Design and Experimental Analysis of the Compact Solar Water Heater

ABSTRACT

The development of compact solar water heaters is the subject of this report, which begins with an overview of solar water heating and an analysis of its active and passive varieties. A comprehensive evaluation of the literature synthesizes prior research, laying the groundwork for comprehending current developments and pointing out areas that require more investigation. The research goes on to describe the experimental configurations used to evaluate the performance and efficiency of the heaters, providing insightful information on how they might be used in real-world scenarios. It also touches on the current production process in brief, summarizing important factors and procedures without getting too technical. The paper seeks to promote sustainable options for home water heating needs by advancing compact solar water heater technology through the integration of lessons from these disparate fields.

1 INTRODUCTION

Hot water is essential both in industries and homes. It is required for taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Hot water is also required in large quantities in hotels, hospitals, hostels, and industries such as textile, paper, food processing, dairy, and edible oil in fact, hot water is required mainly for purposes of hygiene and bathing in homes. For instance, in South Africa, the accepted norm is that each person in a household requires at least 20 l of hot water per day out of which more than one-half is for personal hygiene. Hot water demands appear to be highest within the periods of the day when electric energy demand for other purposes is high. Fig 1illustrates hot water usage trend and its distribution for domestic uses. This figure shows that the hot water usage is highest in the mornings and evenings, with demand for both periods being almost the same, while cooking and bathing present the highest water demanding domestic activity.

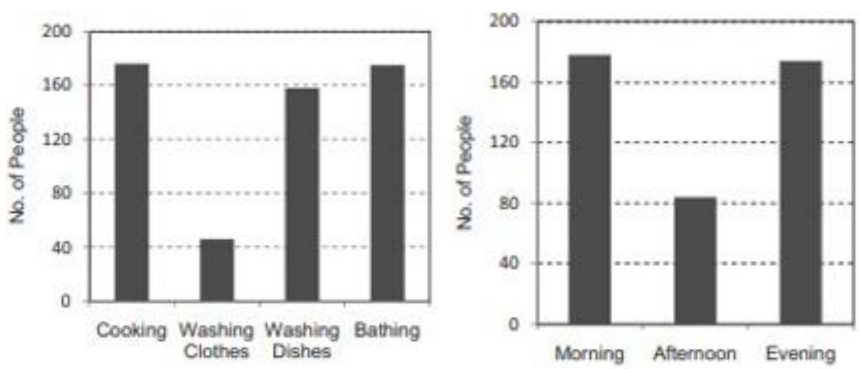


Figure 1-1 Distribution of domestic hot water usage

At present, hot water demands are met mainly fulfil by the use of electric heaters. Unfortunately, rising energy cost, environmental concerns, and the depleting nature of the current primary energy sources in use have made electric heaters less attractive. This is because the primary energy sources of electric energy utilized are mainly the fossil fuels. In addition, the demand for electricity is growing rapidly; thus within those periods when hot water demand is highest the electric energy facilities are often overstretched, resulting in some cases to power shading especially in countries.

These problems can be handled by taking off the energy demand for hot water purposes from electricity. Fortunately, the technical and economic feasibilities of solar hot water systems SHWSs are well established and they have found domestic and commercial applications. These systems use solar energy to generate hot water. The technology employed has been reasonably developed and can be easily implemented at a low cost. Several configurations exist for this purpose. These configurations may be grouped into two, namely, the passive solar hot water system PSHWS and the active SHWS. The solar collectors employed in these configurations could be flat plate, concentrating, or evacuated tube types.

1.1 THE ACTIVE SOLAR HOT WATER SYSTEMS

Active solar water heating systems use electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors. Thus they are more complex and usually more expensive than passive systems.

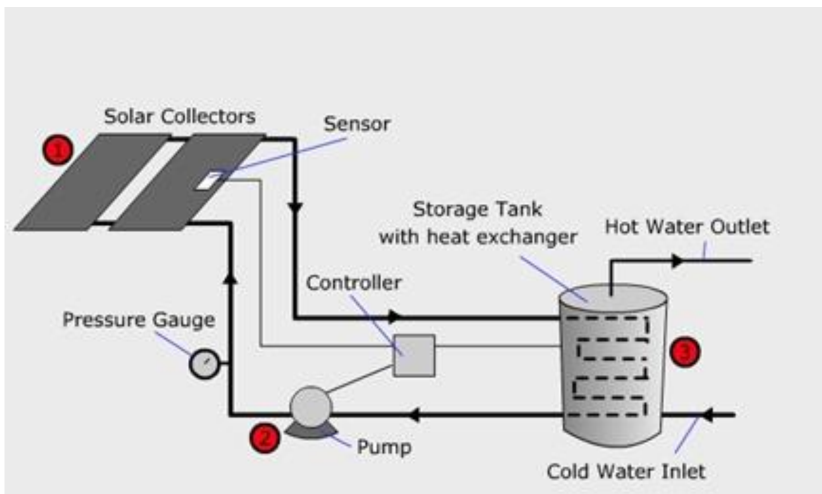


Figure 1-2 Experimental setup of active hot water system

1.2 THE PASSIVE SOLAR HOT WATER SYSTEMS

The PSHWSs generally transfer heat by natural circulation as a result of buoyancy due to temperature difference between two regimes; hence they do not require pumps to function. They are the most commonly used solar water heaters for domestic application and have been designed and investigated by different researchers

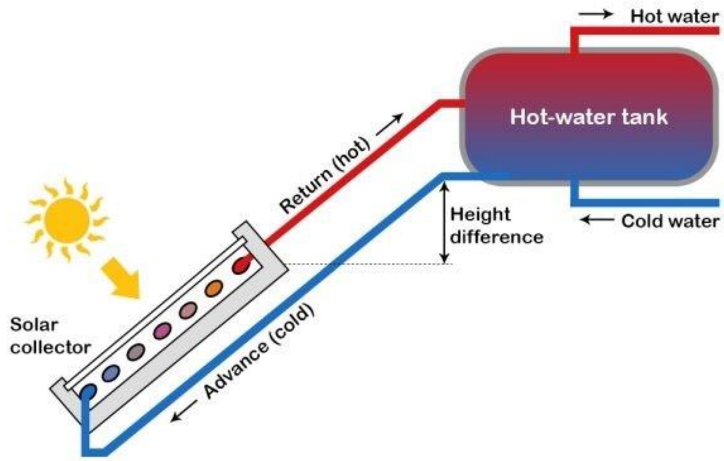


Figure 1-3 Experimental setup of passive solar hot water

1.3 Compact Solar Water Heater

Our project utilizes a passive solar water heating approach to provide hot water for a single room and washroom. A spherical glass dome acts as a greenhouse, capturing sunlight and heating black spiral tubes filled with water that is wrapped around a truncated cone. The cone itself is filled with paraffin wax, a phase change material. During the day, sunlight heats the water in the tubes, transferring that thermal energy to the surrounding paraffin wax which melts to store latent heat. Even after sunset, the warmed wax continues to release its stored heat to the water in the tubes, ensuring a consistent flow of warm water to the storage tank below. This innovative design offers a space-saving and mobile solution for hot water needs, with efficient heat transfer throughout the day and night.

