A review on the potential of fluidized bed for energy storage in CSP

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Abstract

In renewable source energy storage is essential to reduce the mismatch between power supply and demand. This study presents a review of fluidized bed technology used for energy storage in solar power plants. The distinct technologies, particles and processes are showed and analyzed in order to bring an embracing view of the novel technologies that can be implemented in a CSP plant. The use of particles as a heat transfer material in a CSP plant has some advantages as being able to operate at higher temperatures, up to 1000°C, and the fact that the process of heat absorption does not need to occur at high pressure, thus avoiding the high capital investment in pipes and vessels. Particles used in direct and indirect receivers are stable, with low cost and high availablity and with high alowable temperature which in fact increase the power block efficiency. When fluidized bed tequiniques are implemented the storage can be sensible, latent or thermochemical, the advantages and chalenges of this technology is reviewed in this work.

Keywords: Energy storage, Fluidized bed, Concentrating solar power

1. Introduction

Many efforts have been made recently to exchange the way of power generation. A global movement claims for the use of renewable energies as the main sources of electrical energy to supply the needs of modern society. Energy storages is one of the key areas that can substantially enhance the incorporation of renewable energy into modern energy systems, the answer to respond to an increasing need of power supply in a safe and sustainable way. The commercially available and economic feasible energy storage technologies are: pumped hydro storage, batteries, adiabatic compressed air storage, gas/liquid storage and thermal energy storage.

Pumped hydro storage (PES) as the most used technology so far, has a 99% share of worldwide storage capacity (Abele et al., 2011) and has advantage of high cycle efficiency with approximately 70-85% and 40 years lifetime although is intensive in capital investment and has restrictions in site selection (Luo et al., 2015).

Electrochemical cells or batteries had a great technology progress in the last decade, and they have been the main choice to store energy of decentralized energy systems mainly because of its safety, simple installation and maintenance and high energy density, conversely its use in central power systems shows some issues as lifetime based on limited cycles, high investment and the possibility to have toxic materials to environment.

An option commercially available and known as an utility-scale storage technology is the adiabatic compressed air storage (A-CAES) (Azzuni and Breyer, 2018). The CAES systems use the excess electricity to compress ambient air and pump it to a cavern or pressurized vessels and later on running the pressurized air through a turbine to generate electricity during demand periods (Rouindej et al., 2019). As demonstrated by Chen et al., 2009, the A-CAES round trip efficiency is around 43% and it has compatibility with renewable power generation. The specific geographical needs, such as salt deposits and hard or porous caverns, could cause a lack of opportunity to this technology since in most cases the best renewable resources site is far away from the nearest storage location.

The possibility to convert electrical energy into chemical compounds is also an opportunity to store energy, most chemical compounds which are used as energy storage media has higher energy density than pumped hydro and CAES (Aneke and Wang, 2016). The main gases/liquids considered to be employed as energy storage materials

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are: methane and hydrogen. Hydrogen is produced by the water electrolysis and methane can be produced from the hydrogen in the presence of CO or CO_2, this impacts in the need of a water resource near the facility.

Azzuni and Breyer (2018) investigated five different ways to store energy: PHS, TES, batteries, A-CAES and bulk storage for gas/liquid and they concluded that TES systems have a high level of energy security, the capability to both small- and large-scale implementation and easily adaptation to varying load demands.

There are mainly three different technologies in a TES system: sensible, latent and thermochemical. Sensible heat storage is the most common technology and is widely used in industrial plants (Pelay et al., 2017). Latent heat storages make use of PCM and have the advantage of higher energy density when compared to sensible storage. Thermochemical storages are based on reversible reactions and because of the high energy density, up to ten times greater than latent storage (Pardo et al., 2014), and the minimized loss of energy over time (Pelay et al., 2017) can be a great choice in the near future.

Regardless of the storage technology there are a variety of HTF considered on current CSP plants. Oil and molted salt have been widely used in power plants constructed in the last decade, oil with a limited maximum operation temperature up to 400°C and molten salts up to 565°C. As an alternative DSG power plants were introduced in 1983 where the water/steam is the HTF in both blocks (solar field and power) eliminating the need of heat exchangers and increasing the efficiency of solar plant (Biencinto et al., 2016).

An alternative to increase plant efficiency – higher HTF temperature up to 1000°C- is the use of solid particles as HTF. Usually these particles store sensible energy by increasing their temperature, PCM materials can eventually be used too. One way is to integrate solid particles into a solar power plant by using a fluidized bed technic, where the solid material can be the storage material or an alternative where it can be both the storage and the HTF itself, absorbing the energy collected at the solar field. Ho (2016) reviewed the different technologies of particles in central receiver power tower plants and classified them in two categories direct heating and indirect heating technologies. It was seen that the use of particles can operate over a wide range of temperatures without freezing or decomposition problem, they are inert, widely available and inexpensive.

