International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 1, February, 2024, pp. 31-39
Journal homepage: http://iieta.org/journals/ijdne

Enhancing Thermal Efficiency in Solar Water Heaters Using Reflective Mirrors

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https://doi.org/10.18280/ijdne.190104

Received: 3 November 2023
Revised: 22 January 2024
Accepted: 29 January 2024
Available online: 29 February 2024

Keywords:
mirror reflectors, solar vacuum tube systems, reflective technology, thermal efficiency, and reflective walls

ABSTRACT

With the development of solar energy collection technologies and the mechanism of exploiting solar energy as renewable energy, it was necessary to develop a solar vacuum tube system, which is considered one of the old systems with little efficiency. In order for the development process to be completed, it was necessary to place side reflectors that border the pipes from all sides to better reflect solar radiation and raise the temperature of the pipes to the required level. The optimal angle for increasing temperature was determined by adjusting the sidewalls of mirrors, adjusting the wall width, and comparing angles at various angles (30, 40, 50, 60, 70, 80, 90) degrees, to achieve the best results. The angle of the mirrors on the pipes is adjusted from 30 to 90 degrees, as well as their width from 250 mm to 500 mm, and from 5 a.m. to 5 p.m., with a difference of one hour each reading. The temperature gradient on solar collector tubes increases with time and mirror angle, reaching maximum at noon and 30 degrees. Infrastructural radiation increases significantly at 30 degrees, reaching 700 W/m^2. The width of the mirror wall affects radiation reflection and distribution, with a 500 mm width being more effective. The 30-degree angle had the highest thermal efficiency at 84%, while a 500 mm width difference achieved 86%. The novelty of the work varies in terms of developing the thermal efficiency of the solar collector by adding these influential factors to it.

1. INTRODUCTION

For both residential and commercial use, solar water heaters-such as integrated pressure solar water heaters, or IPSWHs-are a clean, sustainable energy source. This quickens the heating process to increase thermal efficiency, enabling IPSWHs to perform better and reach higher water temperatures. By using this method, thermal efficiency might be greatly increased, resulting in lower energy expenses and consumption.

The research explores an air-type double-pass solar collector with a PCM-rod inserted in a vacuum tube, based on an evacuated tube collector. A thermal model was developed to forecast the collector's output temperature, and the change in the collector's thermal efficiency is explained by the corresponding thermal efficiency of the phase change material. The thermal performance of the collector is evaluated and compared to expected values. The results showed high agreement among simulated and empirically found outlet temperatures, with the output temperature slightly losing by using 7.5 K even after half-hour of irradiation intensity. The impact of radiation intensity, ambient temperature, airflow and surrounding air speed on the result temperature were analyzed utilizing thermal model. The phase change material drags out the collector's working duration with the guide of 8 hours, putting away 0.247 MJ of intensity, and arriving at a conversion rate of 99.2% [1]. A solar thermal storage heating system has been progressed and tried, consolidating solar collector heat storage units (HSU) stacked with phase-change material (PCM) and finned heat pipes. The machine offers compactness, simplicity, intelligence, quick heat storage and dissipation rates, and higher utilization efficiency. It will be utilized in green heating, agricultural greenhouse heating, and temperature control systems. The system's performance was studied under various conditions, including solar radiation intensity, equipment elevation angle, ambient air temperature, and flow rate. The optimal elevation angle turned into 60°, and higher heat storage capacity and rate were performed with greater extensive solar radiation. The device's efficiency reached 97% at 18°C and 6.0 m/s in a wind tunnel [2]. A look at on micro heat pipe arrays (MHPA)-primarily based vacuum tube solar air collectors has determined that smaller entrances growth performance because of much less heat loss to the surroundings. The examiner additionally found that between

50% and 70% of thermal efficiency changes every day. Variable go with the flow rates have been used to assess changes in performance, outlet temperature, MHPA temperature behaviour, sun radiation, and airflow rate. The findings advised that MHPA-primarily based vacuum tube solar air collectors have capability for big-scale applications, together with area heating in farms, industrial buildings, and isolated outposts [3].

The study examined a double basin solar still with vacuum tubes in Mehsana, Gujarat, for a yr. The lower basin became linked to traditional vacuum tubes, resulting in better water temperature and distillate output. The latent heat of condensation, increasing distillate output, heated the upper basin. The system with a depth of 0.03 m generated greater distillate, with a mean of 8 and a water value of around 0.37 Rs/kg [4]. This painting offered a solar air-heating device, such as a vacuum tube air solar collector (SC) and latent heat thermal energy storage (LHTES). The SC heat is stored in the course of the day and launched into the constructing at night thru LHTES, increasing sun power use for heating, especially in low-power buildings with passive heating. The concentric-tube LHTES layout became optimized for optimal air temperature and height heat supply. The system's overall performance confirmed that 54-67% of the heat generated all through the day might be transported to the constructing for heating [5]. The examiner provided a solar still with a spiral-shaped multiple-effect diffusion unit, ensuing in a considerable day by day easy water output of 40.6 kgd^{-1}. The maximum productiveness turned into found at 34.7, 40.6, and 7.96 $kgm^{-2}d^{-1}$, with a performance range of 2.0-3.5%. The overall performance improvement is attributed to the lateral diffusion mechanism within the spiraling still cell, which permits vapour drift freely and laterally via the spiral channel while solar heat input is powerful [6]. A double-basin solar still with vacuum tubes is being advanced to growth the distillate yield of a solar still. The research record investigates the top basin of the current solar still with energy-absorbing materials like calcium stones, black granite gravel, and pebbles.

