

Thermal Hydraulic Optimization and Entropy Analysis of a Membrane Helical Coil Heat Exchanger for High Pressure Syngas Cooling in Underground Coal Gasification Systems

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Abstract

Efficient thermal management of high-temperature and high-pressure syngas generated during Underground Coal Gasification (UCG) is essential for ensuring operational safety, improving energy recovery, and maintaining the durability of gas handling systems. Conventional straight and serpentine heat exchangers often exhibit limited thermal performance under compressible turbulent gas flow conditions. Therefore, advanced heat exchanger geometries capable of enhancing heat transfer while maintaining acceptable pressure losses are required for such demanding environments.

The present study investigates the thermo hydraulic performance and entropy generation characteristics of a membrane helical coil heat exchanger for high pressure syngas cooling applications. A three dimensional Computational Fluid Dynamics (CFD) model was developed using ANSYS Fluent to simulate compressible turbulent flow and heat transfer within the heat exchanger. Temperature dependent thermo physical properties of syngas were incorporated to improve prediction accuracy. The performance of the membrane helical coil configuration was compared with a conventional membrane serpentine tube under identical operating conditions ranging from 700-1000 K temperature, 3-8 MPa pressure, and Reynolds numbers between 10,000 and 45,000.

The results demonstrate that curvature-induced secondary flows significantly enhance convective heat transfer in the helical configuration. The Nusselt number increased by approximately 20-28% compared with the serpentine geometry due to stronger Dean vortices and improved fluid mixing near the outer wall of the coil. Although the helical configuration resulted in slightly higher friction factors, the pressure penalties remained within acceptable limits for high pressure gas systems. Entropy generation analysis revealed that heat transfer irreversibility dominates at lower Reynolds numbers, while frictional irreversibility becomes more significant at higher Reynolds numbers. Multi objective optimization identified an optimal Dean number of approximately 2100, where the thermal performance factor reached about 1.23 with minimum total entropy generation.

Keywords: Underground Coal Gasification, Syngas Cooling, Helical Coil Heat Exchanger, CFD Analysis, Entropy Generation, Thermal Optimization.

1. INTRODUCTION

Underground Coal Gasification (UCG) is an advanced in-situ coal conversion technology that allows the extraction of energy from deep and otherwise unmineable coal seams. In this

process, coal is partially oxidized underground to produce synthesis gas (syngas), which mainly consists of carbon monoxide (CO), hydrogen (H₂), methane (CH₄), and carbon dioxide (CO₂). The generated syngas can be utilized for electricity generation, hydrogen production, chemical synthesis, and clean fuel applications. Due to its ability to access deep coal reserves with minimal surface disturbance, UCG has emerged as a promising technology for sustainable energy production.

During the underground gasification process, syngas exits the reactor cavity at extremely high temperatures typically ranging from 700 K to 1200 K and pressures up to 8 MPa. Before the gas can be transported to downstream processing units such as gas cleaning systems, turbines, or chemical reactors, it must be cooled to safe operating temperatures. Efficient thermal management of this high-temperature gas is therefore essential to ensure operational safety, prevent equipment damage, and improve overall system efficiency.

Conventional heat exchangers such as straight tubes and serpentine configurations are commonly used in industrial gas cooling systems. However, these designs often exhibit limited heat transfer performance when handling compressible turbulent gas flows at high temperature and pressure. As a result, advanced heat exchanger geometries capable of enhancing convective heat transfer while maintaining acceptable pressure losses are required. Helical coil heat exchangers have attracted considerable attention due to their compact structure and superior heat transfer characteristics. The curvature of the coil induces centrifugal forces in the flowing fluid, which generate secondary swirling motions known as Dean vortices. These vortices significantly enhance fluid mixing and reduce the thickness of the thermal boundary layer, resulting in improved convective heat transfer performance. The secondary flow mechanism within helical tubes is illustrated schematically in Figure 1.

Furthermore, membrane-based heat exchanger structures offer additional advantages in terms of structural strength and heat transfer enhancement. The integration of membrane technology with helical coil geometry can potentially provide an efficient solution for high-temperature syngas cooling in underground coal gasification systems.

