Proceedings of ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference
SAND2014-3321C
ESFuelCell2014
June 29 – July 2, 2014, Boston, Massachusetts

ES-FuelCell2014-6328

HIGH-TEMPERATURE RECEIVER DESIGNS FOR SUPERCRITICAL CO_2 CLOSED-LOOP BRAYTON CYCLES

C.K. Ho,[1] T. Conboy,[1] J. Ortega,[2] S. Afrin,[2] A. Gray,[3] J.M. Christian,[1] S. Bandyopadyay,[4] S.B. Kedare,[4] S. Singh,[4] P. Wani[4]
[1]Sandia National Laboratories, Albuquerque, New Mexico, 87185-1127, USA, (505) 844-2384, ckho@sandia.gov
[2]University of Texas El Paso, USA
[3]National Renewable Energy Laboratory, Golden, Colorado, USA
[4]Indian Institute of Technology Bombay, India

ABSTRACT

High-temperature receiver designs for solar powered supercritical CO_2 Brayton cycles that can produce ~1 MW of electricity are being investigated. Advantages of a supercritical CO_2 closed-loop Brayton cycle with recuperation include high efficiency (~50%) and a small footprint relative to equivalent systems employing steam Rankine power cycles. Heating for the supercritical CO_2 system occurs in a high-temperature solar receiver that can produce temperatures of at least 700 °C. Depending on whether the CO_2 is heated directly or indirectly, the receiver may need to withstand pressures up to 20 MPa (200 bar). This paper reviews several high-temperature receiver designs that have been investigated as part of the SERIIUS program. Designs for direct heating of CO_2 include volumetric receivers and tubular receivers, while designs for indirect heating include volumetric air receivers, molten-salt and liquid-metal tubular receivers, and falling particle receivers. Indirect receiver designs also allow storage of thermal energy for dispatchable electricity generation. Advantages and disadvantages of alternative designs are presented. Current results show that the most viable options include tubular receiver designs for direct and indirect heating of CO_2 and falling particle receiver designs for indirect heating and storage.

1. INTRODUCTION

The Solar Energy Research Institute for India and the United States (SERIIUS), a consortium funded jointly by the governments of India and the U.S., is focused on developing emerging solar electricity technologies toward the success of India's Jawaharlal Nehru National Solar Energy Mission and the U.S. Department of Energy's SunShot Initiative. One of the thrust areas is multi-scale concentrating solar power (CSP), which includes the evaluation of CSP systems with high-temperature, closed-loop CO_2 Brayton cycles.

Supercritical CO_2 (s-CO_2) thermodynamic cycles are projected to improve overall CSP plant economics due to their high power conversion efficiency and compact system layout; these attributes should allow for a reduction in installed cost in comparison to more conventional alternatives including steam turbines and open-cycle gas turbines [1-3]. The s-CO_2 Brayton cycle is essentially a recuperated, low pressure ratio closed-cycle gas turbine concept (Figure 1). Use of a closed-cycle system permits a working fluid other than air, in this case carbon dioxide, and allows cycle operation at elevated pressures. For the s-CO_2 Brayton cycle in particular, the high cycle thermal efficiency (45-50%) is achievable by means of pumping CO_2 in its high pressure supercritical dense phase (at 7.5MPa, 31°C), where little compression work is expended, then taking full advantage of recuperative heat transfer for pre-heating, before finally expanding the supercritical fluid at high temperature (at 20 MPa, 550-700°C). High fluid densities at the compressor and turbine (500 kg/m^3 and 100 kg/m^3, respectively) are largely responsible for an anticipated order of magnitude reduction in turbomachinery size as compared to steam plants.

A number of key challenges surrounding this technology have been identified and addressed. This includes achieving compressor stability and control near the critical point [4], devising high pressure approaches to bearings and seals [5], and developing control procedures from cold start-up to break-even conditions for both the simple recuperated Brayton cycle [6] and for a full-fledged recompression Brayton cycle [7]. Experimentally-measured cycle operating characteristics at steady-state power levels have also been reported in detail [8].

More recently, the performance of the s-CO_2 cycle at transient conditions characteristic of a direct-heated solar-to-CO_2 receiver has been reported [1]. In successive tests, the demonstration s-CO_2 Brayton cycle was brought to its design conditions, then the thermal input was cut to 50%, then to 0% for several minutes, before being restored. Pressure, temperature, and electricity generation transients were observed. It was noted that the overall system's large thermal mass enabled the cycle to continue operation with relatively small impact in each case. Thermal storage may be designed to eliminate the transient response altogether.

