REVIEW OF ENHANCEMENT THE THERMAL PERFORMANCE FLAT PLATE SOLAR COLLECTOR WITH MULTIPLE TECHNIQUES

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ABSTRACT

The rising demand for sustainable energy sources has driven further study and development in solar energy systems. Capturing solar energy for many applications, such as space heating, water heating, and power generation, flat plate solar collectors (FPSCs) are very necessary. This work is to provide a comprehensive overview of present development and strategies used to increase the efficiency of the solar collector as well as fundamental ideas guiding the operation of (FPSC). Among the many methods examined, the use of modern materials and nanotechnology especially the inclusion of nanoparticles and nanostructured coatings has been shown to greatly improve thermal performance, therefore attaining the most increase in efficiency. The overview of these significant findings in the assessment points to topics of future investigation direction. It emphasizes the need for all-encompassing strategies that take environmental issues into account along with technical advancement to enhance performance and general use(FPSC). Academics, engineers, and legislators working toward the sustainable development of technologies will find great value in this work.

Keywords: Flat plate, solar energy systems, space heating, water heating, and power

NOMENCLATURE

CFD	Computational Fluid Dynamics
CP	Specific Heat Capacity
CPSC	compound parabolic solar collectors
FPSC	Flat Plate Solar Collector

HTF Heat Transfer Fluid

kW Kilowatt

m2 Square meter

MW Megawatt

PCM Phase Change Material

PSO Particle Swarm Optimization

PV/T Photovoltaic/Thermal

PVT Photovoltaic Thermal

SR Solar Radiation

SWH Solar water heating

UV Ultraviolet

INTRODUCTION

The global quest for sustainable and clean energy solutions has propelled the evolution of solar technologies, with (FPSCs) emerging as indispensable components in the harnessing of solar power. As the need for renewable energy sources intensifies, there is a critical need to optimize the performance of FPSCs to maximize their efficiency and broaden their applicability across diverse sectors. The need of renewable energy, namely solar energy, has shown consistent growth due to the rising consumption of energy globally and the depletion of fossil fuel resources (Özil & Yaşar,1987) ;(Pandey& Chaurasiya, 2017) ;(Ravi Kumar& Reddy,2009). A well-recognized and prevalent use of solar energy is the solar water heater (SWH) system, which is very feasible and offers economic benefits. (SWH) systems consists of two primary components: storage tanks and solar collectors. The classification of solar collectors primarily includes flat plate solar collectors (FPSC), photovoltaic thermal hybrids (HPV/T), evacuated-tube solar collectors (ETSC), and compound parabolic solar collectors (CPSC) (Abdul-Ghafou et al 2016) (A. Özcan et al. 2021). The collectors may have further classified into tracking and non-tracking collectors (Selmi et al., 2008). The preferred methods for harnessing sunshine as a heating source for residential applications are either lower-temperatures solar thermal technology or photovoltaic (PV) technology, notwithstanding the existence of several additional solar collector systems (Kannan & Vakeesan, 2016); (Solangi et al.,2011) ;(Bahadori & Nwaoha,2013); (Sakhaei & Valipour, 2019). Solar photovoltaic (PV) is often regarded as a superior method for directly harnessing sunshine to power electric heaters (Bahadori & Nwaoha,2013). Nevertheless, electrical efficiency of the system experiences a significant decline when the temperature of the PV module rises (Kannan & Vakeesan, 2016). From a broad standpoint, solar thermal technology, which converts solar insolation into heat and transfers it via a medium, seems to be a more convenient approach for generating heated fluid for household use. (Ravi Kumar& Reddy,2009) ; (Md. Shouquat Hossain, 2013) ; (Maouassi et al 2017). Solar water heating (SWH) has been extensively implemented in several nations including Australia (Perlin, 2004) Pakistan (Bahadori & Nwaoha,2013) Rwanda, South Africa (Bhutto et al.,2012) Canada, and China. (Sterman,2006) In Australia, Using SWH (solar water heating) has been limited in recent years, despite the favorable solar radiation levels, mostly owing to concerns of cost and dependability (Nshimyumuremyi & Junqi, 2018). In regions with limited solar power, such as Malaysia, the average potential solar irradiance is 4-4.9 KWh/m2/day, which is lower compared to other parts of the world with an average of 6-6.9 KWh/m2/day. (Kabir et al.,2018); (Kannan & Vakeesan, 2016). In such regions, the preferred technology for harnessing solar energy is a low-temperature solar thermal energy conversion method, specifically the FPSC system (Hohne et al.,2019). FPSC, ideal for low and medium heating applications, can absorb both the direct and scattered components of solar radiation. In contrast, when contrast to concentrating solar collectors, the FPSC has a comparatively lower level of efficiency (Selmi et al., 2008) (Kadhim et al. 2021). In 1760, Horace De Saussure conducted pioneering research on SWH (Solangi et al. 2011). Since then, several researches have been performed, leading to substantial advancements in the performance of solar water heaters (SWH). These improvements include the use of either (FPSC) or an evacuated tube solar collector to capture power from the sun and heat the fluid to a temperature below 80 °C, suitable for home usage (Han et al.,2010). Comparing both collectors, the ETSC demonstrates superior efficiency over the FPSC as a result of its design (Urmee et al.,20118). which effectively minimizes the loss of solar heat via radiation. Nevertheless, the FPSC is preferable for that reason its simplicity, low maintenance needs, and greater cost-effectiveness (Mekhilef et al.,2012). Solar water heaters (SWHs) may be categorized as passive and active. Passive systems, like thermosyphon, use the natural increase in enthalpy in the fluid. On the other hand, active systems, such as forced circulation, depend on a pump for operation (Mekhilef et al.,2012). The (FPSC) as shown in Figure (1) has many crucial components that might impact its thermal efficiency. The components of this system consist of casing, absorber plate, riser tube, glass cover, and insulating material (Selmi et al., 2008) ;(Gaafar-Elnugoumi et al.,2012); (Klevinskis & Buˇcinskas, 2012); (Hossain et al. 2011) At the highest point, the glass layer encloses the tube raiser and effectively retains heat inside the collector. The riser tube functions as a heat exchanger, while the absorber plate enhances the heat-transfer surface area of the system. The parts at the bottom and sides the (FPSC) are insulated with insulating material to minimize heat loss by conduction and radiation, enhancing the system's efficiency. An issue often encountered that diminishes the efficiency of (FPSC) over time is the accumulation of dust, necessitating frequent cleaning to maintain its function (Jamar et al. 2016); (Balaji et al. 2019). identified overheating as a prevalent reliability problem in FPSC caused by stagnation temperature. Excessive heat may cause the material to deteriorate, perhaps resulting in leaks and system malfunctions, hence decreasing the dependability of the FPSC (Zhou et al., 2019) (H. Bhowmik et al. 2017)

