Journal of Power Technologies 101 (4) (2021) 173 --189

Prospects for the use of supercritical CO2 cycles

Jaroslaw Milewski[1*]✉, Piotr Lis[1], Arkadiusz Szczęśniak[1], Łukasz Szabłowski[1], Olaf Dybinski[1], Kamil Futyma[1]

[1]Warsaw University of technology, Faculty of Power and Aeronautical Engineering, Institute of Heat Engineering, 21/25 Nowowiejska street, 00-665 Warsaw, Poland
✉ jaroslaw.milewski@pw.edu.pl

Abstract

The paper contains a comprehensive summary of potential sCO2 cycle applications being considered for power generation. The authors give examples of different sCO2 based cycles used in combination with conventional energy sources like fossil fuels or nuclear as well as renewable energy sources like solar. The article presents sCO2 recompression cycle simulation model results and – using this example, cycle flexibility and parameters – discusses potential application of the cycle.

Introduction

European Union countries are addressing climate change concerns through introducing regulations in the 2030 and 2050 time perspectives. One goal in the 2030 horizon is to boost energy efficiency to 27%. These regulations will lend added impetus to the development of low-carbon economy in individual countries [1]. This positively impacts the development of new technologies like fuel cells [2] which can generate power with ultra high efficiency (60%+ [3]) and the search for improvements in classical heat cycle based solutions [4]. Other issues which need to be addressed regard energy storage, especially coupled with unpredictable renewable energy sources [5].

In the 1960s, Feher [7] studied the properties of various gases with a view to finding the optimal choice for a supercritical thermodynamic cycle. Carbon dioxide was proposed as a working fluid due to several reasons. First, its physical properties e.g., critical pressure, which is significantly lower than water, enables lower operating pressures. Secondly, the thermodynamic and transport properties of CO2 are well known, hence cycle analysis is based on reasonably firm data. Finally, carbon dioxide is abundant, non-toxic and relatively low cost. The analysis proved that the CO2 supercritical cycle offers several desirable features such as high thermal efficiency (the investigated cycle reached thermal efficiency of 55% under ideal conditions), low volume-to-power ratio and no blade corrosion and cavitation. The paper suggests using it as electric power generation (both terrestrial and space) or as shaft power for marine propulsion.

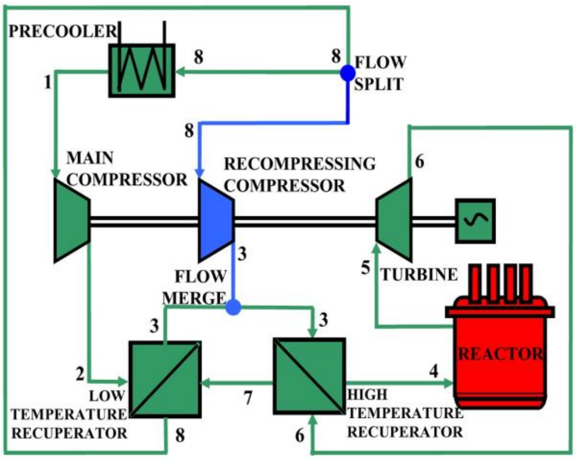


Figure 1: Recompression Brayton cycle layout [6]

Research on the supercritical CO2 power cycles was resumed after four decades by Dostal. In 2004 [6] he performed a systematic, detailed major component and system design evaluation and multi-parameter optimization of the family of supercritical CO2 Brayton power cycles for application to advanced nuclear reactors. His analysis showed that the recompression cycle shown in Figure 1 was the best performing cycle layout due to its simplicity, compactness, cost, and thermal efficiency. Three direct cycle designs of this layout were selected for further investigation. They achieved thermal efficiencies of 45.3%, 50% and 53%, assuming turbine inlet temperatures of 550°C, 650°C and 700°C respectively. According to the analysis the turbomachinery is highly compact—the 600 MWth/246 MWe power plant is fitted with a turbine of 1.2 m in diameter and 0.55 m long, which translates into power density of 395 MWe/m3.

These two papers have spawned several further studies of the CO2 supercritical cycle in the field of parameters and layout optimization, possible applications, and modeling of critical cycle components. Chen [8] evaluated transcritical CO2 as a working fluid in low-grade waste heat recovery cycles by comparing it to R123 Organic Rankine Cycle (ORC). Figure 2 shows the basic ORC system layout and the ORC schematic cycle in a T–S chart. The results of the comparison showed that when utilizing the low-grade heat source with equal thermodynamic mean rejection temperature the CO2 transcritical cycle has slightly higher power output than ORC and is more compact too. On the other hand, further research provided by Vidhi et al. in 2011 [11] showed that although CO2 has the advantages of being available in abundance, environmentally safe and economically favorable, its performance in a transcritical power cycle is not as efficient as R32 based organic Rankine cycle over the range of source temperatures from 140°C to 200°C. A comparative analysis of a recompression CO2 Brayton cycle combined with ORC and a single recompression cycle was also performed. It showed that the exergy efficiency of a combined cycle could be higher than that of a single recompression cycle by up to 11.7% and total product unit cost lower by up to 5.7% [12].

Parametric optimization performed by Wang et al. [13] using a genetic algorithm and artificial neural network showed that key thermodynamic parameters, such as turbine inlet pressure, turbine inlet temperature and environment temperature, have a significant effect on the performance of a supercritical CO2 power cycle and exergy destruction in each component. Kulhanek and Dostal [14] found that among the various cycle layouts shown in Figure 3, a recompression Brayton cycle achieves the highest efficiency in the range of turbine inlet temperatures between 500 and 600°C, whereas a partial cooling cycle is better at higher temperatures. On the other hand, Bryant [15] proved that, indeed, the recompression cycle will always be more efficient than a simple cycle provided that the two cycles have the same precooler inlet temperature, but in order to satisfy this condition the recompression cycle will always require more total recuperator area. The paper demonstrated that when two cycles are compared based on equal total recuperator area, the efficiency advantage of the recompression cycle falls substantially or even disappears altogether.

Kim and Favrat in 2012 [16] presented a novel transcritical Rankine cycle using both low and high temperature heat sources to maximize the power output of the CO2 power cycle with a given high temperature source for use in applications such as nuclear power, concentrating solar power and combustion. The analysis showed the large internal irreversibility in the recuperator related to the higher specific heat on the high-pressure side than on the low-pressure side. Additional low temperature heat provided to the recuperator in the proposed cycle mitigates specific heat difference and delivers higher recuperator CO2 outlet temperatures. This feature in conjunction with reduced compression work and exergy losses makes this low-high temperature Rankine cycle even more effective than the recompression Brayton cycle.

An application of a supercritical CO2 cycle in a cogeneration power plant was considered by Moroz in 2014 [17]. Performance of several stand-alone supercritical CO2 cycles and combined steam/supercritical CO2 cycles was compared with typical steam cogeneration cycles. The cascaded supercritical CO2 recompression Brayton cycle achieved the best electrical efficiency: 39.44% at turbine inlet temperature of 540°C, which beat the ordinary steam CHP unit.

