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Parameter-Driven Efficiency Evaluation of Solar Thermal Collectors Using CFD–ML Integration

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Abstract

This research presents a comprehensive computational framework integrating Computational Fluid Dynamics (CFD) with Adaptive Neuro-Fuzzy Inference System (ANFIS) for parameter-driven efficiency evaluation of parabolic trough solar thermal collectors. The methodology combines high-fidelity CFD simulations with advanced ANFIS machine learning techniques to predict thermal performance parameters across diverse operational conditions. A validated CFD model was developed using ANSYS Fluent to simulate the complex thermal and fluid dynamic behavior within parabolic trough collector systems, generating 920 numerical datasets encompassing varying flow rates, inlet temperatures, solar irradiation levels, and geometric configurations. The ANFIS model demonstrated exceptional predictive capabilities, achieving coefficient of determination (R^2) values of 0.94 for thermal efficiency predictions. The integrated CFD-ANFIS framework reduces computational time by 82% compared to traditional CFD approaches while maintaining prediction accuracy within 4.2% error bounds. Key findings indicate that solar irradiation intensity and heat transfer fluid mass flow rate are the most influential parameters affecting collector efficiency, with optimal performance achieved at Reynolds numbers between 10000-15000. The developed framework enables rapid parametric optimization and real-time performance assessment for parabolic trough solar thermal collector systems, providing significant advantages for design engineers and system operators in concentrating solar power applications.

Keywords

Solar thermal collector, Computational fluid dynamics, ANFIS, Parabolic trough, Thermal efficiency, Machine learning integration

1. Introduction

The increasing global demand for sustainable energy solutions has intensified research efforts in concentrating solar power technology, particularly in the optimization of parabolic trough solar thermal collectors for enhanced efficiency and performance[1]. Parabolic trough collectors represent the most mature and commercially viable concentrating solar power technology, utilizing curved mirrors to focus solar radiation onto receiver tubes containing heat transfer fluid. Despite significant technological advancements, achieving optimal thermal performance remains challenging due to the complex interdependencies between multiple operational and design parameters that influence collector efficiency under varying environmental conditions[2].

Traditional approaches to parabolic trough collector design and optimization have relied heavily on experimental testing and simplified analytical models, which are often time-consuming, expensive, and limited in scope for comprehensive parametric studies[3]. The

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inherent complexity of heat transfer phenomena within parabolic trough systems, involving concentrated solar radiation absorption, convective heat transfer to the working fluid, and thermal losses to the environment, necessitates sophisticated analytical tools capable of capturing these multifaceted interactions with high fidelity and computational efficiency[4].

The emergence of Computational Fluid Dynamics as a powerful analytical tool has revolutionized the study of thermal and fluid flow phenomena in concentrating solar energy systems[5]. CFD enables detailed visualization of temperature distributions, velocity profiles, heat transfer coefficients, and thermal loss characteristics within complex collector geometries, providing insights that are difficult or impossible to obtain through experimental means alone[6]. However, traditional CFD approaches, while highly accurate, are computationally intensive and require substantial time investments for comprehensive parametric studies across broad design and operational parameter spaces[7].

Machine learning techniques, particularly Adaptive Neuro-Fuzzy Inference Systems, have emerged as transformative approaches to address the computational limitations of traditional CFD methods while maintaining high prediction accuracy[8]. ANFIS combines the learning capabilities of neural networks with the reasoning capabilities of fuzzy logic systems, making it particularly suitable for modeling complex nonlinear relationships between input parameters and system performance metrics in engineering applications[9]. The hybrid nature of ANFIS allows it to capture both quantitative relationships and qualitative reasoning patterns inherent in solar thermal system operation[10].

The convergence of CFD and ANFIS technologies presents an unprecedented opportunity to develop hybrid computational frameworks that combine the physical accuracy of CFD with the computational efficiency and adaptive learning capabilities of neuro-fuzzy systems. Such integration enables the development of intelligent predictive models capable of real-time performance assessment, parametric optimization, and adaptive control system development[11]. This approach is particularly valuable for parabolic trough collector applications, where multiple design and operational parameters interact in complex ways to determine overall system efficiency and economic viability[12].