In this paper a comprehensive review about storage systems that take advantage of fluidization techniques applied in high temperatures particles, including sensible, latent and thermochemical technologies are considered with main attention to the newer research and experiments. A brief description of design and methods of direct and indirect heat receivers are introduced and their performance analyzed.

2. Fluidized Bed

The use of fluidized bed as thermal storage began in the 80's. Flamant and Olalde (1983) compared the behavior of packed and fluidized bed as solar thermal storage and they conclude that fluidized bed has the best results. Elsayed et al. (1988) designed and built an air-sand test bed model and studied the dependence of efficiency varying time, temperature and heat recovery.

Fluidized beds are widely used in the chemical and process industries for a large variety of processes. In order to improve design and scale-up procedures of fluidized beds, a sound understanding of the transport phenomena in these systems is crucial. This knowledge can be imported into the energy storage sector.

Swaiger and Haider (2013) in their research pointed several advantages about applying solid particles as energy storage to CSP plants, as: low cost, no freezing, no corrosion, local availability and high allowable range of temperatures. Swaiger and Haider (2014) simulated the operation of a sensible (preheating/superheating) and a latent heat exchanger (evaporation/condensation) involving powder sand in a fluidized bed system with positive results, as a disadvantage it was pointed the combination of latent temperature difference with a sensible behaving material. Sakadjian (2015) developed a research under solar particle receivers under high temperatures focus on fluidized bed where HTM (heat transfer material) or solid particles act as both heat transfer and energy storage. In their study a fluidized bed heat exchanger was used to transfer the heat received from solar field to the working fluid of power cycle on a bed of fine solids (< 100 micron average size) and it was showed the feasibility of fluidized bed heat exchanger to be applied at different power cycles: SubC Rankine, SC Rankine, Brayton S-CO2 and Brayton Air.

Investigations on thermochemical thermal storages applying fluidization techniques was also performed. Chen et al (2018) in a thermochemical energy storages review concluded that conventional reactors increasing the life cycle and heat availability in chemical reactions. De Miguel (2017) shows that fluidized bed seems to achieve a better result when compared with packed beds in thermochemical storages because of the homogenizations caused by the gas flow. Flamant et al. (1980) designed and built an experiment with reversible reaction of calcite and compared the process between rotary kiln and the fluidized bed where the results showed a 100% decarbonation in the FB and 60% for the rotary kiln.

Pardo et al. (2014) compared different storage processes for thermochemical TES of $Ca(OH)_2$ powder, the chemical reaction is based on a reversible reaction with temperatures around 450ºC, where CaO is hydrated and dehydrated to perform the exothermic reaction. In their research 50 cycles were performed and the feasibility of storing thermal energy was shown. An energy density of 60 $kW.h.m^{-3}$ has been reached. Kunii and Levenspiel (1991) brought fluidized bed advantages in thermochemical storage the high heat transfer, homogeneous temperature and the possibility of forward and backward reactions in the same reactor.

2.1 Fundamentals

As it was stated by Kunii and Levennspiel, 1963 "fluidization is the operation by which solids are transformed into a fluidlike state through suspension in a gas or liquid." In an experiment with a gas running through fine particles if the gas velocity is not high enough to move the particles this is a fixed bed or packed bed. When the gas velocity is increased, and all the particles are just suspended by the gas flow, the bed is fluidized, and this is the minimum fluidization velocity at this moment the weight of particles is counterbalanced by frictional force between particle and gas. Depending on the velocity of the gas, the dimension and density of the particles the fluidized bed can be smooth, bubbling, slugging (axial and flat) or turbulent. This phenomenon and its characteristics can be applied in thermal storages and in direct and indirect heat receivers on solar plants.

2.2 Sensible Storage

Sensible energy storages can be categorized according to the type of storage medium in a passive and an active heat storage medium. The active is characterized by forced convection where the heat transfer fluid circulates in the solar field and it can be stored directly or indirectly. In the direct systems the solar field HTF is itself stored in a vessel, unlike that in the indirect system the fluid responsible to collect heat in the solar field is going to transfer this energy in a heat exchanger to another fluid which is going to be stored in the thermal energy storage. In the passive heat storage, the medium is fixed and the heat transfer fluid flows through it transferring its energy to the storage material, usually a solid one. The three main sensible energy storage technologies in a power plant are: steam accumulator, direct active two tanks and active indirect two tanks.

