MIGHTY MITE

A turbine that uses supercritical carbon dioxide can deliver great power from a small package.

By Steven Wright

In most respects, carbon dioxide is an energy problem. The gas is mixed to varying degrees with methane in underground formations and must be stripped before natural gas is injected into pipelines. It's created by the combustion of carbon fuels and must be vented away from engines. And the build-up of that CO$_2$ in the atmosphere has been implicated in global climate change.

Carbon dioxide has some interesting properties, however. Blocks of frozen carbon

These impellers, designed and fabricated by Barber Nichols, compress supercritical carbon dioxide in a research turbine at Sandia.

dioxide don't melt but rather sublimate into a gas; solid CO_2 is known as "dry ice." Indeed, CO_2 won't liquefy at all unless a pressure greater than five atmospheres is applied. But at a somewhat greater pressure—around 73 atmospheres—and roughly room temperature, CO_2 makes a strange transition from a gas to a state known as a supercritical fluid.

Supercriticality is a hybrid state. A supercritical fluid is dense, like a liquid, but it expands to fill a volume the way a gas does. Small changes in temperature near the critical point—31 °C—will cause large changes in density, similar to boiling where the liquid changes to a vapor. The density change, however, is only a factor of three or four, not a thousand as when water becomes steam at atmospheric pressure.

Similarly, it takes a lot of energy to increase the temperature a small amount when the fluid is near the critical point, much the way the heat of vaporization requires energy to convert a liquid to a vapor. Consequently, a large spike in heat capacity occurs near the critical point of CO_2 .

There are also viscosity changes that mimic the viscosity difference caused by transitioning from a very dense liquid-like fluid to a vapor-like fluid. And there are no drops and no bubbles because there can be no free surface.

These properties make supercritical carbon dioxide an incredibly tantalizing working fluid for Brayton cycle gas turbines. For the past several years, I have been part of a team of researchers at Sandia National Laboratory that has investigated these sorts of turbines for power generation, and we are now moving into the demonstration phase. Such gas turbine systems promise an increased thermal-to-electric conversion efficiency of 50 percent over conventional gas turbines.

The system is also very small and simple, meaning that capital costs should be relatively low. The plant uses standard materials like chrome-based steel alloys, stainless steels, or nickel-based alloys at high temperatures (up to 800 °C). It can also be used with all heat sources, opening up a wide array of previously unavailable markets for power production.

For these reasons the technology is quite promising. It could represent a breakthrough power system for the 21st century.

As an illustration of the broad interest these power systems are generating, Sandia and Barber Nichols, a contractor from Arvada, Colo., organized and hosted a symposium dedicated to supercritical carbon dioxide power cycles at the University of Colorado at Boulder in 2011. The conference presented 58 papers, and had 140 registered participants from 34 companies and 13 countries.

While recent interest is strong, the idea of using supercritical CO_2 in a power system is not a new one. Sulzer Bros. submitted a patent for a partial condensation Brayton cycle as early as 1948, but nothing ever came of that patent. The idea was rediscovered two decades later and was thoroughly described by Gianfranco Angelino in 1968. System designs were developed and some fabrication was started in the early 1970s, but then the momentum of the research dropped off.

It is likely that the early attempts to fabricate these systems faltered because the high power density made small-scale systems impractical or made the costs of systems that could be fabricated unaffordable for a first of a kind. And without such benchtop systems to prove the concept, the idea was left to the realm of myth.

After another three decades of neglect, the cycle began receiving more interest at the turn of this century. Vaclav Dostal, now an assistant professor at the Czech Technical University in Prague, studied the use of supercritical CO_2 in Brayton cycle turbines for his Ph.D. thesis, and this work has led to the development of multiple research and power cycles.

At Sandia, we began studying these turbines more than five years ago as part of the lab's work on advanced nuclear reactors. We have selected supercritical CO_2 as the working fluid operating at approximately 73 bar and 33 °C at the compressor inlet. Under those conditions, the CO_2 gas has the density of 0.6-0.7 kg per liter—nearly the density of water. Even at the turbine inlet (the hot side of the loop) the CO_2 density is high, about 0.1 kg/liter.

The high density of the fluid makes the power density very high because the turbomachinery is very small. The machine is basically a jet engine running on a hot liquid, though there is no combustion because the heat is added and removed using heat exchangers. A 300 MWe S-CO_2 power plant has a turbine diameter of approximately 1 meter and only needs 3 stages of turbomachinery, while a similarly sized steam system has a diameter of around 5 meters and may take 22 to 30 blade rows of turbomachinery.

