ME-301 Project
Supercritical CO_2 Brayton Cycles

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Introduction

The Supercritical CO_2 (s-CO_2) Brayton cycle has emerged as a highly promising technology for efficient thermal energy conversion. With the pressing need to improve energy efficiency and reduce environmental impact, the s-CO_2 Brayton cycle offers significant advantages due to its high thermal efficiency and compact design. Operating at moderate turbine inlet temperatures (500–700°C) and near the critical point of CO_2 (31.1°C, 7.38 MPa), this cycle can achieve efficiencies of 45–50%, surpassing those of traditional steam Rankine cycles [1]. These attributes make it particularly suitable for next-generation energy systems, such as Generation IV nuclear reactors, which benefit from the high thermal efficiency and environmental friendliness of the s-CO_2 cycle. In addition, the potential to couple s-CO_2 cycles with a wide range of heat sources—including nuclear, solar, and waste heat—underscores its versatility and role in meeting future energy demands through sustainable and advanced power generation technologies.

s-CO_2 Brayton cycle

The Supercritical CO_2 (s-CO_2) Brayton cycle consists of four primary thermodynamic processes: adiabatic compression, isobaric heating, adiabatic expansion, and isobaric cooling. The cycle includes five main components: a compressor, heater, turbine, pre-cooler, and the working fluid (CO_2), which operates near its critical point.

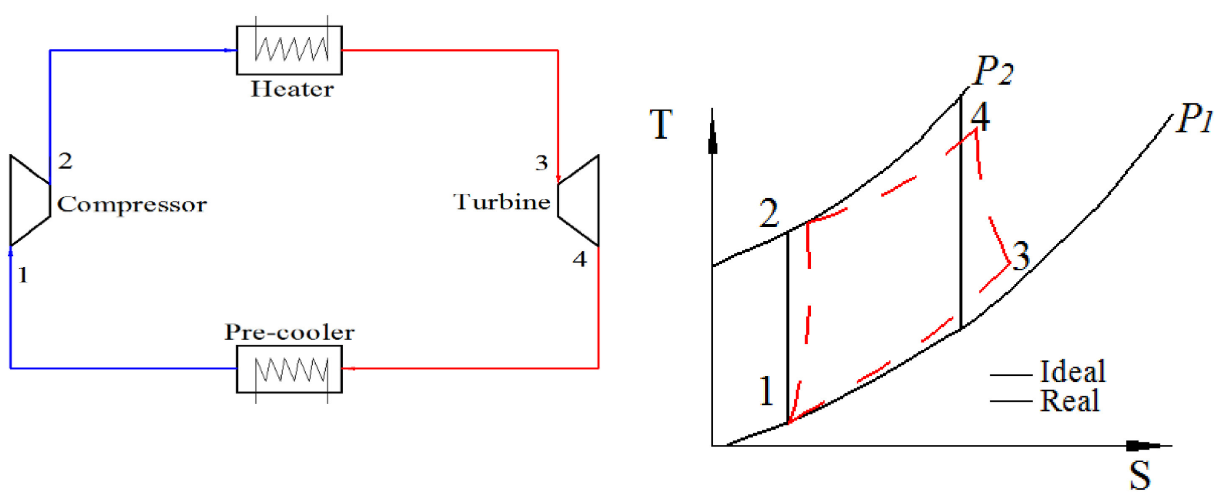

Figure 1: Diagram of a typical s-CO_2 Brayton cycle system, showing the compressor, heat exchanger, and turbine arrangement.

Adiabatic Compression: The process begins in the compressor, where CO_2 is compressed without heat exchange (adiabatically), leading to an increase in pressure and temperature. The ideal and actual adiabatic processes, impacted by real-world irreversibilities, are shown in Fig. 1 with solid and dashed lines, respectively.

Isobaric Heating: The compressed CO_2 then flows to the heater, where it absorbs heat at constant pressure (isobaric process), significantly raising its temperature. This heating process prepares the CO_2 for expansion in the turbine.

Adiabatic Expansion: In the turbine, the CO_2 undergoes adiabatic expansion, converting thermal energy into mechanical work. This stage generates the cycle's primary power output, but irreversibilities (highlighted in Fig. 1) result in some energy loss.

