been gathered to store water. An aluminum reflector is carefully placed behind the evacuated glass tubes to improve heat collection. Storage tank contains 2 liters and is constructed of galvanized steel with a thickness of 0.8 mm. For hot water removal experiments, an insulated 120-liter constant-level water supply tank is used to replenish the solar-heated water as it is consumed. The assembled solar water heating system was positioned at various tilt angles on a south-facing stand.

The innovative design of the heat pipe makes it easier for water to be distributed thermally evenly, which substantially enhancing heat transfer and increasing the overall system yield[4]. Calibrated thermocouples were placed at J-type at intake outflow as well as K-type at distinct locations to measure temperatures in the solar system. A calibrated rotameter-type flow meter with a measuring range L/h was utilized to measure the water flow rate. From December to May, experimental testing was conducted on sunny days under clear sky conditions. The Taguchi method was employed to minimizes the number of tests before they are conducted via the partial fraction method. The heat pipes were filled to 30%, 40%, and 50% of their capacity and operated using deionized water containing 0.1%, 0.2%, and 0.3% multi-walled carbon nanotubes (MWCNTs). Measurements were recorded every 15 minutes from 9:00 AM until 5:00 PM. Throughout the time of data collection, the solar system's functioning was regarded as constant.

Three loading patterns were utilized in the experiments: 25°, 35°, and 45° inclination angles. The second parameter was the working fluid filling ratio at 30%, 40%, and 50%, with flow rates of 0.004167 kg/s, 0.004722 kg/s, and 0.00556 kg/s, respectively, beginning at 9:00 AM.

2.1. Nanofluid Preparation

To improve the stability along with durability of the nanofluids, a two-step procedure was implemented as shown in Figure 3. Utilizing an ultrasonic homogenizer, multiwalled carbon nanotubes were added to distilled water at a pH of 7 at concentrations of 0.1%, 0.2%, and 0.3% by weight. Triton X-100, a nonionic surfactant, was determined to be the best dispersing agent for the MWCNTs suspension according to data acquired and a comprehensive literature survey.

Table1. Properties of the nanofluids used in the experiments

MWCNT Properties	
Purity	99%
Sp. Surface Area	310 M^2/G
Diameter	AVG. O.D. 5-20 NM
Density	0.20-0.35 G/CM^3
Length	10 μM