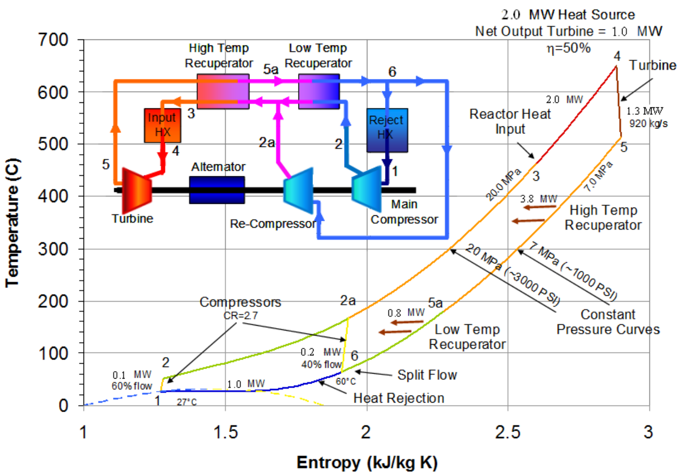

Figure 1. Supercritical CO_2 power cycle schematic and thermodynamic cycle for 1 MW Power Turbine

The desired power generating capacity for these systems in the SERIIUS program is 100 kW$_e$ to 1 MW$_e$. The focus for these high-temperature systems is on central receiver power-tower systems. The remainder of this paper (Section 2) describes alternative receiver designs for power towers that can provide the necessary heating for the s-CO_2 power cycle given the constraints above. In addition, a discussion of the heliostat field requirements is presented in Section 3.

2. ALTERNATIVE RECEIVER DESIGNS

2.1. Direct Receiver Designs

Direct receiver designs for s-CO_2 applications require high pressures (up to 20 MPa) and temperatures (~500 °C – 700 °C). Figure 2 shows a schematic of a solar-driven, direct-heated, closed-loop s-CO_2 Brayton power cycle. Several direct receiver designs are evaluated in the following sections.

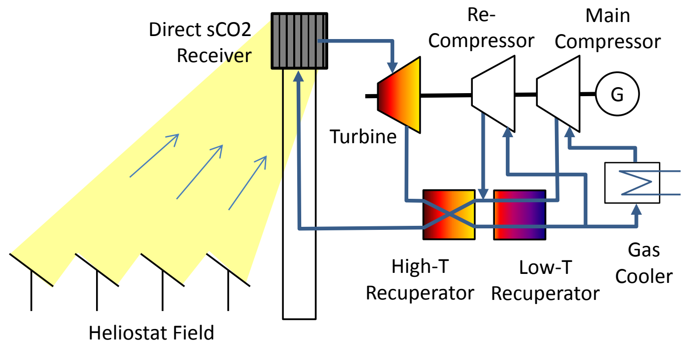

Figure 2. Schematic of a solar-driven, directly heated, closed-loop supercritical CO_2 Brayton power cycle.

2.1.1. Direct Volumetric Receiver

Volumetric receivers use highly porous structures (honeycomb, foam, wire mesh, etc.) of metal or ceramic to absorb concentrated sunlight and allow penetration of the incident radiation into the volume of the receiver. This absorbed heat is transferred to a fluid passing through it. The thermal energy of the fluid is then converted to electricity by adopting suitable thermodynamic power cycles (e.g. Rankine, Brayton cycle, etc.) [9].

Directly heated volumetric receivers require a closed (pressurized) design that can be coupled directly to the gas turbine (single loop operation) to operate at higher pressures. Such receivers have been tested with absolute operating pressure of 15 bar and air outlet temperatures of 800 °C [9, 10] (see Figure 3). The higher pressure operation is feasible because of a transparent window which separates the receiver cavity from ambient air. Also, the window minimizes thermal losses. However, containing s-CO_2 at ~ 20 MPa (200 bar) and up to 700°C would require a robust window design having excellent optical properties to prevent reflective losses and degradation. It would need to be equipped with sealing and cooling systems to prevent mechanical damage and leakages. Other challenges associated with volumetric receivers are absorber durability and unstable gas flow, which, as predicted by Kribus et al. [11], can cause local overheating leading to its poor performance and local failures (melting or cracking).