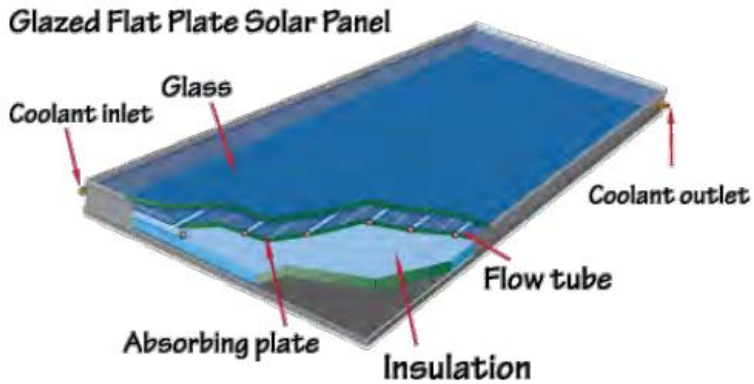

Fig. 1. Photograph of FPSC (Álvarez et al.,2010).

Flat solar collectors, characterized by their simplicity and versatility, are integral to converting sunlight into thermal energy for various applications, including residential heating, water heating, and industrial processes. Their widespread adoption is contingent upon continuous advancements that address challenges related to efficiency, durability, and environmental impact (Pandey & Chaurasiya, 2017). This review delves into the intricate landscape of FPSC technology, encompassing key facets such as absorber plate design, materials, heat transfer fluids, control systems, and environmental sustainability. By examining recent breakthroughs in each of these domains, we aim to provide a comprehensive overview of the innovative strategies employed to elevate the effectiveness of flat collectors (Suman et al.,2015); (Harrison & Cruickshank,2012).