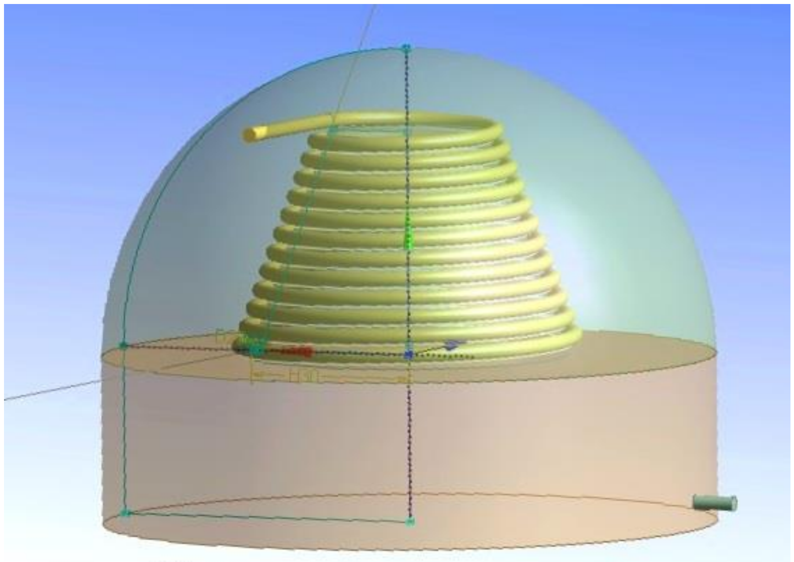


Figure 1-4 Designed Compact solar water heater

1.4 Problem Statement

Conventional solar water heaters, while a sustainable solution, have limitations that hinder their use in many homes. Their large, fixed size can be a challenge for rooftops with limited space or aesthetics in mind, and these bulky collectors can block scenic views or sunlight for windows below. Furthermore, in densely populated areas, finding suitable roof space for conventional systems can be difficult, limiting accessibility to solar hot water for a significant portion of the population. Finally, conventional solar water heaters can overheat during intense sunshine, leading to inefficiencies and potential damage. Your innovative design offers a compelling alternative by addressing these shortcomings.

1.5 Aims and Objective

The main objective of this study is following

- Design of compact solar water heater with thermal storage system.
- Short term heat storage for stable outlet temperature of the water heater
- Minimize effect of solar fluctuation
- Compact in size

- Manufacturing of the design
- Arrangement of experimental setup for experimentation
- Comparison with the result of conventional solar water heater

2 LITERATURE REVIEW

2.1 Solar Water Heaters.

Energy consumptions in certain developing countries, particularly in Asia, were still growing. Furthermore, the depletion of fossil fuels due to overuse of primary energy sources means that, with current proven reserves, there will only be 119 years of coal production, 46 years of oil production, and 63 years of natural gas flow left in the ground. According to the law of supply and demand for energy, growing energy costs will have an effect on how the world economy develops as long as fossil fuel reserves are depleted. However, the burning of fossil fuels for transportation, industry, and energy has resulted in a major rise in the amount of greenhouse gases released into the atmosphere. The majority of scientists concur that this expansion is what is primarily responsible for global warming. The global temperature has already increased by 1.4 1C over the last 30 years of the 20th century, and it will climb further over the ensuing decades. Significant changes in sea levels, ecosystems, and weather patterns brought about by this warming may endanger people's health and way of life and result in irreversible extinctions of both plant and animal species.[1]

Hot water is necessary for families and businesses alike. In both urban and rural locations, it is necessary for bathing, cleaning clothes and utensils, and other household tasks. Additionally, a lot of hot water is needed in hospitals, hostels, hotels, and businesses that produce textiles, paper, dairy, edible oil, and food processing.1. In actuality, households primarily need hot water for bathing and cleanliness. For example, it is standard practice in South Africa that every member of a home needs at least 20 liters of hot water per day, of which more than half is used for personal hygiene.2. Demands for hot water seem to be highest during the times of the day when other uses of electricity are high. Currently, electric heaters are the primary means of meeting hot water demands. Unfortunately, electric heaters are becoming less appealing due to increased energy costs, environmental concerns, and the depletion of the principal energy sources now in use. The reason for this is that the main energy The primary electric energy sources that are used are fossil fuels. Furthermore, the need for electricity is increasing quickly, which means that during times when hot water demand is at its peak, electric energy infrastructure is frequently overextended, sometimes leading to power shadowing, particularly in developing nations.[2]

In Brazil, the common practice of using electrical showerheads to heat water for home usage results in a load curve that peaks early in the evening, placing a significant strain on utilities involved in production, transmission, and distribution. These 3–8 kW electrical resistance showerheads are typically used by over 73% of Brazilian households. Over 90% of residential buildings in some of the more moderate temperature parts of the country's south, where the majority of Brazil's population is concentrated, have electricity showers. The issue has gotten worse in recent years because these devices' nominal powers have steadily climbed from an average of 3 kW to a range of 4.4 kW to 6.5 kW, and in some more expensive models, 8 kW. One of the major energy issues the power sector in Brazil is dealing with is the use of electricity for direct water heating.[3]

In four different areas—electric power generation, hot water production, fuel transportation, and rural (off-grid) power services—renewable energy sources have the potential to significantly outperform fossil fuels. The utilization of solar technologies has grown at a pace of roughly 30% since 1980. According to 2010 research by Renewable Energy Policy Network, around 70 million homes currently use solar water heating. (SWH) networks globally. The major ways that using SWH can assist the economy are by reducing fuel costs for water heating and by addressing environmental concerns. SWH systems are becoming more common and have a big impact on the industrial and home sectors in a number of nations. At the moment, China leads the world market for solar thermal products. In 2009, Chinese companies produced 28 million square meters of solar systems, accounting for more than 80% of the world's solar hot water and heating market. Germany, Turkey, Brazil, and India are the global leaders for solar hot water, excluding China. The majority of the European Union's (EU) percentage of the built SWH capacity that is still available.[4]

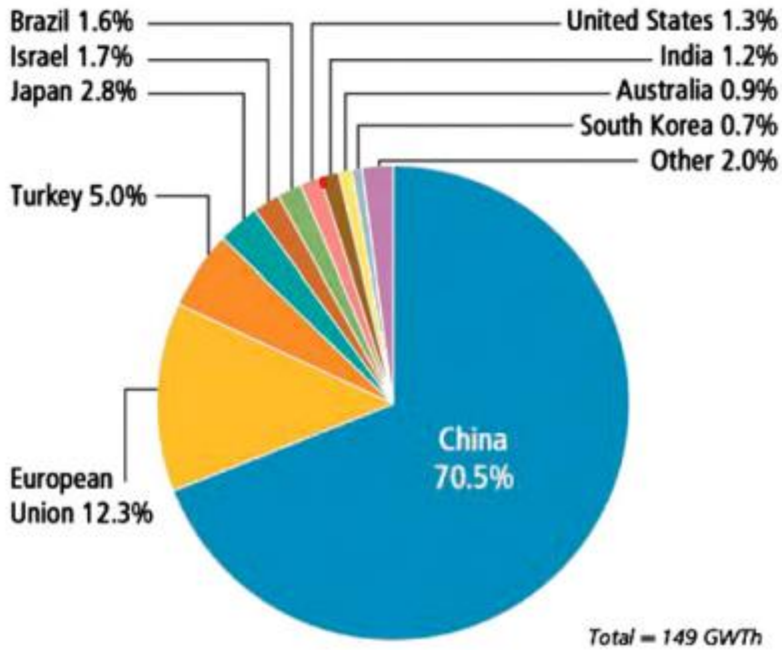


Figure 2-1 solar thermal products around the globe

2.2 Portable solar water heater

A compact solar water heater was the subject of extensive experimental research to assess the heater's performance and establish the ideal storage tank depth. The trials were carried out with single and double glazing at tank depths of 5, 10, and 15 cm. According to experimental results, the heater can raise the temperature by roughly 68 °C in July at a storage tank depth of 10 cm. The ideal depth for the tank to provide hot water for a full day is 10 cm. While the double-glazed system is more effective at maintaining higher temperatures, the single-glazed system causes the water temperature to rise somewhat more than the double-glazed system.[5]

A theoretical and experimental investigation on a tiny solar heater was carried out by Garg and Rani. Energy balance equations that were transformed into finite difference form and computer-solved comprised the theoretical portion of the research. The Fourier Series is used to describe both the ambient temperature and solar radiation. In that method, the loss of stored energy during the dark or times of low insolation created an issue. An insulated baffle plate within the tank next to the absorber plate and an insulating cover helped to reduce the amount of energy lost.[6]

2.3 PCM (Phase Change Material)

Energy should be stored and used as needed if solar energy is to be utilized throughout the day. One potential solution for solar water heating systems' thermal energy storage is Phase Change Material (PCM). Its high energy storage density and isothermal behavior during charging and discharging are its advantages. The most effective method of storing thermal energy for use in heating water for home use at night is to use a solar water heater that uses phase change materials (PCMs) in the storage tank. Sensible heat was absorbed by the phase-changing substance, and any remaining heat was latently stored.

