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Integrated Thermal Enhancement Strategies for High Temperature Gas Energy Systems: Applications in Solar Thermal Power and Underground Energy Conversion

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Abstract

High temperature gas based energy systems play a critical role in both renewable and non renewable energy technologies, including solar thermal power plants and underground energy conversion systems. Efficient thermal management under extreme temperature and pressure conditions remains a major engineering challenge due to low gas side heat transfer coefficients, high thermal stresses, and long-term material degradation. Conventional heat exchanger designs often exhibit limited performance and reduced reliability under such demanding operating environments.

This paper presents an integrated and critical review of advanced thermal enhancement strategies for high temperature gas energy systems, with a focus on augmented and membrane based heat exchanger configurations. Design concepts originally developed for underground high pressure gas applications are systematically reviewed and extended to solar thermal systems, including concentrated solar power and solar chimney technologies. Heat transfer mechanisms, geometric evolution, numerical and experimental investigations, and material considerations are discussed in detail. Comparative tables are used to highlight performance trends and application suitability. Key research gaps are identified, and unified future research directions are proposed to support efficient, reliable, and sustainable energy conversion systems.

Keywords: Solar thermal energy, high temperature gas, membrane heat exchanger, augmented heat transfer, sustainable energy systems

1. Introduction

The global transition toward sustainable and efficient energy systems has intensified research into both renewable and advanced fossilbased technologies. Solar thermal power generation and underground energy conversion systems represent two important pathways for meeting future energy demands. Although these systems differ in energy source, both involve the handling of high temperature gaseous working fluids and face similar thermal management challenges.

In solar thermal systems such as concentrated solar power (CSP) plants and solar chimney power plants, air or superheated gases are heated to high temperatures and used to generate power. Similarly, underground energy conversion systems generate hightemperature gases

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that must be cooled and controlled before utilization. In both cases, heat exchanger performance strongly influences system efficiency, safety, and durability.

This paper aims to integrate research developments across these domains by reviewing advanced thermal enhancement strategies that improve heat transfer performance in high temperature gas systems.

2. Engineering Challenges in High Temperature Gas Heat Transfer

Heat transfer involving gases is inherently less efficient than liquidbased systems due to lower thermal conductivity and heat capacity. When operating at high temperatures, additional challenges arise:

- Large thermal gradients leading to thermal fatigue
- Increased pressure losses in compact heat exchangers
- Material degradation due to oxidation and creep
- Performance variation under cyclic thermal loading

These challenges motivate the development of advanced heat exchanger geometries and enhancement techniques.

3. Augmented Heat Exchanger Concepts

Augmented heat exchangers improve thermal performance by modifying internal surfaces or flow paths to enhance convection. Common augmentation methods include fins, ribs, inserts, and membranes. These techniques increase surface area and disturb boundary layers, resulting in higher heat transfer rates.

Table 1. Common Heat Transfer Enhancement Techniques for Gas Applications

Enhancement technique	**Primary mechanism**	**Advantage**	**Limitation**
Extended fins	Increased surface area	Simple design	Higher pressure drop
Ribs / inserts	Flow disturbance	Improved mixing	Manufacturing complexity
Curved flow paths	Secondary flow generation	High heat transfer	Space requirement
Membrane augmentation	Surface extension + turbulence	Compact and efficient	Structural design complexity

Table 1 summarizes commonly used heat transfer enhancement techniques for gasbased systems. Among these, membrane based augmentation stands out due to its ability to combine surface extension with strong flow mixing, making it particularly suitable for high temperature applications.

4. Membrane Based Heat Exchanger Technologies

Membranebased heat exchangers integrate thin metallic membranes within the flow channel. These membranes increase effective heat transfer area and disturb thermal boundary layers, significantly enhancing convective heat transfer.

4.1 Heat Transfer Enhancement Mechanisms

- Boundary layer disruption
- Secondary vortex formation
- Increased turbulence intensity

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- Improved temperature uniformity

5. Helical and Serpentine Configurations

Curved flow geometries play a vital role in enhancing gas side heat transfer.

Table 2. Comparison of Helical and Serpentine Heat Exchanger Geometries

Parameter	Helical coil	Serpentine tube
Flow behaviour	Continuous swirl	Repeated flow redirection
Heat transfer rate	High	Moderate to high
Pressure drop	Moderate	Relatively high
Temperature uniformity	Excellent	Good
Compactness	High	Moderate

Table 2 highlights the comparative performance of helical and serpentine heat exchangers. Helical coils offer superior temperature uniformity and lower pressure loss, while serpentine tubes provide better control over outlet temperature due to increased residence time.

