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# Dense suspension of solid particles as a new heat transfer fluid for concentrated solar thermal plants: On-sun proof of concept

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## HIGHLIGHTS

- A new concept of solar receiver using dense particle suspensions (DPS-SR) is developed.
- The concept opens new applications for concentrated solar energy.
- DPS-SR is tested successfully at the focus of the CNRS solar furnace.
- Particle flow rate and volume fraction are controlled.
- Wall-to-particles heat transfer coefficients up to 500 W/m² K are obtained.

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## ABSTRACT

This paper demonstrates the capacity of dense suspensions of solid particles to transfer concentrated solar power from a tubular receiver to an energy conversion process by acting as a heat transfer fluid. Contrary to a circulating fluidized bed, the dense suspension of particles' flows operates at low gas velocity and large solid fraction. A single-tube solar receiver was tested with 64 μm mean diameter silicon carbide particles for solar flux densities in the range 200–250 kW/m$^2$, resulting in a solid particle temperature increase ranging between 50 °C and 150 °C. The mean wall-to-suspension heat transfer coefficient was calculated from experimental data. It is very sensitive to the particle volume fraction of the suspension, which was varied from 26 to 35%, and to the mean particle velocity. Heat transfer coefficients ranging from 140 W/m$^2$ K to 500 W/m$^2$ K have been obtained, thus corresponding to a 400 W/m$^2$ K mean value for standard operating conditions (high solid fraction) at low temperature. A higher heat transfer coefficient may be expected at high temperatures because the wall-to-suspension heat transfer coefficient increases drastically with temperature. The suspension has a heat capacity similar to a liquid heat transfer fluid, with no temperature limitation but the working temperature limit of the receiver tube. Suspension temperatures of up to 750 °C are expected for metallic tubes, thus opening new opportunities for high efficiency thermodynamic cycles such as supercritical steam and supercritical carbon dioxide.



## 1. Introduction

Concentrated solar systems may produce high temperature heat and power efficiently and firmly thanks to heat storage and hybridization. Among available technologies, solar towers, or central receiver systems, offer numerous options for producing heat at temperatures higher than 500 °C, temperatures that are needed to power efficient Rankine thermodynamic cycles. In solar towers, sun-tracking heliostats reflect solar radiation to the top of a tower where the receiver, or solar absorber, is located. In the receiver, solar heat is transferred to a heat transfer fluid (HTF). The HTF transports the heat to the energy conversion sub-system that includes heat storage, heat exchangers, an optional burner for fuel back-up and a power block. Industrially, current HTF are steam and nitrate salts, air at atmospheric pressure and pressurized is under development. These existing HTF have drawbacks, in particular a limited working temperature domain for salt (typically 240–565 °C for binary sodium-potassium nitrate salt), very high pressure for

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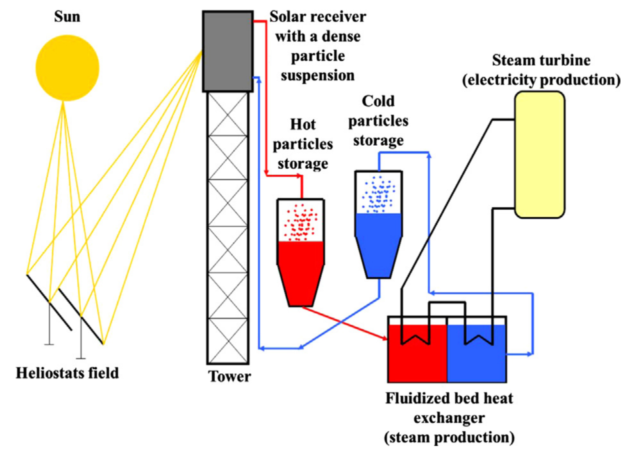


**Fig. 1.** Schematic view of a thermal CSP plant with a receiver using particles as HTF.

steam and poor heat transfer capacity for air. Other prospective options, such as liquid metals, offer high flux limit on the receiver and extend operation to temperatures higher than 565 °C, as described by Pacio, Wetzel (2013). But this kind of HTF is highly corrosive. Moreover, it involves safety risks which explain why there is currently no industrial application. A solution to overcome these drawbacks is using solid particles as HTF. A general diagram of the complete setup using a solid particle receiver is given in Fig. 1. The loop is composed of a hot storage tank connected to the exit of the solar receiver, which feeds a fluid bed heat exchanger (FBHE), where the particles transmit their energy to submerged tubes inside whose working fluid (for example steam) is generated, the latter is then expanded in a turbine. FBHE is indeed a classical device in the electrical power industry (mostly implemented for coal combustion in fluidized bed). The cooled particles exit the exchanger (continuous circulation) and are sent towards the cold storage tank; this can be done either by mechanical or pneumatic conveying or by gravity depending on the available space or on the facility geometry (tower configuration is particularly favourable for gravity for instance). Finally, connecting the cold bin to the solar receiver inlet by a conveying system raising the particles completes the loop. Consequently, solid particles are used as heat transfer fluid and heat storage medium. Actually, it should be noted that the proposed solar power plant is combined with a vapour cycle and steam turbine, but the system is very similar to the case of a gas turbine, the main difference being the heat exchanger, which is changed to adapt to the chosen type of turbine. In this concept the particle solar receiver is the key component. The next paragraph summarizes the state-of-the-art in the field of solar receivers using particles as HTF.

