Review of solid particle materials for heat transfer fluid and thermal energy storage in solar thermal power plants.

Running Head: Solid particle materials in solar thermal power plants

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Abstract

Current CSP plants that operate at the highest temperature use molten salts as both Heat Transfer Fluid (HTF) and Thermal Energy Storage (TES) medium. Molten salts can reach up to 565 °C before becoming chemically unstable and highly corrosive. This is one of the higher weakness of the technology. Solid particles have been proposed to overcome current working temperature limits, since the particle media can be stable for temperatures close to 1000 °C. This work presents a review of solid particles span style="font-family:'Times New Roman'">candidates to be used as HTF and TES in CSP plants in open receivers. In addition, the interactions between solid particles with major system components are described in this review e.g. with TES system or heat exchanger. The parameters and properties of solid particles are identified from the material science point of view explaining their nature and the relation to the power plant efficiency and lifetime durability. Finally, future development is proposed; such as material selection according to each specific design, materials characterization or durability test.

Keywords: solid particles, CSP, TES, solar tower, granular materials, sensible heat, thermal storage.

Acronyms

CSP - Concentrated Solar Power

HEX - Heat Exchanger

HTF - Heat Transfer Fluid

IEA - International Energy Agency

PSD - Particle Size Distribution

SPR - Solid Particle Receiver

TEM - Transmission Electron Microscopy

TES - Thermal Energy Storage

XRD - X-Ray Diffraction

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1. Introduction

It has been well established that renewable energy have a major role in energy systems development, energy security and climate change fight [1]. In the last years, electricity capacity additions have grown for renewable technologies such as photovoltaic and wind, reaching greater development than coal or gas utilities [2]. Therefore, the total electricity generation from renewables reached 25% in 2018 and is expected to grow up to 40% in 2040 [3]. This can be understood by the current downfall of renewable prices, which is expected to continue with the new International Energy Agency (IEA) expected policies scenario [4] in contrast with the increase of oil prices up to 80 USD/barrel in 2018.

Nevertheless, the variable renewable energies growth has some limitations due to lack of flexibility. Solar and wind production (which are the ones that are being more developed) do not match the electricity daily demand. Other dispatchable renewables such as geothermal, hydropower or bioenergy, have resource limitations either because of geographical resource availability or because of conflict with other human activities (such as agriculture and human consumption) [5–7]. Several strategies have been considered for solving this lack of flexibility, being energy storage one of the most promising. Nowadays, one of the most commercially viable energy storage solutions with high capacity is thermal energy storage (TES) system integrated with concentrated solar power (CSP) thermal plants. CSP central tower can achieve high power, high efficiency in the electric generation cycle due to the high operation temperatures, high land efficiency and enough heat storage to overcome solar energy resource variability [8,9]. Power output in CSP thermal plants is important, which is in part influenced by the operating temperature. Achieving high temperature reflects in an increase of heat to electricity conversion efficiency; therefore, increasing temperature is desirable. Central receiver tower concentrator using molten salts reaches temperatures up to 565ºC - this limit is determined by the molten salt material itself. For higher temperatures molten nitrates salt becomes chemically unstable, becoming highly corrosive and decomposing [10].

Solid particle CSP technology can overcome the molten salts temperature and stability drawbacks, since solid particles are used as TES and heat transfer fluid (HTF) material [11]. The solid particles TES system is expected to have high performance due to the high service temperature, and to the relatively low cost of the material itself [12]. Direct solar absorption receivers, in which particles fall through a beam of concentrated radiation, have the potential to increase temperature of HTF/TES media over 1000 °C [13]. Therefore, a complete CSP solar tower system that operates over 600 °C and up to 1000 °C is feasible, since stable materials are available and thermal self-insulation can minimize thermal losses in the heat storage medium [14]. Finally, media storage system is projected to have cheap maintenance and low material costs [10].

Thus, the main advantages relative to the storage media compared with current commercial molten salts solution can be summarized [13]:

a. Proposed solid particles materials are chemically inert and stable beyond 1100 ˚C.
b. Particles are capable of storing energy over a greater temperature span compared with other media currently in use; thus, increasing the energy storage density.
c. Materials cost is expected to be relatively low.

Proposed power plant configuration can be appreciated in *Figure 1*. The sunlight is reflected and concentrated by the solar field heliostats into a central tower. Particles are flowing through the receiver at the top of the tower, capturing the concentrated sunlight. After reaching the desired temperature, the solid particles are moved by the conveyance system to a hot storage tank, in which the material is collected until it's moved into a heat exchanger (HEX) to transfer the high temperature heat to the power generation cycle [32].

Exhausted heat particles are then moved to a (relatively) low temperature storage tank to be stored until they can be moved back to the solar receiver on the top of the tower to harvest solar heat again [12]. This plant distribution is similar to the current commercial molten salts CSP tower system [15]; however, almost all the components of the plant should be specially redesigned for working with solid particles at high temperature.

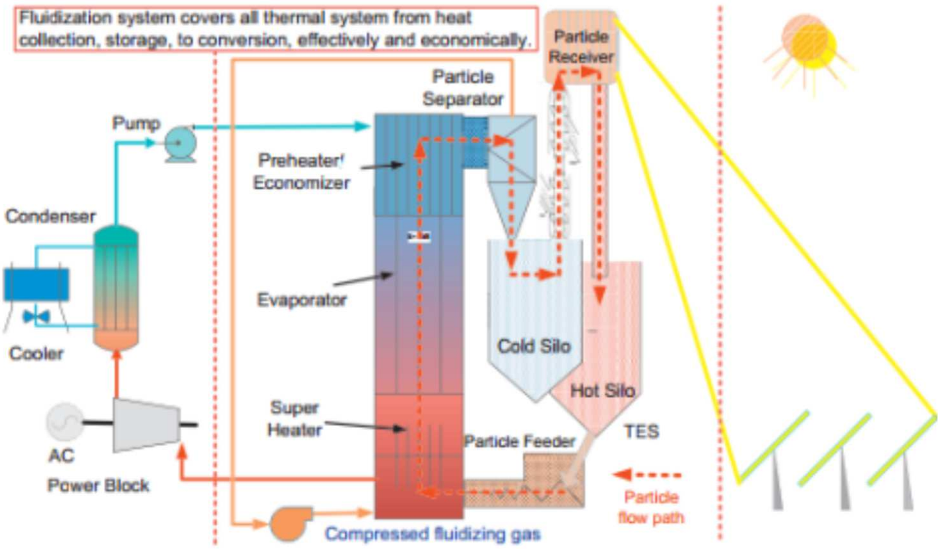


Figure 1. CSP solid particle system with TES and fluidized bed [14]**.**

The main facets involved in solid particle CSP development that have been identified are:

- The receiver design in which particles receive concentrated solar flux and get to the desired high temperature is of great importance. Several designs had been proposed, although some of them are still under development. The most important goal for the receiver is to retain the particles so that they can reach the desired temperature with a high solar absorptance efficiency (either directly or indirectly) [16].
- The Solid Particle TES will allow the power plant to operate at any time and in the most convenient moment (according to the electricity production needs). Reduce heat losses and guarantee silo durability are the main objectives of current research efforts.
- The heat exchanger must provide heat to the power block as quickly as possible and in the shortest possible length. The heat exchanger is expected to be one of the most expensive parts of the system, so making it smaller is highly desirable.
- Particle conveyance considers how to move the solid particles between the receiver, the particle silos and the heat exchanger.
- A solid particle material selection of the must be made to the best meet requirements of each part of the system. In addition, the material compatibility between the particles and the materials of which system parts are built of, must be taken into account.

CSP solid particle technology progress has several challenges. The main concerns that are subject to more study and development are [17]:

a. The complete integration of all concepts. Some functional units are at early stages of study, in contrast to other parts that are much more developed such as solar receiver or heat exchanger. An example of underdeveloped functional unit is the particle conveyance system; even that the energy employed in moving the solid particles through the power plant can seriously affect the energy balance of the plant, and therefore its viability. There is only one reported solar tower developing some integration studies (the National Thermal Test Facility in New Mexico [28,36]); nevertheless, reported studies show that their focus is centered in the receiver concept and heat exchanger design. A full integration study can detect possible conflicts with the working requirements so thathey can be properly solved.
b. Prove the commercial feasibility for each functional part of the plant, including but not limited to the solar receiver, heat storage, heat exchanger, conveyance system and the particle medium.
c. Selecting the optimal materials for solid particles and the system is of big relevance and they must be chosen together, since the interactions between the particles and the components' materials can affect in a great manner the plant and particle medium lifetime and system maintenance cost. Particle media have been suggested and compared in bibliography, but an exhaustive search, selection and evaluation has not been performed. Since there are only a limited number of particle materials that can be used under these high temperature conditions, it is difficult to perform an appropriate materials selection. Selecting materials that are not available reduce the projected viability of the technology. The main desirable characteristics under research for particulate media reported in the literature can be grouped by:
    - ✓ Complete optical characterization.
    - ✓ Research for new formulations to increase solar absorptance efficiency and absorptance durability over time.