The six-month results confirmed that calcium stones have a better distillate yield than black granite gravel and pebbles, making the present day solar still extra realistic for the universe's potable water supply [7]. The latent heat of condensation in single basin solar stills is dissipated into area, making it tough to enhance distillate production. To deal with this, a second basin became attached to the primary basin, and vacuum tubes were attached to the bottom basin of the double-basin solar still. This improved overall performance with the aid of permitting the lower basin to preserve a better temperature for the duration of the day. However, the top basin's distillate yield was lower. A specific technique become proposed, which protected adding energy storage materials like pebbles, black granite gravel, and calcium stones to increase the basin area. Experiments showed that calcium stones produced extra distillate (74%) [8]. The study has a look at proposed a multiple-effect diffusion solar still (MEDS) with a bended-plate design in a multiple-effect diffusion unit (MDU) to address the peel-off problem with wick material. The MEDS-1L prototype turned into tested outdoor, and its performance was assessed the usage of four performance indices: day by day output of pure water consistent with unit area of glass cover, sun absorber, and evaporating surface (Mcov, Msol, and Mevp), and solar distillation efficiency (Rcov). The MEDS-1L achieved a solar collector supply temperature of 100°C at 800 Wm^{-2} solar radiation, with the highest Mcov of 23.9 $kgm^{-2}d^{-1}$. The measured (Rcov) was greater than the basin-type MEDS [9]. This study introduced a new solar cooker based on a vacuum tube, featuring a one-dimensional solar tracking system and a solar collector made of rectangular glass mirror strips. The cooker can reach temperatures up to 250°C and offers more cooking power than traditional models due to its larger collecting surface. Additionally, the study offers theoretical performance analysis, comparative experimental results utilizing a 1.775 m^2 collector prototype, and cost/benefit analysis [10].

This study included single and two-phase flows to investigate the thermal performance of a single vacuum tube solar collector with coaxial pipework. The model solved a discretized set of equations describing flow conditions and heat transfer procedures using an analytical steady state model. For a good vacuum, the performance curve for single-phase flow varies with growing collector temperature; although, at low pressure, it agrees nicely with gas conduction. For all-liquid, single-phase fluid flow, the model proven that collector performance decreases with decreasing mass go with the flow rate [11]. This has a look at covered single and two-phase flows to investigate the thermal performance of a single vacuum tube solar collector with coaxial pipework. The model solved a discretized set of equations describing go with the flow conditions and heat transfer processes usage of an analytical steady state model. For an excellent vacuum, the efficiency curve for single-flow go with the flow varies with growing collector temperature; despite the fact that, at low pressure, it consents well with gas conduction. The version confirmed that collector performance declines with decreasing mass flow rate for all-liquid, single-phase fluid flow [12]. The goal of this examine was to build a heat transfer model with an all-glass vacuum tube collector for a pressured-flow solar water heating system. The model includes forced flow in a manifold header and natural convection in a single glass tube. The thermal balance equations for water and flow equations are built, taking into account the relationship among collector temperature, outlet temperature, and natural convection flow rate. The model's validity become tested in the course of wintry weather tests in Beijing [13]. A 3-dimensional analytical model become used to study the thermal overall performance of a parallel all-glass vacuum tube solar system. Water flows thru the tubes to take in solar heat energy. To improve heat transfer and prevent freezing, antifreeze solution is placed between the fluid conduit and glass tube. This version predicts spatial adjustments in water temperature, helping perceive key factors for the solar machine's functioning when using all-glass vacuum tubes [14]. A study analyzed a solar device together with double-skinned, all-glass solar vacuum tubes. The tubes have a coaxial fluid conduit for heating water, and antifreeze answer is poured to hurry up heat transmission and save you freezing. The results confirmed brilliant settlement with experimental statistics, proving the validity of the modern version. The one-dimensional numerical version may be used to assemble solar collector tubes with different geometrical characteristics [15].

Integrating mirrors to enhance the incidence solar radiation beams on the collector surface is a capacity strategy to enhance the thermal efficiency of IPSWHs. In this idea, mirrors are cautiously located to focus sunlight onto the solar collector, accelerating the heat absorption method. In order to enhance solar energy absorption and raise the temperature of the water inside the system, the solar water heater's ordinary efficiency should be increased. Although the notion of using mirrors to magnify incoming solar radiation beams isn't always new, it has these days attracted clean attention because of its capacity to improve the efficiency of solar thermal systems. IPSWHs can function better even in less ideal weather circumstances by increasing the solar energy input, which leads to higher water temperatures, faster heating times, and higher water temperatures. This development is especially essential in areas with unpredictable weather since it guarantees a steady and dependable supply of hot water all year long. The objectives of the study are to enhance the thermal efficiency of the solar collector by incorporating these significant parameters.

2. METHODOLOGY

COMSOL Multiphysics is a finite element analysis program used to simulate and resolve various physics and engineering issues. It involves modelling geometry, meshing, selecting physics modules, defining boundary requirements, and material characteristics. The program also allows metaphysics capabilities. However, familiarity with the software and understanding of the simulation's physical principles is required. As technology for solar energy collecting and solar energy use have advanced, solar energy is becoming a viable source of renewable energy. A solar vacuum tube system, which is regarded as one of the outdated and inefficient methods, has to be developed. To better reflect solar radiation and increase the temperature of the pipes to the desired level, side reflectors that surround them on all sides had to be installed before the development process could be finished. To find the ideal angle that would have the most impact on rising the temperature, many lengthy angles were taken. A container of mirrors was built covering the bottom and sides of the solar vacuum tube to reflect solar radiation onto the tubes, and an absorbing wall at the back. The sidewalls of the mirrors were angled at several angles (30, 40, 50, 60, 70, 80, and 90) degree for all mirror in order to compare them and see the best results. The wall width of the reflectors was also changed to 250 mm and 500 mm.

