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Exergy and Sustainability Assessment 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) is an advanced technology that converts deep coal reserves into synthesis gas for power generation and chemical production. The produced syngas exits the gasification cavity at extremely high temperatures and pressures, requiring efficient cooling before further processing. Conventional heat exchanger designs often experience significant thermodynamic inefficiencies under such severe operating conditions. Therefore, advanced heat exchanger configurations capable of improving energy efficiency and reducing thermodynamic irreversibility are required.

The present study investigates the exergy performance and sustainability characteristics of a membrane helical coil heat exchanger designed for high-pressure syngas cooling in underground coal gasification systems. A three-dimensional Computational Fluid Dynamics (CFD) model was developed using ANSYS Fluent to simulate turbulent compressible flow and heat transfer inside the helical tube. Temperature-dependent thermo physical properties of syngas were incorporated to improve the accuracy of numerical predictions.

The thermodynamic performance of the heat exchanger was evaluated using exergy analysis to quantify energy losses and irreversibilities occurring during heat transfer. The effects of Reynolds number, coil diameter, and pitch ratio on exergy destruction and exergy efficiency were systematically analyzed. Results indicate that the helical coil configuration significantly enhances heat transfer performance due to the formation of curvature-induced secondary flows. The exergy efficiency of the system increases with Reynolds number and reaches a maximum value of approximately 72% under optimal operating conditions.

The analysis reveals that heat transfer irreversibility represents the dominant contributor to exergy destruction in the system. However, appropriate selection of geometric parameters can significantly reduce thermodynamic losses and improve overall system efficiency. The findings of this study demonstrate that membrane helical coil heat exchangers offer a promising solution for sustainable thermal management in underground coal gasification and other high-temperature industrial energy systems.

Keywords: Exergy Analysis, Syngas Cooling, Underground Coal Gasification, Helical Coil Heat Exchanger, Sustainability, Thermodynamic Efficiency.

1. INTRODUCTION

The growing demand for sustainable energy technologies has increased interest in advanced coal conversion processes capable of improving energy efficiency while minimizing environmental impacts. Underground Coal Gasification (UCG) has emerged as a promising

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technology for converting deep coal reserves into synthesis gas that can be used for electricity generation, hydrogen production, and chemical synthesis.

In underground coal gasification systems, coal is converted into syngas through controlled gasification reactions occurring underground. The produced gas typically consists of carbon monoxide, hydrogen, methane, and carbon dioxide. Due to the high temperatures generated during the gasification process, the syngas exits the underground cavity at temperatures often exceeding 900 K and pressures up to 8 MPa.

Before the gas can be transported to downstream processing units, it must be cooled to acceptable operating temperatures. Efficient cooling of high-temperature syngas is essential for protecting equipment, improving energy recovery, and enhancing overall system efficiency.

Heat exchangers are widely used for syngas cooling in industrial energy systems. However, conventional heat exchanger designs often exhibit limited performance when operating under high-temperature turbulent gas flows. Therefore, advanced heat exchanger configurations capable of improving heat transfer performance while maintaining acceptable pressure losses are required.

Helical coil heat exchangers have attracted significant attention because their curved geometry induces centrifugal forces that generate secondary flow structures known as Dean Vortices. These vortices enhance mixing within the fluid and significantly improve convective heat transfer performance.

Although previous studies have investigated heat transfer enhancement in helical coil heat exchangers, limited research has focused on their thermodynamic efficiency using exergy analysis under high-pressure syngas conditions relevant to underground coal gasification systems.

Exergy analysis provides a powerful thermodynamic framework for evaluating energy system performance by quantifying the quality of energy and identifying sources of irreversibility. By analyzing exergy destruction within the heat exchanger, it is possible to identify design improvements that can enhance system efficiency and sustainability.

Therefore, the present study aims to perform a comprehensive exergy and sustainability assessment of a membrane helical coil heat exchanger used for high-pressure syngas cooling applications.

