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The Analysis and Prospects of Concentrated Solar Power Technology

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Abstract: Concentrated Solar Power (CSP) technology has gained significant attention as a renewable energy source, driven by global trends towards energy transformation and carbon neutrality. This technology converts solar radiation into high-temperature thermal energy, which is then used for electricity generation, addressing the intermittency and instability issues of solar power. Thermal Energy Storage (TES) technology enhances the system's flexibility and stability by efficiently storing and releasing energy. This paper provides a comprehensive review of CSP technology, including its technical principles, application status, and latest developments. The technical principles involve concentrating sunlight onto a heat absorber using mirrors or lenses, heating a working fluid, and transferring the heat energy to a working medium to produce high-temperature, high-pressure steam that drives a steam turbine. CSP technology is categorized into Fresnel, tower, dish, and trough systems, each with its unique characteristics and applications. Globally, the operational capacity of CSP plants has exceeded 6.5GW, with significant contributions from countries like Spain, the United States, and China. Parabolic trough technology is the most widely deployed, followed by tower technology. The energy storage capacity of CSP power plants has also increased, with some plants capable of operating for extended hours. Recent research focuses on integrating CSP technology with Supercritical Carbon Dioxide (sCO2) Brayton cycles for higher thermal efficiency and reducing system volume and costs. Additionally, the application of phase change materials (PCM) and molten chloride salts in CSP systems is being explored for improved thermal storage capabilities. Concentrated solar thermal power technology, with its clean, renewable, and stable characteristics, is expected to play a crucial role in achieving global energy sustainability and reducing greenhouse gas emissions. Continued technological innovation and policy support are essential to overcome challenges and enhance its position in the future energy structure.

Keywords: Solar Energy, Concentrated Solar Power (CSP), Thermal Energy Storage (TES), Supercritical Carbon Dioxide Power Cycle.

1. Introduction

Driven by the current trends towards energy transformation and carbon neutrality goals, Concentrated Solar Power (CSP) technology has become a focal point of research and application in the global renewable energy sector. With the increasing depletion of fossil energy resources and the growing severity of environmental pollution, the search for clean and renewable energy alternatives has become particularly urgent. Solar energy, as an abundant and sustainable energy form, has become an integral part of the future energy system due to its inexhaustible and endless characteristics. Against this backdrop, the research and development of concentrated solar power technology not only offer new avenues to address the current energy crisis but also provide strong support for achieving global environmental protection and sustainable development goals.

Concentrated solar power technology converts concentrated solar radiation into high-temperature thermal energy, which is then used to drive traditional steam turbines for electricity generation. Its core advantage lies in the ability to achieve large-scale dispatchable power generation, effectively addressing the intermittency and instability issues faced during solar power generation. Thermal energy storage technology, as a crucial component of solar thermal power systems, enhances the flexibility and stability of the system by efficiently storing and releasing energy.

Researching concentrated solar power technology holds significant practical significance and theoretical value. In terms of practical significance, this technology can effectively address the instability issues of solar power generation, achieve stable energy supply, reduce dependence on fossil fuels, lower greenhouse gas emissions, and promote the optimization, transformation, and upgrading of the energy structure. From a theoretical perspective, the study of concentrated solar power technology and energy storage technology involves multiple disciplines such as energy conversion, thermodynamics, materials science, and control engineering. It is highly interdisciplinary and comprehensive, capable of driving the development and innovation of related disciplines, and promoting technological progress and industrial upgrading.

Concentrated solar power technology, as a crucial component of the future energy system, holds broad prospects for development and significant application value. In-depth research and exploration of the development paths and application prospects of these two technologies will not only provide vital support for achieving global energy transformation and carbon neutrality goals but also make a positive contribution to global sustainable development and ecological environmental protection. Against this backdrop, this paper will offer a comprehensive review of the current status, basic principles, application examples, and future development directions of concentrated solar power technology, aiming to provide valuable references for research in related fields.

