

# SUPERCRITICAL CARBON DIOXIDE TECHNOLOGY

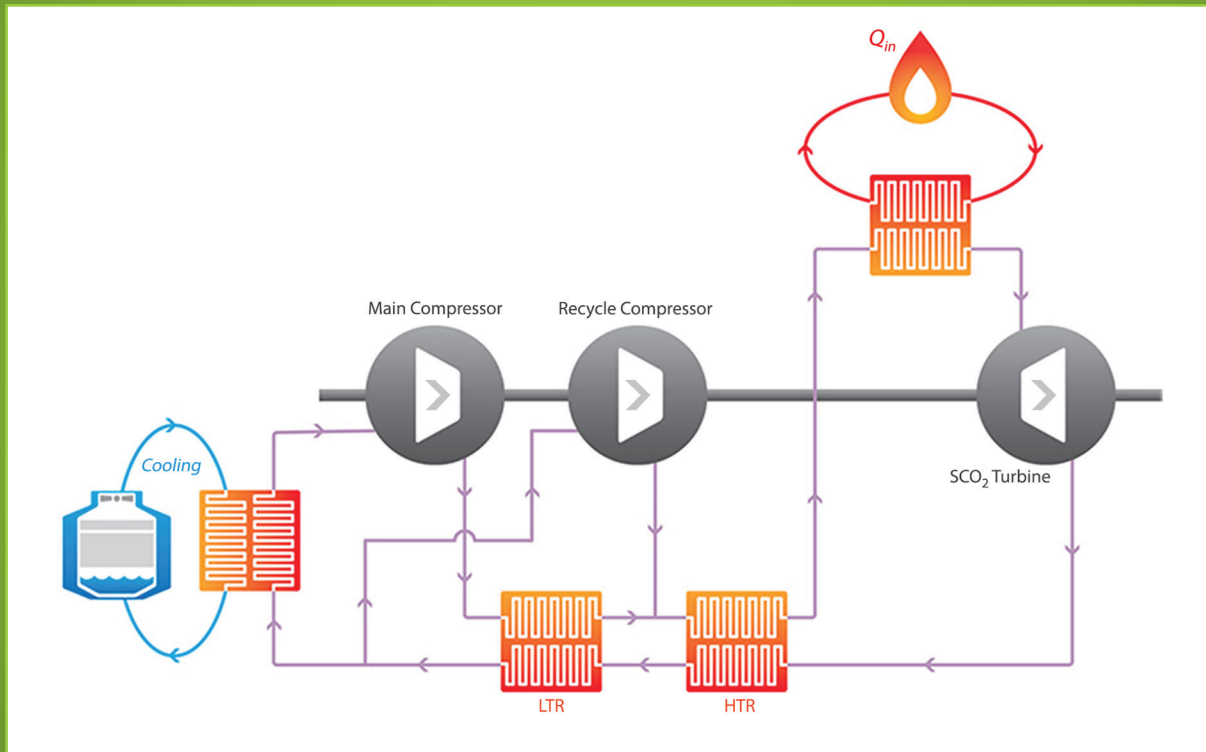


Figure 1: Indirect-fired supercritical CO<sub>2</sub> recompression Brayton cycle.

# NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

## PROGRAM OVERVIEW

The Supercritical Carbon Dioxide Technology Program is focused on developing technologies for the implementation of highly efficient power cycles utilizing supercritical carbon dioxide (CO<sub>2</sub>) as the working fluid. Supercritical CO<sub>2</sub>-based power cycles have shown the potential for increased heat-to-electricity conversion efficiencies, high power density, and simplicity of operation compared to existing steam based power cycles. The supercritical CO<sub>2</sub> power cycle uses small turbomachinery, is fuel- and/or heat-source neutral, and is efficient. These factors make the cycle appealing to a wide range of applications and stakeholders. In addition to solar, nuclear, fossil, and geothermal heat sources, the supercritical CO<sub>2</sub> power cycle has applications for shipboard use in propulsion, power, and waste heat recovery. This broad range of applications makes the market-based development and deployment of the supercritical CO<sub>2</sub> power cycle highly attractive.

