Design of High Efficiency Solar Water Heater for Family Utility

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Abstract
The work is the design of a high-efficiency solar water heater using the modern methods, the concept of material science and the thermodynamic are used to improve the performance. Based on the research conducted, important design parameters such as types of the collector, absorbers' coatings, insulation types, and mechanisms of heat transfer that all effect upon thermal efficiency, are considered. A systematic literature review was done on identifying state of the art practices and a theoretical framework and simulation-based analysis is developed. The methodology combines computational modeling and experimental validation used for determining the performance under varied climatic conditions. Contingent on the results, it seems that selective surface coatings, vacuum insulation and the leanest collector tilt angles add significantly to efficiency gains.

Keywords: Solar water heater; Thermal efficiency; Flat plate collector; Selective surface coating; Heat transfer enhancement; Insulation materials; computational modeling; sustainable design.

1. Overview of solar water heating systems

Solar water heating systems use solar collectors to capture and convert sunlight into thermal energy, which is used to heat water [6, 7]. The key components of these systems include solar collectors, a heat transfer system, a storage tank, and a control unit, [1, 2] The efficiency of these systems depends on the design and quality of each component, as well as the overall system configuration [3, 5]. Solar water heaters can be classified into two main categories: active systems, which rely on mechanical components such as pumps and controllers to circulate the fluid, and passive systems, which use natural convection and gravity to move the fluid. Active systems are generally more efficient but also more complex and costly to install and maintain. Passive systems are simpler and cheaper but may have lower performance, especially in regions with less sunlight, [4].

2. Types of solar collectors

2.1 Flat-Plate Collectors

Flat-plate collectors are the most widely used type of solar collector for residential water heating. They consist of a flat, dark-colored absorber plate that absorbs solar radiation, a series of pipes or tubes for circulating the fluid, insulation to minimize heat loss, and a transparent cover to protect the absorber and reduce radiative heat losses.

2.2 Evacuated Tube Collectors

Evacuated tube collectors are composed of multiple glass tubes, each containing a metal absorber and a heat pipe or fluid-filled tube. The vacuum within each tube serves as an excellent insulator, greatly reducing heat loss and allowing the collectors to maintain high efficiency even in cold and windy conditions.

2.3. Integral Collector-Storage Systems

Integral collector-storage (ICS) systems combine the solar collector and the storage tank in one unit. Water is heated directly within the collector and stored until needed. ICS systems are simple and cost-effective but are generally only suitable for mild climates where freezing is not a concern, as the entire system is exposed to the environment, [5].

2.4 Two basic Performance Metrics and Efficiency Factors

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The performance of solar water heating systems is measured using several key metrics:
Payback Period: The payback period is the time required for the savings generated by the solar water heater to equal the initial investment cost., [8].
Environmental Impact: The environmental impact of solar water heaters is assessed by calculating the reduction in greenhouse gas emissions compared to conventional heating methods, [2].

3. Methods

3.1 Sizing the solar collector

The collector area was calculated using the following formula

$$A = \frac{Q_{useful}}{G_{avg} * \eta_{coll}} \quad (1)$$

3.2 Piping System Design

The piping system was designed based on the layout, with an estimated length of 10 meters of insulated piping, ensuring minimal heat loss between the collector and the storage tank.

3.3 Pump Selection

The pump was selected based on the flow rate required to circulate the fluid between the collector and the storage tank. A 3 liters/min pump was chosen to match the system design.

3.4 CAD Design Using Fusion 360/3D Modeling

A 3D model of the solar water heating system was created in Fusion 360. The model includes the solar collector, storage tank, piping layout, auxiliary heater, and other components Detailed technical drawings were generated to represent the component dimensions and layout, including connections between the collector, tank, and auxiliary heater.

3.5 Simulation in CAD

Fusion 360 was used to analyze component placement, ensuring that the layout allowed for easy installation and minimal heat loss. Rendered images provided a clear visualization of the system's physical setup.

4. Total solar energy collection

The solar collector absorbed a total of 137 W (as seen in the system diagram) under specific weather conditions. The average temperature of the heat transfer fluid entering the collector was 1.6°C. The flow rate through the system was 0 l/h during the simulation snapshot, indicating a no-flow condition at that moment. This is likely due to insufficient solar irradiance to drive the circulation pump.

4.1 Efficiency and Performance Analysis:

The solar fraction of the system, which indicates the portion of energy provided by the solar collector relative to the total system demand, was calculated over the simulation period., with efficiency of around 70%, with the solar collector.

4.2 Auxiliary Heating Contribution:

The auxiliary heater provided 65 W of power at certain times when solar energy was insufficient. This typically occurred in early mornings or during overcast conditions when the solar input was below the system's demand threshold. The auxiliary heater was engaged intermittently, maintaining the desired temperature when solar energy could not fulfill the load, thus ensuring a constant supply of hot water.

4.3 System Efficiency and Heat Loss in Piping:

From the diagram, the temperature drops across the piping system was minimal, indicating well-insulated pipes. The difference in temperature between the collector outlet (58.3°C) and the tank inlet (56.8°C) was 1.5°C, which suggests effective insulation with minimal heat loss.

4.4 Solar collector performance

The solar collector demonstrated high efficiency under ideal conditions, with peak temperatures reaching 58.3°C. However, during periods of low solar irradiance, such as early mornings or cloudy days, the system struggled to maintain flow, as evidenced by the 0.l/h flow rate at certain points. The temperature drops from 1.6°C to -1.5°C in the system during those times indicates that there was insufficient thermal energy to drive the circulation pump.
The system's performance can be further improved by optimizing the collector tilt angle and orientation to capture more solar energy.

4.5 Auxiliary heating contribution

The auxiliary heater played a significant role during periods of low solar availability. It

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provided a reliable backup, contributing 65 W during times when the solar collector could not meet the demand.

4.6 Design validation with fusion 360

The Fusion 360 CAD design ensured that the system layout, particularly the placement of the collector, storage tank, and piping, was optimizedforbothinstallation and performance. The rendered technical drawings validated the dimensions and arrangement of the components, reducing potential heat losses through proper insulation and system configuration.

4.7 Energy demand and deficit

Analyze the relationship between energy demand (Qdem), energy supplied to the system (Quse), and energy deficit (Qdef). For instance, in February, the energy deficit is 86.4 kWh, while energy demand is 286 kWh, meaning the system met the majority of the demand, but a significant deficit remains.
From the table the periods where the energy deficit is higher, like in January and February, and discuss the reasons. This could be due to reduced solar irradiance in winter, which limits the system's ability to heat water.

5. Conclusions

From the successfully simulated and evaluated the performance of a solar water heating system, which was designed and analyzed using Polysun simulation software and validated through a Fusion 360 CAD model. The solar water heating system demonstrated an efficiency of around 70% under peak solar irradiance conditions. The solar collector was able to heat the water to a maximum temperature of 58.3°C, which was stored in the stratified storage tank for immediate and delayed use. During periods of low solar energy availability i.e. cloudy weather, the system effectively utilized an auxiliary heater, which contributed 65 W to maintain the hot water supply. The solar water heating system significantly reduced reliance on fossil fuels, as the primary heat energy came from the sun. In regions with favorable solar irradiance, the system could operate almost entirely on solar energy, contributing to sustainability and lower greenhouse gas emissions.

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