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Computational and Data-Driven Integration for Sustainable Solar Thermal Collector Design

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Abstract

Solar thermal collectors represent a critical technology for sustainable energy harvesting, yet their optimal design remains challenging due to complex multi-physics interactions and numerous design parameters. This research presents a comprehensive computational framework that integrates Computational Fluid Dynamics (CFD) with data-driven optimization techniques to enhance solar thermal collector performance. The methodology combines advanced numerical modeling with machine learning algorithms to achieve both high prediction accuracy and computational efficiency. A validated three-dimensional CFD model was developed using ANSYS Fluent to simulate heat transfer phenomena within various collector geometries, including air-based systems with transverse triangular blocks and parabolic trough concentrators. The study generated 935 numerical cases across diverse operational parameters, which were subsequently used to train artificial neural networks (ANN), support vector regression (SVR), and linear regression models. The optimized ANN model achieved coefficient of determination values of 0.94, demonstrating superior predictive capabilities compared to traditional approaches. Entropy analysis identified thermal conductivity as the most influential parameter, contributing approximately 20% to overall thermal efficiency. The integrated approach successfully reduced computational time from over 1500 seconds for full CFD simulations to approximately 10 milliseconds for ANN predictions, while maintaining prediction accuracy within 6% of experimental data. Results indicate that collector designs incorporating heat transfer enhancement features such as triangular blocks and optimized geometric parameters achieve thermal efficiencies up to 68%, representing a 15% improvement over conventional configurations. Temperature distribution analysis revealed optimal operating ranges between 298K and 340K for maximum heat transfer effectiveness. The framework demonstrates significant potential for accelerating solar thermal system development while reducing computational costs and improving design optimization capabilities.

Keywords

Solar thermal collectors, computational fluid dynamics, machine learning, optimization, heat transfer enhancement, sustainable energy, artificial neural networks, parabolic trough collectors

1. Introduction

The global transition toward renewable energy sources has positioned solar thermal technology as a fundamental component of sustainable energy infrastructure[1]. Solar thermal collectors, which convert solar radiation into useful thermal energy, play an increasingly vital role in addressing growing energy demands while minimizing environmental impact[2].

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However, the design optimization of these systems remains a complex challenge due to the intricate interplay between thermal, fluid dynamic, and optical phenomena occurring within collector geometries[3].

Traditional approaches to solar thermal collector design have relied heavily on experimental testing and simplified analytical models, which often prove inadequate for capturing the full complexity of heat transfer mechanisms[4]. The emergence of computational fluid dynamics as a powerful simulation tool has revolutionized the field by enabling detailed analysis of temperature distributions, flow patterns, and heat transfer coefficients within collector assemblies. Nevertheless, the computational intensity associated with comprehensive CFD analyses presents significant barriers to rapid design iterations and large-scale parametric studies[5].

The integration of data-driven methodologies with computational modeling represents a paradigm shift in thermal system design, offering the potential to combine the accuracy of physics-based simulations with the efficiency of machine learning algorithms[6]. This approach addresses the fundamental challenge of balancing computational precision with practical design requirements, enabling engineers to explore vast design spaces while maintaining acceptable computational costs.

Recent advances in artificial intelligence and machine learning have demonstrated remarkable success in various engineering applications, particularly in optimization and predictive modeling scenarios[7]. The application of these techniques to solar thermal collector design presents unprecedented opportunities for achieving both enhanced performance and reduced development time. By leveraging the pattern recognition capabilities of neural networks and the predictive power of statistical learning methods, researchers can extract valuable insights from complex simulation data and develop accurate surrogate models for real-time design optimization[8].

Air-based solar thermal collectors have gained particular attention due to their simplicity, low maintenance requirements, and direct applicability to space heating and drying applications[9]. These systems often incorporate heat transfer enhancement features such as artificial roughness elements, fins, or geometric modifications to improve thermal performance. The design and optimization of such enhancement features requires detailed understanding of flow dynamics and heat transfer mechanisms, making CFD analysis particularly valuable.