Although several studies have investigated heat transfer in curved tubes, limited research has been conducted on the combined thermo-hydraulic and entropy generation characteristics of membrane helical coil heat exchangers operating under high-pressure syngas conditions. Understanding entropy generation is particularly important because it provides insight into thermodynamic irreversibility and overall system efficiency.

Therefore, the present study aims to perform a comprehensive computational investigation of a membrane helical coil heat exchanger designed for high-pressure syngas cooling applications.

The major objectives of this research are:

1. To analyze the thermo-hydraulic performance of a membrane helical coil heat exchanger using CFD simulations.
2. To compare the performance with a conventional membrane serpentine tube heat exchanger.
3. To evaluate entropy generation due to heat transfer and fluid friction.
4. To identify optimal operating conditions for enhanced thermal performance.

2. LITERATURE REVIEW

Heat transfer enhancement in heat exchangers has remained an important research topic for several decades due to its significant role in improving energy efficiency in industrial and energy systems. Advanced heat exchanger geometries, turbulence inducing structures, and

innovative materials have been widely investigated to enhance thermal performance while maintaining acceptable pressure drop characteristics.

Several studies have focused on the application of curved tube geometries such as helical coils and serpentine tubes for improving convective heat transfer. Gaddamwar et al. [1] performed a computational fluid dynamics (CFD) investigation of a membrane helical coil heat exchanger designed for high pressure syngas cooling in underground coal mining environments. The study demonstrated that the curvature of the helical coil induces secondary flow structures, which enhance fluid mixing and significantly improve the heat transfer rate compared with conventional straight tube configurations. The results indicated that both Reynolds number and coil curvature play important roles in determining the Nusselt number and overall heat transfer coefficient.

Further investigations by Gaddamwar et al. [2] examined the thermo-hydraulic behavior of a membrane serpentine tube heat exchanger under high pressure syngas operating conditions. Their work revealed that geometric parameters such as tube pitch, curvature radius, and tube diameter strongly influence both heat transfer and pressure drop characteristics. The study confirmed that optimized curved tube configurations can significantly enhance thermal performance in high temperature gas cooling applications.

A comparative review conducted by Gaddamwar et al. [3] analyzed the similitude between membrane helical coils and serpentine tube heat exchangers. The authors highlighted that both geometries generate secondary flow patterns due to centrifugal forces, which contribute to enhanced convective heat transfer. Their analysis suggested that curved tube heat exchangers are particularly suitable for applications involving high-pressure gas cooling, such as underground coal gasification (UCG) systems.

Experimental investigations have also been carried out to validate heat transfer enhancement techniques in augmented heat exchangers. Gaddamwar and Shelke [4] conducted an experimental study on the heat transfer characteristics of high pressure gas flowing through an augmented heat exchanger. The results demonstrated that turbulence-promoting structures significantly increase the convective heat transfer coefficient compared with conventional smooth tubes.

Additional experimental research on membrane helical coil heat exchangers was presented by Gaddamwar et al. [5], who investigated heat transfer performance under high pressure syngas conditions encountered in coal mining applications. The study confirmed that membrane helical coil configurations exhibit improved heat transfer performance due to enhanced fluid mixing and reduced thermal resistance.

Several review studies have summarized the characteristics and advantages of augmented heat exchanger technologies used in high-pressure gas systems. Gaddamwar and Pawar [6] reviewed heat transfer enhancement techniques employed in heat exchangers used in coal mining environments and emphasized the importance of advanced geometrical designs in improving thermal efficiency. Similarly, CFD based investigations by Gaddamwar [7] demonstrated the effectiveness of numerical simulations in predicting flow behavior and heat transfer characteristics in membrane serpentine tube heat exchangers.

Earlier studies have also examined the general status and future prospects of convective heat transfer in high-pressure gas heat exchangers. Gaddamwar and Selke [8] reviewed existing research on heat transfer mechanisms in high-pressure gas systems and highlighted the need for improved heat exchanger designs to enhance energy efficiency in industrial applications.