The Supercritical Carbon Dioxide Technology R&D program consists of developing turbomachinery and recuperators for indirect- and direct-fired cycles, oxy-fuel combustion for direct-fired cycles, and system integration and optimization of the supercritical CO<sub>2</sub> power cycle. The program aims to demonstrate improved power generation efficiency and progress toward lower cost of electricity using supercritical CO<sub>2</sub> power cycles. Advancements in supercritical CO<sub>2</sub> technologies can lead to significant progress in meeting national climate and energy goals, including decreased greenhouse gas emissions, promoting domestic manufacturing and technology job creation, facilitating industrial competitiveness, maintaining U.S. technology leadership, and providing the nation with cleaner and more affordable electric power.

## **SUPERCRITICAL CARBON DIOXIDE-BASED POWER CYCLES BACKGROUND**

Supercritical CO<sub>2</sub>-based power cycles can be implemented with indirectly and directly heated applications. The indirectly heated power cycle is applicable to boiler-type plants where the combustion gases and cycle working fluid are separated. There is essentially no loss or addition of CO<sub>2</sub> during operation after the system is initially charged. A heat source (boiler) is used to indirectly heat the CO<sub>2</sub> working fluid through a heat exchanger, similar to current supercritical steam cycles. This cycle is a noncondensing closed loop Brayton cycle with heat addition and rejection on either side of the expander. Energy is extracted from the supercritical CO<sub>2</sub> as it is expanded in the turbine. The remaining heat is recovered from the stream post-expansion via recuperators and used to preheat the compressed CO<sub>2</sub> returning to the primary heat source. In the recuperators, the CO<sub>2</sub> stream is cooled prior to compression. The compressed CO<sub>2</sub> stream is then preheated in the recuperators prior to returning to the heat source to complete the cycle. The recovery of waste heat in the recuperators limits the heat rejection from the cycle. Additionally, the ability to modulate the temperature of the supercritical CO<sub>2</sub> at the bottom of the cycle without condensing, provides potential for dry cooling with either low or no water consumption.

In the directly fired supercritical CO<sub>2</sub> power cycles, the combustion of fuels, such as natural gas or coal syngas, and oxygen produce a steam and CO<sub>2</sub>-mixed stream that is

integral to the process and is used as the working fluid to drive the turbine and produce power. The turbine for direct-fired cycle operates at higher inlet temperatures than that of the indirect-fired cycle. Unlike the indirect-fired cycle, the direct fired supercritical CO<sub>2</sub> power cycle can produce a high purity stream of CO<sub>2</sub> that is ready for use/reuse or storage, without expensive and energy intensive capture/separation technologies.

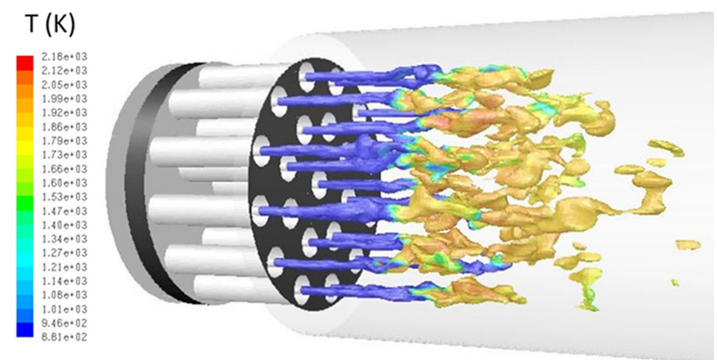


Figure 2: CFD simulation of oxy-combustor showing temperature contours on surface of fuel jets.

## **SUPERCRITICAL CARBON DIOXIDE TECHNOLOGY R&D PROGRAM**

The Supercritical Carbon Dioxide Technology research and development (R&D) program is composed of technology focus areas dedicated to the development of the individual components of the power cycle along with systems analysis and modeling to address technical issues, reduce risks, and mature the technology. Furthermore, the R&D program is supportive of the Supercritical Transformational Electric Power Program (STEP) that is focused on the development of a 10-MWe supercritical CO<sub>2</sub>-based power cycle pilot facility.

