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Additive Manufacturing Based Design and Thermal Performance Evaluation of Advanced Membrane Helical Coil Heat Exchangers for High Temperature Syngas Cooling

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ABSTRACT

Efficient thermal management of high-temperature synthesis gas produced during underground coal gasification (UCG) remains a major challenge in advanced energy systems. Conventional heat exchanger manufacturing techniques impose limitations on geometric complexity, which restricts the potential for heat transfer enhancement. Recent advancements in additive manufacturing (AM) technologies offer new possibilities for fabricating complex heat exchanger geometries with improved thermal performance.

The present study investigates the design and thermal performance of additively manufactured membrane helical coil heat exchangers for high temperature syngas cooling applications. A novel heat exchanger configuration incorporating internal micro-fins and optimized coil curvature was developed using computer-aided design and manufactured through Selective Laser Melting (SLM) technology.

Computational fluid dynamics (CFD) simulations were performed using ANSYS Fluent to analyze heat transfer characteristics, pressure drop behavior, and entropy generation under high-temperature syngas flow conditions. The performance of the additively manufactured heat exchanger was compared with a conventionally manufactured membrane helical coil heat exchanger.

The results indicate that the integration of internal micro-fins and optimized coil geometry significantly enhances heat transfer performance. The Nusselt number increased by approximately 35%, while the overall thermal performance factor improved by nearly 1.35 compared with conventional designs. Although the advanced geometry resulted in a slight increase in pressure drop, the overall thermo hydraulic performance remained favorable.

The findings demonstrate that additive manufacturing enables the development of highly efficient heat exchanger structures capable of operating under extreme temperature and pressure conditions. The proposed design offers promising applications in underground coal gasification, hydrogen production systems, and high-temperature energy conversion technologies.

Keywords: Underground Coal Gasification, Syngas Cooling, Additive Manufacturing, Helical Coil Heat Exchanger, Thermal Enhancement, CFD Analysis.

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1. INTRODUCTION

Underground Coal Gasification (UCG) is a promising technology for extracting energy from deep coal reserves that are difficult or uneconomical to mine using conventional methods. In this process, coal is converted into synthesis gas (syngas) directly within underground coal seams through controlled gasification reactions.

The produced syngas typically contains hydrogen, carbon monoxide, methane, and carbon dioxide. This gas can be utilized for power generation, hydrogen production, and chemical synthesis. However, the gas exits the underground reactor at extremely high temperatures, typically between 800 K and 1200 K, which necessitates efficient cooling before it can be transported to downstream processing units.

Heat exchangers are therefore critical components in underground coal gasification systems. Conventional heat exchanger designs such as straight tubes, serpentine tubes, and shell-and-tube configurations are widely used in industrial gas cooling systems. However, these designs often suffer from limited heat transfer performance when handling high-temperature compressible gases.

Helical coil heat exchangers have attracted considerable attention due to their compact structure and superior heat transfer characteristics. The curvature of the helical tube generates centrifugal forces that induce secondary flow structures known as Dean vortices, which significantly enhance convective heat transfer.

Despite these advantages, conventional manufacturing techniques restrict the complexity of heat exchanger geometries. Recently, additive manufacturing (AM) technologies have emerged as powerful tools for fabricating complex thermal components that were previously impossible to manufacture using traditional techniques.

Additive manufacturing allows the integration of internal fins, lattice structures, and optimized flow channels within heat exchanger tubes, leading to significant improvements in heat transfer performance.

Therefore, the present study aims to investigate the design and thermal performance of an additively manufactured membrane helical coil heat exchanger intended for high-temperature syngas cooling applications.

The main objectives of this research are:

1. To develop an advanced membrane helical coil heat exchanger design using additive manufacturing techniques.
2. To evaluate thermo-hydraulic performance using CFD simulations.
3. To compare the performance of additively manufactured and conventional heat exchanger designs.
4. To analyze entropy generation and thermodynamic efficiency of the proposed system.

2. HEAT EXCHANGER DESIGN USING ADDITIVE MANUFACTURING

Additive manufacturing enables the fabrication of complex heat exchanger geometries that significantly enhance heat transfer performance.

In the present study, the proposed heat exchanger design incorporates the following features:

- Helical coil geometry
- Internal micro-fins for turbulence enhancement
- Membrane support structure for mechanical strength
- Optimized coil pitch and diameter

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The heat exchanger geometry was developed using SolidWorks CAD software, and the design was prepared for additive manufacturing using Selective Laser Melting (SLM).
SLM technology builds metallic components layer-by-layer using a high-power laser to melt metal powder, enabling the fabrication of complex internal structures.
The material selected for manufacturing the heat exchanger was Inconel 718, which provides excellent thermal stability and corrosion resistance under high-temperature conditions.

3. CFD SIMULATION METHODOLOGY

To evaluate the thermal performance of the proposed design, computational fluid dynamics simulations were performed using ANSYS Fluent.
The governing equations for mass, momentum, and energy conservation were solved using the finite volume method.

Turbulence Model
The RNG k-ε turbulence model was used due to its capability to accurately predict turbulent flow behavior in curved tubes and heat exchanger systems.

Boundary Conditions
The following operating conditions were considered in the simulations:

Table I Boundary Conditions

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

The outer surface of the heat exchanger tube was subjected to a constant heat flux boundary condition representing the cooling process.

4. RESULTS AND DISCUSSION

4.1 Flow Structure Analysis
The CFD results reveal strong secondary flow structures within the helical tube due to curvature-induced centrifugal forces.
The presence of internal micro-fins further enhances turbulence intensity, leading to improved radial mixing of the fluid.

4.2 Heat Transfer Enhancement
The Nusselt number increased significantly with Reynolds number for the additively manufactured heat exchanger.
At Re = 35,000, the proposed design demonstrated approximately 35% higher heat transfer coefficient compared with conventional helical coil heat exchangers.

4.3 Pressure Drop Characteristics
The addition of internal micro-fins increases frictional resistance within the tube.
However, the resulting pressure drop increase was limited to approximately 15%, which is acceptable for high-pressure industrial gas cooling applications.

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4.4 Entropy Generation Analysis

Entropy generation analysis was performed to evaluate thermodynamic efficiency.
The results indicate that the optimized additively manufactured design reduces total entropy generation by approximately 10%, demonstrating improved energy efficiency.

5. CONCLUSION

The present study investigated the design and thermal performance of an additively manufactured membrane helical coil heat exchanger intended for high-temperature syngas cooling in underground coal gasification systems.
The results demonstrate that additive manufacturing enables the development of highly efficient heat exchanger geometries with significantly improved heat transfer performance.

The Major Findings Are Summarized As Follows:

1. Additive manufacturing allows the integration of complex internal structures that enhance turbulence and heat transfer.
2. The proposed heat exchanger design achieved approximately 35% improvement in heat transfer performance compared with conventional designs.
3. The pressure drop increase remained within acceptable limits for high-pressure gas systems.
4. Entropy generation analysis showed improved thermodynamic efficiency.

Overall, the proposed additively manufactured heat exchanger design offers significant potential for advanced energy systems including underground coal gasification, hydrogen production, and high-temperature thermal power generation.
Future research may focus on experimental validation of the additively manufactured heat exchanger and large-scale industrial implementation.

5. 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 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

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