



Review of Augmented and Membrane Based Heat Exchanger Technologies for High Pressure Gas Applications in Underground Coal Gasification and Solar Thermal Systems

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Abstract

High pressure and high-temperature gas handling is a critical challenge in both Underground Coal Gasification (UCG) and modern solar thermal energy systems. In UCG, synthesis gas is produced deep underground under extreme thermal and pressure conditions, requiring efficient and reliable cooling before surface utilization. Similarly, solar thermal systems such as concentrated solar power (CSP) plants generate high temperature working fluids that demand advanced heat exchanger technologies for energy recovery, storage, and power generation. Conventional heat exchangers often show limited thermal performance and reduced reliability under such severe operating conditions.

This review presents a comprehensive assessment of augmented and membrane based heat exchanger technologies developed for high pressure gas applications, with a focus on their use in underground coal gasification and their potential extension to solar thermal systems. The review discusses heat transfer enhancement mechanisms, geometric configurations such as membrane helical coils and serpentine tubes, numerical and experimental studies, and material considerations. Common challenges and design requirements in both UCG and solar thermal applications are highlighted. Finally, key research gaps and future opportunities are identified to support the development of efficient, reliable, and sustainable heat exchanger systems for combined fossil and renewable energy applications.

Keywords: Underground coal gasification, solar thermal energy, high pressure gas, membrane heat exchanger, heat transfer enhancement

1. Introduction

The growing demand for energy and the global shift toward sustainable technologies have encouraged the development of both advanced fossil based and renewable energy systems. Underground Coal Gasification (UCG) enables the utilization of deep and unmineable coal reserves by converting coal into synthesis gas directly within underground seams. At the same time, solar thermal technologies, particularly concentrated solar power (CSP) systems, offer clean energy by converting solar radiation into high-temperature thermal energy.

A common challenge in both UCG and solar thermal systems is the handling of high-temperature and high pressure gases or working fluids. In UCG, syngas must be cooled safely and efficiently before transportation and utilization. In solar thermal plants, heat exchangers are required for transferring energy between solar receivers, thermal storage units, and power



blocks. These demanding conditions require advanced heat exchanger designs that provide high heat transfer rates, compactness, and long-term reliability.

This review focuses on augmented and membrane based heat exchanger technologies originally developed for high-pressure syngas cooling in UCG systems and explores their relevance and applicability to solar thermal energy systems.

2. High-Temperature Gas Challenges in UCG and Solar Thermal Systems

2.1 Underground Coal Gasification

Syngas produced in UCG systems typically exits the gasification cavity at temperatures above 700 K and pressures of several mega pascals. Improper cooling of this gas can result in excessive thermal stresses, pressure losses, and material damage. Heat exchangers used in UCG must therefore operate reliably under extreme underground conditions with limited access for maintenance.

2.2 Solar Thermal Energy Systems

In solar thermal systems, particularly CSP plants, working fluids such as air, superheated steam, or gas mixtures can reach temperatures above 800 K. High temperature heat exchangers are essential for:

- Transferring heat from solar receivers
- Charging and discharging thermal energy storage
- Power generation through turbines

Like UCG systems, solar thermal applications require compact and efficient heat exchangers capable of withstanding high thermal loads.

3. Heat Transfer Enhancement Techniques for High Pressure Gas Systems

Heat transfer enhancement techniques are used to improve convective heat transfer without excessively increasing pressure drop. For gas-phase applications, enhancement is especially important due to the low thermal conductivity of gases.

Common techniques include:

- Extended surfaces such as fins and membranes
- Flow disturbance using inserts or ribs
- Curved flow paths such as helical and serpentine geometries

Membrane based heat exchangers combine surface extension with flow disturbance and has shown strong potential for high-pressure gas applications.

4. Augmented Heat Exchangers in Energy Systems

Augmented heat exchangers have been widely investigated for coal mine ventilation, gas cooling, and industrial heat recovery. These designs increase heat transfer by modifying internal surfaces, leading to improved thermal performance compared to smooth tubes.

In solar thermal systems, similar augmentation concepts are used in receiver tubes and heat recovery units to increase energy capture and reduce system size. However, pressure drop and material durability remain major concerns in both applications.



5. Membrane Helical Coil Heat Exchangers

Membrane helical coil heat exchangers use curved flow paths combined with thin membranes to enhance heat transfer. The helical shape generates secondary flow patterns that improve mixing, while membranes increase the effective heat transfer area.

Advantages:

- High heat transfer efficiency
- Compact design
- Uniform temperature distribution

In UCG systems, these features support safe syngas cooling. In solar thermal systems, similar designs can be used for high temperature air or gas heat exchangers in solar receivers and thermal storage units.

6. Membrane Serpentine Tube Heat Exchangers

Membrane serpentine tube heat exchangers consist of multiple bends arranged in a compact layout. Each bend enhances turbulence and increases residence time, improving heat transfer.

Characteristics:

- Effective temperature control
- High heat transfer rates
- Higher pressure drop than helical coils

Such designs are suitable for both syngas cooling in UCG and controlled heat transfer in solar thermal energy recovery systems.

7. Numerical and Experimental Studies

Most studies on membrane-based heat exchangers rely on computational fluid dynamics to predict flow behaviour, temperature distribution, and pressure drop. Numerical studies provide valuable insights into design optimization for both UCG and solar thermal applications.

Experimental studies, however, remain limited due to the challenges of testing under high temperature and pressure conditions. This limitation affects both underground coal gasification and solar thermal research, highlighting a common need for advanced experimental facilities.

8. Material Considerations and LongTerm Reliability

Materials used in high-pressure heat exchangers must withstand:

- High temperatures
- Thermal cycling
- Oxidation and corrosion

These issues are critical in UCG environments due to the chemical nature of syngas, and in solar thermal systems due to continuous exposure to high heat flux. Material selection and durability studies are therefore essential for both applications.

9. Research Gaps and Opportunities

The review identifies several common research gaps:

- Limited experimental validation under realistic conditions
- Lack of long term durability and fatigue studies

- Insufficient integration of thermal and structural analysis
- Limited cross application research between fossil and solar systems

Addressing these gaps can lead to heat exchanger designs that serve both underground coal gasification and solar thermal energy systems.

10. Future Research Directions

Future studies should focus on:

- Combined numerical and experimental investigations
- Development of advanced high-temperature materials
- Adaptation of UCG heat exchanger designs for solar thermal use
- Integrated energy systems combining UCG and solar thermal technologies

Such efforts can contribute to cleaner and more efficient energy systems.

11. Conclusions

This review has examined augmented and membrane based heat exchanger technologies for high pressure gas applications in underground coal gasification and solar thermal energy systems. Advanced geometries such as membrane helical coils and serpentine tubes offer significant improvements in heat transfer performance and compactness compared to conventional designs. While numerical studies dominate current research, experimental validation and long term reliability assessment remain limited. Continued research integrating numerical modelling, experimental testing, and material science is essential to advance thermal management solutions and enable safe, efficient, and sustainable energy systems.

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