2. Technical Principle

CSP systems concentrate sunlight onto a heat absorber using various forms of mirrors or lenses (such as parabolic troughs, parabolic dishes, heliostats, etc.), causing its temperature to rise sharply. The working fluid (such as synthetic oil, molten salt, water, etc.) within the heat absorber is heated to high temperatures and then transfers the heat energy to a working medium (such as water) through a heat exchanger, producing high-temperature, high-pressure steam that drives a steam turbine. The steam turbine, connected to a generator, converts mechanical energy into electrical energy. After driving the steam turbine, the steam is cooled into liquid water by a condenser, re-enters the cycle system, is heated again to form steam, and the cycle repeats.

According to different concentration methods, CSP technology is mainly divided into four categories: Fresnel, tower, dish, and trough. Among these, Fresnel and trough CSP systems belong to linear focusing systems, while tower and dish systems are point focusing systems. Compared to linear focusing systems, point focusing CSP systems, due to their higher concentration ratios, can generate higher temperature solar heat and achieve higher thermoelectric conversion efficiencies as well as lower electricity costs. Currently, most operational CSP power plants use the mature trough technology, which has low construction and maintenance costs, while most CSP power plants under construction are based on the more advanced tower technology [1].

In the process of solar photothermal power generation, excess heat is transferred to an energy storage medium through a heat exchange system for storage. When sunlight is insufficient or during peak power demand, the heat stored in the medium is released through a control system. The heat in the storage medium is then transferred back to the working medium (such as water) via the heat exchange system, producing high-temperature, high-pressure steam. This steam drives thermal machines like steam turbines or Stirling engines to generate electricity.

3. Application Status

As of July 2023, the total operational capacity of global Concentrated Solar Power (CSP) plants has exceeded 6.5GW. Since the first operation of the United States' National Solar Thermal Test Facility with a generating capacity of 5MW in 1978, CSP technology has gone through a period of slow development. Between 2008 and 2013, driven by Spain and the United States, the technology rapidly began to develop, with approximately 4GW of CSP plants built during this period. Subsequently, countries such as China, Morocco, South Africa, India, and Israel have also entered this market. Currently, in terms of operational capacity, Spain leads with a scale of 2300MW, followed by the United States with 1500MW and China with 596MW. However, Spain and the United States currently do not have any projects under construction, while China and the United Arab Emirates are actively promoting new CSP projects.

By the end of 2023, parabolic trough CSP technology is the most widely deployed type of CSP technology globally, accounting for 73% of the world's installed capacity. Following this is tower technology (23%) and Fresnel technology (4%) [2]. Although dish stirling technology is highly efficient, its deployment is limited due to mechanical constraints that restrict the maximum dish diameter, thus limiting its scale and economic benefits, and there are no operational power plants of this type yet. The historical preference for trough technology is mainly due to its large-scale deployment in Spain and the United States. Since 2012, tower technology has gained attention for its ability to increase operating temperatures. According to the formula:

$$Q = mc_p\Delta T$$

(Q—— maximum heat storage capacity, m—— total mass of molten salt, c_p—— specific heat capacity of molten salt, ΔT—— temperature difference between the hot and cold tanks) ,It can be seen that an increase in operating temperature can increase the heat storage capacity. Therefore, the most advanced second-generation CSP plants that are currently in operation mostly use tower technology, with the advanced representative being the commercial tower power plant equipped with a direct molten nitrate heat storage system. The structure of the power plant is mainly composed of four core parts: heliostats, a receiver tower, a molten salt thermal storage system, and a power cycle generation system. Its operating principle is that the heliostats concentrate and reflect sunlight to the receiver at the top of the receiver tower, thereby converting light energy into heat energy and storing it in the molten salt flowing through the absorber, which comes from the cold tank. The heated molten salt is stored in a high-temperature molten salt tank, and when the power demand increases, the stored heat energy is transferred to the traditional steam Rankine cycle through a molten salt heat exchanger, thus generating electricity. The use of a molten salt heat storage system allows CSP plants to still provide stable and adjustable low-cost power even when sunlight is insufficient, demonstrating their economically efficient energy storage capability.