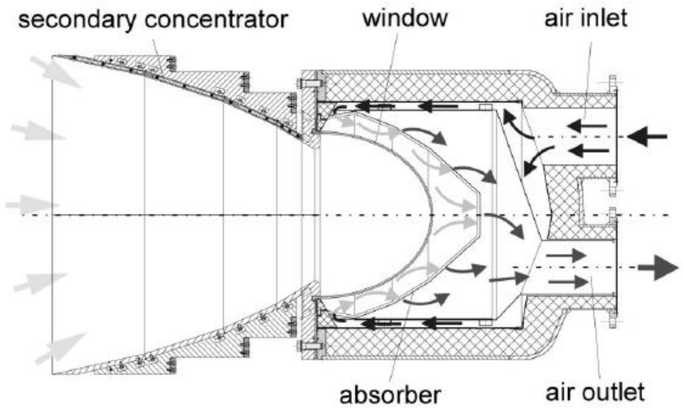

Figure 3. Direct pressurized volumetric receiver for air-Brayton cycle [10].

2.1.2. Direct Tubular Receiver

Direct tubular receiver designs for power towers have been employed at the Solar One pilot facility in the 1980's [12], the first commercial power towers, PS10 and PS20, operating since 2007 in Spain, and the recently commissioned Ivanpah Solar Electric Generating System in California. These systems used water/steam as both the heat transfer fluid and the working fluid in steam Rankine power cycles, where the steam pressure and temperature can reach ~10 - 16 MPa and ~560°C [13].

Solar-heated air-Brayton systems with tubular receivers have been proposed and tested that heat air up to ~800 °C with a pressure of ~5 – 7 bar (0.5 – 0.7 MPa) [14-16]. Figure 4 shows designs from these direct tubular receiver systems. Challenges associated with these direct tubular receiver systems include the potential for high radiative and convective losses, relatively low heat-transfer coefficients from the tubes to the heat transfer fluid, and fatigue due to transient thermo-mechanical loads [17]. Previous researchers have attempted to overcome these challenges by using segmented quartz windows, copper inserts to increase the conductivity in the tubes, and the use of Inconel, Haynes, and other nickel-based alloys to increase the strength of the tubes and their resistance to thermo-mechanical cyclic fatigue [16-18].

For s-CO_2 closed-loop Brayton cycles, in which the pressure and temperature can reach ~20 MPa and ~700 °C, addition direct tubular receiver designs have been considered. Design requirements include the ability to achieve and withstand the high pressures and temperatures, resistance to thermo-mechanical fatigue, good heat transfer to the working fluid to reduce tube wall temperatures, compactness to accommodate high concentration ratios, scalability, and mitigation of radiative and convective heat losses to achieve thermal efficiencies of 90%.

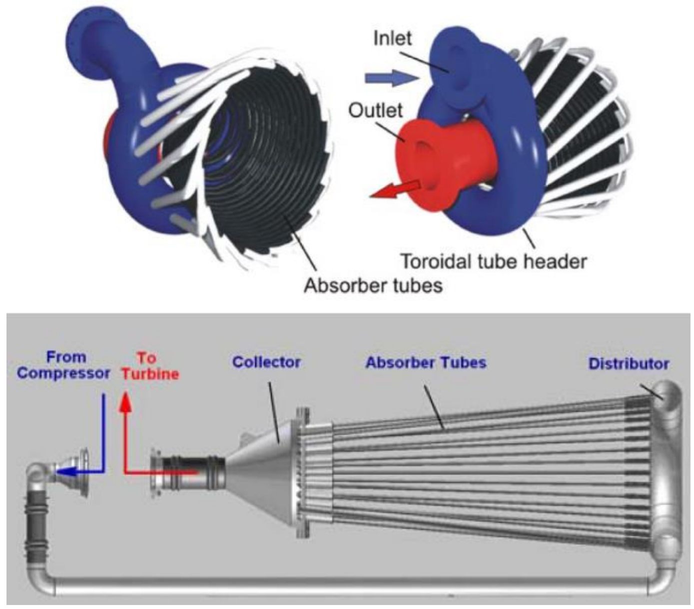

Figure 4. Direct receiver designs for solar air-Brayton systems [15, 16].