Kumar [9] created a system for latent heat storage. In order to meet the hot water needs in the evening and morning, a box-type solar collector has been used for further development and performance evaluation. The system comprised of three heat exchangers with fins. A heat-storage material in the system was paraffin wax, which has a melting point of 54°C. It was discovered that paraffin wax performed exceptionally well in the desired temperature range of hot water (15 and 20 liters).Shukla has built two water heating systems based on paraffin of the two systems, one used a tank for tank-style storage, while the other used two systems based on a 24-hour cycle. The systems' respective efficiencies were found to be 45% and 60%. Carbazole et al.'s water heating system was developed both with and without conventional PCM. After comparing the two systems

further, it was discovered that the heat storage tank with the PCM had an outlet temperature that was 6°C higher than the system without a PCM.
[7]

2.3.1 PCM Categories

The two main categories of PCMs are organic and inorganic substances. The majority of organic PCMs have low vapor pressure, a high latent heat per unit weight, little to no subcooling, are compatible with most building materials, and are non-corrosive and chemically stable. Their flammability, significant volume fluctuations upon phase shift, and limited thermal conductivity are drawbacks. Compared with organic chemicals, inorganic compounds are less expensive and non-flammable, and they possess a higher latent heat per unit volume and high thermal conductivity. They do, however, corrode most metals and experience subcooling and disintegration, which can alter their phase change characteristics. Since the melting point is the most crucial factor, a PCM with an easily changeable melting point would be required[8]

3 EXPERIMENTAL SETUP

The designed compact solar water heater will be sufficient for a single room or an office. Our experimental setup featured a compact solar water heater incorporating a dome-shaped solar collector, a storage tank, and a helical coil containing phase change material (PCM). The PCM placed inside the dome to maximize solar absorption and increase thermal storage efficiency.

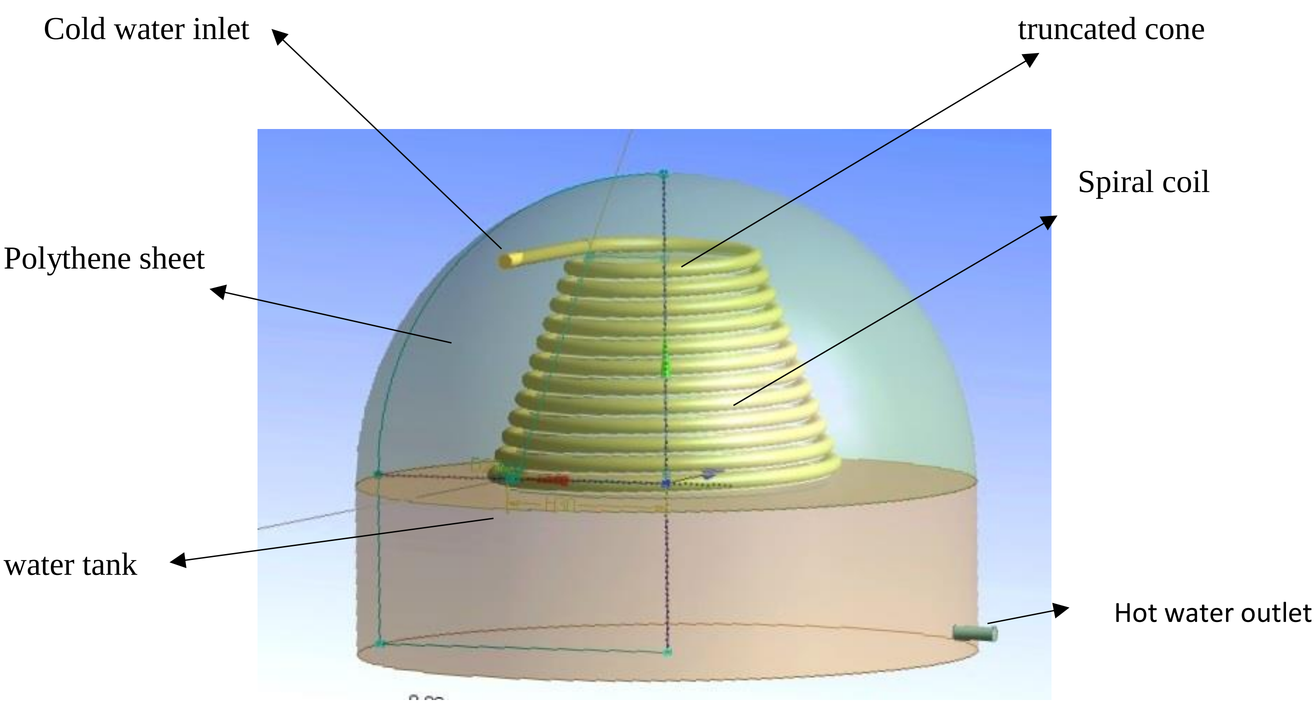


Figure 3-2 labeled diagram of designed compact solar water heater

3.1 Experimental equipment

3.1.1 Polythene sheet

Using a polyethylene sheet to cover a solar water heater boost both efficiency and durability. The translucent characteristic of polyethylene allows maximum sunlight to permeate, optimizing solar energy absorption while providing a protective barrier against environmental components like UV radiation, moisture, and debris. Additionally, its thermal insulation capabilities help keep heat within the system, decreasing heat loss and ensuring the water remains warm for longer times. This makes polyethylene a great choice for preserving the performance and longevity of solar water heaters.

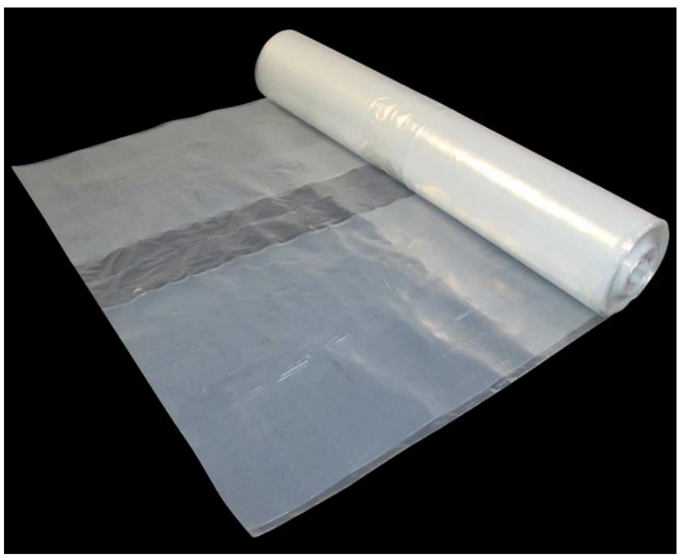


Figure 3-3 polythene sheet

3.1.2 Spiral tube :

In the design of sophisticated solar water heaters, a spiral tube wound around a truncated cone is adopted to maximize heat absorption and transfer. This arrangement maximizes the surface area exposed to sunlight, allowing for efficient harvesting of solar energy. The spiral design ensures consistent dispersion of heat along the tube, while the truncated cone shape improves the system's orientation towards the sun, boosting total efficiency. This setup not only increases the thermal performance but also offers a more compact and effective design for solar heating applications.