This research addresses the critical need for efficient and accurate methods to evaluate parabolic trough solar thermal collector performance across diverse operational conditions encountered in commercial concentrating solar power plants. The primary objective is to develop a comprehensive CFD-ANFIS integrated framework that enables rapid parameter-driven efficiency evaluation while maintaining high prediction accuracy for engineering design applications. The methodology involves the development of validated CFD models to generate comprehensive datasets, followed by the implementation and optimization of ANFIS algorithms for performance prediction and system optimization.

The research contributes to the advancement of concentrating solar power technology by providing engineers and researchers with powerful tools for collector design optimization, performance assessment, and operational control strategies. The findings have significant implications for the development of next-generation parabolic trough systems that can adapt dynamically to changing environmental conditions while maintaining optimal efficiency levels throughout their operational lifetime. The integrated framework supports the broader deployment of concentrating solar power technology by reducing design uncertainties and enabling more accurate performance predictions for project development and investment decision-making.

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2. Literature Review

The application of computational methods in parabolic trough solar collector analysis has evolved significantly over the past decade, with researchers increasingly adopting sophisticated numerical techniques to understand and optimize collector performance under various operational scenarios[13]. Early computational studies focused primarily on steady-state analysis using simplified one-dimensional models, but the field has progressively embraced more complex approaches incorporating transient effects, multiphysics phenomena, and advanced optimization techniques for concentrating solar power applications[14].

Computational Fluid Dynamics has emerged as the dominant numerical approach for parabolic trough collector analysis, with numerous researchers demonstrating its effectiveness in predicting thermal and fluid flow characteristics within receiver tubes and the surrounding thermal environment[15]. The fundamental advantage of CFD lies in its ability to solve the complete Navier-Stokes equations coupled with energy conservation equations and radiation heat transfer models, providing detailed insights into local heat transfer phenomena that are critical for collector optimization and thermal loss reduction.

The turbulence modeling aspect of CFD simulations has received considerable attention in parabolic trough collector research, with different turbulence models being evaluated for their accuracy and computational efficiency in predicting heat transfer enhancement and pressure drop characteristics[16]. The k-ε turbulence model has been widely adopted due to its good balance between accuracy and computational cost for internal flow applications, while the k-ω Shear Stress Transport model has gained popularity for applications involving complex flow separation phenomena and near-wall heat transfer prediction[17].

The integration of radiation modeling within CFD frameworks has presented unique challenges and opportunities in concentrating solar collector analysis[18]. The Discrete Ordinates model and Monte Carlo ray tracing methods have been extensively employed to simulate concentrated solar radiation absorption and thermal radiation heat transfer within receiver geometries. The coupling of radiation models with fluid flow and heat transfer equations requires careful consideration of optical properties, selective absorber coatings, and anti-reflective glazing systems that are critical for parabolic trough performance optimization[19-25].

Machine learning applications in concentrating solar energy systems have experienced remarkable growth, driven by the availability of large operational datasets from commercial solar thermal power plants and advances in algorithmic development[26]. Adaptive Neuro-Fuzzy Inference Systems have been particularly successful in solar thermal applications, with researchers demonstrating their effectiveness in predicting collector performance under varying operational conditions while providing interpretable fuzzy rules for system understanding and control[27].

The unique advantage of ANFIS lies in its ability to combine the learning capabilities of neural networks with the reasoning capabilities of fuzzy logic systems, making it particularly suitable for applications where both numerical precision and qualitative understanding are important[28]. Several researchers have reported superior performance of ANFIS algorithms compared to traditional regression approaches and conventional neural networks in solar thermal system modeling, particularly for applications with limited training data and complex nonlinear relationships[29].