Eventually, this compactness will be a design advantage, but as we develop prototypes to study the concept, it presents a distinct challenge. Early proof-of-concept demonstrations are often performed at the 1-to-20 kWe power level because many research labs have sufficient financial resources and support equipment to fabricate and operate power systems on this scale. It is quite easy to estimate the physical size of turbomachinery if one uses the similarity principle, which guarantees that the velocity vectors of the fluid at the inlet and outlet of the compressor or turbine are the same as in well-behaved efficient turbomachines.

Using these relationships, one finds that a 20 kWe power engine with a pressure ratio of 3.1, would ideally use a turbine that is 0.25 inch in diameter and spins at 1.5 million rpm! Its power cycle efficiency would be around 49 percent. This would be a wonderful machine indeed.

But at such small scales, parasitic losses due to friction, thermal heat flow losses due to the small size, and large bypass flow passages caused by manufacturing tolerances will dominate the system. Fabrication would have been impossible until the mid-1990s when the use of five-axis computer numerically controlled machine tools became widespread.

The alternative is to pick a turbine and compressor of a size that can be fabricated. A machine with a 6-inch (outside

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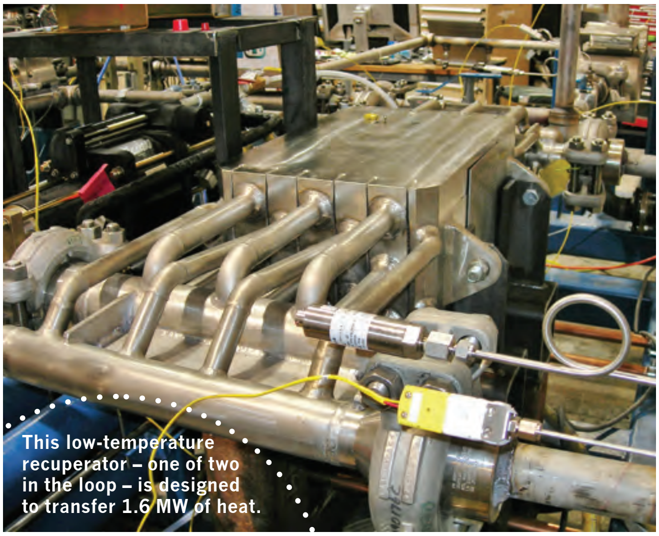
Steven Wright recently retired from Sandia National Laboratories in Albuquerque, where he was the principal investigator for S-CO_2 systems. He has started his own consulting company, Critical Energy LLC.

diameter) compressor would have small parasitic losses and use bearings, seals, and other components that are widely available in industry. A supercritical carbon dioxide power system on that scale with a pressure ratio of 3.3 would run at 25,000 rpm and have a turbine that is 11 inches in its outer diameter. It would, however, produce 10 MW of electricity (enough for 8,000 homes), require about 40 MW of recuperators, a 26 MW CO_2 heater, and 15 MW of heat rejection. That's a rather large power plant for a "proof-of-concept" experiment. The hardware alone is estimated to cost between $20 million and $30 million.

Our development approach at Sandia was to compromise a bit on the performance, but we selected a size that could fit within the Department of Energy's nuclear energy budget. We currently have two supercritical CO_2 test loops. (The term "loop" derives from the shape taken by the working fluid as it completes each circuit.)

A power production loop is located at the Arvada, Colo., site of contractor Barber Nichols Inc., where it has been running and producing electricity during the developmental phase. It is now being upgraded and is expected to be shipped to Sandia in Winter 2012. The loop has the design capabilities to produce 240 kilowatts of electricity.


This low-temperature recuperator – one of two in the loop – is designed to transfer 1.6 MW of heat.

The turbo-alternator-compressor designed by Barber Nichols relies on such key enabling technologies as gas-foil bearings (both journal and thrust), a permanent magnet motor/generator, advanced labyrinth seals, the use of seal leakage for bearing cooling, and a reduced rotor cavity region to manage and control frictional power losses.

