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Thermal Performance Enhancement Strategies for a Compact Solar PV-Powered Concentrating Water Heating System Through Integrated Collector Design

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Abstract

Solar water heating systems have emerged as one of the most promising renewable energy technologies for reducing dependence on conventional fossil fuels and electricity-based water heating. However, the thermal performance of compact solar water heaters is often limited by inadequate solar absorption, poor heat transfer, and thermal losses within the collector assembly. This study presents a theoretical investigation of thermal performance enhancement strategies incorporated into a compact solar photovoltaic (PV)-powered concentrating water heating system. The proposed design integrates multiple heat transfer enhancement techniques, including a spiral copper coil heat exchanger, black-coated absorber surface, reflective mirror concentrator, active water circulation using a photovoltaic-powered direct current (DC) pump, and a provision for a transparent glass cover to minimize heat losses. Each enhancement technique is examined from the perspective of solar radiation absorption, conductive heat transfer, convective heat exchange, and thermal energy retention. The influence of collector geometry, material selection, and active circulation on overall thermal performance is also discussed. Standard heat transfer equations are presented to establish the theoretical framework governing the operation of the system. The study demonstrates that integrating several passive and active thermal enhancement strategies into a compact collector design can significantly improve the utilization of available solar energy while maintaining low fabrication cost and operational simplicity. The proposed approach offers an economical and environmentally sustainable solution for domestic water heating, educational demonstrations, and small-scale renewable energy applications, while providing a foundation for future experimental performance evaluation and system optimization.

Keywords: Solar water heater, heat transfer enhancement, concentrating solar collector, spiral copper coil, renewable energy, solar thermal system, active water circulation

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INTRODUCTION

The increasing global demand for energy, coupled with concerns regarding environmental pollution and depletion of fossil fuel resources, has accelerated the development and deployment of renewable energy technologies. Among the available renewable resources, solar energy is considered one of the most abundant, sustainable, and environmentally friendly energy sources. Solar thermal technologies, in particular, have gained considerable attention because they enable the direct conversion of solar radiation into useful thermal energy for applications such as domestic water heating, industrial process heating, agricultural drying, and space heating [1, 2].

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Domestic water heating constitutes a significant portion of residential energy consumption in many countries. Conventional electric geysers and fossil fuel-based water heating systems consume considerable amounts of energy and contribute to greenhouse gas emissions. Solar water heating systems provide an attractive alternative because they utilize freely available solar radiation while reducing electricity consumption and operating costs. Their widespread adoption can contribute to energy conservation, carbon emission reduction, and sustainable development [3].

Although solar water heaters have been widely implemented, their thermal performance depends strongly on the efficiency of solar energy absorption and heat transfer within the collector. A substantial fraction of the incident solar radiation may be lost through reflection, convection, and radiation if the collector is not properly designed. Consequently, researchers have focused on improving collector efficiency by enhancing absorber materials, optimizing collector geometry, increasing heat transfer area, reducing thermal losses, and employing active water circulation mechanisms [4].

One of the most effective approaches for improving heat transfer involves increasing the surface area available for thermal exchange between the absorber and the working fluid. Spiral copper coil heat exchangers have attracted considerable interest because they provide a large heat transfer surface within a compact collector volume. Copper possesses excellent thermal conductivity, allowing rapid transfer of absorbed solar energy to circulating water. When combined with a spiral configuration, the heat exchanger offers prolonged contact between the heated surface and the working fluid, thereby improving thermal energy transfer [5, 6].

Another important enhancement technique is the application of black surface coatings on absorber components. Black surfaces exhibit high solar absorptivity and low reflectivity, enabling greater conversion of incident solar radiation into thermal energy. Similarly, reflective mirror sheets and concentrating collector geometries increase the effective solar radiation incident on the absorber by redirecting sunlight toward the heat exchange region. Such concentrating arrangements improve solar energy utilization without substantially increasing the collector size [7].

Active water circulation also plays a significant role in improving thermal performance. Unlike passive thermosiphon systems, which rely solely on density differences to circulate water, active systems employ pumps to maintain continuous fluid movement through the collector. Continuous circulation reduces thermal stratification, increases convective heat transfer, and promotes more uniform water heating. The integration of photovoltaic-powered DC pumps further enhances sustainability by eliminating dependence on external electrical power while allowing automatic operation during periods of adequate solar radiation [8].

In addition to heat absorption, minimizing thermal losses is equally important for achieving high collector efficiency. Transparent glass covers reduce convective heat losses while allowing short-wave solar radiation to enter the collector. The resulting greenhouse effect traps thermal energy inside the collector chamber, increasing the absorber temperature and improving the water heating capability [9].