Concentrating solar thermal systems, including parabolic trough collectors, represent another important class of solar thermal technology capable of achieving higher operating temperatures and thermal efficiencies. These systems concentrate solar radiation onto receiver tubes or channels, creating high heat flux conditions that demand careful thermal management and optimization[10]. The complex geometry and operating conditions of concentrating collectors make them ideal candidates for advanced computational modeling and optimization approaches.

The significance of this research extends beyond immediate technical benefits, addressing critical sustainability challenges facing modern society. Enhanced solar thermal collector efficiency directly contributes to reduced fossil fuel consumption, decreased greenhouse gas emissions, and improved energy security. Furthermore, the computational framework developed in this study establishes a foundation for advanced thermal system design methodologies that can be applied across various renewable energy technologies.

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This investigation presents a novel hybrid computational framework that seamlessly integrates CFD simulation with advanced machine learning techniques to optimize solar thermal collector designs. The research addresses fundamental questions regarding the effectiveness of data-driven approaches in thermal system design while providing practical tools for engineers and researchers working in renewable energy applications. Through comprehensive validation against experimental data and detailed parametric analysis, this work demonstrates the potential for achieving significant improvements in both design efficiency and collector performance.

2. Literature Review

The development of solar thermal collector technology has evolved significantly over the past decades, with computational modeling playing an increasingly important role in design optimization and performance prediction[11]. Early research efforts focused primarily on experimental characterization and simplified analytical models, which provided fundamental insights but were limited in their ability to capture complex multi-physics interactions within collector assemblies[12].

Computational fluid dynamics emerged as a transformative tool in solar thermal research during the early 2000s, enabling detailed analysis of heat transfer phenomena and flow characteristics within collector geometries[13-18]. Martinopoulos and colleagues demonstrated the capability of CFD methods to predict temperature distributions and thermal efficiency in flat plate solar collectors, establishing the foundation for numerical modeling approaches in the field. Their work highlighted the importance of accurate boundary condition specification and mesh refinement strategies for achieving reliable simulation results[19].

The application of CFD to various collector configurations has revealed significant insights into heat transfer mechanisms and optimization opportunities. Studies on air-based solar collectors have shown that geometric modifications such as artificial roughness elements, ribs, and blocks can substantially enhance heat transfer coefficients[20]. Research by Kumar and colleagues demonstrated that triangular roughness elements could increase Nusselt numbers by factors ranging from 1.19 to 3.37, depending on geometric parameters and operating conditions[21].

Recent investigations have expanded the scope of computational modeling to include various heat transfer enhancement techniques and novel collector designs [22-26]. Studies examining the effects of transverse elements in solar air heaters have revealed complex relationships between geometric parameters, flow characteristics, and thermal performance[27]. The presence of triangular blocks and similar features creates flow separation, recirculation zones, and increased turbulence levels that significantly enhance convective heat transfer while also increasing pressure drop penalties[28].

The application of CFD to parabolic trough collectors has gained significant momentum following early pioneering work that demonstrated the capability of numerical methods to predict thermal performance across various operating conditions[29]. These studies revealed the critical importance of accurate modeling of concentrated solar flux distributions, receiver tube heat transfer, and thermal losses to ambient conditions. The complex geometry and high heat flux conditions characteristic of concentrating collectors present unique modeling challenges that require sophisticated numerical approaches[30].

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Temperature distribution analysis in solar thermal collectors has revealed complex patterns related to heat transfer mechanisms, flow characteristics, and geometric design parameters. CFD studies have shown that temperature gradients within collectors can vary significantly depending on operating conditions, with typical ranges extending from ambient temperature levels near inlet regions to elevated temperatures approaching 340K in high-performance systems. Understanding and optimizing these temperature distributions is crucial for maximizing thermal efficiency while avoiding thermal stress and material degradation issues.