Figure 5 shows direct tubular receiver designs that are being evaluated as part of the SERIIUS program. Computational fluid dynamics (CFD) simulations have been performed to evaluate the temperature rise of the s-CO_2 working fluid and the thermal efficiencies, and structural analyses have been performed to determine critical stresses under static conditions (Figure 6). Future work will include transient loading and analyses for low-cycle fatigue. Current challenges are to reduce wall temperatures, heat losses, and critical stresses at joints while achieving a desired s-CO_2 outlet temperature of 700 °C.

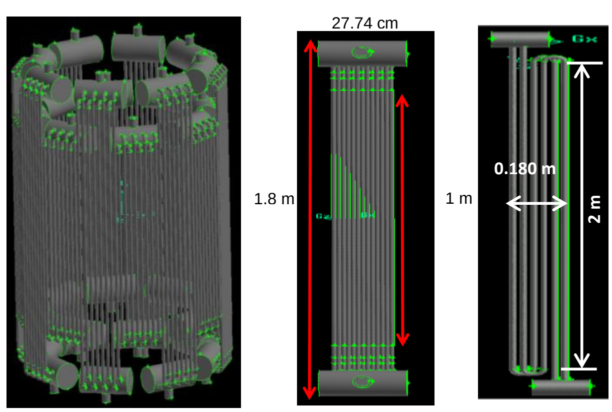

Figure 5. Examples of tubular receiver designs for direct heating of s-CO_2.

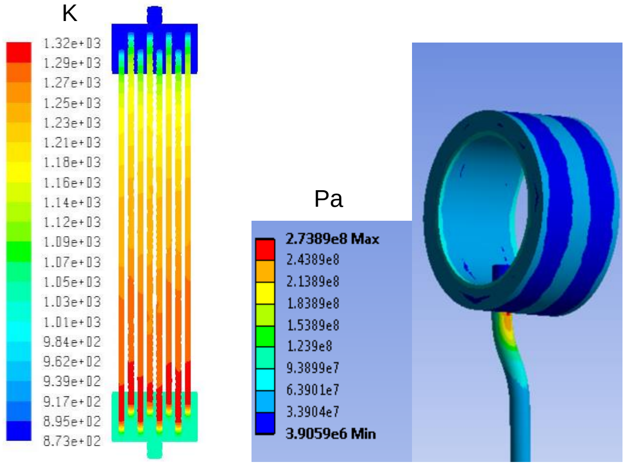

Figure 6. Simulations of wall temperature (left) and stress (right) distributions for direct tubular s-CO_2 receiver with irradiance of 400 kW/m^2 and 10 kg/s of CO_2 flowing through the tubes at 20 MPa and an initial temperature of 600 °C.

2.2. Indirect Receiver Designs

Indirect receiver designs for s-CO_2 applications alleviate the need for high pressures within the receiver, but high-temperature heat exchangers are required to transfer the heat from the heat-transfer fluid to the working fluid (s-CO_2). Examples of heat-transfer fluid (media) include air, molten salt, liquid metals, or solid particles. The primary advantages of indirect receivers is the ability to incorporate thermal storage and to suppress transient effects (e.g., cloud passages). Figure 7 shows a schematic of a solar-driven, indirectly heated, closed-loop s-CO_2 Brayton power cycle that incorporates an additional heat exchanger and storage. Some heat-transfer media that can be stored directly include molten salt, liquid metals, and solid particles. Other heat-transfer media, such as air, would require and additional heat exchanger if storage is desired. Several concepts for indirect s-CO_2 receiver designs and heat-transfer media are presented in the following sections.

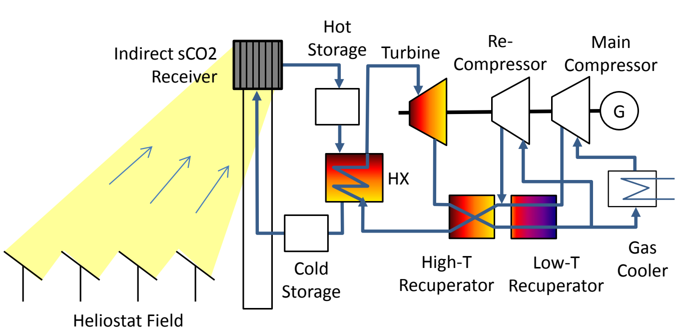

Figure 7. Schematic of a solar-driven, indirectly heated, closed-loop supercritical CO_2 Brayton power cycle.

