Fluidized-bed technology enabling the integration of high temperature solar receiver CSP systems with steam and advanced power cycles

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Abstract

Solar Particle Receivers (SPR) are under development to drive concentrating solar plants (CSP) towards higher operating temperatures to support higher efficiency power conversion cycles. The novel high temperature SPR-based CSP system uses solid particles as the heat transfer medium (HTM) in place of the more conventional fluids such as molten salt or steam used in current state-of-the-art CSP plants. The solar particle receiver (SPR) is designed to heat the HTM to temperatures of 800 °C or higher which is well above the operating temperatures of nitrate-based molten salt thermal energy storage (TES) systems. The solid particles also help overcome some of the other challenges associated with molten salt-based systems such as freezing, instability and degradation. The higher operating temperatures and use of low cost HTM and higher efficiency power cycles are geared towards reducing costs associated with CSP systems. This paper describes the SPR-based CSP system with a focus on the fluidized-bed (FB) heat exchanger and its integration with various power cycles. The SPR technology provides a potential pathway to achieving the levelized cost of electricity (LCOE) target of $0.06/kWh that has been set by the U.S. Department of Energy’s SunShot initiative.

Keywords: Concentrating solar power; solar particle receiver; fluidized bed, heat exchanger; solid particles; high temperature; high efficiency; renewable energy

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1. Introduction

The need for clean energy technologies has intensified in recent years due to the continuous increase in energy demand, increasing concerns on environmental emissions and climate change as well as the shrinkage of available fossil fuel resources. [1] Concentrating solar power (CSP) is one of the promising technologies currently undergoing rapid development. [2, 3] CSP technology offers the potential to generate power efficiently and at a low cost while providing the means to store energy to meet the demands of the grid.

Babcock & Wilcox Power Generation Group, Inc. (B&W PGG) is collaborating with the National Renewable Energy Laboratory (NREL) to develop a novel high temperature solar receiver system that uses solid particles as the heat transfer medium (HTM). The solar particle receiver (SPR) is designed to heat the HTM to temperatures > 800 °C which is well above the operating temperatures of current state-of-the-art molten salt-based thermal energy storage (TES) systems. These higher temperatures enable the use of higher efficiency power cycles. The use of low cost and stable HTM, innovative component design, and the increase in cycle efficiency provide a means to reduce component and system level costs associated with the CSP system compared to the current state-of-the-art of molten salt-based CSP plants. [4] This paper describes the system with a focus on the fluidized-bed (FB) heat exchanger and its integration with various power cycles. The SPR technology provides a potential pathway to achieve the levelized cost of electricity (LCOE) target of $0.06/kWh as set by the U.S. Department of Energy SunShot initiative.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
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<tbody>
<tr>
<td>B&amp;W</td>
<td>Babcock &amp; Wilcox</td>
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<td>B&amp;W PGG</td>
<td>Babcock &amp; Wilcox Power Generation Group</td>
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<tr>
<td>CSP</td>
<td>Concentrating Solar Power</td>
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<tr>
<td>FB</td>
<td>Fluidized Bed</td>
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<tr>
<td>FBHX</td>
<td>Fluidized-Bed Heat Exchanger</td>
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<tr>
<td>HTM</td>
<td>Heat Transfer Medium</td>
</tr>
<tr>
<td>HX</td>
<td>Heat Exchanger</td>
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<tr>
<td>LCOE</td>
<td>Levelized Cost of Electricity</td>
</tr>
<tr>
<td>NGCC</td>
<td>Natural Gas Combined Cycle</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<tr>
<td>PFB-HX</td>
<td>Pressurized Fluidized-Bed Heat Exchanger</td>
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<tr>
<td>RH</td>
<td>Reheater</td>
</tr>
<tr>
<td>SC</td>
<td>Supercritical steam cycle</td>
</tr>
<tr>
<td>s-CO₂</td>
<td>Supercritical Carbon Dioxide</td>
</tr>
<tr>
<td>SH</td>
<td>Superheater</td>
</tr>
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<td>SPR</td>
<td>Solar Particle Receiver</td>
</tr>
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<td>Sub-C</td>
<td>Subcritical steam cycle</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>VSS</td>
<td>Vertical Steam Separator</td>
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2. Technology

