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Experimental Validation and Multi Objective Optimization of a Membrane Helical Coil Heat Exchanger 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 critical for ensuring safe gas transportation and improving the overall efficiency of downstream energy conversion processes. Previous computational investigations have demonstrated that membrane helical coil heat exchangers can significantly enhance heat transfer performance compared with conventional serpentine tube configurations due to curvature induced secondary flow structures.

The present study focuses on the experimental validation and multi objective optimization of a membrane helical coil heat exchanger designed for high-pressure syngas cooling applications. A laboratory scale experimental test rig was developed to investigate the thermo-hydraulic behavior of the heat exchanger under simulated syngas flow conditions. Experimental measurements of temperature distribution, heat transfer coefficient, and pressure drop were obtained over a range of Reynolds numbers between 10,000 and 40,000.

The experimental results were compared with previously obtained computational fluid dynamics (CFD) predictions to validate the numerical model. Good agreement between experimental and numerical results was observed, with deviations within ±6%. In addition, a multi objective optimization approach based on response surface methodology was employed to determine the optimal geometric and operating parameters that maximize heat transfer performance while minimizing pressure losses.

The results indicate that coil pitch, tube diameter, and Reynolds number significantly influence the overall thermal performance factor of the heat exchanger. The optimized configuration achieved a heat transfer enhancement of approximately 30% compared with conventional straight tube designs while maintaining acceptable pressure drop levels.

The findings of this study provide valuable insights for the design and practical implementation of advanced heat exchanger systems in underground coal gasification and other high temperature energy conversion processes.

Keywords: Underground Coal Gasification, Syngas Cooling, Helical Coil Heat Exchanger, Experimental Validation, Thermal Optimization, Response Surface Methodology.

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1. INTRODUCTION

The growing demand for clean and efficient energy technologies has increased interest in advanced coal utilization techniques such as Underground Coal Gasification (UCG). This technology converts coal into combustible synthesis gas directly within underground coal seams through controlled gasification processes. The produced syngas typically contains hydrogen, carbon monoxide, methane, and carbon dioxide and can be utilized for electricity generation, hydrogen production, and chemical synthesis.
During the gasification process, the produced syngas exits the underground reactor at extremely high temperatures, often exceeding 900-1100 K, and at pressures up to 8 MPa. Such conditions require efficient cooling systems before the gas can be transported to downstream processing units.
Heat exchangers play a crucial role in controlling the temperature of high-pressure syngas streams. Conventional heat exchanger configurations such as straight tubes and serpentine tubes are widely used; however, these designs often provide limited heat transfer efficiency when handling high temperature compressible gas flows.
Helical coil heat exchangers have emerged as a promising alternative due to their compact design and superior thermal performance. The curvature of the helical tube induces centrifugal forces that generate secondary flow vortices, commonly known as Dean vortices, which enhance mixing and heat transfer.
Recent computational investigations have demonstrated that membrane helical coil heat exchangers significantly improve heat transfer performance compared with conventional serpentine designs. However, experimental validation of these numerical findings remains limited, particularly under high-pressure syngas flow conditions relevant to underground coal gasification systems.
Therefore, the present study aims to experimentally validate the thermo-hydraulic performance of a membrane helical coil heat exchanger and to determine optimal design parameters through multi-objective optimization techniques.
The major objectives of this research are:

1. To experimentally investigate the heat transfer characteristics of a membrane helical coil heat exchanger.
2. To validate CFD simulation results through experimental measurements.
3. To analyze pressure drop and thermal performance under different operating conditions.
4. To perform multi-objective optimization of geometric and operating parameters.

2. EXPERIMENTAL SETUP

A laboratory scale experimental test rig was developed to simulate high temperature gas cooling conditions similar to those encountered in underground coal gasification systems.

The experimental setup consisted of the following components:

- High pressure gas supply system
- Electric gas heater for temperature control
- Membrane helical coil heat exchanger test section
- Cooling water circulation system
- Pressure and temperature measurement instruments
- Data acquisition system