The most recent developments in improving (FPSC) thermal efficiency are presented in this review article. This work is unique in its methodical comparison of many improvement strategies, therefore stressing the better efficiency of modern materials and nanotechnology in raising thermal efficiency. This work highlights important areas where thermal performance has been notably improved by combining the results of current studies. Emphasizing the possibilities of creative materials and nanotechnology in the sustainable development of solar energy systems, this thorough analysis not only compiles present information but also suggests new directions for future research. Academics, engineers, and legislators trying to maximize solar energy systems for greater efficiency and more general applicability depend on this input.

METHODS TO ENHANCE THE PERFORMANCE

Enhancing the performance of (FPSCs) involves the implementation of various methods and technologies across different aspects of the collector's design and operation (Yasser et al.,2023) (M. Geyer et al.,2002). key methods for improving FPSC performance:

1-Selective Surface Coatings:

Applying advanced coatings to the absorber plate with high solar absorptance and low emittance can significantly enhance the collector's efficiency by maximizing solar radiation absorption and minimizing heat losses (Madhukeshwara & Prakash,2012); (Zhang,2000).

2-Advanced Absorber Plate Design:

Innovations in absorber plate design, such as using high-conductivity materials or incorporating finned structures, could increase the transmission of heat and improve the overall thermal performance of the collector (Moss et al.,2018); (Moss et al.,2017) (Y. Elhenawy et al., 2022).

3-Materials and Nanotechnology:

Utilizing advanced materials, such as nanomaterials or nanostructured coatings, may increase the collector components' endurance and thermal conductivity. Nanofluids with enhanced heat transfer properties can also be employed as heat transfer fluids (Aggarwal et al.,2021); (Hussein, 2016).

4-Improved Insulation:

Enhancing insulation around the collector helps minimize heat losses and improves overall efficiency. Using high-performance insulation materials or incorporating vacuum insulation can be effective methods (Nadir et al., 2019); (Chandra et al.,2017).

5- Optimized Fluid Circulation:

Enhancing the design of the fluid circulation system, such as using a more efficient pump or optimizing the flow path, can enhance heat transfer within the collector (Alfaro-Ayala et al., 2018); (Yurddaş, 2020).

6- Advanced Heat Transfer Fluids:

Introducing advanced working fluids, such as nanofluids or phase-change materials, can enhance thermal conductivity and storage capacity, leading to improved overall performance (Krishna et al., 2020) ;(Vutukuru et al., 2019).

7- Optimized Collector Tilt and Orientation:

Implementing tracking systems or adjusting the tilt and position the collector according to the sun's position can maximize solar radiation absorption throughout the day, increasing overall efficiency (Yakup& Malik, 2001) ;(Juuso & Yebra 2013) (B.H. Upadhyay et al.,2019).

8- Smart Control Systems:

Integrating advanced control systems with sensors and actuators can optimize the operation of the collector in response to changing environmental conditions, ensuring optimal performance (Juuso,2012); (Boldyrev & Gorkavyy, 2021) (Visconti et al.,2016).

9- Polymer Material

Polymer materials are becoming more often used in collectors because of their low weight, cost efficiency, and simplicity of production. Polymers have the potential to be used in several components such as the absorber plate, glass, and insulation. However, due to their poor thermal conductivity, it is necessary to include innovations such as integrating fillers or coatings in order to improve their thermal performance (Selmi et al., 2008).

10- Nanofluids

Nanofluids consist of particles that are nanometer-sized, and these particles improve the thermal conductivity and heat transfer qualities of the fluids. Nanofluids have the potential to greatly improve the heat transfer fluid's efficiency in FPSCs by augmenting the thermal conductivity and heat absorption capacities of the underlying fluid (Bharathiraja et al., 2024); (Kadhim et al., 2021); (Hussain et al. 2021) ;(He, 2024) (Mashrur Muntasir Nuhash et al., 2023)

11- Mini and Microchannel

Mini and microchannels are used in the absorber plates of FPSCs to augment heat transmission. These channels are designed on a tiny size. By augmenting the surface area to volume ratio, these channels enhance heat transfer coefficient, hence improving the thermal efficiency of the collector (Shamra et al., 2022); (A.T. Fatigun et al.,2012).

