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High temperature systems using solid particles as TES and HTF material: A review

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HIGHLIGHTS

- Several issues must be solved to transfer to the market solid particle CSP plants.
- Solid particles combine roles: as TES media and HTF within CSP plants configuration.
- Review of operating conditions and parameters that make solid particles attractive.
- Review about whole system: the storage, heat exchangers and material conveyance.
- Solid particle systems can increase heat conversion efficiency to electric power.

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ABSTRACT

Thermal energy constitutes up to 90% of global energy budget, centering on heat conversion, transmission, and storage; therefore, the technology for harvesting solar energy worth to be developed. One of them is the concentrated solar power (CSP) solar towers where sun-tracking heliostats reflect solar radiation to the top of a tower where the receiver is located. The great advantage of CSP over other renewable energy sources is that energy storage is feasible, particularly when the heat transfer fluid (HTF) is also used as thermal energy storage (TES) material which is the case of solid particles. A lot of development efforts are under way for achieving commercial direct solar solid-particle systems. Solid particle systems for transferring high temperature thermal energy are purposed for increasing the efficiency of these systems when converting heat into electric power. This review recapitulates the concept of these systems taking into account the main receiver designs, particle conveyance, particle storage systems and components, the heat exchanger, and the main challenges that must be overcome to split this technology as a commercial one, especially from the materials availability point of view. This review summarizes the actual status of the use of solid particles for TES and as HTF for CSP Tower, and condenses all the available information and classifies them considering the main functional parts and remarking the current research in each part as well as the future challenging issues.

1. Introduction

Thermal energy constitutes up to 90% of global energy budget, centering around heat conversion, transmission, and storage [1]. Almost all this thermal energy comes directly or indirectly from sunlight. Therefore, the technology for harvesting solar energy is worth to be developed. Concentrating sunlight technologies allow increasing the operation temperature by increasing the type of applications and their efficiency.

Concentrating Solar Power (CSP) potential changes according to the region where is developed. Moreover, CSP can reach up to 11.3% of global electricity production with the appropriate support [2]. The installed capacity of CSP in 2015 reached 4650 MW compared with 1256 MW on 2010 [3]. Global technical potential of CSP amounts to almost 3,000,000 TWh/y against 22,000 TWh/y consumed globally on electricity [4,5]. It is expected that CSP will reach more installed capacity that geothermal [6]. CSP technologies have most favorable potential for North Africa, the Middle East, northwestern India, the southwestern United States, Mexico, Peru, Chile, the western part of China and Australia; and more moderate potential on extreme southern

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Europe, Turkey, central Asian countries, Brazil, Argentina and other locations on USD and China [2,7]. Initially CSP were more developed on Spain and the United States, but recently other markets are developing CSP plants such as de 160 MW plant on Auarzazete, Morocco [6].

Solar energy can be harnessed by different technologies [8,9]. Particularly, CSP with central tower is a promising option because of the high power that can be reached, high efficiency of the power block (due to the high temperatures that can be reached), high land efficiency and large scale heat storage [2,4]. On CSP towers, sun-tracking heliostats reflect solar radiation to the top of a tower where the receiver, or solar absorber, is located [10]. Then, solar heat is transferred to a heat transfer fluid (HTF) in the receiver [11], in order to get the heat energy input into the system. After the receiver captures the heat on the HTF, thermal energy is transported either for conversion or for storage. The energy transport consists on moving the HTF through the system pipe network that connects the storage and energy exchange systems. If the energy conversion takes place on a different cycle, the collected thermal energy is carried away by the HTF that will transfer heat to the electricity conversion cycle (or power block) using a heat exchanger (HEX) [12]. Nevertheless, when the energy is stored for further use on conversion, there are two options to store it: the first is to keep the HTF in a storage device, and the second to use a HEX to store heat in a different media.

Unlike other renewable energy sources (except hydro), solar thermal CSP plants have the inherent capacity to store high inventory of energy (in form of heat) for later conversion to electricity [2] at low cost. In this case, it is desirable that the HTF and thermal energy storage (TES) material is the same.

CSP-TES systems are classified depending on whether it has an active or passive TES, a direct or indirect storage unit, or if the system is open or closed (only for active) [5]. Active TES is divided into direct storage, which refers when the HTF is used as the heat storage medium, and indirect storage, when other material is heated using a heat exchanger in order to save heat [13]. CSP-TES closed systems use controlled pressure and environment inside the system, while open systems use the same outside ambient atmospheric conditions for the control. Finally, these systems can also be classified depending on the kind of receiver used and if the HTF is directly or indirectly (using another material/structure as HEX) irradiated by the concentrated sunlight [14].