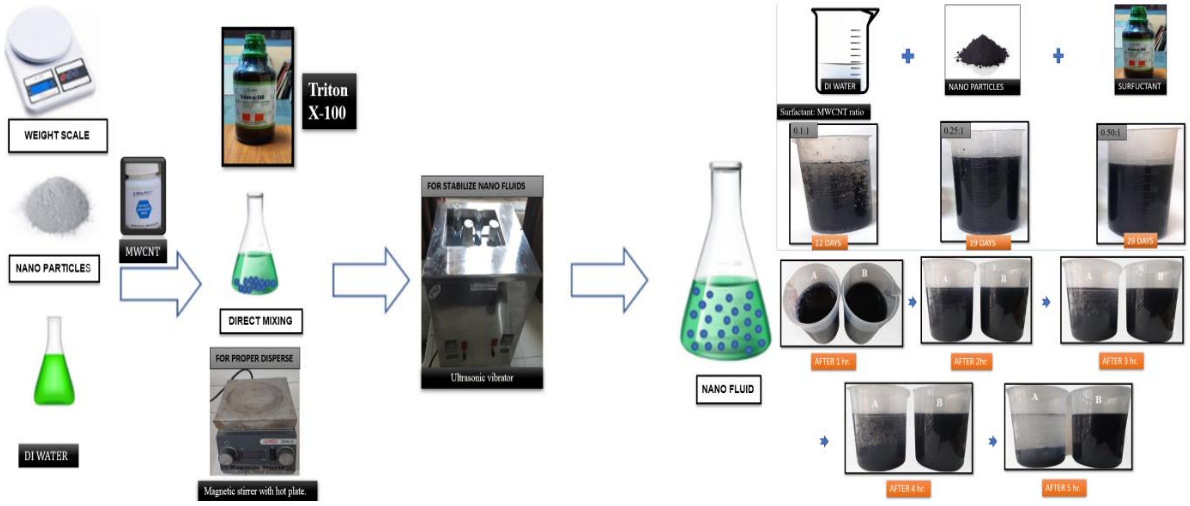

Fig. 3. Steps of Nanofluids preparation

The nanoparticles remained uniformly distributed in the base fluid for a minimum of 10 days and for up to 1month when the nanofluid contained a surfactant. A safe and eco-friendly method for achieving nanofluid stability was found to be the use of a surfactant. Utilizing the ideal amount of surfactant, a pilot experiment was carried out to examine stability period of nanoparticles in the base fluid. Findings showed that Triton X-100, the surfactant, and an MWCNT concentration of 0.50% by weight produced adequate stability in the suspension for a substantial period of time. To prepare the samples, each concentration was mixed with water employing magnetic stirring for 2 hours. This was followed by sonication for 2, 3, 4, as well as 5 hours. For 3 hours, the sonication process was run at 40 kHz, 60% amplitude, and a pulse duration of 0.5 seconds. Table 1 contains the MWCNT specifications.

3. Thermal Analysis

In an open experimental setup, solar energy was directed towards the collector's absorber surface to determine the heat pipe solar collector's thermal efficiency. Instantaneous power was utilized to quantify the energy that was transmitted to the fluid. Mass flow rate, incidence of solar radiation, temperature, as well as other pertinent variables, were measured as primary experimental variables. Incident solar energy is denoted by Qs, which is computed through Equation (1).

$$Q_s = I \times A \quad (1)$$

'I' stands for the density of solar irradiation, while 'A' is the surface area that receives solar radiation. As a consequence of thermal energy being transferred from condenser's heat pipes to the storage tank's circulating fluid, the temperature of the colder incoming fluid rises. Specific heat, mass flow rate, along with temperature differentials are employed to calculate the thermal energy that the moving water has acquired.

$$Q_{net} = \dot{m}C_p(T_{0ut} - T_{in}) \quad (2)$$

Proportion of thermal energy absorbed through "water from absorber tube (Q_{net}) in relation to total amount of solar radiation" that reaches the collector has been utilized to measure instantaneous efficiency of solar collection system. Equation (3) illustrates this instantaneous efficiency [7].

$$\eta_{inst} = \frac{Q_{net}}{Q_s} = \frac{\dot{m}c_P(T_{out}-T_{in})}{IA} \quad (3)$$

However, the concentrator thermal efficiency via the first Law has been denoted by Loni [21],

$$\eta_t = F_R\left[\eta_{0pt} - \frac{U_L}{c}\left(\frac{\Delta T}{I}\right)\right] \quad (4)$$

where ΔT= temperature rise across the receiver, η_{0pt} = optical efficiency and $\Delta T = T_i - T_{amb}$, T_{amb} is the ambient temperature. In this equation, UL denotes the heat loss coefficient, and FR denotes the heat removal factor. If η_t thermal efficiency vs. $\frac{T_{in}-T_{amb}}{I_{beam}}$ is illustrated, the coordinate distance constant value and plotted graph's slope implies values of FRηopt and FRUL/C, respectively. The FRηopt has been based upon concentrator construction, and FRUL/C is based on receiver construction. HPETSCs' efficiency curves are illustrated in Fig. 4. he plotted points represent the instantaneous thermal efficiency, and a best fit straight line can be drawn through these points to determine the thermal efficiency characteristics of the solar concentrators.

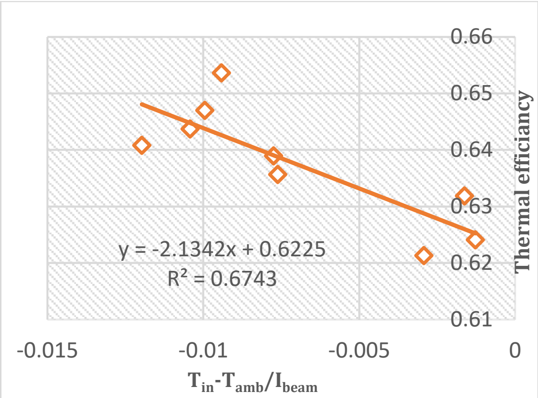

Fig. 4. Overall performance of HPETSC for MWCNT (0.2%)

The uncertainty related to experimental measurement can be found in Table 2. This table provides a comprehensive overview of the equipment's accuracy and standard uncertainty, allowing for a clear understanding of the experimental results.