The main HTF options in CSP plants are thermal oil with a limit temperature of 400ºC due to fluid degradation above that value, or alternatively molten salts with a current limit of 565ºC for Plants like Gemasolar 19MWe in south of Spain,. Another issue on working with fluids is the high pressure necessary to reach acceptable thermal cycle efficiency. In case solid particles as a HTF are used with following advantages: no need of intermediate heat exchangers leading to reduced energy losses, high temperature limit in central receiver power plants, reducing high stresses in vessels due to high pressure. Ho (2016) classified the receiver design in: direct and indirect particle receiver, where both can use the technics of fluidized bed to transfer energy from solar irradiation to solid particles.

Almendros-Ibáñez et al. (2018) in his review summarized the main process of solid particles HTF studied so far, an research conducted by Flamant and Olalde (1983) analyzing the efficiency of packed and fluidized bed in solar systems and they conclude that FB has a higher absorptance, the advantage of uniform temperature distribution and a higher heat transfer when compared with packed beds. The main reason for higher efficiency in FB when compared with packed beds is the IR losses (can reach 70%) due to high temperature on the bed surface. At the same review, Almendros-Ibáñez et al. (2018), presented the prerequisites for FB achieve effective application on CSP plants, these conditions were proposed by Salatino et al. (2016) and they are: minimization of parasitic energy losses associated with fluidized state, high thermal diffusivity and maximization of surface heat transfer.

2.2.1 Direct and Indirect Particle Radiation

In the direct particle radiation two schemes are used in CSP reflector systems. Matsubara et al. (2014) presented a comparison between conventional tower system and beam down reflector, (fig 1). The beam down reflector is the most used in many investigations (Almendros-Ibáñez et al., 2018) and has advantages of lower pumping power requirement and it's easier to perform any maintenance operation.

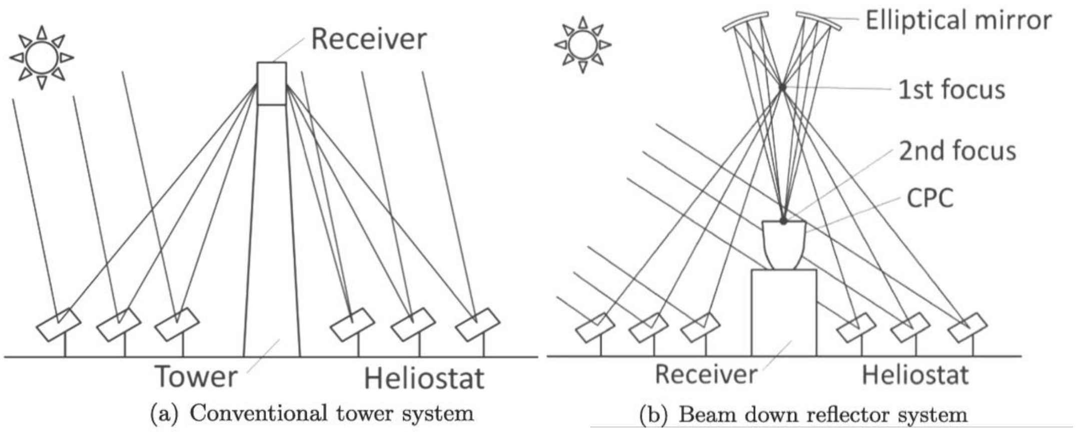


Fig. 1: Matsubara (2014) designs of direct particle radiation.

As can be seen in Fig. 1 the ratio area between the secondary reflector and the primary field (heliostat) impose a high temperature on the secondary reflector even though the material used in this mirror is highly reflective. As a solution to this problem Gomez-Hernández et al. (2017) proposed a Fresnel system where the ratio area between heliostat and second mirror are reduced and the temperature of particles increase linearly in a horizontally fluidization process (fig. 02).

