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Thermodynamic Modelling, Technical and Operational Issues of Supercritical Carbon Dioxide Power Generation Cycles for Industrial Applications: A Literature Review

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ABSTRACT

Future electricity production systems will be able to harness the power of supercritical carbon dioxide (S-CO_2) as it moves through thermal cycles. It serves the same goal as sources of energy such as fossil fuels, nuclear power, solar power, and the recovery of waste heat (or surplus heat from industrial processes). When the heat source temperature is between 350°C and 800°C, CO_2 as a working fluid exhibits excellent thermal efficiency. Its novel technological benefits over conventional steam Rankine cycles, such as the use of small turbo gear and compact heat exchangers, have captured the attention of scientists. It has excellent operational flexibility and may induce significantly cheaper energy costs. Aligned with these goals, this paper presents a panoramic work, exploring the current state of the art of S-CO_2 power generation, with a particular emphasis on the technical and operational perplexities. After providing a comprehensive overview of the thermodynamic principles that underpin this study, the foundation is established for an engaging discourse on the continuous research and development of supercritical carbon dioxide (S-CO_2) cycles in power generation. Upon delving into the thermodynamic facets of CO_2 that propel this investigation, the spotlight is cast upon dissecting the existing state of research and development of S-CO_2 cycles in power generation before transitioning into encapsulating the principal domains of application and noteworthy thermodynamic modelling inquiries of S-CO_2 cycles. The present advancements and hurdles within the primary application areas are succinctly summarized, while future research trends are identified.

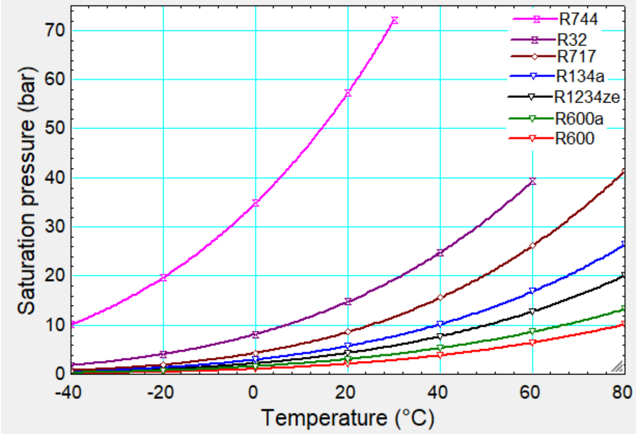
Keywords: S-CO_2; Carbon dioxide; Electricity cycle; Sustainable development, Power plants.

1. Introduction

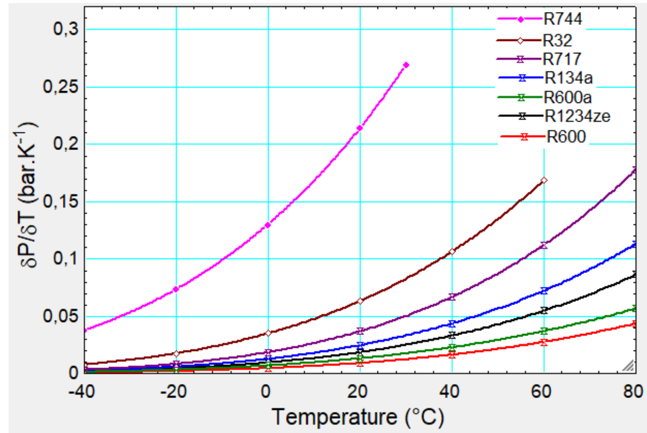
The exhaustion of fossil energy resources has fervently spurred the quest for devising electrical energy production methods rooted in renewable sources (geothermal, biomass, and solar) (Hou et al., 2018). The demand for energy will persistently surge in the forthcoming decades due to the emergence of developing nations (AIE, 2015). According to the International Energy Agency (IEA) of France, global energy consumption is projected to surge by 75% from 2013 to 2040. The reliance on electricity generation from fossil fuels to sustain economic growth has wreaked havoc on the environment by unleashing greenhouse gas emissions, ultimately leading to global warming and environmental contamination (IRENA, 2020). Consequently, there has been an exponential proliferation in the adoption of renewable energy technologies like solar PV and wind, which liberate themselves from the clutches of thermodynamic power cycles (AIE, 2015). Nevertheless, in order to fulfil the demand for secure, reliable, and sustainable energy, it is widely acknowledged that an extensive array of energy conversion and storage technologies will be imperative (Y. Song et al., 2020). This will likely encompass nuclear power generation, concentrated solar power plants, and the utilization of blue and green hydrogen, in conjunction with the implementation of technologies to enhance overall energy efficiency (Ma et al., 2022), such as recuperating waste heat(Xiao et al., 2022) and the perpetual utilization of fossil fuels, the production of biodiesel (Syimir Fizal et al., 2022), ultimately with carbon capture and storage. Consequently, thermodynamic cycles will probably persist as a pivotal component of forthcoming energy networks (Liu et al., 2019). The retrieval and transformation of industrial waste heat into electricity at low temperatures is arousing considerable interest, such as optimizing the energy efficiency of industrial processes and abating thermal pollution instigated by the direct discharge of heat into the environment (Muhammad et al., 2022; R. Sun et al., 2022). In practical terms, the water vapour cycle (conventional Rankine cycle) prevails as the most extensively employed in systems for generating electricity from heat (Ma et al., 2022). Indeed, water proves to be an exceptional working fluid for the Rankine cycle provided that the temperature of the heat source is sufficiently high. However, for applications wherein the heat source possesses low energy quality, particularly in low power scenarios, water is not technologically nor economically the most favourable choice (Xiao et al., 2022). Manufacturers have pushed the boundaries of improvement, but now they face the daunting challenge of prohibitive costs if they want to achieve even the tiniest additional gains. The production of water vapour at lower temperatures, under low pressure, necessitates the use of bulkier equipment. One solution, which has proven to be reliable, involves replacing the traditional Rankine cycle that uses water vapour (H_2O) with a Brayton cycle that employs supercritical carbon dioxide (S-CO_2) (R. Wang et al., 2022). This alternative offers a favourable compromise between the efficiency of energy gains and the simplicity of the cycle (Mecheri & Le Moullec, 2016). The comprehensive categorization of S-CO_2 cycles has not yet been explored in depth within the existing literature. While certain combinations of these cycles have been proposed, they are merely amalgamations of commonly utilized processes in power plant engineering, such as the intercooled S-CO_2 cycle, the reheat S-CO_2 cycle, and the recovery S-CO_2 cycle (Ahn & Lee, 2014). The potential of supercritical CO_2 has been substantiated by the remarkable surge in research during the past decade (Syimir Fizal et al., 2022). Given this rapid growth in research and the potential of S-CO_2 power cycles, it is imperative that we conduct a meticulous analysis of current research endeavours, as well as identify the most promising applications and future research trends. Previous studies have predominantly focused on various cycle configurations, as well as the thermodynamic modelling and optimization of these cycles. However, this review distinguishes itself by placing a strong emphasis on the practical technological challenges associated with S-CO_2 systems and their components, while also providing a concise overview of the primary areas where these systems can be applied.