The present study examines the thermal enhancement strategies incorporated into a compact solar PV-powered concentrating water heating system designed for domestic applications. Unlike studies primarily focused on fabrication, this work emphasizes the engineering principles governing heat transfer enhancement through integrated collector design. The combined influence of spiral copper tubing, reflective concentration, black absorber coating, active water circulation, and thermal insulation is discussed using established heat transfer principles. Standard thermal engineering equations are introduced to provide a theoretical basis for analyzing system performance, while future experimental investigations are proposed to validate the expected improvements [10].

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HEAT TRANSFER MECHANISMS IN THE PROPOSED SOLAR WATER HEATING SYSTEM

The operation of the proposed solar PV-powered concentrating water heating system is governed by the combined action of solar radiation, conduction, convection, and thermal energy storage. The integration of these heat transfer mechanisms determines the overall thermal effectiveness of the collector. Unlike conventional electric water heaters that generate heat through electrical resistance, the developed system utilizes naturally available solar radiation and transfers the absorbed energy to water through an actively circulated heat exchanger.

Solar Radiation Absorption

Solar radiation is the primary energy source for the developed water heating system. Incident sunlight enters the collector chamber and is intercepted by the black-coated spiral copper coil and the surrounding absorber surfaces. The quantity of solar energy available depends on solar irradiance, collector orientation, geographical location, and weather conditions.

The collector incorporates reflective mirror sheets that redirect a portion of the incident sunlight toward the absorber. This concentration of solar radiation increases the amount of energy reaching the copper coil without increasing the physical size of the collector. Consequently, a greater proportion of the available solar energy is converted into useful thermal energy.

The black surface coating applied to the copper tube further enhances solar absorption by minimizing reflection losses. Black surfaces exhibit high absorptivity across the solar spectrum, allowing them to absorb significantly more incident radiation than uncoated metallic surfaces. Consequently, the absorber temperature increases more rapidly, thereby improving the heat transfer rate to the circulating water.

Conduction Through the Copper Heat Exchanger

Following solar energy absorption, heat is transferred from the outer surface of the copper tube to the flowing water by thermal conduction.

Copper was selected because of its exceptionally high thermal conductivity, which is substantially greater than that of commonly used structural materials, such as mild steel or stainless steel. High thermal conductivity reduces thermal resistance within the heat exchanger and enables rapid transfer of absorbed heat from the collector surface to the working fluid.

The rate of conductive heat transfer through the tube wall is influenced by the temperature difference between the absorber surface and the flowing water, the thermal conductivity of copper, and the wall thickness of the tube. By minimizing thermal resistance, the copper heat exchanger significantly contributes to improved collector performance.

Forced Convective Heat Transfer

The developed system employs a photovoltaic-powered DC pump to maintain continuous water circulation through the spiral heat exchanger.

Unlike passive thermosiphon systems, where water circulation depends solely on density differences, active circulation provides controlled fluid movement regardless of collector orientation. Continuous circulation continuously removes heated water from the collector while replacing it with cooler water from the storage tank, thereby maintaining a high temperature gradient across the heat exchanger.

A higher temperature gradient promotes greater convective heat transfer between the copper surface and the circulating water. Forced convection also reduces the temperature stratification inside the collector and enhances the overall heat extraction capability of the system.

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Thermal Energy Storage

After passing through the collector, the heated water returns to the high-density polyethylene (HDPE) storage tank, where the thermal energy is retained until use.

The storage tank functions as both a water reservoir and a thermal storage unit. Continuous circulation allows the water temperature inside the tank to increase progressively during periods of solar radiation.

Although HDPE has lower thermal insulation characteristics than specialized insulated tanks, its corrosion resistance, lightweight construction, and economic advantages make it suitable for compact prototype development. The addition of external insulation in future designs may further reduce thermal losses during storage.

THERMAL PERFORMANCE ENHANCEMENT TECHNIQUES

The thermal performance of solar water heating systems depends largely on the effectiveness of the collector in absorbing, transferring, and retaining solar energy. The proposed system integrates several enhancement techniques that collectively improve heat transfer without significantly increasing system complexity or manufacturing cost.

Spiral Copper Coil Heat Exchanger

One of the most important design features of the developed collector is a spiral copper heat exchanger.

Compared with straight pipe arrangements, the spiral configuration provides a substantially larger heat transfer surface area within a compact collector volume. Increasing the available surface area improves the interaction between the heated copper tube and the flowing water, thereby increasing the amount of thermal energy transferred during circulation.

