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Recent Developments in Solar Thermal Power Plants: A Review

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ABSTRACT: The increasing demand for environmentally friendly and sustainable energy sources has led to significant interest in solar thermal power generation. Solar thermal power plants utilize solar radiation to produce thermal energy, which is subsequently converted into electrical power through conventional energy conversion cycles. In recent years, considerable progress has been achieved in the design of solar collectors, thermal energy storage systems, heat transfer fluids, and power generation cycles, resulting in enhanced efficiency and operational reliability. This review paper discusses recent developments in solar thermal power plant technologies, with particular emphasis on concentrating solar power (CSP) systems such as parabolic trough collectors, solar power towers, linear Fresnel reflectors, and dish–Stirling systems. Advancements in thermal energy storage techniques, working fluids, and hybrid energy systems are also reviewed. Furthermore, the key challenges and potential future research directions for large-scale implementation of solar thermal power plants are presented.

KEYWORDS: Solar thermal power plant, Concentrating solar power, Thermal energy storage, Heat transfer fluids, Renewable energy.

I. INTRODUCTION

The rapid growth in global energy consumption, coupled with the depletion of fossil fuel reserves and rising environmental concerns, has intensified the search for sustainable energy alternatives. Renewable energy technologies have emerged as promising solutions to reduce greenhouse gas emissions and dependence on conventional energy sources. Among the available renewable options, solar energy is one of the most abundant and widely accessible resources.

Solar power technologies can be broadly categorized into photovoltaic systems and solar thermal systems. While photovoltaic systems directly convert solar radiation into electricity, solar thermal power plants first transform solar energy into heat, which is then used to generate electricity through established thermodynamic cycles. Concentrating solar power (CSP) systems have gained particular attention due to their ability to integrate thermal energy storage, allowing continuous power generation even during periods of low solar radiation.

Recent technological advancements in materials, thermal storage, and power conversion methods have significantly enhanced the efficiency, reliability, and economic feasibility of solar thermal power plants. This review focuses on recent developments in CSP technologies, thermal energy storage methods, heat transfer fluids, and hybrid system configurations.

II. CLASSIFICATION OF SOLAR THERMAL POWER PLANTS

Solar thermal power plants are generally classified based on the type of solar concentrator and receiver arrangement used to collect and convert solar energy.

A. Parabolic Trough Collectors (PTC)

Parabolic trough collector systems represent the most commercially established CSP technology. These systems employ curved mirrors to concentrate sunlight onto a linear receiver tube carrying a heat transfer fluid. Recent improvements

include advanced selective coatings, increased operating temperature limits, and the adoption of molten salts as working fluids to enhance thermal efficiency and reduce energy losses.

B. Solar Power Tower Systems

Solar power tower systems, also known as central receiver systems, use a large number of heliostats to reflect sunlight toward a receiver located at the top of a tower. These systems operate at higher temperatures, often exceeding 550°C, which leads to improved thermodynamic efficiency. Recent developments in receiver design and molten salt technology have contributed to improved performance and durability.

C. Linear Fresnel Reflector Systems

Linear Fresnel reflector systems utilize multiple flat or slightly curved mirrors to concentrate solar radiation onto a fixed receiver positioned above the mirror field. Although their optical efficiency is generally lower than that of parabolic trough systems, their simpler structure and lower installation costs make them attractive. Current research focuses on enhancing optical performance and receiver efficiency.

D. Dish–Stirling Systems

Dish–Stirling systems consist of parabolic dishes that focus solar radiation onto a receiver connected to a Stirling engine. These systems offer high conversion efficiency and modular design but are limited by high costs and challenges related to large-scale deployment.

III. RECENT ADVANCES IN THERMAL ENERGY STORAGE

Thermal energy storage (TES) is a critical component of solar thermal power plants, enabling stable power output during intermittent solar conditions and nighttime operation.

A. Sensible Heat Storage

Sensible heat storage systems, particularly those using molten salts, are widely employed in commercial CSP plants. Recent advancements include the development of salt mixtures capable of operating at higher temperatures and improved thermal insulation methods to minimize heat losses.

B. Latent Heat Storage

Latent heat storage systems utilize phase change materials (PCMs) to store energy during phase transitions. These systems offer higher energy storage density compared to sensible heat storage. Ongoing research aims to improve the thermal conductivity, cycling stability, and long-term reliability of PCMs.

C. Thermochemical Energy Storage

Thermochemical energy storage relies on reversible chemical reactions to store and release thermal energy. This method offers high storage capacity and minimal thermal losses over extended periods. Although still under development, thermochemical storage shows strong potential for future high-efficiency CSP applications.

IV. ADVANCEMENTS IN HEAT TRANSFER FLUIDS

Heat transfer fluids significantly influence the performance and operating temperature range of solar thermal power plants. Recent research has focused on the development of advanced working fluids to improve heat transfer and system efficiency.

Key developments include:

- Adoption of molten salts as combined heat transfer and storage media
- Investigation of supercritical carbon dioxide (sCO₂) for high-efficiency power cycles
- Use of nanofluids to enhance thermal conductivity
- Development of high-temperature synthetic oils with improved thermal stability

These innovations enable solar thermal systems to operate at elevated temperatures, leading to higher overall efficiency.

V. POWER CYCLES AND HYBRID SYSTEMS

Conventional solar thermal power plants commonly utilize steam Rankine cycles for electricity generation. However, recent studies have explored advanced power cycle configurations to improve efficiency and reduce operational losses. These include:

- Supercritical steam Rankine cycles
- Brayton cycles
- Combined Brayton–Rankine cycles

Hybrid solar thermal systems that integrate fossil fuels, biomass, or photovoltaic technologies enhance operational flexibility and reliability. Integrated solar combined cycle (ISCC) plants have demonstrated improved efficiency and reduced environmental impact.

VI. CHALLENGES AND FUTURE DIRECTIONS

Despite notable progress, several challenges hinder the widespread adoption of solar thermal power plants. These include high initial investment costs, significant land and water requirements, material degradation at elevated temperatures, and grid integration issues.

Future research efforts should focus on reducing system costs through technological innovation and large-scale manufacturing, developing advanced high-temperature materials, improving thermal storage performance, and integrating solar thermal systems with emerging applications such as hydrogen production and desalination.

VII. CONCLUSION

Solar thermal power plants offer a promising solution for sustainable and dispatchable renewable energy generation. Recent advancements in concentrating technologies, thermal energy storage, heat transfer fluids, and power cycle configurations have substantially improved system efficiency and reliability. Although challenges related to cost, materials, and scalability remain, continuous research and development are expected to facilitate broader adoption. With supportive policies and further technological progress, solar thermal power generation can play a significant role in meeting future global energy demands.

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