2. Thermodynamic Properties of CO_2

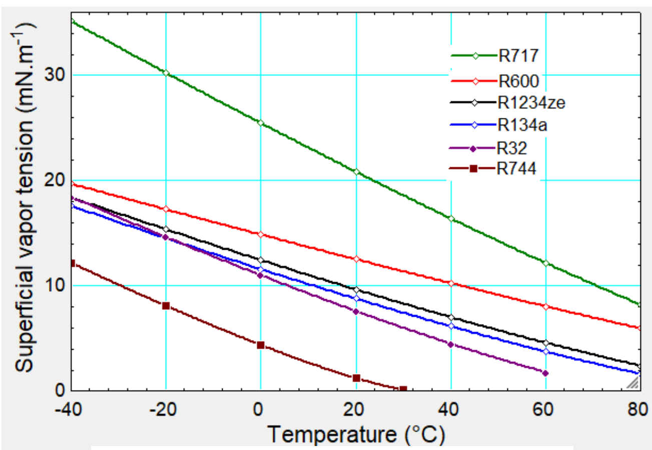
Operating a closed-loop cycle with a working fluid has the potential to address some of the limitations associated with air- or water-powered power plants. The organic Rankine cycle (ORC) is a method for generating electricity that functions similarly to the steam cycle, but instead utilizes an organic compound as the working fluid. Various organic fluids have been investigated for use in the ORC by multiple researchers (Akbari & Mahmoudi, 2014, 2017; Bao & Zhao, 2013). While these fluids have demonstrated good performance, they also have negative environmental impacts and some are highly flammable. However, the focus has shifted towards CO_2 due to its critical point, which is characterized by a critical temperature of 31.1°C, close to ambient conditions. It should be noted that the critical pressure of CO_2 (73.8 bar) is one-third that of water, allowing for a low work compression process after heat rejection, which can be achieved at temperatures near room temperature. Additionally, CO_2 is abundant in nature, cost-effective, non-toxic, non-flammable, and thermally stable at high temperatures. The thermodynamic behaviour of CO_2 in the vicinity of the critical points and the rationale for operating the compression process near the critical point are illustrated in Figure 1. Below the critical point, the saturation pressures of CO_2 and their temperature dependence are significantly higher compared to other refrigerants (see Figure 1. a). The temperature change (δT) associated with a pressure drop (δP) is minimal (see Figure 1. b). As a result, higher flow velocities can be achieved, leading to improved heat exchange. CO_2 has a much lower surface tension compared to other fluids (see Figure 1. c), which reduces the energy required for bubble nucleation and growth. This lower surface tension promotes nucleate boiling, resulting in enhanced heat transfer where nucleation plays a dominant role compared to convection. The phenomenon of early drying of the wall with CO_2, at higher liquid mass flow rates compared to other refrigerants, can be attributed to the lower ratio of liquid/gas viscosities, which promotes the rupture of the liquid film and deteriorates heat exchange. The temperature at the end of evaporation is also affected by this behaviour (see Figure 1. d). These results were obtained using EES (Engineering Equation Solver) for the calculation of thermodynamic properties.



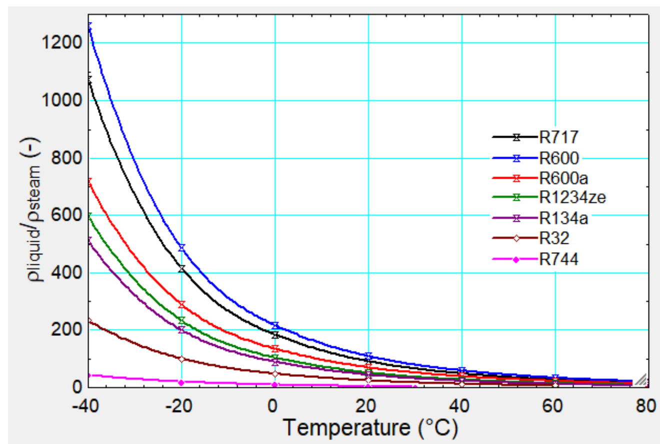
(a) Saturation pressure of R744 and other refrigerants



(b) δP/δT of R744 and other refrigerants



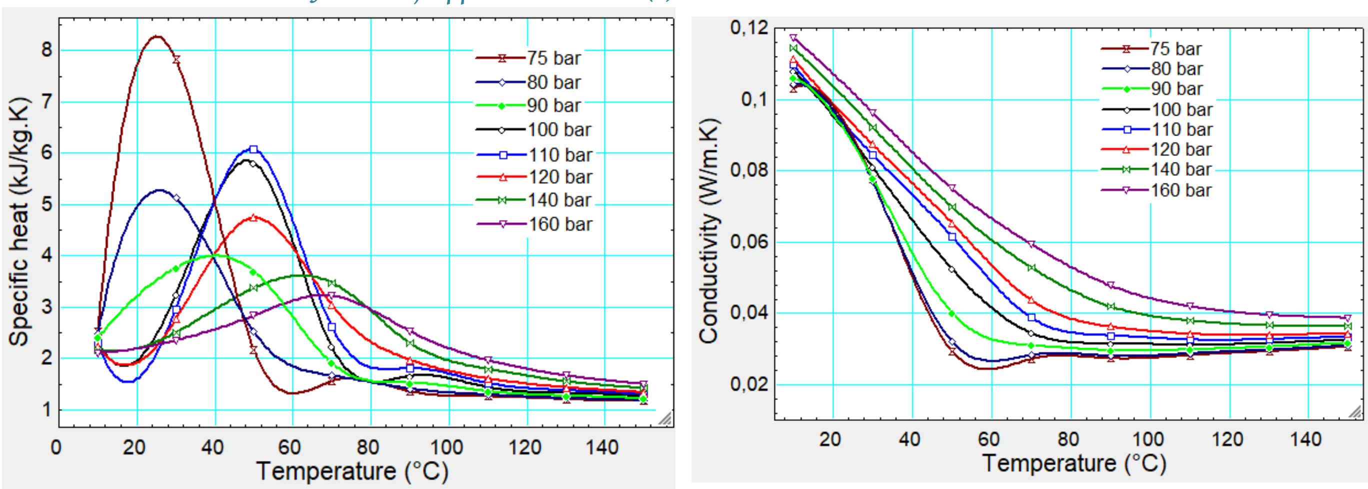
(c) Superficial vapor tension dependence on temperature



(d) Ratio of liquid and gaseous densities dependence on temperature

Figure 1: Thermodynamic properties of CO_2 compared to other refrigerants

Carbon dioxide exhibits a high density and its viscosity falls between that of gas and liquid, although it leans towards the lower end of the liquid viscosity spectrum. Luz et al. conducted a recent numerical study that confirmed CO_2's high density by comparing its performance with that of air, helium, and nitrogen (Luz et al., 2022). Notably, CO_2 undergoes significant variations without undergoing any phase change (Chegnimonhan et al., 2021). Additionally, CO_2 demonstrates favourable fluidity and heat transmission properties. The specific heat of CO_2 decreases at higher pressures, with the peak occurring at higher temperatures. At pseudo-critical points, the specific heat exhibits a peak for a specific supercritical pressure (see Figure 2. a). Conversely, the thermal conductivity of carbon dioxide decreases as temperature increases (see Figure 2. b), with the highest values observed at lower pressures. Ultimately, CO_2 exhibits excellent heat transmission characteristics.