2.1 Governing equations

●Radiative heat transfer

The radiative heat transfer equation describes the heat transfer due to solar radiation. The equation can be expressed as:

$$Q_{\text{rad}} = A \cdot \epsilon \cdot \sigma \cdot (T_{\text{mirror}}^4 - T_{\text{ambient}}^4) \tag{1}$$

where, Q_{rad} is the radiative heat transfer (W). A is the surface area of the mirrors (m^2). ϵ is the emissivity of the mirror surface. σ is the Stefan-Boltzmann constant $\left(5.67 \times 10^{-8} \text{W}/(\text{m}^2 \cdot \text{K}^4)\right)$. The temperature of the mirrors is T_{mirror} (K). The ambient temperature (K) is given by T_{ambient}.

●Mirror reflection

The reflectivity (R) of the mirror surface can be used to compute the percentage of incident solar radiation that is reflected by the mirrors. The reflected radiation is given by:

$$Q_{\text{reflected}} = (1 - R) \cdot I \tag{2}$$

where, $Q_{\text{reflected}}$ is the reflected solar radiation (W/m^2). R is the reflectivity of the mirror surface. I is the incident solar intensity (W/m^2).

●Solar collector heat absorption

The amount of solar energy absorbed by the solar collector can be determined by considering the intensity of concentrated solar radiation and the collector's absorptivity (α):

$$Q_{\text{absorbed}} = \alpha \cdot I_{\text{concentrated}} \tag{3}$$

where, the absorbed solar energy (W/m^2) is denoted by Qabsorbed. The collector surface's absorptivity is represented by α. The concentrated sun intensity (W/m^2) upon reflection is denoted as $I_{concentrated}$.

●Energy balance in the collector

The solar collector's energy balance formula accounts for both heat losses and solar energy absorption. It can be expressed as:

$$Q_{\text{absorbed}} = Q_{\text{losses}} + \dot{m} \cdot C_p \cdot (T_{\text{outlet}} - T_{\text{inlet}}) \tag{4}$$

where, the heat losses (W/m^2) are denoted by Q_{losses}. The heat transfer fluid's mass flow rate, or kg/s, is represented by $\dot{m}$. The fluid's specific heat capacity, expressed in J/(kg·K), is Cp. The fluid's output temperature (K) is Toutlet. Tinlet is the fluid's inlet temperature (K).

These equations provide the foundation for simulating the thermal performance of an integrated pressure solar water heater with mirrors to enhance solar radiation capture and thermal efficiency. Depending on your specific simulation setup and assumptions, you may need to consider additional equations and boundary conditions for a comprehensive analysis.

2.2 Mesh generation

As can be seen in Table 1, the solar heater was created to fit the actual size of the business. The choice of the unstructured 3D grids was made since they are effective with intricate geometries. A solid geometry mesh and 3D model were created using COMSOL as shown in Figure 1. This research used 1191665 cells in total (see Figure 2).

Table 1. Specifications of vacuum tube [16]

Inner Tank	Thickness: 0.5 mm^2
Outer Tank	Thickness: 0.4 mm^2
Vacuum Tube	D58-L1800 mm
Frame	Thickness: 1.2-1.5 mm
WATERTANK	460 mm
TUBE	30
Diameter	58 mm
Length	1.8 m

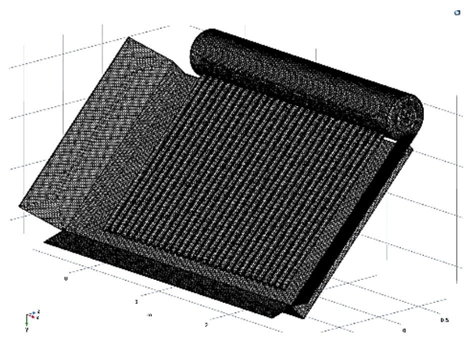


Figure 1. Mesh generated

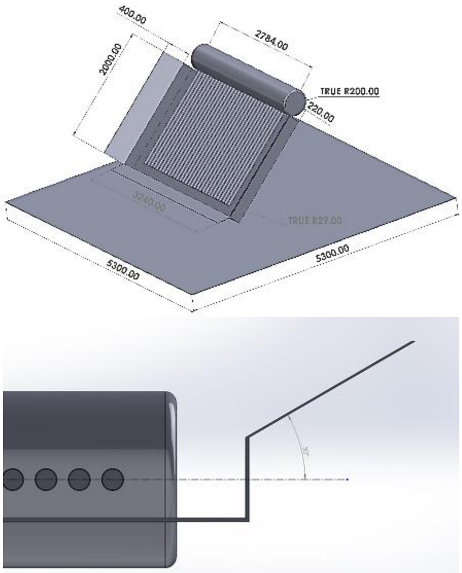


Figure 2. System geometry

For accurate results, the mesh size should be changed so that the output can be tracked as the number of elements is increased. When the output stability is attained with a mesh size of 0.001 m, the procedure ends the error of result was 0.29% (see Table 2).