2.2.1. Indirect Volumetric Receiver

Power plants with an indirect or open volumetric receiver design are generally equipped with two loops consisting of two different fluids. The heat-transfer fluid (usually air) at atmospheric pressure gets heated and pulled through the open volumetric receiver, and a heat exchanger transfers this heat to higher pressure fluid in the secondary loop. The secondary fluid then drives the turbine to generate power (e.g., 1.5 MW_e Rankine cycle at the Julich Solar Tower, Germany) [9, 19]. Brayton-cycle-based power plants consisting of s-CO_2 as the working fluid would require an air-s-CO_2 heat exchanger of large surface area due to the low overall heat transfer coefficient. The presence of two loops and high air temperature lead to higher thermal losses, thus increasing the system complexities and also reducing system efficiency.

2.2.2. Indirect Tubular Receiver

Indirect tubular receivers have been used at Solar Two in Daggett, CA, in the 1990's (see Figure 8) [20]; the Gemasolar plant near Seville, Spain, which became the first operating commercial power tower employing molten-salt technology for thermal storage in 2011; and the Crescent Dunes Solar Energy Project in Nevada, which is scheduled to be commissioned in 2014. Each of these systems used molten nitrate salts as the heat-transfer and storage fluid to heat steam for a steam Rankine cycle. Thermal efficiencies of the Solar Two receiver were measured to be between 80 – 90% [20]. However, above 600 °C, conventional nitrate salts become unstable and decompose [21-23]. While s-CO_2 cycles could feasibly operate with a maximum temperature below 600 °C, the thermal-to-electric efficiency decreases by several percentage points [2]. Other molten-salt systems (fluorides, chlorides) that can achieve higher temperatures have also been investigated [17]. The advantage of using an indirect molten-salt tubular receiver design is that this technology and its components (including piping, pumps, valves, and thermal storage) been previously demonstrated, and the primary challenge would be to develop a molten-salt/s-CO_2 heat exchanger.

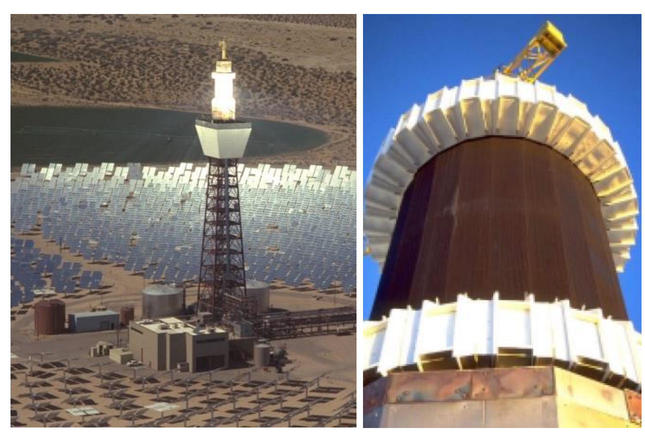

Figure 8. Solar Two molten-salt power tower (left) and receiver (right).

Liquid metal (e.g., sodium) receivers have also been studied previously [13, 17]. Liquid metals have the advantage of higher thermal conductivities and heat transfer rates to remove the heat from the tube wall. Therefore, higher concentration ratios and solar fluxes (in excess of 1.5 MW/m^2) can be applied to the receiver, which reduces the size of the receiver and the resulting radiative and convective heat losses. However, the reactivity of sodium or other liquid metal heat transfer fluids with oxygen, combined with the potential for leaking, can be a concern.

2.2.3. Falling Particle Receiver

Falling solid particle receivers were proposed in the 1980's [24] as a means to increase receiver outlet temperatures to over 1000 °C with inherent storage capabilities of the solid particles. Solid particles (e.g., silica sand, ceramic proppants) fall through a cavity receiver and are directly irradiated by concentrated sunlight. Once heated, the particles may be stored in an insulated tank and then used to heat a secondary working fluid (e.g., steam, CO_2, air) for the power cycle (see Figure 9). Because the solar energy is directly absorbed in the solid particles, the flux limitations associated with tubular central receivers (high stresses resulting from the containment of high temperature, high pressure fluids) are avoided. The falling particle receiver appears well-suited for scalability ranging from 10 – 100 MW$_e$ power-tower systems [25]. For integration with a s-CO_2 power cycle, a suitable particle-to-CO_2 heat exchanger would need to be developed that can withstand the high CO_2 pressures and still provide the necessary heat transfer rates. Fluidized beds have been proposed as an effective solid-to-gas heat exchanger, but the use of high-pressure CO_2 may be challenging. Shell-and-tube heat exchangers have also been investigated, but the solid-side heat transfer coefficient can be relatively low [26, 27].