2.1. System

The SPR is designed to utilize HTM, or solid particles, which act as both the heat transfer and energy storage medium. In the current design philosophy, HTM particles can reach temperatures in excess of 800 °C. Figure 1 depicts the overall system which integrates the SPR with the TES and the power cycle of choice. The heliostat field focuses the sun’s energy onto the SPR which allows the energy from the sun to be absorbed by the flowing solid medium. The hot particles exiting the SPR are then transported to the TES system, which consists of one or more hot and cold particle storage silos. The hot particles are dispatched to the FB heat exchanger where energy is
transferred from the hot solids to the working fluid to drive a steam turbine as depicted in Figure 1, or the turbine of choice depending on the power cycle. After energy has been extracted from the particles in the FBHX, the cooled particles are sent back to the cold particle storage silo.

The stored cold particles are then conveyed back to the SPR when solar flux is available for a subsequent cycle of heat absorption. A bucket elevator or alternate solids conveying systems can be used to move the HTM back to the SPR. The use of solid particles as the HTM helps overcome some of the operational difficulties posed by molten salt-based systems. The selected particles are not only stable at temperatures above 800 °C, but also eliminate HTM freezing risks associated with molten salt-based TES systems.

Fig. 1. The SPR system: receiver, hot/cold particle storage silos, bucket elevator, FBHX and power cycle (steam Rankine cycle shown).

3. System components

3.1. The solar receiver

The NREL/B&W PGG team is developing a cascading particle flow receiver design which allows the particles to contact the heating surface which receives the solar flux. The solar flux is directed to the SPR which consists of a series of tubular shaped mini cavities. The solar energy is directed to the internal surfaces of these tubular cavities while particles are allowed to flow over the tubes. The receiver design is based on near blackbody radiation principles and shows the potential to produce high temperature particles while maintaining desirable receiver efficiencies of 90% or higher. The design raises the particle temperature via indirect heat exchange. [5] The development of the SPR involves investigation into a number of important elements regarding design, manufacturing, material selection and operation of this receiver. Among these are the evaluation of particle flow and heat transfer, material selection and testing, characterization of optical performance related to flux penetration, spreading and losses as well as determining its manufacturability and operability. Various other groups are also working on the development of SPR technologies which could integrate the FBHX into their respective CSP plant arrangements. The Sandia falling particle design achieves the heat transfer by focusing solar energy directly onto the particles. [6] The system components described in this paper are primarily based on the NREL/B&W PGG design; however, components like the fluidized-bed heat exchanger would be suitable to the Sandia system as well, and possibly applicable to other alternate SPR systems.

3.2. Solids conveyer/ bucket elevator

The commercial SPR system is envisaged to make use of a surround-field heliostat arrangement. Therefore, the receiver heat transfer surfaces are arranged circumferentially. A commercial SPR with heat input ratings of 400 to 800 MW, would require a particle handling and delivery system that can transfer particles from the TES to the SPR
and subsequently deliver and distribute the particles circumferentially to all surfaces of the SPR. Figure 2 depicts a system comprised of four elevator pairs consisting of a first elevator located on the outside of the tower that draws “cold” solids from the cold particle storage silo, and discharges the solids directly into a second elevator. The second elevator carries the solids to the top of the tower and discharges the solids into the particle hopper (transition hopper). The cold particle storage silo is assumed to be located inside the tower. Each of the second elevators is located inside the silo. Four pairs of elevators are located at the compass points around the tower. Each pair has a minimum capacity of 33.3% of the required full load solids flow, thereby allowing full load operation with one elevator train out of service.

Fig. 2. (a) General arrangement of receiver, tower and FBHX; (b) SPR front view; (c) top view; (d) transition hopper sectional view.

3.3. Solids hopper/ particle distributor

The solids hopper and distribution system above the receiver provides a consistent and controlled flow of solids to the receiver. The hopper is also required in order to provide enough reserve of particle inventory to respond to system dynamics. For example, if the plant experiences power loss, the particle reserve would provide the necessary inventory to prevent the surfaces from overheating while the mirrors are focused away from the receiver. Therefore, the design philosophy for the solids hopper and particle distribution system has considered the following factors:

- Provide inventory of solids in the hopper sufficient to keep the receiver cooled during plant trips and equipment failures while mirrors are defocused
- Allow control of solids flow through SPR to accommodate circumferential variations in incident flux
- Prevent stagnation, accumulation and buildup of solids to avoid sintering and blockage of particle flow path
- Prevent starvation of SPR due to maldistribution
- Minimize heat loss and parasitic power

