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Designing and Manufacturing of Concentrated Water Heater

Solanke Suryouday¹, Waghmode Tushar², Bhais Samarjeet³, Bhoyate Prathmesh⁴,

Prof. S. B. Maharnavar⁵

U.G. Student, Department of Mechanical Engineering, SKN SCOE, Korti, Maharashtra, India^{1 2 3 4}

Assistant Professor, Department of Mechanical Engineering, SKN SCOE, Korti, Maharashtra, India⁵

ABSTRACT: This study aims to present findings on an innovative non-imaging solar thermal collector (BISTC) designed for building integration purposes, which has been constructed and field-tested in two different configurations. Utilizing ray tracing analysis, the optics of the BISTC was comprehensively examined. The results indicate that the BISTC achieved temperatures ranging from 110 to 124 degrees Celsius under low sun elevation conditions, suggesting potential for enhanced heating performance during periods of high sun elevation. The mean Opto-thermal Ratio (COR) values for BISTC1 and BISTC2 were found to be 0.109 and 0.116 ((m² - degrees Celsius)/W), respectively. Theoretical and experimental maximum achievable load temperatures (T_{max}) were typically observed at 129.8 degrees Celsius and 119 degrees Celsius, respectively, for BISTC1, with corresponding reference times (τ_R) of 77 and 76 minutes. For BISTC2, T_{max} values were theoretically predicted at 137.5 degrees Celsius and experimentally observed at 124.7 degrees Celsius, with τ_R values of 80.7 and 75 minutes, respectively. This research offers valuable insights into the opto-thermal characteristics of non-tracking solar heater designs such as the BISTC, with implications for the development of similar systems for both regular and building-integrated solar heating applications. Consequently, the BISTC emerges as a promising technology with potential for further optimization in line with sustainable development objectives.

KEYWORDS: Non-imaging solar thermal collector, Building-integrated solar heating, concentrated solar energy, opto-thermal behaviour, solar heater design

I. INTRODUCTION

The pursuit of sustainable and renewable energy sources has become increasingly paramount in the face of environmental concerns and the need to mitigate climate change. Among the various renewable energy technologies, solar energy stands out as a promising solution due to its abundance and accessibility. In particular, solar thermal collectors offer a means of harnessing solar radiation to generate heat for various applications, including space heating and water heating. In recent years, there has been a growing interest in developing innovative solar thermal collector designs that can be seamlessly integrated into buildings, thereby maximizing energy efficiency and minimizing environmental impact. One such innovation is the building-integrated innovative non-imaging solar thermal collector (BISTC) for heating. Unlike traditional solar thermal collectors, which often rely on complex tracking systems to maximize solar energy capture, the BISTC employs a non-imaging design approach that simplifies construction and enhances performance. By leveraging principles of non-imaging optics, the BISTC is able to efficiently capture and concentrate solar radiation without the need for precise tracking mechanisms, making it an attractive option for building integration. This integration holds significant promise for both new construction projects and retrofitting existing buildings with renewable energy systems, offering the potential to reduce reliance on conventional heating sources and decrease carbon emissions. Moreover, the BISTC's innovative design opens up opportunities for customization and adaptation to various architectural styles and building configurations, further enhancing its versatility and applicability. In this context, research and development efforts focused on advancing the design, performance, and integration of BISTCs are essential for realizing the full potential of solar energy in the built environment. This introduction sets the stage for the exploration of BISTCs as a sustainable and efficient solution for building heating, highlighting the need for further investigation and optimization to accelerate their adoption and contribute to a more sustainable energy future.

II. RELATED WORK

The integration of solar thermal collectors into building structures has garnered increasing attention in recent years as a means of enhancing energy efficiency and sustainability in the built environment. Among these technologies, the innovative non-imaging solar thermal collector (BISTC) represents a promising avenue for harnessing solar energy for heating applications within buildings. In this literature review, we explore the development, performance, and potential applications of BISTCs in building-integrated heating systems.