✓ Finding ways to reduce abrasion and attrition caused by/to the particles.

This work presents a review of solid particle CSP technology, its importance, its impact compared with current CSP solutions and their interactions with major components of the plant design not only focused on the receivers or other components because this revisions are available in the literature. Thereby, the key overview is motivated on the particle media point of view, interacting with all the components of the system design.

2. CSP components: conceptual design

2.1. Solid Particles Receiver

The most studied functional part of solid particle power plants is the particle receiver, since there are several proposed designs [14,16–27]. Only some of them have been deeply studied, and the most remarkable designs are presented in *Figure 2*. Solar receivers can be classified according to the way they capture solar heat [32]:

a. Direct receivers, in which the particle media (acting as HTF) directly absorb the solar irradiance. These receiver designs make high solar absorptance to be included among particle media desirable properties.
b. Indirect receivers, that use another material to absorb the solar heat and then exchange it to the particle media.

Once classified in direct or indirect receivers, they are divided according to their working principle. On one hand, the most noticeable direct receivers are the free-falling particle, the obstructed flow, the rotating kiln and the fluidized receivers. On the other hand, the most outstanding indirect receivers are the particle flow with HEX and the fluidized indirect receivers .
It is noticeable that there are no material compatibility studies, for any of the reported receiver designs, between the HTF-TES particle material and the material of which the receivers are going to be built with. Future design studies should include the interactions of plant component with the particle media and their stability in the long term. These interactions have been already observed during the receiver prototype development [30], but even then, has been reported no material selection based on them.

The most groundbreaking designs are for direct receivers' design, in which there is an important need to increase the solar irradiation exposure time to reach the desired high temperatures. To decrease radiative losses and reduce exposure time, the solar absorptance becomes and important property, and a high priority for directly irradiated receiver development [31].

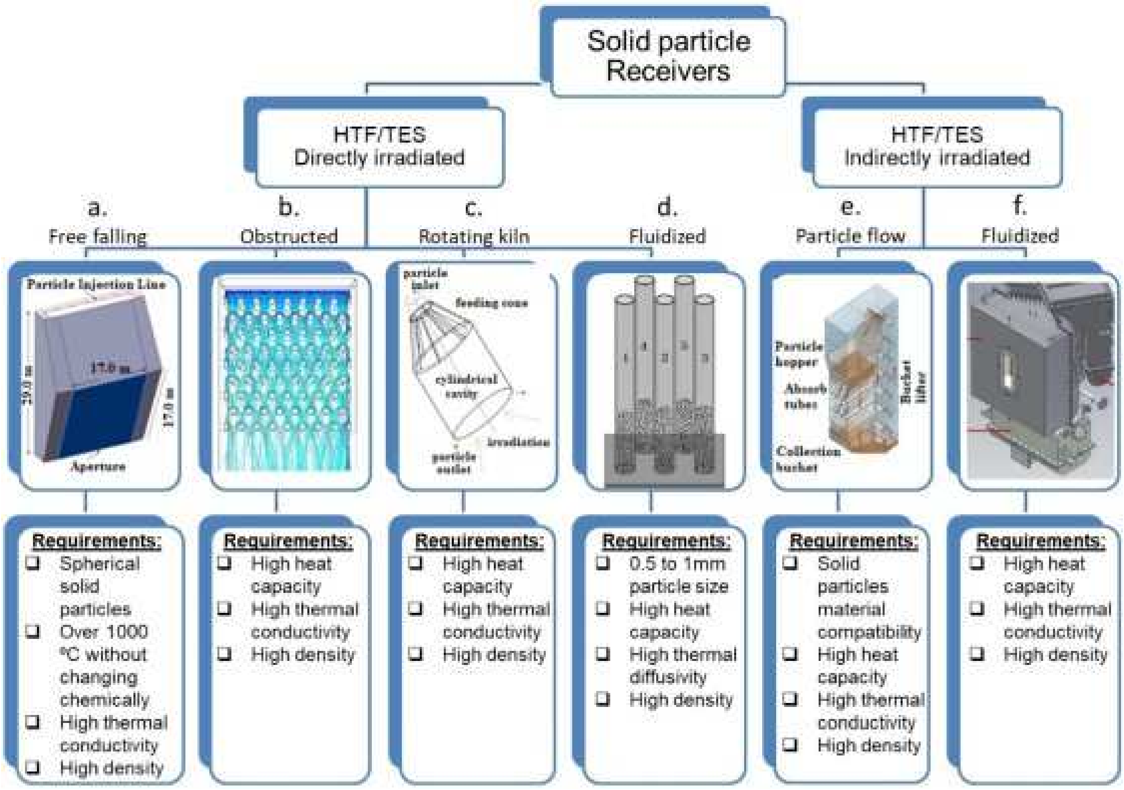


Figure 2. Main parameters and properties for different solid particle solar receivers.

The most relevant receiver designs that are under progress or being designed can be appreciated in *Figure* 2. Their working principles are explained below:

a. **Free falling particle receiver.** In this design, the particle media falls through the receiver in a curtain shape, while an aperture allows concentrated solar flux entering the receiver and thereby heat the particles. Current efforts are centered in researching ways to increase particle exposure to concentrated sunlight [18]. As mentioned before, it is expected that temperature goes over 1000 °C without changing the chemical properties or composition of the material, while additionally achieves high solar absorptance efficiency due to direct solar absorption. It is projected that this design will be feasible for 10 – 100 MW systems [13]. Current studies are centered in [17]:

- ✓ Effects of the receiver aperture size tilt and dimension.
- ✓ Different ways to increase the particles residence time.
- ✓ Develop an air curtain for protecting the receiver aperture.

One option to control residence time is the particle recirculation by making the particles to pass several times through the aperture until they reach the desired temperature [32]. This approach has been modeled and simulations have shown it is effective enough to reach 800 °C; nevertheless, possible particle losses in the aperture must be reduced either by using an air curtain or by any other solution.

b. **Obstructed particle flow receiver.** Another option to increase particle exposure is by mechanically obstructing the particle media flow. Despite of shortage of material properties considerations (heat capacity, density or thermal conductivity), several options have been proposed [16]:
   - ✓ **Ceramic porous structures.** In this option particle media flow by gravity across porous interconnected structures; thus reducing flow speed and allowing more irradiance exposure. Some tests have already been performed on these structures; results show that there should be a previous material selection that can deal with the deterioration over the porous structure at high temperature.
   - ✓ **Porcupine structure.** Theoretically by placing quills inside the solar receiver, particle media flow can be reduced [17]; however, several testing and material selection must be performed to experimentally assure it.

c. **Rotating kiln receiver.** In this receiver centrifugal forces are used to slow particle media fall by making them to impact with the kiln walls. Research is focused in maintaining mass flow stability at a large scale and minimizing the energy spent for moving the kiln [18]. Other considerations are related to the particle attrition effect, since the main force that is delaying media flow is due to friction between the kiln walls and the particles.

d. **Fluidized direct receiver.** Fluidization in the receiver is only possible by controlling the particle flow atmosphere; therefore, to continue working as a direct receiver at high temperature, quartz receivers have been proposed [33]. By controlling particle media flow by fluidization, the solar irradiance over the particles can be increased. A possible drawback that must be studied is the effect of the quartz tube on the solar absorptance of the particle flow. Further studies on different candidate materials show that the particle flow is influenced by particle size, since very small particles decrease the receiver efficiency and very big particles are more difficult to fluidize. Optimal size has been found between 500 a 1000 microns at ambient temperature [33], but it is expected to change at higher temperatures. One improvement compared with other designs is that outside wind has no influence on particle flow.

e. **Particle flow integrated with heat exchanger receiver.** This indirect receiver considers using an special designed heat exchanger (*Figure 2*), in which an array of tubes receive the solar irradiance in their interior surface, heating the particles that flow outside the tubes [18]. It is expected that with this design outlet temperature of the particles can reach up to 900°C. Current studies do not report any material design consideration, not even that they have a central impact on receiver's durability, and on a correct heat exchange and good particle media flow through the receiver.

f. **Fluidized indirect receiver.** This receiver design considers absorbing the solar heat by a mostly black surface (defined by its weighted solar absorptance in the whole solar spectrum length wave). Then, the heat is exchanged to the particle media flow, controlled by a fluidized bed and forcing the particles upwards, increasing heat transfer by convection with the tube walls [18].

