SUPERCRITICAL CARBON DIOXIDE TECHNOLOGY

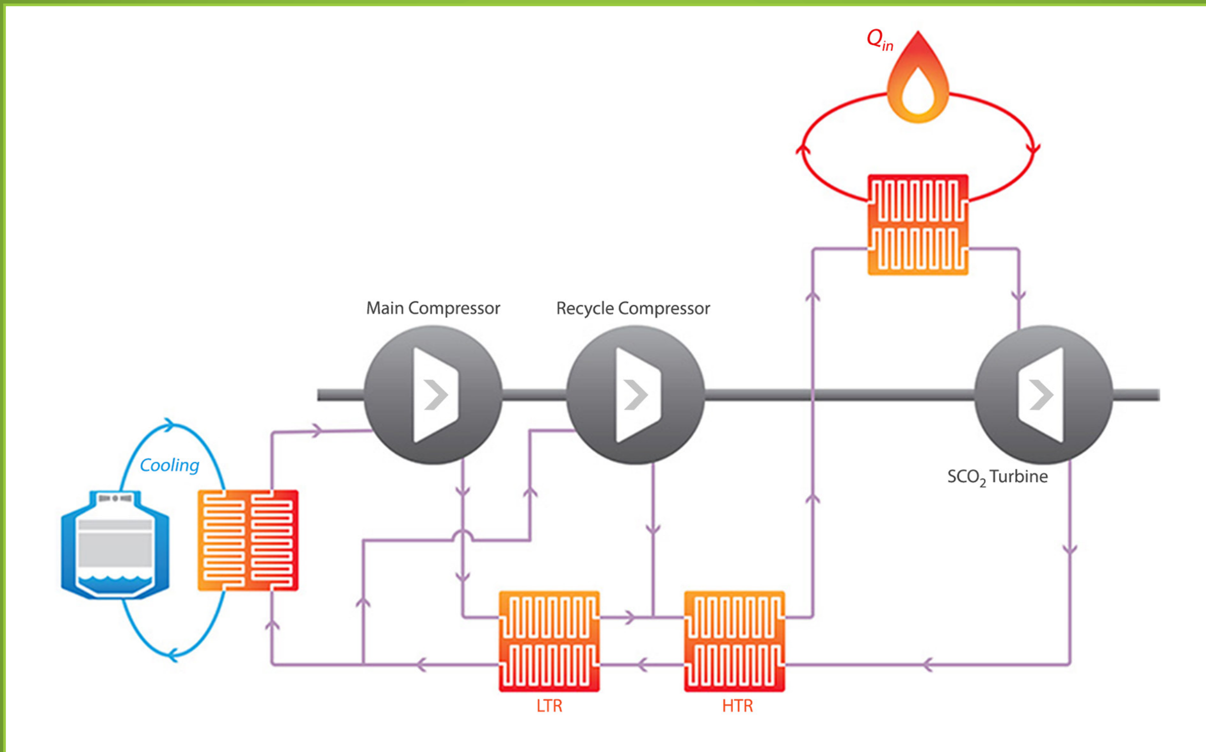

Figure 1: Indirect-fired supercritical CO_2 recompression Brayton cycle.

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_2) as the working fluid. Supercritical CO_2-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_2 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_2 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_2 power cycle highly attractive.

NETL implements this effort as part of DOE's Clean Coal and Carbon Management Program.

Program 144, December 2020

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_2 power cycle. The program aims to demonstrate improved power generation efficiency and progress toward lower cost of electricity using supercritical CO_2 power cycles. Advancements in supercritical CO_2 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_2-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_2 during operation after the system is initially charged. A heat source (boiler) is used to indirectly heat the CO_2 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_2 as it is expanded in the turbine. The remaining heat is recovered from the post-expansion stream via recuperators and used to preheat the compressed CO_2 returning to the primary heat source. In the recuperators, the CO_2 stream is cooled prior to compression. The compressed CO_2 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_2 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_2 power cycles, the combustion of fuels, such as natural gas or coal syngas, and oxygen produces a stream of CO_2 and water that becomes the working fluid. This new fluid drives the turbine and produces 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_2 power cycle can produce a high purity stream of CO_2 that is ready for use/reuse or storage, without expensive and energy intensive capture/separation technologies.

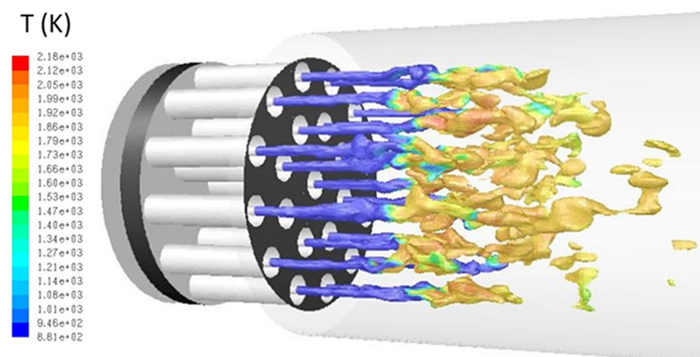

Figure 2: CFD simulation of oxy-combustor showing temperature contours on surface of fuel jets.