In addition to the turbomachinery, the other enabling technology for the S-CO_2 power cycle is the use of printed circuit heat exchangers that are manufactured by Heatric. Those heat exchangers are composed of sheets of steel with flow passages etched into them. The parts are diffusion bonded to provide a core-block that can have heat transfer areas exceeding 1,000 square meters per cubic meter. The heat exchangers are very compact and can withstand very high pressure and high temperatures. The high-temperature recuperator and gas chiller also use this technology.

Those technologies and the advanced high power switching electronics that made it possible to build a small proof-of-concept S-CO_2 power loop have only recently become commercially available.

In this cycle the peak inlet temperature was selected to be 538 °C, and the pressure ratio was limited to 1.8. The lower pressure ratio increased the volumetric flow rate through the compressor, which increased its diameter and lowered the shaft speed to something that is within the range of gas foil bearings or magnetic bearings.

Other changes to the system were to use two 125 kWe motor/generators rather than one. This choice was made because the high-speed permanent magnet generator power level was limited by rotor dynamics.

The final modification we selected was the use of a re-compression Brayton cycle, which uses two recuperators and splits a fraction of the flow. Part of the flow is sent to a re-compressor that increases the temperature rise in the high-pressure leg of the recuperators to assure that the temperature rise there nearly equals the temperature drop in the low-pressure leg. It also reduces the likelihood of a pinch point, which occurs when there is little or no temperature difference between the hot- and low-temperature legs in the recuperator, so no heat flows from one to the other. The re-compression cycle has large amounts of recuperation (note that the recuperators transfer 2.8 MW while the heater only supplies 0.78 MW).

A second loop, located at Sandia, is used to research the unusual issues of compression, bearings, seals, and friction that exist near the critical point, where the carbon dioxide has the density of liquid but otherwise has many of the properties of a gas.

Immediate plans call for Sandia to continue to develop and operate the two small test loops to identify key features and technologies. Test results will illustrate the capability of the concept, particularly its compactness and efficiency; confirm models; and demonstrate the scalability to larger systems.

Down the line, we want to commercialize the technology. That would entail the development of an industrial demonstration plant at 10 MW of electricity, perhaps in partnership with industry. Sandia would use or modify its loops to study the behavior of various types of components not previously tested (for example, other types of seals or bearings). Alternatively, our Brayton loop could be reconfigured to test the behavior for other types of power cycles that may more optimally couple to gas turbines, solar plants, or fossil plants.

Brayton-cycle turbines using supercritical carbon dioxide would make a great replacement for steam-driven Rankine-cycle turbines currently deployed. Rankine-cycle turbines generally have lower efficiency, are more corrosive at high temperature, and occupy 30 times as much turbomachinery volume because of the need for very large turbines and condensers to handle the low-density, low-pressure steam. An S-CO_2 Brayton-cycle turbine could yield 10 megawatts of electricity from a package with a volume as small as four to six cubic meters.

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Four situations where such turbines could have advantages are in solar thermal plants, the bottoming cycle on a gas turbine, fossil fuel thermal plants with carbon capture, and nuclear power plants.

For solar applications, an S-CO_2 Brayton-cycle turbine is small enough that it is being considered for use on the top of small concentrated solar power towers in the 1-10 MWe class range. Unlike photovoltaics, solar power towers use heat engines such as air gas turbines or steam turbines to make electricity. Because heat engines are used, the power conversion efficiencies are two to three times better than for photovoltaic arrays.

Placing the power conversion system at the top of the power tower greatly simplifies the solar power plant in part because there is no need to transport hot fluids to a central power station. Additionally, CO_2 will not freeze under normal conditions and thus does not need to be kept warm at night during cold weather. Plus, S-CO_2 power systems can operate at higher temperatures than steam due to the better material compatibility of CO_2 with high-temperature stainless steels.

The small size and simplicity of the system also make it attractive as a power cycle that can use the waste heat that is normally rejected from a standard gas turbine. These types of conversion systems are called bottoming cycles. Typically, steam is used, but bottoming cycle plants can also take advantage of the small size and simplicity of the S-CO_2 power conversion system.

An S-CO_2 bottoming cycle will be about as efficient as a steam bottoming cycle, but its small size will make it easier to install, and the single phase nature of the fluid will simplify the operation of the power plant. Some evaluations estimate that a supercritical carbon dioxide Brayton cycle turbine will use only a tenth the number of valves of a similarly sized steam plant.