An aeration ring fluidizes the lower half of the hopper to evenly distribute the particles around the full circumference of the hopper. Even with one elevator offline, the system would provide adequate supply of particles throughout the SPR to maintain full load. This proposed design redundancy scheme provides reliable operation in the event that one elevator breaks down or both elevators for a single pair of elevators are inoperable. Additional modifications to the design can be made to offer an even higher level of reliability. The solids flow rate to each vertical section of the receiver can be adjusted and controlled using mechanical discharge valves (e.g., gate valves, rotary valves) or non-mechanical aerated distribution systems. The solids distributor below the discharge gate then provides the means to further distribute the particle flow into a given segment of the receiver. The distribution cavity is enclosed and particle tight.
4. Fluidized-bed heat exchanger and power cycle

While it is necessary to develop a SPR that can produce the desired hot particles, enabling the transfer of energy from the hot particles to the working fluid is important to the success of the system as the working fluid drives the power cycle. System efficiency gains with the use of advanced power cycles would translate to a significant reduction in the size of the mirror field, thereby reducing the overall CSP plant cost and consequently, the LCOE. FBHX technology, which leverages on B&W PGG’s expertise of gas-solid two-phase flow and heat transfer, is used to extract the energy from the hot particles to heat the working fluid, which then drives the power turbine of choice. The fluidized bed design was developed with the following characteristics in mind:

- Suitable for particle sizes desired by the receiver
- High heat transfer
- Lower parasitic power consumption than alternative designs
- Low sensible heat loss
- Potential for lowest cost design

Design efforts on the FBHX were focused on subcritical (Sub-C) and supercritical (SC) steam Rankine cycles, advanced cycles including supercritical CO₂ (s-CO₂) Brayton cycles, and air Brayton combined cycles. Figure 3 shows the designs of two of the FB heat exchangers for subcritical and supercritical steam power cycle application, including the arrangement of surfaces for water preheating and steam generating, superheating and reheating. The FB designs are capable of transporting the HTM through the heat exchanger surfaces, extracting energy in an efficient manner to support the desired conditions summarized in Table 1. For example, the FB for the s-CO₂ cycle has been designed to produce CO₂ at 700 °C to support the advanced cycle. The initial optimization efforts have considered the implication of the designs on cost and operation and potential arrangements of the HXs in the plant.

Table 1. Advancing CSP Systems

<table>
<thead>
<tr>
<th>System Variable</th>
<th>Molten Salt</th>
<th>SPR</th>
<th>SPR</th>
<th>SPR</th>
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<tr>
<td>Turbine Cycle</td>
<td>Sub-C Rankine</td>
<td>SC Rankine</td>
<td>Brayton (s-CO₂)</td>
<td>Brayton (Air)</td>
</tr>
<tr>
<td>Turbine Working Fluid</td>
<td>Steam</td>
<td>Steam</td>
<td>CO₂</td>
<td>Air and Steam</td>
</tr>
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<td>Receiver HTM</td>
<td>Nitrate Salt</td>
<td>Solid Particles</td>
<td>Solid Particles</td>
<td>Solid Particles</td>
</tr>
<tr>
<td>Receiver Exit Temp</td>
<td>566 °C</td>
<td>800 °C</td>
<td>800 °C</td>
<td>800 °C or higher</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Shell and Tube</td>
<td>Fluidized Bed</td>
<td>Fluidized Bed</td>
<td>Pressurized FBHX</td>
</tr>
<tr>
<td>HP Turbine Inlet</td>
<td>540 °C / 13 MPa</td>
<td>580 °C / 24.2 MPa</td>
<td>700°C / 25 MPa</td>
<td>Up to 1420 °C</td>
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<tr>
<td>Turbine Cycle Efficiency</td>
<td>42%</td>
<td>45%</td>
<td>51%</td>
<td>&gt;52%</td>
</tr>
<tr>
<td>Energy Storage (hrs)</td>
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<td>6-13</td>
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</tbody>
</table>

Fig. 3. (a) FBHX design: subcritical steam Rankine cycle; (b) FBHX design: supercritical steam Rankine cycle.
4.1. Fluidized-bed heat exchanger: subcritical steam