2.2. Storage

The original proposed design considers two containers for storing the particle media: a hot and a cold storage. The hot container will hold the particles coming from the solar receiver at high temperature (~800 °C), and will held them until the electricity production is convenient. The cold container will hold the solid particles after they exit the heat exchanger, storing them at low temperature (~350 °C) before sending them back to the solar receiver to be heated up again [34,35]. The cold tank will store the particle media until the solar resource is available for solar heat harvesting.

Current research is focused on two main approaches [10]:

a. Interaction between storage elements and other plant components.
b. Cost reduction of storage containers based on understanding heat transfer processes.

The study of possible thermal losses has been found remarkable, and should be studied for several charge/discharge cycling. Efficient insulation TES systems are important due to the high temperature of the stored particle media [28].

2.3. Heat exchanger

There are several options available for discharging heat from the particle media into the power generation block, such as using fluidized bed or packed bed heat exchangers. The most studied is the fluidized bed, which uses two phase gas-solid HTF flow [12,14,36]. The solid phase corresponds to the particle media while the gas phase corresponds to pressurized air. This design has also been studied for latent and thermochemical storage heat discharge, besides the sensible heat used in particle media [14]. In the past, HEXs have been proven to be useful for integration of solid particles with fluids such as compressed air and steam; nevertheless, no studies on their implementation at high temperatures are found, or on the optimization of working conditions, fitting flow rates such as those used in solid particles CSP, or considering shape and size variations of particles during plant lifetime [22].

Other studies can be found related to gravity driven packed bed heat exchangers that evaluate the heat transfer coefficient under different flows and temperatures. They state that when increasing the flow rate the heat transfer increases as well [37]; but also, when temperature is over 600 ºC heat transfer changes from a linear heat transfer coefficient to a faster one [38]. Another proposed HEX solution has been made by Albrecht et al [29] by using a particle sCO_2 heat exchanger. Predictive numerical models have been performed for moving packed-bed exchangers, finding performance relations with particle size, operating temperature, and flow speed. These models are expected to allow heat exchange simulations after being it experimentally validated.

2.4. Conveyance

Particle transport is considered to be of special importance due to the energy spent in moving the solids. By now, only the particle media lift to the solar receiver has been reported; while other conveyance elements for the rest of media transportation have not been described. For fluidized bed, there are some testing on erosion and corrosion protections, such as weld overlay and plasma spray coatings which have been useful for ceramic materials [12]. A formal material selection must be performed, since the used particle media determines the interaction and durability of the possible materials used for the conveyance system caused by their interaction.

Energy spent in particle lifting is a main concern when considering the whole system viability. Almost all the proposal lifting technologies come from mining industry, such as mine hoists, bucket elevators, pocket elevators, screw conveyors, olds elevators, pneumatic conveyors, conveyor belts, cleated conveyor belts, metallic belted conveyors, En-masse's elevators, bucket wheels, linear induction motor powered elevators, and electromagnetic field conveyors. Nevertheless, only olds elevators, conventional bucket lifts, and pocket elevators have been tested at temperatures above 800 °C and had been considered for efficiency calculations [28].

3. Plant components interaction with particle media

The overall concept in solid particles as HTF and TES for CSP tower was explained in previous sections. The suitable selection of the particle media is one of the most important considerations to evaluate the viability of the overall plant. In order to reach an optimal performance several aspects must be considered, which must be congruent with the desired particle media properties and other design parameters such as low price and high temperature stability [34]. Natural materials or byproducts should be considered due to their low price, while composite materials that can enhance some desired behaviors, must be with caution considered due to their possible high price.

A material selection must be performed to choose the best material available for particulate media [39]. Thus, the main properties and funciontal parameters must be identified before starting any material selection process. Some efforts for indentifying these parameters have been made before [40]; specific heat, thermal shock, thermal conductivity, particle size and shape, and attrition effect have been considered. Nevertheless, further efforts to identify all properties and their interaction on the different parts of the solid particle solar plant have been not found on literature. There are specific requirements for the solid particle material according to functional parts of the plant or to desirable behavior of the solids. In *Table 1*, suggested properties and funciontal parameters are presented according to the mentioned criteria.

Table 1. Desired properties and functional parameters for solid particles for CSP.

	Range	Desired value	Unit	Reference
		Receiver thermal efficiency		
Absorptivity	0.55-0.93	High	%	[28]
Emissivity	0.72-0.88	Low	%	[28]
Particle size	200-1000	ATD*	μm	[26]
Sphericity	0.9	High	parts per unit	[23,26,41]
Roundness	0.9	Low	parts per unit	[42]
		HEX efficiency		
Particle size	160-504	Low	μm	[43]
Thermal conductivity	0.5-2	High	W/m K	[14]
		Thermal energy storage capacity		
Density	2.56-5.37	High	g/cm^3	[44]
Specific heat	621.75-923.36	High	J/kg K	[44]
		Agglomeration		
Sphericity		High		[45]
Size uniformity		High		[43]
Melting point	1135	High	ºC	[46]
Particle size	150-200	High	μm	[46]
Absorptance		Low		[17]
		Sintering		
Melting point	>1000	High	ºC	[47]
Sphericity	0.9	High	parts per unit	[23,26,41]
Roundness	0.9	High	parts per unit	[42]
Size uniformity (mass median diameter)	As much as 0.26	High	parts per unit	[47]
Particle size	200-1000	High	μm	[26]
Agglomeration		Low		[45]
Sintering heat *	>1000	High	ºC	[31]
		Durability		
Sand erosion	0.0001-0.1	Low	%	[34]
Thermal shock degradation		Low		[28]
Mechanical shock degradation	0.004-0.01	Low	%	[28]
		Economic factors		
Price	0.01-17	Low	USD/kg	[17,48]
Sand erosion		Low		
Durability		High		

*ATD: according to the design.

Different approaches for determining the most important functional parameters have been made; sometimes there are focused on a general view of the plant, while in other cases they are analyzed from the perspective of a single functional unit or constraint (HEX, receiver, storage, durability, etc.). In the following sections, different perspectives have been grouped according to the functional unit or constraint, without differentiating the plant design, in order to consider all parameters and properties. Future work should consider these elements for specific material selection according to each type of plant design.

3.1. Receiver thermal efficiency

Some traditional high temperature ceramic materials available in the particle sizes of interest for falling particle receiver development have been considered for evaluation studies. Some of these materials are: alumina, silica, silicon carbide, zirconia, as well as sintered materials such as those used as proppants [16].

For direct receivers, the particle media serve as solar absorber, HTF and TES material. Therefore, optical radiative properties of the particles have a critical role in the receiver overall efficiency. Thermal losses can increase if solar absorptance of the particle media is too low and/or if the emissivity is too high because within this scenario the time of residence of the particles to achieve the desired temperature must be increased, and this fact will increment the energy losses.

Solar absorptance has shown to be a more important parameter to maximize compared to getting down emissivity; meaning that a high emissivity material can be considered as good if solar absorptance is high, while a low solar absorptance material cannot be considered even if its emissivity is low [28].

The fraction of radiation absorbed on material surface is called the absorptance or absorptivity [57]. Absorptance is determined by the amount of light absorbed by a material surface compared with a black body [70], and it depends on the source from which the surface absorbs radiation [71]. Solar absorptance is weighted according to the amount of light received from sunlight into the Earth. *Figure 3* shows the variation of solar irradiance according to each wavelength starting in the ultraviolet, including the visible spectra and finishing in the infrareds.

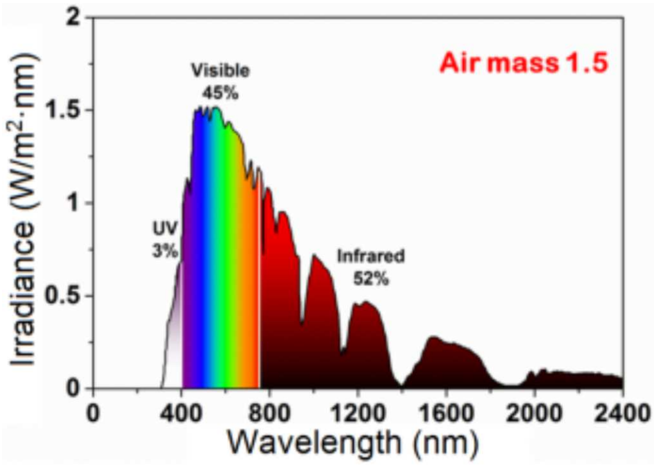


Figure 3. AM 1.5 solar irradiance on Earth [49].