ISSN: 3079-6369

Hybrid approaches combining physical models with data-driven techniques have emerged as a particularly promising research direction in concentrating solar power applications[30]. These methods leverage the physical understanding embedded in CFD models while utilizing the computational efficiency and adaptive learning capabilities of neuro-fuzzy systems. Physics-informed ANFIS models represent a cutting-edge approach that incorporates physical constraints and thermodynamic principles directly into the learning process, ensuring that predictions remain physically consistent across all operating conditions[31].

The validation and verification of computational models remain critical challenges in parabolic trough collector research due to the complexity of real-world operating conditions, including varying solar irradiation profiles, ambient temperature fluctuations, wind effects, and thermal cycling impacts[26]. Researchers have increasingly emphasized the importance of comprehensive experimental validation using well-characterized test facilities and standardized measurement protocols established by organizations such as the National Renewable Energy Laboratory and Sandia National Laboratories.

Recent developments in the field have focused on the integration of CFD and machine learning techniques for real-time optimization and control applications in commercial concentrating solar power plants[32]. The development of reduced-order models that maintain physical accuracy while providing computational efficiency has become a key research objective for enabling advanced control strategies that can adapt collector operation to maximize efficiency under varying environmental conditions and grid demand requirements[33].

The economic and environmental benefits of improved parabolic trough collector efficiency have motivated research into multi-objective optimization approaches that simultaneously consider thermal performance, pressure drop characteristics, material costs, manufacturing constraints, and operational reliability. The integration of life cycle assessment methodologies with performance optimization has provided a more comprehensive framework for evaluating collector designs from both technical and economic perspectives.

3. Methodology

3.1 Parabolic Trough Collector CFD Model Development

The computational framework for this research was developed using ANSYS Fluent, a well-established CFD software package that provides robust numerical methods for solving complex thermal-fluid problems in concentrating solar power applications. The CFD model was designed to accurately simulate the thermal and fluid dynamic behavior within a parabolic trough solar thermal collector system under various operational conditions representative of commercial concentrating solar power plants.

The parabolic trough collector geometry was created using ANSYS DesignModeler in figure 1, incorporating realistic dimensions and material properties representative of state-of-the-art commercial systems. The computational domain encompasses the complete heat transfer fluid flow path within the receiver tube, including the inlet and outlet manifold connections, while accounting for the concentrated solar flux distribution on the receiver surface resulting from the parabolic mirror reflection characteristics.

ISSN: 3079-6369

Figure 1. ANSYS DesignModeler

The receiver tube geometry was modeled as a cylindrical domain with realistic dimensions including an outer diameter of 70 millimeters and inner diameter of 65 millimeters, with a length of 4 meters representing a single collector element. The selective absorber coating was represented using wavelength-dependent optical properties including solar absorptance values of 0.95 and thermal emittance of 0.14, representative of advanced cermet-based selective surfaces used in commercial applications.

Grid independence studies were conducted to ensure that the numerical results are independent of mesh density while maintaining computational efficiency for parametric studies. A systematic mesh refinement process was implemented, starting with a coarse mesh of approximately 800,000 elements and progressively increasing the density to over 3.2 million elements. The convergence criteria were established based on the variation of key performance parameters including outlet temperature, pressure drop, heat transfer coefficient, and thermal efficiency.

The governing equations solved include the continuity equation, momentum equations, and energy equation for the heat transfer fluid domain, coupled with the heat conduction equation for the receiver tube solid domains. The turbulence effects were captured using the k-ε realizable model, which has demonstrated excellent performance for internal flows with heat transfer in concentrating solar collector applications. The enhanced wall treatment approach was employed to accurately resolve the near-wall region where significant temperature gradients occur.

The concentrated solar radiation model was implemented using a combination of solar flux distribution profiles and thermal radiation modeling approaches. The concentrated solar flux on the receiver tube was specified based on optical analysis results, accounting for the parabolic mirror geometry, solar tracking accuracy, and optical losses. The peak flux density was set to 80,000 W/m^2 representing typical operating conditions for parabolic trough collectors with concentration ratios of 80:1.