Table 2. Mesh independency

Case	Element	Max. Temperature (K)	Error %
1	352603	348	-
2	603454	339	2.58
3	963423	336	0.88
4	1191665	335	0.29

2.3 Boundary conditions

Reflecting mirrors were used to cover the solar system to reflect a greater amount of incident solar radiation. A material was also used that absorbs incoming radiation at the same distance from the solar collector. In order to estimate the amount of incident solar radiation with great accuracy, the coordinates of the target location (Baghdad), and the angle of the mirrors on the pipes is adjusted from 30 to 90 degrees, as well as their width from 250 mm to 500 mm, and from 5 a.m. to 5 p.m., with a difference of one hour each reading. To obtain the greatest possible time, the sun's rays can be focused on the solar collector. The increase in the temperature of the solar collector increases the efficiency of the system significantly through the reflectors and mirrors used.

3. RESULTS AND DISCUSSION

In this section, the results will be reviewed and discussed with regard to reflector angles, and dimensional details. The thermal efficiency of the system will also be discussed.

3.1 Effect of mirror angles

A solar water heater's effectiveness and water temperature may be considerably raised by using mirrors to focus solar energy on the device. The new design of the solar water heater by placement the mirrors and its angle are only the two variables that affect temperature and overall performance. A critical factor is the orientation of the mirrors. Mirrors should be positioned such that sunlight is reflected onto the absorber or collector panels of the solar water heater.

The mirror angle may sometimes be changed to follow the seasonal passage of the sun. To optimum sunlight collection at higher latitudes, mirrors may need steeper angles in the winter and shallower angles in the summer, according to the geographical location of the study. In an integrated pressure solar water heater, a number of variables affect how the temperature and system performance are affected by mirror angles.

Through Figure 3, which shows the temperature gradient with varying time and with the change in the angle of the mirror in relation to the solar collector tubes, it is noted that the temperature value begins to rise to reach its maximum at one o'clock in the afternoon. Which in turn is at the maximum value of the angle of 30 degrees, where it reached 330 K, which is the highest. A temperature reached compared to other cases and with stable temperatures in the hours when the sun's rays set.

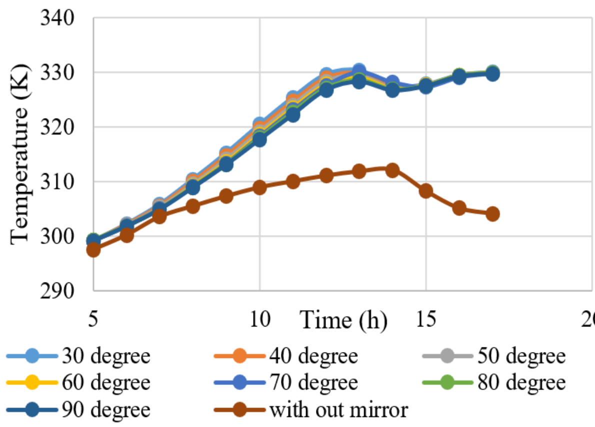


Figure 3. Temperature gradient by using mirror at different angle between mirror wall and vacuum pipe

As for the incident solar radiation, depending on the angle of entry of the rays into the tubes, the radiation value increases significantly to reach 680 W/m^2 at an angle of 30 degrees, and this differs from other cases in terms of preference, as shown in Figure 4.

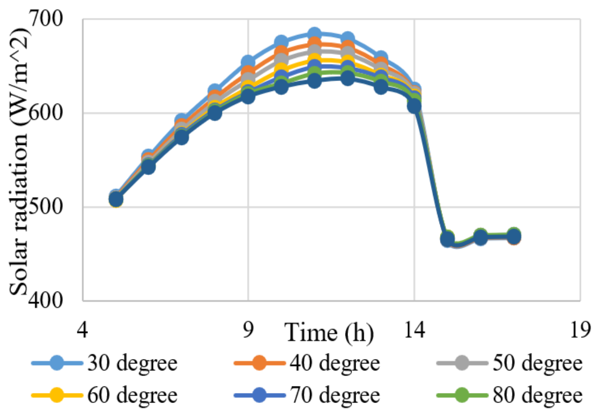
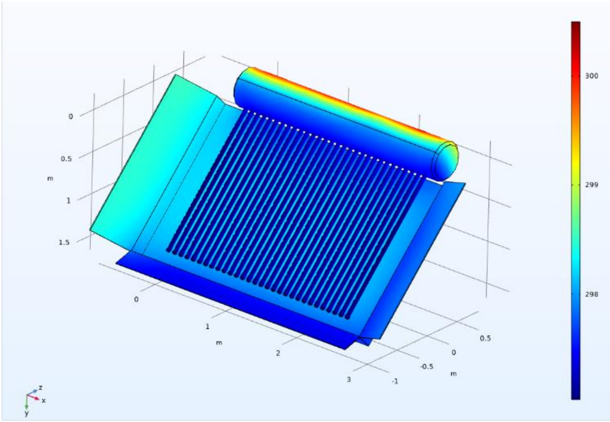
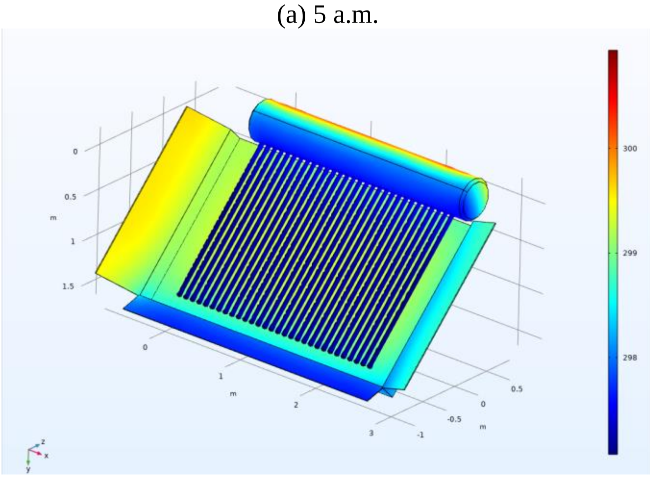


