Alternative Cycles for Power Converters

James J. Sienicki
Argonne National Laboratory, 9700 South Cass Avenue, Argonne Illinois 60439, USA,
Tel: 1 (630) 252-4578, Email: sienicki@anl.gov

For Sodium-Cooled Fast Reactors (SFRs), the Rankine superheated steam cycle is the traditional power conversion technology for converting the thermal energy liberated in the reactor core into electricity delivered to the electrical power grid. For SFRs, the core outlet temperature is typically 510 to 550 °C, depending upon the SFR design and fuel type. The superheated steam cycle can also be utilized with Lead-Cooled Fast Reactors (LFRs) for which the core outlet temperature in a near-term deployable design might be 480 °C. Raising the core outlet temperature is an approach to gaining greater cycle efficiency and, in turn, greater plant efficiency. However, the efficiency of the superheated steam cycle does not increase significantly with further temperature increases in this regime (i.e., diminishing returns) as it does at lower temperatures. If it is desired to retain water/steam as the working fluid, a significant increase in efficiency can be realized by introducing a Supercritical Water (SCW) cycle. The SCW cycle is currently used on some fossil power plants to take advantage of its greater efficiency. Studies have revealed that significantly higher efficiencies could be realized for LFRs with a SCW cycle. A key finding is that it is necessary to reheat steam following expansion in the high pressure turbine by passing it through an additional lead-to-steam heat exchanger (HX). This can be a complication relative to the superheated steam cycle. The SCW cycle also requires operation at significantly higher pressures increasing the cost of power converter components and piping. Another approach is to utilize a non-condensable gas such as helium as the working fluid in a recuperated gas turbine Brayton cycle. Helium (He) coolant is sometimes viewed as desirable because it does not interact chemically with sodium coolant eliminating the potential for sodium-water reactions that the designer must otherwise accommodate. However, studies have revealed that at typical SFR core outlet temperatures the efficiency provided by the recuperated gas turbine Brayton cycle is inferior to that of a superheated steam cycle.

The alternative power conversion technology that has recently been the subject of the most research and development is the supercritical carbon dioxide (S-CO_2) Brayton cycle. The S-CO_2 Brayton cycle was originally proposed by Ernest G. Feher at Astropower Laboratory, A Division of McDonnell Douglas Corporation, in 1967. For this reason, it was sometimes called a "Feher cycle." Feher and his team designed a 150 kWe power converter for use with a small He-cooled nuclear reactor for the U.S. Army. In recent years, the S-CO_2 cycle has gained renewed interest as the result of work initially carried out at the Massachusetts Institute of Technology (MIT) mainly by Vaclav Dostal for his Ph.D. dissertation. The S-CO_2 Brayton cycle was subsequently investigated at ANL and elsewhere. It has been adopted as the reference power conversion technology for SFR and LFR preconceptual designs developed at ANL. Research and development of the S-CO_2 Brayton cycle is being carried out in the U.S., France, Japan, Republic of Korea, and the Czech Republic.

The CO_2 critical pressure and temperature are 7.3773 MPa and 30.98 °C, respectively. The supercritical CO_2 properties vary significantly in the vicinity of the critical point. In particular, the density increases significantly as the critical temperature is approached from above at constant pressure immediately above the critical pressure. This results in a relatively low work to compress the CO_2 immediately above the critical point (i.e., Pdv work); this is a major contributor to the greater cycle efficiencies calculated for the S-CO_2 Brayton cycle. Figure 1 shows the conditions around a S-CO_2 Brayton cycle preconceptual design developed at ANL for a 406 MWe (1000 MWt) SFR medium-sized reactor.

