



A Comprehensive Review on Enhancing Heat Transfer Rate and Innovation Design of a Heat Exchanger with Phase Change Material for Storing Solar Thermal Energy

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ABSTRACT

Now a day human are paying more attention on renewable energy, especially solar energy, instead of traditional energy sources. Thermal energy storage systems help us to uses solar heat well. The primary objective of this study is to investigate the heat transfer characteristics within the heat exchanger system and optimize its design to enhance the efficiency of solar thermal energy storage. Designing a heat exchanger for solar thermal energy storage systems with phase change materials (PCMs) involves critical considerations. These include selecting appropriate materials, configuring heat transfer surfaces, and optimizing fluid flow. The design must align with PCM requirements. The utilization of phase change materials offers distinct advantages in thermal energy storage due to their ability to store and release large amounts of latent heat during the phase transition process. Integrating PCM-based thermal storage into solar applications offers efficient energy storage. Heat exchanger design is pivotal for optimizing energy transfer and system efficiency. Designing of heat exchangers are important in PCM solar systems.

Keywords: Solar Thermal Energy, Phase Change Materials (PCMs), Heat Exchanger, Thermal Energy Storage Systems, Latent Thermal Energy Storage (LTES)

Introduction to Solar Thermal Energy Storage

Solar thermal energy storage is a technology that allows for the efficient capture, storage, and utilization of heat energy generated from the sun [1]. This technology plays a crucial role in the integration of solar energy into various applications, including power generation, heating and cooling systems, and industrial processes.

In traditional solar energy systems, the energy generated from the sun is used immediately or stored in batteries for later use. However, due to the unstable and intermittent nature of solar energy availability, a more reliable and efficient method of storage is required. Solar thermal energy storage provides a solution to this challenge by capturing and storing heat energy for later use [2].

Types of Thermal Energy Storage systems There are several types of thermal energy storage systems that can be used in conjunction with solar thermal energy [1]. These include sensible heat storage, latent heat storage, and chemical heat storage. Sensible heat storage involves storing thermal energy within the storage medium by increasing temperature without undergoing any phase transformation [3]. Latent heat storage involves storing thermal energy within the material during the transition phase, as it undergoes a phase change, such as melting or solidification [1]. One of the most exciting possibilities for solar energy storage is the use of salt hydrates as phase change latent heat materials, which have a wide range of temperature range from -50 °C to 120 °C and are commercially available on the market [12]. Chemical heat storage, on the other hand, involves the use of chemical reactions to store and release heat energy.

1.1 Importance of Phase Change Material in Energy Storage

Phase change materials play a crucial role in solar thermal energy storage systems, especially in latent heat storage [4]. Phase change materials are substances that exhibit the unique property of undergoing a phase change, such as melting or solidification, at a specific temperature [5]. This property allows phase change materials to store and release large amounts of heat energy while maintaining a relatively constant temperature during the phase transition. Phase change materials are particularly attractive for thermal energy storage due to their high energy density and stability. Additionally, phase change materials have a high latent heat of fusion, meaning they can store a significant amount of energy in the form of latent heat during the phase transition. The utilization of phase change materials in thermal energy storage systems offers numerous advantages in terms of efficient energy storage and reliable heat release [4].

2. Analysis of Heat Transfer

In solar thermal energy storage systems, heat transfer plays a crucial role in the efficiency and effectiveness of the storage process [6]. Various factors affect heat transfer in these systems, including the type of phase change material used, the design and configuration of the heat exchanger, and the temperature difference between the storage material and the surrounding environment [7]. It is important to optimize heat transfer in order to maximize the storage and release of thermal energy [8].

One type of heat exchanger that can enhance heat transfer in solar thermal energy storage systems is the porous solid matrix heat exchanger. This type of heat exchanger allows for heat transfer between the hot fluid and the cold fluid through a coupling medium in the form of a porous solid matrix. The use of a porous solid matrix heat exchanger facilitates efficient heat transfer due to its ability to enhance fluid flow and increase surface area for heat exchange.

Advanced heat transfer analysis techniques can be employed to evaluate and optimize heat transfer in solar thermal energy storage systems with phase change materials. These techniques include computational fluid dynamics simulations, experimental heat transfer measurements, and mathematical modeling. The future of solar thermal energy storage lies in the advancement of thermal energy storage technologies.