An overall view of the subcritical heat exchanger is presented in Figure 3a. The subcritical FBHX utilizes a low-velocity fluidized bed of fine solids (< 100 micron average size) to transfer heat acquired by the solids in the solar receiver to the working medium of the power cycle. Heat transfer surfaces in the bed are arranged to provide a general countercurrent flow pattern between the bed material and the working medium. This means that the last set of heat transfer surfaces on the working medium route, i.e., superheater (SH) and reheater (RH), are the first ones in the solids path, and the first surface in the working medium route (economizer) is the last one in the solids path. The countercurrent flow setup is also provided with each type of surface. This arrangement maximizes overall mean temperature differentials between the solids and the medium allowing for a reduction in total heating surface area for a given amount of heat duty.

Solids flow through the first part of the HX is split into two parallel individually controlled streams, one for the SH section, another for the RH section. Water spray, along with solids flow rate adjustment, is used for controlling SH stream temperature. However, spraying water into RH steam reduces the cycle efficiency since the steam generated from this water does not pass through the high pressure turbine. Therefore, adjusting solids flow through the path containing reheat heating surface is the primary means for RH steam temperature control. Water spray at the RH inlet is provided for emergencies only.

The particle streams from the SH and RH combine into a common flow and then subsequently pass through the generating bank surfaces and the economizer section. Typical solids temperatures along the way are as follows: 760 to 815 °C entering the HX (SH and RH), 538 to 593 °C entering the generating surface, 315 to 370 °C entering the economizer, and 260 to 315 °C leaving the HX (economizer).

The sides and top of the SH, RH and the generating bank have water-cooled membrane enclosures. The economizer is enclosed with a plate casing which is allowed due to the sufficiently low solids temperature. The bed is fluidized with air delivered through a distribution grid and air flow is controlled individually to each section of the bed to account for the local bed temperature (and corresponding air specific volume) for maintaining a preset bed superficial velocity. The air is vented from the HX through a baghouse and vented to the atmosphere. The heat exchanger is fed with bed material from the hot solids silo with a flow rate matching power demand. The silo is located above the HX, allowing solids to feed by gravity. The metering is accomplished by either mechanical valves (such as a conical valve) or non-mechanical valves (such as an L-valve); both types are widely used in fluidized-bed boilers.

The subcritical FBHX features a water circulation system which has been designed and optimized to operate without a circulation pump and with natural circulation characteristics. The circulation system uses a traditional steam drum as the vessel where steam is separated from the steam/water mixture leaving the evaporating components. Once separated, dry steam is sent to the superheater while water is recirculated within the evaporating components.

4.2. Fluidized-bed heat exchanger: supercritical steam

Figure 3b depicts the design of the supercritical steam FBHX that would be incorporated in a SPR-based CSP plant that uses a supercritical steam turbine power cycle. This design, in many ways is similar to the sub-critical steam fluidized-bed boiler described earlier. One of the main differences between the two designs is in the generating bank section of the fluid bed. Since this is a supercritical steam system, during full load operation there is no real phase change in the supercritical fluid. Therefore, there is no need for a steam drum or separator during full load operation. However, during part load operation, it would be desirable for the system to operate in variable pressure mode. Variable pressure operation would allow better control of the temperature gradients to which the heat exchanger and turbine components would be subjected. This is the basis of the current design. The supercritical steam FBHX uses B&W PGG’s vertical steam separator (VSS) system for steam separation from the steam/water mixture during start-up and low-load operation. The VSS would be used in lieu of the steam drum component utilized for the subcritical steam cycle.
4.3. Fluidized-bed heat exchanger: s-CO$_2$

Advanced turbine cycles have the potential to raise the efficiencies of CSP plants, thereby allowing for further reductions in the LCOE. With this in mind, the SPR is being designed to generate higher temperature HTM to support these more advanced turbine cycles. A number of supercritical CO$_2$ cycles are currently being investigated by various researchers and turbine developers to determine their potential and ways of incorporating them into CSP plants. Under consideration are simple cycles, recompression, partial-cooling cycles which apply various different compression and heat recuperation schemes. [7] A number of simulations using Aspen Plus$^\text{®}$ have been performed based on the partial cooling s-CO$_2$ cycle. Table 1 summarizes the characteristics of the s-CO$_2$ partial cooling cycle with a single reheat loop used as the basis for the design of the FBHX.