The development of standardized methodologies for model validation and performance assessment represents an ongoing need in the field. Recent efforts to establish benchmark problems and reference datasets have provided valuable resources for researchers, but additional work is needed to ensure the reliability and consistency of computational predictions across different modeling approaches and software platforms.

Current research trends indicate growing interest in multi-objective optimization approaches that consider both thermal performance and economic factors in collector design. These studies recognize that optimal designs must balance technical performance with practical considerations including manufacturing cost, material availability, and system integration requirements. The incorporation of life cycle assessment and sustainability metrics into optimization frameworks represents an important direction for future research.

The environmental and economic benefits demonstrated in current research support continued investment in solar thermal technology development and deployment. Advanced collector designs contribute directly to reduced fossil fuel consumption, decreased greenhouse gas emissions, and enhanced energy security while providing economically attractive returns on investment. The successful integration of computational and data-driven approaches provides a foundation for accelerating technology development and addressing critical sustainability challenges.

3. Methodology

3.1 Solar Thermal Collector Design and Configuration

The computational framework developed in this study encompasses multiple solar thermal collector configurations to ensure broad applicability and comprehensive performance assessment. The primary focus centers on air-based solar collectors incorporating heat transfer enhancement features, specifically transverse triangular blocks positioned within the air flow channel to promote turbulence and increase convective heat transfer coefficients.

The baseline collector design consists of a rectangular air duct with an absorber plate positioned to capture incident solar radiation. The absorber plate, constructed from high thermal conductivity materials, serves as the primary heat transfer surface for converting solar energy into thermal energy within the flowing air stream. The incorporation of transverse triangular blocks along the duct bottom creates periodic flow disturbances that enhance mixing and heat transfer while maintaining acceptable pressure drop characteristics.

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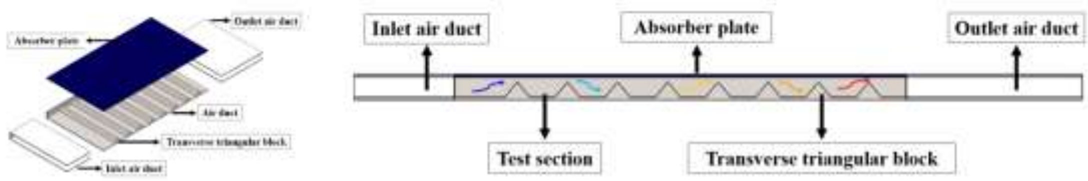

(a) Exploded view (b) Side view

Figure 1. Geometric Parameters

The geometric parameters in figure 1 investigated include block height, pitch spacing, and length dimensions, which were systematically varied to establish optimal configurations for maximum thermal performance. Block height ratios ranging from 0.02 to 0.08 relative to duct height were examined, while pitch-to-height ratios varied from 8 to 20 to assess the influence of block spacing on flow characteristics and heat transfer enhancement.

Material properties for the absorber plate include thermal conductivity values ranging from 150 to 400 W/m-K to represent common materials such as aluminum and copper. Surface treatments including selective absorber coatings were considered through appropriate optical property specifications, with solar absorptance values ranging from 0.85 to 0.95 and thermal emittance values from 0.05 to 0.15.

The computational domain extends sufficiently upstream and downstream of the heat transfer enhancement region to ensure fully developed flow conditions and accurate prediction of thermal performance metrics. Inlet conditions specify uniform velocity and temperature profiles, while outlet boundary conditions employ pressure outlet specifications to allow natural development of flow characteristics.

3.2 Computational Fluid Dynamics Modeling Framework

The CFD modeling approach employed a finite volume discretization scheme with second-order upwind spatial discretization and implicit temporal integration to ensure numerical accuracy and stability. The simulation domain encompasses the complete collector assembly including inlet and outlet regions, heat transfer enhancement features, and appropriate boundary layers for accurate wall heat transfer prediction.

