TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

SUPERCRITICAL CO_2 RECEIVER AND POWER CYCLE FOR CONCENTRATING SOLAR POWER APPLICATIONS

THE TECHNOLOGY

A solar receiver uses supercritical CO_2 in a microchannel heat exchanger to achieve higher working fluid temperatures

THE VALUE

The potential is for superior thermodynamic efficiency, lower costs, and power production at a lower levelized cost relative to current technology

EPRI'S FOCUS

Independent assessments, including demonstration of sub-systems necessary to develop commercial-scale plants

TECHNOLOGY OVERVIEW

Sol Xorce has developed an innovative solar receiver with supercritical CO_2 (S-CO_2) as the working fluid. The solar receiver contains a microchannel heat exchanger (Figure 1) made of refractory metals and is designed to withstand fluid temperatures up to 1000°C (1830°F). S-CO_2 heated by a solar field is directly tied to an S-CO_2 Brayton power cycle. It is expected that the high temperatures will enable superior thermodynamic efficiencies relative to today's conventional steam Rankine-cycle solar plants.

S-CO_2 is being considered as a working fluid for thermal applications across several power generation technologies, but no commercial systems have been deployed. There is considerable field experience in compressing CO_2 for industrial purposes and for enhanced oil recovery, but S-CO_2 solar receivers and expansion turbines are not commercially available. Challenges with solar S-CO_2 power generation systems include designing for high pressures (on the order of 200 bar (3000 psi), integrating thermal energy storage, lack of demonstrated S-CO_2 turbines at MW-scale and limited industry experience with S-CO_2 Brayton power cycles.

BASIC SCIENCE

Above 31.0°C (87.8°F) and 74 bar (1071 psia) carbon dioxide is a supercritical fluid. Unlike most other solar heat transfer fluids, S-CO_2 is non-corrosive at high temperatures, non-toxic, and has beneficial thermodynamic properties. Low fluid viscosity enables a microchannel heat exchanger design in the receiver, potentially improving heat transfer to the working fluid compared to synthetic oil, molten salt or direct steam solar systems. High fluid density allows for compact turbomachinery and reduced compressor loads, potentially lowering system cost and boosting efficiency.

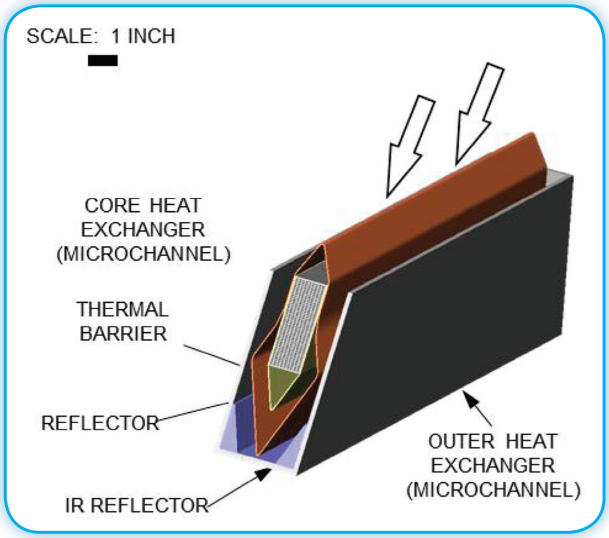

Figure 1. Illustration of Sol Xorce receiver (Source: Sol Xorce)

POTENTIAL IMPACT

$S\text{-}CO_2$ cycles hold the promise of higher efficiency and lower cost for the solar, geothermal, nuclear and fossil industries. Some estimates place the potential net power plant efficiency for an $S\text{-}CO_2$ cycle multiple percentage points higher than a comparable steam Rankine cycle. High temperature cycles that are feasible with $S\text{-}CO_2$ could push the efficiency even higher. Figure 2 illustrates current and theoretical power cycle efficiencies across a range of temperatures. In addition to efficiency improvements, the simpler $S\text{-}CO_2$ cycle design and more compact turbomachinery dimensions could potentially lower plant costs relative to Rankine cycle systems.