Spiral geometry also increases the residence time of water inside the collector, allowing more heat to be absorbed before the water exits the system. Uniform spacing between adjacent turns of the coil ensures that all portions of the heat exchanger receive adequate solar exposure while maintaining an unrestricted water flow.

From a heat transfer perspective, the spiral configuration represents an efficient method of maximizing thermal performance without increasing collector dimensions.

Black-Coated Absorber Surface

Surface coating plays an important role in determining collector efficiency.

Bare metallic surfaces reflect a significant portion of incoming solar radiation, thereby reducing the amount of energy available for heating. Applying a matte black coating to the copper tube increases solar absorptivity while decreasing surface reflectivity.

The black coating enables the absorber to convert a larger fraction of incident solar radiation into thermal energy, thereby increasing the absorber temperature and enhancing conductive heat transfer to the circulating water.

The use of black absorber coatings is widely adopted in solar thermal engineering because it represents a simple, economical, and highly effective method of improving collector performance.

Reflective Solar Concentration

The proposed collector incorporates reflective mirror sheets positioned along the internal surfaces of the collector chamber.

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These mirrors redirect sunlight that would otherwise be lost onto the spiral copper coil, thereby increasing the effective solar radiation received by the absorber. Unlike high-cost concentrating solar technologies requiring solar tracking systems, the proposed reflective arrangement provides a low-cost method of improving solar energy utilization.

The reflective concentrator also promotes a more uniform distribution of solar radiation throughout the collector chamber, thereby reducing localized heating and improving the overall thermal performance.

Active Water Circulation Using Solar PV

Continuous circulation is essential for maintaining efficient heat transfer between the collector and the working fluid.

The integration of a photovoltaic-powered DC pump enables active circulation without relying on grid electricity or battery storage. As pump operation depends directly on solar radiation, circulation automatically increases during periods of high solar intensity, coinciding with maximum thermal energy availability.

Active circulation minimizes thermal stagnation within the collector, maintains a uniform absorber temperature, and improves the rate of heat removal from the collector. Consequently, the collector operates under more favorable thermal conditions than passive circulation systems.

Greenhouse Effect

To further reduce thermal losses, the collector design includes a transparent glass cover.

The glass cover permits short-wave solar radiation to enter the collector while restricting the escape of long-wave infrared radiation emitted by the heated absorber. This phenomenon, commonly known as the greenhouse effect, increases the internal collector temperature and reduces convective heat loss to the surrounding environment.

The incorporation of a glass cover is expected to improve collector efficiency, particularly during periods of moderate wind or lower ambient temperatures.

Integrated Thermal Enhancement Strategy

The novelty of the proposed design lies not in any single component but in the integration of multiple thermal enhancement techniques into a compact and economical system. The spiral copper coil increases the heat transfer area, the black coating improves solar absorptivity, reflective mirrors enhance solar concentration, the photovoltaic-powered pump provides continuous circulation, and the glass cover reduces thermal losses.

The combined action of these features is expected to improve the overall thermal performance while maintaining a simple construction and low manufacturing cost. Such an integrated approach offers a practical solution for domestic solar water heating, particularly in regions with abundant solar radiation and limited access to conventional energy sources.

THEORETICAL THERMAL ANALYSIS

The thermal performance of the proposed solar PV-powered concentrating water heating system can be analyzed using standard heat transfer and solar energy equations. Although the present study focuses on system design and thermal enhancement strategies rather than experimental validation, these equations provide a theoretical framework for evaluating collector performance under operating conditions.

Solar Energy Incident on the Collector

The amount of solar energy available for water heating depends on the collector area and the intensity of incident solar radiation. The theoretical solar heat input can be expressed as

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$$Q_s = I \times A$$

where:
Q_s= solar energy incident on the collector (W)
I= solar irradiance (W/m²)
A= effective collector area (m²)

The collector dimensions of the developed system provide an effective area capable of intercepting a significant portion of the available solar radiation. The incorporation of reflective mirror sheets further increases the effective solar energy reaching the absorber by redirecting additional sunlight toward the spiral copper coil.

Heat Transfer to the Working Fluid

The useful thermal energy transferred to the circulating water is governed by the following relationship:

$$Q_u = \dot{m} C_p (T_o - T_i)$$

where
Q_u= useful heat gain (W)
$\dot{m}$= mass flow rate of water (kg/s)
C_p= specific heat capacity of water (J/kg·K)
T_i= inlet water temperature (°C)
T_o= outlet water temperature (°C)

The spiral copper heat exchanger increases the contact area between the heated surface and the working fluid, thereby improving the amount of thermal energy transferred during circulation. Continuous pumping maintains a steady flow of water, which enhances convective heat transfer and prevents excessive temperature gradients within the collector.