## PROGRAM GOALS

The Supercritical Carbon Dioxide Technology Program is working to develop highly efficient and lower cost indirectly heated power cycles that surpass the performance of advanced ultra-supercritical steam cycles and provide the technology base for directly heated power cycles using more advanced fossil energy conversion systems. This will be accomplished by developing the individual components and maturing the technology of the power cycle through Technology Readiness Level paths to scaled-up testing. To accomplish the pilot-level demonstration, the R&D program is coordinated with the STEP program that aims to design, build, operate a 10-MWe indirect-fired supercritical CO<sub>2</sub> power cycle pilot-scale facility and demonstrate the component performance, cycle operability, and progress toward a lower cost of electricity.

The objectives for the program are as follows:

- Develop and mature the supercritical CO<sub>2</sub> technology and allow the cost, efficiency, and lower water consumption benefits to be broadly realized in the energy sector
- Mature the direct-fired cycle for cleaner and lower cost electric power with its inherent benefit of separating high purity CO<sub>2</sub> at near-pipeline pressure and its clean water byproduct

## TECHNOLOGIES AND RESEARCH FOCUS AREAS

The Supercritical Carbon Dioxide Technology program supports R&D activities within four key technology areas: (1) Turbomachinery, (2) Recuperators, (3) Advanced Concepts for Direct-Fired Cycles, and (4) Systems Integration and Optimization. The R&D work is complementary to the STEP 10-MWe pilot facility program.

### TURBOMACHINERY

Turbomachinery R&D focuses on advancing technologies and understanding of the supercritical CO<sub>2</sub> turbomachinery, including the interactions of the fluid with the turbomachinery, effects of high supercritical CO<sub>2</sub> densities on turbomachinery design, and operation at high temperatures and pressures of the supercritical CO<sub>2</sub> power cycles. R&D will consider all aspects of the turbomachinery, including the turbo-expander, compressors, pumps, airfoils, turbine coupling with the motor/generator, seals, casings, bearings, and shafts. The approach would cover a multiphase development to design and test supercritical CO<sub>2</sub> turbomachinery, followed by manufacture of commercial prototypes. Turbomachinery development will be supported by associated materials development efforts to test and identify materials compatible for use with supercritical CO<sub>2</sub> at the turbomachinery operating conditions.

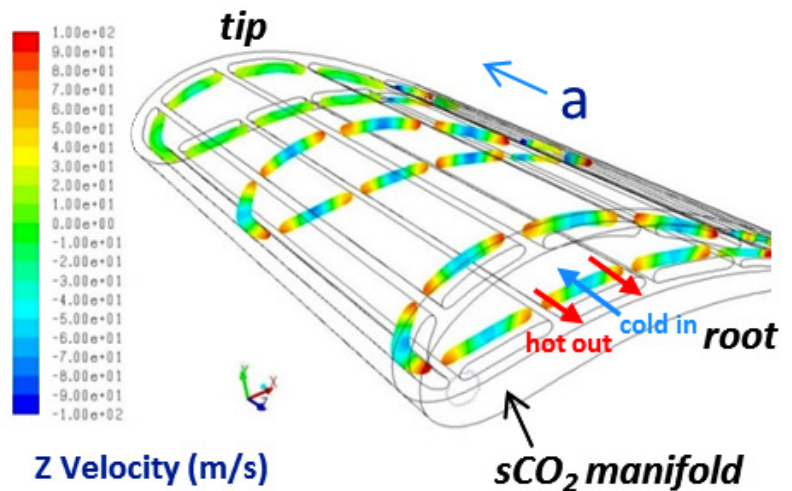
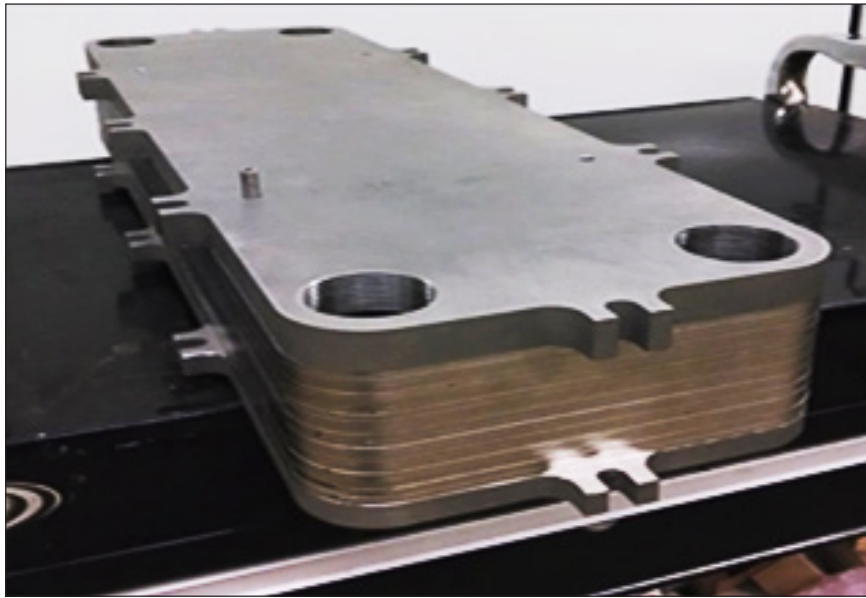


