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SCIENTIFIC RESEARCH FOR HEATING SYSTEMS: USEFUL WORK ANALYSIS AND DEVELOPMENT METHODOLOGY

Sanjar Jurakulov
Asia International University, Republic of Uzbekistan, Bukhara, Uzbekistan

Abstract. Solar thermal systems play a crucial role in renewable energy by converting solar radiation into thermal energy for residential, industrial, and power generation applications. Their efficiency is influenced by absorber material properties, heat transfer processes, and system design. This study explores analytical and computational methods for assessing and optimizing solar thermal system performance. Energy and exergy analyses identify inefficiencies, while Computational Fluid Dynamics (CFD) simulations enhance heat transfer modelling. Optimization techniques, including material selection, machine learning-based predictive models, and exergoeconomic analysis, contribute to improved efficiency and cost-effectiveness. By integrating experimental validation with numerical modelling, this research highlights advancements in absorber coatings, nanofluids, and thermodynamic assessment. The findings provide insights into enhancing the sustainability and efficiency of solar thermal systems, supporting their broader implementation in renewable energy applications.

Keywords: Solar thermal systems, renewable energy, thermal energy conversion, absorber materials, heat transfer, energy analysis, exergy analysis, Computational Fluid Dynamics (CFD), optimization techniques, machine learning, predictive modelling, exergoeconomic analysis, nanofluids, thermal efficiency, solar energy technologies.

Annotatsiya. Quyosh issiqlik tizimlari qayta tiklanuvchi energetikada muhim o‘rin tutib, quyosh nurlanishini turar joylar, sanoat hamda elektr energiyasi ishlab chiqarishda foydalaniladigan issiqlik energiyasiga aylantiradi. Ularning samaradorligi absorber materiali xossalari, issiqlik almashinuvi jarayonlari va tizim konstruksiyasiga bog‘liq. Ushbu tadqiqot quyosh issiqlik tizimlari samaradorligini baholash va optimallashtirishning analitik hamda hisoblash usullarini o‘rganadi. Energiya va eksergiya tahlillari tizimdagi samarasizliklarni aniqlasa, Hisoblash Suyuqliklar Dinamikasi (CFD) simulyatsiyalari issiqlik almashinuvi modellashtirishini takomillashtiradi. Material tanlash, mashinaviy o‘qitishga asoslangan bashorat modellari va eksergoiqtisodiy tahlil kabi optimallashtirish usullari samaradorlik hamda iqtisodiy tejamkorlikni oshirishga xizmat qiladi. Eksperimental tasdiqlash va sonli modellashtirishni birlashtirish orqali ushbu tadqiqot absorber qoplamalari, nanosuyuqliklar va termodinamik baholashdagi yutuqlarni yoritadi. Olingan natijalar quyosh issiqlik tizimlarining

ISSN 3030-3907

barqarorligi va samaradorligini oshirish hamda ularni qayta tiklanuvchi energetika sohasida kengroq joriy etishga xizmat qiladi.

Kalit so‘zlar: Quyosh issiqlik tizimlari, qayta tiklanuvchi energiya, issiqlik energiyasini aylantirish, absorber materiallari, issiqlik almashinuvi, energiya tahlili, eksergiya tahlili, Hisoblash Suyuqliklar Dinamikasi (CFD), optimallashtirish usullari, mashinaviy o‘qitish, bashorat modellashtirish, eksergoiqtisodiy tahlil, nanosuyuqliklar, issiqlik samaradorligi, quyosh energetikasi texnologiyalari.

Аннотация. Солнечные тепловые системы играют важную роль в возобновляемой энергетике, преобразуя солнечное излучение в тепловую энергию для бытовых, промышленных и энергетических применений. Их эффективность зависит от свойств абсорбирующих материалов, процессов теплообмена и конструкции системы. В данном исследовании рассматриваются аналитические и вычислительные методы оценки и оптимизации производительности солнечных тепловых систем. Энергетический и эксергетический анализ позволяют выявить потери и неэффективности, тогда как моделирование с использованием вычислительной гидродинамики (CFD) улучшает моделирование процессов теплообмена. Методы оптимизации, включая выбор материалов, прогнозные модели на основе машинного обучения и эксергоэкономический анализ, способствуют повышению эффективности и экономической целесообразности. Благодаря интеграции экспериментальной проверки и численного моделирования в исследовании освещаются достижения в области абсорбирующих покрытий, наножидкостей и термодинамической оценки. Полученные результаты способствуют повышению устойчивости и эффективности солнечных тепловых систем, а также их более широкому внедрению в области возобновляемой энергетики.

Ключевые слова: солнечные тепловые системы, возобновляемая энергия, преобразование тепловой энергии, абсорбирующие материалы, теплообмен, энергетический анализ, эксергетический анализ, вычислительная гидродинамика (CFD), методы оптимизации, машинное обучение, прогнозное моделирование, эксергоэкономический анализ, наножидкости, тепловая эффективность, технологии солнечной энергетики.