12- Phase Change Material (PCM) Heat Loss Reduction

(PCMs) store thermal energy by undergoing a phase transition, such as shifting from a solid to a liquid state, at particular temperatures. By incorporating Phase Change Materials (PCMs) into Flat Plate Solar Collectors (FPSCs), the amount of heat lost may be minimized. To accomplish this, institutions are used any surplus thermal energy and then releasing it when the temperature decreases, so ensuring a more stable and consistent temperature (Krishna et al., 2020).

13- Enhancement devices

Enhancement devices such as fins, corrugated surfaces, and other alterations to the surface may greatly enhance heat transmission inside FPSCs. These devices augment the surface area obtainable for heat exchange and disturb the layers of air or fluid near the surface, so improving the process of convective heat transfer (G. Vishal et al.,2015) (Verma et al., 2020).

14-Turbulators

Turbulators are devices or alterations that induce turbulence in the fluid flow within the collecting tubes. The turbulence causes disturbance in the thermal boundary layer, which raises the rate of convective heat transfer and enhances the overall efficiency of the FPSC (A.S. Abdullah et al.,2023); (Ameen Braa Khalid et al., 2015) (P.K. Mongre et al.,2013).

15- Heat-transfer enhancement using vibration

Enhancing heat transfer is the use of vibration, which entails the application of mechanical oscillations to the collector or fluid flow system (Z.D. Cheng et al. 2020). These vibrations can improve heat transmission by interrupting the thermal barrier layer and facilitating more efficient fluid mixing (Alfaro-Ayala et al., 2018).

Enhancement of the thermal performance of FPSC in the literature:

1- Selective surface coatings

(Diamantino et al., 2017) studied the selective surface coating and concluded that the long-term performance of aluminum absorber surfaces treated with various physical vapor deposition (PVD) techniques and paint coatings (PCs) at outdoor testing sites with varying levels of atmospheric corrosiveness (Diamantino et al., 2017); (D'Alessandro et al., 2022) studied the selective surface coating and concluded it is necessary to characterize the radiative characteristics of absorbers at elevated temperatures and under operational circumstances. Using the calorimetric method measured the commercial selective solar absorber's (SSA) total solar absorptance and infrared emittance under direct sunlight. (De Maio et al., 2020) studied the selective surface coating and concluded coating efficiencies higher than 0.8 have been obtained at 200 °C (300 °C) (De Maio et al., 2020);(Zhang et al., 2024) studied the selective surface coating and concluded the Mn0.6Ni1.4Co2Oy solar absorption coating has an absorbance/emissivity ratio of 6.22 and a solar absorbance value of 0.89. The coating has a high level of photothermal conversion efficiency and demonstrates outstanding performance in terms of infrared stealth (Zhang et al., 2024).

2- Absorber plate design

(Sharma et al., 2022) studied the absorber plate design and concluded that versions of collector absorber plate designs have been tested for improved performance. Circular plates get 8.74% thermal efficiency while trapezoidal plates get 12.85%. Circular plates increase exergy efficiency by 16.88% and trapezoidal plates by 23.31%. The circular and trapezoidal plates reduce heat loss by 7.49% and 8.72%. Optimal conditions are 1000 W/m2 sun intensity and 1.5 L/m mass flow (Shamra et al., 2022); (Verma et al., 2020) studied the flow pipe design and concluded that a single spiral-shaped collector tube has been designed to improve solar collector efficiency by 21.94%, and 6.73%, and reduce manufacturing and maintenance costs, while achieving a 30% reduction in material use overall, compared to traditional flat plate designs. (Visa et al., 2015) studied the absorber plate design and concluded that the shape was chosen and then gradually optimized with a focus on the glazing, meander tube length and diameter, insulation, and bonding between the tubes and absorber plate. The optimized model reached an efficiency of 60.7% on an indoor testing rig after analyzing eight distinct kinds of solar thermal collectors. According to steady-state testing conditions, this translates to a maximum conversion efficiency of 62.38%. On a bright day, the ideal collector was tested outside with two hours of irradiance in the same range as the indoor testing rig. The efficiency results were 61.85% (Visa et al., 2015); (Fan et al., 2019) studied the absorber plate design and concluded that although it has minimal impact on energy efficiency, the design of a V-corrugated absorber may greatly minimize pressure drop and pump power usage while also increasing collector optical and thermal efficiency. Despite this, the V-corrugated absorber has enormous potential for performance development, the design and production of the collector may be improved (Fan et al., 2019); (Reddy et al., 2021) studied the absorber plate design and concluded that a cross-trapezoidal absorber combined with SAC can increase thermal efficiency by up to 8%. A threefold resulting in increasing of air flow rate in a 105% improvement in thermal efficiency. Reverse trapezoidal SAC has a greater environmental impact factor (Reddy et al., 2021) ;(Ameen Braa Khalid et al., 2015) studied the flow pipe design and concluded that three different twisted tape types are used in the research to compare plain tubes with twist ratios (TR=2) in order to enhance heat transfer in flat plate collectors. The experimental investigation found that twisted tape collectors have a 10°C higher output water temperature than plain tube collectors, copper collectors have a 6°C higher output water temperature, and collectors with two glass covers increase the outflow water temperature by 4°C from one glass cover (Ameen et al., 2015);(Al-Manea et al., 2021) studied the flow pipe design and concluded that a new collector with a single serpentine-shaped collector tube has been developed to improve the efficiency of FPSCs. The model, developed by TRNSYS, was validated using experimental data from Al-Samawa, Iraq. The model showed an average efficiency of 58%, with a 1% temperature difference between tests and simulations. This model could be crucial for future improvements (Al-Manea et al., 2021).

