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An Experimental Analysis of Solar Geysers with Direct Flow Evacuated Tube Collectors

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Abstract

This study examines advancements in solar geyser technology, which is key to sustainable water heating. Solar geysers use solar radiation to heat water through components like Direct Flow Evacuated Tube Collectors (DF-ETC), a Double Pipe Heat Exchanger (DPHX), and control systems. Solar collectors convert solar energy into heat, which is transferred to the DPHX, raising the water temperature in a storage tank. Performance depends on factors such as location, climate, and installation. Parametric studies explored the impact of DPHX design variations (e.g., tube diameter, length, and wall thickness), with optimal results used in the final prototype. Flow and thermal simulations using SolidWorks matched closely with real-life tests, including pressure and thermal performance assessments under various weather conditions. The experimental study evaluated the performance of a solar geyser, which achieved an effectiveness of 0.267 with a heat transfer rate of 87.94 kJ/s and an overall heat transfer coefficient of 18.89 W/m²K. Testing revealed that, starting from an average inlet fluid temperature of 31.6°C, the system could raise the temperature to 45.3°C on sunny days and 39.7°C on rainy days. These findings indicate that the solar geyser can effectively heat water in varying weather conditions, demonstrating its potential for consistent performance in both sunny and overcast environments hence validating solar geysers as a promising energy-efficient solution in the shift toward sustainability.

Keywords: Solar Geyser, Direct-Flow type Evacuated Tube Collectors (DF-ETC), Double Pipe Heat Exchanger (DPHX), Sustainable Water Heating.

1. Introduction

In wintry weather regions, maintaining a consistent hot water supply is imperative. However, relying on non-renewable electric energy to heat substantial volumes of water is environmentally unsustainable. Utilizing solar energy for water heating offers an eco-friendly alternative. The key to this approach lies in the design of efficient heat transfer equipment, primarily composed of a network of direct-flow evacuated tube collectors. These collectors harness the sun's energy to warm water, presenting a greener solution. Radiation from solar source is used to increase the temperature of the water enclosed within copper tubes housed within glass tubes. This process leverages the greenhouse effect, wherein solar energy is trapped and concentrated, effectively heating the water. To facilitate this, a double-pipe system is employed as a heat exchanger. Not only does it facilitate the heat transfer between cold and hot water, but it also serves as a reservoir for maintaining a ready supply of hot water. In essence, this solar-based water heating system offers an environmentally conscious and energy-efficient approach to meet the demands of cold weather regions. It capitalizes on renewable solar resources. The goal is to harness solar energy through an efficient energy conversion process that reduces costs and promotes environmental sustainability. This model was designed to deliver energy independence, featuring low-maintenance requirements and high efficiency by using tube collectors. Additionally, it emphasizes longevity and durability.

Solar based water heating systems are typically made of materials like copper or stainless steel due to their excellent thermal conductivity and corrosion resistance. There are three notable types of heat exchangers often used, such as: liquid-to-liquid, air-to-liquid (or liquid-to-air), and compact. Each has unique designs, such as coil-in-tank, shell-and-tube, tube-in-tube, and series of plates, which vary in applicability, efficiency and safety features, particularly with toxic fluids. Proper sizing of heat exchangers is important, which depends on the type of the heat exchanger, fluid properties, flow rates, and temperature differences. For sizing heat exchangers, either Log Mean Temperature Difference and NTU-Effectiveness Method can be followed according to suitability. [1]

The Direct Flow Evacuated Tube Collector is also known as a U-pipe collector; two heat pipes run through the center of the tube. One acts as the flow pipe, while the other acts as the return pipe. Both are connected at the

bottom with a U-bend. The heat-absorbing reflective plate functions as a divider, separating the flow and return pipes within the solar collector tubes. This setup improves efficiency by preventing heat loss and ensuring better heat transfer between the fluid streams. The absorber plate along with the heat transfer tube are vacuum sealed inside a tube made of glass which is providing exceptional insulation properties. Advantages over other kinds of Evacuated Tube Collectors is that it is more efficient. Moreover, there is no need for solar tracking for maximizing performance of the Tube Collectors. [2]

