COMPARISON OF S-CO$_2$ POWER CYCLES FOR NUCLEAR ENERGY

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ABSTRACT. The supercritical carbon dioxide (S-CO$_2$) is a possible cooling system for the new generations of nuclear reactors and fusion reactors. The S-CO$_2$ power cycles have several advantages over other possible coolants such as water and helium. The advantages are the compression work, which is lower than in the case of helium, near the critical point and the S-CO$_2$ is more compact than water and helium. The disadvantage is so called Pinch point which occurs in the regenerative heat exchanger. The pinch point can be eliminated by an arrangement of the cycle or using a mixture of CO$_2$. This paper describes the S-CO$_2$ power cycles for nuclear fission and fusion reactors.

KEYWORDS: S-CO$_2$, power cycle, fusion.

1. INTRODUCTION

The supercritical carbon dioxide (S-CO) cycles are recently very prospective power cycles for different applications. These applications are ranging from nuclear through geothermal, solar energy and waste heat recovery systems. These cycles are researched all around the world.

The research of the power cycles with CO$_2$ as working medium has a long history. The first reference is dated back to 1948, when Sulzer Bros. patented a Brayton cycle with the partial condensation of CO$_2$. The worldwide research of S-CO$_2$ power cycles is dating to the second half of the 20th century [1]. Researchers began to realize benefits of CO$_2$ as working medium in power cycles at that time. Among the first researchers who studied benefits of CO$_2$ power cycles belongs Angelino, Feher, Verhivker and Gokhstein [2].

The research on Czech Technical University in Prague (CTU) is oriented on the analysis of the S-CO$_2$ power cycles with a potential for the nuclear reactors, as well as for the fusion power reactors.

The design of the S-CO$_2$ power cycle is very important and it has effect on the cycle efficiency and net power. The S-CO$_2$ cycle is also suitable for utilization of heat from multiple heat sources with different temperature and heat power. This is important in a case of multiple heat sources providing high and low potential heat like fusion power reactors.

This paper is focused on comparison of the S-CO$_2$ cycles for Nuclear energy. Benefits of the S-CO$_2$ cycle will be described for the nuclear fission and fusion reactors. The design of the S-CO$_2$ cycle will be applied for multiple heat source in fusion reactor.

2. ADVANTAGES AND DISADVANTAGES OF S-CO$_2$ CYCLES

The main advantage of the S-CO$_2$ cycles is the compression work which is lower than in case of helium [2]. A compressor work reduction is caused due to operation in near the critical point. The critical point of CO$_2$ occurs at the temperature 30.98 °C and pressure 7.32 MPa.

The S-CO$_2$ cycle is more compact than water and helium because this cycle operating at high pressure and allows small size of components. Another advantage is that the S-CO$_2$ cycle achieves high efficiency with low operates temperature. The S-CO$_2$ cycles also have several disadvantages. The existence of so called "pinch point" in heat exchangers significantly affecting their design is the most important and well-known disadvantage.

The pinch point may be present for any type of medium, but its influence on components is especially high when CO$_2$ is employed as a working medium. The pinch point primarily occurs in recuperative heat exchangers with identical working media and mass flow on both the hot and the cold side. The pinch point is caused by the variations of heat capacity of CO$_2$ and occurs when the heat capacity of the hot and cold streams (each at a different pressure level) intersect. Due to the pinch point, the heat exchangers may have a large size and low efficiency. However, this problem can be removed in several ways. One of them is an addition of the small amount of other substance into the pure CO$_2$. The substances for shift of pinch point could be Ar, He, CO, O$_2$ or N$_2$ [3]. The other ways is a change of the design of cycles and usage of different mass flows in hot and cold side of heat exchangers.

3. Description of Gas cycles

The S-CO$_2$ cycle is a gas cycle derived from the Ericsson-Brayton cycle, which offers many different layouts for solar, geothermal or nuclear power plants and waste heat recovery. Each layout tries to approach the Carnot cycle and its efficiency. The basic layouts considering the use of S-CO$_2$ are [2]:

- Simple Brayton cycle,
- Re-compression cycle,
- Pre-compression cycle,
- Split expansion cycle,
- Partial cooling cycle,
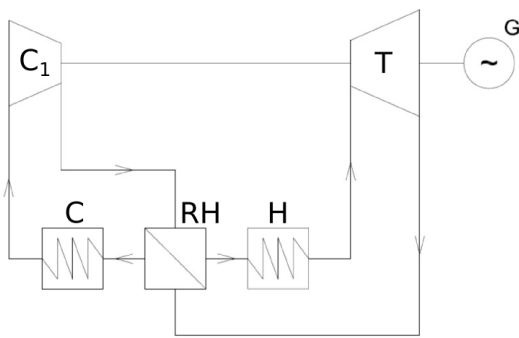- Partial cooling with improved regeneration.

