

REVIEW OF HIGH-TEMPERATURE SOLID PARTICLE RECEIVER/REACTOR CONCEPTS

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Abstract. *Recently, solid particles have been considered both as storage medium and heat transfer fluid (HTF) with great potential to improve the performance of concentrated solar power (CSP) technologies. Thermo-chemical energy storage using reacting solid particles furthermore has the potential to significantly reduce CSP costs. This paper therefore summarizes the state of the art on high temperature solar thermal energy storage and conversion based on reversible chemical gas-solid reactions and in this context relevant particle receiver/reactor designs. Depending on the heat integration mode into the reaction chamber, solar reactors can be categorized into indirectly or directly heated reactors/receiver. The reactor concepts are further classified according to the solid circulation concepts within the solar reactor/receiver, which define possible gas/solid contacting modes appropriate to carry out chemical reactions.*

Keywords: *solid particle receiver, solar reactor, CSP, thermochemical storage.*

1. INTRODUCTION

Concentrated Solar Power (CSP) plants currently in operation use direct steam generation or molten salts as heat transfer fluids (HTF). When large-scale heat storage is included, the HTF are normally molten salts, with its drawbacks of temperature limitation, required heat tracing of the molten salt circuits and high pumping power requirements (Zhang et al., 2016). On the other hand, the low volumetric heat capacities and the very high pressures at critical conditions prevent the use of direct steam production systems for temperatures above 300 K (Belmiloudi, 2011 apud Marti et al., 2015). Due to these limitations of the commercially HTF, CSP plants operate at temperatures and pressures below the corresponding state-of-technology fossil fuel power plants, resulting in lower efficiencies (Zhang et al., 2016). Recently, solid particles are being considered both as novel storage medium and as heat transfer fluid with great potential to improve the CSP concept. The main goal is thus to overcome the temperature limitation of current HTF, enabling the incorporation of advanced power cycle configurations not yet exploited in current CSP plants such as subcritical and supercritical steam, supercritical CO₂ and air Brayton combined cycles (Sakadjian et al., 2015).

In addition, high temperature receivers are also able to drive reversible chemical processes for integrated long-term thermal energy storage. Thermochemical storage systems have the highest energy density than any other thermal energy storage. They involve stable energy storage media at near ambient temperature, and are able to store energy for as long as the reaction products are kept separately stored. In comparison to other promising chemical reactions, reactions involving solid particles have the additional advantage of easily separable products.

Concerning the particle circulation loops used for thermal energy conversion and storage, different gas/solid contacting modes can be defined according to the gas velocity applied, e.g. moving bed, fluidized bed (FB), fluidized bed with pressure-driven up-flow, falling particles and mechanical conveying (rotary drum, screw conveyor). Solar reactors/receivers can be further classified as direct or indirect according to the heat integration into the reaction chamber. In direct irradiated systems, reactants are directly irradiated and heated by incoming solar concentrated radiation. Reactors are opened or closed to atmosphere by a transparent window through which radiations enters into the reaction chamber. Since the absorption of radiation occurs on the particles surface, high solar flux density is acceptable, hence very high temperatures can be achieved. Direct particle irradiation can also provide faster response to transient CSP operation, superior part-load operation, and extend daily hours of operation through faster start-up (Roger et al., 2011). Particle receiver designs based on simple open geometries can further mitigate thermal stress issues associated to fixed storage media (Kim et al., 2009; Steinfeld et al. 2010). However, this concept can present high convection losses, and particle flow instability if opened to air (Tan and Chen, 2010). On the other hand, in indirect absorption receivers, the external reaction chamber walls are heated by solar energy and the heat flux is transferred by conduction from the walls to the particles. In general, these reactors offer a better control of particle stability within the reactor/receiver, but the flux density allowed and the response to transient as well start-up time are restricted (Oles and Jackson, 2015).

In the long term, solar thermal technologies via thermochemical conversion paths are considered to be a promising technology with respect to allow CSP plant to continuously generate electricity with relatively low costs (Gil et al., 2010). According to Ma et al. (2015), the economic benefits of using inert solid particles as storage medium in a fluidized bed concept compared to a molten-salt CSP plant, indicates that the system can achieve about a 20 % cost reduction, assuming identical operating conditions for a traditional steam-Rankine cycle. Based on the U.S. Department

of Energy SunShot targets, further reduction in the levelized cost of energy (LCOE) of CSP require lower solar-field cost (\$75/m²) and increased power-cycle efficiency (> 50%). Those targets can be realistic by using reactive particles as HTF and storage medium to achieve heat-release temperatures above 600 K in order to obtain power-cycle efficiency over 50 %. As such, thermochemical energy systems can enable the future CSP plant to reach the aimed LCOE and the solar field cost reduction, making CSP become competitive with conventional power generation.

Apart from achieving economic targets, other requirements and criteria have to be considered when deciding on the type and design of the solar receiver system. The challenge is to design and construct a particle receiver/reactor able to maintain a constant and sufficient mass flow rate of particles at large scale, and to operate at high temperatures, matching the chemical reaction temperature. The particles should also be able to travel through the receiver, in order to enable long-term storage. Finally, the proposed innovative concepts must be scalable from kW to MW to be integrated into the power plant.

For thermochemical energy storage applications, from the technical point of view, critical requirements are high energy density; mechanical and chemical stability; complete reversibility for a large number of charging/discharging cycles; low thermal losses; and low environmental impact (Hermann and Kearney, 2002; Kuravi et al., 2013). On the other hand, the most important design criteria have been identified as the nominal temperature and specific enthalpy drop in the load (discharge and conversion side); the maximum load; the operational strategy; and the integration into the power plant (Hermann and Kearney, 2002; Kuravi et al., 2013).