The heat-pipe has great thermal conductivity that transports thermal energy with minimal temperature drop. Its operation consists of evaporation, condensation and convection processes. The heat pipe's tip is connected to a heat transfer manifold, which heats water passing through it. Housed in an insulated aluminum casing, the heat-pipe contains a little amount of fluid that vaporizes at around 30ºC, rises to the tip, and transfers heat to the water. The vapor then condenses and repeats the cycle. This dry connection system allows for a system where individual tubes can be substituted with ease, without disrupting the solar system or causing water leaks. As the solar collector heats up, the fluid in the collector increases in temperature. The heated fluid is then transferred from the collector to extract the heat for practical use. A mixture of ethylene glycol and water is typically used as the working fluid. Ethylene glycol-based aqueous solutions are common, especially in systems where the fluid may experience temperatures below freezing. Ethylene glycol is often used as antifreeze in standard heat transfer systems due to its high heat transfer capacity, affordability, low toxicity, low flammability, and minimal corrosiveness. Water, on the other hand, is non-toxic and cost-effective. Having high value of specific heat, and very low viscosity, it is easy to pump. Hot water outlet temperatures depend on the number of Heat Pipe Evacuated Tube Collectors (ETC), amount of solar radiation and environment conditions. Heat Pipe ETC can absorb heat easily due to the cylindrical shape. So, Heat Pipe ETC can be applied not only summer but also winter. [3]

The solar water heating system may be easily coupled with an electric geyser. The hybrid system will conserve 50% of the electrical energy used in the geyser. It was observed that down flow configuration is more effective than up-flow condition at all flow rates due to lesser losses in down-flow. Results from these experiments show that Evacuated Tube Collectors can have improved performance than the Non-evacuated Tube Collectors as most thermal power reaches to tubes in the form of thermal radiation and no acquire by conduction or convection. The reflective surfaces are important for increasing heat gain by solar collectors. [4]

Evacuated tube solar collectors (ETSCs) are widely recognized for their high efficiency and ability to operate effectively in both domestic and industrial applications, especially under varying weather conditions. Compared to flat-plate collectors, ETSCs offer superior performance by minimizing heat loss through vacuum insulation and passively tracking the sun throughout the day. Their applications range from water heating to air conditioning, steam generation, and agricultural drying. However, challenges such as fragility, snow accumulation, and potential overheating remain, with ongoing research focusing on structural improvements and the use of advanced materials, like nanofluids, to enhance overall efficiency. [5]

A study was conducted to analyze the performance of a solar water heating system using heat pipe evacuated tube collectors (HP-ETCs) in Dublin, Ireland. The system was monitored for a year to assess energy collection, delivery, and efficiency. Results indicated an annual collector efficiency of 63% and system efficiency of 52%. However, about 17.7% of the energy was lost through supply pipes, suggesting better insulation could improve overall performance. Additionally, energy losses during overcast conditions highlighted the need for improved pump control strategies to enhance system efficiency.[6]

Hot water is vital for industrial and household heating in Ethiopia, where most industries rely on boilers powered by conventional energy sources, which contribute to environmental issues and rising fuel expenses. Solar water heating (SWH) systems, particularly those using heat pipe evacuated tube collectors (ETCs), offer a more sustainable solution, especially given Ethiopia's strong solar potential. ETCs are known for their high efficiency, minimizing heat loss and achieving high temperatures, making them well-suited for industries like food processing and beverage production. Research indicates that ETCs perform 41% better than flat plate collectors and provide 30% more energy annually, especially in colder climates. Advancements such as heat pipe-based ETCs have further enhanced their efficiency, positioning SWH as a promising alternative for reducing CO2 emissions and energy costs. Despite Ethiopia's favorable solar conditions, solar technology adoption remains limited, indicating a need for greater investment and awareness. [7]

2. Methodology

This Solar Geyser mainly comprises a Heat Exchanger and an array of Tube Collectors. When sunlight from the solar source falls on the solar collectors, they absorb the solar energy and transfer it to the water circulating through them. As the water heats up, it rises and moves into the storage tank. Simultaneously, the water that is relatively cool at the bottom of the tank flows into the collectors, completing the circulation loop. The insulated storage tank helps retain the heat, ensuring supply of hot water even when sunlight is unavailable.