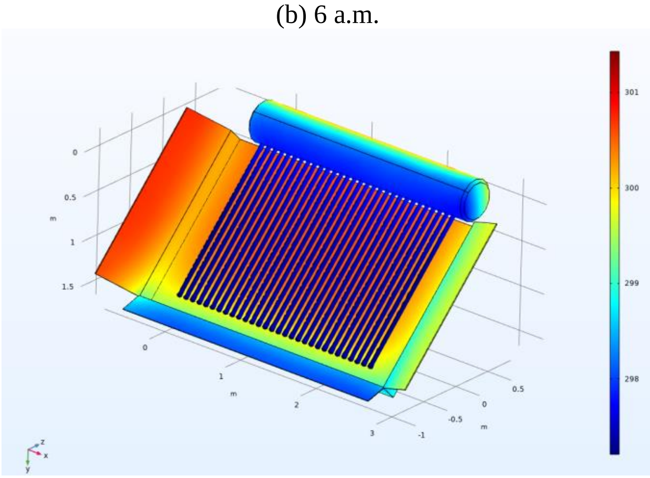
Figure 4. Solar radiation gradient by using mirror at different angle between mirror wall and vacuum pipe



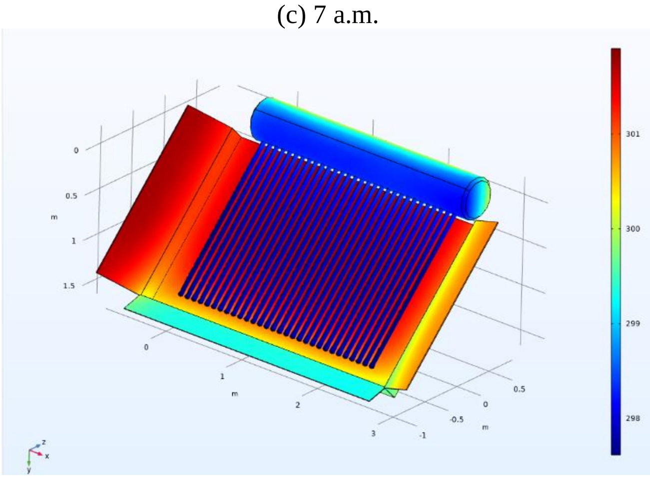
(a) 5 a.m.



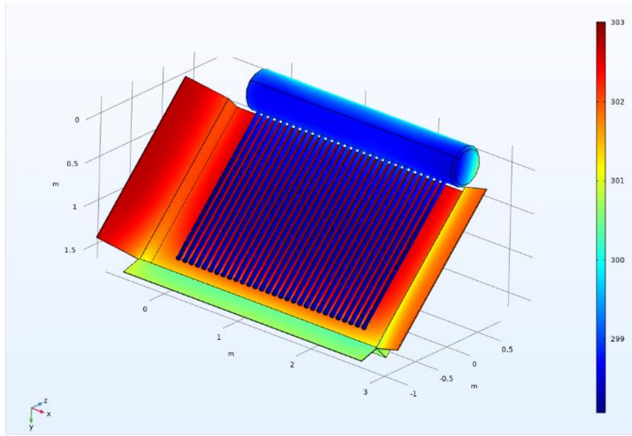
(b) 6 a.m.



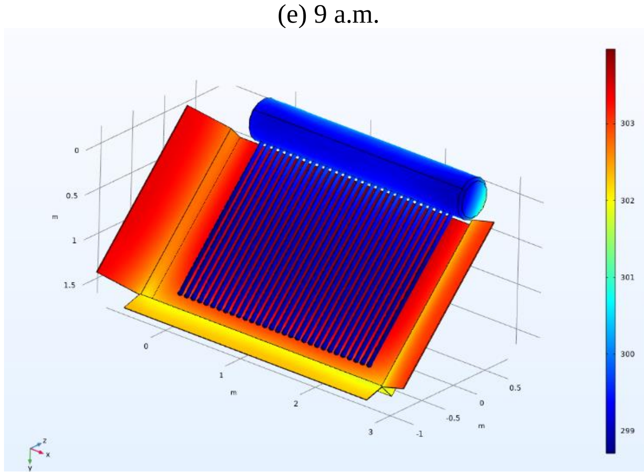
(c) 7 a.m.



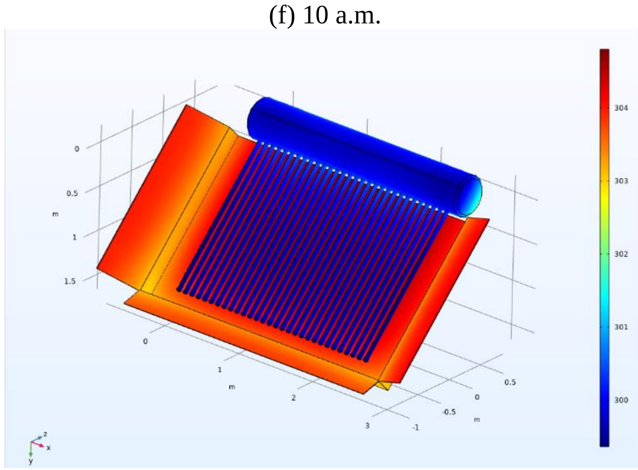
(d) 8 a.m.