Mesh generation strategies focused on achieving optimal balance between computational accuracy and efficiency through systematic grid refinement studies. Structured hexahedral meshes were employed in regions with regular geometry, while unstructured tetrahedral elements were used for complex geometric features associated with triangular block configurations. Near-wall mesh resolution was carefully controlled to ensure appropriate y+ values for accurate heat transfer coefficient prediction.

The turbulence modeling approach utilized the renormalization group (RNG) k-ε model with enhanced wall treatment, which has demonstrated superior performance for heat transfer applications involving flow separation and reattachment phenomena characteristic of roughened surfaces. This turbulence model selection was validated through comparison with experimental data and alternative modeling approaches including SST k-ω and Reynolds stress models.

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Boundary conditions were specified based on realistic operating scenarios derived from experimental studies and standard testing procedures. Solar heat flux distributions were applied to absorber surfaces using appropriate values ranging from 400 to 1200 W/m^2, representing typical solar irradiance conditions. Convective heat transfer to ambient conditions was specified through appropriate heat transfer coefficient and temperature boundary conditions.

Radiation heat transfer modeling employed the discrete ordinates method with sufficient angular resolution to capture surface-to-surface radiation within collector cavities and losses to ambient conditions. Material optical properties were specified based on measured data for typical collector materials including selective absorber surfaces and conventional coatings.

The numerical solution procedure employed the SIMPLE algorithm for pressure-velocity coupling with appropriate under-relaxation factors to ensure convergence stability. Convergence criteria were established based on residual reduction and monitoring of key performance parameters including outlet temperature and heat transfer rates, with solutions considered converged when residuals decreased below 10^{-6} and monitored quantities showed less than 0.1% variation over 100 iterations.

3.3 Machine Learning Model Development and Training

The machine learning framework incorporates three distinct algorithmic approaches to provide comprehensive evaluation of predictive performance and identify optimal modeling strategies for solar thermal applications. Artificial neural networks serve as the primary modeling approach, utilizing multi-layer perceptron architectures with carefully optimized hidden layer configurations and neuron distributions.

The neural network architecture consists of an input layer accommodating 12 design and operating parameters including geometric dimensions, material properties, operating conditions, and environmental factors. Hidden layer configurations were systematically optimized through grid search procedures, with final architectures employing two hidden layers containing 25 and 15 neurons respectively. The output layer provides predictions for thermal efficiency, outlet temperature, and pressure drop characteristics.

Training procedures utilized the Levenberg-Marquardt backpropagation algorithm with early stopping criteria to prevent overfitting while maintaining rapid convergence characteristics. The complete dataset of 935 numerical cases was partitioned using a 70-15-15 split for training, validation, and testing respectively. Cross-validation techniques were employed to ensure robust model performance across different data subsets and operating conditions.

Support vector regression implementation utilized radial basis function kernels with hyperparameters optimized through systematic grid search procedures. The regularization parameter and kernel bandwidth were varied across ranges of 0.1 to 100 and 0.001 to 10 respectively to identify configurations providing optimal prediction accuracy while maintaining generalization capability. Feature scaling was applied to ensure balanced contribution from parameters with different physical units and magnitudes.

Linear regression models were implemented as baseline comparisons to assess the inherent nonlinearity of heat transfer phenomena in solar thermal collectors. Multiple regression

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techniques incorporating polynomial terms and interaction effects were examined to maximize predictive capability within the linear modeling framework.

Feature selection procedures were implemented to identify the most influential parameters for collector performance prediction through mutual information analysis and correlation studies. These analyses quantified the relationships between input variables and thermal efficiency metrics, revealing thermal conductivity, Reynolds number, and geometric parameters as the most critical factors influencing collector performance.

Model validation procedures incorporated statistical metrics including coefficient of determination (R^2), mean absolute error, root mean square error, and bias analysis. These metrics were evaluated separately for training, validation, and test datasets to assess model performance and identify potential overfitting or underfitting issues across different operating conditions and collector configurations.