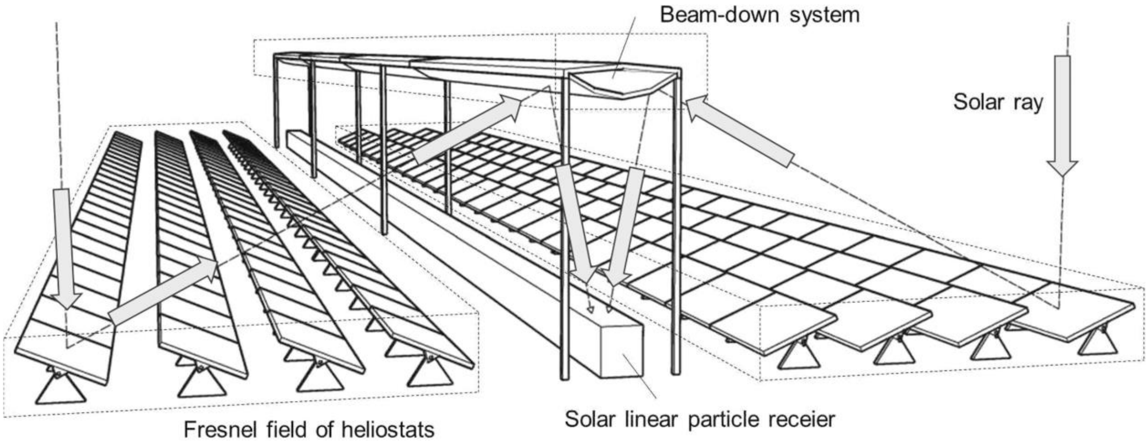
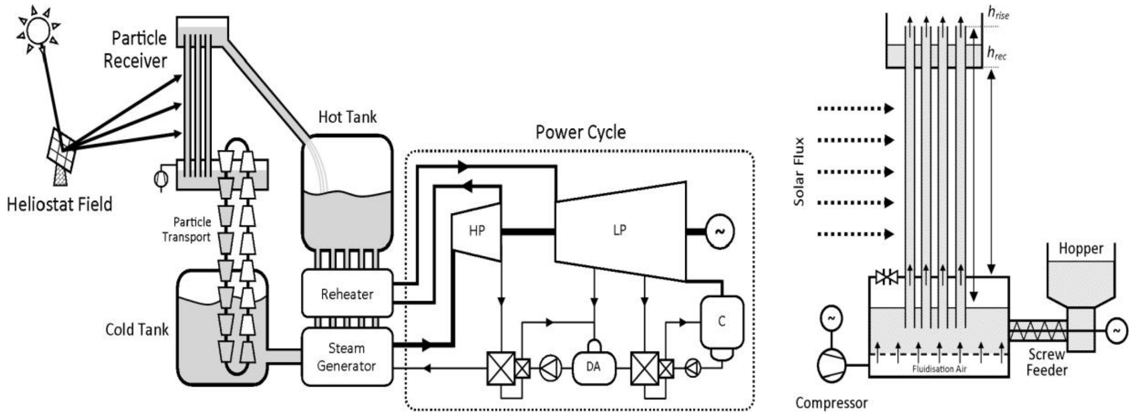


Fig. 2: Fresnel direct particle receiver proposed by Gómez-Hernández et al (2017).

Reyes-Belmonte et al (2019) in his recent work presented a novel indirect particle receiver based on dense particle suspension principle. The designed system begins in a storage hopper with cold particles feed the air driven fluidized bed formed by tubes onto which the solar energy is going to be absorbed. The fluidized hot particles are taken to a heat exchanger where energy will be transferred to the working fluid to the power block.

To the best performance from this novel particle receiver Reyes-Belmonte et al (2019) indicated some requirements as very small particles – in this experiment Silicon Carbide with diameter 63.9 µm was used - low fluidization velocities and a high particle volume fraction enabling the fluidized material to have a density similar to that of a liquid thus maximizing the heat transfer coefficient. Low speeds have the advantage of reducing auxiliary pumping power, minimizing components abrasion and particle attrition. This configuration reached on a computational simulation a receiver efficiency of until 82.3% in a power plant of 22.1 MW_{th}.

In Figure 3 is possible to see in detail the concept brought by Reyes-Belmonte et al (2019) where the number of tubes is a function of an energy balance between the energy received from the solar field and the thermal characteristics of the fluidization material. The optimized system proposed by Reyes-Belmonte et al (2019) achieved an efficiency of 41% at Rankine cycle and a 23% sun-to-electricity efficiency.



(a) Power plant

(b) Particle suspension receiver

Fig. 3: (a) Concentrated solar power plant (b) Detail from particle suspension receiver by Reyes-Belmonte (2019).

Miller et al. (2019) presented a counterflow fluidized bed of oxide particles whith a design based on the idea of maximizing the heat transfer coefficient and in this way minimizing the wall receiver temperature and consequently the irradiation losses. In order to demonstrate the potential of application they designed and build a prototype of a particle receiver with a net-downward-flowing particles in a narrow vertical channel where a upward-flowing fluidizing gas is applied.

In the experiment proposed by Miller et al. (2019) an inert oxide particle made by Accucast ID 50 was used and the heat transfer coefficient was indirectly measured varying the fluidized conditions as solid volume fraction and superficial gas velocities. The novel design receiver experiments resulted in a high heat transfer coefficient of 1000 W m^{-1} K^{-1} when the gas velocity was between 2 and 4 times the minimum fluidization velocities.