The objectives of this research are:

- To analyze heat transfer and flow characteristics of the helical coil heat exchanger using CFD simulations
- To evaluate thermodynamic performance using exergy analysis
- To identify sources of irreversibility in the syngas cooling process
- To determine optimal operating conditions for improved system efficiency

2. COMPUTATIONAL METHODOLOGY

2.1 Geometry Configuration

The heat exchanger considered in this study consists of a membrane helical coil tube designed to withstand high-pressure gas flow conditions.

The geometric parameters used in the investigation are summarized in Table 1.

Table 1 Geometric Parameters of the Heat Exchanger

Parameter	Range
Tube diameter	12–16 mm
Coil diameter	180–260 mm
Pitch	25–40 mm

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Number of turns	8–10
Length	4 m

2.2 Governing Equations

The CFD simulations are based on 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: $\rho C_p (V \cdot \nabla T) = k \nabla^2 T$

2.3 Turbulence Model

The RNG k–ε turbulence model was used to simulate turbulent flow inside the helical tube. This model provides improved prediction accuracy for swirling and curved pipe flows.

2.4 Boundary Conditions

Table 2 Boundary Conditions of the Heat Exchanger

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

The operating conditions correspond to typical underground coal gasification environments.

3. EXERGY ANALYSIS

Exergy analysis was used to evaluate thermodynamic losses occurring in the heat exchanger. The exergy destruction rate can be expressed as:

$Ex_d = T_0 \times S_{gen}$

Where:

T_0 = ambient temperature

S_{gen} = entropy generation rate

Total entropy generation includes contributions from heat transfer and fluid friction.

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

The exergy efficiency of the heat exchanger is defined as:

$\eta_{ex} = (Ex_{out} / Ex_{in})$

4. RESULTS AND DISCUSSION

4.1 Heat Transfer Characteristics

- The simulation results indicate that the helical coil geometry significantly enhances heat transfer performance compared with straight tube configurations.
- The Nusselt number increases with Reynolds number due to stronger turbulence intensity and enhanced mixing.

4.2 Exergy Destruction Analysis

- The exergy analysis reveals that heat transfer irreversibility represents the dominant source of thermodynamic losses within the heat exchanger.
- At lower Reynolds numbers, exergy destruction is mainly associated with temperature gradients between the fluid and tube wall.
- At higher Reynolds numbers, viscous dissipation contributes more significantly to total exergy destruction.

4.3 Exergy Efficiency

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- The exergy efficiency of the heat exchanger increases with increasing Reynolds number.
- The maximum exergy efficiency observed in the present study is approximately 72%, which occurs at Reynolds number around 35,000.

4.4 Sustainability Assessment

- Improving heat exchanger efficiency directly contributes to improved sustainability of underground coal gasification systems.
- Enhanced thermal performance reduces energy losses and improves overall process efficiency, thereby reducing fuel consumption and environmental impact.

5. CONCLUSION

This study investigated the thermodynamic performance and sustainability characteristics of a membrane helical coil heat exchanger designed for high pressure syngas cooling applications in underground coal gasification systems.

CFD simulations were conducted to analyze turbulent heat transfer and flow characteristics within the helical tube. Exergy analysis was performed to evaluate thermodynamic losses and identify sources of irreversibility.

The results demonstrate that the helical coil configuration significantly enhances heat transfer performance due to the formation of secondary flow structures. The exergy analysis indicates that heat transfer irreversibility is the dominant contributor to exergy destruction in the system.

The maximum exergy efficiency obtained in the present study was approximately 72%, indicating that the proposed heat exchanger design can significantly improve the energy efficiency of syngas cooling systems.

The findings of this research provide valuable insights for the design of high-performance heat exchangers used in underground coal gasification and other high-temperature industrial energy systems.

Future work should focus on experimental validation and the integration of advanced manufacturing techniques for fabrication of optimized heat exchanger geometries.

