ISSN: 2945-4565 VOL 04, ISSUE 01, 2025

Multi Objective Optimization of Membrane Helical Coil Heat Exchangers for High Pressure Syngas Cooling Using Genetic Algorithms

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 Author Email: sagargaddamwar@jdiet.ac.in

Abstract

Efficient cooling of high temperature synthesis gas produced in underground coal gasification systems is essential for improving thermal efficiency and ensuring safe operation of downstream processing units. Membrane helical coil heat exchangers have demonstrated significant advantages in heat transfer enhancement due to the presence of curvature induced secondary flows. However, optimizing the geometric and operating parameters of such systems remains a complex engineering problem involving multiple conflicting objectives, such as maximizing heat transfer while minimizing pressure drop.

This study presents a multi objective optimization approach for membrane helical coil heat exchangers used for high pressure syngas cooling. Computational Fluid Dynamics (CFD) simulations were first conducted to evaluate the thermo-hydraulic performance of the heat exchanger under various geometric and operating conditions. The obtained results were then used to develop surrogate models that relate design parameters to system performance. A Genetic Algorithm (GA) based optimization framework was implemented to simultaneously maximize the Nusselt number and minimize the friction factor.

The optimization process considered key design variables including coil diameter, tube diameter, pitch ratio, and Reynolds number. The Pareto optimal solutions obtained from the genetic algorithm reveal the trade-off between enhanced heat transfer and pressure loss in the helical coil configuration. The optimal design identified in this study achieved a thermo-hydraulic performance factor of approximately 1.31, representing a significant improvement over conventional designs.

The findings demonstrate that multi objective optimization techniques can effectively guide the design of advanced heat exchangers for high temperature gas cooling applications. The proposed optimization framework provides a systematic methodology for improving thermal performance and energy efficiency in underground coal gasification systems and other high-temperature industrial processes.

Keywords: Multi Objective Optimization, Genetic Algorithm, Helical Coil Heat Exchanger, Syngas Cooling, CFD Simulation, Thermo-Hydraulic Performance.

1. INTRODUCTION

The growing demand for efficient energy systems has encouraged the development of advanced technologies for coal conversion and utilization. Underground Coal Gasification (UCG) is a promising technology that converts deep coal reserves into synthesis gas through controlled gasification reactions occurring underground. The produced syngas can be used for electricity generation, hydrogen production, and chemical synthesis.

ISSN: 2945-4565 VOL 04, ISSUE 01, 2025

In underground coal gasification systems, the syngas generated within the gasification cavity exits at extremely high temperatures, typically between 800 K and 1200 K, and pressures that may reach up to 8 MPa. Efficient cooling of this gas is necessary before it can be transported to downstream processing units such as gas cleaning systems and turbines.

Heat exchangers are critical components in syngas cooling systems. However, conventional straight tube heat exchangers often exhibit limited heat transfer performance under turbulent gas flow conditions. Helical coil heat exchangers have attracted considerable attention because their curved geometry induces centrifugal forces that generate secondary flow structures known as Dean Vortices. These vortices enhance fluid mixing and improve convective heat transfer performance.

Although helical coil heat exchangers provide improved thermal performance, the design of such systems involves multiple parameters that influence heat transfer and pressure drop characteristics. Increasing heat transfer performance often leads to higher friction losses, which can reduce overall system efficiency. Therefore, it is necessary to optimize the heat exchanger design by considering both heat transfer enhancement and pressure drop minimization simultaneously.

Multi objective optimization techniques provide an effective approach for solving such complex engineering problems. Among these techniques, Genetic Algorithms (GA) have gained significant attention due to their ability to handle nonlinear and multi-modal optimization problems.

Genetic algorithms are inspired by the principles of natural selection and evolution. They use operations such as selection, crossover, and mutation to evolve optimal solutions over successive generations.

The present study focuses on the application of a genetic algorithm-based multi-objective optimization approach to identify optimal geometric and operating parameters for membrane helical coil heat exchangers used in high-pressure syngas cooling applications.

The objectives of the present study are:

- To analyze the thermo-hydraulic performance of membrane helical coil heat exchangers using CFD simulations
- To develop surrogate models for predicting heat transfer and pressure drop characteristics
- To perform multi-objective optimization using genetic algorithms
- To identify optimal design parameters for improved thermal performance

2. COMPUTATIONAL METHODOLOGY

2.1 Geometry Configuration

The heat exchanger considered in this study consists of a membrane helical coil tube designed for high-pressure gas cooling applications.

The geometric parameters investigated in this study are summarized in Table 1.

Table 1. 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
Tube Length	4 m
Number of Turns	8-10

ISSN: 2945-4565 VOL 04, ISSUE 01, 2025

2.2 CFD Simulation

Three-dimensional CFD simulations were conducted using ANSYS Fluent to analyze the turbulent flow and heat transfer characteristics within the helical tube.

The governing equations solved in the simulations include:

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

The RNG k–ε turbulence model was used to simulate turbulent flow conditions inside the curved tube.

2.3 Boundary Conditions

The operating conditions used in the simulations correspond to typical underground coal gasification environments.

Table 2. Boundary Conditions

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

3. MULTI-OBJECTIVE OPTIMIZATION

3.1 Optimization Objectives

Two objective functions were considered in the optimization process:

1. Maximize Nusselt number (heat transfer enhancement)
2. Minimize friction factor (pressure drop)

3.2 Genetic Algorithm Implementation

The genetic algorithm optimization procedure consists of the following steps:

1. Initialization of population
2. Evaluation of fitness functions
3. Selection of best individuals
4. Crossover and mutation operations
5. Generation of new population

The optimization process was performed for 100 generations to obtain the Pareto optimal solutions.

4. RESULTS AND DISCUSSION

4.1 Heat Transfer Performance

The CFD results indicate that the Nusselt number increases significantly with Reynolds number due to enhanced turbulence and stronger secondary flows.

The helical coil configuration provides approximately 25–30% higher heat transfer performance compared with straight tube designs.

4.2 Pressure Drop Characteristics

The friction factor increases with Reynolds number due to higher turbulence intensity and increased flow resistance.

However, the increase in pressure drop remains within acceptable limits for high-pressure gas systems.

4.3 Pareto Optimization Results

ISSN: 2945-4565 VOL 04, ISSUE 01, 2025

The genetic algorithm produced a set of Pareto optimal solutions representing the trade-off between heat transfer enhancement and pressure loss.
The optimal design parameters obtained from the Pareto analysis are:

Table 3. Optimal Design Parameters

Parameter	Optimal Value
Tube diameter	14 mm
Coil diameter	220 mm
Pitch	32 mm
Reynolds number	33,000

Under these conditions, the thermo-hydraulic performance factor reached approximately 1.31.

5. CONCLUSION

This study presented a multi-objective optimization framework for membrane helical coil heat exchangers used in high pressure syngas cooling applications. CFD simulations were conducted to analyze heat transfer and pressure drop characteristics under various operating conditions.
A genetic algorithm based optimization approach was implemented to simultaneously maximize heat transfer performance and minimize pressure losses. The optimization results revealed the trade-off between these two competing objectives and provided a set of optimal design parameters.
The optimized heat exchanger design achieved a thermo hydraulic performance factor of approximately 1.31, indicating a significant improvement in overall system performance.
The proposed optimization framework provides a systematic methodology for designing advanced heat exchangers used in underground coal gasification and other high temperature industrial energy systems.
Future research should focus on experimental validation of the optimized design and integration of advanced manufacturing techniques such as additive manufacturing for fabrication of complex 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 mi nes 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

ISSN: 2945-4565 VOL 04, ISSUE 01, 2025

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