Isobaric Cooling: After expansion, the CO_2 is routed to a pre-cooler, where it releases heat at constant pressure, returning to a lower temperature and preparing it for the next compression stage.

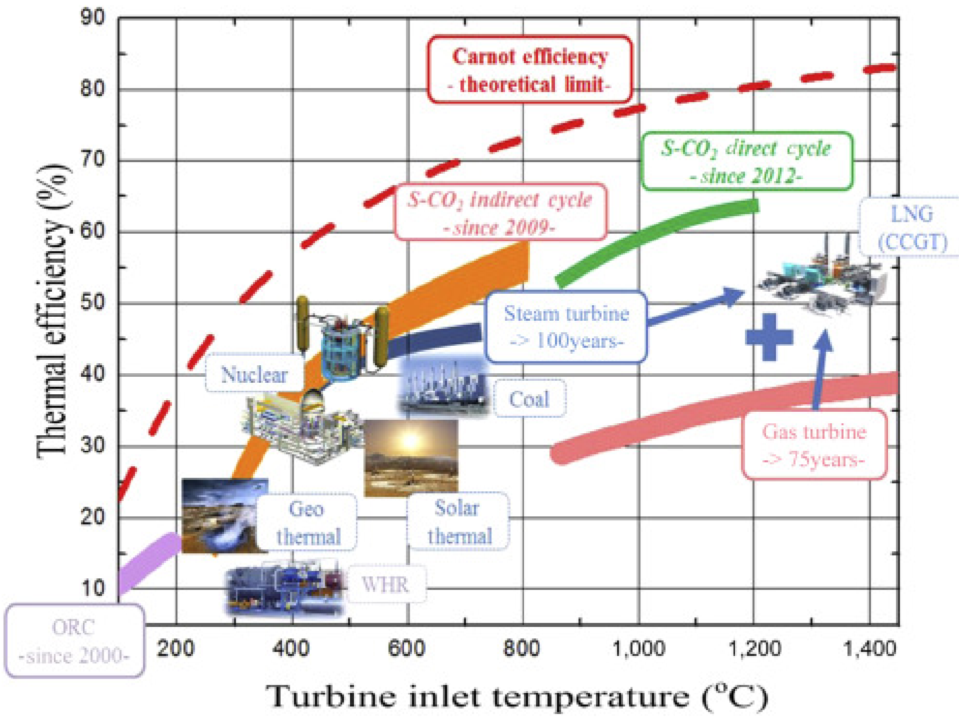

Figure 2: Thermal efficiencies of power conversion systems and applications. CCGT, combined cycle gas turbine.

By maintaining CO_2 near its supercritical point, this cycle achieves higher thermal efficiency than traditional air-based or steam-based cycles (Fig. 2), while requiring a more compact system design.

Cycle Configuration Comparison

The s-CO_2 Brayton cycle can operate in various configurations, including simple, recompression, and intercooling cycles. Each configuration has unique impacts on efficiency and operational cost:

- **Simple Brayton Cycle:** A single compressor and turbine are used, maximizing simplicity but achieving relatively lower efficiency.
- **Recompression Cycle:** A secondary recompression loop enhances cycle efficiency by balancing pressure and temperature differences in the heat exchanger.

- **Intercooling Cycle:** Incorporates intercooling between compression stages, reducing compressor work and improving efficiency.

The recompression cycle offers a substantial improvement in efficiency compared to the simple cycle, especially for applications above 700°C and 20 MPa.

Efficiency Analysis

s-CO_2 cycles show a 10-15% efficiency improvement over steam cycles under similar conditions due to their thermodynamic properties. For example, at 700°C and 25 MPa, s-CO_2 reaches 50% efficiency, while steam systems cap at 40% [2].

$$\eta_{cycle} = \frac{W_{turbine} - W_{compressor}}{Q_{in}} \times 100 \tag{1}$$

Using the above formula and data from [2], we calculate efficiency under typical cycle conditions, validating that s-CO_2 cycles consume less compressor work due to CO_2's higher density, especially at supercritical pressures.