The Sol Xorce receiver technology used for solar power generation uses $S\text{-}CO_2$ as the heat transfer fluid and the power cycle working fluid. The combination of high operating temperature, low-cost working fluid, and a direct $S\text{-}CO_2$ power cycle could result in a "step change" in the levelized cost of electricity for CSP. Although the market for CSP is typically limited to locations with high direct normal irradiation, lowering the levelized cost of electricity broadens geographic regions where the technology could be economical. As mentioned, proving the $S\text{-}CO_2$ power cycle has benefits for other generation technologies; however, the optimal thermal designs will differ for geothermal, fossil and nuclear applications. These industries are focused on cycles operating up to temperatures of 760°C (1400°F), whereas Sol Xorce is aiming for 1000°C (1830°F).

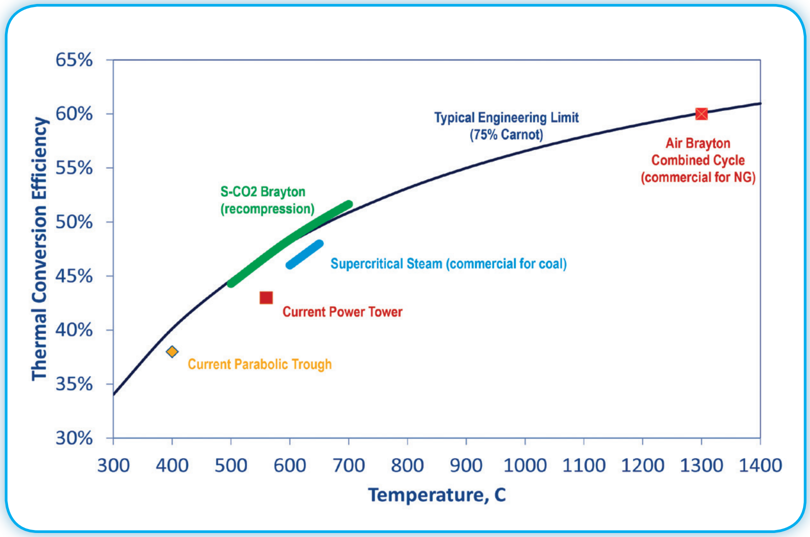

Figure 2. Thermal conversion efficiency as a function of temperature (Source: NREL)

VALUE TO THE INDUSTRY

The technology has the potential to dramatically lower CSP systems' levelized cost of electricity through higher efficiency and lower capital cost. Full-scale demonstrations with individual modules of 10 MW are feasible in the next five years. Proving the cycle for high-temperature solar applications also would support R&D in the fossil, nuclear and geothermal power industries, which could similarly benefit from knowledge gained in designing and operating $S\text{-}CO_2$ systems.

STATE OF THE TECHNOLOGY

The Sol Xorce receiver is at Technology Readiness Level (TRL) 2. Sol Xorce has filed for three patents since 2009. The most recent (U.S. Patent Application 20110030404) was filed in February 2011 for a hybrid solar heat pump. The description specifies using a single working fluid in a system with a microchannel heat exchanger to absorb solar energy and a thermodynamic cycle using the same fluid. At least two national laboratories are considering development of $S\text{-}CO_2$ receivers, including Sandia and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), but to EPRI's knowledge no organization has demonstrated such a technology.

Closed loop $S\text{-}CO_2$ Brayton cycle technology has achieved TRL 4 and is moving toward TRL 5. Several organizations, including EPRI, are actively pursuing this research, primarily focused on CSP and advanced nuclear power applications.

PUBLIC LITERATURE

The nuclear industry has developed most of the literature on $S\text{-}CO_2$ power cycles.[2,3,4,5] Symposia dedicated to $S\text{-}CO_2$ research and development were held at Rensselaer Polytechnic Institute in 2009 and the University of Colorado-Boulder in May 2011,[6] and the 2012 ASME Turbo Expo in Copenhagen dedicated sessions to the topic. Theoretical and practical development work is under way in support of deploying the cycle in naval nuclear and non-nuclear applications.[2]

Abengoa Solar has compared supercritical steam and $S\text{-}CO_2$ power towers that use either $S\text{-}CO_2$ or molten salt in the receiver.[7] All systems analyzed were steam Rankine-cycles, and it was assumed that 450 MWe was the smallest reasonable plant size, based on available supercritical steam turbines. The highest supercritical cycle temperature was 650°C (1200°F).