Table 2. Measurement of Uncertainty

Particulars	Range	Accuracy	% Error
Solar meter	0-2000 W/m2	± 10 w/m2	3
K type thermocouple	0-200 ˚C	± 2.2 ˚C	0.1
Flow meter	0-30 L/min	± 10 %	1.3

uncertainties in computing tools "(Kline and McClintock, 1953 [22])" assessed in recent experiment has been provided. The maximum uncertainty in η_t has been denoted by Equation (5) to be 2.8%.

$$\delta\eta_{tn}/\eta_{tn} = \sqrt{\left(\frac{\delta Q_{solar}}{Q_{solar}}\right)^2 + \left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta\dot{m}}{\sin}\right)^2} \qquad (5)$$

4. Results and Discussions

Three levels of filling ratio, mass flow rate, working fluid, along with inclination angle were examined in the experimental investigation of the HPETSC. To determine the performance of the HPETSC, fluctuations in ambient temperature and solar irradiation were also investigated. Optimization of the influencing factors was also executed as part of the investigation.

Measurements of tube temperature and solar radiation intensity recorded at 10-minute period showed a consistent trend. Efficiency is at its peak at noon and declines with increasing distance from noon.

Due to energy that ETSC-HP adds, the water temperature rises from the morning 9:00 AM to until 5:00 PM, with a peak observed at noon as shown in Figure 5.

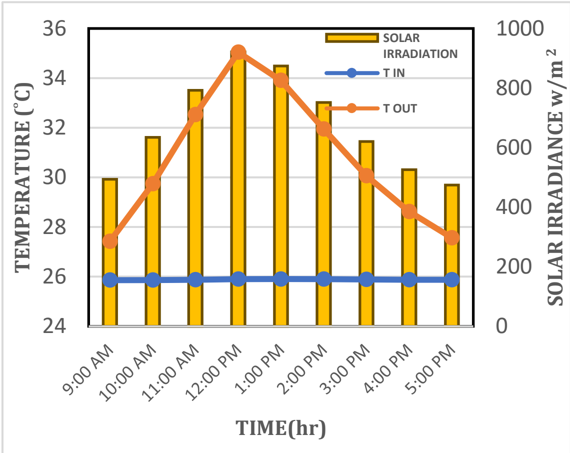

Fig. 5. Effect of solar irradiance on ambient temperature and outlet HTF temperature

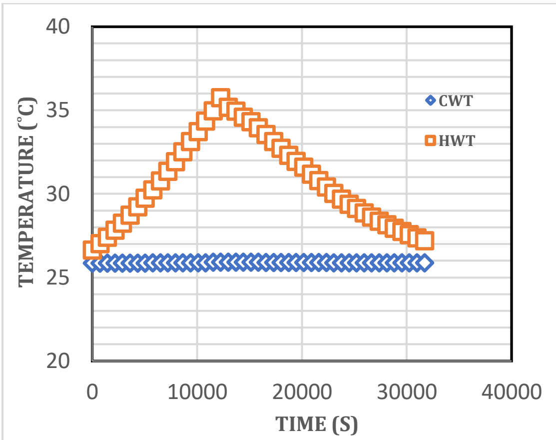

Fig. 6. Temperature Variation of Fluid

The highest inlet and outlet temperatures were 26°C and 37°C, respectively as seen in Figure 6, whereas the ambient temperatures varied from 25°C to 26°C due to consistent weather patterns, stable atmospheric pressure and time-of-day factors that limited the temperature fluctuations. The heat pipe condenser reached a maximum temperature of 105.6°C, influenced by changes in the mass flow rate.

Reflectors increase the amount of solar energy received by the collector surface by redirecting incoming sunlight. Figure 7 illustrates the evolution of the collector's total input energy rate on ETSC-HP surface over time. The findings show that the input energy rate closely resembles the trend of solar intensity, peaking and then gradually declining. When reflectors are added, the input energy is substantially increased.