Solid particles may be used as a heat transfer fluid in solar thermal concentrating systems in direct heating and indirect heating receivers. In the former case solid particles absorb directly the concentrated solar radiation, and in the latter case a heat transfer wall is used, the wall absorbs solar radiation and transfers the heat to a flowing heat transfer medium. In particular tubular absorbers are mainly used in current solar thermal power plants. Solid particle solar receivers associated with solar tower concentrating systems offer very interesting options for high temperature and high efficiency power cycles, thermal storage integration (using the same particles as HTF and storage medium) and chemical applications of concentrated solar energy (thermo-chemical water splitting process to produce hydrogen, cement processing, for example).

The first studies on direct absorption solar receivers started in the early 1980s with three concepts, the fluidized bed receiver (Flamant, 1982), the free falling particles receiver (Martin and Vitko, 1982) and the rotary kiln receiver (Bataille et al. 1989). In the first concept the solid particles are fluidized in a transparent tube but do not flow outside, there is no solid circulation. Consequently the system was used to heat air or to process reactive particles in batch operation, as indicated by Flamant et al. (1980). In the free falling particles curtain concept, the solid is dropped directly into the concentrated solar beam from the top of the receiver and is heated during the time of its pass through the concentrated radiation. Particle selection and radiative heat transfer modeling have been proposed by Falcone et al. (1985) as well as Evans et al. (1987). CNRS developed a “Sand heater loop” using sand particles as HTF (Bataille et al., 1989). It combined a solar rotary kiln that delivered hot sand to a heat storage / heat recovery sub-system consisting of a hot and a cold heat storage bin and of a multistage fluidized heat exchanger.

After about twenty years without new development, this concept was again proposed as a promising option for a new generation of high temperature solar thermal concentrating plants. Improved models have been developed (Chen et al., 2007) and validated by on-sun experiments at pilot scale (Siegel et al., 2010). The receiver prototype was tested at the National Solar Thermal Test Facility (NSTTF) in Albuquerque NM, USA. The cavity receiver was 6.3 m in height by 1.85 m in width and 1.5 m in depth with a 3 m high and 1.5 m wide aperture. Selected particles were alumi-nosilicate containing 7% of $Fe_2O_3$ (marketed as CARBO HSP 20/40) with 697 μm mean diameter. Batch runs were performed from 3 min to about 7 min (for a total particle inventory of about 1800 kg). Measured temperature increase (from ambient temperature) during experiments was ranged from 100 °C to about 250 °C for a single pass and solar power in the range 1.58–2.5 MWth. The receiver efficiency increased generally with the particle flow rate and varied from about 35% to 52%, thus in good agreement with simulated data. A review of the falling particle receiver was proposed by Tan and Chen (2010) with emphasize on the effect of wind speed on receiver performances. Particle aerodynamics in this type of receiver is affected by the wind and various parasitic air flows inside the cavity induced by the particles' falling and convection due to temperature difference, as well as by air jet flow if an aerowindow (Tan et al., 2008) is used. These effects may be partially avoided by using the face-down solid particle receiver concept of Röger et al. (2011) in which the particle curtain lines the inner wall of a cylinder closed at its top; the bottom part facing the concentrated solar beam. In this study, a circa 350 MWth receiver placed at the top of a 309 m high tower surrounded by a heliostat field was modeled. It was shown that solid recirculation improves drastically the receiver efficiency from 79% to 90% at full load and from 45% to 86% at 50% load. Concerning the comparison of a solid particle solar power plant with other more standard options, the study of Giuliano et al. (2011) gives interesting conclusions for solar-hybrid operation. It is clearly shown that none of the analysed solar-hybrid plants can meet low $CO_2$ emission and low LEC (Levelized Electricity Cost). For example a particle-receiver tower with a combined cycle has the lowest solar LEC (about 10 c €/kWh) but high specific $CO_2$ emission (high fossil fuel consumption). Moreover, one of the main conclusions is that solar-hybrid plants have a high potential to reduce $CO_2$ emission with high storage capacities (large solar fields). In solar power plants using solid particle receiver, storage may be achieved using the same particles as the HTF (similarly to molten salt solar plants). Heat recovery from the hot storage is then possible using fluidized bed heat exchangers as described by Warerkar et al. (2011), or particle-air heat exchangers tested by Al-Ansary et al. (2012) in which particles flow through. In this last study storage bins are integrated at the top of the tower.

Direct absorption systems using particles are very attractive because no window is necessary and they accept very high solar