In 2009 Moisseytsev [19] examined alternative supercritical CO2 Brayton cycle layouts, which were presumed to perform better than the recompression Brayton cycle when coupled with Sodium Fast Reactors. This assumption was since SFRs operate at lower temperatures (core outlet temperature of 510°C) than temperature for which a satisfactory recompression cycle performance had been proved. Even though a double recompression cycle, intercooling between compressor stages and reheating between high- and low-pressure turbine were analyzed, the recompression cycle demonstrated the highest efficiency. Later, Perez-Pichel [18] conducted similar analysis in which he compared a wide range of configurations, from the simplest one to combined cycles (with organic Rankine cycles, ORC). As a result, he discovered that the most basic layouts (such as recompression cycle, and basic combine ORC cycle) could reach thermal efficiencies as high as

43.3%, which is comparable to efficiencies obtained through supercritical steam Rankine cycles. The simplest combined cycle, which achieved the highest efficiency, is presented in Figure 4.

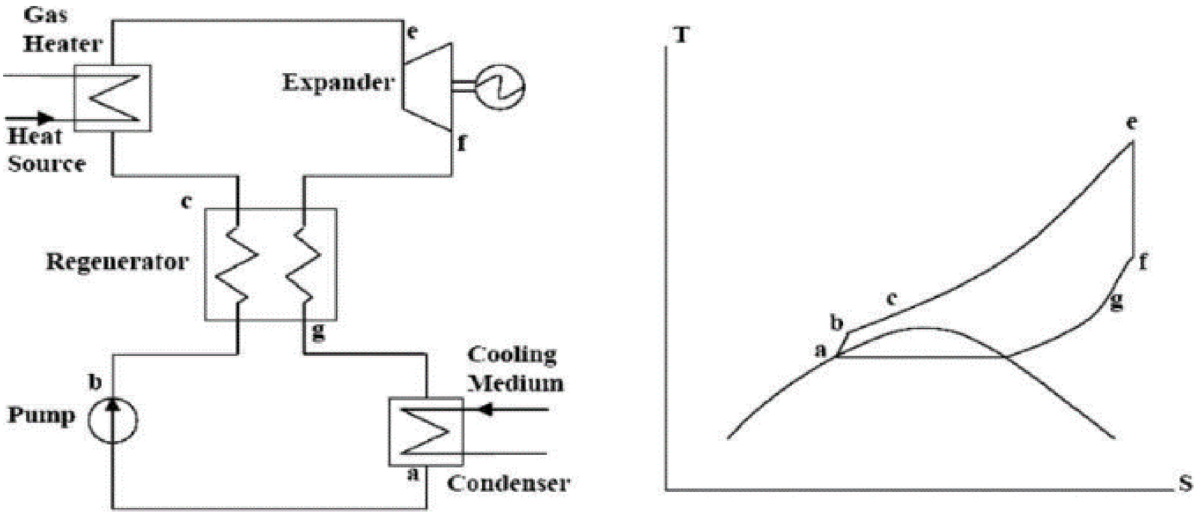


Figure 2: CO2 transcritical system layout and cycle T-S chart [8]

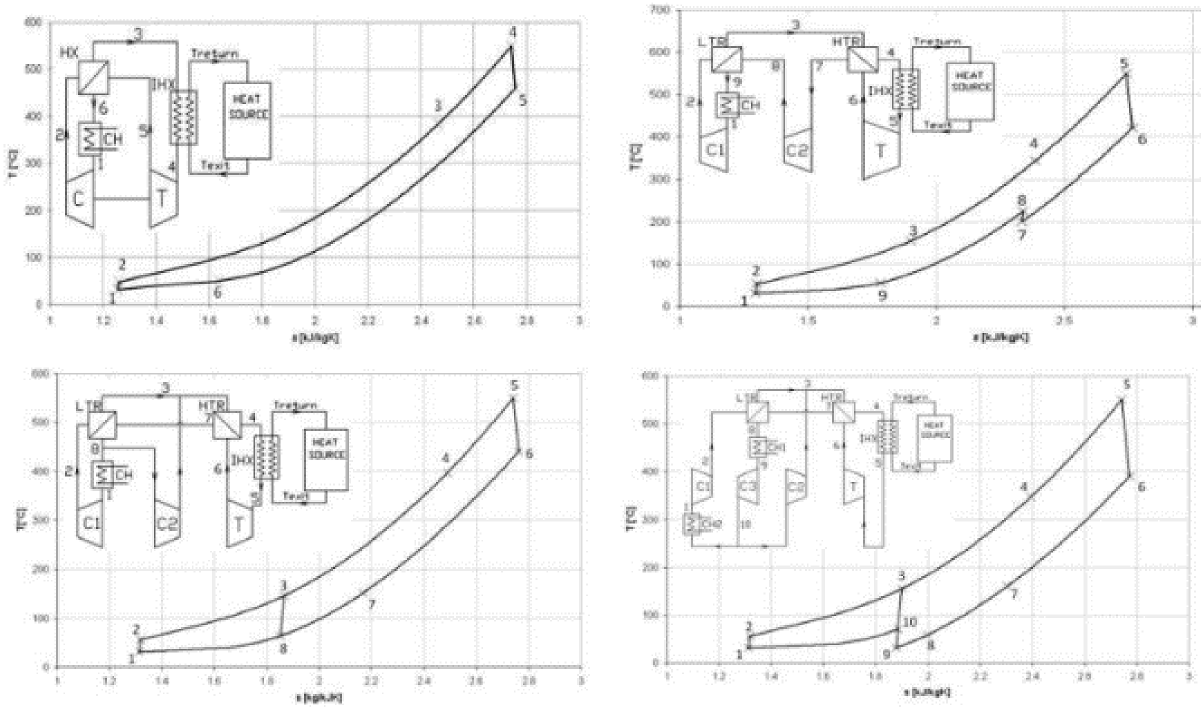


Figure 3: Simple Brayton, Precompression, Recompression and Partial Cooling cycle [9]

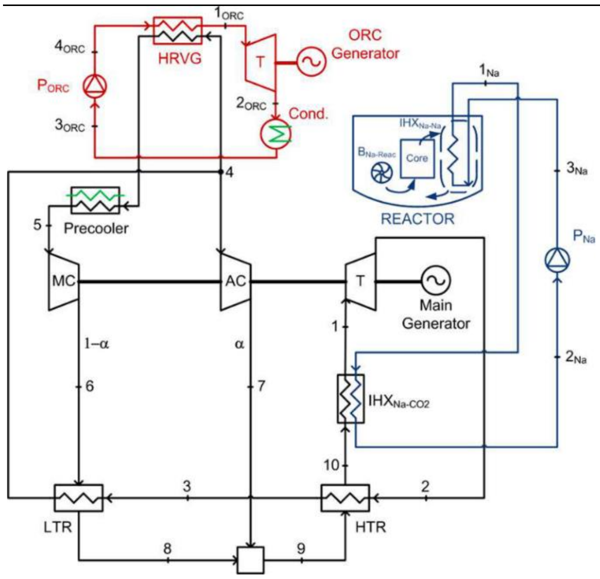


Figure 4: Recompression Brayton Simple sCO2 - ORC cycle [18]

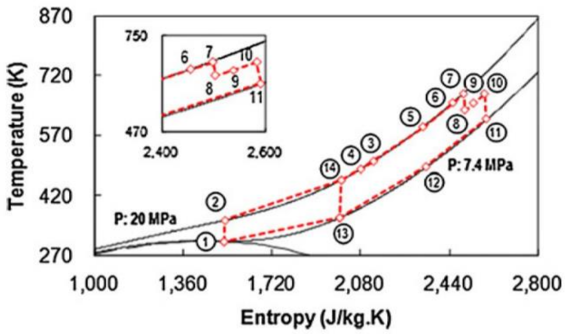


Figure 5: T-s diagram of the recompression cycle with reheating [20]

