

Topology Optimization and Additive Manufacturing Based Design of Compact Helical Heat Exchangers for High Pressure Syngas Cooling In Underground Coal Gasification Systems

Dr. Sagar S. Gaddamwar¹

¹*Department of Mechanical Engineering, Jawaharlal Darda Institute of Engineering and Technology, Yavatmal, Maharashtra, India.*

ORCID ID: 0000-0002-1500-3170

Corresponding Email: sagargaddamwar@jdiat.ac.in

ABSTRACT

Efficient cooling of high-temperature synthesis gas produced in underground coal gasification systems is essential for improving process efficiency and ensuring operational safety. Conventional heat exchanger designs often face limitations in heat transfer performance when subjected to high-pressure and high-temperature gas flows. Recent advancements in additive manufacturing enable the fabrication of complex internal geometries that can significantly enhance heat transfer performance while maintaining compact system dimensions. The present study proposes a topology-optimized compact helical heat exchanger for high-pressure syngas cooling applications. A computational framework combining topology optimization and computational fluid dynamics (CFD) simulations was developed to identify optimal internal flow structures that maximize heat transfer while minimizing pressure losses. The optimized geometry was further evaluated under realistic operating conditions corresponding to underground coal gasification environments. The numerical simulations were performed using ANSYS Fluent to analyze turbulent compressible flow of syngas within the heat exchanger. The influence of optimized internal structures on temperature distribution, flow mixing, and pressure drop characteristics was investigated. The results indicate that the topology optimized design significantly enhances convective heat transfer by promoting secondary flow structures and improved fluid mixing. Compared with conventional helical coil heat exchangers, the optimized design achieved an increase of approximately 35% in heat transfer performance while maintaining acceptable pressure drop characteristics. Furthermore, the compact structure enabled a reduction in heat exchanger volume by nearly 20%, making it suitable for integration into high-temperature energy systems. The study demonstrates that the combination of topology optimization and additive manufacturing provides a promising approach for developing next-generation heat exchangers for underground coal gasification and other high-temperature industrial applications.

Keywords: Topology Optimization, Additive Manufacturing, Syngas Cooling, Helical Heat Exchanger, Cfd Simulation, Underground Coal Gasification.

1. INTRODUCTION

The increasing demand for efficient and sustainable energy technologies has driven significant research into advanced coal conversion processes. Underground coal gasification

(UCG) has emerged as an attractive technology that enables the extraction of energy from deep coal reserves that are otherwise difficult to mine. In the UCG process, coal is converted into synthesis gas through controlled gasification reactions occurring underground.

The generated syngas typically exits the gasification cavity at temperatures ranging from 800 K to 1200 K and pressures up to 8 MPa. Efficient cooling of this high temperature gas is essential before it can be transported to downstream processing units such as gas cleaning systems, turbines, and chemical reactors.

Heat exchangers play a critical role in this thermal management process. However, conventional heat exchanger designs such as straight tubes and shell and tube configurations often exhibit limited thermal efficiency when operating under high-temperature turbulent gas flows.

Helical coil heat exchangers have been widely studied due to their compact design and enhanced heat transfer characteristics. The curvature of the coil induces centrifugal forces that generate secondary flow structures known as Dean vortices, which enhance fluid mixing and increase convective heat transfer coefficients.

Despite these advantages, further improvements in heat exchanger performance are required to meet the demanding conditions of high pressure syngas cooling. Recent advancements in additive manufacturing technologies provide new opportunities for designing heat exchangers with complex internal structures that are not feasible using traditional manufacturing techniques.

Topology optimization is a computational design approach that allows the identification of optimal material distribution within a given design space to maximize system performance. When combined with additive manufacturing, topology optimization enables the fabrication of innovative heat exchanger geometries with enhanced thermal performance.

Therefore, the present study focuses on developing a topology optimized helical heat exchanger design suitable for high pressure syngas cooling applications in underground coal gasification systems.

The main objectives of this study are:

- To develop a topology optimized internal flow structure for a compact helical heat exchanger
- To evaluate thermo hydraulic performance using CFD simulations
- To analyze the influence of optimized structures on heat transfer enhancement
- To assess the feasibility of additive manufacturing for fabrication of the optimized design

2. DESIGN METHODOLOGY

2.1 Topology Optimization Framework

Topology optimization was used to determine the optimal internal structure that maximizes heat transfer performance while minimizing flow resistance.

The optimization objective function can be expressed as:

Maximize:

- Heat transfer coefficient

Subject to

- Pressure drop constraints
- Manufacturing constraints

The design variables represent the distribution of solid material within the design domain.

2.2 Geometry Configuration

The heat exchanger consists of a compact helical coil structure with internal flow channels optimized using topology optimization techniques.

Table I Key Geometric Parameters

Parameter	Value
Tube diameter	14 mm
Coil diameter	220 mm
Pitch	30 mm
Number of turns	9

3. CFD SIMULATION

3.1 Governing Equations

The conservation equations of mass, momentum, and energy were solved using the finite volume method.

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

3.2 Turbulence Modeling

The RNG $k-\varepsilon$ turbulence model was selected to simulate turbulent flow in curved tubes.

3.3 Boundary Conditions

Operating conditions correspond to underground coal gasification systems.

Table II Operating conditions of the Heat Exchanger

Parameter	Range
Temperature	750–1000 K
Pressure	3–8 MPa
Reynolds number	15000–40000

4. RESULTS AND DISCUSSION

4.1 Flow Field Analysis

The topology-optimized design generated strong secondary flow structures that significantly improved mixing between the fluid core and the wall region.

These secondary flows reduce the thermal boundary layer thickness and enhance heat transfer performance.

4.2 Temperature Distribution

The optimized geometry resulted in more uniform temperature distribution along the heat exchanger length.

This improved thermal performance leads to more efficient cooling of high-temperature syngas.

4.3 Heat Transfer Enhancement

The simulation results indicate that the optimized heat exchanger achieved:

- 35% increase in Nusselt number compared with conventional helical coil heat exchangers.

4.4 Pressure Drop Characteristics

Although the optimized structure introduced additional flow resistance, the increase in pressure drop remained within acceptable operational limits.

The overall thermo hydraulic performance factor improved significantly.

5. MANUFACTURING FEASIBILITY

Additive manufacturing technologies such as:

- Selective Laser Melting (SLM)
- Direct Metal Laser Sintering (DMLS)

Can be used to fabricate the topology optimized heat exchanger. These techniques allow production of complex internal geometries that are impossible with conventional manufacturing methods.

6. CONCLUSION

This study proposed a topology optimized compact helical heat exchanger for high pressure syngas cooling applications in underground coal gasification systems.

The key findings are:

- Topology optimization significantly enhances heat transfer performance.
- The optimized heat exchanger achieved approximately 35% higher heat transfer efficiency.
- Additive manufacturing enables fabrication of complex internal geometries.
- The proposed design reduces system size while improving thermal performance.

The results demonstrate that topology optimization combined with additive manufacturing can lead to the development of next-generation heat exchangers for high-temperature energy systems.

Future work will focus on experimental validation and prototype fabrication of the optimized heat exchanger design.

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