STEP Pilot Plant Advances Supercritical CO_2 Power Cycles for Gas-Fired Power Generation

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Power cycles utilizing supercritical carbon dioxide as a working fluid show promise for many power generation applications, including high-efficiency waste heat recovery on pipeline gas turbines. Component development efforts for commercializing these power cycles have progressed rapidly in recent years and the technology is poised for demonstration at the 10 MWe-scale at the Supercritical Transformational Electric Power (STEP) pilot plant that is nearing completion. These power cycles show promise to improve the cost, efficiency, and responsiveness of power generation.

Introduction to sCO_2 Power Cycles

Supercritical Carbon Dioxide (sCO_2) power cycle technologies utilize CO_2 at pressures and temperatures above the critical point (1070 psi, 88 °F) as a working fluid in a closed cycle system with some similarities to steam Rankine cycles. A simple recuperated Brayton cycle utilizing sCO_2 is shown in Figure 1, where sCO2 turbine exhaust heat is transferred to the heater inlet to increase cycle efficiency. More complex cycle architectures include additional complexity to achieve higher efficiencies[1], resulting in more heat exchangers or turbomachinery components. Most sCO_2 cycle applications can provide heat input to the cycle through a heat exchanger from gas turbine exhaust, solar thermal, geothermal, or even nuclear sources. Some direct-fired variation such as the Allam cycle[2] are directly heated through high-pressure oxy-combustion of natural gas.

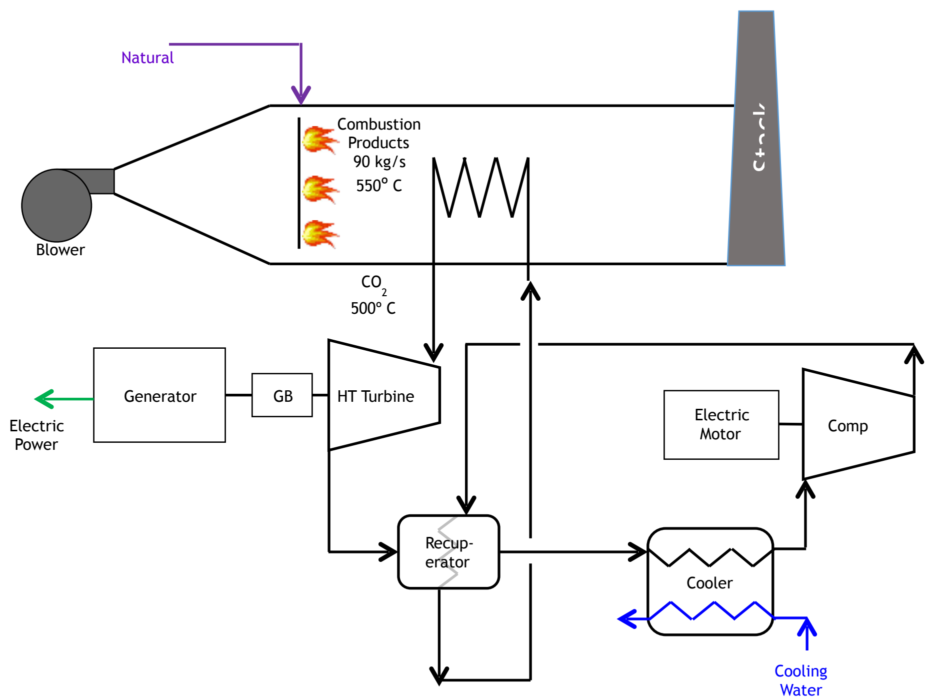

Figure 1. Simple Recuperated Cycle Configuration at STEP Pilot Plant

sCO_2 systems offer high fluid density at low temperatures, enabling relatively low compressor work and extremely power dense turbomachinery and heat exchangers. The thermodynamic properties of sCO_2 offer better efficiency than organic Rankine cycles at low temperatures and improved efficiency vs. steam Rankine cycles at turbine inlet temperatures exceeding 1000-1100 °F. The high power density of sCO_2 is attractive for WHR applications due to the potential for compact system packaging and fast startup capability, all with an inert fluid. Although sCO_2 cycles have been conceptualized since the 1960s, recent advancements in heat exchangers and turbomachinery components have enabled their implementation into hardware.