2.1 Parametric Study and Calculation

A parametric study was conducted to determine the several dimensional characteristics of the DPHX. This study included parameters like length, wall thickness, annulus diameter, pipe diameter, flow rate of fluid and fluid temperature at inlet. The results from this study were analyzed to determine the dimensional parameters of the Heat Exchanger which was later used to maximize its performance. All the mathematical calculations for the DPHX were done following Hlaing et. al. [3]. This paper does not show any mathematical equations. Rather the focus is kept on experimental data and analysis.

2.2 Design and Manufacturing

The system was designed in SolidWorks. The isometric view of the CAD model is shown in Fig. 1(a). The Heat Exchanger is one type of Double Pipe which also acts as a Storage tank for the water. The DPHX is made of TIG welded SS201 sheet of 1 mm thickness. The dimensional parameters of the chosen DPHX are length, annulus diameter, pipe diameter and wall thickness, all of which were optimized by the parametric study.

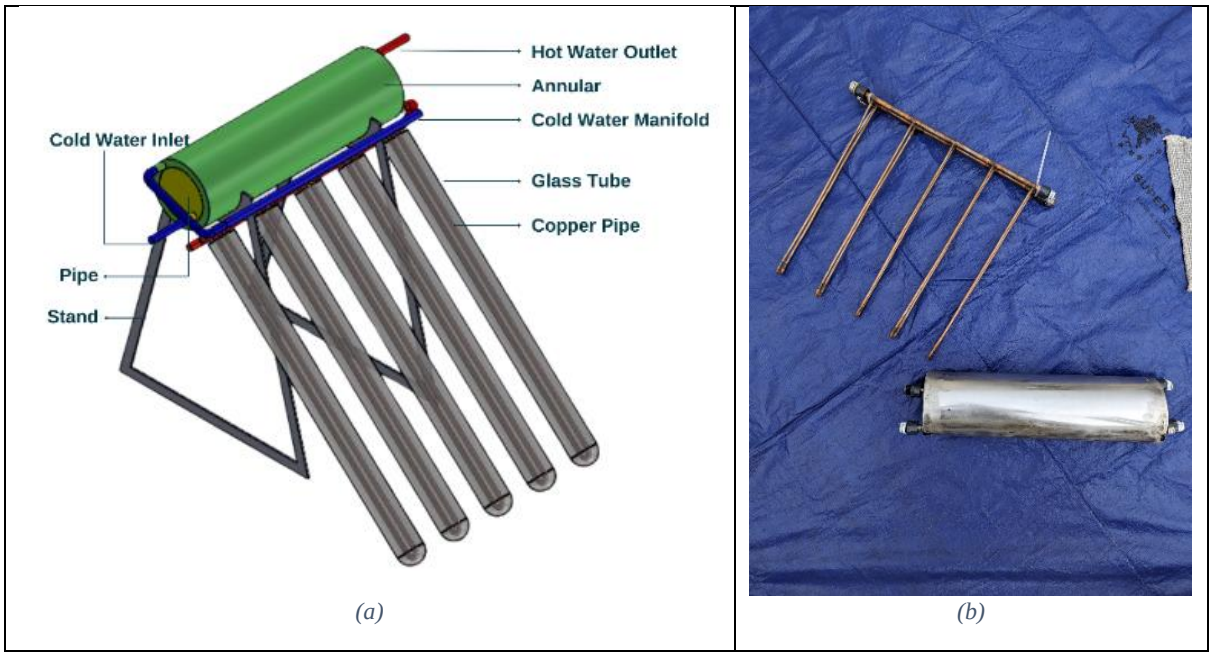


Fig. 1. (a) CAD Model of the Prototype Solar Geyser, (b) Manufactured Parts of the Prototype Solar Geyser.