(a) Specific heat dependence on temperature

(b) Conductivity dependence on temperature

Figure 2: Comparison of the properties of supercritical CO_2 at different pressures

However, operating at supercritical pressures presents challenges for both cycle operation and component design. Firstly, operating at pressures ranging from 50 to 250 bar necessitates the design of all components to withstand these pressures, potentially requiring the use of specialized materials capable of enduring harsh operating conditions. Additionally, high pressures result in high densities and, consequently, low volumetric flow rates throughout the system (Cao, Dhahad, et al., 2022; Cao, Zhan, et al., 2022; Thanganadar et al., 2021). This poses difficulties in designing turbomachinery components with high power density. Furthermore, initiating the compression process near the critical point presents its own set of challenges. Notably, there appears to be a lack of studies investigating the thermodynamic CO_2 cycles in meteorological conditions specific to tropical climatic zones.

3. The Operating Principle of S-CO_2 Cycles

According to Kowalski et al.(Mecheri & Le Moullec, 2016), cycles utilizing supercritical carbon dioxide as the working fluid can be categorized into two groups based on the operating temperature level.:

- Low-temperature S-CO_2 cycles
- High-temperature S-CO_2 cycles

3.1. Low Temperature S-CO_2 Cycles

Low-temperature cycles are ingeniously devised primarily to recover the dissipated heat during industrial processes. The heat source temperature of these systems plummets below 300°C. Low-temperature systems can function in a transcritical cycle (Kowalski et al., 2020). The cycle comprises an expansive turbine, a heat exchanger, an optional heat recuperator, a pump, and a condenser. Figure 3 unveils the block diagram of an S-CO_2 cycle propelled by a low-temperature heat source (300°C). A pump dispatches the fluid from point 1 to point 2. The process is assumed to be adiabatic since heat losses are trivial. The heat exchange transpires within the energy recuperator (points 2-3 and points 5-6). At this stage, the temperature of the CO_2 at the outlet of the high-pressure heat exchanger dwindles, thus less heat is conveyed into the condenser. This step (process in the exchanger) is theoretically dispensable, yet it substantially enhances the thermal efficiency of the system. The preheated CO_2 (points 3 and 4), under immense pressure and temperature, is directed to the high-pressure heat exchanger nourished by the waste heat. During expansion (points 4 and 5), the CO_2 undergoes a grandiose expansion through a turbine, precipitating a drop in pressure and temperature. A fraction of the mechanical energy generated can be deployed, for instance, to propel an electrical generator (alternator). The waste heat is infinitesimal and the process can be treated as adiabatic. Stage 6 to 1 constitutes a process wherein the heat transfer fluid relinquishes heat to the coolant. Raj et al.(Di Marcoberardino et al., 2020)engineered a diminutive S-CO_2 cycle that operates on the closed-loop Brayton cycle principle. Calculations divulged that the cycle yielded 4.5 kW of power with a pressure of 17.23 MPa and an inlet temperature of 358.15 K; the thermal efficiency of the system was estimated at 12.75%. To enhance the efficiency, some researchers proposed a customized working fluid in which CO_2 is blended with specific additives to enable condensation at higher ambient temperatures, thus making it viable to endure the required peak temperatures without penalizing the efficiency of the power cycle, ultimately leading to substantial reductions in energy cost (Di Marcoberardino et al., 2020). The work of Niu et al. (Niu et al., 2022) unveiled that the thermal and exergy efficiencies of the electricity production cycle, operating with the CO_2-propane mixture, escalated respectively by 2.34% and 1.51%compared to that of S-CO_2 in the same operating condition.

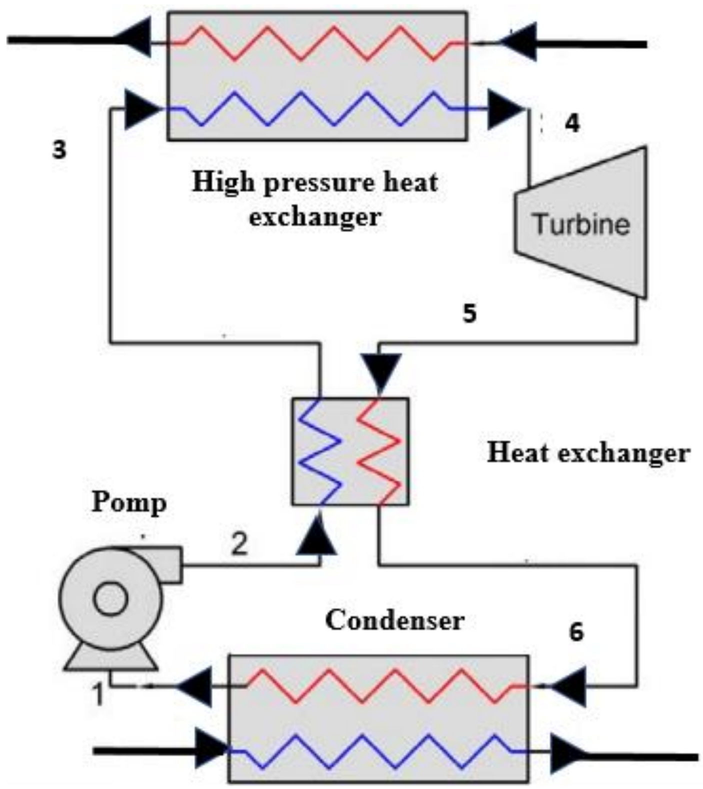


Figure 3: Block diagram of the low-temperature S-CO_2 cycle

3.2. High-Temperature S-CO_2 Cycles

S-CO_2 cycles typically cater to heat source temperatures surpassing 300°C (Kowalski et al., 2020). The diagram showcasing the high-temperature S-CO_2 cycles mimics Figure 3, albeit with the substitution of a compressor and a chiller for the pump and condenser, respectively. In 2014, Akbari and Mahmoudi conducted an exergy-economic analysis on both the standalone S-CO_2 cycle and its integration with the Organic Rankine Cycle (ORC). The authors deduced that the exergy efficiency of the combined cycle (S-CO_2/ORC) outperformed that of the S-CO_2 cycle by a staggering 11.7% (Akbari & Mahmoudi, 2017). Numerous configurations were explored, ranging from the simplest to combined cycles (S-CO_2/ORC) (Kim & Perez-Blanco, 2015). Wang et al. proposed an ingenious thermodynamic configuration method to facilitate the design and implementation of combined S-CO_2 systems for recuperating high-temperature waste heat from marine engines (Z. Wang, Jiang, Han, et al., 2022). They concluded that, under the system's optimal operating conditions, the total energy production stood at a remarkable 538.97 kW, with a corresponding cost of electricity generation of 5.34 cents/kWh. Moreover, the thermal and exergy efficiencies reached an impressive 33.17% and 61.93%, respectively.

