Advanced Supercritical Carbon Dioxide Power Cycle Configurations for Use in Concentrating Solar Power Systems

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Abstract

Concentrating Solar Power (CSP) utilizes solar thermal energy to drive a thermal power cycle for the generation of electricity. CSP technologies include parabolic trough, linear Fresnel, central receiver or "power tower," and dish/engine systems. The resurgent interest in CSP has been driven by renewable portfolio standards in southwestern states and renewable energy feed-in tariffs in Spain. CSP systems are deployed as large, centralized power plants to take advantage of economies of scale. A key advantage of certain CSP systems, in particular parabolic troughs and power towers, is the ability to incorporate thermal energy storage. Thermal energy storage is less expensive and more efficient than electric storage and allows CSP plants to increase capacity factor and dispatch power as needed – for example, to cover evening or other demand peaks.

Current CSP plants utilize oil or steam to transfer solar energy to the power block. These fluids have properties that limit plant performance; for example, the synthetic oil has an upper temperature limit of 400°C while direct steam generation requires complex controls and has limited storage capacity. Higher operating temperatures generally translate into higher thermal cycle efficiency and often allow for more efficient thermal storage. To obviate these limitations, alternative fluids are under investigation by research teams worldwide.

Supercritical carbon dioxide (S-CO_2) operated in a closed-loop recompression Brayton cycle offers the potential of equivalent or higher cycle efficiency versus supercritical or superheated steam cycles at temperatures relevant for CSP applications. The S-CO_2 pressure is higher than superheated steam but lower than supercritical steam at temperatures of interest. The high pressure required for S-CO_2 makes application to trough fields difficult [4], and preliminary analysis suggests the fluid may be better suited for use in Power Towers. Even circulating high pressure S-CO_2 through a large Power Tower would be a challenge due to the volume and pressure of fluid being moved [9]. However, a modular power tower design introduced in this paper can take advantage of S-CO_2's potential without prohibitive piping costs.

In the proposed design, a single-phase process using S-CO_2 as both heat transfer fluid (HTF) and thermal power cycle fluid simplifies the power system configuration. The design is compatible with sensible-heat thermal energy storage, if desired. The simpler machinery and compact size of the S-CO_2 process may also reduce the installation, maintenance and operation cost of the system. Brayton-cycle systems using S-CO_2 have smaller weight and volume, lower thermal mass, and less complex power blocks versus Rankine cycles due to the higher density of the fluid and simpler cycle design. The lower thermal mass makes startup and load change faster for frequent start up/shut down operations and load adaption than a HTF/steam based system. The research will characterize and evaluate advanced S-CO_2 Brayton cycle power generation with a modular power tower CSP system.

Introduction

Supercritical CO_2 operated in a closed-loop recompression Brayton cycle offers the potential of equivalent or higher cycle efficiency versus supercritical or superheated steam cycles at temperatures relevant for CSP applications [2, 7]. A single-phase process using S-CO_2 as both heat transfer fluid for solar collector and working fluid for power cycle will simplify the power plant and may reduce the installation, maintenance and operation costs of the system. The high pressure required for S-CO_2 makes application to trough fields difficult due to the extensive piping in these plants [4], and the fluid may be better suited for use in Power Towers. In particular, modular towers can integrate an S-CO_2 power block within each tower to minimize piping size and length while taking advantage of the small size and weight with S-CO_2 turbine and compressor.

Modular S-CO_2 Receiver/Generation Unit for Tower/Solar Field

The CSP plant design described in this paper uses S-CO_2 as both HTF and working fluid. The assumed capacity of the power block is approximately 5 to 10 MW. Each modular tower would house its own turbomachinery and multiple towers could be assembled in a single power park. Such a modular power park has been proposed by eSolar, although in their system a single power block is shared by multiple towers. The proposed configuration includes two-stage turbines to drive the CO_2 compressor and generator respectively, as shown in Figure 1. Because of the compactness of the S-CO_2 turbine/compressor, it is possible to reduce the size of the generation unit and integrate the generator unit in the tower as depicted in Figure 2. The benefits of integration include shorter piping and associated pressure loss, lesser thermal losses, and improved transient response. As a result, the system achieves high performance and significant cost benefits for CSP power generation.