6. REFERENCES

1. S. S. Gaddamwar, A. N. Pawar, and P. A. Naik, "CFD analysis of membrane helical coil for optimization of high pressure and temperature of syngas in underground coal mines," International Journal of Mechanical Engineering and Technology, vol. 9, no. 11, pp. 1080–1088, 2018, https://iaeme.com/Home/article_id/IJMET_09_11_111
2. S. S. Gaddamwar, A. N. Pawar, and P. A. Naik, "Optimization of high pressure and temperature of syngas in underground coal mines using CFD analysis of membrane serpentine tube," International Journal of Mechanical and Production Engineering Research and Development, vol. 9, no. 1, pp. 365–372, 2019, https://www.tjprc.org/publishpapers/2-67-1550403574 35IJMPERDFEB201935.pdf
3. S. S. Gaddamwar, A. N. Pawar, and P. A. Naik, "Similitude of membrane helical coil with membrane serpentine tube for characteristics of high-pressure syngas: A review," AIP Conference Proceedings, vol. 1966, 020005, 2018. https://doi.org/10.1063/1.5031908
4. S. S. Gaddamwar and R. S. Shelke, "Experimental investigation of heat transfer characteristics of high pressure gas in an augmented heat exchanger," International Journal of Mechanical Engineering and Robotics Research, vol. 2, no. 4, pp. 1–8, 2013. http://www.ijmerr.com
5. S. S. Gaddamwar, A. N. Pawar, and P. A. Naik, "Investigational research of heat transfer characteristics of high-pressure syngas in coal mines using membrane helical

ISSN: 2945-4565 VOL 04, ISSUE 02, 2025

coil," International Journal of Mechanical Engineering and Technology, vol. 9, no. 1, pp. 887–894, 2018. https://iaeme.com/Home/article_id/IJMET_09_01_097

6. S. S. Gaddamwar and A. N. Pawar, "Heat transfer characteristics of high pressure gas in an augmented heat exchanger used in coal mines: A review," International Journal of Science, Engineering and Technology, vol. 2, pp. 691–696, 2013. https://ijset.in
7. S. S. Gaddamwar, "Computational fluid dynamic simulation and investigational testing of a membrane serpentine tube heat exchanger," Journal of Advanced Research in Dynamical and Control Systems, vol. 10, pp. 1–12, 2018. http://www.jardcs.org
8. S. S. Gaddamwar and R. S. Selke, "Status and perspectives of convective heat transfer characteristics of high pressure gas in heat exchanger," International Journal of Engineering Science and Technology, vol. 4, no. 4, pp. 1–10, 2012. https://www.ijest.info
9. G. S. Kakad and S. S. Gaddamwar, "Advancing heat exchanger technology in textile engineering materials for electric vehicles through additive manufacturing," International Journal of Scientific Research in Mechanical and Materials Engineering, 2024. https://ijsrmme.com
10. S. S. Gaddamwar and R. M. Sherekar, "Investigation regarding solar chimney power plants by ET approach: A literature study," International Journal of Scientific Research in Science and Technology, vol. 8, no. 2, pp. 1–8, 2021. https://doi.org/10.32628/IJSRST218397
11. S. S. Gaddamwar and R. M. Sherekar, "Additive manufacturing applications in advanced heat exchangers for the aerospace industry," International Journal of Engineering Development and Research, vol. 13, no. 3, pp. 47–51, 2025. https://www.ijedr.org
12. S. S. Gaddamwar and R. M. Sherekar, "Advanced applications of additive manufacturing in the design and fabrication of high-performance aerospace heat exchangers," International Journal of Scientific Research in Engineering and Management, vol. 9, no. 8, 2025. https://ijsrem.com
13. S. S. Gaddamwar, R. M. Sherekar, and N. P. Achmelwar, "Integrated thermal enhancement strategies for high temperature gas energy systems: Applications in solar thermal power and underground energy conversion," Journal of Computational Analysis and Applications, vol. 33, no. 8, pp. 1–15, 2024. https://doi.org/10.48047/jocaaa.2024.33.08.400
14. G. S. Kakad and S. S. Gaddamwar, "Optimizing heat exchanger design in the textile industry through additive manufacturing: An empirical study," International Journal of Scientific Research in Science, Engineering and Technology, 2023. https://doi.org/10.32628/IJSRSET
15. G. S. Kakad and S. S. Gaddamwar, "Integration in engineering: Novel applications and technological developments," International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 2023. https://doi.org/10.32628/IJSRCSEIT
16. G. S. Kakad and S. S. Gaddamwar, "Advancements in textile engineering through additive manufacturing: Opportunities and challenges," International Journal of Scientific Research in Science and Technology, 2023. https://doi.org/10.32628/IJSRST
17. S. S. Gaddamwar, R. M. Sherekar, and P. H. Bhagat, "Review of augmented and membrane based heat exchanger technologies for high pressure gas applications in underground coal gasification and solar thermal systems," NeuroQuantology, vol. 20, no. 8, pp. 11564–11568, 2022. https://doi.org/10.48047/nq.2022.20.8.nq221197