This paper focuses therefore on the most relevant high-temperature particle receiver/reactor designs employing reversible solid-gas chemical reactions. However, whereas lot of work has been done on the one hand on inert particle receivers for CSP applications using sensible storage and on the other hand for solar thermal fuel generation and other solar thermochemical process, solar thermochemical storage technology are still in an early development stage. As the thermochemical storage development can profit from the experience gained in these two areas as well, in this paper, relevant existing solar receiver/reactor concepts in these two fields are therefore also briefly discussed and assessed with respect to their application for CSP.

2. DIRECT IRRADIATED SOLAR REACTORS

2.1 Fluidized bed reactors

In view of the well-known properties of gas-solid fluidized bed, e.g. high absorptance, uniform temperature distribution, and high values of heat transfer coefficient, solar fluidized bed reactors have been considered for chemical processes and energy conversion and storage. In 1978, Flamant demonstrated the feasibility of using concentrated solar energy to drive thermochemical processes in fluidized bed reactors at the Laboratoire d'Énergetique Solaire in Odeillo, France. In 1980, an inert fluidized bed solar receiver was tested on top of a tower located at the center of a heliostat field at the Georgia Tech Research Institute (GTRI). In 1985, direct absorption fluidized bed receivers were investigated at the German Aerospace Center (DLR). In general, the main issues identified were poor fluidization causing high radiation losses and thermal gradients, as well as discoloration and eventual breakage of the quartz window (Koenigsdorff and Kienzle, 1991).

In 1995, at PSI, a fluidized-bed tubular quartz solar reactor was developed by Steinfeld et al. (1995) to investigate the combined processes of thermal reduction of ZnO and reforming of CH₄. Uniform irradiation on the tubular reactor was ensured with a secondary concentrator composed of a compound parabolic concentrator (CPC) and an involute (Fig. 1, left side). A similar reactor concept was later employed by Nikulshina et al. (2009) to capture CO₂ from atmospheric air via consecutive CaO carbonation and CaCO₃ calcination cycles (Fig. 1, right side). While in the experiment of Steinfeld et al. (1995) the tube was irradiated along its length, Nikulshina et al. directed the concentrated solar energy to the top of the tube.

More recently, fluidized bed reactors using inert particles have been proposed as high-temperature receiver to be used in concentrated solar power generation plants. Matsubara et al. (2014) proposed a beam-down radiated fluidized bed reactor using ceramic particles. Experiments using a 3 kWh solar simulator and numerical computation were performed for the prototype receiver. Particle temperatures exceeding 1200 K were measured. The authors are at present working towards a reactor scale-up to be tested at the Miyazaki beam-down reflector system, also currently under construction. Bai et al. simulated and experimentally tested a quartz tube solid particle air receiver using silicon carbide particles (Bai et al., 2014; Wang et al., 2015; Zhang et al. 2016). Transient simulations were carried out to assess heat transfer and flow processes occurring within the tube under concentrated solar radiation. The maximum outlet air temperature was about 900 K, and the minimum temperature difference between particles and outlet air was below 10 °C, showing good heat transfer performance inside the receiver. Figure 2 shows schemes of both receivers. Again, Matsubara et al. (2014) conceived their receiver to be irradiated at the top of the tube, while the one proposed by Bai et al. (2014) was designed to be irradiated along its perimeter.

Fluidized bed concept ensures good contact between the gaseous and solid reactants, which provides high heat transfer coefficients and homogeneous temperature distribution. As such, reactions that require good thermal transfer properties can be properly carried out in fluidized bed reactors. High heat transfer coefficients further allow for heat

transfer area reduction, and hence reduction of the entire system, which is a requirement for CSP storage systems. Moreover, fluidized bed reactors can take advantage of substantial commercial experience.

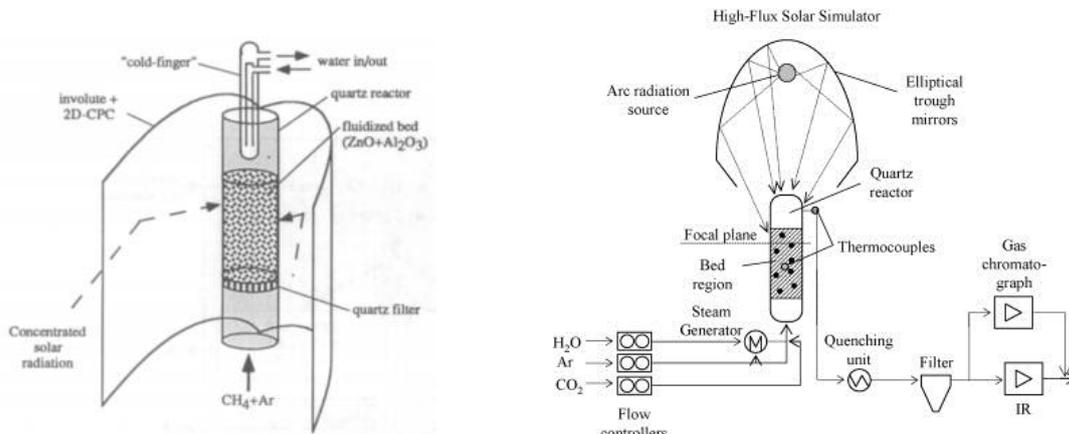


Figure 1. Left side: scheme of the solar receiver-reactor configuration and secondary concentrator used by Steinfeld et al. (1995). Right side: experimental set-up at ETH's High-Flux Solar Simulator by Nikulshina et al. (2009).