The design proposed by Miller et al. (2019) differs from other experiments mainly because the HTF flows from the top to the bottom of the bed with an upward gas flow. Such structure has the advantage to facilitate the gas-particle separation enabling easier particle collection and reducing thermal losses in the thermal energy storage.

Figure 4 shows the main components of the proposed particle receiver heat transfer test. The particles were stored in a hopper above the fluidized bed where the particles were preheated at 600ºC, then the particles by an controlled orifice were introduced in a narrow vertical channel – receiver. The particles exit from the bed by a button orifice which has its area controlled in order to set the amount of particles inside the bed.

The solar receiver performance test demonstrated a robust operation from the counterflow arrangement over a broad range of conditions with very low gas-to-particle mass ratio, an average of heat transfer coefficient of 1000 W $m^{-2}K^{-1}$ at gas velocities of no more than twice the minimum fluidization velocity and it was showed the possibility of integrating the heat exchanger inside the bed maximizing the efficiency as the heat transfer over a fluidized bed is 3 to 4 times better than that of a fixed bed.

Table 1 resumes different materials widely used in experiments and investigation in the last years. Flamand (1982) has study this topic broadly using different materials (sand, silicon carbide,zirconia) as particles. The characteristics of the particles are an important step in the reactor design, where the knowledge of the size of particle and its density are important parameters to define the fluidization conditions, as well the radiation coefficients emissivity and absorptance can help in the numerical assessment of thermal losses by irradiation in direct and indirect heat transfer reactors.

2.3 PCM Storage

Latent heat thermal energy storages were described by (Abhat, 1983) as “the storage of heat as the latent heat of fusion in suitable substances that undergo melting and freezing at a desired temperature level”. A large number of organic and inorganic materials with the required thermodynamic characteristics have been studied so far, known as phase change materials – PCM – they have the advantage, compared to sensible heat storage, to have three times the energy density thus being able to store more energy in a smaller volume.

Tab. 1: Characteristics of Particles used in CSP Systems. Adapted from Almendros-Ibáñez (2018)

Material	**Geldart**	**Diameter (mm)**	**Density** (kg/m^3)	**Emissivity**	**Absorptance**	**Other**	**Reference**
Silicon Carbide	D	< 0.72	3×10^{-3}	1	0.9	Maximum Temperature: 1920 K	Flamant and Olalde (1983)
Zirconia	D	< 0.60	5.2×10^{-3}	0.5	0.5	Maximum Temperature: 2700 K	Flamant and Olalde (1983)
Ceramic Particles ($NiFe_2O_4/mZrO_2$)	-	0.21 – 0.71	-	-	-	Maximum Temperature: 1700 K	Matsubara et al. (2014)
Silicon Carbide	B	< 0.127	3210	-	-	-	Tregambi et al. (2016)
Silicon Carbide	-	0.0639	3210	-	-	Specific heat: 1.150 kJ kg^{-1} K^{-1} Thermal conductivity: 109 W m^{-1} K^{-1}	Reyes-Belmonte et al. (2019)
Carbo Accucast ID50		0.260	3230	0.754		Specific heat: 1.218 kJ kg^{-1} K^{-1} Thermal conductivity: 0.7 W m^{-1} K^{-1}	Miller et al (2019)

Another contribution from PCM is the increasing of thermal efficiency from the characteristics of the exchange energy process, in a sensible energy storage there is a significant temperature difference from charging (condensation) and discharging (evaporation) processes resulting in an exergy efficiency loss (Ferreira, 2018) as the maximum available work occurs at the highest temperature . As a solution to increase storage efficiency is the use of latent heat storages, as the overall heat transfer process occurs at an isothermal condition.

Despite the advantages presented by latent heat reservoirs there is no significant research in the use of PCM in a fluidized bed operating at high temperature. In the review presented by Almendros-Ibáñez, et al. (2018) the experiments involving PCM materials applied in reservoirs of a solar process were in an environment where the temperatures were lower than that needed in CSP plants. In Izquierdo-Barrentos et al.(2015) a granular phase changing composite (Rubitherm-GR50) was analysed from different aspects, involving the variation of fluidization velocity, the possibility and results of a storage being charged with hot air and discharged with water inside a coil immersed in the bed and the beneficial results of keeping the bed fluidized during discharge, besides the benefits of their results all of this research is focused on a reservoir temperature of about 50ºC witch is insufficient in power plants.

Almendros-Ibáñez et al. (2019) cited in his review several researches based on the performance of a fluidized bed with a liquid as fluidizing agent. Sozen et al. (1988) analyzed the heat storage efficiency and the heat transfer coefficient of an encapsulated mixture of 96% Glauber’s Salt/4% borax in a hollow polypropylene 25 mm diameter sphere in a liquid fluidized bed operating between 20 – 40ºC.