Figure 3-4 copper coil in truncated cone shape

3.1.3 Truncated Cone:

In this solar thermal system, a truncated tube filled with paraffin wax acts as a phase change material (PCM) for effective heat storage. The paraffin wax absorbs and stores heat from the spiral tube coiled around the truncated cone, allowing the system to retain thermal energy even after the sun has set. The tube is equipped with a water inlet and outlet, connecting it to a tank. Water flows through this system, absorbing the stored heat from the paraffin wax as it circulates. This design ensures a continuous supply of heated water, efficiently utilizing solar energy while maintaining a compact and reliable setup.

Figure 3-5 Truncated cone

3.1.4 Phase Change Material (PCM)

The paraffin wax is encapsulated within the truncated cone to function as a phase change material (PCM) for efficient energy storage. The distinctive shape of the truncated cone increases heat distribution throughout the paraffin wax, allowing it to absorb and store heat effectively during the day. As the wax melts, it preserves the heat energy, which can later be transferred to water or other mediums. This design harnesses the high latent heat capacity of paraffin wax, ensuring a constant and dependable release of stored heat, even when solar energy is no longer accessible.

Figure 3-6 paraffin wax

3.1.5 Water Tank:

The water tank in this solar thermal system works as a reservoir for storing heated water. After cold water enters the system through a separate input, it passes through the heating components where it collects solar energy. Once heated, the water is then delivered to the tank. The tank holds this hot water, keeping it insulated to prevent heat loss, and assuring a reliable supply of hot water when needed. This design allows the system to properly regulate and provide hot water, irrespective of the cold water inflow.

Figure 3-10 water tank

3.1.6 Cold Water Inlet

The cold-water input in a solar thermal system plays a critical role in commencing the heating process. This input allows cold water from an external source, such as a storage tank or mains supply, to enter the system. As the cold-water flows into the solar heater, it is progressively heated by the energy stored in the system, whether by direct sunlight or stored heat in materials like paraffin wax. The design assures a constant flow of cold water, which is efficiently converted into hot water as it travels through the system, giving a stable supply of heated water for diverse purposes.

Figure 3-11inlet pipe

3.1.7 Hot water outlet

The hot water exit pipe is a vital component in the solar thermal system, responsible for transferring heated water from the system to the place of consumption. After the water absorbs heat within the system, it departs through the output pipe, which is connected to the storage tank or directly to taps, showers, or other fixtures. This pipe maintains a consistent flow of hot water, offering an effective and reliable supply for numerous residential or industrial uses. The design of the output pipe is tuned to minimize heat loss during transfer, ensuring that the water remains at the proper temperature until it reaches its destination

Figure 3-12 Hot water outlet

3.1.8 K-type thermocouples

An electrical tool for measuring temperature is a thermocouple. To measure the temperature of the solar receiver, we employed K-type thermocouple wires.

Characteristics:

- K-type thermocouple cables are frequently used to gauge high temperatures.
- The temperature range that K-type thermocouple wires can measure is -200 to 1600 degrees Celsius.
- Thermocouple wires of the K type work better and are more efficient.

Figure 3-13 Fig K-type thermocouples

3.1.9 Control valve

A control valve is a tool used to manage a system's fluid flow rate, whether it steam, gas, or liquid. As the last control element, it modifies the flow passage size in response to a signal from a controller. By adjusting the fluid flow, this makes it possible to precisely manage a number of process parameters, including pressure, temperature, and liquid level. As per requirement, the range of the control valve is from 0.1 L/min to 1 L/min

Figure 3-14 control valve

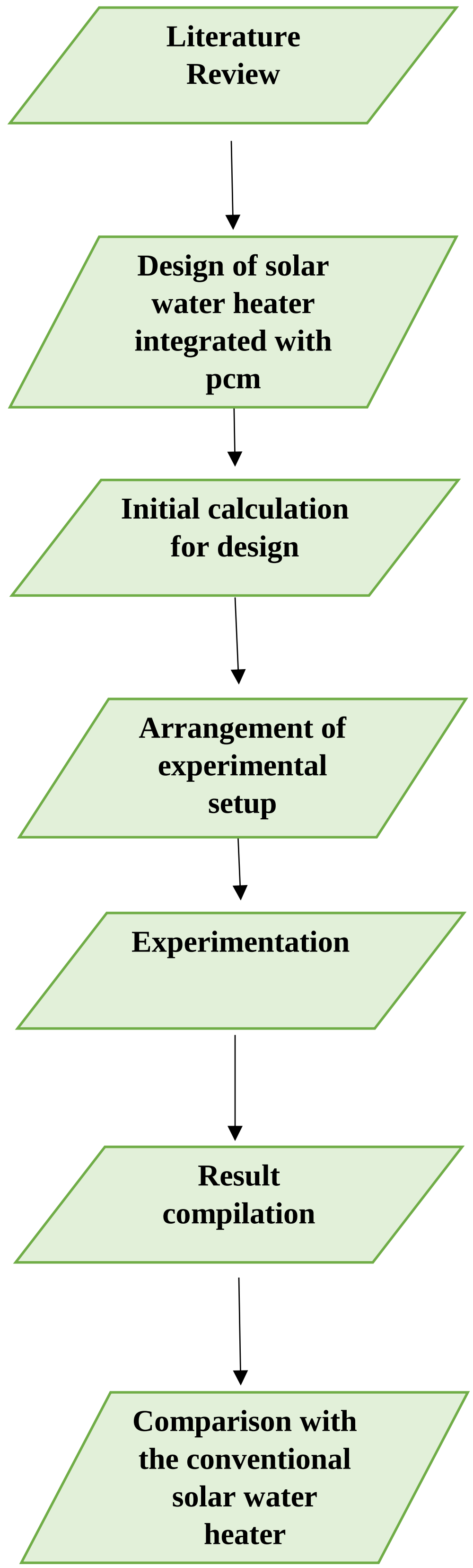
3.2 Solar Thermal Water Heater Configuration

The system's revolutionary design centers on a spherical structure enveloped by a polyethylene sheet that acts as a remarkably efficient greenhouse, gathering and intensifying sunlight throughout the day. This translucent polyethylene sheet not only maximizes the absorption of solar energy but also offers protection from external factors, guaranteeing ideal conditions for heat absorption. Within the framework, there are black helical tubes containing water that are wound around a truncated cone. These tubes have been deliberately selected for their color and shape to optimize the absorption and transfer of heat. When sunlight travels through the polyethylene sheet and hits the tubes, the water inside them rapidly heats up, resulting in a continuous movement of thermal energy. The hot water then transmits this energy to the paraffin wax contained within the cone. Paraffin wax, a phase change material (PCM), is well-suited for this purpose because it has the capacity to store significant quantities of latent heat during its transition from a solid to a liquid state.

Throughout the day, the paraffin wax slowly liquefies, efficiently retaining the surplus heat collected by the system. This stored energy becomes particularly beneficial when the sun sets and direct solar heating is no longer possible. Even after the sun has set, the wax that has melted still emits its stored thermal energy, which keeps the temperature of the water flowing through the spiral tubes constant. The continuous emission of heat guarantees a constant provision of heated water that circulates through the exit pipe into a storage tank located below, readily available for use at any time. The complete arrangement is not only space-saving but also movable, making it an adaptable solution for a number of scenarios. By successfully collecting and storing solar energy, the system provides reliable hot water both day and night, maximizing energy use and lowering dependency on external power sources.