Harvego and McKellar [21] performed a comparative study of direct and indirect recompression Brayton cycles coupled to a nuclear reactor. Both layouts were examined in the same conditions i.e., operating Brayton cycle pressure of 20 MPa and reactor outlet temperature between 550°C and 850°C. The results of the analysis showed that, for the direct supercritical CO2 power plant cycle, thermal efficiencies in the range of 40 to 50% could be achieved over the assumed reactor coolant outlet temperature. For the indirect supercritical power plant cycle, thermal efficiencies were approximately 11-13% lower than those obtained for the direct cycle over the same core outlet temperature range. In 2012 Halimi [20] conducted a computational analysis of the supercritical CO2 Brayton cycle power conversion system for fusion reactor application. The analysis results showed that a thermal efficiency of 42.44% was achievable by a recompression cycle. Additional 0.69% benefits can be obtained by adopting the reheating concept shown in Figure 5. Yoon et al. [22] suggested coupling a supercritical CO2 cycle with small and medium water cooled nuclear reactors (SMR). According to the cycle evaluation, the maximum cycle efficiency at temperature of 310oC and compressor outlet pressure of 22 MPa is 30.05%, which is comparable to the efficiency of current steam Rankine cycles. Moreover, the total volume of turbomachinery which can handle 330 MWth of SMR is less than 1.4 m3 without casing.

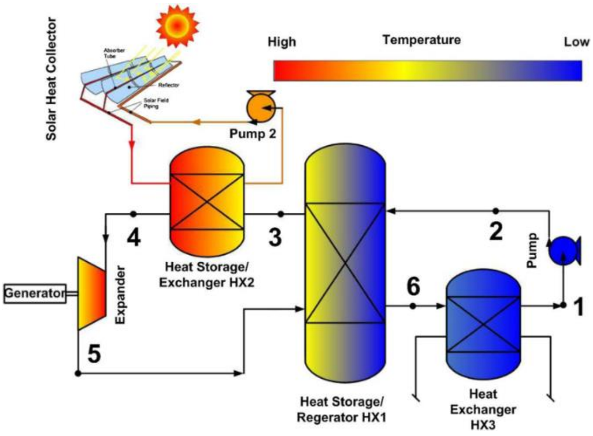


Figure 6: Schematic diagram of the solar energy storage and power generation system based on CO2 [23]

Besides the studies of the supercritical CO2 cycle as a nuclear application, several analyses of these novel cycles coupled with Concentration Solar Power have been performed. Zhang and Yamaguchi conducted three successive semi-experimental studies using a real Rankine cycle with a relief valve as a counterpart of a turbine. They accomplished maximum CO2 temperature of 165°C at the collector outlet [24], which enabled the system to achieve theoretical electric output efficiencies of 11.4% [24] and 11.6% [25] in the next study. These efficiencies were slightly higher than those obtained by a solar cell used in the experiment for the purpose of comparison.

Figure 6 shows a new type of solar energy-based power generation using supercritical CO2 and heat storage. Calculations showed that the supercritical CO2 Rankine cycle not only achieves higher energy conversion efficiency than conventional water-based systems, but also overcomes the intermittent nature of solar energy. The paper also proved that expander efficiency and heat storage/regenerator performance have significant effects on the system's overall performance, while the pump is relatively unimportant [23].

Another solution for utilization of solar energy for CO2 supercritical Brayton cycles are solar tower power plants [26,27], which can be a good heating source for sCO2 cycles. In this setup, a tower with a heat exchanger on top is exposed to the sun, located in the middle of afield surrounded by mirrors following the sun path to supply the heat exchanger with solar energy. As different kinds of cycles can be combined with a solar tower it is possible to reach high efficiency of the system F. Al-Sulaiman and M. Atif [28] presented analysis for several different STPP and Brayton cycle configurations. The cycle with recompression reached the highest thermal efficiency both with highest net power output, reaching 52% of thermal efficiency and 40% of total integrated system efficiency (analyzed for noon summertime). There are already many examples in which STPP and sCO2 cycles are integrated into commercial plants, for example for multi-effect distillation and cogeneration [29] or simply for the emission-free power generation sector [30].

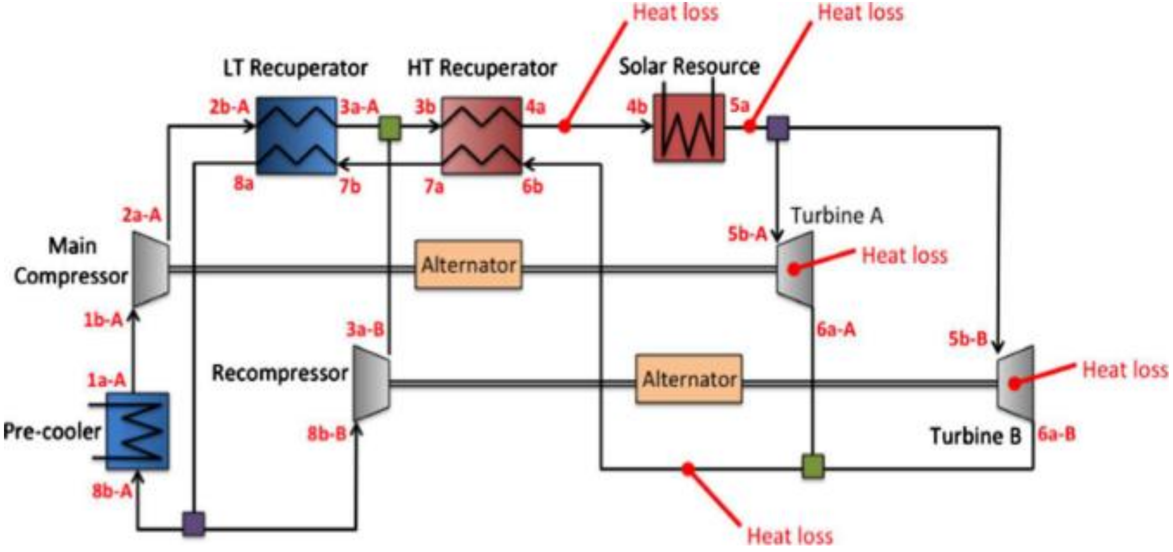
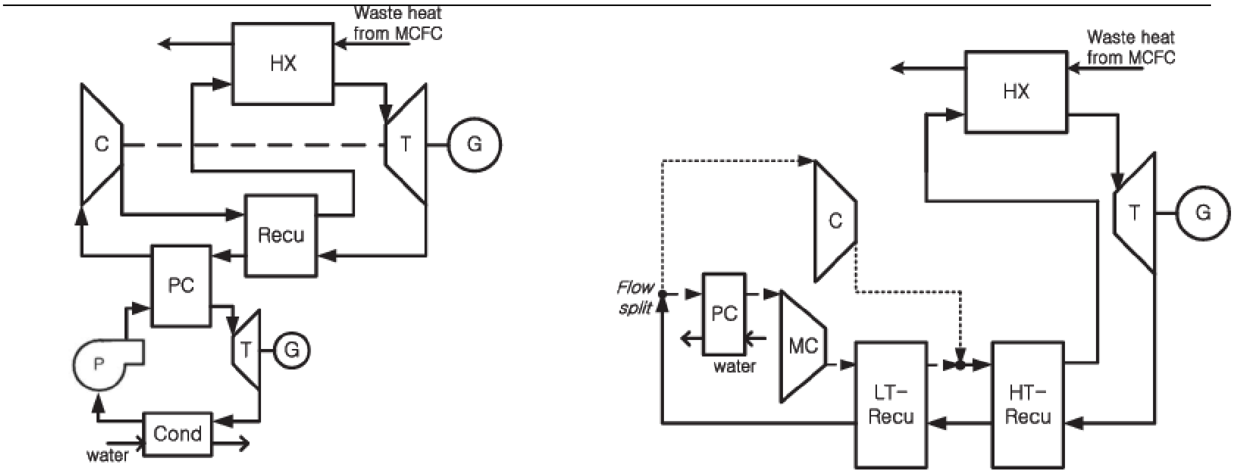