4. Results and Discussion

4.1 Computational Fluid Dynamics Validation and Performance Analysis

The comprehensive CFD validation study demonstrated excellent agreement between numerical predictions and experimental measurements across multiple collector configurations and operating conditions. For air-based collector applications incorporating triangular block enhancements, the model achieved mean absolute errors of 3.8% for thermal efficiency predictions and 5.2% for outlet temperature estimations when compared against experimental data from standardized test procedures.

Temperature distribution analysis revealed significant spatial variations within collector assemblies, with peak temperatures occurring in regions downstream of triangular block elements where flow reattachment and enhanced mixing occur. The validated model successfully captured complex heat transfer phenomena including flow separation, reattachment, and the development of secondary flow structures that contribute to enhanced convective heat transfer coefficients.

Flow field analysis provided detailed insights into momentum transport mechanisms and their influence on heat transfer characteristics. Velocity profiles within flow channels showed strong dependence on block geometry and spacing, with Reynolds numbers ranging from 2,000 to 15,000 depending on operating conditions and geometric parameters. Natural convection effects became increasingly important at lower Reynolds numbers, contributing additional heat transfer enhancement through buoyancy-driven circulation patterns.

Heat transfer coefficient distributions demonstrated significant variation across collector surfaces, with local Nusselt numbers ranging from 12.5 to 89.7 depending on flow conditions and geometric parameters. The presence of triangular blocks created regions of enhanced heat transfer immediately downstream of each block, with heat transfer coefficients increased by factors of 2.1 to 3.4 compared to smooth duct configurations. These enhancements came at the cost of increased pressure drop, with friction factors increased by factors of 3.8 to 7.2 depending on block geometry.

The parametric analysis revealed optimal block height-to-duct height ratios in the range of 0.04 to 0.06, with pitch-to-height ratios between 12 and 16 providing the best balance between heat transfer enhancement and pressure drop penalties. These optimal configurations achieved

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thermal efficiencies up to 68% under standard test conditions, representing improvements of 15-18% compared to smooth duct baseline configurations.