The turbines would also have advantages in coal-fired plants. If carbon capture and sequestration become a requirement for coal power, a fraction of the electricity generated will be diverted to run the CCS equipment. The high efficiency that can be achieved in an advanced pressurized oxy-combustion process with pulverized coal when coupled to a supercritical CO_2 power plant could make up for those losses, and thus keep zero-emission coal power plants economically competitive.

Finally, supercritical carbon dioxide Brayton-cycle turbines would be natural components of next generation nuclear power plants using liquid metal, molten salt, or high temperature gas as the coolant. In such reactors, plant efficiencies as high as 55 percent could be achieved. Recently Sandia has explored the applicability of using S-CO_2 power systems with today's fleet of light water reactors.

Replacement of the steam generators with three stages of S-CO_2 inter-heaters and use of inter-cooling in the S-CO_2 power system would allow a light water reactor to operate at over 30 percent efficiency with dry cooling with a compressor inlet temperature of 47 °C.

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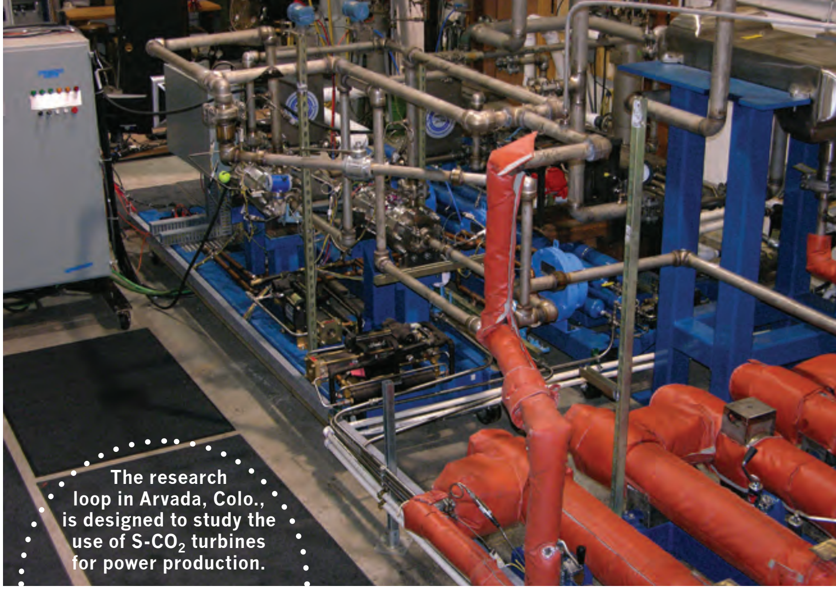

The research loop in Arvada, Colo., is designed to study the use of S-CO_2 turbines for power production.

Compared to power systems such as gas turbines and steam plants, the supercritical carbon dioxide Brayton system can increase the electrical power produced per unit fuel used by up to 50 percent, provided the cycle is correctly designed for the heat source and the heat source combustor/heater is efficient at getting the energy into the CO_2 . In addition, very compact, transportable, and affordable systems are possible due to the combination of low-to-modest turbine inlet temperatures (which enable the use of standard engineering materials such as stainless steel) together with high efficiency and high power density. The small overall size of the system will allow for advanced-modular manufacturing processes and a smaller footprint, both of which ought to decrease costs.

S-CO_2 power systems can use all heat sources and can operate at power levels ranging from a single megawatt to hundreds of megawatts. That flexibility should provide for applications in a variety of systems, improving the economics and marketability of the power cycle.

Sandia is not alone in this field, but we are, however, among of the leaders in developing this technology. We're past the point of wondering if these power systems are going to be developed and commercialized; the question is who will be first to market. Sandia and the U.S. Department of Energy have a wonderful opportunity to support the United States power needs by fostering this commercialization effort. ■

Sandia's S-CO_2 Brayton cycle program was initiated by seed money from the Laboratory Directed Research and Development program and then funded by Department of Energy's Office of Nuclear Energy.

TO LEARN MORE

The following publications contain additional information on supercritical CO_2 Brayton cycle technology.

- Angelino, G., "Carbon Dioxide Condensation Cycles for Power Production," ASME Paper No. 68-GT-23, (1968).
- Balje, O.E., *Turbomachines: A Guide to Design, Selection, and Theory*, John Wiley and Sons, New York, 1981.
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- Hoffmann, John R., and Feher, Ernest G.; "150 kWe Supercritical Closed Cycle System" *Transactions of the ASME*, January 1971.
- www.sco2powercyclesymposium.com.