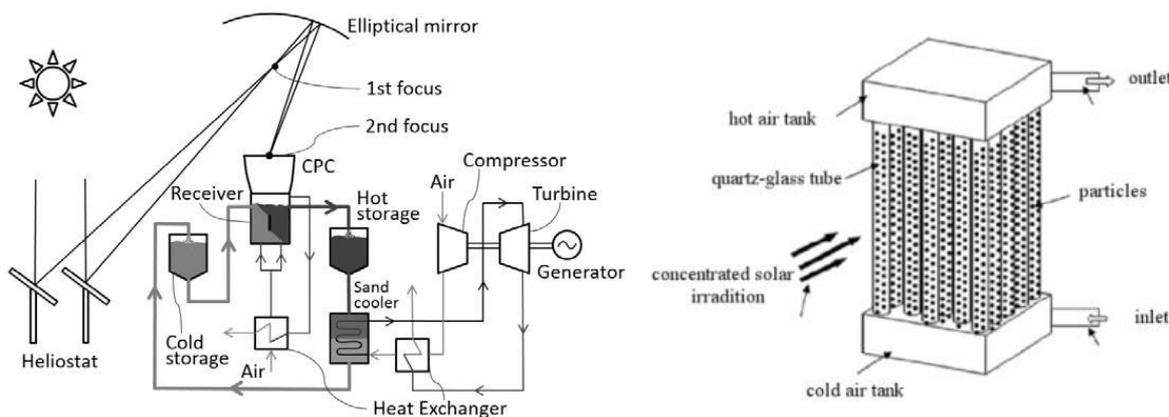


Figure 2. At the left side: CSP plant with beam-down radiated fluidized bed receiver (Matsubara et al., 2014). At the right side: the structure of receiver proposed by Bai et al. (2015).

2.2 Entrained reactors

2.2.1 Free falling particles

In the free falling particles concept, the particles are dropped from the top of the receiver, creating a falling curtain, which is directly exposed to the concentrated solar radiation. Tan and Chen (2010) provided an overview of the prior research on free-falling particle receivers. The majority of those studies focused on modeling the particle falling movement and the radiant heat transfer. Apart from solar-driven water-splitting cycles for hydrogen production using CdO/Cd, ZnO/Zn, and Fe₃O₄/FeO cycles, as well as mixed metal oxides such as zinc-ferrite, manganese-ferrite, and nickel-ferrite particles, no other thermochemical process or chemical reaction was reported.

Martin and Vitko (1982) carried out a pioneering work on falling solid particles at the Sandia National Laboratories (SNL) in 1982. Based on the work of the previous authors, in 2008, Siegel et al. performed the first on-sun tests of a simple free-falling particle receiver also at SNL. The prototype consisted of a 6 m tall cavity through which sintered bauxite particles were dropped and directly heated at power levels between 1.6 and 2.5 MW. Preliminary tests achieved a thermal efficiency of 50%, and the increase in particle temperature over ambient conditions was 250 °C. A model was further developed to simulate the prototype performance, and simulated results showed good agreement with experimental data (Ho et al., 2009). Recently, Ho et al. (2015) also performed on-sun tests of a 1-MWth receiver with recirculation of particles. Outlet temperatures reaching about 1000 K, and thermal efficiencies ranging from 50% to 80% were achieved. Technical challenges identified during the tests include: non-uniform irradiance distributions on the particle curtain, variable mass flow rates, effect of wind and other parasitic air flows, particle loss through the aperture, particle elevator reliability, and wear on the receiver walls due to high direct flux and temperatures.

The particles residence time within the heated region of the falling particles receivers was found to be an important parameter to control both the heat gain as well the maximum temperature of the particles. One method employed to increase the residence time uses the recirculation of particles through the receiver, with increments on temperature at each successive drop, as carried out by Ho et al. (2015) and Gobereit et al. (2015). However, additional particle elevators/conveyance is necessary, increasing parasitic energy requirements. The use of obstacles to mechanically slow the particle circulation was also considered to increase residence time. Interconnected porous structures (metallic or ceramic foam blocks) and staggered array of porous mesh structures were proposed respectively by Lee et al. (2015) and Ho et al. (2014). Thermal efficiency values for obstructed falling particle receivers were reported as approximately 60% at temperatures between 900 and 1100 K. Furthermore, air recirculation and air curtains have been proposed as a means to mitigate the impacts of wind on particle flow and reduce convective losses (Tan and Chen, 2010).

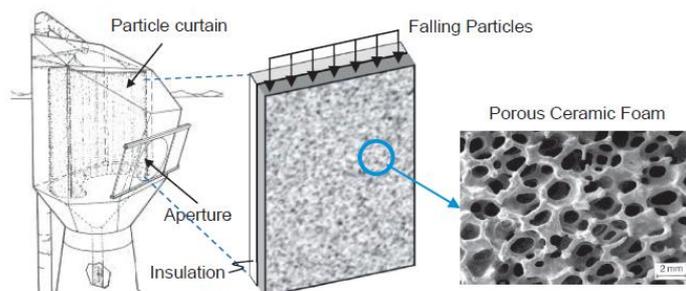


Figure 3. Falling particles receiver proposed by Ho et al. (2014), and the use of interconnected porous panels in the falling particle receiver to increase the residence time of falling particles.

Oles (2014) modeled a falling-particle solar receiver for hydrogen production and thermochemical energy storage. The undoped-ceria, a popular material for solar fuel production, was first chosen. Ceria reduction cycle results demonstrated a very low efficiency due to a combination of poor optical properties and high operating temperatures. Further analyses were carried out employing perovskites aiming to achieve high energy-density storage through thermochemical energy conversion. Both the higher emissivity and the endothermic reduction of perovskites improved overall receiver solar efficiency by reducing the particle temperatures and thus the radiation losses. In this case, the thermochemical storage increased the total storage density, accounting for over 44 % of the storage. The falling particle concept can also be employed in combination with fluidized bed reactors as proposed by Ma et al. (2015). In such system, the particles are heated within the falling particle receiver and thereafter fall into a hot silo to be stored. The fluidized bed technology is used as the heat exchanger to transfer heat between the working fluid and the hot particles coming from the silo. The authors also suggest the use of reactive particles in order to achieve higher temperatures and hence enable the integration of high-efficiency thermal power cycles. Although only inert particles have been tested in falling particles so far, these recent works show that the choice of an appropriate chemical reaction could indeed improve the thermal performance of falling particles concepts, enable long-term thermochemical energy storage and the integration of high-efficiency thermal power cycles.