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_2-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_2 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_2 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_2 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_2 turbomachinery, including the interactions of the fluid with the turbomachinery, effects of high supercritical CO_2 densities on turbomachinery design, and operation at high temperatures and pressures of the supercritical CO_2 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_2 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_2 at the turbomachinery operating conditions.

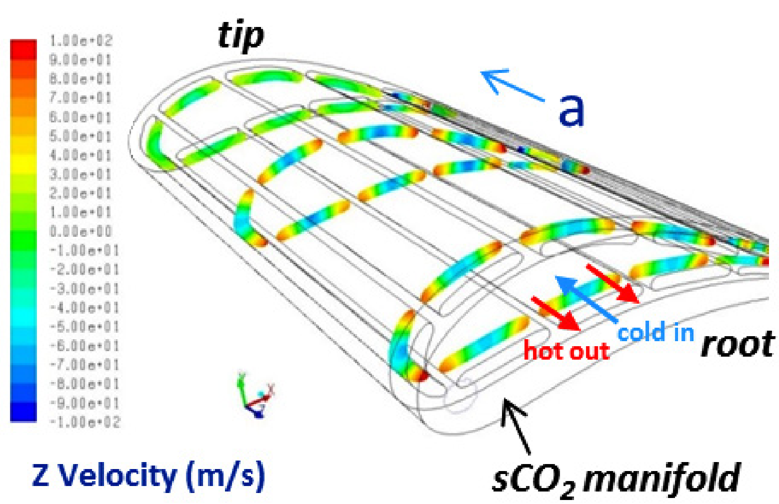

Figure 3: NETL model of turbine blade cooling.

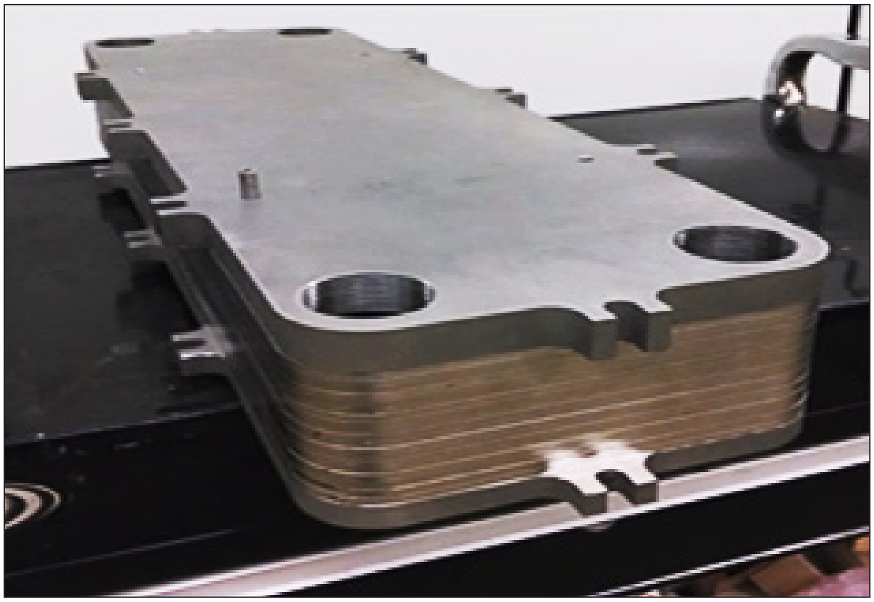

Figure 4: Altex Technologies Corporation—high effectiveness low cost recuperator.

RECUPERATORS

The supercritical CO_2-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_2 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_2 power cycle.

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_2 for either storage or reuse purposes. This work is intended to develop high-pressure and high-temperature oxy-fuel combustion systems with CO_2 as the diluent, to be used for directly-heated supercritical CO_2 power cycles. Work includes the integration of novel oxy-combustors with a direct-fired turbine.

SYSTEMS INTEGRATION AND OPTIMIZATION

The supercritical CO_2 power cycle can be integrated with a fossil energy heat source in various configurations. The key here is to conduct advanced systems and technical/economic analysis with optimization tools to achieve low cost and high performance systems. Analysis by NETL and other national laboratories has allowed direct and indirect systems to be optimized for large-scale power generation with the capture of carbon dioxide. 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_2 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_2 power cycle. The mission is to demonstrate a lower cost of electricity with supercritical CO_2 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_2 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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