The ratio of the total radiating power of a real surface to that of a black surface at the same temperature is called the emittance of the surface (for a perfectly plane surface, the emissivity) [42]. Emittance is determined by physical properties and temperature of the surface [50]; therefore, the higher the temperature, the higher the emittance. In CSP TES and HTF materials, emittance is undesired through the whole plant, except for the heat exchanger (even that it is not de main heat transfer mechanism) [51].

Thermal heat transfer by thermal radiation is almost immediate, and it depends mainly on the concentrating factor, absorptance, emittance, temperature distribution and scattering medium [52].

Concentrated solar radiation harvesting study is not a new subject, since it has been exploited for solar thermal power (thermal energy), solar thermochemistry (chemical energy), and concentrated solar photovoltaics (electric energy) [53].

Solar concentration ratio is the very first parameter to consider in CSP systems. Desired concentrating ratio defines the configuration and dimension of the solar field. Solar field constitutes one of the main expenses of any kind of CSP technology. Ideal solar irradiance is about 1 kW/m^2 without any concentration. For reaching high temperature the concentrating ratio must be increased in order to limit the radiation losses in the solar receiver [53].

Thermal radiation heat transfer is determined by electromagnetic waves emitted by matter, which changes the molecular energy levels of the receptor material [52]; this is significantly different when compared with thermal conduction or convection which require a material medium to transfer the heat (which is ruled by Fourier's law). Solar thermal radiation used for obtaining solar absorptance include wavelengths between 10^{-7} m and 10^{-3} m (ultraviolet, visible, and infrared), since they are determined by solar irradiance spectrum. In contrast, emissivity relies only in the infrared wavelengths [52]. Since the heat transfer net balance goes from the hotter material to the colder (because of the temperature dependence), the heat transfer relative to the absorptance comes from the Sun, while the heat transferred relative to the emittance is transferred from the particle media to its surroundings.

Heat transfer by conduction and convection has a linear relation to temperature, but in radiation heat transfer, there is a proportional relation to at least the fourth power with the temperature. As a consequence, radiative heat transfer becomes much more important when increasing temperature, overriding the conduction and convection heat transfer [52]. Therefore, there are high potential losses due to radiation rejection and radiation emitted by particle media compared to those from the insulation of the solar receiver.

When dealing with small particles, such as solid particles for CSP, the interaction between the electromagnetic waves and the particles can change when compared to a continuous solid. When dealing with a particle cloud, radiation may be transmitted, reflected or absorbed (as well as in homogeneous solids); but the directions in which the particles scatter the electromagnetic waves depend of particle's shape, size, material, and space between the particles [52]. For idal particles, the shape is assumed spherical or cylindrical when making analysis. Therefore, the solar irradiance electromagnetic waves (or photons) will be absorbed or scattered by diffraction, reflection or refraction [54]. Theoretically, the properties that can be measured on solid materials are extinction coefficient, absorption coefficient, and scattered intensity. For some authors, the easiest property to measure is the extinction coefficient.

In *Table 2* several candidate materials for particle media are presented with their solar absorptance at ambient temperatures and thermal emissivity calculated to 700 °C. These materials include sintered bauxite proppants (CarboHSP®, Accucast® and CabroProp®), fracking sand, and Pyromark® paint (used as reference). The reported measurements were made with a Surface Optics Corporation 410 Solar reflectometer. Absorptance for some of the proppants is relatively high; nevertheless, these results are for particles without any exposure to high temperatures. In *Table 2*, selective absorber efficiency, η, is defined as:

$$\eta = (\alpha Q - \varepsilon\sigma T^4)/Q \qquad \text{(Eq 1)}$$

where α is the solar absortance, Q is the irradiance in the receiver (W/m^2), ε is the thermal emissivity, σ is the Stefan-Boltzmann constant ($5.67\text{x}10^{-8}$ W/m$^2\cdot$K^4), and T is the surface temperature (K). For current suggested particle materials, Q is assumed to be $6\text{x}10^5$ W/m^2 and T is assumed to be 700 ºC (973 K) on the reported analysis.

Table 2. Measured solar absorptance and thermal emissivity of candidate particles and Piromark 2500® paint used as reference [28].

Material Name	**Type**	**Solar weighted absorptivity (parts per unit)**	**Thermal emissivity (parts per unit)**	**Selective Absorber Efficiency (parts per unit)**
Carbo HSP	Sintered Bauxite	0.934	0.843	0.864
CarboProp40/70®	Sintered Bauxite	0.929	0.803	0.862
CarboProp30/60®	Sintered Bauxite	0.894	0.752	0.831
AccucastID50®	Sintered Bauxite	0.906	0.754	0.843
AccucastID70®	Sintered Bauxite	0.909	0.789	0.843
Fracking Sand	Silica	0.55	0.715	0.490
Pyromark2500®	High-Temperature Paint	0.97	0.88	0.897

As mentioned above, solar energy received on an individual particle within a particle curtain is absorbed or scattered. Therefore, if the curtain density is high enough, it is expected that a big part of the scattered energy will be absorbed by surrounding particles. This phenomenon allows current solar absorptance and thermal emissivity measurements to use particle media packed bed model, since the incident wavelengths can be absorbed as well as the scattered reflections. Previously commented ceramic proppants have shown high sphericity and roundness; they are ideal for its use in the Solid Particle Receiver (SPR) since scattered radiation can be easily absorbed with current particles shape.

The main design purpose of proppants is hardness, since it is expected to hold hydraulic cracks open in order to allow oil flow out the impermeable rocks. Proposed proppants are made from sintered bauxite, which is non-corrosive, resistant to sintering by pressure, and cheap due to the large production economic scale. Several different proppant formulations have been evaluated in terms of their absorptance with a mean solar absorptance over 90%. Nevertheless, as-received proppants are not designed for high temperatures and are not stable under oxidation conditions [31]. Oxidation changes color of the proppants when reaching temperatures over 700 °C; this will be discussed in section 3.5, which is focused on particle durability.

Manufacture process, as well as raw materials used for proppants, are the cause of high absorptance. The fabrication steps are not usually published. One example is that the humidity in the air at during the particle sinterization affects the color of propanant (due to the change in oxygen partial pressure). Raw feedstock is processed into powder, which is pelletized producing green particles. These particles are sintered at temperatures over 1400 °C in a rotary kiln in a non-oxidizing controlled atmosphere [31]. The main proppants considered by different research groups are the ones from CARBO Ceramics, including CARBO HSP®, CARBO Accucast® and CARBO Prop® formulas. In *Table 3* CARBO HSP® main properties are presented, while in *Table 4* chemical composition, size, specific heat capacity and measured solar absorptance are presented for other CARBO Ceramics products, as well as Norton Masterbeads®, which is no longer produced but was earlier studied.

Table 3. CARBO HSP® particle properties [23].

Property	Value
Density (kg/m^3)	3560
Median diameter (μm)	697
Estimated thermal conductivity (W/m·K)	2.0
Estimated specific heat (J/kg·K)	$-1.12e\text{-}3T^2 + 2.07T + 264$
Estimated emissivity	0.8
Sphericity	0.9

Table 4. Summary of physical properties of commercially available proppants [31].

Composition/Physical property	CARBOHSP®	CARBOCCUCAST®	CARBOPROP®	Norton Masterbeads®
AlO_3 (wt%)	83	75	72	86
SiO_2 (wt%)	5	11	13	3
TiO_2 (wt%)	3.5	3	4	4
Fe_2O_3 (wt%)	7	9	10	7
Others (wt%)	1.5	2	1	-
Mean diameter [μm]	697	300	443	~600
Heat capacity [J/kg^3·k	1275 (700 ºC)	1175 (700 ºC)	1175 (700 ºC)	-
Bulk density [g·cm^3]	2.0	2.0	1.88	1.76
Weighted solar absorptance (%)	93	91	89	94

These proposed particles are engineered materials for high pressure applications; nevertheless, they exhibit high absorptance and durability while remaining useful for temperatures over 1000°C [35].

For falling particle receiver different particle size media have been tested between 200 and 1000 microns. It has been found that smaller particles result on a bigger receiver solar aperture if the same operation conditions remain. The study suggests that particle media selection must consider manufacturing issues, since too small particles can lead to mass flow loose through the concentrated sunlight aperture [26].

For direct fluidized bed receivers a two-phase suspension with small particles is considered, which flows vertically through the absorbing tubes to harvest solar thermal energy. For previous reported testing the particle media used was silicon carbide. This material was chosen due to its high sintering temperature, high specific heat capacity, availability and intermediate cost (depending on the literature reference) [11,12]. Silicon carbide media average diameter also allowed good fluidization quality with low velocities, which yield to parasitic electric charges reduction.