The National Renewable Energy Laboratory (NREL) developed preliminary performance and cost models for a modular 5-10-MW $S\text{-}CO_2$ power tower design with a direct CO_2 Brayton cycle power block embedded in the receiver tower to minimize piping.[8]

General Atomics presented research results at SolarPACES in 2011 on high temperature thermochemical energy storage options that can operate up to 1000°C (1830°F).[1] The analysis includes rough comparisons of cost and efficiency changes as a function of power cycle temperature.

NEXT MILESTONES

Sol Xorce plans to achieve TRL 4 in the next 2-3 months after demonstrating the technology at its design conditions of 1000°C (1830°F) and 207 bar (3000 psia). It will be necessary for the refractory metal to demonstrate rapid cycling capability and sustained operation under hard vacuum to validate emissivity and thermal loss performance.

For the next step, experts from different segments of the power industry agree that it will be necessary to test a nominal 10-MW closed loop S-CO_2 Brayton cycle system to reach TRL 6.

INDEPENDENT ASSESSMENTS

Sol Xorce has tested receiver components, but an independent assessment by a third party has not yet been conducted. On the power cycle side, two projects, hosted by Sandia National Laboratories and Bettis Atomic Power Laboratory, are testing closed loop S-CO_2 Brayton power cycles. Barber-Nichols is hosting the Sandia project, which includes a 120 kW (net power production) microturbine-driven main compressor, a microturbine-driven recompressor with the same rating, and high and low temperature recuperators in a closed S-CO_2 loop heated to 538°C (1000°F). Preliminary tests began in 2010, and net positive power production has been achieved at reduced output. A similar test cycle is underway at Bettis Atomic Power Laboratory. It currently operates at 300°C (570°F) with plans to increase temperature to 370°C (700°F).

As part of the DOE SunShot Initiative, NREL and several industry team members (including EPRI) will design, fabricate, and validate a nominally 10 MWe closed-loop, supercritical-CO_2 power cycle with operating temperatures up to 700°C (1300°F). The recently awarded 3-1/2 year demonstration project will demonstrate the inherent efficiencies of the S-CO_2 power turbine and associated turbomachinery at a scale relevant to commercial CSP projects. The industry consensus is that a nominal 10 MWe cycle is necessary to accurately represent the bearing and seal technologies that would be employed in a commercial design.

COLLABORATION

In 2007 Sol Xorce was formed as a spinoff of Echogen, and maintains ties to the technology developer and their turbomachinery partner, Dresser-Rand. The Gas Technology Institute (GTI) provides engineering support to Sol Xorce and may also provide lab facilities for high temperature component testing in the future. The Edison Welding Institute (EWI) brings manufacturing expertise to the venture. Limited information about the design is publicly available. A high general description of the microchannel receiver concept is presented on the Sol Xorce website, and patent applications contain specifications for the integrated system capabilities. Interested organizations include NREL, Sandia and Argonne National Laboratories, Spanish CSP developer Abengoa Solar, Australian research organization CSIRO, the French National Centre for Scientific Research (CNRS),[9] and various power cycle equipment suppliers, such as Echogen and Pratt & Whitney.