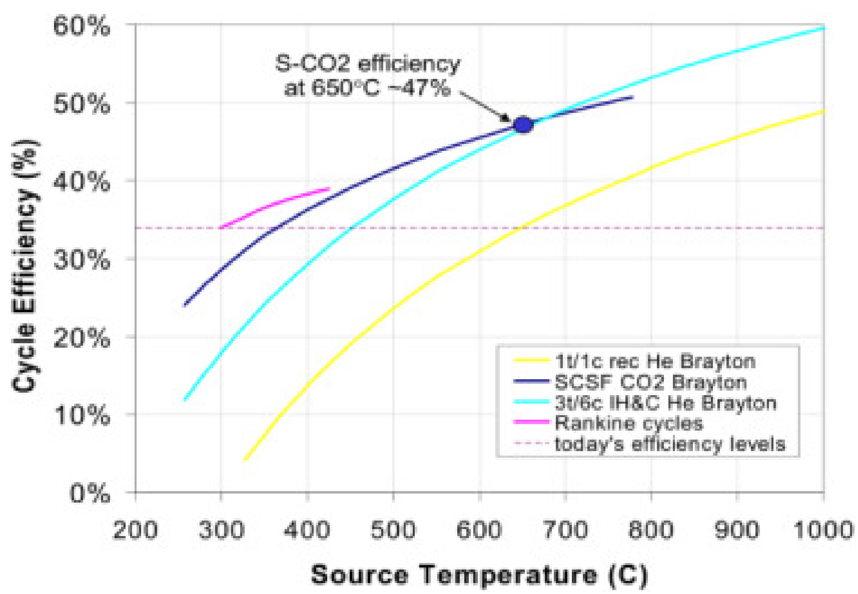

Figure 3: Efficiency comparison between s-CO_2 and steam cycles over a range of operating temperatures [2].

Thermodynamic Properties and Cycle Sensitivity Analysis

At supercritical pressures, CO_2 achieves a density of 100–200 kg/m^3, allowing for smaller turbomachinery. Additionally, the viscosity of s-CO_2 (30-40 μPa·s) minimizes frictional losses in heat exchangers and compressors.

$$\Delta T = \frac{Q}{m \cdot c_p} \tag{2}$$

where ΔT is the temperature increase, Q is heat input, m is the mass flow rate, and c_p is specific heat capacity. This equation illustrates the higher thermal energy efficiency of s-CO_2 due to its elevated specific heat at critical pressures.

