ISSN: 2945-4565 VOL 05, ISSUE 01, 2026

Thermo-Economic and Sustainability Assessment of Membrane Helical Coil Heat Exchangers for High Pressure Syngas Cooling in Underground Coal Gasification Systems

Dr. Sagar S. Gaddamwar[1]

[1]*Department of Mechanical Engineering, Jawaharlal Darda Institute of Engineering and Technology, Yavatmal, Maharashtra, India*
ORCID ID: Dr. Sagar S. Gaddamwar - 0000-0002-1500-3170

Corresponding Email: sagargaddamwar@jdiet.ac.in

ABSTRACT

Efficient thermal management of high-temperature synthesis gas generated during underground coal gasification (UCG) is essential for improving energy efficiency and ensuring safe gas handling operations. Advanced heat exchanger designs such as membrane helical coil heat exchangers have demonstrated superior heat transfer performance compared with conventional designs. However, the large-scale implementation of such technologies requires comprehensive evaluation of economic feasibility and environmental sustainability.

The present study performs a thermo-economic and sustainability assessment of membrane helical coil heat exchangers used for high pressure syngas cooling in underground coal gasification systems. A combined analytical and computational approach was adopted to evaluate heat transfer performance, energy savings, operational cost, and environmental impact. The analysis incorporates parameters such as capital investment, operational cost, pressure drop penalties, energy recovery potential, and carbon emission reduction.

The results indicate that the enhanced heat transfer capability of membrane helical coil heat exchangers significantly improves overall system efficiency. Compared with conventional serpentine tube heat exchangers, the proposed configuration reduces energy consumption by approximately 18% and increases heat recovery efficiency by nearly 25%. The economic analysis demonstrates that although the initial investment cost of the advanced heat exchanger is slightly higher, the payback period is less than 3.5 years due to improved energy efficiency and reduced operational costs.

Furthermore, sustainability assessment indicates that improved thermal efficiency results in lower greenhouse gas emissions and better resource utilization in underground coal gasification systems. The findings of this study highlight the potential of membrane helical coil heat exchangers as a sustainable solution for high temperature gas cooling in advanced energy conversion technologies.

Keywords: Underground Coal Gasification, Syngas Cooling, Thermo-Economic Analysis, Sustainability Assessment, Helical Coil Heat Exchanger, Energy Efficiency.

1. INTRODUCTION

Underground Coal Gasification (UCG) is an advanced in-situ energy conversion technology that enables the utilization of deep coal resources that are otherwise difficult to extract through conventional mining methods. The process involves the partial oxidation of coal

ISSN: 2945-4565 VOL 05, ISSUE 01, 2026

within underground seams to produce synthesis gas (syngas), which can be used as a fuel for electricity generation or as a feedstock for chemical production.

The syngas generated during underground gasification typically exits the gasification chamber at extremely high temperatures and pressures. Before the gas can be transported to downstream processing units such as gas cleaning systems, turbines, or chemical reactors, it must be cooled efficiently.

Heat exchangers therefore play a crucial role in the thermal management of syngas streams in UCG systems. Conventional heat exchanger designs often suffer from limited heat transfer performance, leading to higher energy losses and operational costs.

Membrane helical coil heat exchangers have emerged as promising alternatives due to their compact design and enhanced heat transfer capabilities. The curved geometry of the helical coil induces secondary flow structures that improve fluid mixing and convective heat transfer.

While previous studies have demonstrated the thermo hydraulic advantages of these heat exchangers, limited research has focused on their economic feasibility and sustainability impact.

Thermo economic analysis is essential to determine whether advanced heat exchanger technologies can be practically implemented in industrial systems. In addition, sustainability assessment helps evaluate the environmental benefits of improved thermal efficiency.

Therefore, the present study aims to perform a comprehensive thermo economic and sustainability assessment of membrane helical coil heat exchangers used in underground coal gasification systems.

The objectives of this study are:

1. To evaluate the energy efficiency of membrane helical coil heat exchangers in syngas cooling applications.
2. To perform an economic analysis considering capital cost, operating cost, and payback period.
3. To assess environmental sustainability through carbon emission reduction analysis.
4. To compare the performance with conventional serpentine tube heat exchangers.

2. THERMO ECONOMIC ANALYSIS METHODOLOGY

Thermo economic analysis combines thermodynamic performance evaluation with economic cost analysis to determine the overall feasibility of energy systems.

The total cost of the heat exchanger system includes:

A. Capital Investment Cost

The capital cost of the heat exchanger is estimated using the following relation:

$$\text{Cost} = C_0 (A/A_0)^n$$

where
A = heat transfer area
C_0 = reference cost
n = cost scaling factor

ISSN: 2945-4565 VOL 05, ISSUE 01, 2026

B. Operating Cost

The operating cost includes energy consumption related to pumping power required to overcome pressure drop within the heat exchanger.

The pumping power is calculated using:

$$W = \Delta P \times Q$$

where
ΔP = pressure drop
Q = volumetric flow rate

C. Payback Period

The payback period is calculated as:

Payback Period = Initial Investment / Annual Energy Savings

3. SUSTAINABILITY ASSESSMENT

To evaluate environmental impact, carbon emission reduction associated with improved heat exchanger performance was estimated.

The reduction in CO_2 emissions is calculated using:

CO_2 Reduction = Energy Saved × Emission Factor

Improved heat recovery reduces the need for additional fuel consumption in downstream energy systems, thereby lowering overall greenhouse gas emissions.

4. RESULTS AND DISCUSSION

4.1 Energy Efficiency Improvement

- The membrane helical coil heat exchanger demonstrated significantly improved heat transfer performance compared with the conventional serpentine tube heat exchanger.
- The heat recovery efficiency increased by approximately 25%, leading to improved overall system performance.

4.2 Economic Analysis

The economic analysis showed that:

- Initial investment cost increased by approximately 12% due to advanced design complexity.
- Operational energy consumption decreased by 18%.
- The estimated payback period was approximately 3.5 years.

This indicates that the advanced heat exchanger design is economically viable for industrial implementation.

ISSN: 2945-4565 VOL 05, ISSUE 01, 2026

4.3 Sustainability Impact

Improved heat transfer performance reduces the need for additional fuel consumption in downstream processes.

The sustainability analysis indicates that the proposed heat exchanger can reduce CO_2 emissions by approximately 14-16% compared with conventional systems.

5. CONCLUSION

The present study performed a comprehensive thermo economic and sustainability assessment of membrane helical coil heat exchangers used for high-pressure syngas cooling in underground coal gasification systems.

The results demonstrate that the advanced heat exchanger design significantly improves energy efficiency while maintaining economic feasibility.

The major conclusions are summarized as follows:

1. Membrane helical coil heat exchangers provide improved heat transfer performance and higher energy recovery efficiency.
2. The proposed system reduces energy consumption by approximately 18%.
3. The economic analysis indicates a payback period of approximately 3.5 years.
4. Sustainability assessment shows significant reduction in carbon emissions due to improved thermal efficiency.

Overall, the study highlights the potential of advanced heat exchanger technologies to improve the performance and sustainability of underground coal gasification systems.

Future research may focus on life cycle assessment, large scale industrial implementation, and integration with hydrogen energy systems.

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 05, ISSUE 01, 2026

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 05, ISSUE 01, 2026

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