NEXT STEPS

The next steps are to test receiver components, perform on-sun receiver testing, demonstrate the closed-loop S-CO_2 Brayton cycle at 10-MW scale, and ultimately demonstrate an integrated system using solar as the heat source. Deployment of utility-scale demonstration systems is likely five or more years away, but there will be significant R&D required to achieve TRL 8. Several challenges remain:

- ***Thermal energy storage*** Molten salt working fluids at atmospheric pressure enable low-cost thermal energy storage vessels, whereas an S-CO_2 system either requires a pressurized storage vessel or a heat exchanger to transfer energy to a secondary storage media. In the latter design, the heat exchanger would be subject to high pressure differentials. On the other hand, the volume requirements for thermal energy storage systems drop with higher operating temperatures.
- ***Radiation and convection losses*** The selective surface coatings typically used for molten salt working fluids are not stable at higher temperatures (600-700°C (1110-1290°F)).[7] The alternative coating, called Pyromark, has an emissivity of 85% vs. 8-10%, which means radiation and convective losses from the receiver are higher. Also, because S-CO_2 operates at high pressure, the receiver tubes are thicker and more susceptible to tube strain. They cannot handle high incident heat flux like the thinner walled tubes for atmospheric molten salt systems, which means the absorber surface area must be larger, which also leads to greater thermal losses.
- ***Integrated turbomachinery technologies*** DOE and industry research efforts to develop an S-CO_2 turbine that will operate near 550°C (1000°F) and have a thermal efficiency approaching 45% are under way, and Sandia currently has two S-CO_2 test loops in operation. Sandia plans to continue to develop and operate the small test loops to identify key features and technologies. Test results will illustrate the capability of the concept, particularly its compactness, efficiency and scalability to larger systems. Future plans call for development of an industrial demonstration plant that can generate 10 MW of electricity, such as the project recently awarded to NREL under the SunShot Initiative. This project and others will demonstrate suitable seals and bearings and provide valuable experience with CO_2 compressors and turbines.
- ***Cooling technology*** Availability of cooling water could be problematic particularly in deserts. Development of air-cooled systems may be important for industry adoption.
- ***Capital cost*** Several studies assume that the cost of high temperature and pressure components will be offset by the more compact and efficient system design; however, a General Atomics study[1] showed that increasing the concentration of a central receiver plant to raise the temperature from 600°C to 1000°C (1110°F to 1830°F) increased the cost of the heliostat field dramatically and resulted in a higher LCOE despite the efficiency improvement. The authors acknowledge that typically a central receiver plant design would be optimized for thermal capacity, not temperature, and simply adding more heliostats is not optimal. The costs of higher temperature receiver materials are not well known, and turbomachinery costs are also uncertain.

REFERENCES

1. Buckingham, R., Wong, B., and Brown, L. (General Atomics), *Thermochemical Energy Storage for Concentrated Solar Power – Coupling to a High Efficiency Supercritical CO_2 Power Cycle.* SolarPACES, 2011.
2. Kimball, K., *Overview of Naval Reactors Program Development of the Supercritical Carbon Dioxide Brayton System.* Supercritical CO_2 Power Cycle Symposium. Boulder Colorado. May 24-25, 2011.
3. Wright, S.A., Radel, R.F., Vernon, M.E., Rochau, G.E., and Pickard, P.S., *Operation and Analysis of a Supercritical CO_2 Brayton Cycle.* Sandia National Laboratories: SAND2010-0171. 2010.
4. Dostal, V., Hejzlar, P. and Driscoll, M. (MIT), *The Supercritical Carbon Dioxide Power Cycle: Comparison to Other Advanced Power Cycles,* Nucl. Technol., 154 (2006).
5. Argonne National Laboratory, *"Performance Improvement Options for the Supercritical Carbon Dioxide Brayton Cycle," ANL-GenIV-103, 2007.*
6. ***www.sco2powercyclesymposium.org***
7. Kelly, B. (Abengoa), *Advanced Thermal Storage for Central Receivers with Supercritical Coolants.* Final Report under DOE Grant DE-FG36-08GO18149. June 2010.
8. Ma, Zhiwen, Turchi, C., *Advanced Supercritical Carbon Dioxide Power Cycle Configurations for Use in Concentrating Solar Power Systems.* NREL/CP-5500-50787. March 2011.
9. Caliot, C., and Flamant, G. (PROMES-CNRS), *CO_2 as New Heat Transfer Fluid for CSP: Influence of Radiation on Heat Transfer in Turbulent Pipe Flow at High Pressure.* SolarPACES, 2011.

1026480 November 2012

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com