The tube collectors are insulated with Glass tubes to trap heat from sunlight. The tube collectors are made of 6 mm diameter copper tubes bent in U-shaped to make loops. Several tubes are connected to a common manifold made of 12 mm diameter copper tube as shown in Fig. 1 (b). The copper U-tubes are gas welded with the copper manifold. The manifold ensures uniform flow and velocity of fluid across the U-tube array. The complete system makes an array of solar tube collectors that harness the solar energy and store it in the fluid flowing inside the copper tubes. The Array of Tube collectors are installed at an angle of 40-60 degrees allowing flow of fluid inside the tubes by natural convection. The heat-absorbing components of the Solar geyser were coated with black paint. The paint was thermally conductive and increased the heat absorption rate of the U-tubes by effectively turning them into black bodies. This greatly improved the thermal performance of the system.

2.3 Simulation

SolidWorks Flow simulation was conducted to determine the flow rate, pressure and temperatures of the fluids at the inlets and outlets of the DPHX. Fig. 2 illustrates the fluid temperature contour and 3D flow trajectory obtained from the flow simulation. The simulation results were cross-checked with the parametric study data that helped in determining the final dimensions of the prototype geyser.

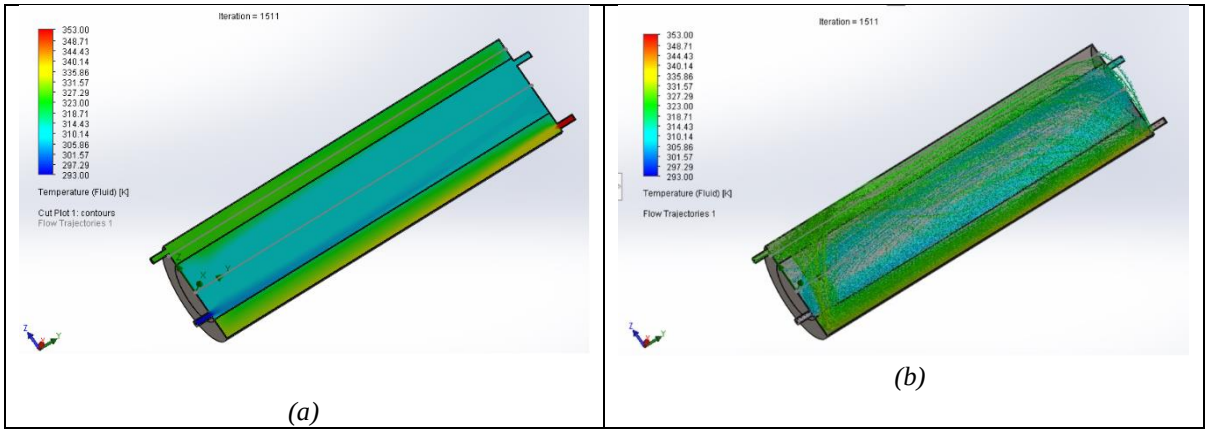


Fig. 2. Thermal and Flow Simulation of the DPHX of the Solar Geyser (a) Fluid Temperature Contour, (b) Flow Trajectory in 3D view.

3. Experimental Setup:

Initially, pressure testing was conducted on the solar geyser system to ensure that it is leak proof. Different views of the Solar Geyser setup are shown in Fig. 3. The flow rate of water was kept constant. Both inlet and outlet temperatures of tube collectors and DPHX were noted. The data was plotted with time. The geyser showed a significant increase in temperature. The water heating rate was in-line with the simulation results.