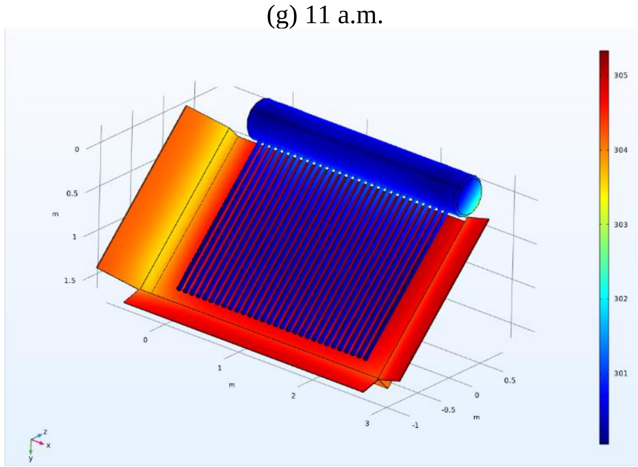
(e) 9 a.m.



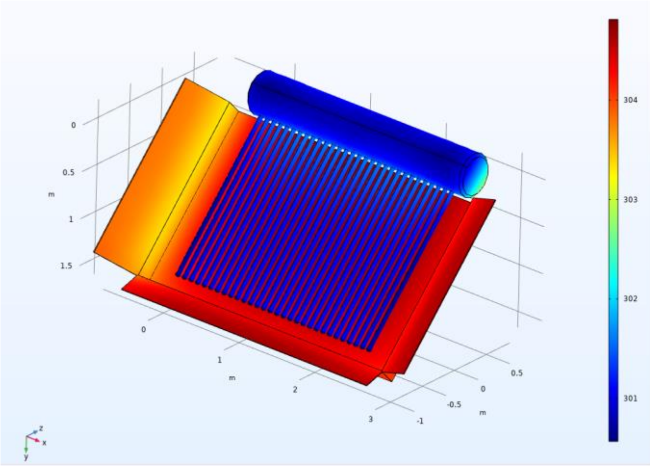
(f) 10 a.m.



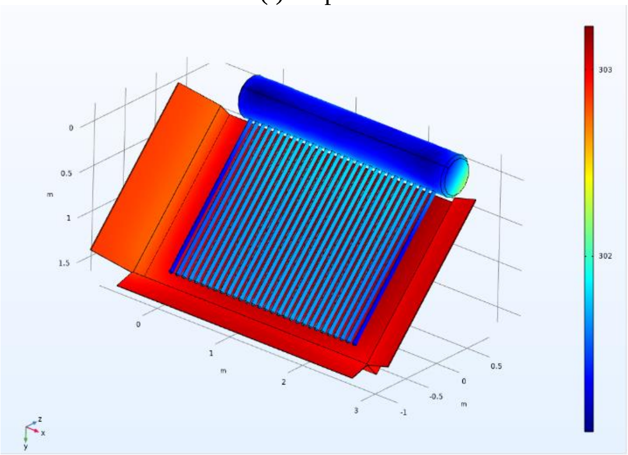
(g) 11 a.m.



(h) 12 p.m.



(i) 13 p.m.



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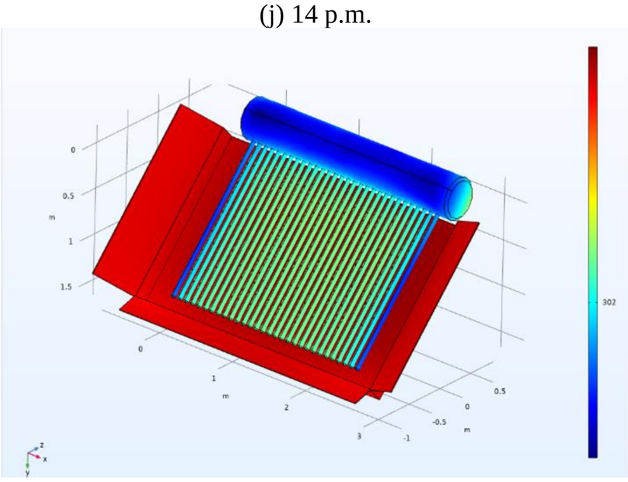
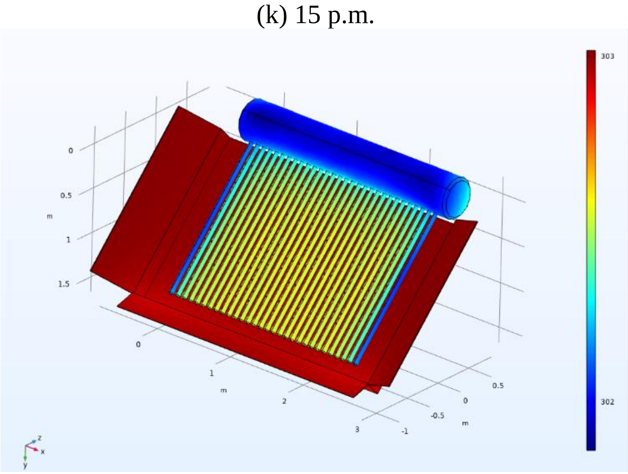
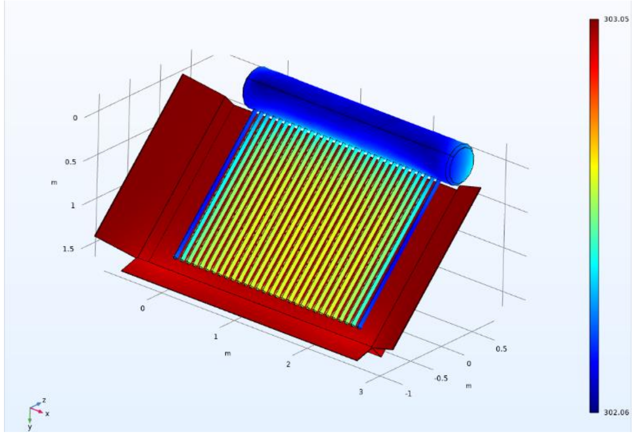


(k) 15 p.m.