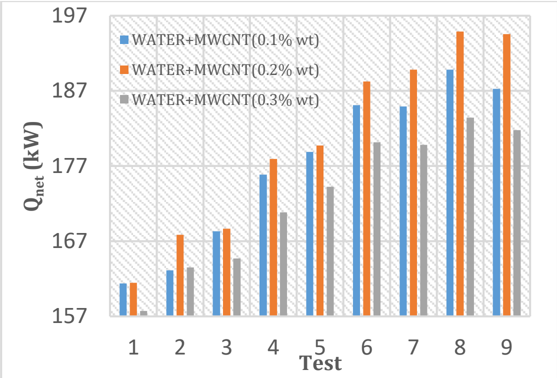

Fig. 7. Maximum heat absorption with different working fluids

The quantity of heat received directly affects effectiveness of heat transfer from the solar collector to the heated water. Enhanced heat absorption leads to better thermal performance, which increase the overall effectiveness of the solar water heating system. In this case, system's maximum heat absorption is 292 kW, and its maximum useful heat gain is approximately 196 kW, as illustrated in Figures 7 and 8.

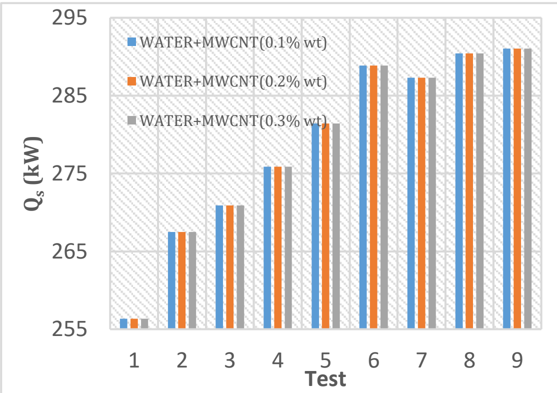

Fig. 8. Maximum heat gain with different working fluids

4.1. *Effect of Mass Flow Rate*

When external water flows through the heat pipe condenser in a solar water heater, a higher flow rate generally enables faster removal of heat from the pipes, keeping the condenser cooler and maintaining a greater temperature gradient, thereby improving overall heat transfer. In contrast, lower flow rates may lead to quicker saturation of the water temperature, reducing the cooling effect on the condenser and thereby decreasing heat transfer efficiency. Through improved heat transfer and collector performance, Figures 9-11 show that increasing the flow rate of distilled water substantially improves energy efficiency. Better collector efficiency results from an increased Reynolds number. Due in large part to Brownian motion, the efficiency values for mass flow rates of 0.004167 kg/s, 0.004722 kg/s, and 0.00556 kg/s were 64.37%, 59.11%, and 58.17%, respectively.

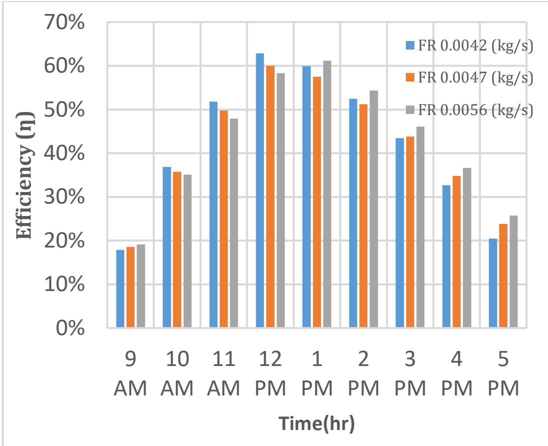

Fig. 9. Effect of different Flow rates (water + MWCNT (0.1%wt))