4. Various Configurations of S-CO_2 Cycles

Martin and Dostal scrutinized the S-CO_2 cycle diagrams derived from Angelino's groundbreaking findings(Angelino & Invernizzi, 2009). Angelino's original research centered on the condensation cycle, yet he also delved into alternative configurations such as the recompression cycle, partial cooling cycle, and pre-compression cycle(Lehar & V., 2013). He encapsulated his work by classifying the S-CO_2 cycles into two distinct configurations. The cycle can be categorized based on whether the stream is bifurcated (divided stream) or unified (single stream), contingent upon the application domain. The S-CO_2 cycle designs examined in this assessment are vividly depicted in Figures 4 and 5.

4.1. The Single-flow S-CO_2 Cycles

In the temperature range of 450°C to 550°C, as per Angelino's research, an innovative S-CO_2 cycle configuration, boasting a streamlined and condensed layout, was employed(Fan et al., 2022; Guo et al., 2022; Oh et al., 2022). Figure 4 showcases the array of distinctive arrangements for single-flow S-CO_2 cycles. The configurations of the single-flow S-CO_2 cycle (with non-fractionated CO_2 flow) are as follows: the fundamental recuperative cycle (a), the cycle decked with intermediate cooling (b) (Fan et al., 2022), the reheat cycle (c), the inter-recovery cycle (d), the pre-compression cycle (e) (Guo et al., 2022), and the double expansion cycle, as depicted in Figure 4. A detailed description of the core system (a) has been presented (refer to the fundamental operational principle of S-CO_2 cycles). In the design of the closed Brayton cycle, the recuperation process typically plays a pivotal role in enhancing cycle efficiency. These measures are essentially indispensable for elevating cycle efficiency by minimizing the squandering of excess heat. Thus, the recuperation arrangement can be considered the quintessential blueprint for designing the S-CO_2 cycle. System (b) is achieved by integrating a secondary compressor and a second condenser into the system presented in (a). By incorporating a preheating circuit and a turbine into the system (a), the configuration of the system (c) can be achieved. The adoption of the S-CO_2 cycle with intermediate cooling (b) and the S-CO_2 cycle of reheating (c) serves to minimize or maximize the compression work and expansion work, respectively (refer to Figure 4). Due to the low cycle compression ratio, resulting in a high CO_2 temperature at the turbine outlet, several methods can be employed to recover the excess heat. In the realm of single-flow diagrams, the inter-recovery S-CO_2 cycle (d), the pre-compression S-CO_2 cycle (e), and the double expansion S-CO_2 cycle (f) are recommended, depending on the location where the recuperation process takes place (Figure 4).

4.2. Split-flow S-CO_2 Cycles

The configuration of S-CO_2 cycles employing fractional (separate) CO_2 flow is harnessed within the temperature ranges spanning from 650°C to 800°C, as per Angelino's findings (Angelino & Invernizzi, 2009). In contrast to the single-flow configuration, its thermal efficiency is higher. Figure 5 visually portrays the various arrangements of fractionated flow S-CO_2 cycles. The split-flow S-CO_2 cycle configurations encompass the recompression S-CO_2 cycle (a), the modified recompression S-CO_2 cycle (b), the preheat-equipped S-CO_2 cycle (c), and the split expansion S-CO_2 cycle, as exhibited in Figure 5(Guo et al., 2022; Saeed & Kim, 2022). The split expansion S-CO_2 cycle encompasses three configurations: the split expansion S-CO_2 cycle (d), the fractional expansion S-CO_2 cycle (e), and the S-CO_2 cycle with fractional expansion (f). The distinguishing factor between the recompression cycle and the remaining ones lies in the recovery process. In the recompression system (a), the CO_2 flow is bifurcated into two streams: (1-x) and (x). The (1-x) high specific heat flux is mixed with the flux (x) to maximize cycle efficiency. In the modified recompression system (b), the CO_2 temperature exhibits variations within the intermediate recuperator. The S-CO_2 system equipped with preheating (c) employs two high-pressure heat exchangers to substantially enhance the efficiency of the S-CO_2 systems (Figure 5).