Figure 7: Layout of split-flow recompression Brayton cycle components [31]

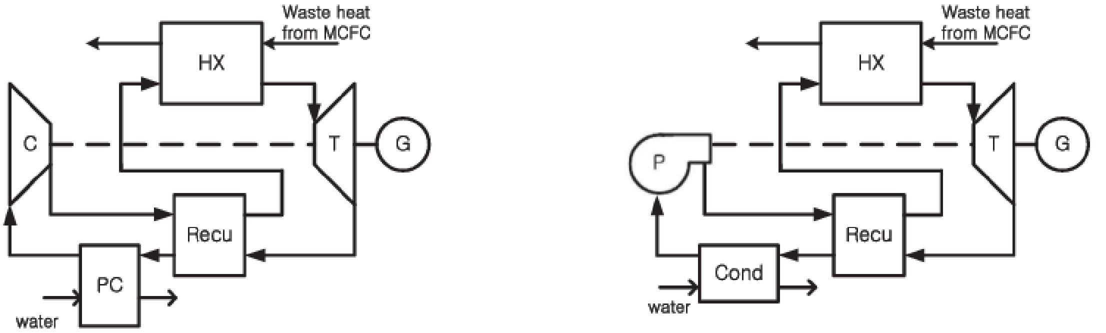
Iverson and Cowboy in [31] supported the statement above, emphasizing good cycle efficiency especially over 600oC. They used an experimental loop installed in Sandia National Laboratories, which was the split flow supercritical CO2 Brayton cycle shown in Figure 7 . The experiment showed good cycle behavior as a response to intermittent heat supply. Measurements of the system indicated overall efficiency of approximately 5% for the operating conditions used in the experiment. However, the authors expected this efficiency to increase to 15% at design conditions and to approximately 24% with minor modifications to improve insulation.

In 2015 Padilla et al. [32] analyzed the effect of turbine inlet temperatures and cycle configuration on the thermal performance and exergy destruction of a supercritical CO2 cycle with a CSP central receiver application. They found that the thermal efficiency of the supercritical Brayton cycle increases in line with the temperature of the cycle. The recompression cycle with the main compressor intercooling achieved the best thermal performance (55.2% at 850oC). However, Cheang et al. [33] in their study of the same year argued that although the supercritical CO2 cycle looks attractive, it is still both less efficient and less cost competitive than a superheated steam Rankine cycle.



A. S−CO₂ Brayton and Rankine Cascading (BRC) cycle

B. S−CO₂ Re−Compressing Brayton (RCB) cycle



C. S−CO₂ Simple Recuperated Brayton (SRB) cycle

D. S−CO₂ Simple Recuperated Transcritical (SRT) cycle

Figure 8: Various sCO2 cycle layouts studied evaluated as a bottoming cycle for the MCFC hybrid system [34]

The next area in which a research has been made is a supercritical CO2 cycle application as a bottoming cycle within fuel cells systems [35,36]. Sanchez et al. in 2009 [37] expected CO2 cycle to perform better for intermediate temperature heat recovery applications than an air cycle. Their paper showed that, even though the new cycle is coupled with an atmospheric fuel cell [38], it is still able to achieve the same overall system efficiency and rated power as the best conventional cycles currently being considered. Furthermore, under certain operating conditions, the performance of the new hybrid systems beats that of existing pressurized fuel cell hybrid systems with conventional gas turbines. Calculations made by Munoz de Escalona [39] proved that an indirect supercritical CO2 Brayton cycle coupled to a Molten Carbonate Fuel Cell (MCFC) [40] can achieve thermal efficiency of almost 40%, which enables the whole system to approach overall efficiency of 60%. In addition, the supercritical CO2 cycle performs better at part load than existing hybrid systems.

Bae et al. compared various cycle layouts presented in Figure 8 in terms of application as a MCFC bottoming cycle. The results showed that all of the analyzed sCO2 Brayton cycle layouts perform better than the air Brayton cycle, in particular recompression Brayton, and cascading Brayton and Rankine cycles can increase net hybrid system efficiency by more than 10% over the single MCFC system. [34]

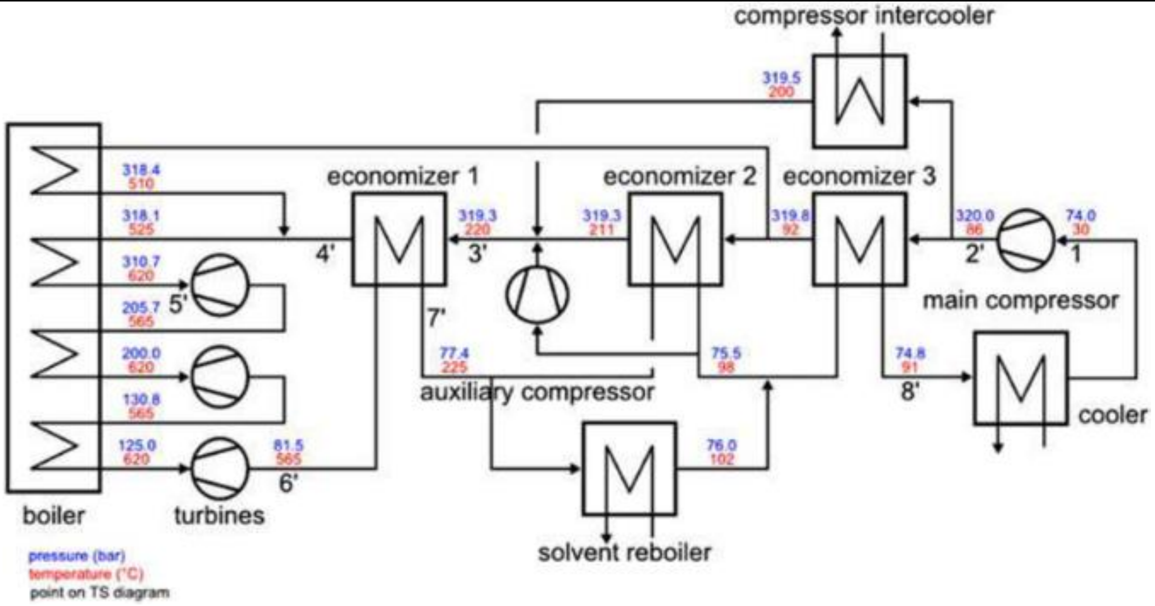


Figure 9: Supercritical Brayton CO2 power cycle adapted for a coal-fired boiler with carbon capture [41]

Another part of the research concerns the use of supercritical CO2 in coal applications. Moullec [41] adopted a supercritical CO2 Brayton cycle to the coal-fired boiler thermal output as shown in Figure 9. An energy evaluation of the overall power plant indicated net power plant efficiency of 41.3% with carbon capture, and CO2 compression to 110 bar. Moreover, a technical-economic analysis of the designed power plant showed a levelized cost of electricity (LCOE) reduction of 15% compared to a reference supercritical coal-fired power plant equipped with standard carbon capture process. Further study showed that the oxy-combustion cycle seems the best fitted for the supercritical CO2 Brayton cycle due to the simpler thermal integration and the CO2 purification devices already integrated in the CO2 processing unit. However, the main technological challenges were also identified, namely, the very large exchanger needed in the cycle in order to achieve high power cycle efficiency, and the development of a supercritical CO2 turbine, which is significantly different to a steam or gas turbine especially due to the very large effort on the wheel and the small size of the equipment [41].