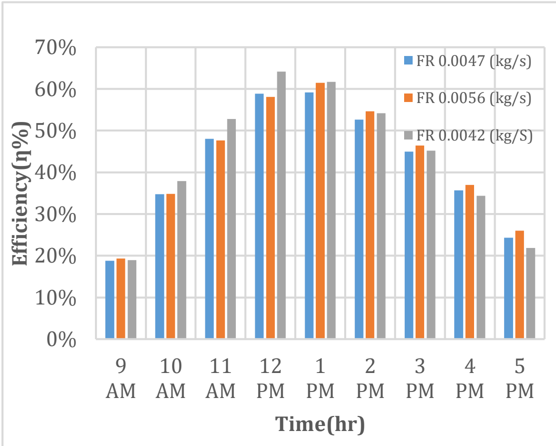

Fig. 10. Effect of different Flow rates (water + MWCNT (0.2%wt))

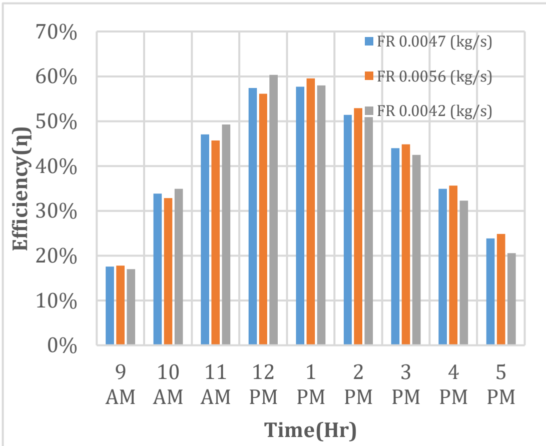

Fig. 11. Effect of different Flow rates (water + MWCNT (0.3%wt))

The greater flow rate improves overall efficiency and convective heat transfer by amplifying the random motion of particles and increasing the possibility of collisions among liquid molecules. Higher concentrations improve efficiency and heat gain, whereas ideal concentrations improve heat conductivity and viscosity of the working fluid (Figure 8).

4.2. Effect of Inclination Angle

The absorption of solar radiation is influenced by inclination variations; steeper angles may result in greater heat loss and lower efficiency at certain times of the day. In conclusion, excessively steep angles might result in higher thermal resistance and operational difficulties, whereas lower inclination angles often improve heat transfer performance and uniformity.

The thermal efficiency of ETSWHs is greatly affected by their inclination angle as seen in Figures 12-14. Optimizing this angle can improve system efficiency, especially when combined with appropriate parameters such as flow rate, inclination angle, and concentration of nanofluid, as illustrated in Figure 11. The optimal inclination angle for the ETSWH is 35°, in which the thermal efficiency peaks at 67.11% with 15 L/h and a 60% filling ratio.

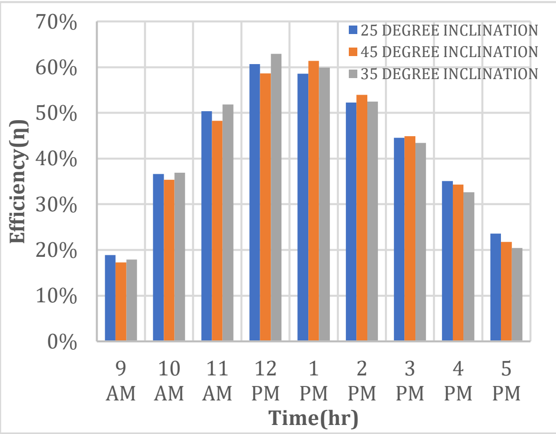

Fig. 12. Effect of different Inclination Angles (water + MWCNT (0.1%wt))

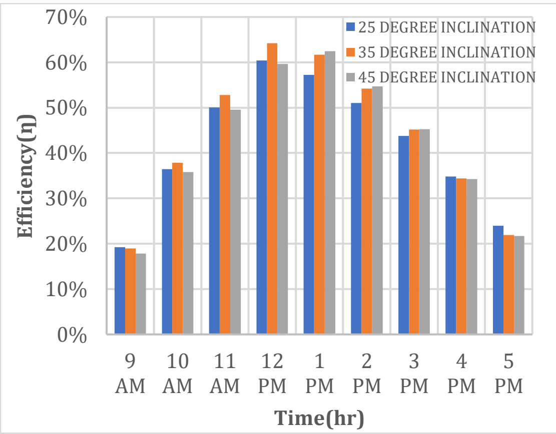

Fig. 13. Effect of different Inclination Angles (water + MWCNT (0.2%wt))