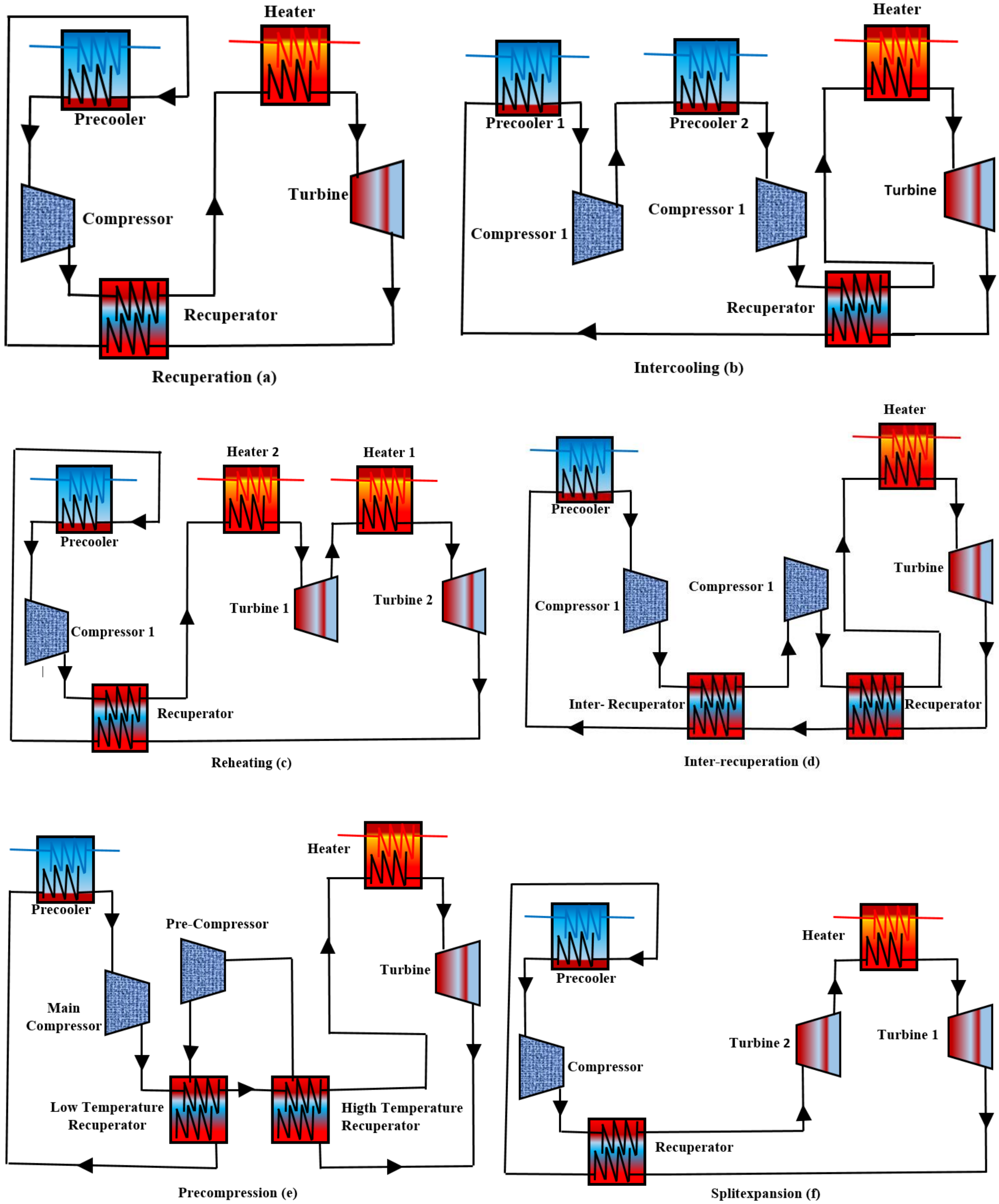


Figure 4 : Single-stream S-CO_2 cycle (Fan et al., 2022; Oh et al., 2022)

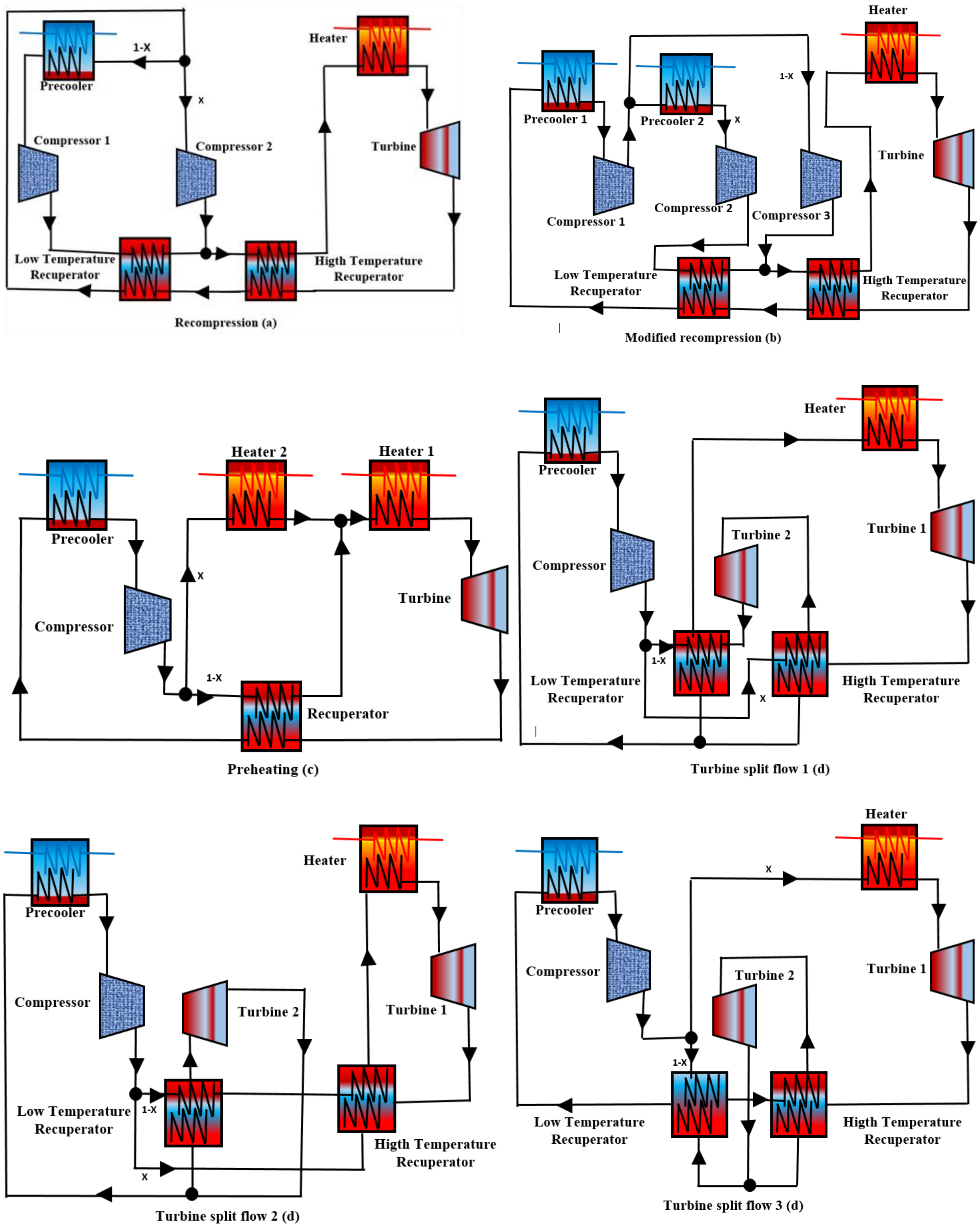


Figure 5: Configuring Split-Flow S-CO_2 Cycle (Fan et al., 2022; Oh et al., 2022)

5. Applications of S-CO_2 Cycles

S-CO_2 cycles have the potential to embrace a myriad of heat sources. They can be harnessed by nuclear energy, spanning from pressurized water reactors (both large and small modular reactors) to upcoming nuclear reactors and fusion reactor applications (Dostal, 2004). Investigating the S-CO_2 cycles on different heat sources becomes imperative, including concentrated solar power, gas turbines recovering exhaust heat, and booster cycles for power plants propelled by fossil fuels (Z. Li et al., 2022; Neises & Turchi, 2019). A comprehensive overview of the principal domains of application and noteworthy studies delving into the thermodynamic modelling of S-CO_2 cycles is presented in Table 1.