Figure 3-15 Compact solar water heater

4 Methodology



4.1 Literature review

Extensive research on compact solar water heaters has focused on optimizing their design for efficient heat retention and consistent water temperature. Experimental studies have shown that the performance of these heaters is significantly influenced by factors such as glazing and tank depth. For instance, tests conducted with different tank depths and glazing configurations revealed that a 10 cm tank depth is optimal, capable of raising water temperature by approximately 68°C in summer conditions. Double glazing, while more effective at maintaining higher temperatures, resulted in slightly slower temperature increases compared to single glazing, highlighting the trade-offs in design considerations for these systems.

Further theoretical and experimental investigations, like those by Garg and Rani, explored the use of energy balance equations to simulate the heater's performance, identifying challenges such as energy loss during low insolation periods. Solutions such as insulating baffle plates and covers were implemented to minimize these losses, demonstrating the importance of insulation in maintaining thermal efficiency. These findings underscore the potential of compact solar water heaters as a sustainable solution for hot water needs, particularly when design elements like glazing and insulation are optimized to enhance performance.

4.2 Design of solar water heater integrated with pcm

In this section, initial calculations were conducted using information on solar irradiance and the optical properties of the polyethylene sheet that covers the system. These calculations aim to determine the expected solar flux on the spiral tubes coiled around the truncated cone, which contains the phase change material (PCM) inside. This process takes into account factors such as the angle of sunlight, the heat-trapping efficiency of the polyethylene sheet, and the surface area of the spiral tubes exposed to the sunlight. Using the surface area of the spiral tubes and the calculated solar flux, the heat transfer rate to the water circulating within these tubes was determined. This involves applying the necessary heat transfer correlations while considering the properties of the working fluid (water), the characteristics of the polyethylene sheet, and the material properties of the spiral tubes. Finally, the temperature distribution within the water in the spiral tubes and the PCM inside the truncated cone was calculated. This involves solving the energy balance equation, accounting for factors such as radiation losses through the polyethylene sheet, convection from the spiral tubes to the water, and heat conduction from the spiral tubes into the PCM within the cone. These calculations are essential for accurately predicting the thermal performance of the system and optimizing the design for efficient solar energy capture and storage.

4.3 Initial calculation for receiver tube design

In this part, initial calculations were undertaken using solar irradiance data and the optical characteristics of the polyethylene sheet to predict the solar flux on the spiral tubes wrapped around the truncated cone filled with phase change material (PCM). This involved analyzing elements including sunlight angle, the heat-trapping effectiveness of the sheet, and the surface area of the tubes.

Using the tube's surface area and predicted solar flux, the heat transfer rate to the water within the tubes was estimated, factoring in the parameters of the water, tube material, and surface features. Finally, the temperature distribution was computed by solving the energy balance equation, accounting for radiation losses, convection, and heat conduction inside the system. These calculations are critical for maximizing the system's thermal performance.

4.4 Arrangement of Experimental Setup

The experimental setup for the tiny solar water heater is divided into several main components, each playing a significant part in the system's operation and efficiency.

4.4.1 Truncated Cone

At the heart of the system is a truncated cone, which is filled with phase change material (PCM). The PCM within the cone is vital for storing thermal energy, allowing the device to maintain a steady supply of hot water even when direct sunlight is not available.

4.4.2 Spiral Tubes

Black spiral tubes are curled around the exterior of the truncated cone. These tubes act as the principal heat exchangers, where water is heated as it runs through them. The spiral structure offers optimum exposure to solar light, enhancing the heating process.

4.4.3 Polyethylene Sheet Enclosure

The entire system is contained beneath a transparent polyethylene sheet. This layer functions as a greenhouse, trapping solar energy to boost the efficiency of heat transfer to the water inside the spiral tubes. The polyethylene covering is snugly fastened around the setup, ensuring optimum heat retention.

4.4.4 Water Tank

The complete structure, including the truncated cone and spiral tubes, is fixed atop a water tank positioned at the base of the system. This tank not only serves as the base but also collects the hot water. It ensures stability and offers a reservoir for the hot water.

4.4.5 Mobility Mechanism

Small tires are placed beneath the water tank to make the apparatus movable. This mobility feature allows the complete arrangement to be quickly adjusted to capture the optimum amount of sunshine throughout the day.

4.4.6 Cold Water Inlet

Cold water is fed into the system through an entrance placed at the bottom of the spiral tubes. This design ensures that the water enters the system smoothly and begins heating as it moves upward through the tubes.

4.4.7 Hot Water Outlet

After being heated in the spiral tubes, the water departs through a hot water outlet placed at the top of the system. This outlet allows the hot water to go into the tank for storage or be used directly.

This configuration ensures efficient operation, effective heat storage, and the ability to shift the system as needed

4.5 Experimentation

The experimentation includes testing the tiny solar water heater under various sunshine situations to evaluate its performance. The system was positioned to catch maximum solar irradiation throughout the day, with water flowing through the spiral tubes wound around the truncated cone filled with phase change material (PCM). A flow rate control valve was included into the arrangement to manage the water flow, guaranteeing optimal heat absorption as it flowed through the tubes. Temperature sensors were put at important points, including the water inflow, outflow, and within the PCM, to monitor the heat absorption and retention capacities of the system. The efficiency was measured by measuring the temperature increase in the water, the impact of varying flow rates, and the time taken for the PCM to release stored heat, guaranteeing a steady supply of hot water. The results were then examined to refine the design and boost the system's overall efficiency.

4.6 Result compilation

Result compilation involved meticulously gathering and analyzing data from the trial phase of the compact solar water heater. The obtained data includes temperature readings at the water intake, outflow, and within the PCM, as well as flow rate fluctuations regulated by the flow rate valve. The data was generated to evaluate the system's performance in terms of heat absorption, retention, and overall efficiency. The link between flow rate and temperature increase was thoroughly analyzed to identify the ideal operating parameters. The collated results were then utilized to analyze the success of the design, highlight any areas for improvement, and provide insights into prospective enhancements for future iterations of the solar water heater.

4.7 Comparison with conventional solar water heater

Compared to conventional solar water heaters, the small solar water heater with a phase change material (PCM) offers higher efficiency and heat retention. While typical systems rely entirely on direct sunlight to heat water during the day, the incorporation of PCM in the compact design allows for the storage of thermal energy, which is gradually released even after sunset. This leads in a more regular supply of hot water, independent of sunlight availability. Additionally, the installation of a flow rate control valve optimizes heat transfer, further enhancing efficiency. In comparison, conventional systems are often bulkier, less portable, and dependent on continuous sunshine, making the compact design a more versatile and efficient solution for varied applications.

5 Experimentation

5.1 Experimentation Process

The testing method for the tiny solar water heater was carefully designed and executed on the rooftop of the Mechanical Engineering Department. The rooftop position was chosen because of its unimpeded access to sunlight, which is crucial for accurately evaluating the system's effectiveness in real-lifle scenarios. The entire procedure was segmented into multiple pivotal stages, each intended to assess distinct facets of the design and performance of the solar water heater. The following is an elaborate account of every phase of the experimental procedure.

1.Installation Setup

The initial phase of the experimentation was the installation of a tiny solar water heater on the rooftop. The setup included of several crucial elements, namely a truncated cone containing phase change material (PCM), black spiral tubes wound around the cone, and a translucent polyethylene sheet that enveloped the entire assembly

Placement: The heater was strategically positioned on the rooftop to optimize its exposure to the sun's rays throughout the day. The location was selected based on meticulous evaluation of the sun's trajectory, guaranteeing that the system would be exposed to uninterrupted sunshine for the maximum length every day. This location is critical for maximizing the solar energy collected by the black spiral tubes and then transferred to the PCM.

System Mounting: The complete arrangement was affixed to a sturdy water tank positioned at the bottom of the system. The water tank acted as the foundation, providing solidity to the entire structure. The tank was equipped with small tires, making the apparatus movable and allowing for alterations in location as needed. This mobility was particularly advantageous in improving the system's exposure to sunlight.