The main motivations for developing and enhancing CSP systems are: increasing the temperature (thus making thermal energy to electricity conversion more efficient), decreasing energy losses from receivers (and therefore using a smaller solar field), and using low cost materials that could meet the optimal operating conditions [12]. The current state of the art of the technology that has better commercial application for CSP towers is the one that uses molten salts as HTF [15], and has the advantage that it is also a good energy storage medium [12,16]. The major drawback of molten salt systems is the allowable operating temperature range, which is limited by the temperature of solidification of the solar salt at the low end, and the onset of thermal decomposition and corrosiveness at the high end [17]. Because of this, conventional central receiver technologies are limited to temperatures of around 565 °C [15]. For higher temperatures, molten nitrate salt (the most common salt used) becomes chemically unstable, producing oxide ions that are highly corrosive, which results in significant mass loss [18], and corrosion thru the storage, HEX, receiver and conveyance system [16].

One solution to overcome these drawbacks is using solid particles as TES material and HTF [11]. The solid particle TES system achieves both high performance at high temperature, and low cost from the material perspective [19]. Direct absorption receivers using solid particles that fall through a beam of concentrated solar radiation for direct heat absorption and storage have the potential to increase the maximum temperature of the heat transfer media to more than 1000 °C [20]. A CSP system that operates from 600 °C to more than 1000 °C is possible because of the use of stable materials and the minimized thermal losses due to thermal self-insulation of particles in the storage medium [21]. The material and maintenance costs are expected to be lower for solid media storage systems [17].

Thus, solid particles have three main advantages as storage media, relative to more conventional materials such as molten salts:

- They are chemically inert and stable beyond 1100 °C.
- They are capable of storing energy over a greater temperature span (effectively increasing storage density in a sensible energy-based system)
- They are expected to be relatively low cost.

The first studies on direct absorption solar receivers started in the early 1980 s with two concepts, the fluidized bed receiver and the free falling particles receiver. In the first concept, the solid particles were fluidized in a transparent tube but did not flow outside, there was no solid circulation. In the free-falling particles curtain concept, the solid drop directly into the concentrated solar beam from the top of the receiver, and is heated during the time of its pass through the concentrated radiation. Particle selection and radiative heat transfer modeling have been proposed [22,23]. After about twenty years without significant new developments, this concept has been again proposed as a promising option for a new generation of high temperature solar thermal concentrating plants. Improved models have been developed and validated by on-sun experiments at pilot scale [11,24–28].

This review summarizes the actual status of the use of solid particles for TES and as HTF for CSP Tower applications taking into consideration the main components of the technology: the receiver, the heat exchanger and the TES unit. Moreover, the review condenses all the available information and classifies them considering the main functional parts and remarking the current research in that part as well as the future challenging issues.

2. Solid particle for use on Concentrating Solar Power (CSP)

Several development efforts are under way for achieving commercial direct solar solid-particle open systems. Several studies, simulations, experiments and pilot plant tests have been or are being performed including receiver design, conveyance systems, material storage and heat exchangers. Nevertheless, the solid-particle material itself has been studied according to the plant engineering specifications, and the availability of materials or a formal material selection has not been performed.

The main approach consists in concentrating solar power reflected by heliostats in a central tower, which has a receiver for capturing concentrated sunlight into the solid particles. This particles are moved across a specially designed conveyance system to a first storage, in which material is stored until its moved (by a fluidized bed system) into a heat exchanger (HEX) in order to transfer the heat to a generation cycle. After losing heat, the particle material is stored in a second silo before getting moved again to the receiver [19]. Solid Particle CSP general concept is shown in Fig. 1. This system is similar to the current state-of-the-art molten salts system [29], but almost all the components must be specially designed for working with solid particles.

Current CSP central tower receiver systems are limited to power-cycle efficiencies up to 40%. By reaching temperatures over 650 °C, power-cycle efficiency can increase up to 50–60% by using more efficient thermodynamic cycles that require higher operation temperature (like Brayton cycle) [20,30–32]. Additional to this, cheaper thermal storage will be allowed, lowering the leveled cost of electricity [20].

3. Solar receiver

There are several studies suggesting different designs for particle