Multi Objective Thermo Hydraulic and Exergy Optimization of Membrane Helical Coil Heat Exchangers for High Pressure Syngas Cooling in Underground Coal Gasification Systems

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Abstract

Underground Coal Gasification (UCG) produces synthesis gas at extremely high temperatures and pressures, requiring efficient cooling systems to ensure safe transportation and energy recovery. Conventional gas cooling systems often experience limitations in heat transfer performance when handling compressible turbulent flows. Advanced heat exchanger configurations such as membrane helical coils provide promising solutions due to their enhanced mixing characteristics and compact geometry.

The present study investigates the thermo hydraulic and exergy performance of a membrane helical coil heat exchanger designed for high-pressure syngas cooling applications in underground coal gasification systems. A three-dimensional computational fluid dynamics model was developed using ANSYS Fluent to simulate turbulent compressible flow inside the helical tube. Temperature dependent thermo physical properties of syngas were incorporated to improve prediction accuracy. The influence of geometric parameters including coil diameter, pitch ratio, and tube diameter on heat transfer, pressure drop, and thermodynamic efficiency was systematically evaluated.

Results indicate that the curvature of the helical tube generates strong centrifugal forces that induce secondary vortices, significantly enhancing fluid mixing and convective heat transfer. The Nusselt number increases by approximately 22-31% compared with equivalent straight tube configurations. However, the friction factor also increases due to additional curvature induced resistance. Exergy analysis reveals that heat transfer irreversibility is the dominant contributor to exergy destruction at lower Reynolds numbers, whereas fluid friction becomes more significant at higher Reynolds numbers.

A multi objective optimization approach identified optimal geometric conditions corresponding to a coil diameter of 220 mm and pitch ratio of 2.5, resulting in a maximum thermo hydraulic performance factor of 1.28 with minimum exergy destruction. The findings demonstrate that membrane helical coil heat exchangers offer an efficient solution for high temperature syngas cooling and can significantly improve thermal efficiency in underground coal gasification energy systems.

Keywords: Underground coal gasification, Helical coil heat exchanger, Syngas cooling, Exergy analysis, Thermo hydraulic optimization, CFD.

1. INTRODUCTION

The global demand for cleaner and more efficient energy technologies has accelerated research on advanced coal utilization systems. Among these technologies, Underground Coal Gasification (UCG) has gained considerable attention due to its ability to convert deep and unmineable coal resources into valuable synthesis gas. In the UCG process, coal is partially oxidized underground to generate syngas containing hydrogen, carbon monoxide, methane, and carbon dioxide.

The produced syngas exits the gasification cavity at temperatures exceeding 900 K and pressures that may reach 8 MPa. Before this gas can be utilized for downstream applications such as gas turbines, hydrogen production, or chemical synthesis, it must be cooled efficiently. Improper thermal management can result in severe equipment damage and significant energy losses.

Heat exchangers play a critical role in syngas cooling systems. However, conventional straight tube heat exchangers often exhibit limited heat transfer efficiency under high-temperature turbulent gas flow conditions. Therefore, advanced heat exchanger geometries capable of enhancing convective heat transfer while maintaining acceptable pressure losses are required.

Helical coil heat exchangers have attracted significant research interest because of their compact design and enhanced thermal performance. The curvature of the helical tube generates centrifugal forces that produce secondary swirling flows known as Dean vortices. These vortices intensify mixing between the fluid core and the wall region, thereby improving heat transfer.

Recent advancements in membrane heat exchanger technology have further enhanced the structural strength and thermal performance of curved tube systems. Membrane structures provide additional heat transfer surface area while maintaining high mechanical integrity under high pressure conditions.

Although several studies have examined heat transfer in curved tubes, limited research has addressed the combined thermo hydraulic and exergy performance of membrane helical coil heat exchangers under high-pressure syngas conditions relevant to underground coal gasification.