3.2. Thermal energy storage capacity

For thermal storage, the thermal capacity of the storage media should be as large as possible (equation 2); *Table 5* show values for iron ores and some slags. However, a high real density will penalize the fluidization, since materials with high density require more energy to get to the minimum fluidization speed, u_{mf}. This minimum speed can be compensated with a smaller particle size in order to keep the design velocity constant no matter the material used. On the other hand, as has been commented on section 2.1, too small particles can be negative for fluidization as well. Finally, smaller size will have a negative effect on sintering, as will be explained on section 2.6.

$$\varepsilon = \rho c_p \qquad \text{(Eq 2)}$$

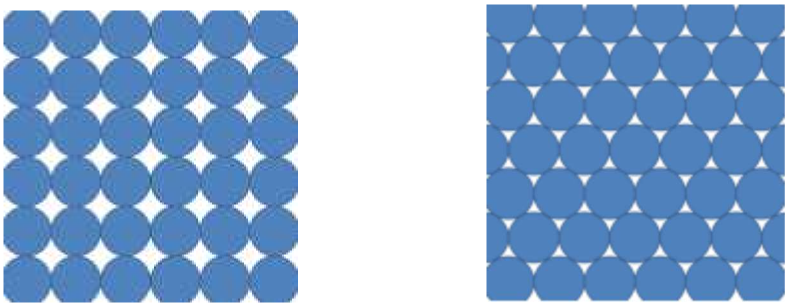
Table 5. Potential storage media [36].

	C_{pm} [J/kgK]	ρ [t/m³]	Ɛ=ρCp [J/cm³·K]	U_{mf} [mm/s] 50 µm	U_{mf} [mm/s] 100 µm	U_{mf} [mm/s] 150 µm
Quartz SiO_2	742.13	2.65	1.97	2.5	8.5	17.2
Feldspar						
Albite $NaAlSi_3O_8$	782.16	2.62	2.05	2.4	8.5	17.0
Microcline $KAlSi_3O_8$	727.19	2.56	1.86	2.4	8.3	16.6
Anorthite $CaAl_2Si_2O_8$	759.85	2.76	2.10	2.6	8.9	17.9
Mica						
Muscovite $KAl_2(AlSi_3O_{18})(F,OH)_2$	818.71	2.83	2.32	2.6	9.1	18.4
Fluorphlogopite $KMg,AlSi_3O_{10}F_2$	812.83	2.88	2.34	2.7	9.2	18.7
Pyroxene						
Jadeite $NaAl(SiO_3)_2$	791.29	3.35	2.65	3.1	10.6	21.8
Diopside $CaMg(SiO_3)_2$	768.96	3.28	2.52	3.0	10.4	21.3
α-Spodumene α-$LiAlSi_2O_6$	853.89	3.19	2.72	2.9	10.2	20.7
β-Spodumene β-$LiAlSi_2O_6$	874.85	2.38	2.08	2.2	7.7	15.5
Iron Ores						
Hematite Fe_2O_3	650.31	5.28	3.43	4.7	16.3	34.2
Magnetite Fe_3O_4	651.25	5.20	3.39	4.6	16.0	33.8
Slags						
Aluminium oxide, Al_2O_3	761.05	3.97	3.02	3.6	12.5	25.8
Magnesium oxide, MgO	923.36	3.58	3.31	3.3	11.3	23.3
Manganese oxide, MnO	621.75	5.37	3.34	4.7	16.5	34.8
Titanium dioxide, TiO_2	687.73	4.23	2.91	3.8	13.2	27.5

Specific heat capacity is the quantity of heat needed to raise the temperature one degree Celsius per gram of sample at constant pressure [55]. This property is inherent to each material, and is different according to the physic state of the material and for each temperature.

Specific heat is of great matter due to its relation to the storage energy density. When combining it with bulk density, it has a major role in determining the size of the heat storage container and to the charge/discharge time. For ceramic materials (which are the most commonly suggested materials for solid particle CSP) the specific heat is between 0.75 and 1 J/g·K [45]. For example, specific heat for granite is 0.79 J/g·K at 25 °C.

Real density of particles is the mass of the material related to its volume, excluding porosity and empty space between particles. On the other hand, bulk density (also known as apparent density) includes the space between particles and the pores (open or isolated) of the material itself. Because of this, bulk density for packed solid particles is closely related to the pack arrangement of the particles [56]. Density variation can be appreciated in *Figure 4*, depending on the way the particles are packed.



(a) (b)

Figure 4. Loosely packed (a) and tightly packed (b) particles.

It can be expected that in particle storage a bulk density gradient can be formed, having tightly packed particles in the bottom of the storage, since material pressure from above help to pack the particles below them [57]. This phenomenon must be considered for avoiding sintering since area contact and pressure increase can enhance sintering. Density values are highly important to be taken into account that will define the energy density of the material and the final total heat storage capacity of the system.

The first suggested particle media is silica sand, since it is a natural product, abundant, available all over the earth crust, it's an inert material, and with a good thermal energy storage capacity. It is mostly made of SiO_2 and has been used as TES material for other applications [34,58]. Also, silica sand can be easily presented in a large variety of size distribution and, since it is used for fluidization technology, the correlations used in fluidization engineering are valid [36]. Thereby, Diago et al. [59] suggested silica sand as storage medium although the calcium content of the sand must be controlled since the highest the calcium content, the highest the sand agglomeration in the receiver. An alternate option to overcome agglomeration is to use two type of sand, a commercial silica and a foundry sand made from olivine [34]. The originality of this system is that it uses a combined sand conveyor and a HEX called Sand Shifter. Test results of this system are shown in *Table 6*. From these results the Sand Shifter system costs are estimated in *Table 7*.

Table 6. Preliminary heat transfer results [34]**.**

Material	Heat transfer ($W/m^2 \cdot K$)
Silica sand over flat plate	310 - 400
Silica sand over finned plate	212 - 405
Olivine sand over flat plate	550 - 925
Olivine sand over finned plate	376 - 635

Table 7. Sand shifter TES system costs [34]

	Storage (hours)				
	2	4	6	8	10
Kind of storage	System costs ($\$/kWh_{th}$)				
Shifter, silica	165	91	68	57	51
Shifter, olivine	128	75	59	51	47
Alternatives (high)	100	100	100	100	100
Alternatives (low)	70	70	70	70	70

3.3. HEX efficiency

From the HEX point of view, the parameters to consider include their thermal and mechanical stability, material properties, performance of fluidization and flowability (either for fluidized or packed bed), understanding of the heat transfer and heat exchange design, and material handling knowledge. Also, other factors that should be considered are grouped to be included into the selection process [14]:

a. Factors that influence in the fluidized bed system performance, stability, and energy density. Some of the properties reported that affect these factors are composition, softening temperature, density, specific heat capacity, mean particle size, particle size distribution, and void fraction.
b. For packed bed solutions, a high packing density with a high heat capacity is desirable. In addition, high resistance to agglomeration and sintering is important for durability considerations. Resistance to mechanical and thermal shock is important due to the high mechanical and thermal stresses that the particles receive in the heat exchanger [16].
c. Factors related to particle size. Although the particle size has little influence in the storage, it has a big influence in the heat transfer, either for indirect receivers or for the heat exchanger performance. It is

expected that smaller particle sizes have a better heat exchange performance for most of the cases; however, there is a limit for fluidized bed heat exchange in order to get the higher heat transfer coefficient.

d. Another factor is related to the fluidized bed boiler, which separates gas/solid phases. This element is influenced by the particle size and density relation in order to get the best possible performance.

Thermal conductivity and specific surface area are related to the HEX size and therefore, to its building cost. The thermal conductivity represents the relation between heat transferred and the temperature difference given a certain material thickness. This can be appreciated in the one dimensional equation:

$$Q = k \cdot \frac{\Delta T}{L} \qquad \text{(Eq 3)}$$

where L is the thickness, Q is the thermal energy, k is the thermal conductivity value and ΔT is the temperature difference between the beginning and end of the conducting material [60].

As shown in *Figure 5*, the molecules in two bodies at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions. Thermal conductivity is related to the heat exchange rate for charging (at solar receiver) and discharging (at heat exchanger), and it is considered one of the main properties that are not related directly to the particle durability [14].

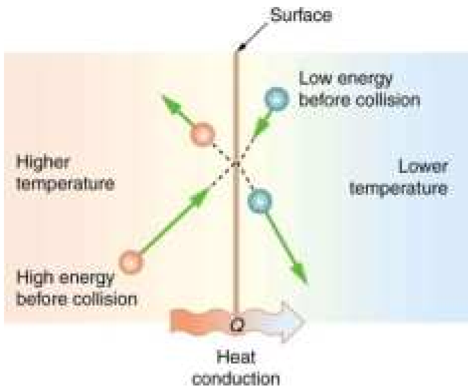


Figure 5. Molecule kinetic energies interaction during thermal conductivity [61].