5.1. Nuclear Applications

Placing nuclear power in the perspective of sustainable development thus necessitates the emergence of a novel generation of reactors: "the fourth generation", capable of harnessing natural or depleted uranium directly and generating 50 to 100 times more electricity with the same amount of ore than current nuclear reactors (CEA, 2012; COE, 2022). Current research is focused on S-CO_2 power cycles for sodium-cooled fast reactor applications (SFR) (Ahn & Lee, 2014; Moisseytsev & Sienicki, 2009). The SFR, in conjunction with S-CO_2, enables the recycling of actinides and the repeated recycling of plutonium (COE, 2022). The S-CO_2 cycle can supplant a fierce Na-H2O reaction with a gentle Na-CO_2 reaction, potentially augmenting the safety and thermal efficiency of the nuclear system. The Korean Institute of Korea Atomic Energy Research Institute (KAERI) has investigated the reaction of sodium and the safety of the S-CO_2 cycle. The ignition temperature of the Na-CO_2 reaction was determined to be 595°C in terms of sodium temperature(Jung et al., 2014). Additionally, numerical modelling is being explored to anticipate the impact of CO_2 in a Na-CO_2 mixture in a heat exchanger, and a corresponding experiment is being devised for validation. Conversely, the nitrogen Brayton cycle is being scrutinized as an alternative power conversion system for sodium-cooled fast neutron reactors, with the aim of intrinsically eradicating the chemical reaction between sodium and fluid conversion power in France. Under high pressure conditions, the nitrogen Brayton cycle can also achieve competitive performance compared to the superheated steam Rankine cycle. The economics of the nitrogen Brayton cycle for the SFR application have been probed by the CEA (Commissariat à l'EnergieAtomique) of France. The application of this cycle can obviate the need for expensive safety systems required to detect and mitigate sodium-water reactions (E. Sun et al., 2022).However, the nitrogen Brayton cycle can only be harnessed in sodium-cooled fast reactor applications and regrettably, aside from nuclear applications, no immediate domain of implementation was discerned. This limitation in scope can prove to be a hindrance in constructing a robust supply chain and garnering support from a diverse array of energy industries. In contrast, the S-CO_2 power cycle harbours the potential to be utilized in small and medium-sized reactors, colossal conventional water-cooled reactors, fusion reactor applications, as well as other power sources, such as coal, natural gas, and renewables (Halimi & Suh, 2012; Q. Wang et al., 2021; Yoon, 2012). Wang et al. conducted a study on three exceedingly high-temperature gas-cooled reactors and on nuclear hydrogen production systems employing the S-CO_2 cycle, the ORC cycle, and the S-CO_2 cycle amalgamated with the ORC(Q. Wang et al., 2021). Under varying hydrogen production loads, the performance of the nuclear hydrogen production system employing the S-CO_2 cycle exhibits sensitivity towards the reactor inlet temperature (Q. Wang et al., 2021). Under low reactor inlet temperatures (below 587° C.), the thermal efficiency of the S-CO_2 cycle plummets below 37%. Moreover, enhancing the compressor pressure ratio of the S-CO_2 cycle can ameliorate the thermodynamic performance of the system, and the thermal and exergy efficiencies of the system are enhanced by approximately 0.7% to 3.7%, respectively, 1.0% to 5.3% utilizing the ORC. Recently, Ming et al. scrutinized a diminutive 5 MW S-CO_2 modular reactor(Ming et al., 2022). The simulation results evinced that the control system exerted a commendable control effect and also possessed a commendable regulation capability under the circumstances of the reactor control rod ejection accident. The system is exceedingly susceptible to fluctuations in temperature and cooling water flow. When the external load is lost, the bypass control method of the turbine can promptly align the system output power and maintain the rotor speed reasonably(Ming et al., 2022). To underscore the research exertion on anaerobic digestion reactors, the S-CO_2 cycle combined with a biomass gasification cycle for the generation of electricity and the preheating of a humidification desalination system – dehumidification was recently scrutinized (Chitsaz et al., 2022).The new tri-generation system underwent a thorough exploration and multi-objective refinement through the utilization of response surface methodology. Power generation, freshwater flow, and methane content in the biosynthetic natural gas were carefully scrutinized as criteria, while biomass feed rate, steam-to-biomass ratio, and supercritical carbon dioxide Brayton cycle pressure ratio were chosen as variable parameters (Chitsaz et al., 2022). The results of the analysis of variance revealed the commanding influence of the biomass supply rate on the outputs. Optimal power generation response variables of 172.6 kW, a freshwater flow of 778.8 kg/h, and methane content of 50.8% in bio-synthetic natural gas were achieved with a biomass feed rate of 1.2 mol/s, a steam-to-biomass ratio of 1.5, and a pressure ratio of 3.5 (Chitsaz et al., 2022).

When implementing the S-CO_2 cycle in confined spaces like nuclear-powered ships and spacecraft, its size becomes a crucial factor to consider (Du et al., 2022). Du et al. conducted a multi-objective optimization of the thermo-economics and component size of a recompression S-CO_2 cycle centered around a small-scale lead-cooled fast reactor (Du et al., 2022). The findings showed that elevating the turbine inlet temperature enhanced thermo-economics, yet it also led to an increase in system volume. The Pareto optimal solution of the bi-objective optimization, based on the levelized cost of electricity and system size, achieved a record-breaking system volume of 3.71 m^3(Du et al., 2022).

5.2. Waste Heat Recovery (Exhaust Gas)

The S-CO_2 power cycle should initially be deployed and marketed to recover the heat from exhaust gases or combustion gases (Xiao et al., 2022). The patents associated with this application are owned by Echogen and General Electric (USA) (Lehar & V., 2013). The exhaust gas temperature from a gas turbine or general boost cycle typically surpasses 450°C, and the S-CO_2 cycle has the potential to supplant the traditional Rankine cycle in order to enhance thermal efficiency. It also has the capability to recover waste heat from a small gas turbine, a feat that is practically unattainable with the Rankine steam cycle (Bella & Francis, 2011). Elattar and Nada showcased the performance of CO_2 in simultaneously generating energy and cold in refrigerated vehicles and trucks by utilizing engine exhaust gases. The proposed combined cycle underwent energy and exergy analysis, enabling the evaluation and comparison of its performance (Elattar & Nada, 2022). The results substantiated the feasibility of employing the proposed systems and highlighted their potential for energy conservation and reduced fuel consumption in comparison to the traditional engine and self-contained refrigerator setup(Elattar & Nada, 2022).. A novel cascade system, wherein waste heat from a partially heated S-CO_2 cycle is recovered by a CO_2 cycle, has been developed for extracting waste heat from engine exhaust (Z. Wang, Jiang, Ma, et al., 2022). The results indicated that by incorporating a transcritical CO_2 cycle with the S-CO_2 cycle for partial heating, the thermodynamic performance of the system can be augmented by 15.35% (Z. Wang, Jiang, Ma, et al., 2022).

5.3. Coal-fired Electric Power

The S-CO_2 cycle emerges as a promising contender to bolster the coal-fired power plant's backup cycle, enhancing its thermal efficiency. Multiple power plant vendors and operators, including Pratt Whitney & Rocketdyne (USA) and Electricity of France, have delved into the design of the S-CO_2 cycle for coal-fired power plant applications (Le Moullec, 2013). This groundbreaking configuration not only rivals the efficiency of conventional energy conversion systems but also masters the art of CO_2 capture and storage. In the quest to curb CO_2 emissions and maximize solar energy utilization, a novel S-CO_2 solar-coal supplemental power generation system takes center stage (Tong et al., 2023). This cutting-edge system boasts unwavering operational stability throughout the year. As the operating load rate surges, the exergy efficiency of this new system skyrockets. At loading rates of 50%, 75%, 100%, and 125%, the exergy efficiencies soar to 16.7%, 25.0%, 33.4%, and 38.0%, respectively (Tong et al., 2023).