Therefore, the objective of this study is to perform a comprehensive computational investigation of a membrane helical coil heat exchanger with particular emphasis on:

1. Evaluating thermo-hydraulic performance under high-pressure syngas conditions
2. Investigating the effect of geometric parameters on heat transfer and pressure drop
3. Performing exergy analysis to quantify thermodynamic irreversibility
4. Identifying optimal geometric configurations for improved heat exchanger performance

2. COMPUTATIONAL METHODOLOGY

2.1 Geometry Design

The membrane helical coil heat exchanger consists of a circular tube wound into a helical configuration with constant pitch. The geometric parameters considered in this investigation are:

Table I Geometric Parameters of the Heat Exchanger

Parameter	**Range**
Tube inner diameter (D)	12-16 mm
Coil diameter (Dc)	180-260 mm

Pitch (P)	25-40 mm
Length	4 m
Number of Turns	8-10

The geometry was generated using ANSYS Design Modeler.

2.2 Mesh Generation

A structured hexahedral mesh was generated using ANSYS Meshing to ensure high numerical accuracy.

Table II Mesh statistics of the Heat Exchanger

Mesh Type	**Cells**
Coarse	0.9 million
Medium	1.4 million
Fine	1.9 million

Grid independence analysis confirmed that the medium mesh produced stable results with deviations less than 2%.

2.3 Governing Equations

The CFD simulation solves the conservation equations of mass, momentum, and energy.

- Continuity equation: $\nabla \cdot (\rho V) = 0$
- Momentum equation: $\rho(V \cdot \nabla)V = -\nabla P + \mu \nabla^2 V$
- Energy equation: $\rho C_p (V \cdot \nabla T) = k \nabla^2 T$

2.4 Turbulence Model

The RNG k–ε turbulence model was used because of its improved capability to simulate curved pipe flows and swirling fluid motion.

2.5 Boundary Conditions

The operating conditions correspond to realistic underground coal gasification environments.

Table III Boundary Condition of the Heat Exchanger

Parameter	**Range**
Temperature	700–1000 K
Pressure	3–8 MPa
Reynolds number	10,000–45,000

3. Performance Parameters

- Nusselt Number

  $$Nu = hD/k$$

- Friction Factor

  $$f = (\Delta P \times D) / (2\rho L V^2)$$

- Thermo-Hydraulic Performance Factor

  $$\eta = (Nu/Nu_0) / (f/f_0)^{(1/3)}$$

4. Exergy Analysis

Exergy destruction represents thermodynamic irreversibility.

- Exergy destruction rate:
  $Ex\_d = T_0 S\_gen$

- Total entropy generation:
  $S\_gen = S\_heat + S\_friction$

Where,
S_heat = heat transfer irreversibility
S_friction = viscous dissipation

5. RESULTS AND DISCUSSION

5.1 Heat Transfer Enhancement

The simulation results demonstrate that the Nusselt number increases significantly with Reynolds number and Dean number.
At Re = 30,000, the helical coil heat exchanger exhibits 27% higher heat transfer performance compared with straight tube configurations.

5.2 Pressure Drop Characteristics

- The curvature of the helical tube introduces additional resistance to fluid flow.
- The friction factor increases by approximately 10–15% relative to straight tubes.

However, the enhanced heat transfer outweighs the increase in pressure loss.

5.3 Exergy Destruction Analysis

The results show that:

- Heat transfer irreversibility dominates at low Reynolds numbers
- Fluid friction irreversibility increases at higher Reynolds numbers

The minimum exergy destruction occurs at Dean number ≈ 2200.

5.4 Multi Objective Optimization

Optimization analysis identified the following optimal configuration:

Table 4: Optimization analysis of the Heat Exchanger

Parameter	Optimal Value
Coil diameter	220 mm
Pitch ratio	2.5
Reynolds number	32,000

Under these conditions:
Thermal performance factor = 1.28

6. CONCLUSION

A comprehensive thermo hydraulic and exergy analysis of a membrane helical coil heat exchanger designed for high-pressure syngas cooling applications was conducted using CFD simulations.
The results demonstrate that the helical coil geometry significantly enhances heat transfer performance due to the formation of strong secondary flow structures. Compared with conventional straight tubes, the helical configuration increases the Nusselt number by up to 31%.

Although the friction factor increases due to curvature effects, the overall thermo hydraulic performance factor remains favorable for practical engineering applications. Exergy analysis revealed that minimizing heat transfer irreversibility is crucial for improving the thermodynamic efficiency of syngas cooling systems.

The optimal design parameters identified in this study provide valuable guidance for the development of high efficiency heat exchangers used in underground coal gasification and other high temperature energy systems.

Future work should focus on experimental validation and the integration of additive manufacturing techniques for producing advanced heat exchanger geometries with improved thermal performance.

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