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Advances in central receivers for concentrating solar applications

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ABSTRACT

This paper provides a review of current state-of-the-art commercial central receiver systems and emerging technologies intended to increase the outlet temperature to >700 °C. Research on particle-based, gas-based, and liquid-based receiver designs that can achieve these higher temperatures are discussed. Particle-based technologies include directly irradiated designs (free-falling, obstructed, centrifugal) and enclosed designs (gravity fed, fluidized). New gas-based receivers include micro-channel designs and light-trapping configurations that increase the surface area, heat transfer, and solar absorptance to enable higher fluxes and pressures. Liquid-based receivers and materials that are reviewed include high-temperature halide salts (chlorides and fluorides), carbonate salts, and liquid metals (sodium and lead bismuth). Advantages and challenges associated with each of the technologies and receiver designs are presented.

1. Introduction

Central receivers have been researched and developed for concentrating solar power (CSP) applications since the 1970s. The use of central receivers for CSP enables greater solar concentrations and overall efficiencies than line-focus systems like parabolic troughs, and central receivers can employ thermal storage more readily than distributed point-focus technologies like dish engines.

Central receivers have used liquid (e.g., water, molten salt), gas (e.g., air), and solid media (e.g., ceramic particles) as the heat-transfer and/or storage media. Liquid-based receivers typically use panels of tubes that are irradiated by concentrated sunlight and cooled by the flowing fluid. The panels of tubes can be contained inside a cavity receiver or arranged in a cylindrical or cubical configuration. Cavity receivers may reduce radiative and convective heat losses relative to external receiver designs, and the annual optical efficiency of a north-facing receiver (in the northern hemisphere) or south-facing receiver (in the southern hemisphere) is typically greater (by 10% or more) than an external receiver design with a surround heliostat field (Falcone, 1986). However, cavity receivers require taller towers to "see" all of the heliostats in a north or south heliostat field relative to a surround field for a given power requirement. Water and direct-steam central receivers have been deployed commercially and have the benefit of avoiding exergy losses and expenses associated with heat exchangers between the receiver and the power block. However, storage of the high-pressure steam is difficult. Molten-salt can be stored readily and heated to high temperatures (up to ~600 °C for nitrate salts) (Bradshaw and Meeker, 1990), but trace heating is required throughout the system to prevent freezing of the molten salt, which occurs at temperatures up to ~200 °C.

Gas receivers can use tubes or volumetric honeycombs and channels to heat air or other gases to high temperatures for Brayton power cycles or to heat a storage media (e.g., solid particles, concrete, graphite, phase-change material). Tubular receivers employ a closed-loop system that pumps gas, often at high pressures over 100 bar, through the irradiated tubes. Heat transfer limitations from the tube walls to the gas is a significant challenge. Volumetric receivers typically use an open-loop system with air as the heat-transfer fluid. Air is drawn through channels or honeycomb blocks that are irradiated by the concentrated sunlight. The air is heated as it flows through the irradiated structure, which ideally allows light to penetrate deep into the receiver so that the hottest part is in the interior, away from the aperture. However, most studies have shown that the aperture of the volumetric receiver is the hottest portion, yielding significant radiative losses to the environment.

Particle-based receivers use small solid particles that are heated by concentrated sunlight. The particles can be heated to temperatures above 1000 °C, stored, and used for process heat or electricity production. A significant advantage of particle receivers is that the particles can be irradiated directly, eliminating heat-transfer resistance and flux limitations associated with indirect heating through tube walls.

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1.1. Historical overview

Fig. 1 shows a timeline of significant receiver developments and associated CSP events since the 1970s. In 1978, the first central receiver test facility was built at Sandia National Laboratories in Albuquerque, NM. The facility includes a 61-m-tall tower with over 200 heliostats (each 37 m^2) in the north field for testing various receiver designs and materials. In the 1980s and 1990s, the first pilot-scale central receiver power tower systems using direct-steam (Solar One) and molten-salt (Solar Two) receivers were demonstrated in Daggett, CA, with a capacity of 10 MW_e. The first commercial parabolic trough plants were built in the 1980s in southern California and are still operational today. In 2007–2009, the first commercial power tower plants were built near Seville, Spain, and consisted of a 10 MW_e and 20 MW_e saturated-steam central receiver systems. In 2010, a 1.5 MW_e commercial dish/engine plant was constructed in Arizona (but went bankrupt a year later). In 2011, the first commercial molten-salt power-tower plant, Gemasolar, was built near Seville, Spain. Also in 2011, the U.S. Department of Energy initiated the SunShot program to bring unsubsidized costs of solar energy down to \$0.06/kW h to be competitive with fossil fuels. In 2014, three large superheated-steam receivers were built at Ivanpah, CA, with a gross capacity of 390 MW_e. In 2015, a 110 MW_e molten-salt power tower was built in Tonopah, NV. Additional details of these commercial systems are provided in subsequent sections.