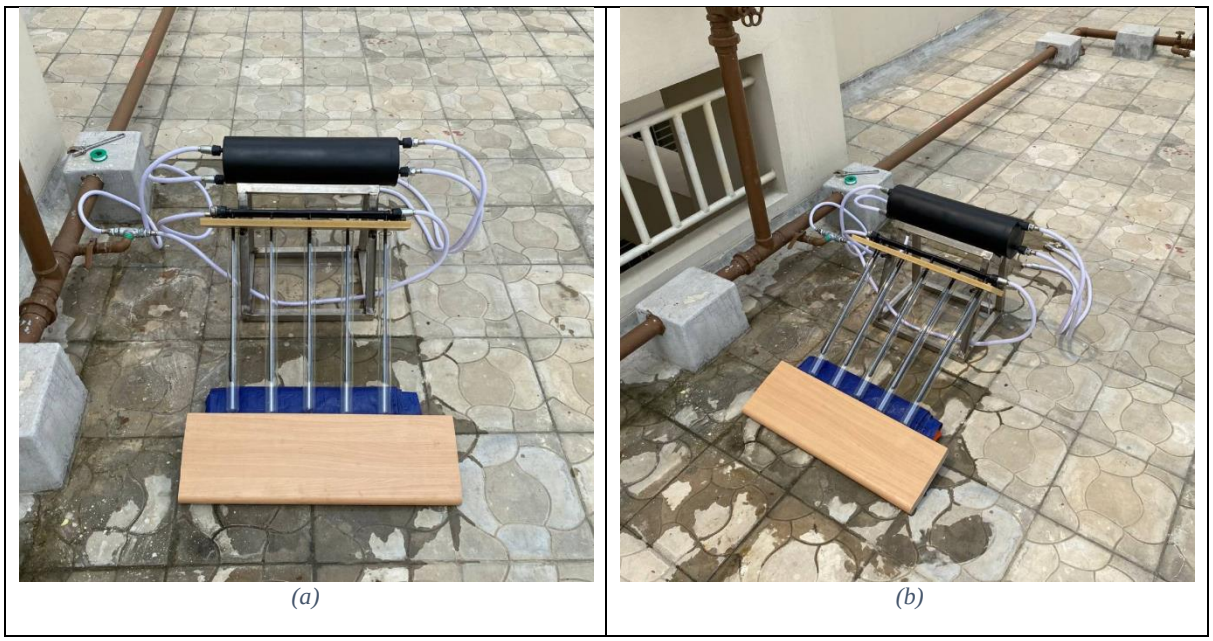


Fig. 3. (a) Front View of the Experimental Geyser Setup, (b) Isometric View of the Experimental Geyser Setup.

4. Results and Discussion:

A total of 30 parametric studies were conducted to determine the overall performance of the selected design. Fig. 4 shows the variation of outlet temperatures (T_{ho} & T_{co}), heat transfer rate (Q), heat transfer coefficient (U) and effectiveness with six parameters: length of DPHX (L), wall thickness of DPHX (x_w), outer diameter of inner pipe (D_{op}), outer diameter of annulus (D_{oa}), mass flow rate and inlet temperature of cold fluid (T_{ci}).