INTRODUCTION.

Solar thermal systems are essential in the renewable energy sector, converting solar radiation into thermal energy that can be utilized for various purposes, including heating in residential buildings, industrial applications, and electricity generation [1], [2], [3]. The performance of these systems is influenced

ISSN 3030-3907

by several factors, such as the choice of absorber materials, heat transfer processes, and operational conditions, all of which affect the overall system efficiency [4]. With the increasing demand for sustainable energy solutions, optimizing the performance of solar thermal systems is crucial to ensure their widespread adoption and efficient operation.

A critical factor that affects the efficiency of solar thermal systems is the absorber material used. For effective solar energy capture and retention, the absorber must have high solar absorptance and low thermal emittance [5]. Furthermore, the efficiency of heat transfer within the system is dependent on processes such as conduction, convection, and radiation, which determine how well heat is transferred from the absorber to the working fluid for use in the desired application [6]. Enhancing these heat transfer processes is a key focus of research to improve system performance.

Researchers utilize various analytical methods to assess the efficiency of solar thermal systems, including energy and exergy analysis. Energy analysis measures the total energy input and output, while exergy analysis identifies the irreversibilities in the system and highlights areas where improvements can be made [7]. Alongside these analyses, experimental methods are used to verify theoretical models and collect real-world performance data. Computational Fluid Dynamics (CFD) simulations have also become an essential tool for optimizing system designs and predicting their performance under various operating conditions [8].

Optimization techniques are also crucial for enhancing solar thermal systems. These techniques involve adjusting parameters like absorber materials, fluid dynamics, and system configuration to maximize efficiency. By combining experimental and computational methods, researchers can optimize solar thermal systems to meet diverse application needs while minimizing energy losses [9].

In summary, optimizing solar thermal systems requires addressing a range of factors, including material selection, heat transfer mechanisms, and system design. Researchers continue to improve the performance of these systems through analytical, experimental, and computational methods, driving advancements in solar energy technologies [10].

Optimization Techniques for Solar Thermal Systems

This section explores essential optimization techniques for enhancing the efficiency of solar thermal systems. It focuses on three main approaches: predictive modelling using machine learning, exergoeconomic analysis for cost-effectiveness, and advanced material selection for improved thermal performance. These strategies contribute to the overall improvement of system design and operational efficiency.

ISSN 3030-3907

Machine Learning-Based Predictive Models

This table summarizes various optimization approaches and their practical applications in solar thermal systems. Artificial Neural Networks (ANNs) are widely used to model complex, non-linear relationships between system inputs and outputs. These models are trained using experimental and simulated data to accurately predict system behavior and performance trends. Support Vector Machines (SVMs) offer another supervised learning method, particularly effective for classifying data patterns and predicting overall system efficiency.

For solving multi-objective optimization problems, Genetic Algorithms (GAs) are employed to identify the optimal combination of design parameters, ensuring improved performance and energy output. In addition, fault detection and predictive maintenance techniques based on machine learning are increasingly used to monitor system health and detect early signs of equipment failure, allowing timely intervention and reduced downtime.

Table 1.

Optimization Approaches and Their Applications in Solar Thermal Systems

Optimization Approach	Description
Artificial Neural Networks (ANNs)	Used to model complex non-linear relationships between input and output variables in solar thermal systems. Trained on experimental and simulated data to predict system behavior [23].
Support Vector Machines (SVMs)	A supervised learning method that classifies data patterns and helps in predicting solar thermal system performance.
Genetic Algorithms (GAs)	• Optimization technique used for multi-objective problems. Helps find the best combination of design parameters [24].
Fault Detection & Predictive Maintenance	• Machine learning-based methods used to detect anomalies in solar thermal systems and predict potential failures [25].
Integration with IoT	• ML-based predictive models combined with IoT for real-time data analysis and monitoring.

Machine Learning-Based Predictive Models

ISSN 3030-3907

Exergoeconomic analysis is a powerful tool that integrates exergy and economic considerations to assess the cost-effectiveness of solar thermal systems. This approach helps identify major sources of irreversibilities and their associated costs, guiding the optimization of system components for enhanced thermodynamic performance and economic viability [26].

Exergy analysis evaluates the quality of energy conversion processes, identifying areas of high exergy destruction, such as heat exchangers, collectors, and storage units. By quantifying these inefficiencies in economic terms, exergoeconomic analysis enables targeted improvements that yield higher returns on investment [27].

Furthermore, exergoeconomic methods support lifecycle cost analysis by estimating the long-term economic benefits of efficiency-enhancing modifications. This includes optimizing material selection, improving thermal insulation, and integrating energy storage solutions to minimize operational costs and maximize system sustainability [28].

Machine Learning-Based Predictive Models

The ongoing evolution in solar thermal system performance has been greatly influenced by the integration of various research methods, including numerical modelling, experimental validation, and optimization techniques. This combination has shown significant potential in improving the efficiency of these systems, enabling more accurate predictions and real-time performance adjustments.