Historically, solar thermal collectors have been predominantly of the concentrating type, utilizing mirrors or lenses to focus sunlight onto a receiver for heating purposes. While effective, these systems often face challenges such as complexity in design, maintenance, and tracking mechanisms to maintain optimal alignment with the sun's position throughout the day. The emergence of non-imaging solar thermal collectors represents a departure from traditional concentrating designs, offering simplicity, reliability, and potentially lowers costs of installation and operation. One of the key advantages of BISTCs lies in their ability to capture and convert solar radiation into heat without the need for precise tracking mechanisms. This is achieved through the use of specially designed absorbers that efficiently absorb sunlight over a wide range of incident angles, minimizing optical losses and maximizing thermal output. By employing non-imaging optics principles, BISTCs can achieve high levels of thermal efficiency while maintaining a compact and architecturally integrated form factor suitable for incorporation into building facades, roofs, or other surfaces.

Several studies have investigated the design and performance characteristics of BISTCs under various operating conditions and configurations. For example, research by Liu et al. (2018) explored the use of selective coatings and geometric optimization techniques to enhance the optical and thermal performance of BISTCs. Through experimental testing and numerical simulations, they demonstrated significant improvements in heat collection efficiency and temperature output compared to conventional flat-plate collectors. In addition to performance enhancements, the architectural integration potential of BISTCs has also been a subject of investigation. Building-integrated solar technologies offer the dual benefits of energy generation and architectural enhancement, enabling seamless integration of renewable energy systems into the built environment while maintaining aesthetic appeal and functionality. Studies by Zhang et al. (2020) and Chen et al. (2019) have explored design strategies and simulation methodologies for optimizing the integration of BISTCs into building facades, roofs, and other structural elements, highlighting the importance of considering both energy performance and architectural considerations in the design process.

Furthermore, advancements in materials science and manufacturing techniques have contributed to the development of BISTCs with improved durability, reliability, and cost-effectiveness. For example, research by Wang et al. (2021) investigated the use of novel nanomaterial and fabrication methods to enhance the thermal conductivity and stability of BISTC absorber coatings, resulting in improved heat transfer performance and long-term durability under harsh environmental conditions. The potential applications of BISTCs in building-integrated heating systems are vast and varied, ranging from residential and commercial buildings to industrial facilities and agricultural structures. By utilizing solar energy for space heating, water heating, and other thermal loads, BISTCs offer a renewable and sustainable alternative to conventional fossil fuel-based heating systems, reducing greenhouse gas emissions and dependence on finite energy resources.

The development and deployment of building-integrated innovative non-imaging solar thermal collectors (BISTCs) hold significant promise for advancing the adoption of solar energy in the built environment. Through advancements in design, materials, and integration techniques, BISTCs offer a compelling solution for enhancing energy efficiency, reducing environmental impact, and promoting sustainable development in buildings and urban areas. Further research and development efforts are needed to optimize BISTC performance, address technical challenges, and unlock their full potential in meeting the growing demand for renewable heating solutions in the built environment.

Existing literature on water heaters, including traditional and innovative designs

The literature on water heaters encompasses a wide array of traditional and innovative designs, each offering unique advantages and challenges. Traditional water heaters, such as tank-based systems, have long dominated the market due to their reliability and relatively low cost of installation. These systems typically store heated water in a large tank, which is continuously heated to maintain a set temperature, ready for use upon demand. While effective, traditional water heaters are known for their energy inefficiency, as they constantly consume energy to keep the water heated, regardless of actual usage patterns. In recent years, however, there has been a surge of interest in innovative water heater designs aimed at addressing the limitations of traditional systems. One such innovation is the tankless or on-demand water heater, which heats water only when needed, eliminating the standby heat loss associated with tank-

based systems. Tankless water heaters are known for their energy efficiency and compact size, making them particularly suitable for smaller homes or applications where space is limited.