2.2.2 Cyclonic reactor

As illustrated in Figure 3, in a solar cyclonic reactor, gas flow with suspended particles enters the reactor cavity tangentially creating a vortex flow. Due to the swirl of the flow, the particles are separated from the flow and exit through the end section of the reactor, while the gas flow is directed inversely towards the reactor top. An aperture allows the incoming solar radiation to heat the particles. Cyclonic reactors feature high heat and mass transfer coefficient, and ensure good contact between gas and particles within small residence times.

In 1991, at the Paul Scherrer Institut (PSI), Imhof (1991) developed the concept of a solar cyclone reactor to carry out the decomposition process of calcite, attempting to combine the advantages of cavity receivers and volumetric reactors, and additionally allow continuous operation (Fig. 4, left side). Based on the proposed concept, Steinfeld et al. (1992) built a small-scale prototype reactor consisting of a conical cyclone gas-particle separator modified to let concentrated solar energy enter the cavity through an aperture open to atmosphere.

Subsequently, in 1994, a novel solar reactor was proposed, modeled and optimized at PSI aiming to achieve temperatures above 1500 K (Ganz et al. 1994; Meier et al., 1996). Many improvements on previous prototypes (Steinfeld et al., 1998; Nikulshina et al., 2005) led to the design and construction of a 300 kW scaled-up reactor in 2008 shown in the middle of Fig. 4 (Z'Graggen and Steinfeld, 2008). The steam-gasification of petcoke was performed and 87% of petcoke conversion was achieved within a temperature range of 1300-1800 K. Solar-to-chemical conversion efficiencies yielded 20%, accounting for sensible heat. This reactor was further scaled up to 300 kW, which improved the solar-to-chemical efficiency to 24% due to higher volume-to-surface ratios of the scaled-up reactor. Main heat

losses were due to re-radiation through the aperture and conduction through the insulation. However, the optimization for minimizing heat losses and maximizing the solar energy conversion efficiency was outside the scope of the study.

Kogan et al. (2003, 2004) developed a vertical cyclone reactor for hydrogen production through solar thermal methane splitting (Fig. 4, right side). The concept proposed uses an optimized gas flow pattern to protect the reactor window and reduce the auxiliary gas flowrate to a minimum. Radiation absorbing particles were also introduced into the flow, creating a cloud of particles to absorb the incoming solar energy before it reaches the cavity inner walls. As such, the central region of the cavity experiences higher temperatures, while wall temperature remains moderate, avoiding carbon deposition. Different reactor geometries were analyzed and the final reactor concept was proposed as shown in Fig. 4 on the right.

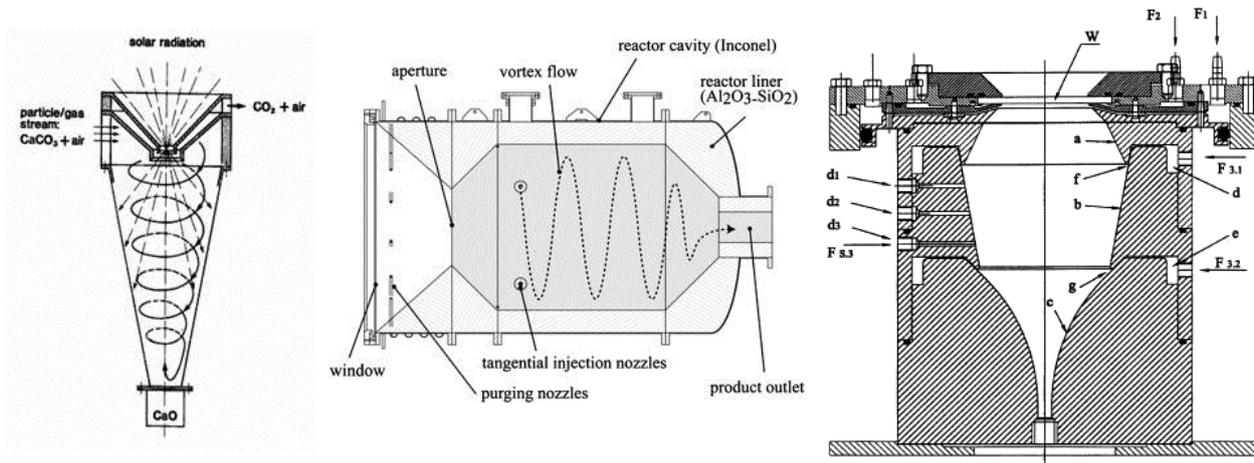


Figure 4. At the left side: the Cyclone Reactor proposed by Imhof (1991). Middle: schematic of the 300 kW scaled-up reactor (Z'Graggen and Steinfeld, 2008). At the right side: axial cross section of final configuration of the reactor (Kogan et al., 2004).

The main design aspects to be considered in cyclonic reactors are the cavity geometry, the window protection and cooling systems, as well as the injection system of gas and particles. In addition, optimization studies have to be carried out in order to reduce thermal losses. Although temperatures in the range of 1200-1800 K, suitable for solar thermochemical storage and conversion, are feasible in cyclonic reactors, this concept has not been explored for this purpose so far. Cyclonic reactors are particularly interesting for solid-gas reactions, as the particles are naturally separated from the gas flow under the centrifugal force. The higher volume-to-surface ratios inherent to scaled-up cyclonic reactors could also be explored to process large mass flow of particles in CSP plants.

2.3 Stacked reactors

2.3.1 Fixed bed (packed bed) reactors

While being capable of achieving very high temperatures, fixed bed reactors also experience very high thermal gradients at the surface of the packed bed, restricting chemical conversion. A fixed bed configuration furthermore does not allow continuous operation and is therefore not suited for application of gas-solid thermochemical storage reactions in CSP.