5.4. Solar Thermal Power Plants

Despite their predominantly nuclear applications, S-CO_2 cycles have recently sparked a surge of interest in their integration into solar thermal power plants. Turchi et al. unveiled a supercritical solar thermal power plant configuration that featured modular towers and a conventional recompression supercritical layout(Moisseytsev & Sienicki, 2009). From a power cycle perspective, this configuration didn't introduce anything groundbreaking. However, it exhibited a comprehensive integration scheme within an S-CO_2 plant. In a subsequent study, Neises and Turchi meticulously scrutinized partial cooling and recompression S-CO_2 cycle configurations, ultimately concluding that the partial cooling setup offered remarkable advantages for solar concentrator applications(Neises & Turchi, 2019). These advantages included a substantial temperature differential across the heat exchanger, resulting in a smaller solar receiver size and heightened thermal efficiency. The efficiency of S-CO_2 turbines in operational concentrated solar power projects has also been extensively assessed to champion the commercial deployment of this technology(Crespi, 2017). Consequently, two pivotal review works emerged. Crespi et al. conducted a comprehensive evaluation of S-CO_2 cycles for electricity generation(Crespi et al., 2018). Meanwhile, Wang et al. identified and analyzed six potential supercritical cycle configurations that could be indirectly coupled with a molten salt solar receiver(Fan et al., 2022). These configurations included the simple recovery cycle, recompression cycle, pre-compression cycle, intermediate cooling cycle, partial cooling cycle, and fractional expansion cycle. The study ultimately concluded that no configuration was superior to the others, as the final choice hinged upon specific operational and ambient conditions and the annual performance of the solar thermal power plant. A subsequent study by the National Renewable Energy Laboratory (NREL) analyzed two S-CO_2 cycles, namely the recompression and partial cooling cycles, based on the overall performance of the solar thermal power plant(Fan et al., 2022). The authors determined that the partial cooling cycle boasted lower capital costs and generated greater net electricity, thanks to the significant temperature difference in the primary heat exchanger.

5.5. Supercritical CO_2 Solar Collectors

In the realm of solar thermal power plants, the exploration of solar S-CO_2 receivers is still in its nascent stage, although there appears to be an emerging interest. Turchi et al. have alluded to the arduousness of applying parabolic solar fields to supercritical CO_2 due to the exorbitant pressure requirements, even though some theoretical investigations have been conducted (NREL, 2013; Zhang et al., 2016). A previous study investigated compact heat exchanger (CHE) structures and the potential integration into pressurized solar receivers (Ho et al., 2014). While the authors claimed that their work could serve as a catalyst for further research, scant studies have actually built upon their findings. One of the pioneering proposals for central supercritical CO_2 receptors centered around the concept of an external tubular receptor(Delkasar Maher et al., 2022; Iverson et al., 2013). This design aimed to heat air to 800°C under pressures ranging from 5 to 7 bars. However, the adaptation of this receptor for direct coupling to an S-CO_2 power cycle operating between 200 bars and 700°C has also been contemplated. When components are subjected to an S-CO_2 environment with immense pressures and temperatures, they exhibit premature failure as a result of fatigue, creep, corrosion, stress corrosion cracking, erosion, and carburetion (Dyreby et al., 2014). Delkasar and colleagues recommended the use of nickel and stainless steel alloys to withstand high pressure and temperature, as well as enhance heat transfer to the supercritical phase(Delkasar Maher et al., 2022). In the study conducted by Besarati et al., the concept of compact heat exchangers was employed in a 3 MW cavity receiver for S-CO_2(Besarati et al., 2015). The cavity receiver comprised multiple plates interconnected through diffusion, with rectangular fins interspersed between them to form square-shaped channels. The optimal geometry of the exchanger structure was determined through an optimization process, elucidated in the same article. Another intriguing configuration was proposed by different researchers (Teng & Xuan, 2019). In this configuration, an intermediate fluid (air) under pressure directly receives the radiation and impacts a receiving cavity equipped with a quartz window and a porous structure. The thermal energy of this working fluid is then transferred to the circulating S-CO_2 via ducts embedded in the porous matrix itself. Lastly, recent endeavours by the

National Renewable Energy Laboratory (NREL) unveiled two concepts for central S-CO_2 receivers (Shaun et al., 2016). The first concept entails a cavity receiver for a 2 MW power cycle, while the second concept entails a cylindrical external receiver for a 10 MW cycle. Both designs incorporate a compact structure consisting of two plates connected by a corrugated fin structure, which serves as the absorbing surface for concentrated solar radiation. The key distinction lies in the arrangement of the absorbent plates, forming a cavity in the first case, and an external cylindrical receiver in the second. In the latter case, a radiation trap has been devised, comprising small perpendicular quartz cylinders that mitigate radiation and convection losses. Consequently, the thermal efficiency of the receiver remains high (80%) when operating at temperatures around 750°C. Both designs successfully achieve the target of 0.06 USD/kWh established by the SunShot Initiative. Narasimhan et al. recently achieved a synergistic integration of the S-CO_2 cycle and adsorption desalination cycle to tackle the challenges posed by energy-intensive desalination technologies and high ambient conditions (Narasimhan et al., 2022). Adsorption desalination enhanced the energy efficiency of the Brayton cycle and the overall system efficiency by more than 6.2% and 8.8% respectively, whereas other energy-intensive desalination technologies act as a parasitic load and penalize the power cycle's efficiency.

Table 1: Summary of the main fields of application and notable studies of thermodynamic modelling of S-CO_2 cycles

Applications	References	Operating conditions					Advantages	Disadvantages
		Cycles	**T_{max} [°C]**	**P_{max} [bar]**	**Power [MW]**	**E [%]**		
Fossils fuel	(Mecheri & Le Moullec, 2016)	RH	620	300	1150	50.3	(i) an increased utilization factor due to greater operational flexibility than steam plants; (ii) parasitic losses due to CCS compensated by high cycle efficiency; (iii) direct cooling reduces water consumption.	(i) competition with ultra-supercritical steam power plants with CCS;(ii) technological gap for the primary heater (S-CO_2 boiler) and the axial turbomachines.
(coal fired)		RH+CCS	620	300	1000	41.49		
	(Park et al., 2018)	RH	620	200	635	43.49		
(oxy -fuel)	(Turchi et al., 2018)	AL	1150	300	846	55.1	(i)integrated carbon sequestration; (ii) higher efficiency than indirect heating cycles; (iii) optimal operation at higher cycle pressure ratios than conventional S-CO_2 cycles; (iv) operational flexibility;(v) small footprint;(vi) very attractive electricity cost	(i) CO_2 impurities;(ii) corrosion and erosion of materials; (iii) cooling the turbine blade film;(iv) alternative control strategies; (v) competition with other electricity production concepts byoxy-fuel
(oxy -coal)	(Weiland & White, 2018)	AL	1204	308	606	40.6		
Waste heat	(Wright et al., 2020)	PH	389	238	8.6	25.99	(i)suitable for concentrated (>350 ∘ C) high quality (>1 MW) waste heat sources ;(ii) high efficiency;(iii) operational flexibility; (iv) smallfootprint	(i) competition with conventional steam systems and organic Rankine cycles; (ii) need primary heating technologies characterized by low pressure drop, resistance to corrosion and fouling, modularity, etc.
(Gasturbines)	(Bai et al., 2019)	RCRH	572	154	146	47.73		
(IC engines)	(J. Song et al., 2020)	SR+ORC	320	200	0.2			
(Industrial)	(Marchionni et al., 2018)	SR	425	200	0.9	25.1		
	(Kizilkan, 2020)	SR	389	256	9.5	27.9		