The comparison between fixed and fluidized bed developed by Beemkumar et al. (2017) was cited by Almendros-Ibáñez et al. (2019) where spheres with 100 mm diameter filled with D-mannitol and a liquid fluidizing agent Therminol-66 as heat transfer fluid, as results is shown the increase of energy transfer in fluidized when compared with packed beds.

Until now, few studies analyzed the use of PCM material in fluidized bed, Izquierdo-Barrento (2014) developed a research on energy storage with PCM in fluidized beds, the materials used in their experiments were sand and a granular phase change composite (Rubitherm®-GR50), the heat transfer was modeled and compared with experimental data which presented a good agreement mainly for slow heat rates of the bed. Even though this PCM temperature is in the range of 50°C and cannot be taken to power generation.

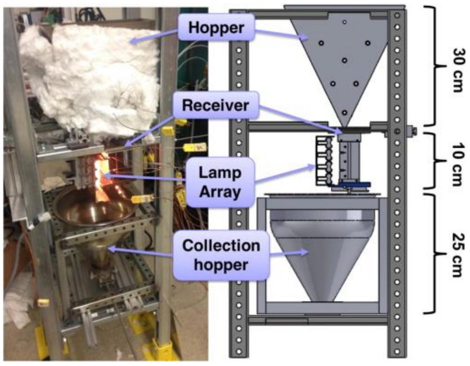


Fig. 4: Particle receiver heat transfer prototype by Miller et al. (2019).

2.4 Thermochemical Storage

Thermochemical energy storage is a technology that has a high energy density and a low thermal loss over time thus enabling this kind of storage to be taken in CSP plants. Chen et al. (2018) in a thermochemical energy storage review concluded that this technology has a "greater possibility for stable and efficient energy generation" based on the study of different technologies and materials as hydride, metal oxides and organic systems.

Almendros-Ibáñez et al. (2018) cited the research from Flamant (1982) who compared the performance of a rotatory kiln and a fluidized bed in a thermochemical reactor (decarbonation of calcite) for CSP application where they concluded that fluidized bed reaches higher thermal efficiency. Pardo et al. (2014) studied a reversible reaction $Ca(OH)_2/CaO$ and had as main difficulty the gas channeling and fissures in the fluidized bed due to particles sizes (1-15 μm). As a solution, Pardo et al. (2014) proposed to mix alumina particles (171.7 μm) in a proportion of 70% alumina 30% calcium hydroxide.

Chen et al. (2018) cited the two main hydroxide systems used for thermochemical energy storages $MgO/Mg(OH)_2$ and $CaO/Ca(OH)_2$ and reviewed investigations only with calcium hydroxide due to its exothermal temperature in the range of 623 to 1173 K. Most of all investigations used a fixed bed reactor in $CaO/Ca(OH)_2$ systems (Chen et al., 2018). It was mentioned on Chen et al. (2018) review the research from Schauble et al (2013) where a upscaling of fixed bed reactor was considered uneconomical due its poor thermal conductivity and large pressure drop being an alternative the use of fluidized bed.

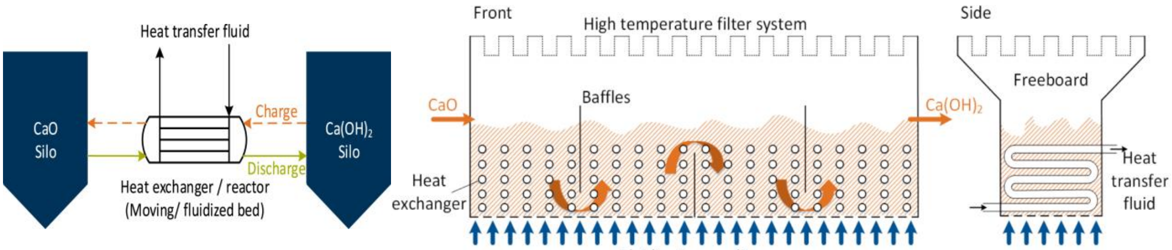
As an alternative cited in different investigations (Flamant, 1980; Almendros-Ibáñez, 2018; Benitez-Guerrero, 2017) the use of carbonate salts as $CaO/CaCO_3$ because its abundance on earth and high energy density besides. It is known that a chemical reaction performance on a thermochemical storage can be measured by cycle life and heat storage capacity. Lu et al. (2016) experimentally demonstrated a cycle life increment when $CaO/CaCO_3$ is mixed with Li_2SO_4 solution – 3.0 to 5.0 wt% from 27.3% in pure material to 51% in the mixture. Wu et al. (2008) suggested a nano CaO/Al_2O_3 composite and found out a maximization of cyclic conversion of 68.3% after 50 runs at 800ºC. Another technic that could increment the cycle life of thermochemical storage with calcite is the periodic hydration of CaCO3 such action improve the cycle stability by increasing grain volume and porosity result of a greater volume of $Ca(OH)_2$ per molar than CaO (Valverde, 2017). In this case, it was related by Blamey et al. (2016) that the hydration was more suitable in fixed bed than fluidized bed due to the energy loss in a fluidized environment.