2.3.2 Rotary reactors

Rotary reactors have been largely employed in many industry segments, in view of their combined advantages of good heat transfer between the gas and solid particles, high mass flow rate, and high reactive surface area. The particle movement inside the rotating cavity further prevents particles sintering. Direct radiated rotating solar reactors have been proposed as early as 1980 (Flamant et al., 1980). From 1999, two 10 kW rotary reactor prototypes were developed at PSI for the thermal reduction of ZnO (Haueter et al., 1999; Schunk et al., 2008). The second prototype was further scaled up to 100 kW and tested at the 1 MW Solar Furnace in Odeillo (Villasmil et al, 2014; Koepf et al., 2016). Abanades et al. (2007) also designed a lab-scale cylindrical rotary reactor for the continuous ZnO thermal dissociation. Researchers at PSI developed and tested a 10 kW rotary kiln reactor for the solar thermal production of lime (Meier et al., 2004). The same concept was proposed as an indirect irradiated reactor and will be later discussed. The indirect heating concept was preferred over the direct concept mainly due to the formation of a white powder cloud of calcined particles at the exiting open aperture, which in turn reflected and absorbed a significant amount of the incident sunlight.

Thermochemical energy storage in a solar rotary kiln was proposed by Neises et al. in 2012 at DLR. The authors developed and tested a solar rotary reactor based on the thermal reduction and oxidation of cobalt oxide. A thermal model describing the rotary kiln reactor model was also developed (Tescari et al., 2013). The rotary reactor was set-up to operate in batch mode at the 22 kW Solar Furnace at DLR. The redox material was reduced on-sun at temperatures of about 1200 K and re-oxidized off-sun in the same rotary kiln, both steps carried out in an air atmosphere. Up to 30 cycles were performed with one batch showing no material degradation. On average, only half of the metal oxide reacted during testing, which according to the authors was probably due to insufficient particle mixing inside the reactor. The authors concluded the rotary kiln is a feasible reactor set-up for thermochemical energy storage and recommend further improvements in order to increase particle mixing and avoid particle loss with the exiting gas stream (Fig. 5, right). Later, Alonso et al. (2015) used a direct radiated rotary kiln to demonstrate the suitability of copper oxide as a promising material for thermochemical storage. Rotation movement improved the particles reactivity due to better particles mixing, leading to CuO conversion into Cu₂O in argon atmosphere up to almost 80%.

A 10 kWth solar rotary receiver called CentRec (Centrifugal Particle Receiver) was conceived, designed and built in laboratory scale at DLR. The prototype employing bauxite inert particles for solar energy harvesting and storage was tested at the High-Flux Solar Simulator at DLR (Wu et al. 2014a; 2014b; 2015a; 2015b). A three-dimensional, steady-state finite-element model was developed and validated with experimental data. For a target particle outlet temperature of 900°C and a design input flux of 1 MW/m², a receiver thermal efficiency of over 85% is predicted, indicating promising perspectives for the proposed receiver concept.

Rotary reactors have been successfully scaled up to laboratory scale. Larger scale operation entails some challenges though. High parasitic energy requirements, reliability and stability associated to a large rotating receiver system still need to be addressed. On the other hand, advantages of such reactors are high particles temperature and the possibility to control the residence time of the particle inside the reactors through the rotational speed.

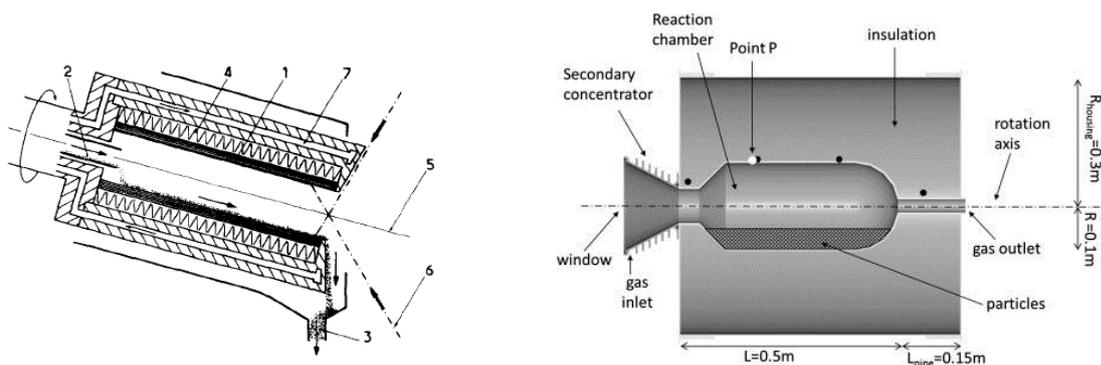


Figure 5. Left side: scheme of the solar rotary kiln developed by Flamant et al. (1980) depicting (1) refractory tube; (2) powder inlet; (3) powder outlet; (4) insulator; (5) axis of the kiln be tilted at 5°; (6) concentrated solar rays; and (7) water cooled shell. Right side: schematic of the rotary kiln reactor proposed at DLR (Tescari et al., 2013).

2.3.3 Moving bed

Moving bed reactors were developed aiming at a uniform particle distribution inside the cavity, similarly to rotary reactors, but without the engineering difficulties associated to them. Furthermore, due to low relative velocities, this reactor concept works under low attrition and abrasion. Thermal gradients can be avoided by bed aeration or powder circulation. Two innovative reactors employing moving bed concepts are presented in this section.