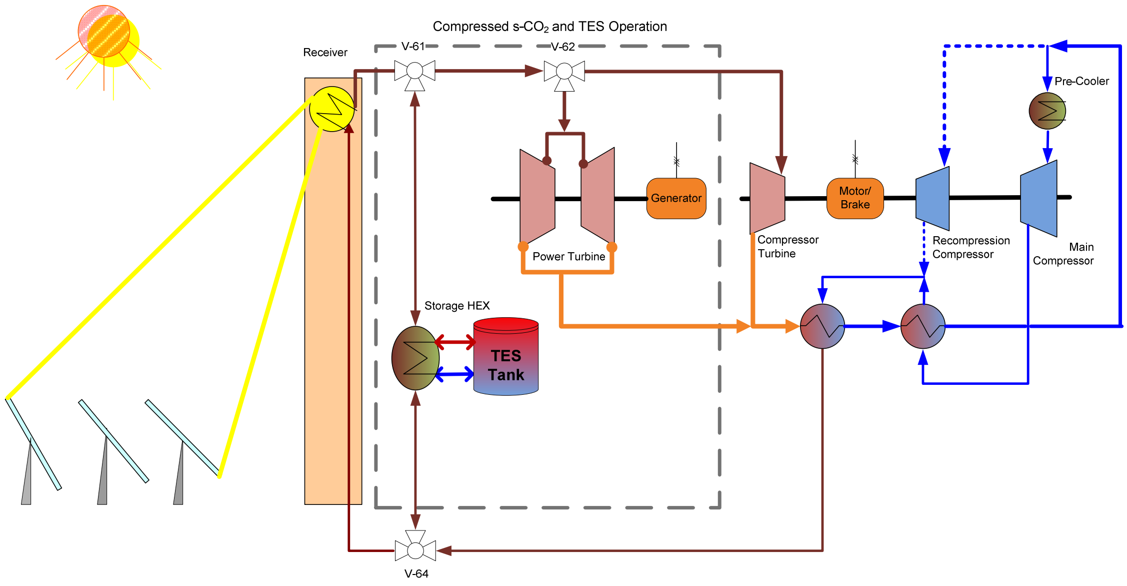

Figure 1. Dual-shaft, tower receiver S-CO_2 Brayton Cycle solar thermal power system with thermal energy storage.

There are two options for arranging the turbine/compressor/generator with the modular receiver generation set to operate with or without energy storage. The design options for the modular configuration are described below:

1. **Modular generation unit in the receiver without energy storage.**

This is a baseline design that uses a modular tower with a small heliostat field. Turbine/compressor size depends on power rating and design parameters, such as compression ratio, shaft speed, and/or selection of axial or radial flow for the compressor and turbine. In order to have the S-CO_2 generation module integrated into the receiver, the design considers the power rating and generation configuration for power block.

The power block design assumes a dual-shaft turbine layout to separate gas compression and power generation shafts. The gas compression and power generation can run at different shaft speeds – each at its own optimum condition – so that the power generation matches the grid power frequency at 3600 RPM without gearbox. The compressor and compressor turbine run at much higher speeds for better efficiency. The high shaft speed for the compressor and compressor turbine reduces their sizes and improves performance. The high shaft speed results in a small size and better sealed system, and is very suitable for small power unit, as indicated in Table 1.

Figure 2 shows a face-to-face layout of compressors and the compressor turbine that improves thrust balance. A motor/brake system is inserted in the compressor and compressor turbine for startup and shutdown. Power turbine runs at constant speed in synchronization with the grid frequency. The face-to-face layout for power turbines also cancels the force exerted on the thrust bearing.

Table 1 shows the turbine size, shaft speed, and CO_2 mass flow rate for power rating of 0.3, 3 and 300 MW. At the 3 MW level the turbine size is 15 cm (6 inch) with a speed of 50,000 RPM, and it is possible to locate the turbine in the receiver. The module power selected in the current design is between 5 MWe to 10MWe, so as to take advantage of S-CO_2 Brayton turbine/compressor compactness.

The power rating will be designed for maximum system performance, size and weight, and commercial availability for a modular solar field. Future performance and cost models will study whether recompression benefits would outweigh the complexity and cost of additional compressor stage and heat exchanges.