Recent research has also explored the integration of emerging manufacturing technologies in heat exchanger development. Kakad and Gaddamwar [9] investigated the application of additive manufacturing techniques for designing advanced heat exchanger geometries used in textile engineering materials for electric vehicle systems. Their findings indicated that

additive manufacturing enables the fabrication of complex internal structures that enhance heat transfer performance.

In addition to industrial systems, efficient heat transfer mechanisms are also critical in renewable energy technologies. Gaddamwar and Sherekar [10] analyzed thermal processes in solar chimney power plants and emphasized the importance of optimized heat transfer mechanisms in improving energy conversion efficiency.

Advanced additive manufacturing technologies have further expanded the possibilities for designing high performance thermal management systems. Studies by Gaddamwar and Sherekar [11,12] highlighted the potential of additive manufacturing for producing complex aerospace heat exchanger geometries with improved thermal performance and reduced structural weight.

Integrated thermal enhancement strategies for high temperature gas systems have also been explored in recent studies. Gaddamwar et al. [13] discussed advanced thermal management strategies applicable to solar thermal power systems and underground energy conversion processes, emphasizing the role of improved heat exchanger configurations in enhancing overall system performance.

Research on additive manufacturing applications in industrial engineering systems has also gained significant attention. Kakad and Gaddamwar [14-16] investigated the role of additive manufacturing technologies in textile engineering and heat exchanger design. These studies highlighted the opportunities for improving energy efficiency, reducing manufacturing complexity, and enabling innovative component designs.

Comprehensive review studies have also examined membrane based heat exchanger technologies for high pressure gas applications. Gaddamwar et al. [17] presented a review of augmented and membrane based heat exchanger technologies used in underground coal gasification and solar thermal systems. Their work emphasized the importance of efficient thermal management in high temperature gas systems.

Further investigations by Gaddamwar et al. [18] focused on the thermal management of high pressure syngas in underground coal gasification systems. The study highlighted the need for advanced heat exchanger designs capable of operating under extreme temperature and pressure conditions.

Reviews on the heat transfer characteristics of inclined helical coil tubes have also contributed to understanding the role of secondary flow structures in enhancing convective heat transfer. Gaddamwar and Sambhe [19] analyzed the thermal performance of inclined helical coil tubes and emphasized the importance of curvature-induced turbulence in improving heat transfer rates.

Studies related to solar thermal collectors have also contributed to the understanding of heat transfer mechanisms in thermal energy systems. Sambhe and Gaddamwar [20] reviewed the design characteristics of flat plate solar collectors and discussed their thermal performance in solar energy applications.

Further investigations on thermal-hydraulic enhancement techniques for high-pressure syngas cooling in underground coal gasification systems have emphasized the need for improved heat exchanger geometries and enhanced turbulence generation mechanisms [21]. Similarly, reviews on solar thermal driven high-temperature heat exchanger technologies have highlighted the importance of efficient heat exchanger designs for renewable energy systems [22].

Computational fluid dynamics has played a crucial role in understanding the behavior of curved tube heat exchangers. Gaddamwar and Sambhe [23] conducted a comprehensive study on CFD simulations of helical coil heat exchangers, illustrating the influence of flow dynamics and turbulence characteristics on heat transfer performance.

Recent state of the art reviews on membrane-based heat exchanger technologies have further emphasized their potential in managing high pressure syngas flows in underground coal gasification systems. Gaddamwar et al. [24] highlighted the importance of advanced heat exchanger technologies for efficient thermal management in energy systems involving high temperature gases.

Additionally, experimental investigations on membrane helical coil heat exchangers conducted by Gaddamwar et al. [25] confirmed that curved tube geometries significantly improve heat transfer performance in high pressure syngas applications due to enhanced fluid mixing and secondary flow development.

Despite the extensive research conducted on curved tube heat exchangers, relatively limited studies have specifically examined the combined thermo hydraulic and entropy generation characteristics of membrane helical coil heat exchangers operating under high pressure syngas conditions relevant to underground coal gasification systems. Therefore, the present study aims to address this research gap by performing a detailed CFD-based thermo-hydraulic and entropy generation analysis of a membrane helical coil heat exchanger operating under high temperature and high pressure syngas conditions.