The first, abbreviated as GRAFSTRR (Gravity-Fed Solar-Thermochemical Receiver/Reactor), was designed, constructed and tested for the reduction of Zn particles by Koepf et al. (2011; 2012) at PSI. The reactor proposed is closed to the atmosphere with a quartz window, and features an inverted conical-shaped reactor composed of fifteen trapezoidal tiles supported shaped into an inverse cone at 40° inclination (Fig. 6, left). In this reactor, particles are fed to each tile-surface, where they undergo a thermochemical reaction upon exposure to beam-down concentrated solar energy. The movement is induced with vibration, forming a moving-bed reactive layer along the tile. Initial experiments using a high-flux solar simulator at temperatures above 1200 K successfully demonstrated the mechanical stability of the reactor. The second reactor was proposed by Ermanoski et al. in 2013, and employs a moving packed bed of reactive particles for fuel production (Fig. 6, right). A screw elevator lifts the particles upward towards the reactor aperture. At the top of the rotating elevator, the particles are exposed to beam-down concentrated solar energy, and then spilled into the hollow screw. The reduced particles are stored and subsequently undergo oxidation to produce fuel. No prototypes have been tested so far.

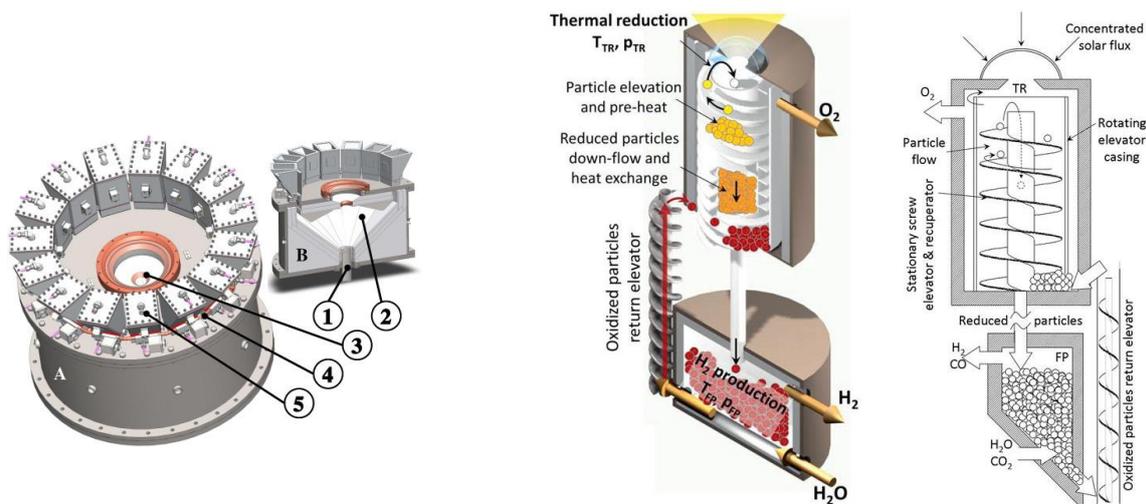


Figure 6. Left side: top-down view of the solar reactor depicting the aperture (3), assembly of 15 powder-feeding hoppers (5), and water-cooling loop (4). Right side: schematic drawing of the moving packed particle bed reactor proposed by Ermanoski et al. (2013; 2014; 2015).

3. INDIRECT IRRADIATED SOLAR REACTORS

3.1 Rotary kiln

Based on previous experience (Meier et al., 2004) with a direct heating rotary reactor prototype, Meier et al. (2005, 2006) designed, built, and tested an indirect heating 10 kWth multi-tube rotary kiln prototype for solar calcination of lime. The indirect reactor consisted of 16 SiC absorber tubes contained in a tilted rotating cylindrical solar cavity with a circular aperture, as shown in Fig. 8. Concentrated solar radiation enters through the aperture and heats the absorber tubes arranged along the cylindrical cavity wall. The particles are continuously fed into the preheating chamber, where they are heated at near reaction temperature, and then transported to the absorber tubes due to the rotational movement. The tubes indirectly heat the particles which undergo the chemical reaction. The products are collected with a funnel at the front of the cavity. Experimentally determined solar-to-chemical efficiencies reached 30–35% for a temperature range of 1200–1400 K. The quality of the solar produced quicklime was found to meet the highest industrial standards, with a degree of calcination exceeding 98%. Moreover, the prototype operated reliably for more than 100 h at solar flux inputs of about 2000 kW/m², withstanding the thermal shocks that occur in solar high temperature applications. The design and principal dimensions of scale-up reactors with solar power input of 0.5 to 20 MW were laid out. The authors expect the industrial reactor efficiency to be higher in comparison to the small-scale prototype, achieving values between 45–55%, while keeping high quality produced quicklime.

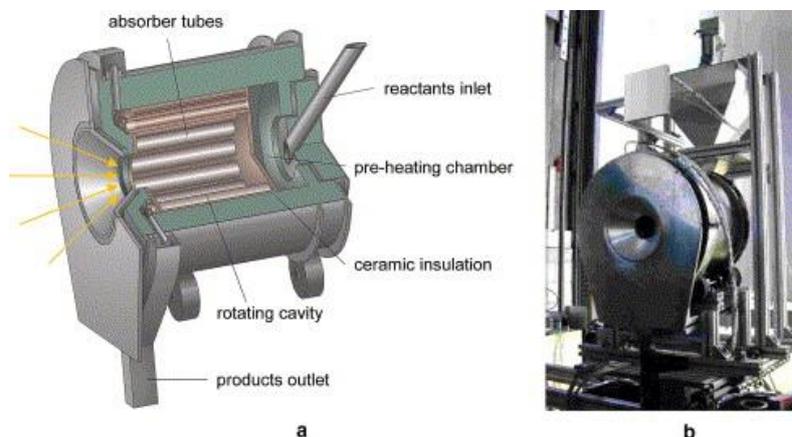


Figure 8. (a) Schematic representation of the multi-tube rotary kiln prototype; and (b) 10-kWth solar lime kiln prototype mounted on the experimental platform at PSI's solar furnace (Meier et al., 2006).