Fig. 2. experimental design of collector: (1) inlet -tank 1; (2) outlet - tank 2; (3) collector enclosure; (4) angle guide rod; (5) serpentine absorber tube; (6) fiberglass insulation; (7) plastic cover.

(Zheng et aL.,2016) studied the flow pipe design and concluded that glazed transpired solar collector (GTC) with a perforating corrugated plate is examined for its thermal performance. A math model is created to forecast the GTC's thermal properties, and the experimental findings validate it (Zheng et al., 2016); (G. Shelke et al., 2015) studied the flow pipe design and concluded that examining the impact of different tube shapes on flat solar collectors. In this investigation, a circular tube with a diameter of 12.7 mm was taken into consideration, and ANSYS CFD FLUENT software was used for the numerical analysis. Temperature comparisons between the intake and outflow were done for various heat fluxes. Additional examination was done for various elliptical tube configurations. When the water's outlet temperature is compared to the circular findings, there is a strong correlation (G. Shelke et al., 2015) ;(Kumar et al., 2010) studied the absorber plate design and concluded that it is found that a solar water heater with a corrugated surface operates at a greater temperature for a longer period than one with a level surface. It indicates that more solar energy is transformed into usable heat while the water heater is operating. Nevertheless, this change has somewhat decreased the system's efficiency (Kumar et al., 2010); (Das et al., 2020) studied the absorber plate design and concluded that for radiation intensities of 400, 600, and 800 W/m2 and air flow rates ranging between 0.01 and 0.02 $kg/s/m^2$. The thermal effectiveness of a plain absorber SAC was found to be improved by around 68% when the air flow rate was increased by 90%. Amount increasing was higher for the absorber coated with sand (Das et al., 2020); (Yehualashet et al., 2022) studied the absorber design and concluded the sinusoidal corrugation increases bond conductance, which raises the outlet temperature and decreases the plate-to-fluid temperature differential, improving the collector's efficiency, according to both computational and experimental studies. It was a strong correlation between the computational and experimental data regarding collector efficiency and collector outlet temperature (Yehualashet et al., 2022); (Elwekeel et al., 2023) studied the absorber plate design and concluded that four examples comprise the arrangement of the ribs on the flat circular collector. Using the Taguchi approach, the best-performing instance is verified and empirically validated. The best heat transmission performance is provided by fins that cut straight through (Elwekeel et al., 2023).

3- Materials and Nanotechnology:

(Bharathiraja et al., 2024) studied the materials and nanotechnology and concluded that an incremental improvement in thermal efficiency was reported, reaching 71.7% with the addition of HnPCM, compared to the initial value of 64.7%. The greatest recorded temperature of the water leaving the outflow is 70 °C (Bharathiraja et al., 2024).