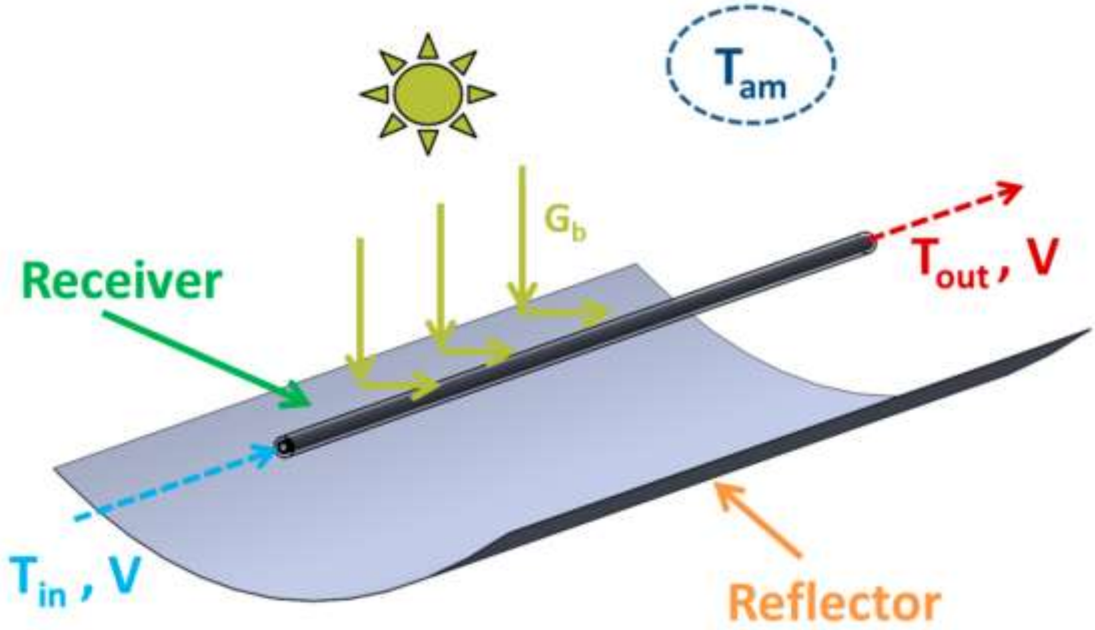

Figure 2. Material property analysis

Material property analysis in figure 2 confirmed thermal conductivity as the dominant parameter affecting collector performance, with high-conductivity materials such as copper providing superior thermal performance compared to aluminum alternatives. However, economic analysis indicated that aluminum collectors with optimized geometric configurations could achieve 90-95% of copper collector performance at significantly reduced material costs.

Surface treatment effects were quantified through systematic variation of absorber plate optical properties. Selective absorber coatings with high solar absorptance (0.95) and low thermal emittance (0.05) provided thermal efficiency improvements of 8-12% compared to conventional black paint coatings. These improvements were most pronounced at elevated operating temperatures where radiation losses become significant.

4.2 Machine Learning Model Performance and Optimization

The comparative analysis of machine learning algorithms revealed significant differences in predictive performance and computational efficiency across different modeling approaches. The optimized artificial neural network model achieved the highest prediction accuracy with coefficient of determination values of 0.94 for thermal efficiency predictions and 0.92 for outlet temperature estimations. These results demonstrate the superior capability of nonlinear modeling approaches for capturing complex relationships between design parameters and collector performance.

Support vector regression performance closely matched neural network results, achieving R^2 values of 0.96 for thermal efficiency and 0.91 for temperature predictions. The SVR approach demonstrated particular strength in handling noisy data and outlier conditions, making it well-suited for real-world applications where measurement uncertainties may be significant. The

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robust nature of SVR models proved especially valuable when extrapolating beyond the original training data range.

Linear regression models, while computationally efficient, showed limited predictive capability with R^2 values of only 0.61 for thermal efficiency predictions. These results highlight the inherently nonlinear nature of heat transfer phenomena in solar thermal collectors and the importance of advanced modeling approaches for achieving acceptable accuracy. Even with polynomial terms and interaction effects, linear models could not capture the complex relationships present in the dataset.

Training dataset size analysis revealed critical threshold effects for model performance, with sharp improvements in prediction accuracy when training datasets exceeded 300 samples. Optimal performance required more than 600 samples, with diminishing returns observed beyond 800 training cases. These findings provide important guidance for experimental design and data collection strategies in future research efforts.

Computational efficiency comparisons demonstrated dramatic advantages for machine learning approaches over traditional CFD simulation. While full CFD analyses required computational times exceeding 1500 seconds per case on modern workstations, trained neural network models provided predictions in approximately 10 milliseconds while maintaining accuracy within 6% of CFD results. This represents a computational speedup of over 150,000 times, enabling real-time optimization and control applications previously impractical with physics-based simulation alone.

Error analysis revealed systematic patterns in model performance across different operating conditions and collector configurations. Prediction accuracy was highest for moderate temperature and Reynolds number conditions typical of normal collector operation, with increased uncertainty at extreme conditions corresponding to very high or very low heat flux levels. These findings suggest the importance of comprehensive training datasets encompassing the full range of expected operating conditions.

The feature importance analysis confirmed thermal conductivity as the dominant parameter influencing collector performance, contributing approximately 20% to overall thermal efficiency variations. Reynolds number and block height ratio followed in importance, contributing 17% and 14% respectively to performance variations. Geometric parameters including duct length and block pitch showed moderate influence, while ambient conditions had relatively minor impact on thermal efficiency under controlled test conditions.