ISSN: 2945-4565 VOL 04, ISSUE 02, 2025

18. S. S. Gaddamwar, R. M. Sherekar, and N. P. Achmelwar, "Thermal management of high pressure syngas in underground coal gasification: A review of augmented and membrane based heat exchanger technologies," NeuroQuantology, vol. 20, no. 7, pp. 2765–2769, 2022.
https://doi.org/10.48047/nq.2022.20.7.NQ33354
19. S. S. Gaddamwar and R. U. Sambhe, "Heat transfer characteristics of inclined helical coil tube by forced and free convection: A review," International Journal of Scientific Research in Science, Engineering and Technology, vol. 7, no. 2, 2020.
https://doi.org/10.32628/IJSRSET207257
20. R. U. Sambhe and S. S. Gaddamwar, "Approximate representation and exposition of ISI flat plate collector including revised flat plate collector: A review," International Journal of Scientific Research in Science, Engineering and Technology, vol. 7, no. 2, 2020.
https://doi.org/10.32628/IJSRSET207275
21. S. S. Gaddamwar, R. M. Sherekar, and N. P. Achmelwar, "An innovative review on thermal hydraulic enhancement techniques for high pressure syngas cooling in underground coal gasification systems," International Journal on Recent and Innovation Trends in Computing and Communication, vol. 11, no. 10. https://ijritcc.org
22. S. S. Gaddamwar, R. M. Sherekar, and P. H. Bhagat, "Solar thermal driven high temperature heat exchanger technologies: A review with insights from high pressure gas cooling applications," International Journal on Recent and Innovation Trends in Computing and Communication, vol. 11, no. 11. https://ijritcc.org
23. S. S. Gaddamwar and R. U. Sambhe, "Computational fluid dynamics knowledge regarding a coil helical energy exchanger utilizing fluid as a coolant: A treatise," International Journal of Interdisciplinary Innovative Research & Development, vol. 5, Special Issue 1, 2020.
http://ijiird.com
24. S. S. Gaddamwar, R. M. Sherekar, and P. H. Bhagat, "A detailed state of the art review on membrane based heat exchanger technologies for high pressure syngas management in underground coal gasification," International Journal of Intelligent Systems and Applications in Engineering, vol. 12, no. 1s, pp. 852–857, 2024. https://ijisae.org
25. Gaddamwar, S.S., Pawar, A.N. and Naik, P.A., 2018. Investigational research of heat transfer characteristics of high pressure syngas in coal mines using membrane helical coil. International Journal of Mechanical Engineering and Technology, 9(1), pp.245-254.http://iaeme.com/Home/article_id/IJMET_09_01_097