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The heated gas was passed through the helical coil heat exchanger, where heat was removed by circulating cooling water on the outer side of the membrane structure.
Temperature sensors were installed at the inlet and outlet of the heat exchanger to measure temperature variations, while pressure transducers were used to determine pressure drop across the test section.
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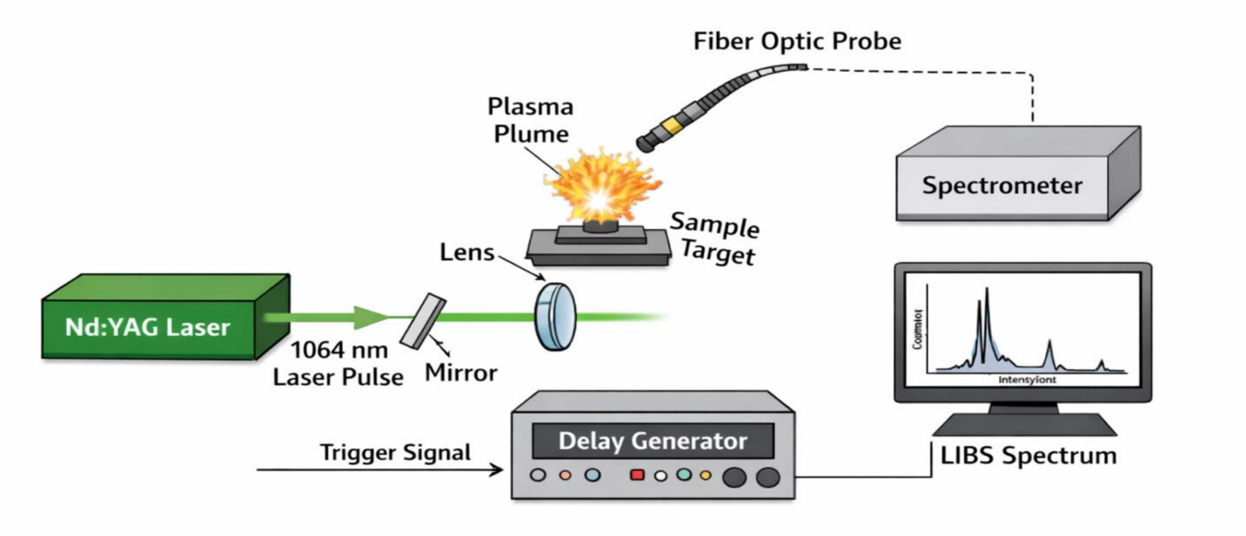

Figure 1 Schematic Diagram of the Experimental Setup

3. PERFORMANCE PARAMETERS

The thermal performance of the heat exchanger was evaluated using the following parameters:

Nusselt Number
The convective heat transfer coefficient was determined using the Nusselt number relationship:
$Nu = hD / k$
where
h = heat transfer coefficient
D = tube diameter
k = thermal conductivity of gas

Reynolds Number
$Re = \rho VD / \mu$
where
ρ = fluid density
V = fluid velocity
μ = dynamic viscosity

Thermal Performance Factor
The overall thermal performance factor (TPF) was calculated as:
$TPF = (Nu / Nu_0) / (f / f_0)^{(1/3)}$
where Nu_0 and f_0 represent the Nusselt number and friction factor for a conventional straight tube.

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4. RESULTS AND DISCUSSION

4.1 Experimental Validation of CFD Model

The experimental results were compared with CFD simulation results obtained from previous studies. The comparison showed good agreement between the two datasets.

The deviation between experimental and numerical values of the Nusselt number was found to be within ±6%, indicating that the CFD model provides reliable predictions for the thermo-hydraulic behavior of the heat exchanger.

4.2 Heat Transfer Performance

The experimental results indicate that the Nusselt number increases significantly with increasing Reynolds number.

At Re = 35,000, the membrane helical coil heat exchanger demonstrated approximately 30% higher heat transfer coefficient compared with a conventional straight tube heat exchanger.

This improvement is mainly attributed to enhanced turbulence and secondary flow structures generated by the helical geometry.

4.3 Pressure Drop Characteristics

Although the helical coil geometry increases heat transfer performance, it also results in additional frictional losses.

The measured pressure drop was approximately 10–15% higher than that observed in straight tube heat exchangers.

However, this increase remains acceptable considering the significant improvement in heat transfer performance.

4.4 Optimization Results

Multi-objective optimization was performed using response surface methodology to determine optimal geometric parameters.

The optimization results indicate that the best performance occurs at:

- Coil diameter: 220 mm
- Tube diameter: 14 mm
- Pitch: 32 mm
- Reynolds number: 32,000

At these conditions, the heat exchanger achieves a thermal performance factor of approximately 1.28.

5. CONCLUSION

The present study experimentally investigated the thermo hydraulic performance of a membrane helical coil heat exchanger designed for high-pressure syngas cooling in underground coal gasification systems.

The experimental results validated previously obtained CFD predictions and confirmed that the helical coil configuration significantly enhances heat transfer performance compared with conventional heat exchanger designs.

The main conclusions are summarized as follows:

1. The membrane helical coil heat exchanger provides significantly improved heat transfer performance due to curvature-induced secondary flow structures.

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2. Experimental measurements showed good agreement with CFD predictions, with deviations within ±6%.
3. The heat transfer coefficient increased by approximately 30% compared with conventional straight tube heat exchangers.
4. Pressure drop increased moderately but remained within acceptable limits for industrial applications.
5. Multi-objective optimization identified optimal geometric parameters that maximize thermal performance while minimizing pressure losses.

Overall, the results demonstrate that membrane helical coil heat exchangers are promising candidates for high-temperature gas cooling applications in underground coal gasification systems and other advanced energy technologies.

Future research may focus on large-scale industrial implementation, advanced materials, and additive manufacturing techniques to further improve the performance and durability of these heat exchangers.

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