Although some supercritical CO2 cycles, such as recompression cycle, exhibit high efficiency they utilize a high degree of recuperation leading to a narrow change across the thermal input device. This narrow window may be acceptable for waste heat and nuclear applications, but it is not suitable for a traditional coal or natural gas fired system. McClung [42] proposed two cycles: Cryogenic Pressurized Oxy-Combustion (CPOC) and Advanced Supercritical Oxy-Combustion (ASOC). Calculations showed that, for both direct cycles, turbine inlet temperature of 1,220oC helps deliver power unit thermal efficiencies approaching 64% and overall power plant efficiency exceeding 52%. However, the CPOC cycle seems to be more attractive due to the wider thermal input window, which leads to simpler combustor designs and more efficient use of fossil based thermal input.

The results of the most significant studies referenced above are plotted in a coordinate system presented in Figure 10, where x- and y-axis correspond to turbine inlet temperature and cycle efficiency respectively. A positive correlation between these two parameters can be seen in the chart. More detailed information about the studies is presented in Table 2 .

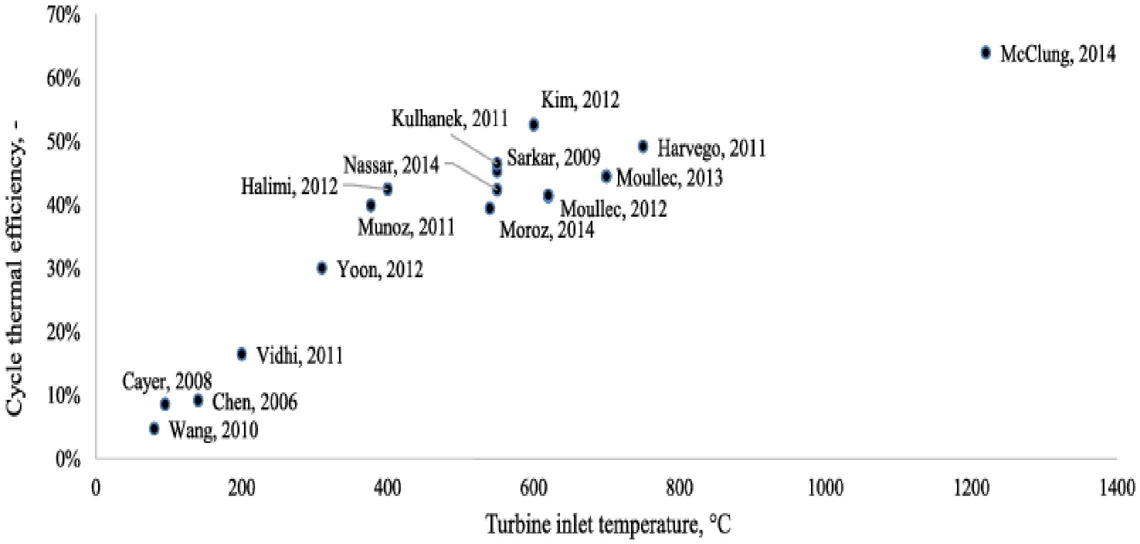


Figure 10: General correlation between cycle efficiency and turbine inlet temperature throughout different studies

Recompression Brayton super CO2 cycle—discusion

Based on available measurement data [43] an off design supercritical Brayton cycle simulation model was prepared. The model represents the recompression Brayton cycle as shown on Figure 11. The system consists of two turbine-compressor-generator units. The first unit powers the main compressor, the second unit powers the recompressor. Total system power output is the sum of power outputs from each unit.

The goal of the simulation was to study the power flexibility of the supercritical CO2 system. The nominal operating point stated in Table 1 was used as a reference for further studies. Simulation was prepared based on previous study, all modeling relevant data can be found in previous works.

Table 1: Off design reference operating point

Variable Name	Unit	Value
Turbine Inlet Temperature	K	750
Rotational Speed	RPM	70 000
Main Compressor Bypass	Pr open	0
Output Power	kW	185.1

The design of experiment (DOE) study was performed using the following assumptions:

- Constant rotational speed - grid mode
- System power control by Main Compressor Bypass Valve and Turbine Inlet Temperature (TIT)

Table 2: Brief review of supercritical CO2 cycles performance

Year	Author	Efficiency, %	TIT, $^\circ$C	Max P, MPa	Application
2006	Chen	9.2	140	16	waste heat
2007	Zhang	16.5	180	-	solar
2008	Cayer	8.6	95	13.6	waste heat
2009	Sarkar	45.27	550	20	general
2010	Wang	4.75	80	10.75	waste heat
2011	Munoz	40	377	21.6	MCFC
2011	Vidhi	16.5	200	-	waste heat
2011	Kulhanek	46.48	550	-	general
2011	Harvego	49.2	750	20	nuclear
2012	Yoon	30.05	310	22	nuclear
2012	Kim	52.6	600	-	general
2012	Moullec	41.3	620	30	coal with CCS
2012	Moullec	44.5	700	-	coal with CCS
2012	Halimi	42.44	400	20	nuclear
2013	Moullec	41.5	620	-	coal with CCS
2013	Moullec	44.5	700	-	coal with CCS
2014	Moroz	39.44	540	21	CHP
2014	McClung	64	1220	29	coal with CCS
2014	Bae	45	-	-	MCFC
2014	Bae	46	-	-	MCFC
2014	Nassar	42.35	550	-	general

The main compressor bypass valve forms part of the system power control strategy. TIT directly impacts output power and can be changed by changing heat source parameters. The design of experiment study was performed for those two parameters according to Table 3.

Based on simulation results a supercritical system performance map was generated using the reduced mass flow, pressure ratio and output power range given in Table 4.

Table 3: Off design DOE study parameters range

Variable Name	Unit	Lower Limit	Upper Limit
Turbine Inlet Temperature	K	500	1200
Compressor Bypass Valve	Pr open	0	100

The map on Figure 12 represents supercritical CO2 Brayton recompression cycle performance. The X axis corresponds to reduced mass flow rate, the Y axis represents cycle pressure ratio. The horizontal lines tagged with % values represent different main compressor bypass valve opening: 0% - fully closed, 100% - fully open. The vertical lines tagged with K values represent different TIT. The lines inside the map indicate system power output in kW.

The relative power performance map is presented on Figure 13. The map also shows the reference operating point corresponding to relative power equal to 1. The power output of the system can by controlled by TIT or Main Compressor Bypass Valve position. The study shows the power can be easily reduced by changing the valve position. At the same time the change in TIT is proportional to system power output

Table 4: Off design study performance map range

Variable Name	Unit	Lower Limit	Upper Limit
Reduced Mass Flow Rate	-	0.7 x 10^{-5}	1.3 x 10^{-5}
Pressure Ratio	-	1.3	1.7
Output Power	kW	0	300

.