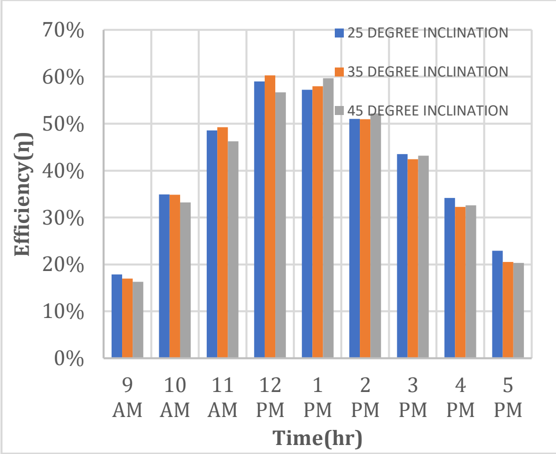

Fig. 14. Effect of different Inclination Angles on (water + MWCNT (0.3%wt))

4.3. Effect of Filling Ratio

The thermal efficiency of heat pipes can be greatly affected by changes in filling ratio, which also influences flow dynamics, startup behavior, and thermal resistance. The complexity of this relationship is highlighted by the fact that the optimal filling ratio varies depending on the particular type of working fluid used. The observed transition is primarily attributable to a complex interplay between hydrostatic pressure, flow resistance, and the dynamic behavior of the two-phase fluid within the system.

At lower filling ratios, the limited liquid volume results in insufficient hydrostatic head to overcome frictional resistance throughout the collector. This leads to cyclical flow reversals driven by localized pressure fluctuations and intermittent vapor generation. However, as the filling ratio increases beyond the stated threshold, the increased hydrostatic pressure establishes a dominant pressure gradient that effectively suppresses these flow reversals. This transition to unidirectional flow signifies a more stable and predictable operational regime for the solar collector, potentially optimizing heat transfer efficiency by ensuring consistent fluid movement and minimizing localized stagnation zones.

When filling ratios are altered in the setting of heat pipes, as seen in Figure 15, thermal resistance first falls as well as then rises, reaching a minimum at a 50% filling ratio. Particularly in situations with high heat input, it has been discovered that a filling range of 40% to 50% minimizes thermal resistance.

Between 40% and 50% filling ratios, the flow becomes unidirectional instead of oscillatory, enhancing the efficiency of heat transfer. At a 40% filling ratio with maximum efficiency as seen in Figure 16, the best performance was noted, which indicates that lower filling ratios might also be efficient under particular conditions. In summary, lower filling ratios might be advantageous in some situations, even though larger ratios can enhance the performance of these systems.

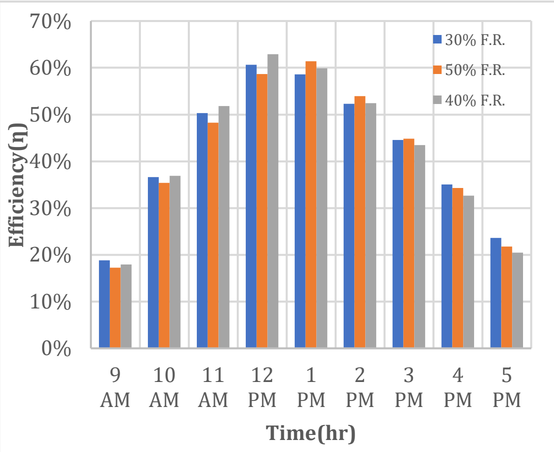

Fig. 15. Effect of filling ratio on water +MWCNT (0.1%wt)