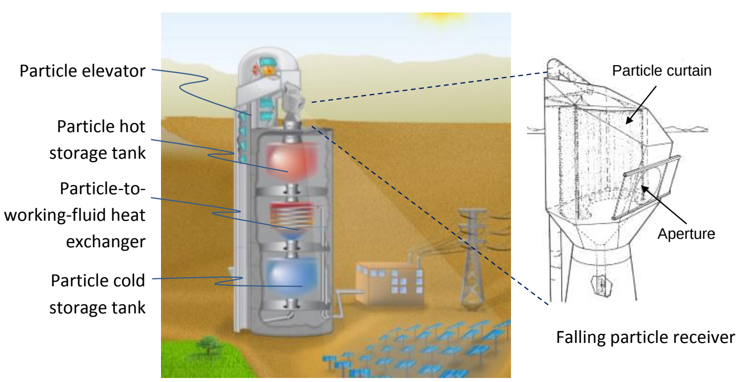

Figure 9. Conceptual sketch of large-scale falling particle receiver system.

3. HELIOSTAT FIELD ANALYSIS

Another task in the SERIIUS program (CSP-2) is to design a heliostat field compatible with the s-CO_2 receiver designs with maximum optical field collection efficiency (desired annual collection efficiency of 70% or greater). The thermal design point is 3 MW with a direct normal irradiance (DNI) of 950 W/m^2 at the Equinox. Considering the modest thermal target, small heliostat aperture sizes are considered, 1, 4, 9, 16, and 25 m^2. SolarPILOT, which was developed at NREL and utilizes the algorithm in DELSOL to optimize the field layout, was used to determine heliostat field layouts for the different heliostat sizes, optical errors, and receiver sizes. Figure 10 shows an example of two different heliostat configurations for 1 m^2 and 25 m^2 heliostats. The heliostat size, optical error budget, receiver size, and tower height are being parametrically evaluated to determine an optimal configuration. Current results show that a receiver size of ~6 m^2 can be employed to reach a 70% field collection efficiency with 1, 4, or 9 m^2 heliostats. Receiver sizes on the order of 4 m^2 resulted in field collection efficiencies that were ~5% lower due to increased spillage.

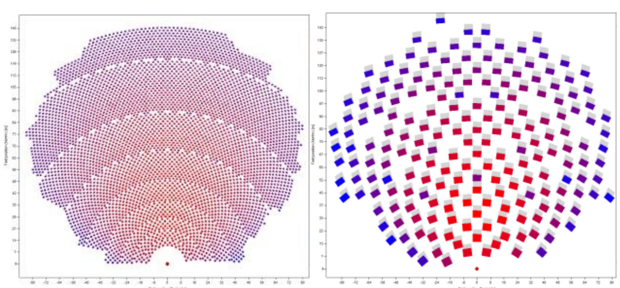

Figure 10. Optimized heliostat configurations (assuming a north field) for 1 m^2 (left) and 25 m^2 heliostats (right).

4. CONCLUSIONS

Alternative high-temperature solar receiver designs for supercritical CO_2 power cycles have been reviewed. Challenging aspects of implementing solar receivers with s-CO_2 power cycles include high CO_2 fluid pressures (~20 MPa) and temperatures (~500 °C – 700 °C). Receiver designs that can heat the s-CO_2 directly include volumetric receivers and tubular receivers. Indirect receiver designs that require an additional heat exchanger to heat the s-CO_2 from the heat-transfer media include volumetric receivers, tubular receivers, and falling particle receivers. The heat-transfer media employed by indirect receiver designs can include air, molten salts, liquid metals, and solid particles. An inherent advantage of indirect receivers is the ability to store thermal energy for dispatchability of electricity as needed. Table 1 summarizes the benefits and challenges of each of the receiver designs reviewed.