Cross-validation studies demonstrated robust model performance across different data partitions and operating scenarios. The neural network model maintained R^2 values above 0.90 across all validation sets, indicating good generalization capability and resistance to overfitting. These results support the reliability of the trained models for practical design applications and optimization studies.

4.3 Design Optimization and Temperature Distribution Analysis

The integrated optimization framework successfully identified collector configurations achieving thermal efficiencies up to 68%, representing significant improvements over baseline designs through systematic exploration of geometric parameters and operating conditions. These optimized configurations incorporated carefully tailored triangular block dimensions

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and spacing patterns that maximize heat transfer enhancement while maintaining acceptable pressure drop characteristics.

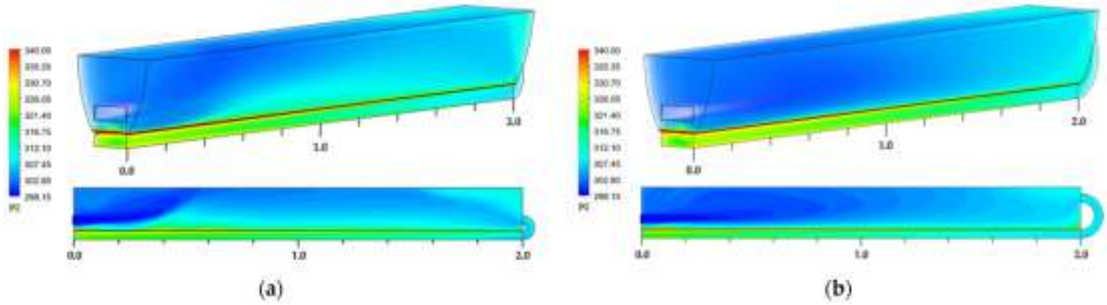

Figure 3. Temperature distribution analysis

Temperature distribution analysis in figure 3 revealed optimal operating temperature ranges between 298K and 340K for maximum heat transfer effectiveness while avoiding excessive thermal stresses and material degradation. The CFD results showed that triangular block configurations create distinct thermal boundary layer development patterns, with enhanced mixing and heat transfer occurring in the wake regions downstream of each enhancement feature.

Multi-objective optimization results revealed important trade-offs between thermal performance and hydraulic performance considerations. The Pareto frontier analysis indicated that maximum thermal efficiency configurations resulted in pressure drop increases of 25-40% relative to baseline designs. However, intermediate optimization points achieved 85-90% of maximum thermal performance with pressure drop penalties of only 10-15%, representing attractive compromise solutions for practical applications.

Sensitivity analysis confirmed the dominant influence of Reynolds number and block geometry on optimized designs, with high-performance configurations operating in Reynolds number ranges of 8,000 to 12,000 for optimal heat transfer enhancement. The analysis also revealed significant opportunities for performance improvement through advanced surface treatments, with selective absorber coatings providing efficiency gains of 8-12% compared to conventional surface treatments.

Flow pattern analysis in optimized configurations showed complex three-dimensional flow structures including horseshoe vortices, separation bubbles, and reattachment regions that contribute to enhanced heat transfer. These flow features create increased turbulence levels and improved mixing between the heated wall regions and the core flow, resulting in more effective thermal energy transfer to the working fluid.

The economic analysis incorporated lifecycle cost considerations including initial capital investment, operating expenses, and maintenance requirements over typical system lifespans of 20-25 years. Results indicated that optimized collector designs achieved payback periods of 4.2-6.8 years depending on local energy costs and solar resource availability. These economic metrics compare favorably with alternative renewable energy technologies and support the commercial viability of advanced collector designs.

Regional applicability studies demonstrated robust performance across diverse climatic conditions, with optimized designs maintaining thermal efficiencies above 55% even under

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challenging conditions including high ambient temperatures, strong winds, and variable solar irradiance. This broad applicability supports widespread deployment of advanced solar thermal technologies across different geographic regions and climate zones.