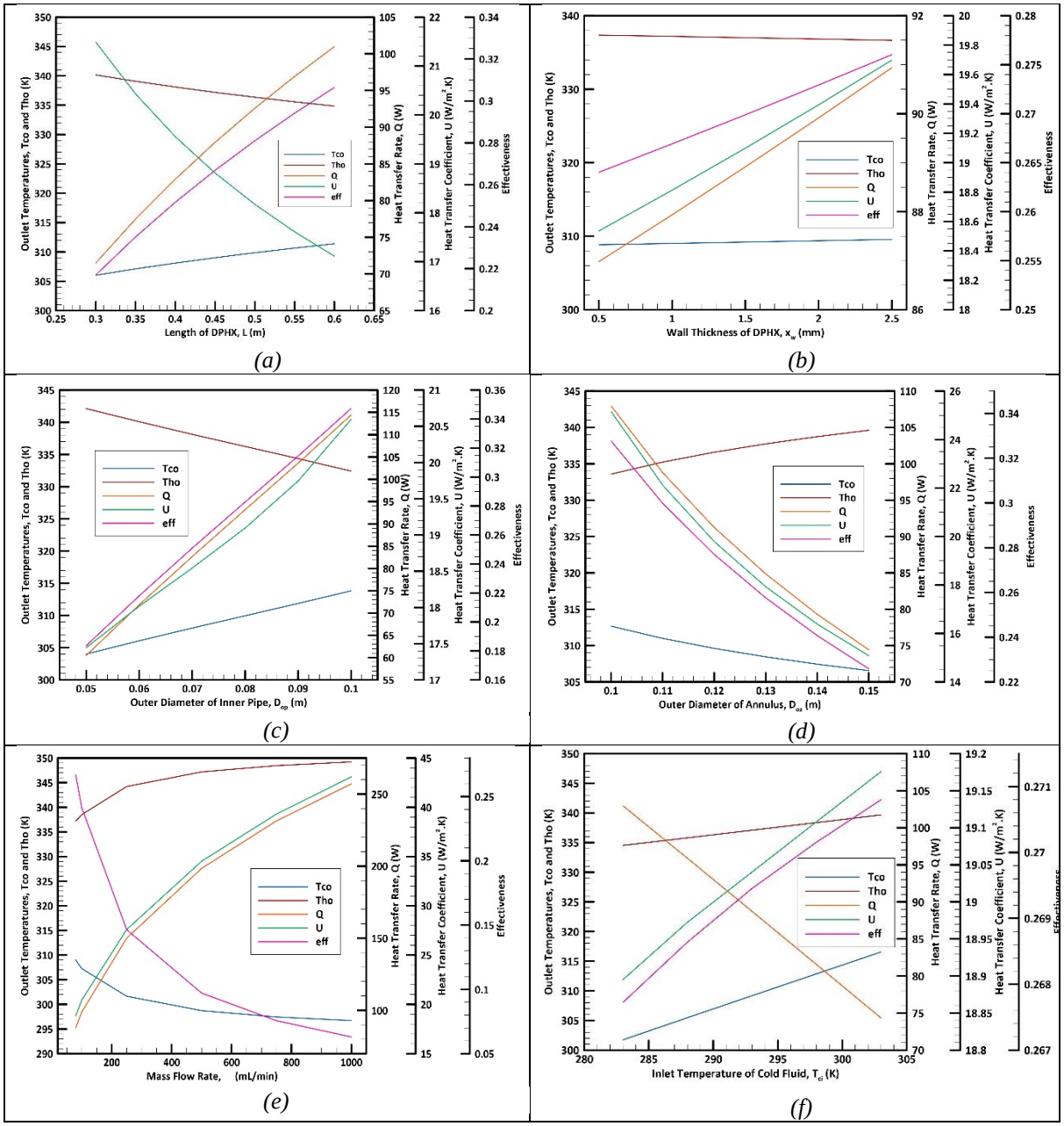


Fig. 4. Variation of the Parameters of the Experimental Solar Geyser with (a) Length of DPHX, (b) Wall thickness of DPHX, (c) Outer Diameter of Pipe, (d) Outer Diameter of Annulus, (e) Mass Flow Rate, (f) Inlet Temperature of Cold Fluid.

The Solar Geyser setup was tested outdoors for 2 days. It was tested in both sunny and rainy weather conditions. The weather conditions and corresponding fluid temperatures are listed in Table 1. The temperature data was collected from 8 am to 4 pm. The collected data, visualized in Fig. 5, show that the solar geyser is performing as intended.