The relation between the surface area of a solid and the mass contained in it is defined as the specific surface (surface area divided by the mass), including the exposed pores in the material [79]. Particles with high specific surface can favor a quick discharge in a convective heat transfer (such as in fluidized bed heat exchangers). Specific surface for some concrete particle materials are presented in *Figure 6*.

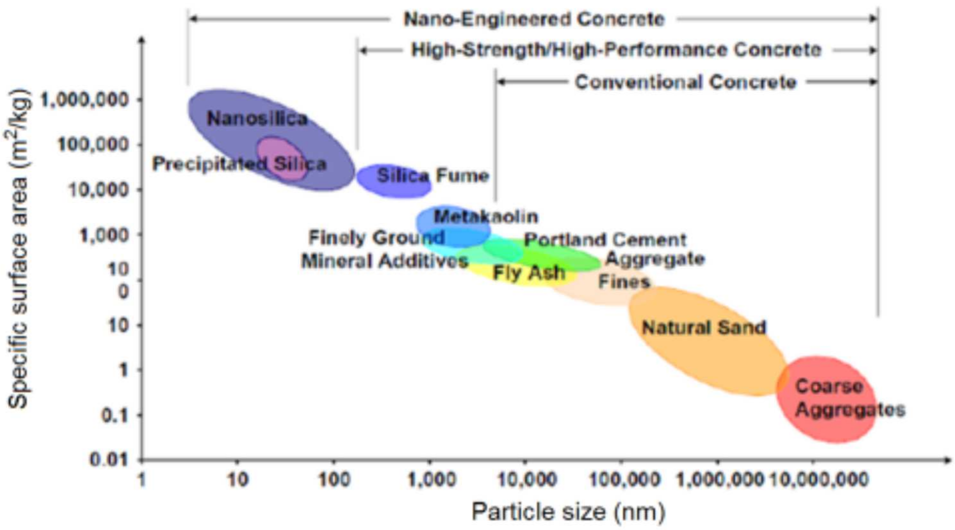
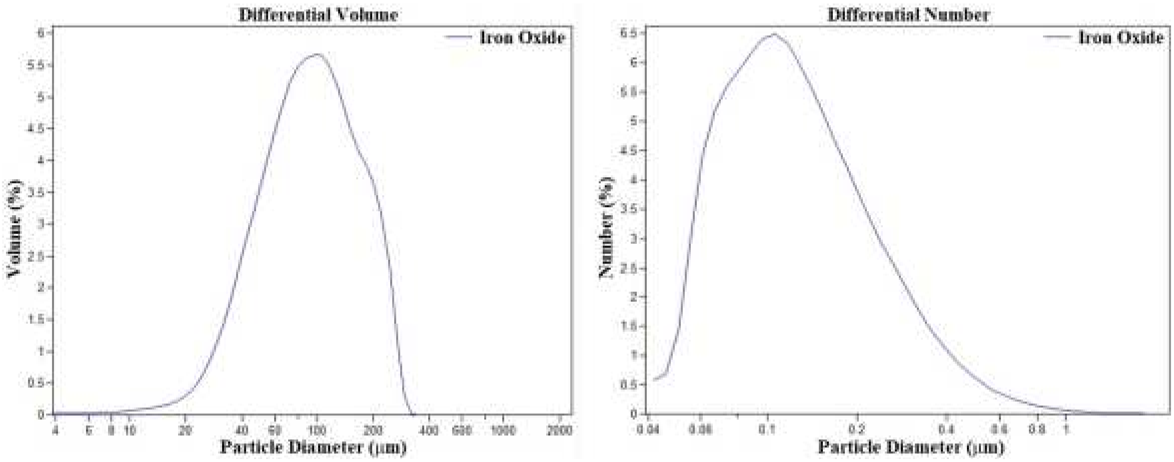


Figure 6. Specific surface area for different concrete materials [62].

In practice, it is not common to find particle materials that are monodisperse, even that it is desirable for solid particle CSP. The reality is that knowing the mean size is not enough to make an enhanced analysis of the material; therefore, a complete distribution analysis is desirable. Particle Size Distribution (PSD) can be analyzed by volume or by number; each one of both interpretations has its advantages [63]. For example, determining PSD by number can easily detect smaller particles, which cannot be seen in a PSD by volume. An example of both ways to analyze PSD results is shown on *Figure 7* for the same sample.

Knowing the size distribution in the particle material is a very useful way to measure and predict solid particle material stability. PSD is an important indicator of quality and performance, and values like mean, median and mode are used to determine the kind of distribution being measured [64]. An increase in bigger particles and a decrease in the smaller ones can indicate sintering, while a decrease in bigger particles and increase in smaller ones can indicate particle rupture. Also, removing particles can help to avoid possible sintering, since smaller particles increase packing and contact area between the particles [45].



(a) (b)

Figure 7. Example of PSD by volume (a) and by number (b) for the same sample.

Some materials have been proposed considering them from the heat exchanger point of view, such as silica sand and fly ash. Since fly ash has Al_2O_3 in its composition, it has a high thermal conductivity and stability when compared to silica sand even that both are low cost and have good thermochemical stability [12]. Some of the proposed materials properties can be appreciated in *Table 8*.

Table 8. Solid-particle materials considered to be used on the heat exchanger [12]

Material	Composition	Cost	Benefits	Concern
Silica sand	SiO_2	Low	Stable	Low thermal conductivity
Quartz sand	SiO_2	Medium	Purity	Quartz inversion
Alumina powder	Al_2O_3	High	Stable	High cost
Fly ash	SiO_2+Al_2O_3	No/low	Experienced	Containing Corrosive minerals
Silicon carbide	SiC	High	High thermal conductivity	Hard surfaces
Graphite pebble	C	High	High specific heat	Oxidization, easy attrition

Other material challenges for particle media from HEX perspective suggested by Zhiwei Ge et al. [65] include: high energy density, great durability, large temperature range, improved thermal properties, and low cost. Also, Geldart et al. [44] suggested a classification founded on material's performance based on particle mean diameter and on material's real density. They concluded that if the particles are too small they cannot be easily fluidized. A diagram was created to classify the particles in A-aeratabel, B-sand like, C-cohesive and D-spoutable; as consequence, optimal materials to be fluidized should be type A and type B granular materials. Other observation was made by Schwaiger et al. who concluded that a higher heat capacity has more benefits than higher real density [36].

Some artificial or sintered materials have been considered, such as crushed fire bricks or powder made of heat resistant coatings. These materials are easy to fluidize, have high specific heat capacity and high density. Main composition for both of them includes aluminum oxide (Al_2O_3) (~2/3) and magnesium oxide (MgO) (~1/3). Actually, it has been proposed to try to minimize particle density so that air needed for fluidization can be reduced as well as the parasitic energy consumption. The main disadvantage for artificial or sintered materials is that the price is expected to be higher compared to natural o byproduct materials.

3.4. Erosion evaluation

When moving particle media there are two phenomena that create particle attrition, the first is the inter-particle collision, and the second is the interaction between the particle media and the walls (either of the conveyance, HEX or SPR systems) [69]. The greater attrition effect is expected on the HEX fins and tubing, but can be important on fluidized bed receivers and some of the particle elevators previously considered.

Roundness and sphericity define the factor shape of particles, and it is an important factor (together with material hardness) that determines the erosion damage to the system. Roundness define how smooth are the edges of the particle, while sphericity defines the relation to its three orthogonal axes [66]. Mathematically, the sphericity can be defined as:

$$Sphericity = \sqrt[3]{\frac{\textit{Particle volume}}{\textit{volume of a sphere that completely surrounds the particle}}} \quad \text{(Eq 4)}$$

While roundness can be calculated by:

$$Roundness = \frac{\textit{Average radius of corners and edges}}{\textit{Radius of maximum inscribed circle}} \quad \text{(Eq 5)}$$

A table guide was proposed by Krumbein et al. in 1956 [67], and showed in *Figure 8*, makes more easy to identify the sphericity and the roundness based on the particle appearance.

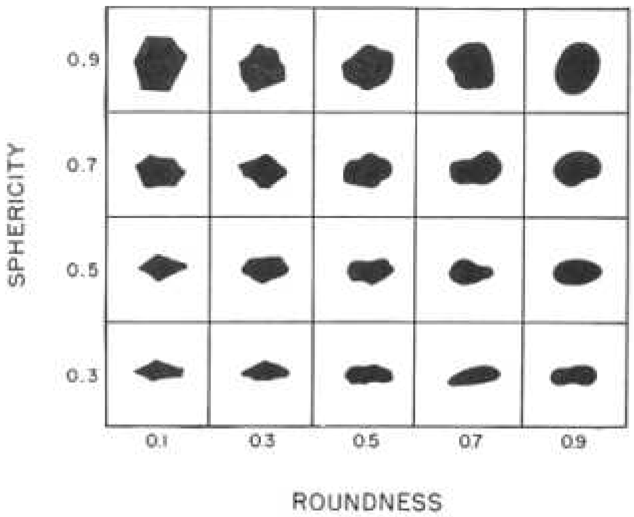


Figure 8. Sphericity and roundness classification [67].