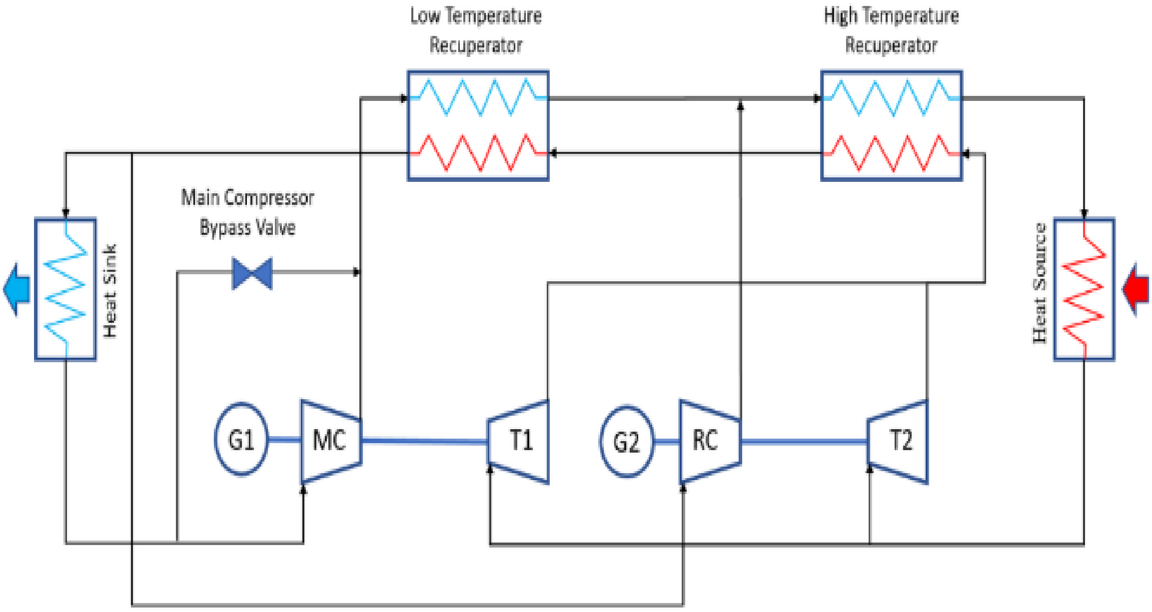


Figure 11: Off design supercritical Brayton cycle

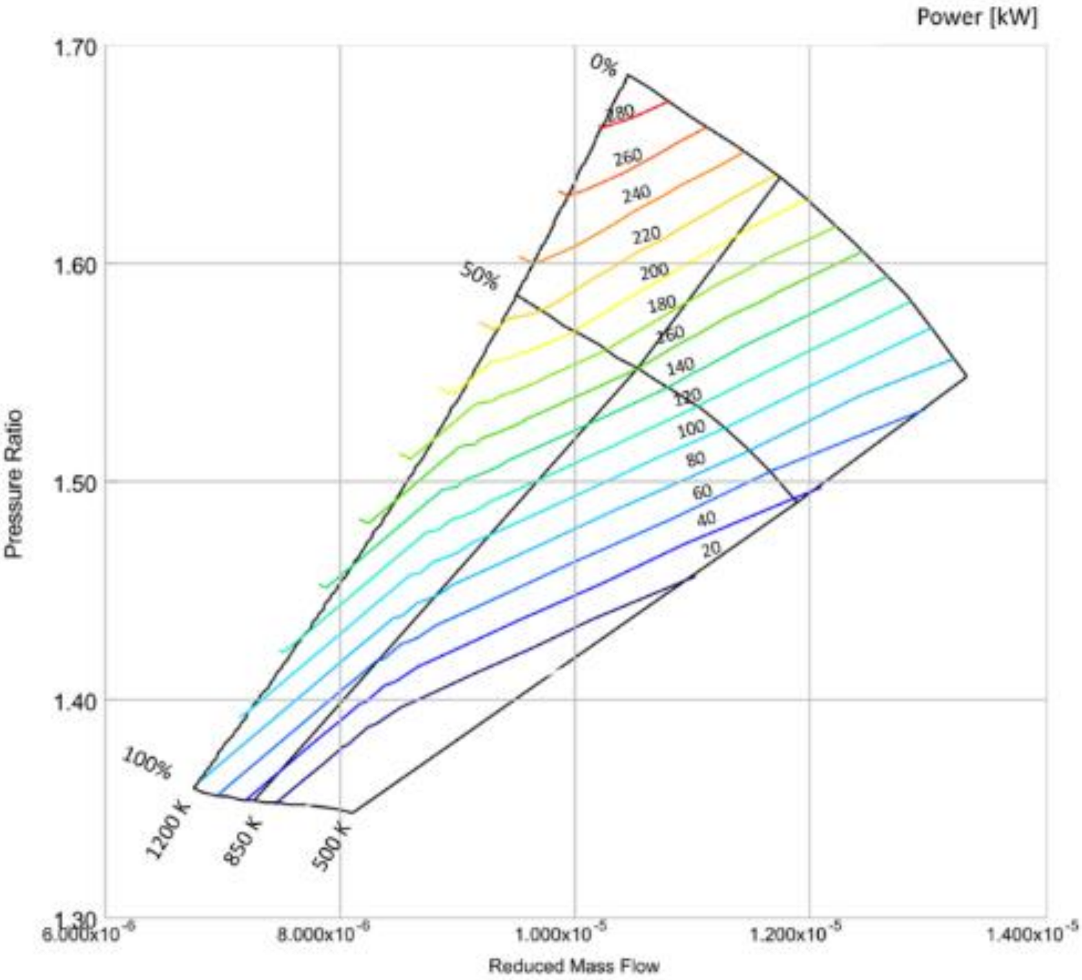


Figure 12: Supercritical system performance map

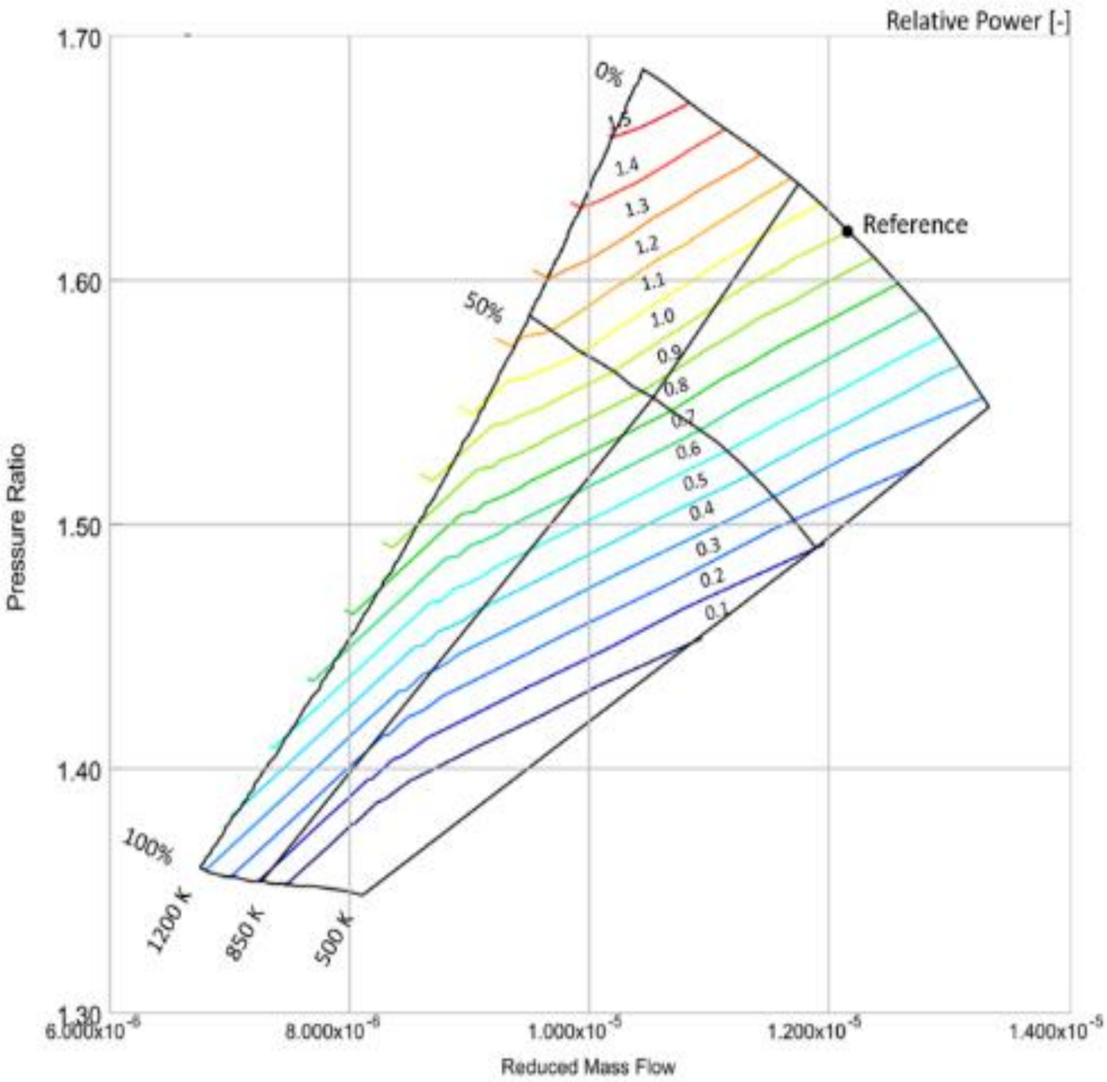


Figure 13: Supercritical system relative power output map

Table 5: Potential applications for sCO2 for power conversion

Application	Cycle type	Motivation	Size, MW	Temperature, °C	Pressure, MPa
Nuclear	Indirect sCO2	Efficiency, size, water reduction	10 .. 300	350 .. 700	20 .. 35
Fossil fuel (PC, CFB)	Indirect sCO2	Efficiency, water reduction	300 .. 600	550 .. 900	15 .. 35
Concentrating solar power	Indirect sCO2	Efficiency, size, water reduction	10 .. 100	500 .. 1000	35
Shipboard propulsion	Indirect sCO2	Efficiency, size	10 .. 10	200 .. 300	15 .. 35
Shipboard house power	Indirect sCO2	Efficiency, size	1 .. 10	230 .. 650	15 .. 35
Waste heat recovery	Indirect sCO2	Efficiency, size, simple cycles	1 .. 10	230 .. 650	15 .. 35
Geothermal	Indirect sCO2	Efficiency	1 .. 50	100 .. 300	15
Fossil fuel (syngas, natural gas)	Direct sCO2	Efficiency, water reduction, CO	300 .. 600	1100 .. 1500	35

Applications

A study performed by Southwest Reaserch Institute [44] states that there are three main parameters considered when selecting application for sCO2 cycle: power output, turbine inlet temperature and cycle pressure. Power output is determined by the size of the system. Turbine inlet temperature in most cases is determined by the available heat source. Cycle pressure is limited by system components mechanical strength and materials properties.

Based on the off design simulation model results and reccomendations from Table 4 the considered off design system appears suitable for the following applications:

- Waste Heat
- Geothermal
- Ship Propulsion & Power Supply

The main factor for selecting these applications was system output power, which does not exceed 0.4 MW. The original application of the considered system was as a laboratory test cell. This explains the limited real life applications. Next generation pilot systems are being designed for much higher power outputs.

Discussion and conclusions

The article discusses potential and existing applications of the supercritical CO2 cycle. Commercial applications and pilot units are still under development. As there is no field operation data available to date, the authors investigate examplary sCO2 cycle power flexibility based on a simulation model of the laboratory supercritical CO2 unit developed by Sandia National Laboratories. The study shows that small scale sCO2 units like this can be used for waste heat, geothermal or ship propulsion applications.

Acknowledgments

The work was financed by the National Science Center, Poland, 2015/19/D/ST8/02780.