(l) 16 p.m.



(m) 17 p.m.

Figure 5. Temperature contours by using mirrors for angle between mirror wall 30 degree and vacuum pipe at different time

Figure 5 shows the distribution of temperatures on the solar collector according to different timings from morning to evening. From it, it is seen that the temperature value increases due to the effect of reflected radiation on the mirrors, which in turn increases the pipe temperatures.

3.2 Effect of mirrors wall width

The width of a solar water heater's mirror wall can significantly influence its temperature and functionality. The mirror wall's width can increase the amount of solar energy collected by the system by capturing and reflecting more sunlight onto the solar collector. However, this does not guarantee increased performance. The best angles for the mirrors must be considered, as they can affect the energy absorption. Wider mirror walls may cause shadowing problems, which can affect the uniformity of solar light dispersion on the absorber. To reduce the impact of shadowing, careful planning is required. High-quality mirrors with high reflectivity are essential for the absorber to receive the most sunlight. Regular cleaning and maintenance are essential for maintaining the mirrors' high reflectivity.

From Figure 6, which shows the effect of the width of the mirror wall on reflecting radiation and distributing it significantly, it is noted that the width of 500 mm is much better compared to 250 mm, which in turn raised the temperature to 335 K in 500 mm as average temperature for the hole domain, which is the best condition that has been achieved. The reason for this is the distribution of the falling radiation on the tubes in a uniform manner is larger.

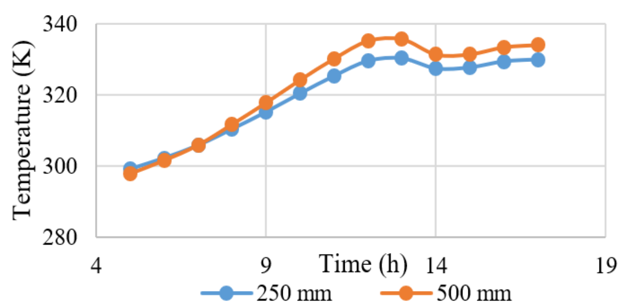


Figure 6. Temperature gradient by using mirrors at different mirrors wall width

It is certain to obtain greater solar radiation distributed throughout the solar system, and this is what is observed in Figure 7, which in turn gives a strong impression of the effectiveness of the width of the mirror wall in improving the magnitude of solar radiation, which reached 710 W/m^2.

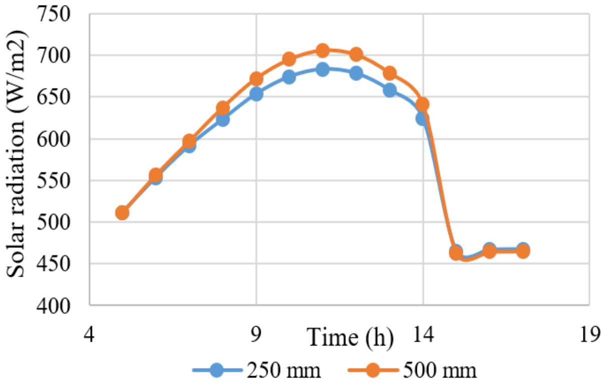


Figure 7. Solar radiation gradient by using mirrors at different mirrors wall width

3.3 Thermal efficiency

The thermal efficiency of a solar thermal system is directly influenced by the width of the mirror wall. A wider mirror wall captures and reflects more sunlight, resulting in increased solar energy capture. leading to higher temperatures and increased thermal efficiency. In partially sunlit conditions, a larger mirror wall is more efficient, maintaining higher thermal efficiency throughout the day. Additionally, a wider mirror wall reduces energy losses due to dispersed or inadequately collected sunlight. To improve thermal efficiency, the mirror wall's angles must be designed correctly, ensuring that sunlight is precisely focused on the absorber.

Figure 8 shows the thermal efficiency of the thermal collector through the different angles of the reflectors with the tube. It is noted that the thermal efficiency of the 30-degree angle was greater compared to other angles, as it reached 85%.

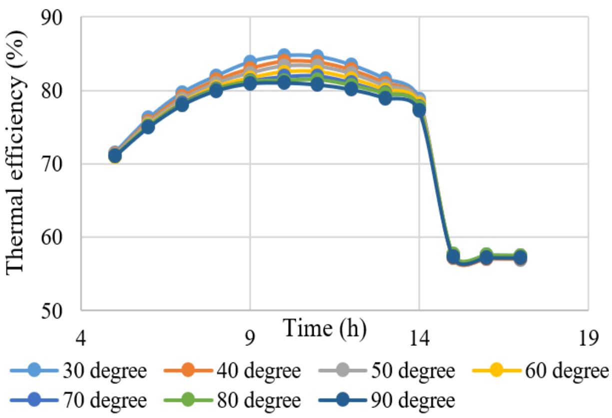


Figure 8. Solar radiation gradient by using mirrors at different mirrors wall width

As for the comparing between the width of the mirrors wall, the width of 500 mm, as it can be seen from Figure 9 that it reached 86% thermal efficiency, which is the best case achieved compared to other cases which represents the peak.