Some studies have made analysis by mass measurement at periodic attrition intervals using silica sand as particle media. The results indicate that copper tubes with aluminum fins experience wear in short time, while copper tubes with steel fins took more than ten times longer to experience the same wear. Early results showed that, by using silica sand, a steel HEX tube can lose only 1% of its mass. When using olivine for evaluating the erosion on the previous described scenarios, no significant wear was found [52]. This suggests that there is a dependence on the combination of materials used for the system and the particle media; hardness (that has a variation with temperature) and shape can have critical influence when evaluating wear.

Erosion effect on the falling particle receiver has been evaluated within the collection hopper and other structures. Loss of less than 0.004% mass was reached by particles velocities below 7 m/s. For velocities of more than 10 m/s loss exceeded 0.01%. The attrition was expected to be high for the first cycles, as the surface of the particles may not be too smooth. The particle media used for the evaluation of the erosion on the falling SPR was proppants, which have high roundness and sphericity, but high hardness [51].

A suggested alternative for reducing wear on falling receiver is to buffer the particle impact by using some of the previously studied porous structures. Nevertheless, it has been appointed that for these structures the attrition effect must be mitigated when considering the ceramic material to be used. Also, curved structures made of resistant ceramics have been suggested for slowly decelerate the particles fall [51]. From the particle media point of view, the fracture resistance tests show that there is a critical impact velocity related to the compressive stress and fracture toughness of the particles. This impact fracture is more relevant for particles with reduced sphericity and roundness [42].

3.5. Particle durability

When evaluating particle media durability for CSP, we must consider that the high temperature conditions will remain years while residing on the thermal energy storage tanks. Some studies suggest that there should be a regenerating process for the particle media; nevertheless, the complexity and energy required has not been evaluated as far [31]. Another effect on durability is the one caused by the stress generated by quick temperature variation and continuous heat charge/discharge cycles. This effect must be further studied since there are no reported works on this matter.

Since proppant materials proposed are primarily composed by sintered bauxite, the variation between them from the chemical composition point of view depends on the ratio of alumina to silica and to the minor oxides present. It is expected that a material used for direct solar irradiance harvest, should have at least 85% of solar absorptance. When considering particle media durability, long term heat effect must be considered, since a minor variation in composition can lead to considerable solar absorptance variation. Solar absorptance characterization has been performed to the previously mentioned proppants after up to 200 hours heat treatment at 700 °C and 1000 °C. Absorptance and emissivity variation can be appreciated on Figure 9 for several proppants. At 1000 °C, CARBO HSP® changes considerably after only 24 hours, dropping from 93% to 91%, while emissivity decays from 85% to 84%. In contrast, at 700 °C the change takes place considerably slower [48].

At long term, the absorptance can be reduced below 85% critical point at 1000 °C, while for 700 °C remains above 92%. Composition analysis by X-Ray Diffraction (XRD) showed evidence of small chemical transformations in the bauxite crystalline phases, containing oxides of aluminum, silicon, titanium and iron. These results suggest that there are changes on the oxidation state without a related phase change [51].

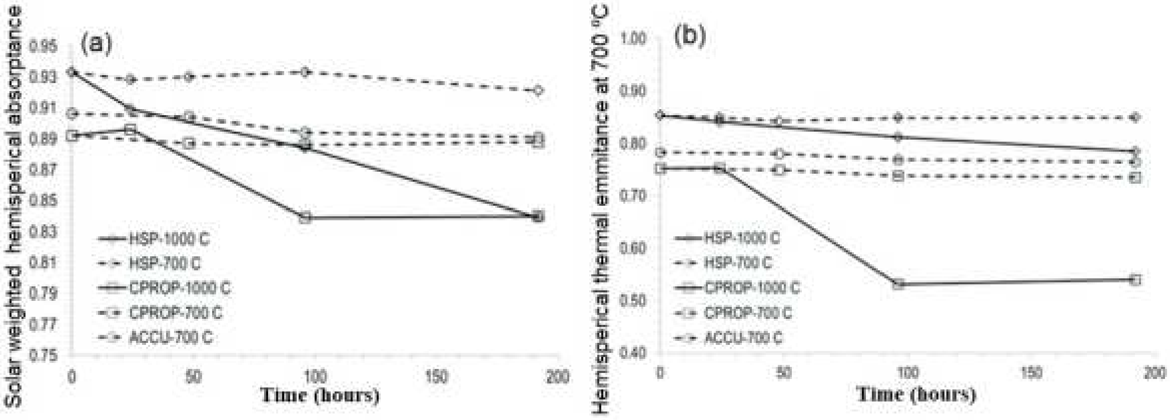


Figure 9

(a) Solar weighted hemispherical absorptivity for three proppant candidates as a function of heating duration; (b) hemispherical thermal emissivity as a function of heating duration [31]**.**

When making the thermal treatments under a chemically reducting atmosphere (5% H_2 in either N_2 or Ar) the solar absorptance increased for either as-received particles or previously degraded particles [31]. Absorptance variation can be appreciated in *Figure 10a* and color change on the particles in *Figure 10b*.

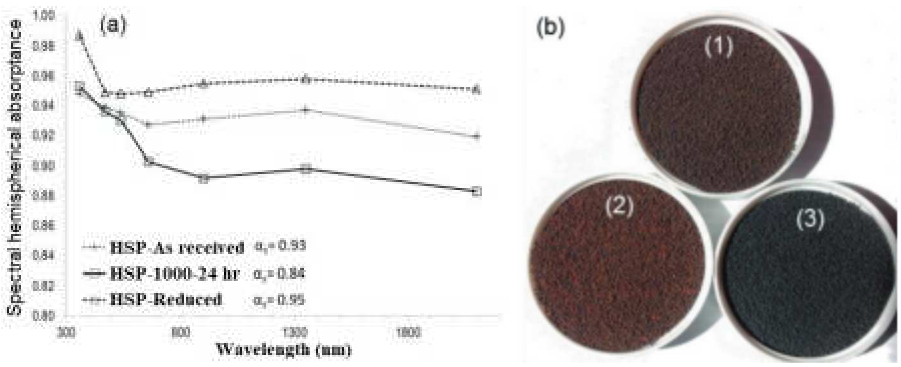


Figure 10. (a) The spectral hemispherical absorptivity of chemically reduced CARBOHSP® (700◦C for 20 hours) compared to as received and heat treated samples; (b) images of CARBOHSP® in the (1) as received condition, (2) after heating in air at 1000 ºC for 24 hours, and (3) after chemical reduction [31]**.**

Sintering happens when material small particles (or powder) transform into a solid body without melting the original material, no matter if it is composed of crystalline o amorphous structures. This phenomenon can seriously affect particle shape and size distribution; therefore, it affects the particle media durability. Sintering is enhanced by high temperatures, high pressure and high contact surface between the particles and the amount of time these conditions are applied over the particle media [62].

Agglomeration happens when there is a radical rearrangement of particles; it is more noticeable in metals and solid ceramics. Agglomeration is considered an early stage of sintering, since it is one of the conditions that favor sintering. Several experiments and simulations have shown that strength, shape, mean size and size distribution affect the evolution of the microstructure on agglomeration process and then on sintering process [61]. A particle size distribution with a big standard deviation causes the smaller particles increase the contact areas, as well as they are more vulnerable to get sintered into a bigger particle. For solid particle CSP the main objective is avoiding agglomeration and sintering, and the most vulnerable moment for particles to agglomerate or sintering is at the lower part of the hot tank storage.

For characterizing the degree of agglomeration of one sub-section of particle media there is a parameter called "variance", for which the effects of particle size distribution and inter-particle viscosity are analyzed [61].

Agglomeration research has found that alumina, silica and zircon have the best behavior when being used between 1000 °C to 1200 °C. There has also been found that there is a relationship with solar absorptance, since low solar absorptance indicates that the particle media can behave better on agglomeration issues. Therefore, further studies on material selection and research has to be performed to find a good balance for these contradictory conditions.

Determining agglomeration by experimental or theoretical research has been found difficult since agglomeration occurs with smaller particles, broader particle size distribution, higher temperature, smaller tangential viscosity or smaller initial volume fraction [42]; therefore, even having different initial particle size distributions it can still lead to different agglomerations.