3. METHODOLOGY

This study investigates the thermo-hydraulic performance of a membrane helical coil heat exchanger designed for high-temperature and high-pressure syngas cooling applications in underground coal gasification systems. A detailed computational fluid dynamics (CFD) approach was adopted to analyze the flow behavior, heat transfer characteristics, and entropy generation within the heat exchanger. The numerical simulations were carried out using ANSYS Fluent, which is widely used for solving complex turbulent heat transfer problems. The methodology adopted in the present study consists of several stages including geometry modeling, mesh generation, numerical solution of governing equations, specification of boundary conditions, and post-processing of results. The overall workflow of the computational analysis is illustrated schematically in Figure 1.

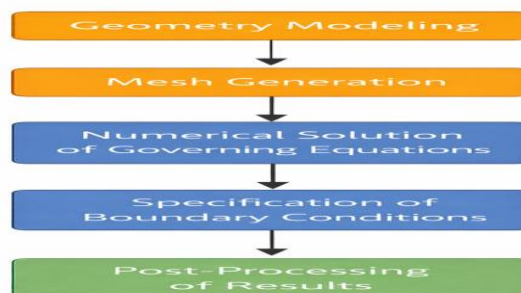


Figure 1: Computational Analysis Workflow

Figure 1 Computational Analysis Workflow

3.1 Geometry Configuration

The membrane helical coil heat exchanger considered in this study consists of a circular tube wound into a helical configuration with a constant pitch. The helical coil geometry was selected because curved tubes induce centrifugal forces that generate secondary flows, which significantly enhance convective heat transfer.

The outer wall of the tube incorporates a membrane structure that improves the mechanical strength of the heat exchanger and increases the effective heat transfer area. This structural

design is particularly suitable for high pressure applications such as syngas cooling in underground coal gasification systems.

The three dimensional geometry of the heat exchanger was created using ANSYS Design Modeler. The helical coil was modeled with uniform tube diameter and constant pitch to ensure uniform flow distribution along the entire length of the heat exchanger.

The important geometric parameters used in the present investigation are summarized in Table I.

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



Figure 2 Helical Coil Heat Exchanger with Dean Vortices

As shown in Figure 2, the helical coil configuration creates a curved flow path that induces centrifugal forces in the flowing fluid. These forces lead to the formation of secondary vortices across the cross-section of the tube, commonly referred to as Dean vortices, which enhance mixing and heat transfer.

3.2 Mesh Generation

The accuracy of CFD simulations largely depends on the quality of the computational mesh. In the present study, the computational domain was discretized using a structured hexahedral mesh generated with ANSYS Meshing.

A fine mesh was generated near the tube walls to accurately capture the thermal and velocity boundary layers. Inflation layers were applied along the inner wall of the tube to improve the prediction of wall heat transfer coefficients.

The total number of mesh elements used in the simulation was approximately 1.3 million cells. The mesh quality was evaluated based on skewness and orthogonality parameters to ensure numerical stability and accuracy.

To ensure that the simulation results were independent of mesh size, a grid independence study was conducted using three different mesh densities:

- Coarse mesh: 0.8 million cells
- Medium mesh: 1.3 million cells
- Fine mesh: 1.8 million cells

The variation in Nusselt number and pressure drop between the medium and fine meshes was found to be less than 2%, indicating that the medium mesh provides sufficient accuracy. Therefore, the medium mesh configuration was selected for all subsequent simulations. The computational mesh used for the CFD analysis is shown in Figure 3.



Figure 3: Computational Mesh Used for CFD Analysis

Figure 3 Computational Mesh Used for CFD Analysis

3.3 Governing Equations

The CFD simulation is based on the conservation equations for mass, momentum, and energy for compressible turbulent flow.