2.1 Exploring Heat Exchanger Design

When designing a heat exchanger for solar thermal energy storage systems with phase change materials, several factors need to be considered. These factors include the selection of appropriate materials for the heat exchanger, the configuration and arrangement of the heat transfer surfaces, and the optimization of fluid flow through the heat exchanger. Additionally, the heat exchanger design should take into account the specific requirements and characteristics of the phase change material being used.

Designing of heat exchangers for PCM solar thermal systems requires careful consideration of several factors such as the desired energy transfer rate, the operating temperature range, the compatibility of materials with PCMs, and the overall system efficiency. Integration of PCM-Based Thermal Energy Storage systems in solar thermal applications offers great potential for efficient and sustainable energy storage. The design of heat exchangers for PCM solar thermal systems plays a crucial role in optimizing energy transfer and enhancing overall system efficiency.

2.1.1. Heat Exchanger Design for PCM Solar Thermal Systems includes:

1. The selection of appropriate heat transfer fluids that can efficiently exchange thermal energy with PCMs.
2. The design of flow channels and fins to maximize the surface area for heat exchange.
3. The optimization of flow rates and velocities to facilitate effective heat transfer.
4. The choice of materials that are compatible with both the heat transfer fluid and the PCM, ensuring thermal stability and preventing any chemical or physical reactions.
5. The incorporation of proper insulation and thermal management strategies to minimize heat losses and maximize the effectiveness of the heat exchanger.
6. The consideration of pressure drop and flow distribution to ensure uniform heat transfer throughout the heat exchanger.
7. The use of advanced computational fluid dynamics simulations to model and analyze the heat transfer and fluid flow within the heat exchanger, allowing for optimization and performance prediction.

These considerations are crucial to ensure effective heat transfer, minimize energy losses, and maximize the overall performance of the PCM solar thermal energy storage system. By carefully considering these factors and implementing an innovative heat exchanger design, the efficiency and effectiveness of PCM solar thermal systems can be significantly improved, leading to greater utilization of renewable energy for a more sustainable future. Overall, the design of heat exchangers for PCM solar thermal systems is essential in optimizing energy transfer, ensuring compatibility with PCMs and heat transfer fluids, and maximizing system efficiency. Additionally, the integration of heat exchangers with other components of the PCM solar thermal system, such as the solar collectors and storage tanks, must be carefully considered to ensure seamless operation and optimal performance. In conclusion, the design and utilization of heat exchangers with phase change materials play a crucial role in optimizing the efficiency of solar thermal energy storage systems [11]

2.2 Energy Efficiency in Solar Thermal Energy Storage

Energy efficiency is a key consideration in solar thermal energy storage systems [9]. Efforts should be made to maximize the efficiency of the thermal energy storage system by optimizing heat transfer processes, minimizing heat losses, and selecting appropriate materials and technologies. One source discusses the evaluation of the thermal performance of solar receivers, including sensitivity analysis to predict energy efficiency under different operating conditions [10].

3. Innovation in Heat Exchanger Design of Solar Thermal Storage

Innovation in heat exchanger design is crucial for enhancing the efficiency and performance of solar thermal storage systems. One approach to innovating heat exchanger design for solar thermal storage systems is to incorporate advanced materials and technologies. For example, using high-efficiency heat-absorbing materials can improve the overall energy absorption and storage capacity of the system. Additionally, optimizing the design for heat transfer and fluid flow can significantly increase the efficiency of the heat exchanger.

One innovative approach to heat exchanger design for solar thermal storage systems is the employing enhanced surfaces with higher thermal conductivity and increased surface area, the heat exchanger can improve heat absorption and transfer rates. This can lead to greater energy capture and storage within the system.

In addition to this we use advanced materials, incorporating novel geometric designs and flow patterns in the heat exchanger can further enhance its performance. Utilizing computational fluid dynamics simulations and advanced modeling techniques can aid in optimizing the heat exchanger's geometry and enhancing heat transfer efficiency.

Furthermore, integrating phase change materials within the heat exchanger can enhance the storage capacity and thermal performance of the system. These materials can store and release thermal energy during phase transitions, improving the overall energy retention of the solar thermal storage system.