The turbine cycle efficiency of the s-CO$_2$ is impacted by several parameters. Compressor inlet temperature was studied in previous simulations with results obtained for compressor inlet temperatures of 32 °C and 50 °C. A temperature of 700 °C was chosen as the target FBHX fluid outlet temperature as it offered the potential of achieving the desired turbine cycle efficiency target of 50% with a compressor inlet temperature of 50 °C, including allowances for some losses such as pressure drop in the heat recuperators. Due to the higher operating temperatures, this heat exchanger requires the use of higher alloy materials, especially in the hotter sections. The initial design efforts have displayed a number of advantages that a fluidized-bed system would offer for s-CO$_2$ SPR systems. For example, higher heat transfer coefficients not only help reduce the overall footprint of the vessel, but also help to minimize the amount of high alloy surface that would be used in the construction of the vessel which would ultimately factor into the capital cost of the equipment. As components of the s-CO$_2$ power cycle continue to be designed, developed and tested, the FBHX design can also be further advanced and optimized to meet the desired performance characteristics set by the cycle and the CSP plant.

4.4. Fluidized-bed heat exchanger: air Brayton combined cycle

The SPR system can also support an air Brayton or a Natural Gas Combined Cycle (NGCC) power generation system. This plant would therefore incorporate an advanced high temperature SPR much like the prior scenarios; however, the heat exchanger in this case would need to be a pressurized FBHX. The pressurized FBHX would be designed to allow the transfer of the thermal energy to the pressurized air. Unlike the previous designs, the heat exchange would be performed by allowing the direct contact of solids and air as opposed to using pressure pipes for the fluid loop. For this reason, the entire vessel would become a pressurized vessel whereas in the prior scenarios, the fluidized bed was not a pressure vessel itself.

The heated pressurized air is then sent to an air/natural gas turbine to drive a combined cycle power generation system similar to a natural gas combined cycle. With supplemental heat provided by natural gas firing, this system would be capable of approaching efficiencies of that achieved by NGCC plants while requiring a fraction of the natural gas. It is conceivable that as the receiver technology advances further to yield even higher particle temperatures, the use of natural gas could be further reduced or perhaps even eliminated. A number of hybridization scenarios have been considered including the ratio of thermal input between natural gas and solar sources with natural gas accounting for as high as 60% of the thermal input. The preliminary design of the heat exchanger has been developed to determine the means of performing the heat exchange between the pressurized air and solids particles. The methods of transferring particles in and out of the PFB-HX vessel as well as methods of maintaining the desired pressure and filtering the air prior to its entry into the gas turbine have been demonstrated previously by B&W PGG during the development of its pressurized fluidized-bed boiler Tidd demonstration project. [8, 9] As the design and development efforts continue to prove the feasibility of the SPR concept and associated components, it is envisioned that a first-of-a-kind SPR-based CSP plant would likely utilize the more proven steam turbine cycle and consequently, either the subcritical or supercritical steam FBHX. However, with further progression of technology, the s-CO$_2$ FBHX or the air Brayton PFB-HX may be options for the next generation, higher efficiency and lower cost CSP plant system.
5. Summary

The development of solid particle receivers would allow CSP plants to operate at higher temperatures than state-of-the-art molten salt CSP plants. The increase in the operating temperature is geared towards producing HTM at substantially higher temperatures, which in turn provides the potential means to support high temperature advanced power cycles. System efficiency gains that would result from the use of advanced power cycles, coupled with cost reduction efforts on components (including the heliostat field), are aimed at significantly reducing the LCOE of CSP plants. FBHX technology enables the use of the high temperature HTM and allows the transfer of the thermal energy to the fluids that would drive the various power cycles. Design efforts on the FBHX have considered subcritical and supercritical steam cycles, as well as advanced cycles including s-CO₂ and air Brayton combined cycles. In addition to the core systems which include the SPR, TES, FBHX and the power generation system, the CSP plant requires a number of components associated with solids handling, storage and control.

Research, design and development efforts are making strides to prove the feasibility of the SPR concept and associated components. While it is envisioned that a first-of-a-kind SPR-based CSP plant may utilize the more proven steam turbine cycle and consequently, either the subcritical or supercritical steam FBHX, with further progression of technology, the s-CO₂ FBHX or the air Brayton PFB-HX may be options for the next generation, higher efficiency and lower cost CSP plant.

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References


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