6. Applications in Solar Thermal Energy Systems

6.1 Concentrated Solar Power (CSP)

In CSP plants, high temperature heat exchangers are required to transfer energy from solar receivers to power blocks and thermal storage units. Membrane based helical and serpentine geometries offer compactness and enhanced thermal performance under fluctuating solar loads.

6.2 Solar Chimney Power Plants

Solar chimney systems rely on heating large volumes of air to drive turbines. Augmented and membrane based heat exchangers can improve heat absorption in collector regions, increasing airflow velocity and overall system efficiency.

Table 3. Application Suitability of Advanced Heat Exchangers in Solar Systems

Solar application	Operating temperature	Suitable exchanger type	Key benefit
CSP receiver	Very high	Membrane helical coil	High heat flux handling
Thermal storage	High	Serpentine membrane	Controlled heat transfer
Solar air heater	Moderate	Augmented surface	Improved air heating
Solar chimney	Moderate	Membrane serpentine	Enhanced airflow

Table 3 links advanced heat exchanger designs to specific solar thermal applications, demonstrating how geometry selection depends on temperature level and performance requirements.

7. Numerical and Experimental Investigations

Most research on hightemperature gas heat exchangers relies on numerical simulations due to experimental challenges. Computational studies provide insight into flow patterns, temperature fields, and pressure losses. However, experimental validation remains limited, especially for long term operation.

8. Material and Reliability Considerations

Materials used in high-temperature heat exchangers must withstand:

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- High thermal stress
- Oxidation and corrosion
- Repeated thermal cycling

Advanced alloys and coated materials show promise but require further testing for durability and cost effectiveness.

9. Research Gaps and Innovation Opportunities

Table 4. Identified Research Gaps and Future Opportunities

Area	Current limitation	Future opportunity
Experimental testing	Limited hightemperature data	Pilotscale test facilities
Material performance	Shortterm studies	Longterm durability analysis
Design integration	Isolated thermal analysis	Coupled thermalstructural models
Cross-domain use	Separate solar & underground studies	Unified design approach

Table 4 identifies critical research gaps and highlights opportunities for innovation, particularly through crossapplication of designs between solar and underground energy systems.

10. Proposed Unified Design Perspective

This paper proposes a unified thermal design philosophy in which heat exchanger concepts developed for underground hightemperature gas systems are adapted for solar thermal applications. Such integration reduces development time, improves reliability, and accelerates deployment of efficient energy systems.

11. Conclusions

This paper has presented a comprehensive and integrated review of advanced thermal enhancement strategies developed for hightemperature gas energy systems, with particular emphasis on their applications in solar thermal power generation and underground energy conversion technologies. The review demonstrates that conventional heat exchanger designs are often inadequate for handling the extreme thermal and operating conditions associated with these systems. In contrast, augmented and membrane based heat exchanger concepts offer effective solutions by increasing heat transfer surface area, promoting enhanced flow mixing, and reducing thermal resistance within compact configurations.

Among the various enhancement approaches reviewed, helical coil and serpentine tube heat exchangers incorporating membrane augmentation have shown strong potential for significantly improving heat transfer performance while maintaining acceptable pressure drops and structural compactness. These configurations enable better temperature uniformity and improved operational reliability, making them suitable for modern solar thermal applications such as concentrated solar power systems and solar chimney plants, as well as for hightemperature gas handling in underground energy conversion processes.

Despite the promising results reported in the literature, this review highlights that current research is largely dominated by numerical and computational investigations. Although such studies provide valuable insights into thermal hydraulic behaviour and design optimization, the limited availability of experimental validation under realistic operating conditions remains a major challenge. Furthermore, longterm material performance issuesincluding

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thermal fatigue, oxidation, corrosion, and mechanical degradation under cyclic thermal loadinghave not been adequately addressed.

To advance these technologies toward large scale industrial implementation, future research must adopt an interdisciplinary approach that integrates detailed thermal analysis, advanced materials science, and systematic experimental testing. The development of high temperature experimental facilities, long duration reliability studies, and coupled thermal structural design methodologies will be essential. Such coordinated efforts will support the realization of efficient, reliable, and sustainable high temperature gas energy systems, contributing meaningfully to the future of clean and advanced energy technologies.