Specialized surface coatings and textures of heat exchanger can lead to significant advancements in the efficiency and performance, heat exchangers can achieve greater heat transfer rates and improved fluid flow. These specialized surfaces can include microchannels, which enhance the convective heat transfer process, and nano-coatings that improve thermal conductivity.

Another innovative method is the use of phase change materials in heat exchanger design. PCMs have the ability to store and release large amounts of energy during the phase transition process, making them ideal for solar thermal storage systems. By integrating PCMs into the heat exchanger design, the system's overall energy storage capacity can be significantly increased. Another approach involves the use of molten salts as a storage medium. This method utilizes the ability of molten salts to retain thermal energy for extended periods of time, allowing for on-demand release of stored energy.

The combination of these innovative approaches can revolutionize the performance and efficiency of heat exchangers in solar thermal storage systems. The use of advanced materials, such as those with higher thermal conductivity and increased surface area, geometric designs of heat exchanger and flow patterns, can greatly improve the efficiency and performance of heat exchangers. These advancements in heat exchanger design can ultimately lead to more efficient and effective solar thermal storage systems, allowing for greater utilization of renewable energy sources and reducing reliance on fossil fuels. By utilizing these innovative heat exchanger design techniques, solar thermal storage systems can achieve higher energy retention, faster heat transfer rates, and overall improved performance.

3.1 Challenges in Heat Exchanger Design of Latent Thermal Energy Storage Systems

Challenges in the heat exchanger design of latent thermal energy storage (LTES) systems include:

1. **Phase Change Material (PCM) Compatibility:** Selecting a PCM that is compatible with the operating conditions and materials of the heat exchanger is crucial. Some PCMs may chemically react with certain metals or degrade over time, affecting system performance.
2. **Heat Transfer Enhancement:** Efficient heat transfer between the heat exchanger fluid and PCM is essential for effective energy storage and retrieval. Achieving uniform heat distribution and minimizing thermal gradients within the PCM can be challenging.
3. **Temperature Control and Stability:** Managing temperature fluctuations and ensuring thermal stability throughout the storage and release cycles are critical. Variations in ambient conditions, thermal losses, and system dynamics may affect the overall performance of the LTES system.
4. **Scale-Up and Manufacturing:** Scaling up heat exchanger designs from laboratory prototypes to commercial-scale systems poses challenges in terms of manufacturing, cost-effectiveness, and reliability. Ensuring consistent performance across different system sizes and configurations is essential.
5. **System Integration and Optimization:** Integrating the heat exchanger within the overall LTES system requires careful consideration of system dynamics, control strategies, and optimization techniques. Balancing thermal efficiency, storage capacity, and system complexity is key to maximizing overall performance.

3.2 Solutions to address these challenges may include

1. **Material Selection and Testing:** Thoroughly evaluate the compatibility of PCMs and heat exchanger materials through testing and analysis to ensure long-term reliability and performance.
2. **Heat Transfer Enhancement Techniques:** Implement heat transfer enhancement techniques such as finned surfaces, extended surfaces, and optimized flow patterns to improve heat transfer efficiency and minimize thermal gradients.

3. **Thermal Management Systems:** Incorporate thermal management systems such as insulation, temperature sensors, and control algorithms to regulate temperature fluctuations and maintain thermal stability within the LTES system.
4. **Prototyping and Testing:** Develop and test prototype heat exchanger designs at various scales to validate performance, optimize system parameters, and identify potential areas for improvement before full-scale implementation.
5. **Advanced Modeling and Simulation:** Utilize advanced modeling and simulation tools to predict system behavior, optimize design parameters, and evaluate performance under different operating conditions.

By addressing these challenges and implementing suitable solutions, heat exchanger design for latent thermal energy storage systems can be optimized to achieve efficient and reliable energy storage solutions for various applications.

4. Conclusion: The Future of Solar Thermal Energy Storage

The future of solar thermal energy storage is marked by technological advancements, increased efficiency, and a growing emphasis on sustainability. As research and development efforts continue, solar thermal energy storage is poised to play a crucial role in ensuring that the electricity generated by renewable sources, like solar power, can be stored and used when needed, enduring times of low or no sunlight. The future of solar thermal energy storage lies in the advancement of thermal energy storage technologies.

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