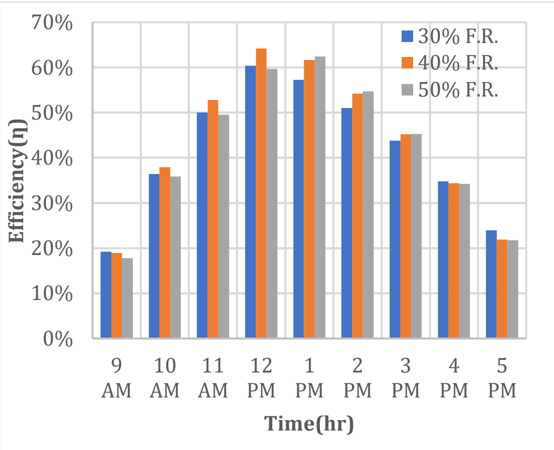

Fig. 16. Effect of filling ratio on water +MWCNT (0.2%wt)

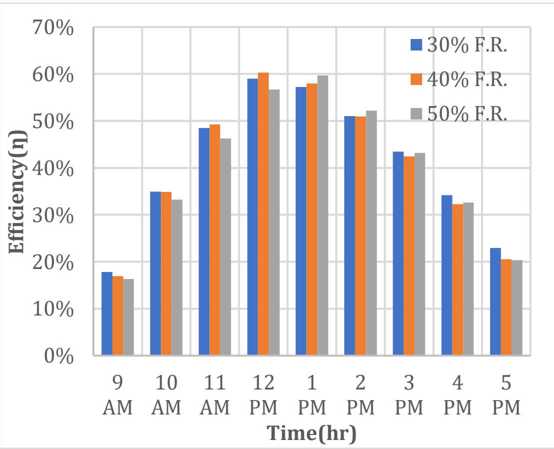

Fig. 17. Effect of filling ratio on water +MWCNT (0.3%wt)

4.4. Future Scope

The possibility of increasing solar collector efficiency offers an intriguing direction for further investigation. The application of a hybrid nanofluid as a working medium in conjunction with an evacuated tube thermosyphon heat pipe merits more research. The discovery of designs that optimize solar radiation absorption will be made possible by comparative examinations of different collector profiles. Furthermore, there is potential for greatly enhancing the whole performance of solar collectors through investigation of various absorber tube shapes and the incorporation of phase change materials for thermal energy storage. Optimizing the capture of solar radiation may also be achieved by utilizing highly reflective materials in the collector's structure. Additionally, altering the nanofluid's particle size and concentration causes changes in flow behavior, which encourages a more uniform distribution of temperature throughout the collector surface. Consequently, absorber systems' effectiveness is increased. These improvements and optimizations would support the continued development of solar energy systems with greater efficiency.

5. Conclusions

In conclusion, the findings of this study carry significant practical implications for the optimization of solar collector design.

- Enhanced nanofluid TC, particularly at a 0.2%wt concentration of MWCNT nanoparticles, demonstrably improves heat transfer and overall thermal efficiency within solar systems. This improvement arises from the increased surface wettability and enhanced bubble formation facilitated by the nanoparticles, effectively expanding the surface area available for heat transfer.
- Furthermore, the identification a 45° tilting angle as optimal, yielding a peak instantaneous efficiency of 67% and minimizing the gravitational forces acting on the working fluid, consequently alters the heat transfer rate.
- Similarly, the determination that a 40% filling ratio results in a 63% instantaneous efficiency ensures effective heat transfer and reduces heat loss reduced offering another valuable insight for practical application.
- Finally, the observed peak efficiency of 64% at 0.0042 kg/s the optimal mass flow rate, which significantly impacts

performance and temperature uniformity, underscores the importance of carefully calibrating fluid dynamics within the collector.

These specific values optimize performance by striking a balance between maximizing solar energy absorption, promoting efficient heat transfer, and minimizing thermal losses, ultimately contributing to more effective and efficient solar energy harvesting.

Nomenclature

I	Solar irradiation [kW/m^2]
A	Surface area [m^2]
Q_s	Incident Solar Irradiation [kW]
Q_{net}	Thermal energy Fluid Acquired [kW]
T_{in}	Inlet Temperature [˚C]
T_{out}	Outlet Temperature [˚C]
C_p	Specific enthalpy [kJ/kg]
I	Exergy destruction rate [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Authors Contribution Statement

Jignesh Patel: Writing – review & editing, Writing – Original draft, Resources, Methodology, Conceptualization, Investigation.

Vijay Dhiman: Review & editing, Supervision, Software, Project administration, Formal" analysis.

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