References

[1] Nikonowicz Ł, Milewski J. Determination of electronic conductance of solid oxide fuel cells. J Power Technol 2011;91:82–92.

[2] Dzierzgowski K, Wachowski S, Gojtowska W, Lewandowska I, Jasinski P, Gazda M, et al. Praseodymium substituted lanthanum orthoniobate: Electrical and structural properties. Ceram Int 2018;44:8210–5. https://doi.org/10.1016/j.ceramint.2018.01.270.

[3] Danilov NA, Lyagaeva JG, Medvedev DA, Demin AK, Tsiakaras P. Transport properties of highly dense proton-conducting BaCe0.8–xZrxDy0.2O3–δ materials in low- and high-temperature ranges. Electrochim Acta 2018;284:551–9. https://doi.org/10.1016/j.electacta.2018.07.179.

[4] Mostowy M, Szablowski L. Comparison of the Brayton-Brayton Cycle with the Brayton-Diesel Cycle. J POWER Technol 2018;98:97–105.

[5] Fragiacomo P, Lorenzo G De, Corigliano O. Performance Analysis of an Intermediate Temperature {SOE} Test Bench Under {CO}$\less$sub$\greater$2$\less$/sub$\greater$-H$\less$sub$\greater$2$\less$/sub$\greater$O Feeding Stream 2018. https://doi.org/10.20944/preprints201807.0452.v1.

[6] Dostal V, Driscoll MJ, Hejzar P. A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors. Adv Nucl Power Technol Progr 2004.

[7] Feher EG. The supercritical thermodynamic power cycle. Energy Convers 1968;8:85–90. https://doi.org/http://dx.doi.org/10.1016/0013-7480(68)90105-8.

[8] Chen Y, Lundqvist P, Johansson A, Platell P. A comparative study of the carbon dioxide transcritical power cycle compared with an organic Rankine cycle with R123 as working fluid in waste heat recovery. Appl

Therm Eng 2006;26:2142–7.

[9] Kulhanek M, Dostal V. Thermodynamic analysis and comparison of supercritical carbon dioxide cycles. Supercrit CO2 Power Cycle Symp 2011.

[10] Driscoll MJ. Supercritical CO2 Plant Cost Assessment 2004.

[11] Vidhi R, Goswami DY, Chen H, Stefanakos E, Kuravi S, Sabau A. Study of supercritical carbon dioxide power cycle for low grade heat conversion 2011.

[12] Akbari AD, Mahmoudi SMS. Thermoeconomic analysis & optimization of the combined supercritical CO2 (carbon dioxide) recompression Brayton/organic Rankine cycle. Energy 2014;78:501–12. https://doi.org/10.1016/J.ENERGY.2014.10.037.

[13] Wang J, Sun Z, Dai Y, Ma S. Parametric optimization design for supercritical {CO2} power cycle using genetic algorithm and artificial neural network. Appl Energy 2010;87:1317–24. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2009.07.017.

[14] Kulhánek M, Dostál V. Thermodynamic Analysis and Comparison of Supercritical Carbon Dioxide Cycles. Supercrit CO2 Power Cycle Symp 2011:1–7.

[15] Bryant JC, Saari H, Zanganeh K. An Analysis and Comparison of the Simple and Recompression Supercritical CO2 Cycles. Supercrit CO2 Power Cycle Symp 2011:1–8.