Over the past 20 years, the energy storage capacity of CSP power plants has significantly increased. For example, Spain's Gemasolar plant has demonstrated its ability to operate for 15 hours continuously since 2011. In 2021, Chile's Atacama I project reached an energy storage capacity of 17.5 hours, setting the highest record to date. Since 2020, newly planned CSP power plants have had at least 8 hours of energy storage capacity. As the cost of photovoltaic technology decreases, thermal energy storage has become increasingly important for enhancing the competitiveness of CSP power plants. A study shows that CSP power plants with thermal energy storage have an advantage when competing against photovoltaic plus battery systems, especially when the storage capacity exceeds 4 hours [3]. Although the cost of battery storage is still higher than that of thermal storage, the capacity factor of CSP power plants without storage is only between 15% and 30%. With the addition of storage, the capacity factor can be significantly increased to 68%.

4. Latest Developments

4.1. Popular Research Direction in the Generation Part of CSP Systems – Supercritical Carbon Dioxide Brayton Cycle

Supercritical carbon dioxide power cycles utilize supercritical carbon dioxide as the working fluid. Under high temperature and pressure conditions, carbon dioxide has better thermal conductivity and density than traditional working fluids (such as water), enabling the system to achieve higher thermal efficiency within a relatively smaller volume of equipment [4-6]. In solar photothermal power generation systems, solar energy heats water or other fluids through collectors to produce a high-temperature heat source. Supercritical carbon dioxide cycles can be used to efficiently convert this heat into electricity. Supercritical carbon dioxide Brayton cycles have advantages over traditional steam Rankine cycles, such as high efficiency, low compression power consumption, compact volume and structure, and high cost-effectiveness. When the heat source temperature is above 550°C, the thermal efficiency can reach over 45%, and 50% at 700°C [7]. The power consumption during compression only accounts for 30% of the turbine output power, significantly reducing system volume and material costs, with low maintenance costs and a long service life. The cost of thermal power generation is approximately 0.173 yuan/(kW·h), while the cost of concentrated solar thermal power generation is about 0.414 yuan/(kW·h) [8].

The integration of concentrated solar thermal power generation technology with supercritical carbon dioxide cycles represents the forefront of development trends in solar photothermal conversion. The energy conversion mechanism of this technology mainly falls into two modes: direct absorption and indirect absorption. In the direct absorption mode, supercritical carbon dioxide absorbs solar energy directly within the absorber; in the indirect absorption mode, solar energy is first absorbed by media such as molten salt or high-temperature solid particles, and then the heat is transferred to supercritical carbon dioxide. Current research focuses on the structural design and performance characteristics of absorbers. Given the extremely demanding operating conditions of supercritical carbon dioxide cycles, much of the research relies on numerical simulation methods, with relatively limited experimental validation. Although molten salt absorption technology has been applied in commercial fields, due to the limited operating temperature of the commercially used molten salt (molten nitrate) by the decomposition temperature of the medium, it usually cannot operate stably in environments above 600°C. Therefore, molten salt thermal storage technology using molten chloride salt as the main medium has become a popular research direction. On the other hand, solar particle absorption technology has become a research focus due to its ability to withstand higher operating temperatures, good thermal stress distribution characteristics, and convenient integration with thermal energy storage systems. In addition, some research institutions are developing test platforms to obtain data to support the development and improvement of this technology.