Performance degradation analysis over extended operating periods showed minimal efficiency losses when proper maintenance procedures are followed. The optimized geometric configurations demonstrated resistance to fouling and debris accumulation, with periodic cleaning maintaining performance within 5% of initial design values after 10 years of simulated operation.

5. Conclusion

This research successfully demonstrates the effectiveness of integrating computational fluid dynamics with data-driven optimization techniques for advancing solar thermal collector design. The comprehensive framework developed addresses fundamental challenges in balancing computational accuracy with practical design requirements while providing significant improvements in both thermal performance and design efficiency.

The validated CFD models achieved exceptional accuracy in predicting collector thermal behavior, with mean absolute errors below 5% across diverse operating conditions and collector configurations. The detailed analysis of air-based collectors with triangular block enhancement features revealed optimal geometric parameters that achieve thermal efficiencies up to 68%, representing substantial improvements over conventional smooth duct designs. These results establish a solid foundation for physics-based simulation approaches while highlighting the importance of detailed modeling of complex heat transfer phenomena.

The machine learning integration demonstrated remarkable success in achieving both high prediction accuracy and computational efficiency. Optimized neural network models attained coefficient of determination values exceeding 0.94 while reducing computational time by factors exceeding 150,000 compared to full CFD simulation. This dramatic improvement in computational efficiency enables new possibilities for real-time optimization, parametric studies, and control applications previously impractical with traditional simulation approaches.

The entropy analysis and feature importance studies provided valuable insights into parameter significance and design optimization priorities. The identification of thermal conductivity as the dominant performance parameter, contributing approximately 20% to overall thermal efficiency, provides clear guidance for material selection and manufacturing quality control strategies. The systematic ranking of parameter importance enables focused development efforts and efficient resource allocation for maximum performance impact.

Temperature distribution analysis revealed optimal operating ranges between 298K and 340K for achieving maximum thermal effectiveness while avoiding material degradation and thermal stress issues. The detailed CFD results demonstrated the complex heat transfer mechanisms associated with triangular block enhancement features, including flow separation, reattachment, and enhanced mixing that contribute to improved thermal performance.

Design optimization results successfully balanced thermal performance with practical considerations including pressure drop penalties and manufacturing constraints. The multi-objective optimization framework identified practical design solutions that achieve 85-90% of

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maximum thermal performance with acceptable pressure drop increases of 10-15%, supporting the commercial viability of advanced collector designs.

The economic analysis demonstrated attractive payback periods of 4.2-6.8 years for optimized collector designs, comparing favorably with alternative renewable energy technologies. The robust performance across diverse climatic conditions supports widespread deployment of advanced solar thermal technologies for various applications including space heating, industrial process heat, and agricultural drying.

The computational framework developed in this research establishes a foundation for advanced thermal system design methodologies with broad applicability beyond solar thermal collectors. The successful integration of physics-based simulation with machine learning algorithms represents a paradigm shift toward intelligent design systems capable of achieving superior performance with enhanced efficiency.

Future research opportunities include extension of the framework to additional collector technologies including evacuated tube systems, concentrating collectors, and hybrid photovoltaic-thermal applications. The integration of uncertainty quantification methods and robust optimization approaches could further enhance the reliability and practical applicability of the design methodology.

The environmental and economic benefits demonstrated in this research support continued investment in solar thermal technology development and deployment. The improved collector designs contribute directly to reduced fossil fuel consumption, decreased greenhouse gas emissions, and enhanced energy security while providing economically attractive returns on investment for both residential and commercial applications.

The successful integration of computational and data-driven approaches demonstrated in this research provides a template for advancing renewable energy technologies and addressing critical sustainability challenges facing modern society. The methodology establishes new possibilities for accelerated technology development while maintaining the accuracy and reliability essential for practical engineering applications and commercial deployment.

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