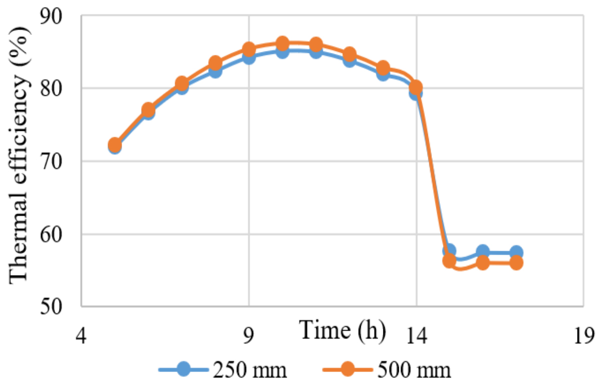


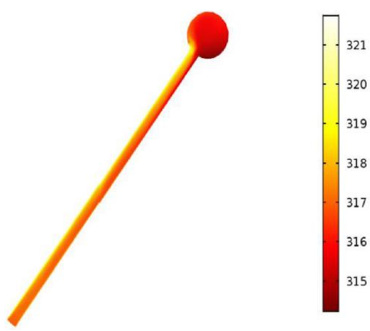
Figure 9. Thermal efficiency gradient by using mirrors at different mirrors wall width

Mirror-based systems require regular maintenance to maintain their performance and reflectivity. Factors like environmental conditions, usage patterns, and mirror technology influence maintenance needs. Accessibility, clear cleaning guidelines, automated monitoring systems, and professional inspections are essential. A maintenance schedule based on installation site conditions and technology is recommended. Mirror-based solar thermal systems are gaining popularity due to their improved efficiency, making them economically viable and attractive. They are suitable for residential and industrial settings, and can be integrated with other renewable energy systems for reliable energy solutions. Governments may incentivize or mandate these systems to meet renewable energy targets.

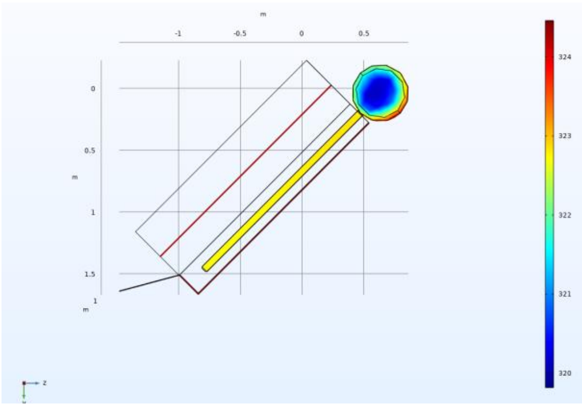
The main limitation that was addressed is the lack of complete flexibility in studying all the real effects of flow and mixing and many physical concepts that are limited to super computers.

3.4 Validation to previous research

A comparison with previous research conducted by Sadeghi et al. [17] showed the importance of adding reflectors in improving heat transfer. The same characteristics, dimensions and details used in previous research were used and applied in the simulation software with the addition of a model to see the obvious improvement in the process. Simulation with regard to temperature, as it is noted that the maximum amount of heat reached during previous research simulations is 321 K. Instead, in the work done by adding reflectors, it is observed that the temperature reached 326 K, which is a clear improvement regarding the proposed idea and research study with this addition, see Figure 10.



(a) Sadeghi et al. [17] work



(b) Present work

Figure 10. Temperature profile of the ETSC water heater with 26 Lit tank capacity

4. CONCLUSIONS

Solar energy is becoming a feasible source of renewable energy as solar energy collection and use technology advances. A solar vacuum tube system, which is considered an obsolete and inefficient approach, must be developed. Before the development process could be completed, side reflectors that encircle the pipes on all sides had to be added to better reflect solar radiation and raise the temperature of the pipes to the necessary level. Different angles were taken to identify the perfect angle that would have the most influence on raising the temperature. The results can be summarized as follows:

1. The temperature gradient on the solar collector tubes increases with time and mirror angle, reaching its maximum at noon and 30 degrees, reaching 330 K. The temperature remains stable during the sun's ray set hours. Infrastructural radiation increases significantly at 30 degrees, reaching 700 W/m^2, differing from other cases. The distribution of temperatures on the solar collector varies from morning to evening, with increased temperature due to reflected radiation on mirrors and tubes.
2. The study demonstrates that the width of the mirror wall significantly affects the reflection and distribution of radiation. A width of 500 mm is found to be more effective than 250 mm, resulting in a temperature increase of 335 K. This is due to uniform distribution of falling radiation on tubes, resulting in greater solar radiation distribution throughout the solar system.
3. The study analyzed the thermal efficiency of a thermal collector using different reflector angles and tube. The 30-degree angle had the highest efficiency at 84%, while a 500 mm width difference in the mirror wall achieved 86% thermal efficiency, making it the best case.

For future work, the efficiency of the mirrors may be increased by using a tracking system that moves with the sun throughout the day to make sure that the heater is constantly receiving sunlight. To fully use concentrated solar energy while guaranteeing safe and effective operation, proper design, tracking, and maintenance are essential. During system design and installation, site-specific factors like latitude and shading should also be taken into account.

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