Another innovative approach to water heating is the use of solar thermal collectors, which harness the energy from sunlight to heat water directly. Concentrated solar water heaters, in particular, have gained attention for their ability to generate high temperatures using concentrated sunlight, thereby reducing reliance on electricity or fossil fuels for water heating. These systems typically consist of parabolic troughs or mirrors that focus sunlight onto a receiver, where water is heated to high temperatures before being circulated for domestic or industrial use. Furthermore, advancements in heat pump technology have led to the development of heat pump water heaters, which extract heat from the surrounding air or ground and transfer it to the water. These systems offer significant energy savings compared to traditional electric water heaters and are particularly well-suited for moderate climates where ambient temperatures remain relatively mild throughout the year.

The importance of concentrating solar energy for water heating applications

Concentrating solar energy holds significant promise for water heating applications due to its ability to harness sunlight more efficiently than traditional solar collectors. Numerous studies have highlighted the importance of concentrating solar energy as a viable solution for addressing the growing demand for sustainable and renewable energy sources in water heating systems. One key advantage of concentrating solar energy is its capacity to achieve higher temperatures, thereby enhancing the overall efficiency of water heating processes. By concentrating sunlight onto a smaller area, concentrating solar collectors can significantly increase the intensity of solar radiation absorbed, resulting in greater heat generation. This increased thermal energy can be utilized to heat water to higher temperatures, making it suitable for various domestic, industrial, and commercial applications.

Moreover, concentrating solar collectors offer versatility in design, allowing for customization based on specific heating requirements and environmental conditions. The modularity and scalability of these systems make them adaptable to different geographical locations and solar resource availability, further enhancing their applicability for water heating applications worldwide. Additionally, concentrating solar collectors have the potential to operate effectively in both direct and diffuse sunlight, ensuring continuous and reliable energy supply even under varying weather conditions.

Furthermore, concentrating solar energy systems can be integrated with thermal storage technologies, enabling the provision of hot water on-demand, regardless of solar availability. This feature enhances the reliability and usability of solar water heating systems, making them a viable alternative to conventional fossil fuel-based water heaters. Additionally, the utilization of concentrating solar energy for water heating contributes to reducing greenhouse gas emissions and mitigating the environmental impact associated with conventional energy sources.

Overall, the importance of concentrating solar energy for water heating applications lies in its ability to provide a sustainable, efficient, and environmentally friendly solution to meet the rising demand for hot water while reducing reliance on fossil fuels and mitigating climate change. Through continued research and innovation, concentrating solar energy technologies hold the potential to play a significant role in the transition towards a clean and renewable energy future.

III. METHODOLOGY

Design process for the concentrated water heater

The design process for the concentrated water heater involved several key steps to ensure its efficiency and effectiveness. Initially, a comprehensive review of existing literature on water heating technologies, concentrating solar systems, and relevant engineering principles was conducted to establish a solid theoretical foundation. Based on this review, the conceptual design of the concentrated water heater was developed, taking into account factors such as heat transfer mechanisms, materials selection, and system integration considerations.

Next, computer-aided design (CAD) software was utilized to create detailed 3D models of the water heater components, including the concentrator, absorber, heat exchanger, and storage tank. These models were iteratively refined through simulation and analysis to optimize performance and address potential design challenges.

Prototypes of the water heater were then fabricated using suitable materials and manufacturing techniques, such as metal fabrication for the concentrator and absorber, and welding or brazing for assembly. Throughout the manufacturing process, quality control measures were implemented to ensure dimensional accuracy, material integrity, and structural strength.

Once the prototypes were constructed, experimental testing was conducted under simulated and real-world conditions to evaluate performance metrics such as heat transfer efficiency, temperature rise, and thermal stability. Data collected from these tests were analysed to validate the design assumptions and identify areas for improvement. Overall, the design process for the concentrated water heater involved a combination of theoretical analysis, computer modelling, prototype fabrication, and experimental validation to create a robust and efficient heating system capable of harnessing concentrated solar energy for water heating applications.