In general, a gas-solid reactor can be classified in four groups: fluidized bed reactor, fixed bed reactor, moving bed reactor and entrained flow reactors. The main objective of this article is to focus on fluidized bed reactors and the novel designs presented to maximize the heat transfer coefficient and heat storage capacity. Angerer et al (2018) "Fluidized bed reactors have the advantage of better heat and mass transfer compared to moving bed reactors and require significantly lower gas velocities compared to entrained flow reactors they have been widely proposed for thermochemical energy storage”. Angerer et al. (2018) presented a reactor designed to fulfill the follow requirements: scalable into multi MW scale, enables storage of energy and capacity and high heat transfer between bed and heat exchanger.

Tab. 2: Storage characteristics of different thermochemical materials

Material	**Commercial Name**	**Energy Density** (kWh/m³)	**Temperature Range** (°C)	**Reference**
Mg/MgH_2	Magnesiun Hydride	580	200 – 500	Chen et al. (2018)
NH_3/H_2	Ammonia	745	400 – 700	Chen et al. (2018)
$CaO/Ca(OH)_2$	Calcite	693	350 – 900	Pardo (2014)
$CaO/CaCO_3$	Calcite	437	700 – 1000	Flamant (1982)

Figure 5 shows the reactor proposed by Angerer (2018), where it is easy to see that the heat exchangers are separated from storage material. The fluidized bed operates under a bubbling bed. The gas is distribute uniformly with high velocity and turbulence reducing the channeling and agglomeration which is an usual problem with small particles. To improve the particle residence time within the reactor baffles are used. As no abrasion is expected with the use of $CaO/Ca(OH)_2$ the heat exchangers are located inside the bed, packed into the bed as dense as possible without compromising the fluidization environment. The idea proposed by Angerer, (2018) is to charge the storage by applying an electrical heater (dehydration) and a discharging with heat exchangers and working fluid. In their study, a 100 m³ reactor was used to deliver power to a 15 MW power plant, with a steam generation at 100 bar and 450º C.



(a) (b)

Fig. 5: (a) Scheme of thermochemical storage (b) detail of fluidized bed inside the thermochemical reactor proposed by Angerer et al. (2018)

2.5 Materials/Particles for thermal bed storage systems

One of the key issues of both packed bed and fluidized beds is the definition of the particles to be used in terms of material and granulometry, which play a crucial role on its thermal properties as well as on the heat transfer rates. Important aspects to characterize are the fluid and particle velocities as well as its porosity. Furthermore, the recent usage of a discrete particle model (DPM) enabled the simultaneous measurement of these properties without perturbing the flow, thus DPM has been used as a way to analyze such systems, including particle size distribution resulting from different nozzle configurations, different flows, determine the boundaries between different types of fluidization solid-to-fluid expected for fine particles, among other relevant aspects.

Sand of different origins is one of the materials that has been most studied for CSP applications, for instance an study (Diago, 2018) was performed for different types of sand in the United Arab Emirates, it was found that the heat capacity values ranged between 0.79 to 1,03 kJ kg−1 K−1 where soft and hard agglomeration phenomena was detected after samples being tested at 800, 1000 and 1200ºC. Moreover, it is observed a distribution shift to finer particles as the samples are subjected to heat treatments at high temperature.

The usage of sand is also important in gasification processes as recently (Gokon 2014) reported, chemically inert quartz sand was used as a particle receiver for both sensible thermal storage and transfer medium inside a circulating fluidized bed reactor for coal-coke gasification driven by concentrated solar radiation through a transparent quartz window.

Another important area of research is the usage of old mining material that is temperature stable and have adequate thermal properties to be used as thermal storage material. Felizardo, Guerreiro et al (2018) have collected and characterized iron rich particles that can be used as Filler material in a Thermocline Tank type of storage, being in contact with molten salts up to 550ºC. This material has been studied in granulometries between 2,5 and 25mm with slightly different compositions (Fayalite being the most relevant) in order to select the best local storage material at a reduced cost. The processes involved in particle production can be seem at figure 6.