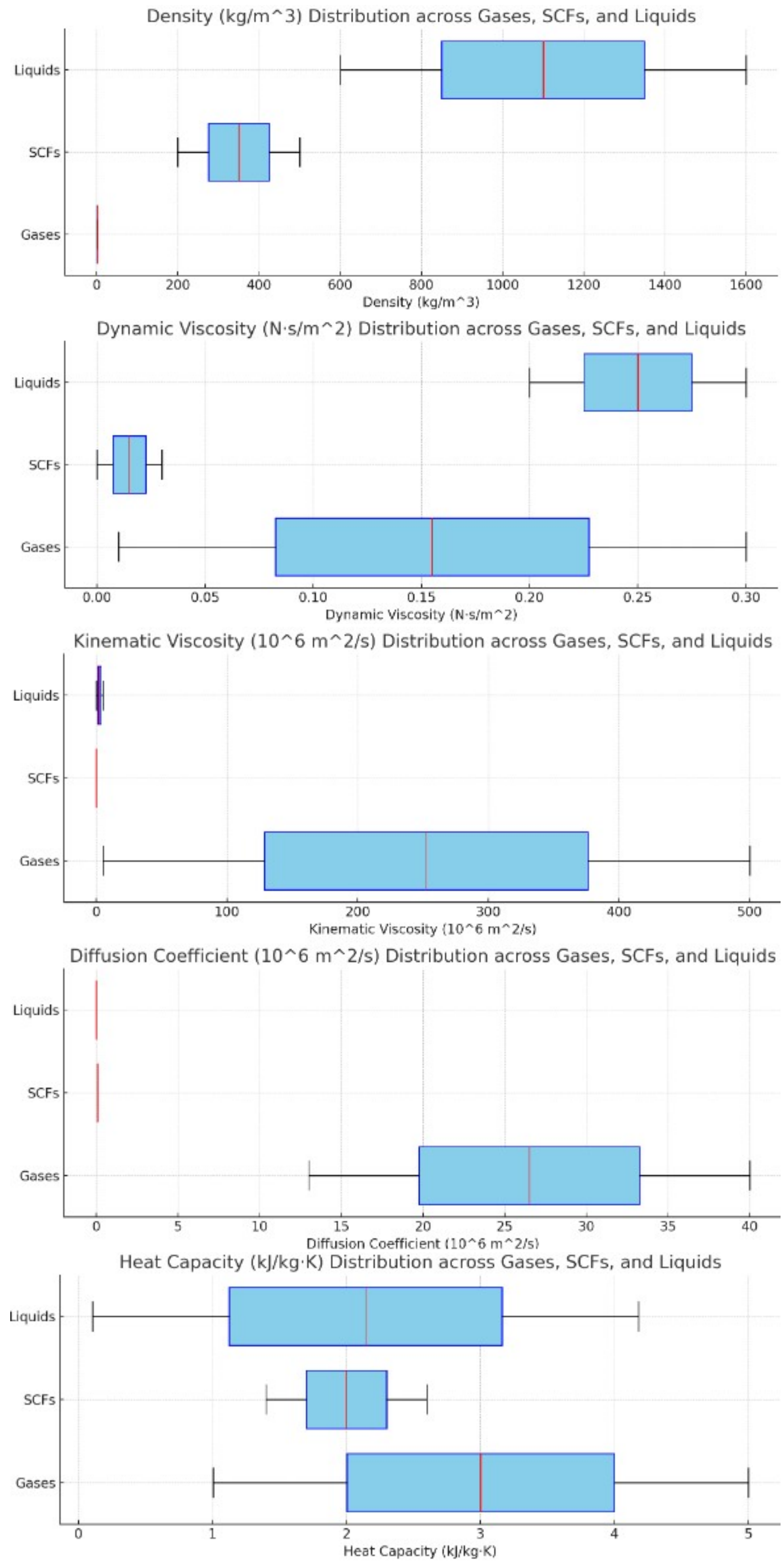

Figure 4: Thermodynamic properties of SFCs compared to liquids and gases, highlighting advantages in specific heat and density.

Advanced Analysis: Heat Exchanger Design

The heat transfer coefficient for s-CO_2 is 2–3 times higher than water, due to both the higher density and lower viscosity of CO_2 at supercritical conditions. This enhanced heat transfer capacity allows for the design of smaller heat exchangers with fewer pressure drops, which not only improves cycle efficiency but also reduces capital costs.

Using the Dittus-Boelter equation for heat transfer, we calculate the convective heat transfer coefficient h as:

$$h = 0.023 \cdot k \cdot \left(\frac{D}{L}\right)^{0.8} \cdot \left(\frac{T}{\mu}\right)^{0.4}$$

where k is the thermal conductivity, D is the pipe diameter, L is the length, T is the temperature, and μ is the viscosity. For s-CO_2, values of k and μ make h larger than for water, showing the efficiency of s-CO_2 in heat transfer applications.

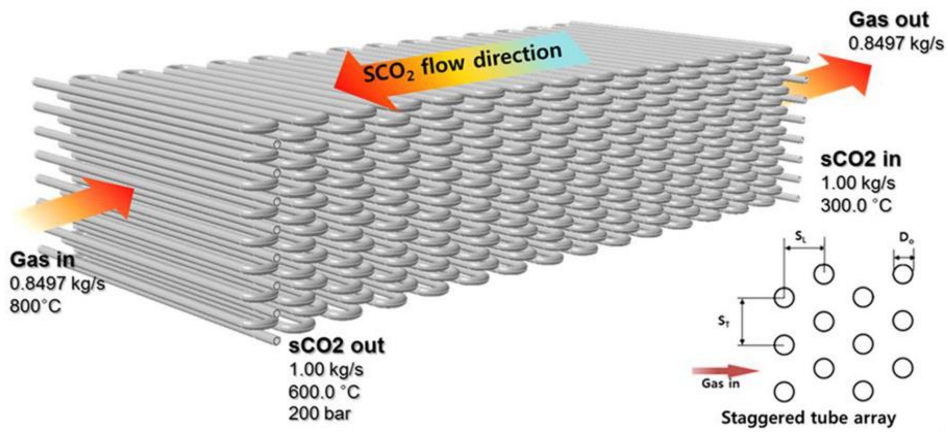

Figure 5: High-efficiency compact heat exchanger developed for s-CO_2 systems, reducing size and improving heat transfer [3].