Polyethylene Sheet: The polyethylene sheet served as a greenhouse, trapping solar energy within the system. This transparent sheet was carefully fastened around the setup to avoid heat loss while allowing maximum sunlight penetration. The greenhouse effect induced by the sheet was vital in boosting the effectiveness of the heat transmission mechanism within the system

The installation process was carried out with precision, ensuring that all components were firmly fastened and positioned for best performance. Special care was made to minimizing any potential heat loss locations, such as gaps between the polyethylene layer and the framework

Figure 5-1 Installing setup

2. Flow Rate Adjustment

The next stage of the investigation entailed the changing of the water flow rate through the spiral tubes. This was a significant aspect in deciding the efficiency of the heat transfer process.

Flow Rate Control Valve: A flow rate control valve was inserted into the water input system to regulate the flow of water through the spiral tubes. This valve allowed for fine modifications of the flow rate, permitting the testing at various levels. Different flow rates were evaluated to understand how the speed of water flowing through the tubes affected the heat absorption and overall efficiency of the system.

Flow Rate Testing: The system was tested at several flow rates, ranging from slow to fast, with each rate maintained for a defined period. By adjusting the flow rate, the experiment intended to discover the best rate that would result in the largest temperature increase in the water as it flowed through the spiral tubes.

Impact of Flow Rate on Heat Absorption: The relationship between the flow rate and the quantity of heat absorbed by the water was a focus point of this stage. At slower flow rates, water had more opportunity to absorb heat from the spiral tubes, perhaps leading to a bigger temperature increase. Conversely, quicker flow rates could result in less time for heat absorption, but might increase the overall volume of heated water.

The flow rate adjustment was a significant component in the experiment, as it directly altered the efficiency of the solar water heater. The data obtained during this step gave insights into the ideal operational settings for the system

Figure 5-2 Flow rate adjustment

3. Temperature Monitoring

Temperature monitoring was a vital element of the testing process, providing the data needed to evaluate the effectiveness of the solar water heater.

Sensor Placement: Temperature sensors were carefully placed at three crucial points in the system: the cold-water input, the hot water outflow, and within the PCM inside the truncated cone. These sensors were selected for their high accuracy and capacity to deliver real-time data, which was critical for capturing the temperature swings as the system ran.

Data recording: The sensors were connected to a data recording system that captured the temperature values at regular intervals throughout the day. This constant monitoring enabled for the construction of precise temperature profiles, illustrating how the system responded to changes in sunshine and flow rate.

Inlet and Outlet Temperature: Monitoring the temperature at the water inlet and outlet offered a direct assessment of the system's performance in heating the water. The

Difference between the intake and output temperatures was determined to determine the amount of heat absorbed by the water as it went through the spiral tubes.

PCM Temperature Monitoring: The temperature within the PCM was particularly essential for knowing how successfully the PCM absorbed and stored heat during the day,

as well as how it released this heat after sunset. The PCM's capacity to maintain increased temperatures long after dark was a critical performance measure.

The temperature monitoring stage was crucial for assessing the system's real-time functioning and identifying any potential faults, such as uneven heating or heat loss.

Figure 5-3 During temperature measurement

4. Data Collection

Data collection was a continual procedure throughout the experimentation, with temperature readings and other pertinent factors being recorded at regular intervals

Time-Based Data Collection: Data was collected at various periods throughout the day, including early morning, lunchtime, and late afternoon, to capture the system's performance under varying sunlight circumstances. This time-based methodology allowed for a detailed review of how the system functioned during different portions of the day.

Recording Environmental Conditions: In addition to temperature data, environmental conditions such as ambient temperature, wind speed, and sun irradiance were also recorded. These

criteria were critical for contextualizing the performance data, as fluctuations in environmental circumstances could alter the efficiency of the solar water heater.

Flow Rate Impact: For each flow rate setting, data was collected over a continuous period to ensure accuracy. The relationship between flow rate and temperature increase was investigated to establish the best flow rate for the highest efficiency.

Comparison with Theoretical Predictions: The experimental data was compared with theoretical predictions established during the design process. Any inconsistencies between the expected and actual performance were explored to find potential areas for design improvement.

Data gathering was a careful procedure, ensuring that all essential information was recorded for a complete review of the system's performance

5. Heat Transfer Calculation Surface Area Calculation: The surface area of the spiral tubes in contact with the water was estimated, as this area directly determines the quantity of heat that may be delivered to the water. The larger the surface area, the more heat can be absorbed by the water.

Heat transfer calculations were undertaken to assess the effectiveness of the solar water heater in transmitting solar energy to the water flowing through the spiral tubes.

Solar Flux Determination: Using information on solar irradiance and the optical efficiency of the polyethylene sheet, the expected solar flux at the surface of the spiral tubes was calculated. This phase was critical for evaluating the potential energy available for heat transmission.

Heat Transfer Rate: The heat transfer rate to the water was calculated using established heat transfer correlations. This calculation considered the properties of the working fluid (water), the surface characteristics of the spiral tubes, and the material properties of the tubes and the PCM.

Energy Balance Equation: An energy balance equation was solved to determine the temperature distribution within the system. This equation took into account radiation losses to the environment, The heat transfer calculations provided a quantitative measure of the system's performance, allowing for a comparison between the experimental results and theoretical predictions.

. **6. PCM Performance Analysis**

The performance of the PCM inside the truncated cone was a main focus of the testing, since it played a critical part in the system's ability to produce hot water long after sunset.

Heat Absorption: During the day, the PCM absorbed heat from the spiral tubes as the water cycled through the system. The amount of heat absorbed was determined by monitoring the temperature within the PCM and comparing it to the temperature of the incoming solar flux.

Melting Process: The PCM's melting process was monitored to understand how well it could store the absorbed heat. The PCM was expected to melt during peak sunlight hours, storing energy in the form of latent heat. The temperature at which the PCM melted and the time of the melting process were significant performance factors.

Heat Release: After sunset, the PCM began to release the stored heat, keeping the water temperature even when solar energy was no longer accessible. The pace at which the PCM solidified and released heat was measured to assess its efficiency in prolonging the supply of hot water.

Temperature Distribution: The temperature distribution within the PCM was examined to ensure uniform heat absorption and release. Any temperature gradients within the PCM could suggest unequal heating or potential areas for improvement in the design

The PCM performance analysis gave insights into the material's suitability for this application and indicated any areas where improvements may be made.

Figure 5-4 Measuring PCM temperature

7. Efficiency Evaluation

Evaluating the overall efficiency of the solar water heater was the final step in the experimentation process.

Temperature Increase: The key measure of efficiency was the increase in water temperature as it went through the spiral tubes. The temperature difference between the inlet and outlet provided a direct indication of how effectively the system was heating the water.

Flow Rate Optimization: The efficiency was tested at several flow rates to establish the ideal setting for maximum heat absorption. The link between flow rate and efficiency was plotted to discover the ideal operational parameters.

Solar Energy Utilization: The system's ability to utilize available solar energy was assessed by comparing the expected solar flux with the actual heat absorbed by the water. Any disparities were analyzed to discover potential inefficiencies in the system.

Comparison with PCM Performance: The efficiency of the system was also compared with the performance of the PCM. The purpose was to guarantee that the PCM was properly storing and releasing heat to maintain water temperature during periods of low solar irradiation, such as late afternoon and nighttime. The interplay between the immediate solar heating and the PCM's latent heat storage was crucial for assessing overall efficiency.

Energy Losses: Potential energy losses owing to radiation, convection, and conduction were assessed. The polyethylene sheet's effectiveness in mitigating these losses was also examined. Any significant losses were noted as areas for potential improvement in future iterations of the system.