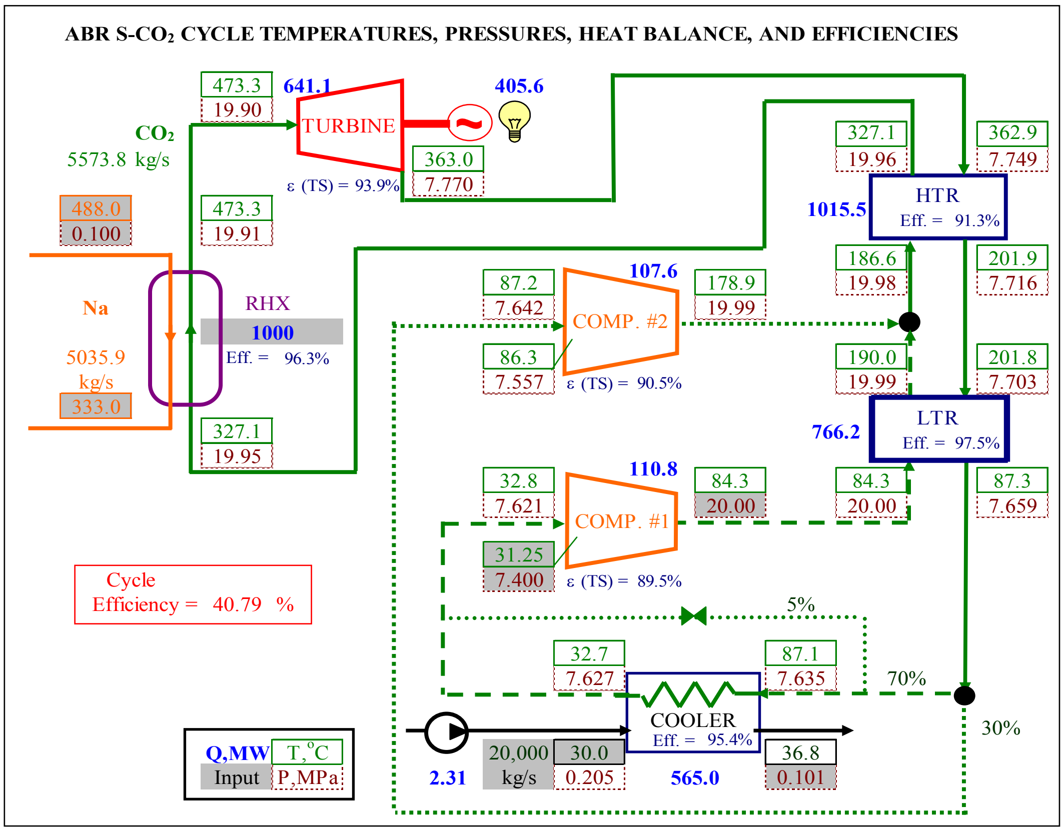

Figure 1. Schematic of S-CO_2 Brayton Cycle for 406 MWe (1000 MWt) SFR.

The supercritical CO_2 is compressed to a maximum pressure of 20 MPa. The compressed CO_2 is heated in an intermediate sodium-to-CO_2 heat exchanger (HX) to a temperature of 473 °C from 327 °C. It expands in the turbine down to a pressure of 7.77 MPa and temperature of 363 °C. The expanded CO_2 then passes through two recuperators (regenerative HXs) in which a portion of the expanded CO_2 thermal energy is utilized to preheat the compressed CO_2 returning to the sodium-to-CO_2 HX. Preheating through recuperation also contributes significantly to the efficiency of the cycle. However, it is not possible to use a single recuperator. A separate high temperature recuperator (HTR) and low temperature recuperator (LTR) are required. This is because the specific heat of supercritical CO_2 at the high compressed pressure is significantly greater than that of the expanded CO_2 close to the critical temperature and pressure. As a result, the preheating of CO_2 in a single recuperator would not be efficient. This effect of the supercritical CO_2 properties variation is handled by splitting the expanded CO_2 flow after it passes through the HTR and LTR. The greater portion of the flow passes through a CO_2-to-water cooler in which heat is rejected from the cycle. The remainder of the flow is directly recompressed. The lower flowrate of the compressed CO_2 relative to the expanded CO_2 in the LTR results in a greater compressed CO_2 temperature rise and recuperator effectiveness. The directly recompressed CO_2 is merged with the flow from the LTR and passes through the HTR. At the higher temperatures of the HTR, the difference between the specific heats of the compressed and expanded CO_2 streams is not as pronounced as in the LTR. Due to this split flow configuration, the S-CO_2 Brayton cycle is sometimes referred to as a split-flow recompression cycle.

For the SFR in Figure 1, a cycle efficiency of 40.8 % is calculated which exceeds that of a superheated steam cycle. Utilization of the S-CO_2 cycle instead of the superheated steam cycle eliminates sodium-water reactions. However, sodium-CO_2 reactions under prototypical conditions following HX failure need to be understood and it must be demonstrated that reliable sodium-to-CO_2 HXs can be designed suitable for use with sodium in an intermediate sodium circuit. Research in these areas is currently being conducted at ANL.

The S-CO_2 Brayton cycle is an excellent match for SFRs because the cycle wants to operate with a temperature rise through the sodium-to-CO_2 HX of about 150 °C which is close to the 155 °C temperature rise of sodium in the reactor core. Other reactors or heat sources are characterized by different temperature increases of the primary heat exchange fluid. For example, a typical temperature rise for the He passing through the core of a Very High Temperature Reactor (VHTR) design is 450 °C. It has recently been shown at ANL that the S-CO_2 cycle can be adapted to the VHTR by utilizing three cascaded S-CO_2 cycle power converters each with its own He-to-CO_2 HX in which the He temperature decreases by 150 °C. Alternatively, a single S-CO_2 cycle power converter can be utilized if the low end pressure is reduced to a subcritical value (e.g., 1.0 MPa) while the temperature remain supercritical. For a maximum He temperature of 850 °C, a cycle efficiency of 49.3 % can be obtained with the cascaded cycles or 49.5 % with a 1.0 MPa low end pressure versus 47.7 % for a He recuperated gas turbine Brayton cycle.

The S-CO_2 cycle may offer cost benefits relative to the superheated steam cycle. Because of the high density of supercritical CO_2 near the critical point, the compressors and turbine are remarkably small in size with the expectation of cost savings. There is much interest in compact heat exchanger technologies that can be used with the cycle to further reduce the overall power converter size reducing, in turn, the size and cost of the turbine building. However, the HTR and LTR are high heat duty HXs and might prove to be costly.