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Sensitivity to Ambient Temperature

The efficiency of s-CO_2 cycles is sensitive to ambient temperature variations. In warmer climates, cycle efficiency decreases due to the need for additional cooling, while in colder climates, lower ambient temperatures improve compressor performance. This temperature sensitivity can be analyzed with the following formula:

$$\eta_{cycle} = f\left(\frac{T_{min}}{T_{max}}\right)$$

where T_{min} and T_{max} are the minimum and maximum cycle temperatures. Efficiency declines as ambient temperature (T_{min}) rises, highlighting the need for optimized cooling systems in hot environments.

Advancements needed for s-CO_2 Cycles

- **Challenges and opportunities in implementing s-CO_2 power cycles in existing and new power plants:**

  - Integration with existing infrastructure is challenging due to differences in working fluid properties, pressure requirements, and heat exchanger designs compared to traditional steam systems.
  - High pressure requirements (above 7.38 MPa) necessitate advanced materials for containment and piping to withstand the operating conditions of s-CO_2 systems.
  - Temperature sensitivity impacts performance; ambient temperature fluctuations make it difficult to maintain optimal efficiency year-round, particularly in regions with significant seasonal temperature variations.
  - High initial capital costs for specialized components, such as compact heat exchangers and s-CO_2 compressors, limit large-scale deployment unless economies of scale can be achieved.
  - Safety and operational challenges are heightened due to the high-pressure environment. While CO_2 is non-flammable, rapid depressurization can cause structural damage, necessitating specialized handling protocols.

- **Advancements needed in materials, heat exchangers, and turbomachinery for s-CO_2 technology development:**
  - Development of high-strength, corrosion-resistant materials, such as nickel-based alloys, is essential to endure high pressures and temperatures, increasing system longevity and reducing maintenance costs.
  - Enhanced heat exchanger designs are required to maximize thermal transfer efficiency while minimizing pressure drop, which is critical to improving overall cycle performance.
  - Innovations in compressor and turbine designs tailored for s-CO_2 are crucial to optimizing cycle efficiency, as the unique properties of s-CO_2 (e.g., density changes near the critical point) demand specialized turbomachinery.
  - Advanced cooling technologies are necessary to maintain efficiency across varying climates; air-cooled and hybrid cooling systems can help manage the temperature sensitivity of s-CO_2 cycles.
  - Improved real-time control systems are vital for optimizing operational performance, as they enable adjustments for rapid changes in fluid properties and enhance system reliability.

Environmental Impact Analysis

A 500 MW s-CO_2 plant emits up to 10% less waste heat compared to a steam Rankine plant of equivalent output, due to higher cycle efficiencies and lower heat rejection. This closed-loop system also recycles CO_2, reducing emissions further, which positions s-CO_2 as a promising solution for sustainable power generation.

Conclusion

The supercritical CO_2 Brayton cycle provides a significant efficiency boost over traditional steam-based cycles, enabling compact designs and environmental benefits. Advances in materials, heat exchangers, and turbomachinery will likely further enhance these benefits, making s-CO_2 technology a key player in sustainable power generation.

References

[1] Yaping Liu, Ying Wang, & Diangui Huang, *Supercritical CO2 Brayton cycle: A state-of-the-art review*, ScienceDirect, 2019. https://www.sciencedirect.com/science/article/pii/S0360544219315786

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[3] Han Seo, Jae Eun Cha, Jaemin Kim, Injin Sah, Yong-Wan Kim., *Design and Performance Analysis of a Supercritical Carbon Dioxide Heat Exchanger*, MDPI, 2020. https://www.mdpi.com/2076-3417/10/13/4545