Table 1. Summary of s-CO_2 receiver designs.

Receiver Design	Benefits	Challenges / Research Needs
Direct Receivers		
Volumetric CO_2 Receiver	Capable of achieving high temperatures, simple and flexible construction, direct heating of CO_2	Window under high pressure, material durability, flow instability, radiative heat loss, low thermal efficiency, storage
Tubular CO_2 Receiver	Proven technology for direct steam and molten salt, direct heating of CO_2	Thermal cycling and fatigue of tubes, material compatibility, pressure limitations, flux limits, storage
Indirect Receivers		
Volumetric Air Receiver	Capable of achieving high temperatures with air in open loop, simple and flexible construction	Material durability, flow instability, radiative heat loss, low thermal efficiency, requires additional heat exchangers to store energy and to exchange heat with CO_2
Tubular Receiver (molten salt or liquid metal)	Proven technology for direct steam and molten salt, direct storage of heat transfer fluid	Thermal cycling and fatigue of tubes; material compatibility; pressure limitations; flux limits, requires fluid/CO_2 heat exchanger
Falling Particle Receivers	Capable of achieving high temperatures, reduced flux limitations, direct storage of particles	Radiative and convective heat losses, particle attrition, requires particle/CO_2 heat exchanger

ACKNOWLEDGEMENTS

This paper is based upon work supported in part under the US-India Partnership to Advance Clean Energy-Research (PACE-R) for the Solar Energy Research Institute for India and the United States (SERIIUS), funded jointly by the U.S. Department of Energy (Office of Science, Office of Basic Energy Sciences, and Energy Efficiency and Renewable Energy, Solar Energy Technology Program, under Subcontract DE-AC36-08GO28308 to the National Renewable Energy Laboratory, Golden, Colorado) and the Government of India, through the Department of Science and Technology under Subcontract IUSSTF/JCERDC-SERIIUS/2012 dated 22nd Nov. 2012. Partial support for Mr. Ortega and Ms. Afrin came through the University of Texas at El Paso under contract DE-EE0004008. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

REFERENCES

[1] Iverson, B.D., T.M. Conboy, J.J. Pasch, and A.M. Kruizenga, 2013, Supercritical CO2 Brayton cycles for solar-thermal energy, *Applied Energy*, **111**, p. 957-970.

[2] Turchi, C.S., Z.W. Ma, T.W. Neises, and M.J. Wagner, 2013, Thermodynamic Study of Advanced Supercritical Carbon Dioxide Power Cycles for Concentrating Solar Power Systems, *Journal of Solar Energy Engineering-Transactions of the Asme*, **135**(4).

[3] Wright, S.A., P.S. Pickard, R. Fuller, R.F. Radel, and M.E. Vernon, 2009, Supercritical Co(2) Brayton Cycle Power Generation Development Program and Initial Test Results, *Asme Power Conference 2009*, p. 573-583.

[4] Wright, S., R. Fuller, J. Noall, R.F. Radel, M.E. Vernon, and P.S. Pickard, 2008, *Supercritical CO2 Brayton Cycle Compression and Control Near the Critical Point*, in *in Proceedings of the International Congress on Advances in Nuclear Power Plants*, Anaheim, CA, June 8 - 12, 2008.

[5] Conboy, T.M., 2013, Real-Gas Effects in Foil Thrust Bearings Operating in the Turbulent Regime, *Journal of Tribology-Transactions of the Asme*, **135**(3).

[6] Wright, S., T. Conboy, and G. Rochau, 2011, *Break-Even Transients for Two Simple Recuperated Brayton Test Configurations*, in *In Proceedings of the Supercritical CO2 Power Cycle Symposium*, Boulder, CO, May 24 - 25, 2011.

[7] Conboy, T., J. Pasch, and D. Fleming, 2013, Control of a Supercritical CO2 Recompression Brayton Cycle Demonstration Loop, *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, **135**(11).

[8] Conboy, T., S. Wright, J. Pasch, D. Fleming, G. Rochau, and R. Fuller, 2012, Performance Characteristics of an Operating Supercritical CO2 Brayton Cycle, *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, **134**(11).

[9] Avila-Marin, A.L., 2011, Volumetric receivers in Solar Thermal Power Plants with Central Receiver System technology: A review, *Solar Energy*, **85**(5), p. 891-910.