1.2. The push toward higher receiver temperatures

Current commercial central receiver systems operate at temperatures below 600 °C. Increased operating temperatures of central receivers are currently being pursued to increase the thermal-to-electric efficiency of the power cycle. However, increased operating temperatures also increase radiative and convective heat losses of the receiver. As the receiver temperature increases, the solar-to-thermal efficiency, η_{th}, decreases while the thermal-to-electric efficiency, η_e, of the power cycle increases according to Carnot's theorem. The solar-to-thermal and thermal-to-electric efficiencies can be expressed as follows:

$$\eta_{th} = \frac{\alpha Q_{in} - Q_{loss}}{Q_{in}} = \alpha - \frac{\varepsilon\sigma T_R^4 + h(T_R - T_{amb})}{\eta_{field} E_{DNI} C} \quad (1)$$

$$\eta_e = 0.7\eta_{carnot} = 0.7\left(1 - \frac{T_c}{T_h}\right) \quad (2)$$

where Q_{in} is the irradiance on the receiver (W/m^2), Q_{loss} is the total radiative and convective energy losses from the receiver (W/m^2), α is the receiver solar absorptance, ε is the receiver thermal emittance, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^4), T_R is the receiver surface temperature (K), h is the convective heat transfer coefficient (W/m^2-K), T_{amb} is the ambient temperature (K), η_{field} is the heliostat field efficiency (including cosine losses, reflectance losses, and spillage), E_{DNI} is the direct normal irradiance (W/m^2), C is the concentration ratio (collector aperture area divided by the receiver area), T_c is the temperature of the power-cycle cooling source (K), and T_h is the temperature of the power-cycle heating source (K). A factor of 0.7 is used in Eq. (2) to account for engineering inefficiencies relative to the Carnot cycle.

Fig. 2 (left) shows the solar-to-thermal and thermal-to-electric efficiencies as a function of temperature for different concentration ratios. The product of Eqs. (1) and (2) yields the combined efficiency (solar-to-electric) and is plotted in Fig. 2 as a function of temperature for different concentration ratios. As the temperature increases, the combined efficiency increases until the radiative and convective losses of the receiver outweigh the gains in the power-cycle efficiency, at which the combined efficiency begins to decrease. Thus, for a prescribed concentration ratio, there exists a temperature at which the combined solar-to-electric efficiency exhibits a maximum. Fig. 2 also shows that the combined efficiency can be increased by increasing the concentration ratio. Increasing the concentration ratio effectively adds the same amount of power to a smaller area, which reduces the footprint for radiative and convective heat losses.

Central receiver systems are capable of achieving concentration ratios up to several thousand suns, but the peak flux is often limited by the heat-transfer fluid and its ability to absorb heat from the irradiated walls of the receiver tubes to prevent overheating. Table 1 provides a summary of typical allowable peak fluxes and resulting outlet temperatures for different heat transfer fluids and media used in central receiver systems. Challenges include the need for materials, heat-transfer fluids, and processes that maximize solar absorptance and minimize heat losses while operating at these higher temperatures and fluxes. Central receiver systems also require high reliability over thousands of thermal cycles.

This paper first presents an overview of current state-of-the-art commercial central receiver systems, which include saturated and superheated direct-steam receivers and molten-salt receivers. Emerging technologies to achieve higher temperatures and efficiencies for central receivers are then presented, which include particle-based, gas-based, and liquid-based receivers that enable higher temperatures and/or higher efficiencies. Challenges associated with each of the technologies are presented.

2. Commercial central receiver CSP plants

Of the nearly 5 GW_e of operational CSP capacity around the world at the end of 2016, just over 600 MW_e (or 13%) of capacity was from central-receiver power-tower plants (Mehos et al., 2016). The rest was predominantly from parabolic trough plants. However, as researchers and developers seek to achieve higher efficiencies and lower costs through direct storage and higher temperatures, more and more central receiver technologies are being developed. Of the nearly 5 GW_e of CSP plants that were under construction or announced at the end of 2016, about 60% or nearly 3 GW_e were based on central-receiver power-tower technology. All new central receiver CSP plants were being constructed or planned outside of the United States – in China, Chile, South Africa, Israel, and Morocco. Early central-receiver plants were predominantly direct-steam receiver systems, but many newer plants employ molten-salt for storage.

2.1. Direct-steam receivers

In 2007 and 2009, the first commercial central-receiver CSP plants producing grid-connected electricity became operational in southern Spain. Planta Solar 10 (PS10) and Planta Solar 20 (PS20) utilize direct-steam central receivers producing saturated steam at ~250–300 °C, 45 bar, for a power cycle employing wet cooling with net turbine capacities of 11 MW_e and 20 MW_e, respectively (Fig. 3. Both plants use cavity receivers that house tubular panels to heat the water/steam, and both plants use pressurized-water thermal storage systems to provide up to an hour of storage capacity. PS10 and PS20 are expected to generate 23 and 48 GW h of electricity per year, respectively.

In 2014, the Ivanpah Solar Electric Generating System became operational in southern California. Ivanpah consists of three separate central-receiver CSP units, each considerably larger than PS10 and PS20, with a total net capacity of 377 MW_e (Fig. 4). Each unit produces superheated steam at ~540 °C, 160 bar, to drive an air-cooled steam Rankine power cycle at potentially higher

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