Fig. 6: Particle collection, preparation and analyses

Another promising line of research are ceramic particles. At Juelich Solar Tower test facility, Ceramic particles have been used as heat transfer and storage medium for temperatures up to 1000°C. A centrifugal particle receiver system including a so called “*Centrec receiver*” prototype has been tested up to 965°C average receiver outlet temperature (Ebert, 2019).

3. Conclusions

Since the first attempts in solar power generation many efforts have been dedicated to increase the market share of solar system and distinct solutions have been taken, as one of most promising technology so far fluidized bed application in solar plants seems to attend to an increase in the thermodynamic performance and reduction on capital costs (Farsi and Dincer, 2019).

From the conventional possibilities to integrate fluidized bed techniques on a solar power plant, as a sensible storage, with PCM particles or by a thermochemical storage system, the technological advances in direct and indirect particle receivers showed important improvements on performance and suitability to MW plants (Ma and Martinek, 2017). In this system the solid particle is used as direct heat transfer medium in solar receiver, thermal energy storage material and fluidized bed heat exchanger. The direct TES system, where the hot particles come from the heat receiver and goes directly to the hot silo (storage), with no need of heat exchanger, can reach a solar efficiency (ratio between energy on heliostat and energy absorbed by particles in the receiver) of 78,5% with an irradiation of 1300 W m^{-2} in a numerical simulation (Farsi and Dincer, 2019).

From Chen et al. 2007 with his design and construction of a solid particle receiver until the Miller et all 2018 narrow tubes counterflow fluidized bed receiver with more than 90% of efficiency, the trajectory is marked by advances step by step. Ho, 2017 presented different designs for direct and indirect receivers with outlet temperature above 700°C. The high temperature can reach values over 1000°C (Almendros-Ibáñez, 2018) without degradation, allowing increase of the overall solar power plant efficiency. When compared with traditional solar systems such as thermal oil, molten salt or steam the particles do not have to handle with high pressure reducing the costs on pipes and vessels. The particles are inert, inexpensive and widely available (Ho, 2017).

The possibility to integrate the particle receiver on a combined cycle, Brayton and Rankine, was showed by Farsi and Dincer, 2019, in their investigation a direct particle receiver was used, with two storages cold and hot silo, and the particles were feed directly in the silos without the need of intermediary heat exchanger they presented by numerical simulation an overall exergy efficiency in the range of 35.1% to 50% depending on solar flux.

As a prominent possibility for energy storage is the thermochemical energy storage with high energy density, that can be ten times higher when compared with a sensible storage, with long-term storage and no heat loss, Chen et al. 2018, is suitable with high thermodynamic efficiency in large-scale solar power plants. Many materials and chemical reactions have been studied so far, hydride, metal oxides and organic systems. Decarbonation of calcite with a temperature on the exothermic process around 900ºC were studied by Flamant, 1982 who proposed a periodically calcite hydration about to extend material cycle life

Hydroxide systems as $CaO/Ca(OH)_2$ with a temperature range between 350ºC and 900ºC were considered in several studies which showed a good reversibility after 100 cycles (Schaube et al. 2012). Schmidt et al. (2014) designed a reactor and in an experiment obtained a cyclic storage conversion after 10 cycles of 77% leading to a stable system. The redox system as Co_3O_4/CoO is a promising energy converting technology in CSP (Chen et al. 2017). Besides its relatively high cost and the toxicity its cycle life stability and the best heat dissipation efficiency among other thermochemical materials make Co_3O_4/CoO relevant. The relatively small size of particles used in fluidized bed in thermochemical storage and the poor mechanical properties are the main issues that must be overcome to impulse the technology commercialization.

With few development PCM is until this moment not been applied to high temperatures in fluidized beds, probably an issue of spheres dimension, which is difficulty at the same body encapsulate a phase change material while give it the size and density necessary to be fluidized.

As it was seem the use of particles in CSP can lead to a higher thermal efficiencies, reduction in installation costs and increase the capacity of energy generation over time. Maybe only one technology is not going to fulfill all the requirements perhaps the integration of distinct techniques can ensure the wider use o CSP globally as a clean and feasible technology.

Despite the technical and experimental advances fluidized bed receivers are not at commercial stage so far, to be competitive with actual technologies they need to achieve feasible costs. It is known that direct storage of particles reduces costs, avoiding the need of extra heat transfer, perhaps the need of a fluidization system leads to generation of parasitic energy requirements. Ho, C. 2016, summarizes the particle receivers components costs and the result was $125/kW$_{th}$ in a falling particle receiver of 100 MW$_{th}$, including hoppers, duction, insulation, the tower, elevator, control, spare parts and contingency. The particle storage tank is expected to be cheaper when compared to molten salt storages due to the use of cheaper materials.

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