[16] Kim YM, Kim CG, Favrat D. Transcritical or supercritical {CO2} cycles using both low- and high-temperature heat sources. Energy 2012;43:402–15. https://doi.org/http://dx.doi.org/10.1016/j.energy.2012.03.076.

[17] Moroz L, Burlaka M, Rudenko O. Study of a Supercritical CO2 Power Cycle Application in a Cogeneration Power Plant. Supercrit CO2 Power Cycle Symp 2014.

[18] Pérez-Pichel GD, Linares JI, Herranz LE, Moratilla BY. Thermal analysis of supercritical {CO2} power cycles: Assessment of their suitability to the forthcoming sodium fast reactors. Nucl Eng Des 2012;250:23–34. https://doi.org/http://dx.doi.org/10.1016/j.nucengdes.2012.05.011.

[19] Moisseytsev A, Sienicki JJ. Investigation of alternative layouts for the supercritical carbon dioxide Brayton cycle for a sodium-cooled fast reactor. Nucl Eng Des 2009;239:1362–71. https://doi.org/http://dx.doi.org/10.1016/j.nucengdes.2009.03.017.

[20] Halimi B, Suh KY. Computational analysis of supercritical {CO2} Brayton cycle power conversion system for fusion reactor. Energy Convers Manag 2012;63:38–43. https://doi.org/http://dx.doi.org/10.1016/j.enconman.2012.01.028.

[21] Harvego EA, McKellar MG. Optimization and comparison of direct and indirect supercritical carbon dioxide power plant cycles for nuclear applications. Int Mech Eng Congr Expo 2011.

[22] Yoon HJ, Ahn Y, Lee JI, Addad Y. Potential advantages of coupling supercritical {CO2} Brayton cycle to water cooled small and medium size reactor. Nucl Eng Des 2012;245:223–32. https://doi.org/http://dx.doi.org/10.1016/j.nucengdes.2012.01.014.

[23] Liu J, Chen H, Xu Y, Wang L, Tan C. A solar energy storage and power generation system based on supercritical carbon dioxide. Renew Energy 2014;64:43–51. https://doi.org/http://dx.doi.org/10.1016/j.renene.2013.10.045.

[24] Zhang XR, Yamaguchi H, Uneno D, Fujima K, Enomoto M, Sawada N. Analysis of a novel solar energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide. Renew Energy 2006;31:1839–54. https://doi.org/http://dx.doi.org/10.1016/j.renene.2005.09.024.

[25] Zhang X-R, Yamaguchi H, Uneno D. Experimental study on the performance of solar Rankine system using supercritical {CO2}. Renew Energy 2007;32:2617–28.

https://doi.org/http://dx.doi.org/10.1016/j.renene.2007.01.003.

[26] Osorio JD, Hovsapian R, Ordonez JC. Dynamic analysis of concentrated solar supercritical {CO}2-based power generation closed-loop cycle. Appl Therm Eng 2016;93:920–34. https://doi.org/10.1016/j.applthermaleng.2015.10.039.

[27] Luu MT, Milani D, McNaughton R, Abbas A. Analysis for flexible operation of supercritical {CO}2 Brayton cycle integrated with solar thermal systems. Energy 2017;124:752–71. https://doi.org/10.1016/j.energy.2017.02.040.

[28] Al-Sulaiman FA, Atif M. Performance comparison of different supercritical carbon dioxide Brayton cycles integrated with a solar power tower. Energy 2015;82:61–71. https://doi.org/10.1016/j.energy.2014.12.070.

[29] Sharan P, Neises T, McTigue JD, Turchi C. Cogeneration using multi-effect distillation and a solar-powered supercritical carbon dioxide Brayton cycle. Desalination 2019;459:20–33. https://doi.org/10.1016/j.desal.2019.02.007.

[30] Milani D, Luu MT, McNaughton R, Abbas A. Optimizing an advanced hybrid of solar-assisted supercritical {CO} 2 Brayton cycle: A vital transition for low-carbon power generation industry. Energy Convers Manag 2017;148:1317–31. https://doi.org/10.1016/j.enconman.2017.06.017.

[31] Iverson BD, Conboy TM, Pasch JJ, Kruizenga AM. Supercritical CO2 Brayton cycles for solar-thermal energy. Appl Energy 2013;111:957–70.

[32] Padilla RV, Too YCS, Benito R, Stein W. Exergetic analysis of supercritical {CO2} Brayton cycles integrated with solar central receivers. Appl Energy 2015;148:348–65. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2015.03.090.

[33] Cheang VT, Hedderwick RA, McGregor C. Benchmarking supercritical carbon dioxide cycles against steam Rankine cycles for Concentrated Solar Power. Sol Energy 2015;113:199–211. https://doi.org/http://dx.doi.org/10.1016/j.solener.2014.12.016.

[34] Bae SJ, Ahn Y, Lee J, Lee JI. Various supercritical carbon dioxide cycle layouts study for molten carbonate fuel cell application. J Power Sources 2014;270:608–18. https://doi.org/http://dx.doi.org/10.1016/j.jpowsour.2014.07.121.

[35] Kupecki J, Motylinski K, Jagielski S, Wierzbicki M, Brouwer J, Naumovich Y, et al. Energy analysis of a 10 {kW}-class power-to-gas system based on a solid oxide electrolyzer ({SOE}). Energy Convers Manag 2019;199:111934. https://doi.org/10.1016/j.enconman.2019.111934.

[36] Mozdzierz M, Berent K, Kimijima S, Szmyd JS, Brus G. A Multiscale Approach to the Numerical Simulation of the Solid Oxide Fuel Cell. Catalysts 2019;9:253. https://doi.org/10.3390/catal9030253.

[37] Sánchez D, Chacartegui R, Jiménez-Espadafor F, Sánchez T. A New Concept for High Temperature Fuel Cell Hybrid Systems Using Supercritical Carbon Dioxide. J Fuel Cell Sci Technol 2009;6:1–11.

[38] Ding X, Lv X, Weng Y. Coupling effect of operating parameters on performance of a biogas-fueled solid oxide fuel cell/gas turbine hybrid system. Appl Energy 2019;254:113675. https://doi.org/10.1016/j.apenergy.2019.113675.

[39] de Escalona JMM. The potential of the supercritical carbon dioxide cycle in high temperature fuel cell hybrid systems. Supercrit CO2 Power Cycle Symp 2011.

[40] Marefati M, Mehrpooya M. Introducing and investigation of a combined molten carbonate fuel cell, thermoelectric generator, linear fresnel solar reflector and power turbine combined heating and power process. J Clean Prod 2019;240:118247. https://doi.org/10.1016/j.jclepro.2019.118247.

[41] Moullec Y Le. Conception of a pulverized coal fired power plant with carbon capture around a supercritical carbon dioxide brayton cycle. Energy Procedia 2013:1180–6.

[42] McClung A, Brun K, Chordia L. Technical and economic evaluation of supercritical oxy-combustion for power generation. 4th Int Symp - Supercrit CO2 Power Cycles 2014.

[43] Pickard SAWRFRMEVGERPS. Operation and Analysis of a Supercritical CO2 Brayton Cycle. SANDIA Rep 2010.

[44] Brun K. FP, Dennis R eds. Fundamentals and Applications of Supercritical Carbon Dioxide ({SCO}2) Based Power Cycles. Fundam. Appl. Supercrit. Carbon Dioxide Based Power Cycles, Elsevier; 2017. https://doi.org/10.1016/b978-0-08-100804-1.01001-x.