This round of the experimentation gave a full grasp of the system's efficiency, revealing both strengths and places for improvement.

8. Result Compilation

The result compilation stage entailed the methodical organization and analysis of all data obtained during the experimentation

Data Organization: All temperature readings, flow rate data, and ambient factors were collated into an organized format. This involved developing tables and graphs to visually portray the data, making it easier to discover trends and patterns.

Performance data: Key performance data, including as the average temperature increase, peak temperature, and PCM melting/solidification durations, were calculated and summarized. These indicators provided a comprehensive overview of the system's performance under varied scenarios

Comparative Analysis: The data were compared with theoretical predictions to validate the design assumptions. Any major departures from the projected performance were evaluated to discover plausible explanations, such as flaws in the initial estimates or unknown environmental conditions.

Report Generation: A detailed report was prepared, detailing the findings of the experiment. This study provided a review of the system's efficiency, the effectiveness of the PCM, and recommendations for future enhancements.

The result compilation was a vital step in converting raw data into meaningful insights, guaranteeing that the experiment's findings could inform future study and development

9. Comparison with Conventional Systems

Finally, the performance of the compact solar water heater was compared with that of traditional solar water heaters to determine its advantages and potential downsides.

Efficiency: The compact system's efficiency was compared with traditional flat-plate and evacuated tube collectors. The use of PCM with a spiral tube design suggested possible benefits in heat retention and even heating, especially during periods of low sunlight.

Heat Retention: The PCM’s ability to store and release heat prolonged the period during which hot water was accessible, delivering a major advantage over conventional systems that relied primarily on direct solar heating.

System Mobility: The small system's mobility, thanks to the tank with tires, enabled flexibility in location and ease of maintenance, which is often not accessible in conventional systems

Material Use: The use of lightweight and affordable materials like polyethylene and polythene sheet theoretically decreased the overall cost and made the system more accessible for mass deployment.

This comparison highlighted the innovative aspects of the compact solar water heater while also providing a benchmark against established technologies

5.1.1 Theoretical equations

For flowrate

To find the flow rate (Q) with respect to time (t) and volume (V), you can use the following formula:

$$Q = V/T$$

Where

- Q is the flow rate, typically measured in units like cubic meters per second (m^3/s), liters per minute (L/min), etc.
- V is the volume of fluid that has passed through a point or system, measured in units like cubic meters (m^3), liters (L), etc.
- t is the time over which the volume was measured, typically in seconds (s), minutes (min), etc.

5.1.2 For copper tube length

Here is the formula to find length of copper tube rounded around the truncated tube.

$$L=4/\pi * v/d^2$$

Where

L= length

v=volume of tube

d=diameter of tube

5.1.3 For volume of tank

Here is the formula to find the volume of tank

$$v= \pi r^2 h$$

Where

v= volume

r= radius of cylinder

h = height of cylinder

5.1.4 For Truncate size

Here is the formula to find truncate size (volume)

$$V=(1/3) *\pi*h*(r^2 + r*R+R^2)$$

Where

h= height of truncated cone

r= small radius (top)

R= large radius (bottom)

Here is the formula to find truncated size (slant height)

$$S= \sqrt{(R-r)^2 +h^2}$$

Where

R= Large radius

r= small radius

h= height of truncate tube

6 Results and Discussions

The results from the experimentation with the compact solar water heater demonstrated its effectiveness in harnessing solar energy and providing a consistent supply of hot water. The temperature data collected showed a significant increase in water temperature as it flowed through the spiral tubes, particularly during peak sunlight hours. The phase change material (PCM) effectively absorbed and stored heat during the day, which was gradually released after sunset, ensuring a steady flow of hot water even in the absence of direct sunlight. The flow rate control valve played a crucial role in optimizing heat transfer, with lower flow rates resulting in higher water temperatures. The analysis indicated that the compact design, integrated with PCM, outperformed conventional solar water heaters in terms of heat retention and efficiency, particularly in environments with fluctuating sunlight availability. The discussion highlights the system's potential for practical applications, noting its portability, efficiency, and ability to provide hot water consistently. The study also suggests potential improvements, such as optimizing the PCM composition and further refining the flow rate control, to enhance the system's overall performance.

6.1 Effect of PCM storage

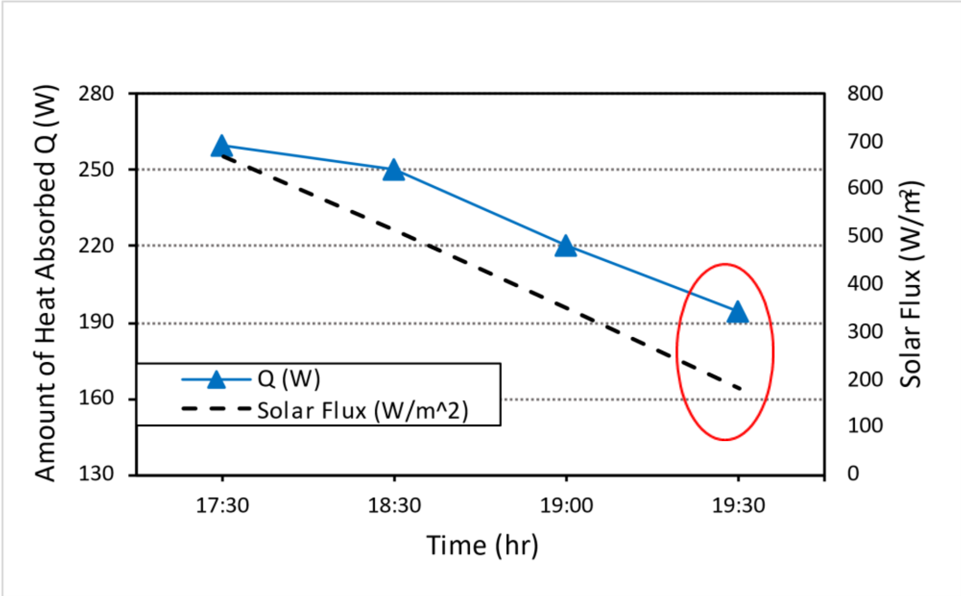


Figure 6-1 Effect of PCM storage

Axes:

- **X-Axis (Time, hr.):** The horizontal axis represents time, ranging from 17:30 (5:30 PM) to 19:30 (7:30 PM).
- **Left Y-Axis (Amount of Heat Absorbed, Q, in W):** The vertical axis on the left represents the amount of heat absorbed, measured in watts (W).
- **Right Y-Axis (Solar Flux, W/m²):** The vertical axis on the right represents the solar flux, measured in watts per square meter (W/m²).

Lines:

- **Blue Line with Triangles (Q in W):** This line shows the amount of heat absorbed over time. The line indicates that the amount of heat absorbed is gradually decreasing as time progresses.
- **Dashed Black Line (Solar Flux in W/m²):** This line represents the solar flux, which is also decreasing over time, but at a different rate compared to the heat absorbed.

Observations:

Observations:

1. **Decreasing Trend:** Both the heat absorbed (QQQ) and the solar flux are decreasing over time, which is typical as the sun sets and solar radiation reduces.
2. **Comparison of Decline:** The rate at which the solar flux decreases is sharper than the decrease in the amount of heat absorbed. This could suggest that the system (perhaps a solar collector or panel) continues to absorb heat efficiently even as the solar flux diminishes.