Melting point of a solid is the phase change from solid to liquid. For solid particle materials for CSP it is very important because this change should be avoided during materials lifetime.

For ceramic materials, low melting points (even if it is over the service temperature) can indicate possible agglomeration and sintering problems. Sintering is enhanced with pressure, temperature and/or surface area increase. For ceramic materials, sintering temperature is close to 70% of the melting point temperature [45]. Sintering process can be appreciated in *Figure 12* (concept model) and *Figure 11* (TEM image).

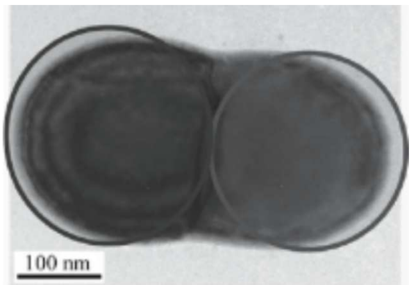


Figure 11. Si particles partially sintered [45].

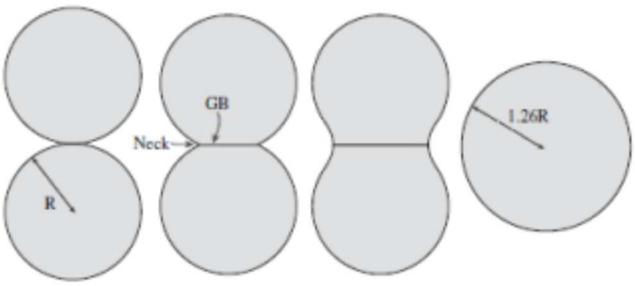


Figure 12. 2D 4 step sintering model [45].

Other solid-solid phase change must be considered and studied for the service temperature range, since they can result in a density change that can modify the particles physically, causing rupture or increasing the specific surface (increasing the possibility for chemical reactivity).

4. Summary of properties of solid particle materials

Table 9 and *Table 10* summarize the solid particles properties which are available in the literature. Therefore, absorptance, thermal conductivity, specific heat, density, and price are listed in this table in order to compare the proper candidates available to be used as solid particles for CSP plants.

Table 9. Summary of solid particle optical properties, cost and density to be used for CSP
where, α - absorptance, ε – emissivity, ρ – bulk density.

Material	Composition	α	ε	Cost (eur/kg)	ρ (g/cm^3)	Reference
Silica Sand	92% - SiO_2 06% - Al_2O_3 <1% - Fe_2O_3 <1% - K_2O <1% - TiO_2	0.44 - 0.66	0.59 - 0.9	0.35 - 0.52	2.1 - 2.65	[36,68–73]
Hematite	98% - Fe_2O_3 01% - FeO <1% - Mn_2O_3	0.85	0.56	N/A	5.28	[36,74,75]
Silicon Carbide	SiC	N/A	0.83 - 0.96	12.3 - 17.5	3 - 3.2	[68,71]
AccucastID®	75% - Al_2O_3 11% - SiO_2 03% - TiO_2 09% - Fe_2O_3	0.906	0.754	N/A	N/A	[28,31,72]
CarboHSP®	83% - Al_2O_3 05% - SiO_2 04% - TiO_2 07% - Fe_2O_3	0.934	0.843	N/A	3.56	[23,28,31]
Alumina	Al_2O_3	0.1 - 0.25	0.3 - 0.5	28.1 - 35.1	3.94 - 3.96	[36,71,76]
Zirconia	95% - ZrO_2 04% - MgO	N/A	0.42 - 0.62	15.8 - 22.8	6.03 - 6.16	[71,77]
CarboProp®	72% - Al_2O_3 13% - SiO_2 04% - TiO_2 10% - Fe_2O_3	0.89 - 0.93	0.75 - 0.80	N/A	1.56	[28,31,78]
Titanium Dioxide	99% - TiO_2	0.4 - 0.7	0.5 - 0.8	21 - 31.6	3.97 - 4.05	[71,76]
Magnesium oxide	MgO	N/A	0.2 - 0.5	29.8 - 43.8	3.54 - 3.58	[36,71,76,79]
Manganosite	98% - MnO 1.7% - MgO <1% Fe_2O_3 + FeO	N/A	N/A	N/A	5.43	[75,80–82]
Olivine	42% - MgO 39% - SiO_2 19% - FeO	N/A	N/A	35 - 43	2.8 - 3.37	[71,83]
Fly ash	88% - SiO_2 05% - CaO 02% - Al_2O_3 <1% - Fe_2O_3	N/A	N/A	0.03 - 0.14	1.83 - 2.2	[71]
Graphite	C	0.84	0.98	9.47 - 14.4	1.61 - 1.67	[69,71,74]
Basalt	48-59% - SiO_2 15-18% - Al_2O_3 07-12% - Fe_2O_3 06-09% - CaO 04-05% - Na_2O 03-05% - MgO	N/A	0.72	2.01 - 2.22	2.5 - 2.89	[68,71,84]

01-02% - TiO_2

Table 10. Summary of solid particle thermal properties to be used for CSP
where, k – thermal conductivity, C_p – specific heat capacity.

Material	Melt point (°C)	Service temp (°C)	k (W/m-℃)	C_p (J/kg-℃)	Reference
Silica Sand	1200 - 1400	400 - 600	1.14	742 - 1175	[36,68–73]
Hematite	1565 - 1597	N/A	N/A	650	[36,74,75]
Silicon Carbide	2150 - 2250	1470 - 1540	90 - 110	663 - 677	[68,71]
AccucastID®	N/A	N/A	0.7	1175	[28,31,72]
Carbo HSP®	N/A	N/A	2	1275	[23,28,31]
Alumina	2050	977 - 1030	20 - 25.6	790 - 800	[36,71,76]
Zirconia	2550 - 2700	2150 - 2250	1.7 - 2	418 - 436	[71,77]
CarboProp®	N/A	N/A	N/A	1175	[28,31,78]
Titanium Dioxide	1830 - 1850	1570 - 1640	4.8 - 9.2	683 - 697	[71,76]
Magnesium oxide	2810 - 2860	1980 - 2130	30 - 60	880 - 1030	[36,71,76,79]
Manganosite	1945	N/A	N/A	621- 788	[75,80–82]
Olivine	1870 - 1950	778 - 821	8 - 10	700 - 900	[71,83]
Fly ash	1270 - 1470	873 - 973	1.11 - 1.25	813 - 867	[71]
Graphite	3530 - 3680	2580 - 2690	44.2 - 48.3	852 - 941	[69,71,74]
Basalt	1410 - 1490	500 - 850	0,03 - 0,04	840	[68,71,84]

5. Conclusions and future work

The use of solid particle materials has big potential for developing a new generation of solar power towers. This new technology can enhance CSP thermal power plants to reduce electricity cost production as well as adding flexibility to the electric network, allowing a bigger renewable energies implementation. This technology will benefit highly irradiated regions, which happens to be the most expected regions to be developed during the following years increasing their energy needs over the world's average.

Incrementing current CSP service temperature has shown to have performance benefits when converting heat into electricity in the power block, by being able to use more efficient thermodynamic cycles or even use combined cycles using exhausted heat from topping cycle as input for one or more bottom cycles.

Current solid particle technology development has proven to be viable in the specific functional units balance (solar particle receiver, HEX, thermal storage). Nevertheless, further studies must be performed for conveyance and storage systems, since the most advanced research has been made on solar particle receivers and heat exchangers. Also, material considerations must be taken into the account, since the different parts of the power plant design expect different properties and parameters to be met by the particle media.

Future work should include:

a. Material selection according to each specific design (direct/indirect receiver, free falling or fluidized receiver, fluidized or packed bed heat exchanger, etc.), and needs to be optimized considering tradeoffs of particle properties in the major components. Therefore, there are properties that are in contradiction with others. For example, the mean size of the particles must be high to avoid sintering and agglomeration but must be low to facilitate heat transfer within the heat exchanger. Hence, the selected materials must present a compromise that fit all the requirements from the different parts of the system.
b. Thermal stress tests due to the high temperature itself in the long term and to the high number of charge/discharge thermal cycles expected during power plant lifetime (up to 11,000 is expected, that is one cycle per day during 30 year standard power plant lifetime). This behavior will influence particle media durability.
c. Mechanical stress tests due to possible attrition and erosion caused by/to the particle media and the plant built in materials.
d. Complete characterization of the best materials obtained from material selection, since most of the properties and parameters are expected to change because of the high temperature exposure, to the thermal cycles, and to the interaction with the plant functional units.

Finally, once best candidate materials have been completely studied, material combinations or material enhancement can be considered to level up the possible drawbacks of the best material selected.

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