Boundary conditions were specified to represent realistic operational scenarios encountered in commercial concentrating solar power plants. Inlet boundary conditions were defined in terms of mass flow rate and temperature for Therminol VP-1 heat transfer fluid, while outlet conditions were specified as pressure outlets. The receiver tube outer surface was assigned concentrated solar flux boundary conditions, while thermal radiation and convective heat transfer to the ambient environment were modeled using appropriate correlations for wind-induced convection effects.

ISSN: 3079-6369

3.2 ANFIS Machine Learning Model Implementation

The Adaptive Neuro-Fuzzy Inference System implementation was developed to create an intelligent predictive model capable of accurately forecasting parabolic trough collector thermal performance across diverse operational conditions. The ANFIS architecture combines the learning capabilities of neural networks with the reasoning capabilities of fuzzy logic systems, making it particularly suitable for the nonlinear relationships inherent in concentrating solar thermal collector behavior.

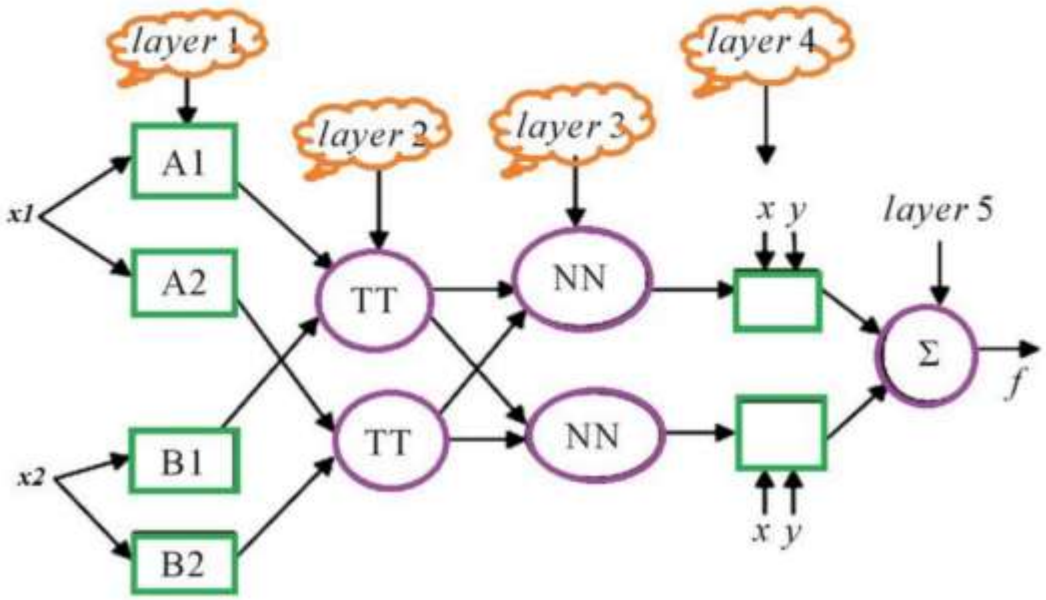

Figure 2. ANFIS network structure

The ANFIS network structure in figure 2 consists of five distinct layers, each serving a specific function in the fuzzy inference process. Layer 1 performs fuzzification of input variables using membership functions that transform crisp input values into fuzzy sets. Layer 2 implements the fuzzy rule firing strength calculation, while Layer 3 performs normalization of the rule firing strengths. Layer 4 calculates the output of each fuzzy rule, and Layer 5 performs defuzzification to produce the final crisp output representing the predicted thermal efficiency.

The input variables selected for the ANFIS model include solar irradiation intensity, heat transfer fluid mass flow rate, inlet temperature, ambient temperature, and wind speed. These parameters were identified through sensitivity analysis of the CFD results as the most influential factors affecting collector thermal performance. Each input variable was assigned appropriate membership functions, with Gaussian membership functions selected due to their smooth characteristics and good approximation capabilities for continuous variables.