In recent years, sCO_2 research programs have targeted multiple technology gaps including the development, construction, and operation of multiple MW-scale test loops[1-4] and prototype development and validation of multiple compressor and turbine designs[3,4]. Notable recent successes include the successful full-pressure full-temperature operation of a 10 MWe axial expander prototype up to 1320 °F and 3600 psi[3] and ongoing tests for an integrally-geared compressor-expander prototype[4], see Figure 2. Research projects targeted specifically at gas turbine WHR systems are underway, adapting high-temperature machinery designs to lower-temperature WHR operation and developing mature technoeconomic models for design optimization over a range of ambient temperatures and typical load profiles[5]. Combined cycle analysis results show that plant efficiencies near 50% are achievable even for small-scale ~20 MW systems with no changes to the gas turbine and with high part-load efficiencies well above open-cycle gas turbine values.

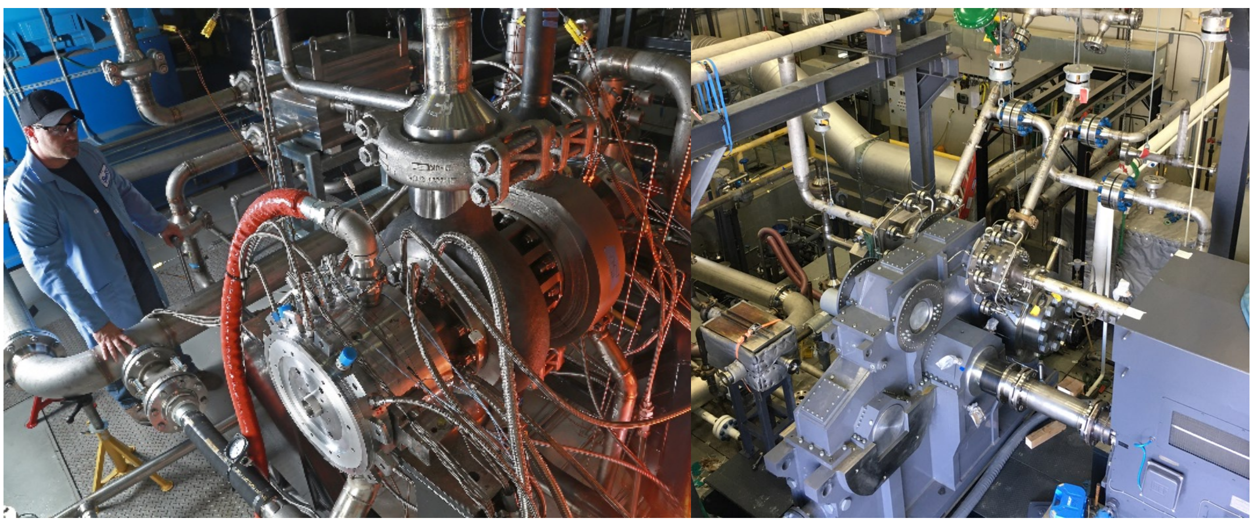

Figure 2. 10 MWe-Scale sCO_2 Expander Successfully Operated up to 1320 °F and 3600 psi (right) and Integrally-Geared Compressor-Expander Prototype on Current Test Program (left)

STEP Pilot Plant Advances Component and System Technologies

The team of Southwest Research Institute (SwRI), Gas Technology Institute, and General Electric are advancing sCO_2 technology by designing, constructing, and operating a pilot plant test facility to demonstrate sCO_2 power cycle technologies at a commercially relevant scale[6]. STEP is a state-of-the-art facility located on SwRI in San Antonio, Texas and is valued at $124M with primary funding provided by DOE and with cost sharing from industry partners and the State of Texas. The overall facility layout and sCO2 power block components are shown in Figures 3 and 4, respectively. This pilot plant will advance these technologies to near-commercial readiness, demonstrate their operability and performance, and serve as a reconfigurable test facility for component development and validation.