Table 1. Data Collection and Visualization of Experimental Analysis

Date: 06 Sep 2023 Weather: Mostly Cloudy Inlet Temperature: 31.7°C Peak Hot Outlet Temperatures: 45.3°C Peak Cold Outlet Temperatures: 39.1°C	Date: 07 Sep 2023 Weather: Mostly Cloudy with Mild Rain at 1 PM Inlet Temperature: 31.5°C Peak Hot Outlet Temperatures: 39.7°C Peak Cold Outlet Temperatures: 38.9°C

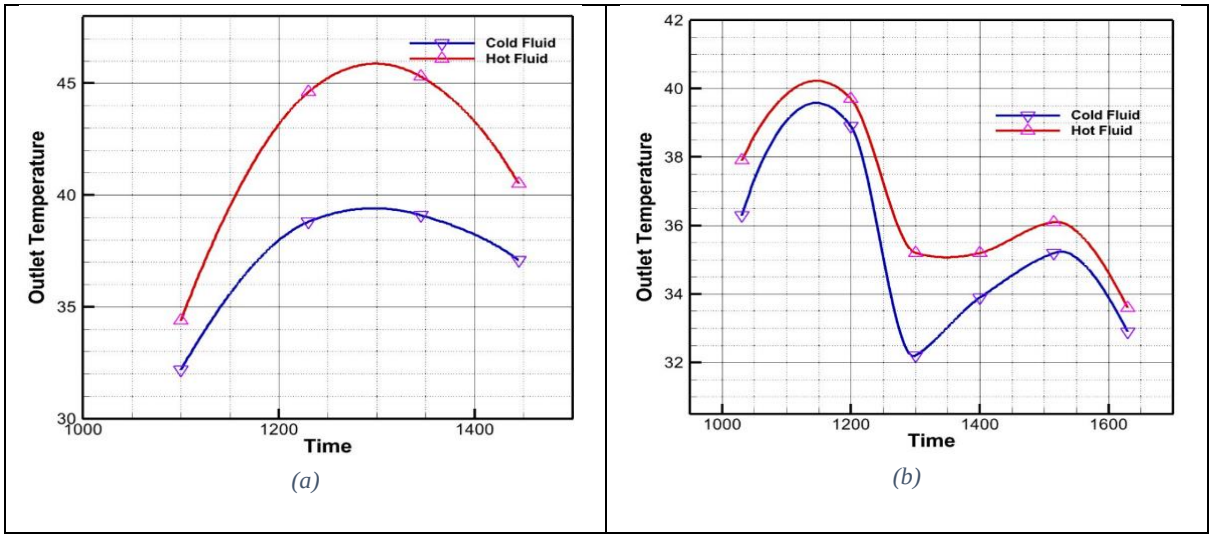


Fig. 5. (a) Variation of Outlet Temperatures of Fluids with Time on 6th September 2024, (b) Variation of Outlet Temperatures of Fluids with Time on 7th September 2024 (sudden dip in temperatures is due to rain).

The experimental geyser had an effectiveness of 0.267, heat transfer rate of 87.94 kJ/s and an overall heat transfer coefficient of 18.89 W/m^{2}K. The inlet fluid temperature was 31.6°C on average which was raised to 45.3°C on a sunny day and 39.7°C on a rainy day. This indicates that the solar geyser can sufficiently raise the fluid temperature on both sunny and rainy conditions.

5. Conclusion

The objective of this experimental analysis is to highlight the significant potential of solar geysers equipped with direct flow type evacuated tube collectors (DFETCs) as a sustainable and cost-effective solution for water heating. The system's ability to be operated without electricity, coupled with locally sourced raw materials and low manufacturing costs, underscores its efficiency and affordability. These solar geysers not only reduce energy consumption and utility costs but also contribute to a notable decrease in emissions of carbon-dioxide, aligning with global sustainability goals.

However, the study also identified several limitations, including inadequate glass tube sealing and vacuuming, insufficient thermal coating, lack of insulation, and a limited heat absorption area. Future work should address these challenges by improving glass tube vacuuming, enhancing thermal coatings, increasing the heat absorption area, and incorporating reflectors to optimize performance.

Despite these limitations, solar geysers remain a compelling choice for both residential and commercial applications, offering long-term reliability with minimal maintenance. As a prudent investment, they support energy autonomy while contributing to a more sustainable and environmentally conscious future.

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