4- Optimized Fluid Circulation

(Aggarwal et al., 2021) studied the optimized fluid circulation and concluded that (CFD) studies demonstrate the impact of nano-fluids as heat transfer fluids and influence of various (PCM) on the efficiency of ETSCs (Aggarwal et al., 2021); (Rostami et al., 2022) studied optimized fluid circulation and concluded that the exergy efficiency attained a maximum value of 7.1%. Conversely, each FPSC had a distinct flow rate at which the exergy efficiency reached its peak. At greater flow rates, the efficiency marginally decreased and eventually stabilized. The greatest exergy efficiency was attained when ϕ was equal to 0.10% (Rostami et al.,2022)

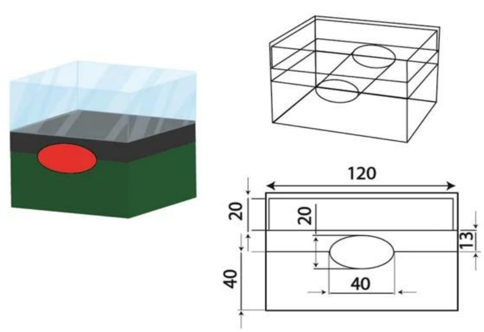

Figure 3: Schematic of the problem. (Rostami et al.,2022)

5- Optimized Collector Tilt and Orientation

(Xu et al., 2021) studied optimized collector tilt and orientation and concluded that the adjusted annual and monthly ideal angles may enhance solar power gathering by

238.72 kWh/m2 (9.73%) and 398.33 kWh/m2 (16.24%) each year, respectively (Xu et al., 2021); (Pourfayaz et al.,2020) studied optimized collector tilt and orientation and concluded that ultimately, (PSO) technique is utilized to decrease the maximum coefficient of heat-loss . The minimal heat coefficient is achieved at a value of 0.99 W/m2K (Pourfayaz et al., 2020); (Kallioğlu et al., 2020) studied optimized collector tilt and orientation and concluded that a scale was used to align and compare the ideal solar panel angle values at a certain site. The scale ranged from 1 to 10, allowing for precise comparisons (Kallioğlu et al., 2020).

Discussion and Conclusion

Enhancement of Thermal Performance of FPSC in the Literature: Advantages and Disadvantages

1. Selective Surface Coatings

Advantages: High Efficiency, Selective surface coatings, especially those using advanced materials like nanostructures and multi-layer techniques, significantly increase the absorptance and reduce the emittance of solar collectors. Temperature Resistance: Coatings designed for elevated temperatures maintain efficiency even in high-temperature environments (De Maio et al., 2020).

Disadvantages: Durability Issues, Coatings may degrade over time, reducing their effectiveness. Cost: Advanced coatings can be expensive to apply and maintain (De Maio et al., 2020).

Selective surface coatings are highly effective in enhancing thermal performance, the trade-off between cost and durability needs further optimization for widespread adoption (De Maio et al., 2020).

2. Advanced Absorber Plate Design

Advantages: Improved Heat Transfer: Designs like trapezoidal, micro-channel, and porous media absorbers significantly improve heat transfer efficiency. Customization: Plates can be tailored to specific applications, optimizing performance (Jawad et al., 2022).

Disadvantages: Complex Manufacturing: Advanced designs often require sophisticated manufacturing processes, increasing production costs. Maintenance: More complex designs can be harder to maintain and repair (Jawad et al., 2022).

The consensus is that while advanced absorber plate designs offer substantial efficiency improvements, their complexity, and cost are barriers that need to be addressed through innovative manufacturing techniques and materials (Jawad et al., 2022).

3. Materials and Nanotechnology

Advantages: High Efficiency using nanomaterials and nanofluids can lead to significant improvements in thermal efficiency (M.L.G. Ho et al., 2023) (Sulyman et al.,2023). Enhanced Properties: Nanotechnology allows for the customization of thermal properties, leading to better performance (Ajeena et al.,2024).

Disadvantages: High Cost: Nanomaterials and nanotechnology-based solutions can be expensive. Long-term Stability: Nanomaterials' long-term stability and environmental impact are still under investigation (Sulyman et al.2023); (Kareem Fouad et al.,2020)

Researchers are optimistic about the potential of nanotechnology to revolutionize FPSCs but emphasize the need for cost reduction and further research into long-term effects and stability (Nešović et al., 2023) ; (Jawad et al., 2023); (Z. Said et al., 2015); (T.K. Murtadha et al.,2022).

4. Optimized Fluid Circulation

Advantages: Enhanced Efficiency: Optimized fluid circulation, including the use of nanofluids and turbulence enhancers, improves heat transfer rates. Flexibility: Fluid circulation systems can be adjusted and optimized for different operational conditions (Kadhim et al.,2023).