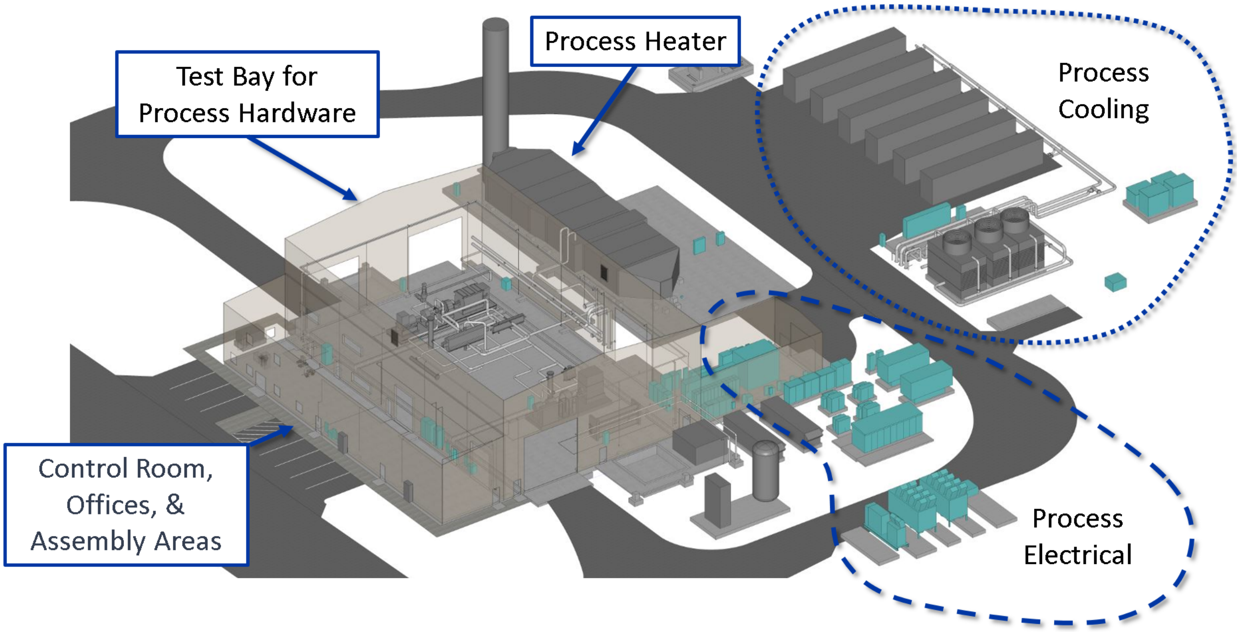

Figure 3. STEP Pilot Plant Layout

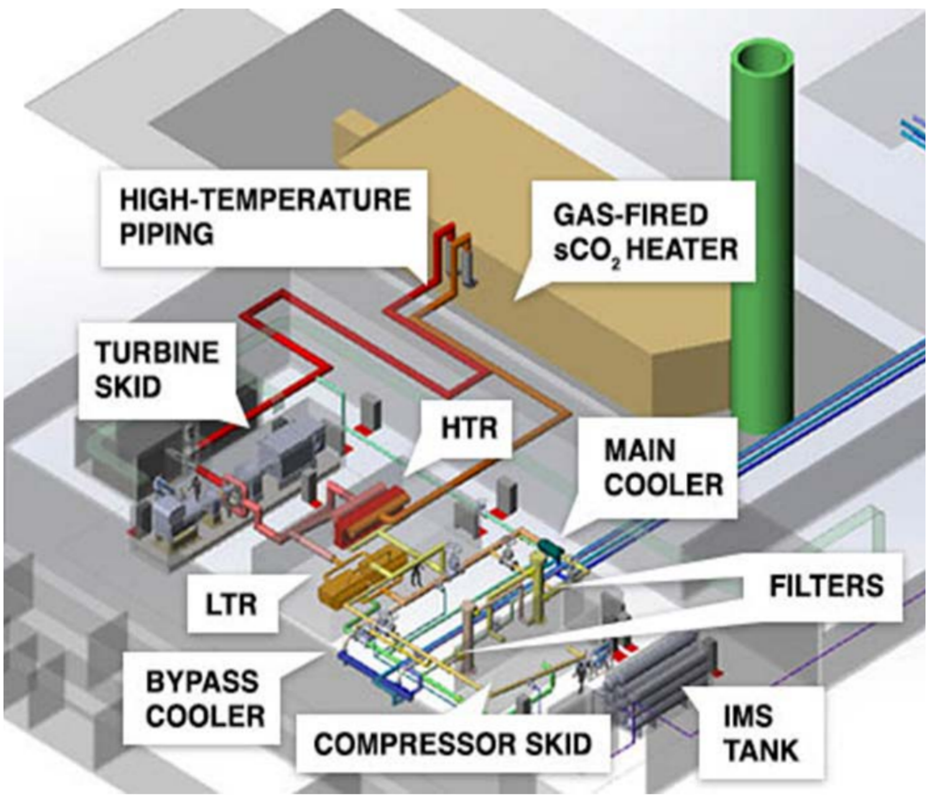

Figure 4. STEP Power Block Equipment [6]

Designed at the 10 MWe scale and for operation at sCO2 turbine inlet temperatures up to 1320 °F, the STEP pilot plant is a significant scale-up from existing sCO_2 test loops and designed as a fully integrated and functional electric power plant. This project mitigates technical risks and challenges for key components including the turbomachinery, recuperators, and materials. The facility will demonstrate the aerodynamics, sealing performance, and durability of full-size turbomachinery for sCO_2 power cycles scalable up to 100s of MW. The performance, fabrication, and durability of compact heat exchanger designs will also be proven. The project sources materials for large-scale hardware and will verify the corrosion, creep, and fatigue characteristics of these materials in high-temperature CO_2. Finally, the project will demonstrate successful integration and operability of all system components through many operating states including startups, transients, shutdowns, and different ambient conditions.

The current project has achieved definition, specification, and procurement activities for numerous major critical components, including:

- Primary process heater provided by Optimus Industries, LLC incorporating a ~80 MWth gas-fired burner and HRSG-style CO_2 heater fabricated from Inconel 740H for operation up to 1320 °F
- 16 MW (gross) axial turbine jointly developed by SwRI and GE with 100,000 hr design life at inlet conditions of 1320 °F and 3626 psi; long-lead rotor and casing procurements place and fabrication in process
- High-temperature and low-temperature recuperators fabricated by Heatric; designed as compact Printed Circuit Heat Exchangers (PCHEs)