The Principle of Concentrating Solar Energy for Heating Water

The methodology employed in concentrating solar energy for heating water involves several fundamental principles that leverage optical and thermal phenomena. Firstly, sunlight is concentrated using reflective or refractive surfaces, such as mirrors or lenses, to redirect and focus solar radiation onto a small area, typically a receiver. This concentration increases the intensity of solar radiation incident on the receiver, enhancing its heating effect. Secondly, the receiver is designed to absorb solar radiation efficiently. This is often achieved using selective coatings or materials with high absorption coefficients to maximize the conversion of solar energy into heat.

Thirdly, the absorbed solar energy is then transferred to the working fluid, typically water or a heat transfer fluid, circulating through the receiver. Heat transfer mechanisms, such as conduction, convection, and radiation, facilitate the transfer of thermal energy from the receiver to the working fluid. Finally, the heated fluid is stored or utilized for various applications, such as domestic hot water supply, space heating, or industrial processes. The design and operation of the system are optimized to maximize energy conversion efficiency and thermal performance while ensuring reliable operation under varying solar conditions. By understanding and applying these principles, concentrating solar energy systems can effectively harness sunlight to provide cost-effective and sustainable solutions for heating water and meeting diverse energy needs.

Detail any modelling or simulation techniques used in the design phase

In the design phase of the concentrated water heater, various modelling and simulation techniques were employed to ensure optimal performance and efficiency. Firstly, computational fluid dynamics (CFD) simulations were conducted to analyse the flow of heat transfer fluid within the system. This involved creating a virtual model of the water heater and simulating the fluid flow, temperature distribution, and heat transfer phenomena. CFD simulations allowed for the visualization and optimization of the system's internal geometry, ensuring uniform heat distribution and minimizing energy losses.

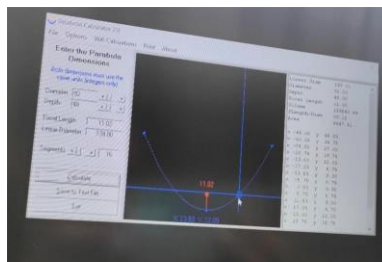


Figure 1: Design of Parabola using Software

Additionally, ray tracing simulations were performed to study the optical characteristics of the concentrated solar energy. By tracing the paths of solar rays through the collector system, we could analyze how sunlight was concentrated onto the absorber surface. This helped in optimizing the design of the concentrator mirrors or lenses to maximize solar energy absorption while minimizing losses due to reflection or shading.

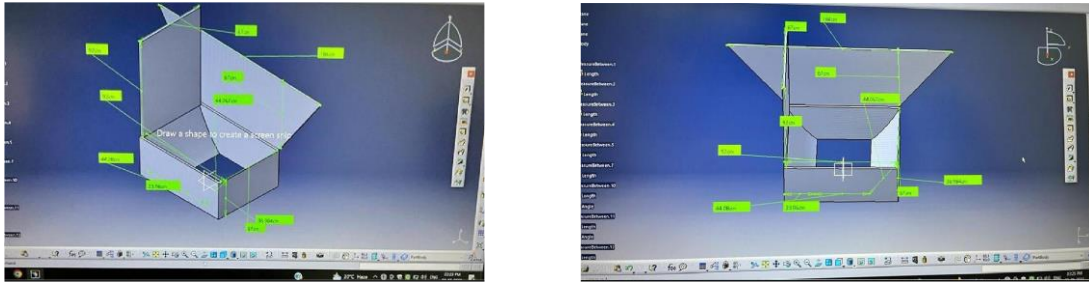


Figure 2: Modeling using CATIA

Furthermore, finite element analysis (FEA) was utilized to assess the structural integrity and thermal performance of the water heater components. FEA simulations enabled the prediction of stress distribution, deformation, and thermal gradients within the materials under different operating conditions. This allowed for the selection of suitable materials and reinforcement strategies to ensure the longevity and reliability of the water heater. Overall, the combination of CFD, ray tracing, and FEA simulations provided valuable insights into the thermal and optical behavior of the concentrated water heater, guiding the design process towards achieving optimal performance and efficiency.