Conduction Through the Copper Tube

The heat transfer through the copper tube wall follows Fourier's law of heat conduction:

$$Q = \frac{kA(T_s - T_w)}{L}$$

Where,
k= thermal conductivity of copper (W/m·K)
A= heat transfer area (m²)
T_s= outer surface temperature (°C)
T_w= water temperature (°C)
L= wall thickness (m)

Copper possesses one of the highest thermal conductivities among commercially available engineering metals. Consequently, the thermal resistance within the heat exchanger is minimized, allowing rapid transfer of absorbed solar energy to the flowing water.

Convective Heat Transfer

Heat transfer from the copper surface to the circulating water occurs by forced convection and can be expressed as

$$Q = hA(T_s - T_f)$$

where
h= convective heat transfer coefficient (W/m²·K)
A= heat transfer surface area (m²)

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T_s= surface temperature (°C)
T_f= fluid temperature (°C)

Active water circulation provided by the photovoltaic-powered pump increases the convective heat transfer coefficient compared with that of natural circulation systems. Therefore, improved fluid motion enhances the thermal energy extraction from the collector.

Collector Thermal Efficiency

The thermal efficiency of a solar collector is generally expressed as

$$\eta = \frac{Q_u}{IA}$$

where
η= collector efficiency
Q_u= useful heat gain
I= solar irradiance
A= collector area

Although efficiency calculations require experimental temperature measurements and flow rate data, the equation provides a standard framework for the future evaluation of the developed system.

ENGINEERING DISCUSSION

The proposed collector integrates several complementary thermal enhancement strategies to improve solar energy utilization within a compact footprint. Rather than relying on a single design modification, the system combines multiple passive and active features that collectively contribute to improved heat transfer.

The spiral copper heat exchanger increases the available heat transfer surface area while maintaining compact collector dimensions. This configuration allows water to remain in contact with the heated absorber over a longer flow path, promoting greater thermal energy absorption. The use of copper further enhances the performance because of its high thermal conductivity and excellent resistance to corrosion.

The reflective mirror sheets incorporated within the collector chamber increase the intensity of solar radiation incident on the absorber. Unlike conventional flat-plate collectors, which depend solely on direct solar radiation, the reflective arrangement redirects additional sunlight toward the heat exchanger, thereby improving the utilization of available solar energy.

The application of a black coating on the copper tube further increases absorber efficiency by reducing reflection losses and maximizing solar absorptivity. This simple and economical modification has been widely adopted in solar thermal engineering because of its significant influence on collector performance.

The active circulation system driven by a photovoltaic-powered DC pump represents another important enhancement. Continuous water circulation reduces thermal stratification, maintains a favorable temperature gradient between the absorber and the working fluid, and improves convective heat transfer. As the pump operation is directly powered by solar energy, the system remains fully renewable without requiring an external electrical supply.

Finally, the provision of a transparent glass cover introduces the greenhouse effect, reducing convective heat losses from the collector while allowing incoming solar radiation to reach the absorber. Together, these integrated features provide a practical approach to improving thermal performance without substantially increasing manufacturing complexity or cost.

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Future research should include experimental validation under different climatic conditions to determine collector efficiency, outlet water temperature, daily thermal energy gain, and long-term operational reliability. Such investigations would enable quantitative comparison with existing solar water heating technologies and support further optimization of the collector design.

CONCLUSION

This study presents a theoretical analysis of thermal performance enhancement strategies incorporated into a compact solar PV-powered concentrating water heating system. The proposed design integrates a spiral copper heat exchanger, reflective solar concentrator, black-coated absorber surface, photovoltaic-powered active water circulation, and greenhouse effect-based thermal retention into a single compact collector assembly.

Engineering analysis indicates that each enhancement technique contributes to improved solar energy absorption, heat transfer, and thermal energy utilization. The combined application of these techniques is expected to improve collector performance while maintaining low fabrication cost, operational simplicity, and environmental sustainability.

The proposed design demonstrates the potential of integrating passive and active thermal enhancement methods for domestic solar water heating applications. Future work should focus on experimental performance evaluation, optimization of collector geometry, and long-term field testing to quantify thermal efficiency and validate the theoretical framework presented in this study.

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