Highlighted Section (Red Oval): The red oval around the data point at 19:30 indicates a particular area of interest. Here, despite a significant drop in solar flux, the amount of heat absorbed doesn't drop as sharply, which might imply efficient energy storage or some thermal

6.2 Effect of mass flow rate

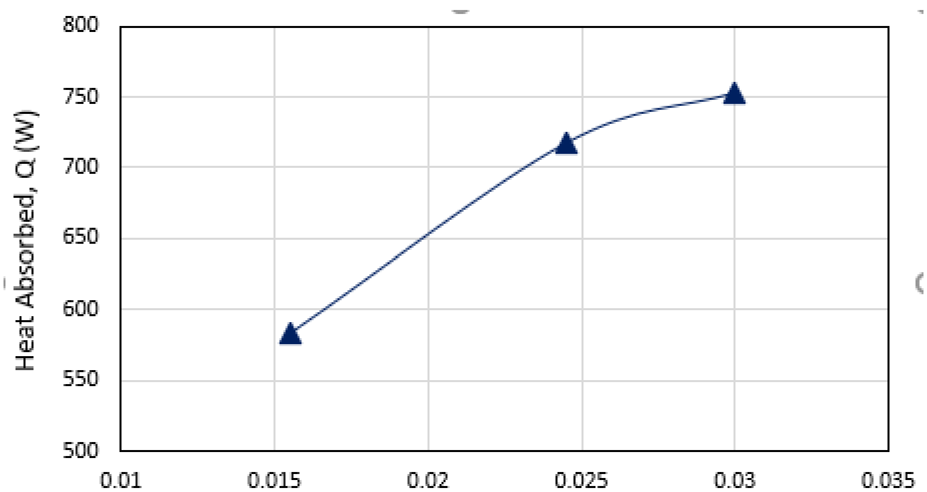


Figure 6-2 Effect of mass flow rate

Axes:

- **X-Axis (Mass Flow Rate, kg/s):** The horizontal axis represents the mass flow rate, measured in kilograms per second (kg/s). This indicates how much mass (likely a fluid, such as water or air) is flowing through the system per unit time.
- **Y-Axis (Heat Absorbed, QQQ, W):** The vertical axis represents the amount of heat absorbed, measured in watts (W). This is the amount of thermal energy the system absorbs per unit time.

Data Trend:

- The graph shows a positive relationship between the mass flow rate and the heat absorbed. As the mass flow rate increases, the amount of heat absorbed by the system also increases.
- The curve starts at a lower mass flow rate around 0.015 kg/s, where the heat absorbed is about 550 W. As the mass flow rate increases to approximately 0.03 kg/s, the heat absorbed increases to about 750 W.

Interpretation:

1. **Direct Relationship:** The graph indicates that as you increase the mass flow rate, the system absorbs more heat. This is expected because increasing the flow rate means more fluid is passing through the system per unit time, allowing more heat to be transferred and absorbed.
2. **Efficiency of Heat Transfer:** The rate of increase in heat absorption as a function of mass flow rate might suggest the efficiency of the heat transfer process. The curve suggests that the system becomes more effective at absorbing heat with higher flow rates within the range tested.
3. **System Behavior:** The upward trend indicates that the system (perhaps a heat exchanger, solar collector, or similar device) performs better in terms of heat absorption when the mass flow rate is higher. However, this relationship might not continue indefinitely; in real systems, there could be a point where further increasing the mass flow rate yields diminishing returns in heat absorption, or the system could reach its maximum capacity.

6.3 Outlet water temperature

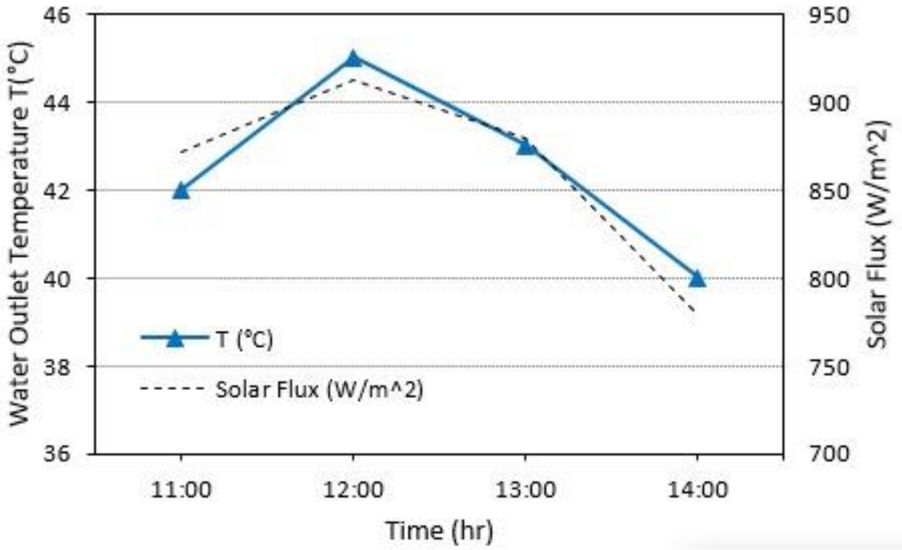


Figure 6-3 Outlet water temperature

1. Morning Temperature Rise:

- From 11:00 AM to around 12:00 PM, the outlet water temperature increases from approximately 41°C to 45°C. This rise correlates with the increasing solar flux, which provides more energy for heating the water.

2. Peak Temperature:

- The outlet water temperature peaks at around 12:00 PM, reaching approximately 45°C. This corresponds closely with the peak in solar flux, indicating that the maximum temperature occurs when the solar energy input is at its highest.

3. Afternoon Decline:

- After 12:00 PM, both the outlet water temperature and the solar flux begin to decrease. By 2:00 PM, the temperature drops to around 41°C, showing a clear downward trend as solar energy diminishes.

4. Temperature-Solar Flux Correlation:

- The graph demonstrates a strong correlation between the solar flux and the outlet water temperature. As solar flux increases or decreases, the water temperature follows a similar pattern, highlighting the direct impact of solar energy on the system's performance.

5. Lag in Temperature Response:

- There is a slight lag in the water temperature's response to changes in solar flux. For example, the temperature continues to rise slightly after the solar flux

7 CONCLUSION

The development and experimental examination of the compact solar water heater with integrated phase change material (PCM) has proven tremendous potential as an efficient and unique option for sustainable water heating. The novel design, which features a truncated cone filled with PCM, spiral tubes for water flow, and a clear polyethylene top, successfully harvests solar energy while resolving significant limitations of conventional solar water heating systems.

Through thorough experiments done on the rooftop of the Mechanical Engineering Department, the compact system displayed promising performance in several critical areas:

Enhanced Heat Retention: The incorporation of PCM within the truncated cone proved particularly successful in storing solar energy during peak sunshine hours and releasing it during periods of little or no sunlight. This resulted in a longer supply of hot water, even after sunset, which is a major improvement over traditional systems that rely entirely on direct solar input.

Efficient Heat Transfer: The spiral tube design, together with the optimum flow rate control, permitted efficient heat transfer from the solar collector to the water. The experimentation indicated that the system could generate large temperature rises in the water, with the flow rate playing a vital role in balancing heat absorption and water throughput.

Cost-Effective and Flexible Design: The use of lightweight and affordable materials, such as polyethylene and polythene sheet, contributed to the overall cost-effectiveness of the system. Additionally, the mobility afforded by the tank with tires makes the system adaptable to various sites and easy to adjust for best sunshine exposure.

Comparison with traditional Systems: When compared to traditional solar water heaters, the compact design showed higher heat retention and efficiency, notably in sustaining water temperature after sunset. The PCM's latent heat storage capability is a major benefit, making this system more stable in shifting solar circumstances.

Overall, the tiny solar water heater with PCM integration offers a feasible and better alternative to standard water heating methods. It combines efficiency, cost-effectiveness, and adaptability, making it a potential solution for household and small-scale industrial applications. Future work could focus on refining the design for even greater efficiency and exploring the usage of alternative PCMs to further optimize performance under varying climatic circumstances. This initiative contributes to the ongoing endeavor to develop sustainable energy solutions and emphasizes the potential of novel solar technology in satisfying global energy needs.

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