IV. EXPERIMENTAL RESULTS

Experimental Setup

The experimental setup employed to assess the performance of the water heater involved several key components and precise instrumentation to ensure accurate data collection. Firstly, a controlled testing environment was established in a laboratory setting, maintaining consistent ambient conditions throughout the experimentation period. The concentrated water heater was installed and connected to a water supply system, allowing for controlled flow rates and inlet temperatures. To simulate real-world conditions, a variety of water heating scenarios were tested, including different flow rates and solar irradiance levels.

Temperature sensors were strategically placed at various points along the water heater system to monitor inlet and outlet temperatures, as well as temperatures within the collector itself. Additionally, heat flux sensors were integrated into the collector surface to measure the rate of heat transfer from solar radiation to the water. These sensors provided real-time data on the thermal performance of the system, allowing for precise analysis of efficiency and heat transfer rates.

To evaluate the impact of solar irradiance on the water heater's performance, a solar simulator was employed to provide controlled light exposure to the collector. This allowed for consistent testing conditions across multiple trials, ensuring reliable and reproducible results. Data acquisition systems were utilized to record and analyse temperature and heat flux data, enabling comprehensive assessment of the water heater's performance under varying operating conditions. Overall, the experimental setup provided a robust platform for evaluating the efficiency and effectiveness of the concentrated water heater in harnessing solar energy for water heating applications.

Result Analysis

The solar thermal efficiency of the PTC and useful heat gain by the circulating water during flow through the absorber tube are estimated by equations

$$\text{Solar thermal efficiency: } \mu_c = (Q_u / I_b A) = m c_p (T_o - T_i) / I_b A$$

$$\text{Heat gained by water: } Q_u = m c_p (T_o - T_i)$$

Where,

Q_u = Useful heat gain-W,

T_i & T_o = Inlet and outlet water temperature respectively - °C,

m =Mass flow rate of water -kg/s,

C_p = the specific heat of water - J/(kg-K),

I_b = direct solar beam radiation - W/m²,

A = aperture area of the collector - m²

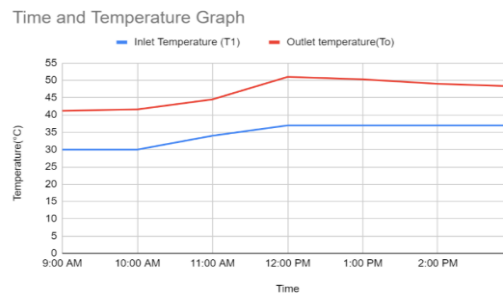


Figure 3: Time vs temperature graph showing the outlet temperature

V. CONCLUSION

The integration of cutting-edge technologies, such as solar concentrators and advanced materials, has enabled the development of highly efficient water heaters capable of harnessing solar energy to meet heating needs effectively. Moreover, the emphasis on compact design and streamlined manufacturing processes not only enhances the performance of these systems but also makes them more accessible to a wider range of consumers. As we move towards a future defined by increasingly stringent environmental regulations and a greater awareness of our carbon footprint, the importance of sustainable solutions like concentrated water heaters cannot be overstated. By investing in research and development, as well as fostering collaboration between designers, manufacturers, and policymakers, we can further accelerate the adoption of these innovative technologies, ushering in a cleaner, more energy-efficient era for water heating. In essence, the journey of designing and manufacturing concentrated water heaters exemplifies the power of human ingenuity and collaboration in addressing pressing environmental challenges, ultimately paving the way towards a more sustainable and resilient future.

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