3.3 Enclosed reactors: gravity driving flow through enclosures

NREL is developing a solid-particle based solar receiver, projected to have significant cost and performance advantages over current nitrate-based molten salt systems (Ma et al., 2015; Sakadjian et al., 2015). The design uses inert solid particles as the heat transfer fluid and storage media. The schematic of the proposed concept is shown in Fig. 11. The novel solar receiver was conceived as a near-blackbody (NBB) enclosed particle receiver capable of reaching high-temperatures. A staggered array of absorber tubes is fixed horizontally inside the reactor cavity, through which the particles flow downward under the force of gravity. The tubes are irradiated by concentrated solar energy on the interior surfaces while transferring heat to the particles flowing around the exterior side of the tubes inside the reactor cavity. A discrete element method (DEM) model was developed by Morris et al. (2016) for a laboratory scale receiver. Different geometric configurations (horizontal and vertical spacing), particle sizes, and mass flow rates were evaluated. The results show that the heat transfer strongly depends on the particle size, where increased heat transfer is obtained using smaller particles. At higher solids mass flow rates, more particles contact the heat transfer surfaces and the overall heat transfer increases. Particle temperature and thermal efficiencies were not reported, and no on-sun tests have been performed yet. The experimental tests and the simulation results showed that the heat transfer to the particles is restricted in points where the particles loose contact with the tubes.

3.4 Fluidized bed up-flow reactors

Fluidized bed up-flow consists in creating upward circulation of a dense suspension of particles in vertical absorbing tubes exposed to concentrated solar energy. The dense up-flow column is fed at its bottom by a circulation flow of solids at an appropriate pressure to overcome the pressure drop of the upwards-moving bed of solids. Contrary to a circulating fluidized bed, the dense suspension of particles operates at low gas velocity and large solid fraction, in the range of 30%-40%. The suspension acts as heat transfer fluid (HTF) with a heat capacity similar to a liquid HTF only with significantly higher maximum HTF temperature, such that temperature is now limited by the working temperature limit of the receiver tubes.

Flamant et al. proposed and demonstrated a fluidized bed up-flow reactor at CNRS solar facility, in France (Flamant et al., 2013; 2014; Benoit et al., 2015). The absorber tube was located inside a cylindrical cavity, and heated by concentrated solar energy over a height of 0.50 m. Figure 11 shows the schematic of the system. Experiments were carried out both at high and low temperature conditions. At solar flux densities in the range 200-250 kW/m² temperatures up to 1000 K were measured at the tube outlet. The wall-to-suspension heat transfer coefficient was calculated on the basis of detailed temperature measurements, accounting for the strong recirculation phenomena occurring at the tube wall. Results obtained range from 420 W/m²K to 1100 W/m²K for a solid mass flux of 10 kg/m²s and 45 kg/m²s, respectively. Thermal efficiencies were not reported. Challenges in this system include high parasitic energy requirements to fluidize the particles through the receiver tubes with sufficient mass flow to meet the desired power requirements, as well as the possibility of hot spots occurrence at reactor wall, and significant radiative losses to the environment.

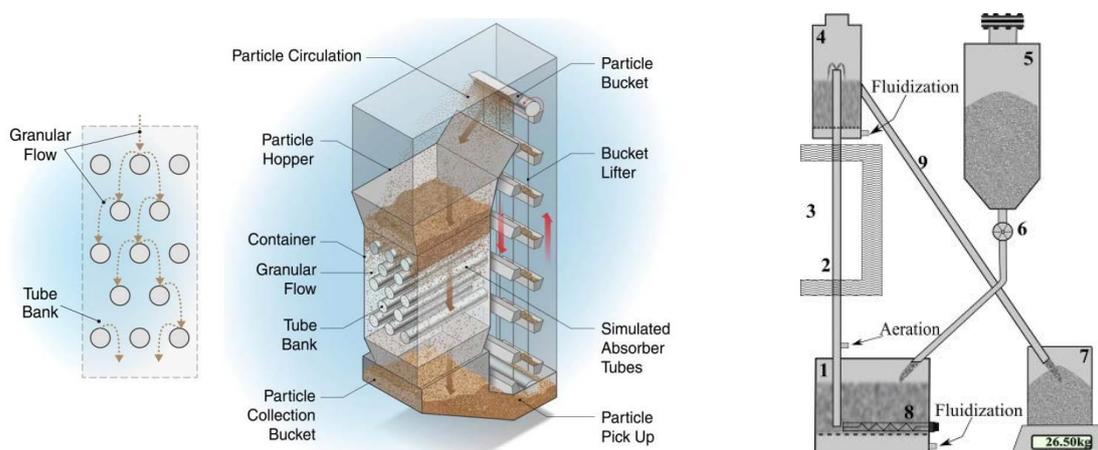


Figure 11. Left side: schematic of the enclosed particle receiver module under development at NREL. Right side: schematic of the fluidized bed up-flow reactor developed by Flamant et al. (2015), depicting (1) dispenser fluidized bed; (2) solar absorber metallic tube; (3) solar receiver cavity; (4) collector fluidized bed; (5) storage tank; (6) rotary valve feeder; (7) weighing scale; (8) electrical resistances; (9) solid evacuation tube.

4. SUMMARY OF PARTICLE RECEIVER/REACTOR DESIGNS AND CONCLUSIONS

Table 1 summarizes the different particle reactor/receiver concepts, detailing their advantages and the challenges to be addressed. In view of the very early stage of development, no detailed comparison between the concepts can be established.

Table 1. Summary of particle reactor/receiver concepts.