[10] Buck, R., T. Brauning, T. Denk, M. Pfander, P. Schwarzbozl, and F. Tellez, 2002, Solar-hybrid gas turbine-based power tower systems (REFOS), *Journal of Solar Energy Engineering-Transactions of the Asme*, **124**(1), p. 2-9.

[11] Kribus, A., H. Ries, and W. Spirkl, 1996, Inherent limitations of volumetric solar receivers, *Journal of Solar Energy Engineering-Transactions of the Asme*, **118**(3), p. 151-155.

[12] Radosevich, L.G., 1988, Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant, SAND87-8022, Sandia National Laboratories, Albuquerque, NM,
[13] Falcone, P.K., 1986, A handbook for solar central receiver design, SAND86-8009, Sandia National Laboratories, Livermore, CA, December 1986.
[14] Amsbeck, L., R. Buck, P. Heller, J. Jedamski, and R. Uhlig, 2008, *Development of a Tube Receiver for a Solar-Hybrid Microturbine System*, in *Proceedings of the 2008 SolarPACES Conference*, Las Vegas, NV, March 4-7, 2008.
[15] Heller, P., M. Pfander, T. Denk, F. Tellez, A. Valverde, J. Fernandez, and A. Ring, 2006, Test and evaluation of a solar powered gas turbine system, *Solar Energy*, **80**(10), p. 1225-1230.
[16] Heller, P., J. Jedamski, L. Amsbeck, R. Uhlig, M. Ebert, M. Svensson, and et al., 2009, *Development of a Solar-Hybrid Microturbine System for a Mini-Tower*, in *Proceedings of SolarPACES 2009*, Berlin, Germany, September 15 - 18, 2009.
[17] Ho, C.K. and B.D. Iverson, 2014, Review of high-temperature central receiver designs for concentrating solar power, *Renewable & Sustainable Energy Reviews*, **29**, p. 835-846.
[18] Uhlig, R., 2011, *Transient Stresses at Metallic Solar Tube Receivers*, in *Proceedings of SolarPACES 2011*, Granada, Spain, September 20 - 23, 2011.
[19] Zunft, S., M. Hanel, M. Kruger, V. Dreissigacker, F. Gohring, and E. Wahl, 2011, Julich Solar Power Tower-Experimental Evaluation of the Storage Subsystem and Performance Calculation, *Journal of Solar Energy Engineering-Transactions of the Asme*, **133**(3).
[20] Pacheco, J.E., 2002, Final Test and Evaluation Results from the Solar Two Project, SAND2002-0120, Sandia National Laboratories, Albuquerque, NM,
[21] Bradshaw, R.W. and D.E. Meeker, 1990, High-Temperature Stability of Ternary Nitrate Molten-Salts for Solar Thermal-Energy Systems, *Solar Energy Materials*, **21**(1), p. 51-60.
[22] Bradshaw, R.W. and R.W. Carling, 1987, A Review of the Chemical and Physical-Properties of Molten Alkali Nitrate Salts and Their Effect on Materials for Solar Central Receivers, *Journal of the Electrochemical Society*, **134**(8B), p. C510-C511.
[23] Freeman, E.S., 1956, The Kinetics of the Thermal Decomposition of Sodium Nitrate and of the Reaction between Sodium Nitrite and Oxygen, *Journal of Physical Chemistry*, **60**(11), p. 1487-1493.
[24] Falcone, P.K., J.E. Noring, and J.M. Hruby, 1985, Assessment of a Solid Particle Receiver for a High Temperature Solar Central Receiver System, SAND85-8208, Sandia National Laboratories, Livermore, CA,
[25] Kolb, G.J., R.B. Diver, and N. Siegel, 2007, Central-station solar hydrogen power plant, *Journal of Solar Energy Engineering-Transactions of the ASME*, **129**(2), p. 179-183.
[26] Al-Ansary, H., S. Jeter, D. Sadowski, A. Alrished, M. Golob, A. El-Leathy, and Z. Al-Suhaibani, 2011, *Experimental Study of a Sand-Air Heat Exchanger for user with a High Temperature Solar Gas Turbine System*, in *SolarPACES 2011*, Granada, Spain, September 20-23, 2011.
[27] Golob et al., 2013, *Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation*, in *SolarPACES 2013*, Las Vegas, NV, September 17 - 20, 2013.

