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Solar Thermal Driven High Temperature Heat Exchanger Technologies: A Review with Insights from High Pressure Gas Cooling Applications

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Abstract

Solar thermal energy systems, particularly concentrated solar power (CSP) technologies, operate at high temperatures and often involve highpressure gaseous working fluids. Efficient thermal energy transfer under such extreme conditions is essential for improving system efficiency, compactness, and operational reliability. However, conventional heat exchanger designs frequently face limitations related to low gasside heat transfer coefficients, excessive pressure drop, and material degradation at elevated temperatures.

This review presents a comprehensive assessment of advanced heat exchanger technologies developed for hightemperature and highpressure gas applications in solar thermal systems. Emphasis is placed on augmented and membrane-based heat exchanger configurations, including helical coils, serpentine tubes, and extendedsurface designs, which have shown strong potential for enhancing heat transfer performance. Design evolution, heat transfer mechanisms, numerical and experimental investigations, and material considerations are critically discussed. In addition, insights from highpressure gas cooling applications in industrial and underground energy systems are used to highlight transferable design concepts for solar thermal technologies. Key research gaps and future directions are identified to support the development of efficient, reliable, and scalable heat exchanger solutions for nextgeneration solar thermal power plants.

Keywords: Solar thermal energy, concentrated solar power, high temperature gas, membrane heat exchanger, heat transfer enhancement

1. Introduction

The increasing global emphasis on renewable energy has positioned solar thermal technologies as an important component of future power generation systems. Concentrated solar power (CSP) plants convert solar radiation into hightemperature thermal energy, which is subsequently used for electricity generation, industrial heating, or thermal energy storage. Unlike photovoltaic systems, solar thermal technologies rely heavily on efficient heat transfer processes.

A key challenge in CSP systems is the effective transfer of thermal energy between solar receivers, heat exchangers, thermal storage units, and power blocks. Many modern CSP concepts employ gaseous working fluids such as air, superheated steam, or gas mixtures, which operate at high temperatures and, in some cases, elevated pressures. Under these conditions, conventional heat exchangers often show limited thermal effectiveness and reduced durability.

This review focuses on advanced heat exchanger technologies designed for high temperature gas applications in solar thermal systems, with particular attention to augmented and membranebased designs that enhance heat transfer while maintaining compactness and mechanical integrity.

2. High-Temperature Gas Heat Transfer in Solar Thermal Systems

Heat transfer with gases is inherently less efficient than with liquids due to lower thermal conductivity and heat capacity. In solar thermal applications, this challenge is intensified by high operating temperatures, strong thermal gradients, and fluctuating solar input.

Key challenges include:

- Low gas-side heat transfer coefficients
- Increased thermal stresses at elevated temperatures
- Pressure drop penalties in compact designs
- Material degradation due to oxidation and thermal cycling

These challenges necessitate innovative heat exchanger designs capable of improving convective heat transfer without compromising system reliability.

3. Heat Transfer Enhancement Strategies for Solar Applications

To overcome gas-side limitations, several heat transfer enhancement techniques have been explored in solar thermal systems. These include:

- Extended surfaces such as fins and membranes
- Flow disruption using ribs, corrugations, or inserts
- Curved and multi-pass flow geometries

Among these, membrane-based enhancement has gained increasing attention due to its ability to increase effective heat transfer area and promote strong flow mixing.

4. Augmented Heat Exchangers in Solar Thermal Systems

Augmented heat exchangers use surface modifications to improve thermal performance. In solar receivers and heat recovery units, augmented surfaces have been shown to significantly enhance heat transfer rates compared to smooth channels.

However, augmentation often results in increased pressure losses, which can reduce overall system efficiency. Therefore, design optimization is essential to achieve a balance between heat transfer enhancement and hydraulic performance in solar thermal systems.

5. Membrane-Based Heat Exchanger Concepts

Membranebased heat exchangers incorporate thin metallic membranes within flow passages to extend surface area and disturb boundary layers. These features are particularly effective in high-temperature gas flows.

5.1 Heat Transfer Mechanisms

- Boundary layer thinning
- Secondary flow generation
- Enhanced turbulence intensity
- Improved temperature uniformity

Such mechanisms make membrane-based designs attractive for high-temperature solar applications.

6. Helical and Serpentine Geometries for Solar Thermal Use

6.1 Helical Coil Heat Exchangers

Helical coil heat exchangers induce centrifugal forces that generate secondary flows, enhancing heat transfer. When combined with membrane augmentation, helical coils offer:

- High heat transfer efficiency
- Compact geometry
- Reduced thermal hotspots

These characteristics make them suitable for solar air receivers and high temperature heat recovery units.

6.2 Serpentine Tube Heat Exchangers

Serpentine tube heat exchangers use repeated bends to increase flow path length and residence time. In solar thermal systems, they offer:

- Controlled outlet temperature
- Enhanced mixing
- Design flexibility

However, pressure drop remains a critical design consideration.

7. Numerical and Experimental Studies

Computational fluid dynamics has been widely used to analyze high temperature solar heat exchangers. Numerical studies provide insights into flow behaviour, temperature distribution, and the effect of geometric parameters on performance.

Experimental investigations, although limited due to high temperature testing challenges, are essential for validating numerical predictions and assessing long-term reliability. Scaled laboratory experiments and pilot-scale testing are commonly employed in solar thermal research.

8. Material Considerations for Solar Thermal Heat Exchangers

Materials used in solar thermal heat exchangers must withstand:

- High operating temperatures
- Thermal cycling due to fluctuating solar input
- Oxidation and corrosion

Advanced alloys, ceramics, and coated materials are increasingly being explored to improve durability and performance in solar thermal environments.

9. Research Gaps and Challenges

Despite significant progress, several challenges remain:

- Limited long term performance data under real operating conditions
- Insufficient coupling of thermal and structural analysis
- High manufacturing costs for advanced geometries
- Lack of standardized design guidelines

Addressing these challenges is essential for largescale deployment of advanced solar thermal heat exchangers.

10. Future Research Directions

Future research should focus on:

- Integrated numerical and experimental validation
- Optimization of membrane and augmented geometries
- Development of cost-effective high-temperature materials
- Hybrid energy systems combining solar thermal and industrial heat recovery

Such efforts will support the next generation of efficient and reliable solar thermal power systems.

11. Conclusions

This review has provided a comprehensive assessment of advanced heat exchanger technologies developed for hightemperature gas applications in solar thermal energy systems. The analysis demonstrates that augmented and membranebased heat exchangers represent a significant improvement over conventional designs, particularly in applications involving gaseous working fluids where heat transfer performance is inherently limited. Configurations such as membrane helical coils and serpentine tube heat exchangers effectively enhance convective heat transfer through increased surface area, improved flow mixing, and the generation of secondary flow structures, while also offering compact system layouts suitable for modern solar thermal installations.

Despite these demonstrated advantages, the review highlights that current research in this field is predominantly based on numerical investigations. Although computational studies provide valuable insight into thermalhydraulic behaviour and design optimization, the limited availability of experimental data under realistic high-temperature operating conditions remains a major constraint. In addition, long-term performance issues, including thermal fatigue, oxidation, material degradation, and structural reliability under cyclic solar loading, have not been sufficiently addressed. Future research should therefore focus on integrated approaches that combine detailed thermal analysis, advanced material development, and controlled experimental validation. Such multidisciplinary efforts are essential for the development of robust, efficient, and durable heat exchanger technologies capable of supporting the reliable and sustainable deployment of solar thermal energy systems at an industrial scale.

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