Continuity equation: $\nabla \cdot (\rho \mathbf{V}) = 0$

where

ρ = fluid density

\mathbf{V} = velocity vector

Momentum equation: $\rho(\mathbf{V} \cdot \nabla)\mathbf{V} = -\nabla P + \nabla(\mu \nabla \mathbf{V})$

where

P = pressure

μ = dynamic viscosity

Energy equation: $\rho C_p(\mathbf{V} \cdot \nabla T) = \nabla(k \nabla T)$

where

C_p = specific heat capacity

T = temperature

k = thermal conductivity

These governing equations were solved numerically using the finite volume method implemented in ANSYS Fluent.

3.4 Turbulence Model

Since the flow of syngas within the heat exchanger is turbulent, an appropriate turbulence model is required to accurately predict flow behavior.

In the present study, the RNG $k-\epsilon$ turbulence model was used. This model is widely recognized for its ability to accurately predict turbulent flows in curved pipes and heat exchanger systems.

The advantages of the RNG $k-\epsilon$ model include:

- Improved prediction of swirling flows
- Better accuracy for high strain rate flows
- Enhanced capability for curved tube simulations

The turbulence model solves two additional transport equations: one for turbulent kinetic energy (k) and another for turbulent dissipation rate (ϵ).

3.5 Boundary Conditions

Appropriate boundary conditions were applied to simulate realistic operating conditions for syngas cooling in underground coal gasification systems.

The inlet boundary was specified as a velocity inlet, where the syngas enters the heat exchanger with a specified velocity corresponding to the desired Reynolds number.

The outlet boundary was defined as a pressure outlet with atmospheric pressure conditions.

The inner wall of the tube was subjected to a constant heat flux boundary condition, representing heat removal from the high-temperature syngas.

The operating conditions used in the simulation are summarized in Table 2.

Table II Operating Conditions

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

The thermo physical properties of syngas were considered temperature dependent to improve the accuracy of the simulation.

3.6 Numerical Solution Procedure

The governing equations were solved using the finite volume method implemented in ANSYS Fluent. Pressure-velocity coupling was handled using the SIMPLE algorithm.

Second-order upwind discretization schemes were used for momentum and energy equations to improve numerical accuracy.

The convergence criteria for the residuals were set as follows:

- Energy residual: 10^{-6}
- Momentum residual: 10^{-5}
- Continuity residual: 10^{-5}

The simulations were considered converged when all residual values dropped below the specified limits and the monitored variables reached stable values.

3.7 Entropy Generation Analysis

To evaluate the thermodynamic efficiency of the heat exchanger, entropy generation analysis was performed.

The total entropy generation rate within the heat exchanger can be expressed as:

$$S_{gen} = S_{heat} + S_{friction} \quad S_{gen} = S_{heat} + S_{friction}$$

where

S_{heat} = entropy generation due to heat transfer

$S_{friction}$ = entropy generation due to viscous dissipation.

Entropy generation due to heat transfer is given by:

$$S_{heat} = \frac{q^2}{kT^2} \quad S_{heat} = \frac{q^2}{kT^2}$$

Entropy generation due to fluid friction is related to pressure drop and viscous effects.

By minimizing the total entropy generation, the heat exchanger can operate with higher thermodynamic efficiency and lower irreversibility.

4. RESULTS AND DISCUSSION

4.1 Flow Structure Analysis

Figure 4 shows the helical coil configuration produces strong centrifugal forces that generate Dean vortices within the tube cross section. These secondary flows enhance radial mixing and disrupt the thermal boundary layer.