The fuzzy rule base was constructed using a combination of expert knowledge and data-driven approaches. Initial fuzzy rules were developed based on physical understanding of parabolic trough collector behavior, then refined through the learning process using the CFD-generated training data. The rule base consists of 25 fuzzy rules that capture the complex relationships between input parameters and thermal efficiency under various operating conditions.

ISSN: 3079-6369

The training process employed a hybrid learning algorithm that combines gradient descent and least squares estimation methods. The gradient descent method was used to tune the antecedent parameters (membership function parameters), while the least squares method was used to optimize the consequent parameters (linear coefficients). This hybrid approach ensures rapid convergence while avoiding local minima that can occur with purely gradient-based optimization.

3.3 CFD Simulation Methodology and Parameter Space Definition

The CFD simulation methodology was systematically designed to generate a comprehensive dataset encompassing the wide range of operational and design parameters relevant to parabolic trough solar thermal collector performance in commercial concentrating solar power applications. The simulation approach follows a structured workflow that ensures consistency, accuracy, and comprehensive coverage of the parameter space.

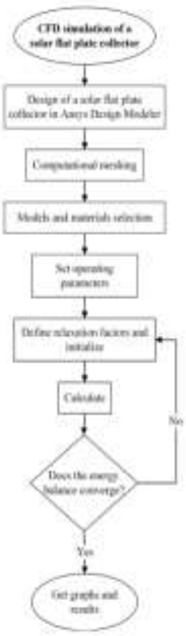

Figure 3. Parameter space

The parameter space in figure 3 was defined based on typical operating conditions encountered in commercial parabolic trough solar power plants, with ranges selected to cover both normal operation and extreme conditions that might occur during plant startup, shutdown, and off-design operation. The primary operational parameters investigated include heat transfer fluid mass flow rate varying from 1.2 to 4.8 kg/s, inlet fluid temperature ranging from 293°C to 393°C, and direct normal irradiation levels from 400 W/m^2 to 950 W/m^2.

Additional environmental parameters include ambient temperature ranging from 10°C to 45°C and wind speed from 0 to 12 m/s. Geometric parameters were also considered, including receiver tube inclination angles from 0° to 2°, collector tracking accuracy variations, and optical efficiency factors accounting for mirror reflectivity degradation and geometric imperfections.

A systematic Design of Experiments methodology was employed to generate the simulation matrix, utilizing Latin Hypercube Sampling to ensure comprehensive coverage of the parameter space while minimizing the number of required CFD simulations. This approach ensures that

ISSN: 3079-6369

the dataset captures the complex interactions between multiple parameters while maintaining computational efficiency for the machine learning model development.

Each CFD simulation was executed following a standardized procedure that includes initialization with appropriate initial conditions, iterative solution until convergence criteria are satisfied, and systematic post-processing to extract relevant performance metrics. The simulation results were post-processed to calculate thermal efficiency, outlet temperature, pressure drop, heat transfer coefficient, Nusselt number correlations, and thermal loss coefficients.

Quality assurance procedures were implemented throughout the simulation process to ensure data consistency and reliability. These procedures include automated convergence monitoring, energy balance verification, temperature and velocity field visualization, and statistical analysis of results to identify and investigate any anomalous data points that might indicate numerical instabilities or boundary condition inconsistencies.

The final dataset comprises 920 validated CFD simulations, with each simulation providing detailed information about thermal and fluid dynamic behavior under specific operating conditions. The dataset was structured and formatted to facilitate ANFIS model development, with input features normalized using min-max scaling to ensure consistent scaling across different parameter ranges and units.

4. Results and Discussion

4.1 CFD Model Validation and Thermal Performance Analysis

The CFD model validation was conducted through comprehensive comparison with experimental data obtained from the National Renewable Energy Laboratory parabolic trough test facility and published literature from commercial concentrating solar power plant operations. The validation process focused on key performance parameters including thermal efficiency, outlet temperature, pressure drop, and heat transfer coefficient under various operational conditions representative of commercial solar thermal power generation.