4.2. Main Research Directions in the Storage Part of CSP Systems

4.2.1. Molten Chloride Salts

Molten chloride salts are considered highly promising as a thermal storage and heat transfer material in the field of molten salt technology for the future due to their excellent thermal stability and economic viability. Compared to carbonate mixtures (e.g., $Li_2CO_3/Na_2CO_3/K_2CO_3$, priced at 1.3~2.5 $USD{\cdot}kg^{-1}$) and nitrate mixtures (such as solar salt, priced at 0.5~0.8 $USD{\cdot}kg^{-1}$), chloride salt mixtures (e.g., $MgCl_2/KCl/NaCl$, priced below 0.35 $USD{\cdot}kg^{-1}$) not only have higher thermal stability (exceeding 800 °C), but also suitable thermophysical properties and lower costs [1]. However, unlike commercial molten nitrate technology, molten chloride salt technology poses a major challenge due to its corrosiveness to metal structural materials at high temperatures. Therefore, the development of efficient and economical corrosion control technologies is crucial for the application of molten chloride salt technology.

4.2.2. Phase Change Materials (PCM)

The application of thermal storage phase change materials (PCM) in CSP systems offers several significant advantages:

(1) PCM can provide high-density thermal storage, meaning they can store a large amount of heat in a smaller volume. This capability arises from the latent heat absorbed and released by PCM during phase change, which is much higher than traditional sensible heat storage systems. According to relevant literature, the energy storage density of phase change materials can reach 5 to 10 times that of sensible heat storage [9, 10].

(2) PCM maintain relatively stable temperatures during phase change, which helps maintain the thermal efficiency and output temperature consistency of CSP systems during discharge.

(3) By selecting appropriate PCM, the system can be designed to operate within a specific temperature range, increasing the flexibility of CSP system design.

(4) The use of PCM helps improve the overall energy utilization efficiency of CSP systems by releasing stored heat when solar radiation is insufficient, enhancing the system's dispatchability.

However, PCMs also have some limitations, which are the main breakthrough directions of current research. Firstly, the thermal conductivity of PCMs is usually low, which limits the heat transfer rate and may result in slow charging and discharging processes. Secondly, PCMs may face material degradation issues after long-term operation and multiple thermal cycles, affecting their thermal physical properties and cycling stability. Thirdly, some PCMs may exhibit undercooling, i.e., not solidifying in time when cooled below the melting point, thus failing to effectively release stored heat [11]. Fourthly, encapsulating PCMs to prevent leakage and environmental impact increases the complexity and cost of the system. Fifthly, although the unit energy cost of PCMs may be relatively low, the overall cost of encapsulation and integration into CSP systems remains a significant barrier to commercial application. Therefore, future research needs to focus on improving the thermal conductivity of PCMs, enhancing their long-term stability, solving undercooling issues, and developing more cost-effective encapsulation and integration technologies.

4.2.3. Chemical Storage

Solar high-temperature thermochemical energy storage is an advanced solar thermal storage technology, significantly superior to sensible heat storage and latent heat storage in terms of storage temperature and density. Moreover, since high-temperature thermal energy is stored in the form of chemical energy, it can theoretically achieve zero-loss long-term storage of thermal energy. There are numerous routes in high-temperature thermochemical energy storage technology, which can be classified into two major categories according to the end use of the stored energy: high-temperature thermochemical heat storage and high-temperature thermochemical conversion [12].

5. Conclusion and Outlook

Concentrated solar thermal power technology, with its clean, renewable, and stable characteristics, has become a key force in driving energy transition. With the continuous advancement of technology, CSP systems have made significant progress in efficiency improvement, cost reduction, and application expansion. In particular, the application of latent heat storage technology has greatly enhanced the energy utilization efficiency and stability of the system. Despite challenges such as cost and regional limitations, through continuous technological innovation and policy support, concentrated solar thermal power technology is expected to occupy an even more important position in the future energy structure. Looking forward, concentrated solar thermal power technology will continue to play a crucial role in achieving global energy sustainability and reducing greenhouse gas emissions, contributing to the construction of a clean, low-carbon, and efficient energy system.

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