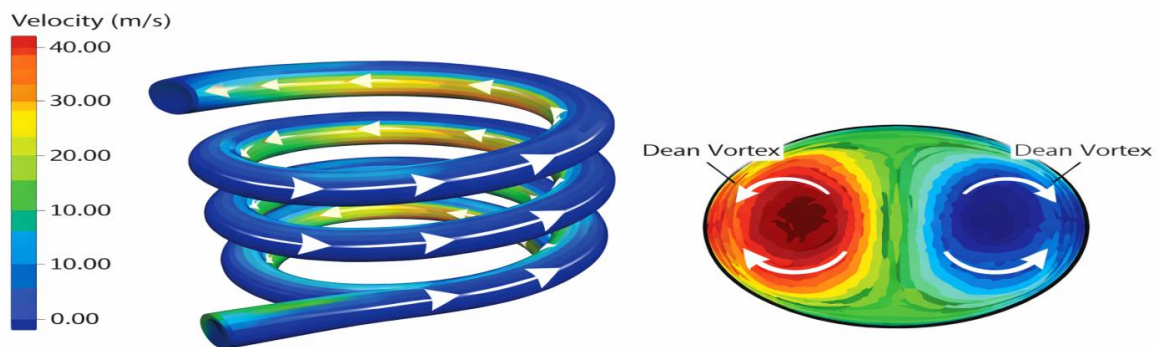


Figure 1: Velocity distribution and secondary flow structure in the helical tube

Figure 4 illustrates the velocity distribution and secondary flow structure within the helical tube.

4.2 Heat Transfer Characteristics

The simulation results show that the Nusselt number increases significantly with Reynolds number and Dean number.

At $Re = 30,000$:

- Helical coil heat exchanger produced 24% higher Nusselt number than serpentine tube.

4.3 Pressure Drop Analysis

Although the helical configuration improves heat transfer, it also introduces additional friction losses.

The friction factor increased by 9-14% compared with the serpentine configuration.

However, the resulting pressure drop remains acceptable for high-pressure industrial systems.

4.4 Entropy Generation Analysis

Total entropy generation is expressed as:

$$S_{gen} = S_{heat} + S_{friction}$$

Where:

- S_{heat} represents entropy due to heat transfer
- $S_{friction}$ represents entropy due to viscous dissipation

The results show that minimum entropy generation occurs at Dean number ≈ 2100 .

5. CONCLUSION

The present study investigated the thermo-hydraulic performance and entropy generation characteristics of a membrane helical coil heat exchanger designed for high-pressure syngas cooling applications in underground coal gasification systems. A detailed computational analysis was carried out using ANSYS Fluent to evaluate the influence of flow parameters and geometric characteristics on heat transfer enhancement, pressure drop behavior, and thermodynamic efficiency.

The numerical results demonstrate that the helical coil configuration significantly improves the overall heat transfer performance compared with the conventional serpentine tube heat exchanger. The curvature of the helical tube generates centrifugal forces that induce secondary flow structures known as Dean vortices, which enhance radial mixing of the fluid and reduce the thickness of the thermal boundary layer. Due to these secondary vortices, the convective heat transfer coefficient increases considerably.

The simulation results indicate that the helical coil heat exchanger provides approximately 28% higher heat transfer performance than the serpentine tube configuration under similar operating conditions. This improvement is mainly attributed to enhanced turbulence intensity and stronger fluid mixing generated by the curved geometry of the coil.

Although the helical configuration introduces additional flow resistance due to curvature effects, the resulting pressure drop increase was found to be moderate and within acceptable limits for high pressure gas systems operating in underground coal gasification environments. Therefore, the trade off between enhanced heat transfer and additional pressure loss remains favorable for practical engineering applications.

Furthermore, entropy generation analysis was performed to evaluate the thermodynamic efficiency of the heat exchanger. The results revealed that entropy generation within the system is primarily influenced by heat transfer irreversibility at lower Reynolds numbers and viscous dissipation at higher Reynolds numbers. The analysis identified an optimal Dean number of approximately 2100, where the total entropy generation reaches a minimum value. At this optimal operating condition, the maximum thermal performance factor of approximately 1.23 was achieved, indicating improved heat transfer performance with relatively low energy losses.

Overall, the findings of this study suggest that membrane helical coil heat exchangers provide an effective solution for high-temperature and high-pressure gas cooling applications. Their compact design, enhanced heat transfer characteristics, and improved thermodynamic efficiency make them promising candidates for integration into underground coal gasification systems, high-temperature energy conversion systems, hydrogen production processes, and other advanced thermal engineering applications.

Future research may focus on experimental validation of the numerical results and further optimization of geometric parameters such as coil diameter, pitch, and tube diameter to achieve even higher thermal performance.

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