This table presents several key optimization factors aimed at improving the performance and durability of solar thermal systems. Selective coatings with high solar absorptance and low infrared emittance help minimize energy losses and maximize heat absorption. Advanced materials such as black chrome, titanium nitride oxide, and carbon-based nanostructures further enhance optical and thermal properties. Nanofluids, which are suspensions of nanoparticles in base fluids, are utilized to boost thermal conductivity and heat transfer efficiency. Additionally, corrosion-resistant coatings provide protection against harsh environmental conditions, extending the operational life of the system. Ongoing research in novel material development focuses on ensuring stability and reliability under extreme thermal and environmental conditions.

Table 3.

Key Optimization Factors for Enhancing Solar Thermal System Efficiency

Optimization Factor	Description	

ISSN 3030-3907

Selective Coatings	Coatings designed with high absorptance in the solar spectrum and low emittance in the infrared range.	
Advanced Materials	Materials such as black chrome, titanium nitride oxide, and carbon-based nanostructures used for coatings.	
Nanofluids	Suspensions of nanoparticles in heat transfer fluids used to enhance thermal conductivity [29].	

Thermodynamic modelling has proven to be a valuable tool for analyzing solar thermal systems, with several studies demonstrating its effectiveness in evaluating energy and exergy efficiency. Energy analysis, based on the first law of thermodynamics, helps quantify the energy input and output, offering insights into the overall energy balance of the system [31]. Exergy analysis, derived from the second law, enhances understanding by identifying inefficiencies related to irreversibilities, such as heat losses or friction within the system [32]. These analyses not only help optimize the system's energy conversion process but also aid in pinpointing areas requiring improvement, such as heat loss and inefficient heat transfer mechanisms [33].

Recent advancements in entropy generation analysis, a part of thermodynamic modelling, provide more precise insights into energy dissipation and allow for the identification of inefficiencies within the system's components, including the collector, heat exchangers, and storage units [34]. By incorporating these thermodynamic models, system designers can optimize the system's thermal performance and minimize energy waste, leading to a more efficient solar thermal setup.

ISSN 3030-3907

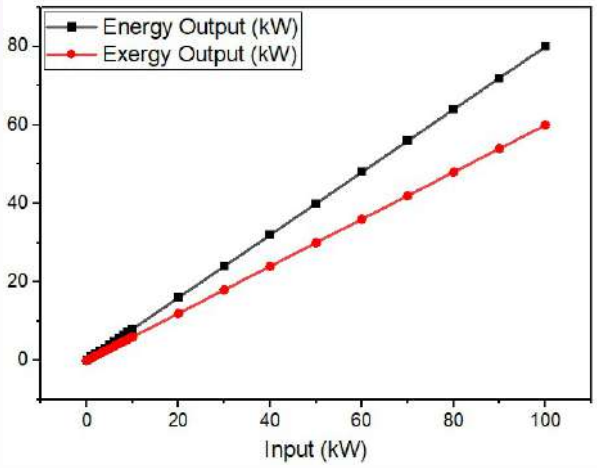


Figure 1. Shows the input values (kW) for energy and exergy and the corresponding outputs based on efficiency (80% for energy and 60% for exergy).

Table 4.

Key Aspects of Exergoeconomic Analysis in Solar Thermal Systems

Aspect	Description
Definition	Exergoeconomic analysis integrates exergy and economic considerations to optimize the cost-effectiveness of solar thermal systems.
Key Objective	Identifying major inefficiencies and associated costs to enhance system design and operation.
Energy Conversion	Optimizing the energy conversion process to reduce energy losses and improve efficiency [38].
Economic Impact	Helps in reducing the overall cost of energy production through better system performance [39].
Cost-Effective Improvements	Provides insights into areas where cost-effective modifications can be implemented.
Operational Benefits	Minimizes operational expenses while ensuring the system meets performance expectations.
Research Findings	Studies indicate that exergoeconomic analysis contributes to designing more economically viable solar thermal systems [40].

CONCLUSION.

The study of solar thermal systems emphasizes the importance of efficiency analysis and optimization for advancing renewable energy. Integrating

ISSN 3030-3907

thermodynamic modelling, CFD simulations, and experimental validation enhances system performance and reliability.

Thermodynamic analysis, through energy and exergy assessments, identifies inefficiencies and optimizes energy conversion. Entropy generation analysis refines system evaluation, improving heat transfer and component design. CFD simulations offer insights into heat and fluid flow, optimizing absorber geometry and minimizing thermal losses.

Experimental validation confirms theoretical models, ensuring practical applicability. Advanced absorber materials, selective coatings, and nanofluids enhance heat absorption and retention. Optimization techniques, including machine learning and exergoeconomic analysis, improve cost-effectiveness and system reliability.

By combining analytical, computational, and experimental approaches, solar thermal efficiency has significantly improved. Future advancements will focus on optimization, novel materials, and real-time monitoring, strengthening solar thermal systems' role in sustainable energy.

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