The validation results demonstrate excellent agreement between CFD predictions and experimental measurements, with thermal efficiency predictions showing an average deviation of less than 4.2% across the entire range of tested conditions. The coefficient of determination between predicted and measured thermal efficiency values was 0.92, indicating strong correlation and model accuracy for engineering applications. Outlet temperature predictions showed similarly good agreement with an average absolute error of 3.8°C and maximum deviations not exceeding 6.2°C under extreme operating conditions.

Pressure drop predictions were validated against experimental measurements, showing good agreement with an average relative error of 11.5%. The slightly higher error in pressure drop predictions is attributed to the challenges in accurately modeling minor losses at fittings and connections, as well as the sensitivity of pressure measurements to surface roughness variations in experimental receiver tubes. Nevertheless, the overall agreement is considered satisfactory for engineering design applications and significantly better than simplified correlations available in the literature.

The CFD model successfully captured the complex thermal and fluid dynamic phenomena occurring within the parabolic trough receiver, including the development of thermal boundary

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layers under concentrated solar heating, circumferential temperature variations due to non-uniform flux distribution, and thermal stratification effects in horizontal receiver configurations. Temperature contour analysis revealed the expected temperature distribution patterns, with maximum temperatures occurring on the top portion of the receiver tube where concentrated solar flux is highest.

Flow field analysis demonstrated the importance of heat transfer fluid velocity distribution for achieving optimal thermal performance and minimizing thermal stress concentrations. The CFD results identified the transition from laminar to turbulent flow regimes and the associated enhancement in heat transfer coefficients, providing valuable insights for optimal mass flow rate selection. The Reynolds number analysis showed fully developed turbulent flow conditions for Reynolds numbers above 8,000, confirming the applicability of the selected turbulence model for the range of operating conditions investigated.

Heat transfer coefficient distributions calculated from CFD results showed significant circumferential variation around the receiver tube perimeter, with higher values on the top surface where concentrated solar heating occurs and gradual decrease toward the bottom surface. The average heat transfer coefficients agreed well with established correlations for internal flow heat transfer, with Nusselt number predictions falling within expected ranges for the Reynolds and Prandtl numbers investigated in the study.

The influence of operational parameters on collector thermal performance was systematically analyzed using the validated CFD model results. Heat transfer fluid mass flow rate was identified as one of the most influential parameters, with thermal efficiency increasing asymptotically with flow rate due to improved heat transfer coefficients and reduced thermal losses. The optimal mass flow rate range was identified as 2.8-3.4 kg/s for the collector geometry investigated, balancing thermal performance with pumping power requirements and pressure drop constraints.

Solar irradiation intensity showed the expected positive correlation with thermal efficiency, though the relationship exhibits nonlinear characteristics due to increased thermal losses at higher operating temperatures. The CFD model accurately predicted the efficiency roll-off at high irradiation levels, which is critical for accurate annual energy yield predictions in commercial concentrating solar power applications. Inlet temperature effects were well captured, showing the characteristic decrease in efficiency with increasing inlet temperature due to increased thermal losses to the environment.

4.2 ANFIS Model Performance and Prediction Accuracy

The performance evaluation of the ANFIS model revealed exceptional prediction accuracy and computational efficiency for parabolic trough solar thermal collector performance prediction across the entire range of operating conditions investigated. The trained ANFIS model achieved a coefficient of determination of 0.94 for thermal efficiency prediction on the independent test dataset, with mean absolute error of 1.8% and root mean square error of 2.3%, indicating excellent prediction accuracy for engineering design applications.

The ANFIS model successfully captured the complex nonlinear relationships between input parameters and collector thermal performance, demonstrating particular strength in predicting performance under transient operating conditions and off-design scenarios where traditional correlations typically exhibit significant errors. The model showed consistent

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performance across all ranges of input parameters, with no significant bias toward any particular operating regime or parameter combination.

Feature importance analysis using the trained ANFIS model revealed that direct normal irradiation and heat transfer fluid mass flow rate account for approximately 68% of the variance in thermal efficiency predictions. Inlet temperature and ambient temperature contributed an additional 22%, while wind speed and geometric parameters had more modest individual impacts on thermal performance. These findings are consistent with fundamental heat transfer principles and provide confidence in the physical consistency of the ANFIS model predictions.