Table 1. Turbine and compressor size vs. power (Ref. [7])

Power Rate (MW)	Turbine Wheel diameter (m)	Desired Shaft Speed (RPM)	CO_2 Flow (kg/sec)
0.3	0.04	125,000	3.5
3	0.15	50,000	35
300	1.5	3,600	3500

Starting from the basic modular design, the energy storage option is considered by adding the thermal energy storage for the capability of continuous power generation.

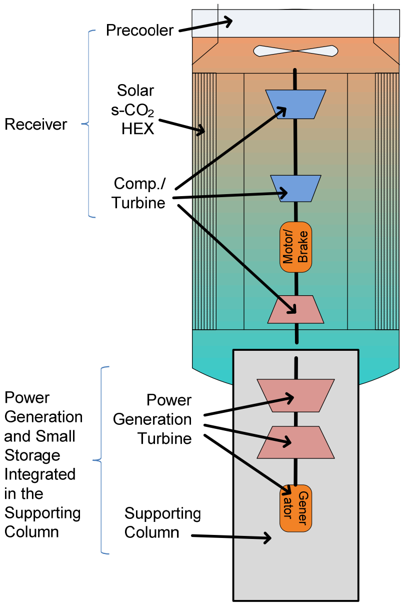

Figure 2. Schematic of a solar thermal tower receiver with embedded dual-shaft, S-CO_2 Brayton Cycle power generation.

2. Modular receiver with high-temperature, thermal energy storage integration

Modular S-CO_2 system plus thermal energy storage (TES) can reduce the impact of weather conditions on generation variability. Implementation of a large TES for longer storage hours may shift generation to accommodate peak hours or allow for continuous power generation. Unlike water/steam Rankine cycles, S-CO_2 undergoes no phase change and can be matched to current molten salt TES technology. Using design option (1) as a starting point, this design adds TES tank in the field to store solar energy for use during peak demand or under no-solar heat conditions. The TES system would probably be ground-mounted and shared between towers. This design can provide short term storage for weather transition and load shift simply and economically.

Several operating CSP plants use molten salt TES. The "two-tank" salt system maintains hot and cold salt in separate tanks. During discharge, the salt is pumped from hot tank to cold tank through heat exchangers that heat the HTF. The process is reversed during charging. The flexibility of the system allows for operating modes described as generation mode, charge mode, and discharge mode:

- Generation mode: All HTF used for power generation turbine and compressor turbine.
- Charge mode: Power generation turbine stops or operates at partial load, and part of the S-CO_2 is sent to the storage system, while heat is stored in the thermal energy storage tank.

- Discharge mode: Compressor and compressor turbine are driven by the thermal energy from the storage tank instead of receiving heat from solar receiver. The power turbine is driven by the high-pressure, high-temperature S-CO_2 from TES heat. This storage design provides short-term energy to drive the engine and bridge weather conditions such as passing clouds.

The shortcomings of a two-tank salt system include high system and material costs and a temperature cap (less than 600 °C) for salt stability. Other TES technologies under development involve thermocline TES, use of phase-change material, or other low-cost, stable material for high performance and more economical operations. Figure 1 depicts a generic TES system.

The advantage of a modular S-CO_2 tower receiver/generator configuration is analogous to a modular dish-Stirling engine of system in terms of factory fabrication and easy deployment. Instead of the low power range (~10 kWe for a Stirling engine), the modular S-CO_2 plant reaches multi-MWe levels that bring a scale advantage in terms of maintenance and cost benefits. In addition, the s-CO_2 process utilizes more reliable turbomachinery rather than reciprocating Stirling engines. The scale of 5-10 MWe is compatible with small tower systems under development by eSolar, which feature close-packed heliostat fields that have lower land usage than other CSP configurations.

Conclusion

Supercritical CO_2 operated in a closed-loop recompression Brayton cycle offers the potential of equivalent or higher cycle efficiency versus supercritical or superheated steam cycles at temperatures relevant for CSP applications. The S-CO_2 pressure is higher than superheated steam but lower than supercritical steam at temperatures of interest. The high pressure required for S-CO_2 makes application to trough fields difficult. A small tower design is recommended for simplicity in the power system. A single-phase process using S-CO_2 as both HTF and thermal cycle fluids would simplify the power block machinery and is compatible with sensible-heat thermal energy storage. The uncertainties in the utilization of such a cycle are: the high pressure required and lack of experience with closed loop Brayton cycles. This is an area of active research for next-generation nuclear power plants.

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