Figure 3: NETL model of turbine blade cooling.



RECUPERATORS

The supercritical CO<sub>2</sub>-based power cycle utilizes high- and low-temperature recuperators to recover heat and increase cycle efficiency. The recuperator projects focus on the advancement of technologies, designs, and fabrication of recuperative heat exchangers. Work includes development and testing of innovative compact recuperator designs and identification of compatible materials to allow for highly efficient heat transfer under operation at high inlet temperatures and large pressure differentials, typical of the supercritical CO<sub>2</sub> power cycles. Multiple compact heat exchanger concepts will be identified, developed, and evaluated. Achieving recuperator cost and performance targets are vital to enabling commercial implementation of the supercritical CO<sub>2</sub> power cycle.

Figure 4: Altex Technologies Corporation—high effectiveness low cost recuperator.

ADVANCED CONCEPTS FOR DIRECT-FIRED CYCLES

The higher temperature and pressure conditions of more advanced direct-fired conversion systems have the potential for even higher cycle efficiencies, while producing CO<sub>2</sub> for either storage or reuse purposes. This work is intended to develop high-pressure and high-temperature oxy-fuel combustion systems with CO<sub>2</sub> as the diluent, to be used for directly-heated supercritical CO<sub>2</sub> power cycles. Work includes the integration of novel oxy-combustors with a direct-fired turbine.

SYSTEMS INTEGRATION AND OPTIMIZATION

The supercritical CO<sub>2</sub> power cycle can be integrated with a fossil energy heat source in various configurations. Optimal integration and process operating conditions must be identified to achieve high efficiency and lower cost electricity generation. Systems integration and optimization work focuses on overall system analysis, modeling, and engineering to integrate and design the supercritical CO<sub>2</sub> power cycle for optimized performance, efficiency, cost, and operability.

SUPERCritical TRANSFORMATIONAL ELECTRIC POWER PROGRAM

The Supercritical Carbon Dioxide Technology Program R&D work described above is closely coordinated with the STEP program. The Office of Fossil Energy leads the STEP program and is part of a Department of Energy-wide collaboration with the Offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy, which leverages the capabilities and interests of these organizations toward the development of the supercritical CO<sub>2</sub> power cycle. The mission is to demonstrate a lower cost of electricity with supercritical CO<sub>2</sub> power cycles as applied to nuclear, concentrated solar, and fossil fuel heat sources. To support this mission, the main objective of the STEP program is to build and operate a 10-MWe supercritical CO<sub>2</sub> power cycle test facility for evaluating power cycle and component performance over a range of operating conditions at a relevant scale.

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