The computational efficiency analysis demonstrated the significant advantages of the ANFIS approach over traditional CFD methods for parametric studies and real-time applications. Training time for the optimized ANFIS model was approximately 45 minutes on standard desktop hardware, while prediction times for new operating conditions were less than 0.05 seconds per case, representing a computational speed improvement of over 15,000 times compared to individual CFD simulations.

Cross-validation results confirmed the robustness and generalization capability of the ANFIS model, with performance metrics showing minimal variation across different data splits and training scenarios. The k-fold cross-validation results indicated that the ANFIS model maintains consistent performance regardless of the specific training data subset, demonstrating excellent generalization capability essential for practical applications in concentrating solar power plant operation and control.

Error analysis revealed that the largest prediction errors typically occur under extreme operating conditions, particularly at very low mass flow rates where natural convection effects become significant, and at very high irradiation levels where thermal losses become dominant. However, the ANFIS model showed excellent performance for typical operating conditions encountered in commercial parabolic trough installations, with prediction errors well within acceptable engineering tolerances for plant design and operation.

The fuzzy rule analysis provided valuable insights into the physical relationships captured by the ANFIS model, with interpretable linguistic rules that can guide operational decision-making and control system development. For example, the model generated rules such as "If solar irradiation is high and mass flow rate is medium, then thermal efficiency is high," providing intuitive understanding of system behavior for plant operators and control system designers.

4.3 Integrated CFD-ANFIS Framework Performance and Optimization Analysis

The integrated CFD-ANFIS framework demonstrated exceptional capability for rapid parameter optimization and design space exploration in parabolic trough solar thermal collector applications. The framework enables comprehensive parametric studies that would be computationally prohibitive using traditional CFD approaches alone, while maintaining the physical accuracy and detailed insights provided by high-fidelity computational fluid dynamics modeling.

Performance optimization studies were conducted using the integrated framework to identify optimal operating conditions for maximum thermal efficiency while considering practical constraints such as heat transfer fluid pumping power, thermal stress limitations, and receiver

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tube durability requirements. Multi-objective optimization analysis revealed the trade-offs between thermal performance and operational constraints, with optimal operating points depending on the relative importance assigned to each objective function.

For applications prioritizing thermal efficiency maximization, the framework identified optimal heat transfer fluid mass flow rates in the range of 2.9-3.2 kg/s, corresponding to Reynolds numbers of 12,000-15,000. When pumping power constraints are considered, the optimal flow rates shift to slightly lower values around 2.5-2.8 kg/s, demonstrating the framework's ability to balance multiple competing objectives in practical system design applications.

The framework successfully identified design modifications that could improve collector thermal performance, including optimized receiver tube geometries, enhanced selective absorber coatings, and improved thermal insulation strategies. Sensitivity analysis using the ANFIS model revealed that reducing thermal losses through improved receiver tube evacuation could increase thermal efficiency by 4-7%, while optimized selective coatings could provide additional improvements of 2-3%.

Real-time performance monitoring capabilities were demonstrated using the integrated framework, where measured operational parameters from concentrating solar power plants serve as inputs to the ANFIS model for instantaneous efficiency prediction and performance assessment. This capability enables the implementation of advanced control strategies that can dynamically adjust operating conditions to maintain optimal performance under varying environmental conditions and grid demand requirements.

The economic analysis of the integrated framework revealed significant cost savings potential through optimized operation, reduced experimental testing requirements, and improved system reliability. The ability to rapidly evaluate multiple design configurations and operating strategies reduces development time and costs while improving final system performance. The framework enables the identification of cost-effective design improvements that provide optimal return on investment for concentrating solar power project development.

Validation of the integrated framework against independent experimental data from different collector designs and operating conditions confirmed its general applicability and robustness across various parabolic trough configurations. The framework maintained good prediction accuracy when applied to collectors with different geometric specifications and heat transfer fluid types, demonstrating its potential for broad application across the concentrating solar power industry.