References

[1] Perkins, G., Sahajwalla, V., & Smith, R. (2006). Underground coal gasification: A review of recent advances and current challenges. Energy & Fuels, 20(2), 596–608. https://doi.org/10.1021/ef050285k

[2]Blinderman, M. S., &Klimenko, A. Y. (2011). Underground coal gasification and carbon capture and storage: A review. Energy,36(8), 5448–5460. https://doi.org/10.1016/j.energy.2011.07.018

[3] Bhutto, A. W., Bazmi, A. A., & Zahedi, G. (2013). Underground coal gasification: From fundamentals to applications. Progress in Energy and Combustion Science,39(1), 189–214. https://doi.org/10.1016/j.pecs.2012.09.004

[4] Verma, S., & Kumar, A. (2017). Underground coal gasification: A review of technology and challenges. Energy,127, 475–490. https://doi.org/10.1016/j.energy.2017.03.089

[5] Naphon, P., &Wongwises, S. (2006). A review of flow and heat transfer characteristics in curved tubes. Renewable and Sustainable Energy Reviews,10(5), 463–490. https://doi.org/10.1016/j.rser.2004.09.014

[6] Zimparov, V. D. (2001). Enhancement of heat transfer by spirally corrugated tubes with twisted tape inserts. International Journal of Heat and Mass Transfer, 44(3), 551–574. https://doi.org/10.1016/S0017-9310(00)00117-8

[7] Manglik, R. M., &Bergles, A. E. (2003). Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes. *Journal of Heat Transfer*, 125(5), 881–889. https://doi.org/10.1115/1.1597619

[8] Gaddamwar, S. S., Pawar, A. N., & Naik, P. A. (2018). Similitude of membrane helical coil with membrane serpentine tube for characteristics of high-pressure syngas. AIP Conference Proceedings, 1966(1), 020005.https://doi.org/10.1063/1.5031234

[9] Gaddamwar, S. S. (2018). 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, 9(1), 112–121.

[10] Gaddamwar, S. S., Pawar, A. N., & 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), 245–254.

[11] Gaddamwar, S. S., Pawar, A. N., & Naik, P. A. (2019). 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, 9(2), 415–426.

[12] Gaddamwar, S.S., & Shelke, R.S. (2013). Experimental investigation of heat transfer characteristics of high pressure gas in an augmented heat exchanger. International Journal of Mechanical Engineering and Robotics Research, 2(4), 1–8.

10.48047/jocaaa.2024.33.08.400

[13] Gaddamwar, S. S., & Shelke, R. S. (2013). Heat transfer characteristics of high pressure gas in an augmented heat exchanger used in coal mines: A review. International Journal of Mechanical Engineering and Robotics Research, 2(4), 45–52.
[14] Gaddamwar, S. S., & Shelke, R. S. (2012). Status and perspectives of convective heat transfer characteristics of high pressure gas in heat exchangers. International Journal of Engineering Science and Technology, 4(4), 1568–1576.
[15] Gaddamwar, S. S., & Sherekar, R. M. (2021). Investigation regarding solar chimney power plants by ET approach: A literature study. International Journal of Scientific Research in Science and Technology, Volume 8, (Issue 2), 693–698.
[16] Behar, O., Khellaf, A., & Mohammedi, K**.** (2013). A review of studies on central receiver solar thermal power plants. Renewable and Sustainable Energy Reviews*,*23**,** 12–39. https://doi.org/10.1016/j.rser.2013.02.017
[17] Ho, C. K., & Iverson, B. D. (2014). Review of high-temperature central receiver designs for concentrating solar power. Renewable and Sustainable Energy Reviews, 29, 835–846. https://doi.org/10.1016/j.rser.2013.08.099
[18] Zhang, H. L., Baeyens, J., Degrève, J., &Cacères, G. (2013). Concentrated solar power plants: Review and design methodology. Renewable and Sustainable Energy Reviews, 22, 466–481.
https://doi.org/10.1016/j.rser.2013.01.032
[19] Zaversky, F., Sánchez, M., & Valdés, M. (2011). High-temperature air solar receivers: Design and performance. Solar Energy, 85(7), 1520–1531. https://doi.org/10.1016/j.solener.2011.03.026
[20] Zhang, X., He, Y., & Cheng, Z. (2018). Heat transfer enhancement in solar air receivers using extended surfaces. Solar Energy, 170, 321–331. https://doi.org/10.1016/j.solener.2018.05.060
[21] Pelay, U., Luo, L., Fan, Y., Stitou, D., & Rood, M. (2017). Thermal energy storage systems for concentrating solar power plants. Renewable and Sustainable Energy Reviews, 79, 82–100.
https://doi.org/10.1016/j.rser.2017.03.139
[22] Romero, M., & Steinfeld, A. (2012). Concentrating solar thermal power and thermochemical fuels. Energy & Environmental Science, **5**, 9234–9245. https://doi.org/10.1039/C2EE21275G