Disadvantages: Complex Systems: These systems can be complex and require precise control mechanisms. Potential for Clogging: Use of nanofluids may result in clogging and requires careful monitoring (Kadhim et al.,2023).Optimized fluid circulation is widely regarded as an effective method to enhance thermal performance, but its complexity and the potential for operational issues like clogging must be managed (Kadhim et al.,2023).

5. Advanced Heat Transfer Fluids

Advantages: Improved Thermal Conductivity: Advanced heat transfer fluids, such as PCMs, ionic liquids, and thermoelectric fluids, offer superior thermal conductivity (S.A. Kalogirou et al.2004). Energy Storage: Some fluids, particularly PCMs, also provide energy storage capabilities, enhancing overall system efficiency (S.A. Kalogirou et al.,2004).

Disadvantages: Cost: Advanced fluids can be expensive. Compatibility Issues: Ensuring compatibility with existing systems can be challenging (K.wang et al., 2021)

Using of advanced heat transfer fluids is promising, with significant potential for efficiency gains. However, cost and compatibility are major concerns that need to be addressed for broader applications (Hossain et al., 2021) ;(L.M. Ayompe et al., 2013)

6. Integration of Hybrid Systems

Advantages: Increased Efficiency: Hybrid systems, such as PV/T, solar-biomass, and combined solar-geothermal systems, offer enhanced efficiency by leveraging multiple energy sources. Versatility: These systems can provide a more stable and reliable energy supply (E. Elshazly et al.,2022).

Disadvantages: Complexity: Hybrid systems are more complicated to design, install, and maintain. Higher Initial Costs: The initial investment for hybrid systems can be higher compared to single-source systems (E. Elshazly et al.,2022).

Hybrid systems are seen as a highly effective way to maximize efficiency and reliability. However, their complexity and cost need to be justified by the long-term benefits they provide (E. Elshazly et al.,2022).

Each method to optimize thermal performance of flat plate solar collectors has its own set of advantages and disadvantages. Selective surface coatings and advanced materials offer high efficiency but are often costly. Advanced absorber plate designs and optimized fluid circulation systems provide significant performance improvements but can be complex and expensive to implement. Advanced heat transfer fluids show promise in enhancing thermal conductivity and energy storage but face cost and compatibility challenges. Finally, hybrid systems offer the best efficiency and reliability but are complex and require higher initial investments. Based on previous research, it is clear that while all these methods contribute to enhanced thermal performance, the choice of method depends on balancing efficiency gains with cost, complexity, and long-term stability. Future research should focus on cost reduction, improving long-term stability, and developing simpler yet effective designs to make these technologies more accessible and widely adopted.

To summarize, improving the performance of (FPSC) requires the use of multiple techniques in the areas of design, materials, and operation. By examining various methodologies, several ways have been identified as very successful in enhancing the efficiency and functioning of FPSC. Selective surface coatings have depicted great potential in improving the performance of FPSCs by increasing their property for absorbing solar radiation. and minimizing the amount of heat they produce. These coatings enhance the absorption of solar radiation while limiting heat dissipation, resulting in significant improvements in thermal efficiency and energy production. In addition, the use of modern absorber plate designs, which may include the integration of high-conductivity materials or finned structures, results in improved heat transmission inside the collector, hence increasing efficiency. Advancements in materials and nanotechnology have significantly contributed to the advancement of FPSCs by providing better thermal conductivity, endurance, and resistance to deterioration. The use of sophisticated working fluids, such as nanofluids and phase-change materials, has increased thermal efficiency and storage capacity in FPSC systems.

By optimizing the tilt and orientation of the collector and incorporating intelligent control systems, it becomes possible to make real-time modifications that optimize the process of absorbing solar power and enhance the gross effictivnness of the system. Enhanced insulation and fluid circulation systems reduce heat losses and improve the efficiency of heat transfer, hence enhancing the operation of the FPSC. In addition, the inclusion of environmental sustainability factors such as life cycle analysis and recycling technology guarantees that improved FPSC systems will play a role in creating a cleaner and more sustainable energy future. Overall, the most effective approaches to optimize the performance of collectors include using selective surface coatings, enhanced absorber plate designs, developments in materials and nanotechnology, optimal system management, and taking into account environmental factors. By incorporating these techniques into the design and operation of FPSC improved.

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