Receiver/reactor design	Advantages	Challenges
Free falling particles	High flux densities and temperatures; high thermal efficiency	Particle loss; attrition; abrasion; radiative losses; impacts of wind; low residence time; particle elevator reliability; parasitic energy requirements
Cyclonic	High heat and mass transfer coefficient; good gas-solid contact within small residence times	Cavity geometry; window protection and cooling systems; injection system of gas and particles
Fluidized bed	High heat transfer coefficients and temperatures; low temperature gradients	High parasitic energy requirements; attrition
Fixed bed	Very high temperatures on the bed surface	High thermal gradients; high pressure drop; impossibility of continuous operation
Rotary kiln	High temperatures; control of residence time through rotation speed	Parasitic energy requirements, reliability and stability associated to rotating parts; high thermal gradients
Moving bed	Simple construction; low attrition and abrasion	Mechanical stability; relatively low heat transfer coefficient
Gravity driving flow through enclosures	No particle loss due to containment	Loss of contact between particles and array of tubes
Dense suspension of particles	No particle loss due to containment	Very high parasitic energy requirements; hot spots occurrence; high radiative losses; attrition

Tables 2 and 3 summarize the most relevant research work done so far on different solar reactor/receiver concepts. Values of temperature achieved, chemical conversion, and solar-to-chemical or thermal efficiency (when inert particles are used) are provided. It should be noted, however, that chemical conversion depends on the residence time of the reactants inside the reactor, which in most of the cases was not reported. In fact, the values reported in the literature vary within a large range. For the reactor concepts considered in this work, the maximum measured temperature ranges between about 900 – 1400 K for fluidized bed designs; around 1173 K for falling particle designs; between 1200 – 1800 K for cyclonic reactors; 800 – 2000 K for rotary reactors; 1100 – 1900 for moving bed concepts and above 1000 K for dense suspension of particles. Solar-to-chemical efficiency ranges between 7 up to 43%, and thermal conversion up to 90% was achieved in obstructed falling particle receivers.

In general, solar receivers based on concepts already explored for other solar chemical processes, such as fluidized bed and rotary reactors, are in a relative more advanced stage, since they take advantage of previous experience. For these concepts, improved prototypes based on previous smaller prototypes have been developed or are currently under construction. The importance of prototyping and scaling up in order to identify design and operating problems is therefore undeniable. On the other hand, the innovative concepts, such as the falling particles concept, gravity-driven enclosed reactors, and the moving bed concepts, are still in a very early stage of development, restricted to laboratory experiments, with no scaled-up prototypes or no prototypes at all. Concerning the application of solid reactor as solar receivers, no pilot project has been implemented so far.

The falling particles, rotary and fluidized bed concepts are considered to be the most promising to be used in solar thermal energy conversion and storage due to better match between their advantages and the requirements for application in large CSP. They have been scaled-up to laboratory level and on-sun tests have been performed. However, their ability to maintain a constant and sufficient mass flow rate of particles at larger scales still need to be assessed. Parasitic energy requirements either to fluidize the particles, provide rotational movement to the rotary reactor or recirculate the particles within the falling particle concept also need to be addressed.

Table 2. Summary of direct particle reactor/receiver concepts.

Reactor type	Reference	Chemical reaction	Temp. [K]	Chemical conversion [%]	Solar to chemical or thermal efficiency [%]	Current pilot/lab scale [kW]
Free falling particles	Ho et al. (2009, 2015); Tan and Chen (2010)	Inert particles	> 1173	inert	50-80	1000
Cyclonic	Steinfeld (1992)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$	1200-1450 (at wall)	53-100	43	
	Steinfeld et al. (1998)	$\text{ZnO} + \text{CH}_4 = \text{Zn} + 2\text{H}_2 + \text{CO}$	1600	90		5
	Nikulshina et al. (2005)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$ $\text{CH}_4 + \text{CO}_2 = 2\text{H}_2 + 2\text{CO}$	1223	CaCO_3 - 83 CH_4 - 38	7-10	10
	Z'Graggen and Steinfeld (2008)	$\text{CH}_2\text{O}_y + (1-y)\text{H}_2\text{O} = (z/2 + 1 - y)\text{H}_2 - \text{CO}$	1300-1800		24	300
	Kogan et al. (2003, 2004)	$\text{CH}_4 = \text{C} + 2\text{H}_2$				
Fluidized bed	Steinfeld et al. (1995)	$\text{ZnO} + \text{CH}_4 = \text{Zn} + 2\text{H}_2 + \text{CO}$	1373	CH_4 - 43		
	Nikulshina et al. (2009)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$	1150			
	Matsubara et al. (2014)	Ceramic particles	> 1173	inert		2
	Bai et al. (2014-2016)	Silicon carbide particles	~ 900	inert		
Rotary kiln	Flamant et al. (1980)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$		60	10-30	
	Haueter et al. (1999)	$\text{ZnO} = \text{Zn} + 0.5\text{O}_2$	2000	35		10
	Schunk et al. (2008)	$\text{ZnO} = \text{Zn} + 0.5\text{O}_2$	1900	90		10
	Villasmil et al. (2014) Koepf et al., (2016)	$\text{ZnO} = \text{Zn} + 0.5\text{O}_2$	1936	12-49		100
	Meier et al. (2004)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$		98	20	
	Neises et al. (2012) Tescari et al. (2013)	$2\text{Co}_3\text{O}_4 = 6\text{CoO} + \text{O}_2$	1173	50		
	Wu et al. (2014; 2015)	Bauxite particles	1173	inert		10
	Alonso et al. (2015) Koepf et al. (2012)	$\text{CuO} = \text{Cu}_2\text{O} + 1/2\text{O}_2$ $\text{ZnO} = \text{Zn} + 0.5\text{O}_2$	800-1200 1100-1900	80		10
Moving bed	Ermanoski et al. (2013)	Fuel production (no tests have been performed)				

Table 3. Summary of indirect particle reactor/receiver concepts.

Reactor type	Reference	Chemical reaction	Temperature [K]	Chemical conversion [%]	Solar to chemical or thermal efficiency [%]	Current pilot/lab scale [kW]
Rotary kiln	Meier et al. (2005, 2006)	$\text{CaO} + \text{CO}_2 = \text{CaCO}_3$		> 98	32	10
Gravity driving flow through enclosures	Ma et al. (2013-2016)	Inert particles				
Dense suspension of particles	Flamant et al. (2013- 2015)	Inert particles	> 1000			

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