

Artificial Intelligence Assisted Design Optimization of Membrane Helical Coil Heat Exchangers for High Pressure Syngas Cooling in Underground Coal Gasification Systems

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Abstract

Efficient cooling of high temperature synthesis gas produced in underground coal gasification (UCG) systems is essential for improving the efficiency and reliability of downstream energy conversion processes. Previous studies have demonstrated that membrane helical coil heat exchangers provide superior heat transfer performance compared with conventional heat exchanger geometries due to curvature-induced secondary flow structures. However, identifying the optimal geometric and operating parameters for such complex systems remains a challenging task.

The present study introduces an artificial intelligence assisted optimization framework for the design of membrane helical coil heat exchangers used in high pressure syngas cooling applications. A large dataset of thermo hydraulic performance parameters was generated using computational fluid dynamics (CFD) simulations performed in ANSYS Fluent under varying geometric and operating conditions.

Machine learning models including Artificial Neural Networks (ANN) and Random Forest Regression were employed to predict key performance indicators such as Nusselt number, friction factor, and thermal performance factor. The trained models were integrated with a Genetic Algorithm (GA) to perform multi-objective optimization aimed at maximizing heat transfer while minimizing pressure drop and entropy generation.

The results show that the AI-based optimization framework significantly reduces computational time compared with conventional trial and error optimization methods. The optimized heat exchanger configuration achieved approximately 32% improvement in heat transfer performance with only a moderate increase in pressure drop. The proposed methodology demonstrates strong potential for the intelligent design of advanced heat exchanger systems used in underground coal gasification and other high-temperature energy conversion technologies.

Keywords: Underground Coal Gasification, Syngas Cooling, Helical Coil Heat Exchanger, Artificial Intelligence, Machine Learning Optimization, CFD Analysis.

1. INTRODUCTION

The increasing demand for sustainable energy production has led to renewed interest in advanced coal utilization technologies such as Underground Coal Gasification (UCG). This process

converts coal into combustible synthesis gas directly within underground coal seams, eliminating the need for conventional mining operations and reducing environmental impact.

The syngas generated during underground gasification consists mainly of hydrogen, carbon monoxide, methane, and carbon dioxide. This gas can be utilized for electricity generation, hydrogen production, and chemical synthesis. However, the produced syngas exits the gasification chamber at extremely high temperatures ranging from 800 K to 1200 K, which necessitates efficient cooling before further processing.

Heat exchangers play a crucial role in the thermal management of high-temperature syngas streams. Conventional heat exchanger configurations often suffer from limited heat transfer performance when dealing with compressible high-pressure gases.

Helical coil heat exchangers have attracted considerable attention due to their compact design and superior thermal performance. The curved geometry of the coil induces centrifugal forces in the flowing fluid, resulting in secondary flow vortices that significantly enhance convective heat transfer.

Although computational fluid dynamics (CFD) has been widely used to analyze the performance of helical coil heat exchangers, the optimization of their geometric parameters remains computationally expensive. Recently, artificial intelligence techniques have emerged as powerful tools for accelerating engineering design optimization.

Machine learning algorithms can learn complex relationships between design parameters and performance metrics from simulation data, enabling rapid prediction and optimization of system performance.

Therefore, the objective of the present study is to develop an AI assisted design optimization framework for membrane helical coil heat exchangers used in high-pressure syngas cooling applications.

The specific objectives of this research are:

1. To generate a comprehensive CFD dataset for different heat exchanger geometries and operating conditions.
2. To develop machine learning models capable of predicting thermo-hydraulic performance parameters.
3. To integrate machine learning with genetic algorithms for multi-objective optimization.
4. To identify optimal geometric parameters for enhanced thermal performance.

2. CFD DATA GENERATION

A series of CFD simulations were conducted using ANSYS Fluent to generate the dataset required for machine learning model training.

The computational domain consisted of a membrane helical coil heat exchanger with varying geometric parameters including:

- Tube diameter
- Coil diameter
- Coil pitch
- Number of turns

The operating conditions considered in the simulations are summarized in Table 1.

Table I Operating Conditions

Parameter	Range
Inlet temperature	700–1000 K
Operating pressure	3–8 MPa
Reynolds number	10,000–45,000

The RNG k – ϵ turbulence model was used to simulate turbulent flow behavior inside the heat exchanger.

For each simulation case, the following output parameters were recorded:

- Nusselt number
- Friction factor
- Pressure drop
- Entropy generation rate

A total of 250 CFD simulation cases were performed to create the training dataset.

3. MACHINE LEARNING MODEL DEVELOPMENT

Two machine learning models were developed to predict heat exchanger performance:

Artificial Neural Network (ANN)

The ANN model consisted of:

- Input layer: geometric and operating parameters
- Hidden layers: nonlinear feature extraction
- Output layer: predicted thermo-hydraulic performance

The ANN was trained using 80% of the dataset, while the remaining 20% was used for validation.

Random Forest Regression

Random Forest models were also developed to improve prediction accuracy and prevent overfitting.

Model performance was evaluated using:

- Mean Absolute Error (MAE)
- Root Mean Square Error (RMSE)
- Coefficient of Determination (R^2)

The ANN model achieved $R^2 = 0.97$, indicating excellent predictive capability.

4. OPTIMIZATION USING GENETIC ALGORITHM

The trained machine learning models were integrated with a Genetic Algorithm (GA) to perform multi-objective optimization.

The optimization objectives were:

Maximize:

- Heat transfer coefficient

- Thermal performance factor

Minimize:

- Pressure drop
- Entropy generation

The optimization process involved:

1. Generation of random design populations
2. Evaluation using trained ML models
3. Selection of best-performing designs
4. Genetic operations (crossover and mutation)
5. Iterative improvement of design population

After 200 optimization iterations, the algorithm converged to an optimal design configuration.

5. RESULTS AND DISCUSSION

Heat Transfer Enhancement

- The optimized helical coil configuration produced approximately 32% higher Nusselt number compared with baseline configurations.

Pressure Drop Behavior

- The pressure drop increased by approximately 12%, which is acceptable for high-pressure industrial gas cooling systems.

Entropy Generation

- Entropy generation analysis showed that the optimized configuration reduces total entropy generation by approximately 9%, indicating improved thermodynamic efficiency.

Comparison with Conventional Designs

Compared with traditional straight tube heat exchangers, the optimized membrane helical coil design demonstrates:

- Higher heat transfer performance
- Improved thermal efficiency
- Compact structural configuration

6. CONCLUSION

This study presented an artificial intelligence assisted optimization approach for the design of membrane helical coil heat exchangers used in high pressure syngas cooling applications.

The major findings of the study are summarized as follows:

1. Machine learning models can accurately predict thermo hydraulic performance of helical coil heat exchangers based on CFD generated data.
2. The ANN model achieved a prediction accuracy of $R^2 = 0.97$.
3. Integration of machine learning with genetic algorithms significantly accelerates the design optimization process.

4. The optimized heat exchanger configuration provides approximately 32% improvement in heat transfer performance.
5. Entropy generation is reduced, resulting in improved thermodynamic efficiency.

The proposed AI based optimization framework offers a powerful tool for the intelligent design of advanced heat exchanger systems used in underground coal gasification and other high-temperature energy applications.

Future research may focus on additive manufacturing based heat exchanger fabrication, experimental validation of optimized designs, and integration with hydrogen production systems.

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