CSP	(Cheang et al., 2015)	RC	580	275	82	38.4	(i) suitable for next-generation CSP systems (> 600 ∘ C); (ii) greater efficiency should reduce the size and cost of the collector array; (iii) a simpler and more compact power supply;(iv) heat exchange temperature profiles allow compact thermal energy storage	(i) CSP LCOE is not yet competitive with solar photovoltaic; (ii) requires appropriate heat carriers to operate at elevated temperatures; (iii) the CSP plants are located in regions with high ambient temperatures; (iv) demonstration required at appropriate scale
		RCPC	580	275	71	33.2		
	(Schmitt et al., 2017)	RC	705	273	100	48.8		
	(Crespi et al., 2018)	RCPC	900	300	50	55		
	(Neises & Turchi, 2019)	RCPC	630	250	115	46.2		
	(Manzolini et al., 2019)	RET	550	250	35	43		
			700	250	35	50		
	(Alsagri et al., 2019)	CR	550	250	50	46		
	(Le Moullec et al., 2019)	RCICPH	468	250	10	35		
Nuclear	(M.-J. Li et al., 2018)	RCRH	465	250	10	43.7	(i) good temperature match with future generation **sodium-cooled fast** reactors and lead-cooled reactors ;(ii) good candidate for small modular reactors	(i) the technology must first be demonstrated in other applications;(ii) need to understand interactions between S-CO_2 and reactor materials (e.g. sodium, lead
	(Wu et al., 2018)	RC+ORC	550	210	250	42.5		
	(M.-J. Li et al., 2019)	RC	550	250	10	36.7-44.5		
Geothermal	(Glos et al., 2019)	S	600	119	51	5	Reduced pumping work compared to indirect brine systems and better performance at low reservoir depth and low permeability	(i) more sensitive to ambient cooling conditions; (ii) operation close to critical point means turbine design differs from other S-CO_2 systems
			86.6	160	157	5		
	(Cao, Li, et al., 2022)	S-CO_2-ORC	550	200	186.26	28.53		

T_{max}: Maximum temperature; P_{max}: Maximum power; E: Efficiency; Ref: Reference; CCS: Carbon Capture System; ORC: Organic Ranckine Cycle, PH: preheating, RC: Recompression; RCICPH: Recompression with Intermediate intercooling and Preheating; RCPC: recompression partially-cooled, RCRCH: recompression reheating; RET: recuperated transcritical; RH: Reheated; S: Simple SR: Simple recuperated, IC: internal combustion, LCOE: levelized cost of electricity, CSP: Concentrator solar power

6. Conclusion and Outlook

S-CO_2 electricity production systems boast exceptional thermal efficiency in comparison to conventional steam Rankine cycles within the temperature range of 350°C to 800°C. S-CO_2 systems unlock the potential for employing diminutive turbomachines and relatively compact heat exchangers, thereby great operational flexibility and the prospect of a notably lower energy expenditure. These unparalleled advantages position these systems as promising contenders for forthcoming energy applications, wherein their implementation could effectively slash energy costs vis-à-vis existing technologies. The realm of S-CO_2 thermodynamic systems has precipitated a profusion of component development campaigns and experimental test facilities, all aimed at attesting technical feasibility and probing operational conundrums. Nevertheless, there remain significant obstacles that demand surmounting, wherein one such hurdle involves the triumphant demonstration of this technology on an industrial scale. It is noteworthy that scant research has been conducted on S-CO_2 cycles in Africa, with CO_2 still confined to the realm of fire extinguishers in West Africa. Consequently, future research and development endeavours pertaining to S-CO_2 systems ought to be fixated upon the evaluation of commercial viability, turbomachinery, heat exchangers, materials, and S-CO_2 cycle audits.

- **Turbomachinery**

The turbomachinery of S-CO_2 systems has yet to triumph, as they must be exuberantly showcased to reach a level of fruition fit for commercialization. Nevertheless, numerous ongoing projects are endeavouring to exhibit industrial-scale (i.e. $\geq$ 10 MW) turbomachinery, even though they remain in an incomplete operational state. In the realm of large-scale industrial applications, the requisite turbomachines may deviate from those tested in current experimental setups. Thus, uncertainty looms over the extent of experimental groundwork that can be seamlessly upscaled to full-scale plants. On the other hand, in the realm of small-scale (i.e., <1 MW) applications, the design of turbomachinery presents a formidable challenge due to high rotational speeds, soaring pressures, and the intricate balancing act between aerodynamic, rotor dynamics, and mechanical prowess. While radial turbomachines, typically fashioned as a single-shaft turbine-generator-compressor ensemble, reign supreme, axial turbines and the employment of separate shafts have been posited. Moreover, existing small-scale systems have encountered substantial hurdles pertaining to bearing and wind losses, which demand surmounting.

- **Heat Exchangers**

Every application imposes unique constraints on the configuration of heat exchangers. Thermo-hydraulic challenges confront the demand for intense heat flux, scorching temperatures, and high pressures between the heat source and the S-CO_2 system. More extensive research is imperative to foster the design of these exchangers or devise a manufacturing process that engenders cost-effective, high-performing exchangers capable of enduring scorching conditions, premature ageing, and environmental strains. The recuperator grapples with the challenge of withstanding high-temperature pressure differentials. In the case of air-coupled coolers, downsizing the heat exchanger can be accomplished by diminishing tube diameter and spacing. Obstacles encompass enhancing heat transfer efficiency on the air-cooling side and optimizing the tubing system to alleviate pinch-point predicaments while minimizing pressure drop. As for water-coupled chillers, pivotal considerations encompass enhancing heat transfer efficiency, reducing pressure drop on the S-CO_2 side, and mitigating the risk of leakage between the two fluids during operation.

- **The Materials**

Choosing materials for various applications requires possessing qualities such as immense strength, environmental harmonization even under the most extreme temperatures and pressures, and resilience against scorching heat sources. It requires an extensive knowledge base regarding the tenacity and durability of materials under practical, high-velocity operational circumstances, all the while taking into account the impurities present in the working fluid to compile comprehensive material databases.

Additionally, one must acquire information pertaining to material expenses and availability, as well as address construction complexities, particularly in relation to metal welding and diffusion bonding for S-CO_2 applications. Developing materials and coatings that are well-suited for S-CO_2 systems demands a dedicated research focus on optimization methodologies that establish a correlation between cost, performance, and material choice.

- **Control Systems**

S-CO_2 control systems unleash the complete potential of load flexibility within the power generation system, enabling the exploration of pivotal operational aspects like safety. Innovative research into S-CO_2 controls has fixated on a select few cycle configurations predominantly governed by proportional-integral controllers, treating the power supply as an isolated entity rather than a vital cog in a larger, interwoven energy system. The exploration and advancement of comprehensive control architectures founded on multivariable control methodologies that seamlessly mix the power supply with the heat source and heat sink can unlock prospects for enhanced system integration and synergistic operation, revolutionizing global energy dynamics.

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