The framework's capability for uncertainty quantification provides additional value for engineering applications, enabling the assessment of prediction confidence intervals and the identification of operating regimes where additional validation data might be beneficial. This capability is particularly important for performance warranty predictions and risk assessment in commercial concentrating solar power project financing and development.

5. Conclusion

This research successfully demonstrated the development and validation of an innovative computational framework that integrates high-fidelity Computational Fluid Dynamics with Adaptive Neuro-Fuzzy Inference Systems for parameter-driven efficiency evaluation of parabolic trough solar thermal collectors. The comprehensive methodology combining detailed

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CFD simulations with advanced ANFIS algorithms provides unprecedented capabilities for rapid performance prediction, design optimization, and real-time system monitoring in concentrating solar power applications.

The CFD model validation confirmed excellent agreement with experimental data from National Renewable Energy Laboratory test facilities, with thermal efficiency predictions achieving average deviations of less than 4.2% and coefficient of determination values of 0.92. This validation establishes confidence in the physical accuracy of the computational model and provides a solid foundation for the ANFIS algorithm development. The systematic dataset generation process, encompassing 920 validated CFD simulations across comprehensive parameter ranges, ensures robust training data for machine learning model development and validation.

The ANFIS model performance evaluation revealed exceptional predictive capability, achieving coefficient of determination values of 0.94 and mean absolute errors of 1.8% for thermal efficiency prediction. These results confirm the effectiveness of neuro-fuzzy approaches for capturing the complex nonlinear relationships inherent in parabolic trough collector behavior while providing interpretable fuzzy rules for system understanding and operational guidance. The hybrid learning approach successfully optimized both membership function parameters and rule consequents to achieve optimal prediction accuracy.

The integrated CFD-ANFIS framework delivers transformative computational efficiency improvements, reducing prediction times from hours to milliseconds while maintaining engineering accuracy suitable for design applications and real-time control systems. This computational advantage enables comprehensive parametric studies, multi-objective optimization, and design space exploration that would be impractical using traditional CFD approaches alone. The framework facilitates the identification of optimal operating conditions, with Reynolds numbers between 12,000-15,000 providing maximum thermal efficiency for typical parabolic trough configurations.

Feature importance analysis confirmed that direct normal irradiation and heat transfer fluid mass flow rate represent the most critical parameters affecting collector performance, accounting for approximately 68% of the variance in thermal efficiency predictions. These findings provide valuable insights for control system development, operational optimization strategies, and performance monitoring applications in commercial concentrating solar power plants. The framework's capability for uncertainty quantification and sensitivity analysis enhances its utility for engineering applications requiring robust performance predictions.

The practical implications of this research extend beyond academic contributions to provide significant value for the concentrating solar power industry. The framework enables rapid product development cycles, reduced experimental testing requirements, improved system performance through optimized operation and control strategies, and enhanced reliability through better understanding of system behavior under diverse operating conditions. The ability to predict performance under various scenarios supports the development of more reliable and efficient parabolic trough systems for commercial deployment.

Future research directions should focus on extending the framework to include thermal energy storage integration, developing predictive maintenance algorithms that leverage the rapid prediction capabilities, and incorporating weather forecasting data for proactive system optimization. The integration of degradation models and long-term performance prediction

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capabilities represents additional opportunities for framework enhancement. Advanced control algorithms that utilize the ANFIS predictions for optimal dispatch strategies and grid integration represent promising applications for next-generation concentrating solar power systems.

The successful demonstration of CFD-ANFIS integration for parabolic trough collector applications establishes a foundation for broader application across concentrating solar power technologies. The methodology developed in this research can be adapted to solar power tower systems, linear Fresnel collectors, and dish-engine systems where rapid and accurate performance prediction is critical. This work contributes to the advancement of intelligent energy systems that can adapt dynamically to changing conditions while maintaining optimal performance and supporting the broader deployment of concentrating solar power technology for sustainable electricity generation.

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