- ~4 MW API 617 real gas compressors provided by Baker Hughes
- Turbine control/stop valve developed by GE and based on their existing commercial product line of steam valves, but with modifications leveraging Advanced Ultrasupercritical (AUSC) steam power development efforts and with changes to accommodate sCO_2 fluid and high operating temperatures
- High temperature piping designed to ASME B31.1 and fabricated from Inconel 740H
- Balance of plant equipment including low-temperature piping, 25 MWth cooling towers, coolers, valves, and CO_2 supply and inventory control systems, 16 MW load banks
- Construction of a 22,000 ft^2 facility on a 5-acre SwRI campus in San Antonio, TX is complete (Figure 5) with certificate of occupancy received in May 2020. The facility includes a 13.2 kV electrical system and 30-ton liquid CO_2 storage.

Figure 5. STEP Pilot Plant Facility Construction Completed June 2020

The primary process equipment will continue to arrive onsite for installation and assembly throughout 2020 and in the beginning of 2021. Commissioning and operation of the facility is expected before the end of 2021. Initial testing is planned for a simple cycle architecture as shown in Figure 2, with a second round of testing for a higher-temperature recompression Brayton cycle configuration afterwards. After this program is complete, the reconfigurable facility is anticipated for future use to perform validation testing of alternate component designs, cycle layouts, or control logic. The system may also be extended to include additional components (e.g., thermal energy storage, oxy-combustion hardware) or to perform validation/qualification testing of full-scale waste heat recovery systems.

References

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