Figure 1. Simple Brayton cycle.

The Simple Brayton cycle is shown in Figure 1. This cycle has a turbine (T), compressors (C1), recuperative heat exchanger (RH), a cooler (C) and a heater (H).
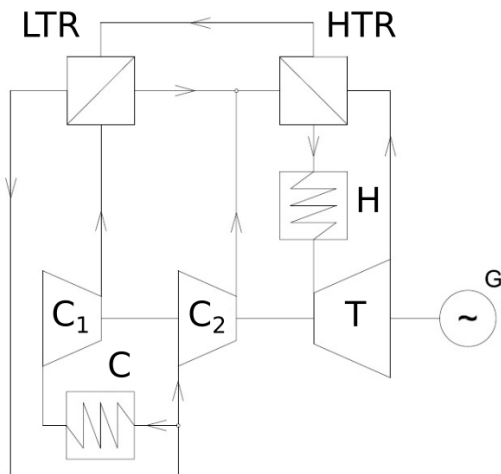

Figure 2. Re-compression cycle.

The Re-compresion cycle is shown in Figure 2. The difference between the Simple Brayton cycle and Recompression cycle is twice a number of the compressors and recuperative heat exchanger. The Re-compression cycle has a turbine (T), two compressors (C1 and C2),

two recuperative heat exchangers (LTR and HTR), cooler (C) and heater (H).

In Figure 3, the Pre-compression cycle is shown, and Figure 4 presents the Split expansion cycle. The Pre-compression cycle and the Split expansion cycle have same components as the Re-compression cycle. Only two turbines has the Split expansion cycle.
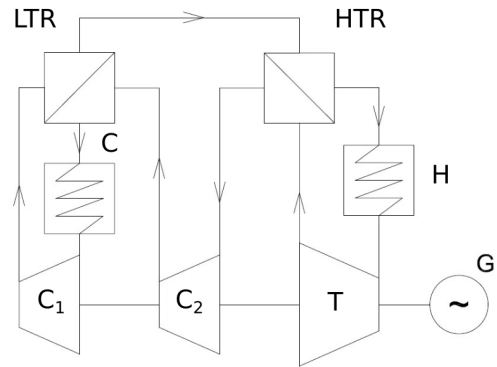

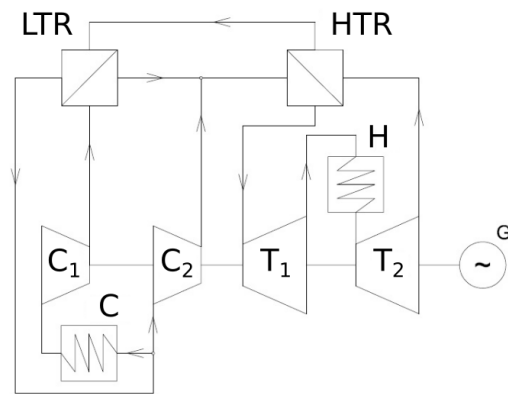Figure 3. Pre-compression cycle.

Figure 4. Split expansion cycle.

The Partial cooling cycle is shown in Figure 5. The Partial cooling cycle contains the two coolers (Ca and Cb) and three compressors.
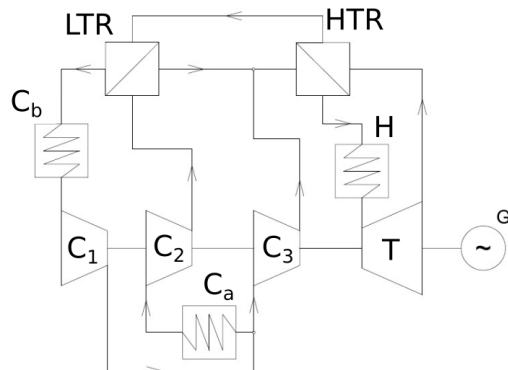

Figure 5. Partial cooling cycle.

4. The GFR Re-compressing cycle

The S-CO$_2$ cycles for nuclear energy are based on the presented cycles of CO$_2$. The Re-compression cycle applied to the gas-cooled fast reactors (GFR) is analyzed in this study. The Re-compression cycle is used as basic concept for GFR. Other type of S-CO$_2$ cycle has similar results as the Re-compression cycle [4]. The cycle layout is arranged according to the Figure 2.

The LTR exchanger is sensitive to the pinch point due to operation near the critical point. The Re-compression cycle eliminates the pinch point using different mass flows of the LTR exchanger. The parameters for calculation are shown in Table 1. The compressor inlet temperature is 34 °C. The turbine inlet temperature is 550 °C. The heat source is considered with the minimum inlet temperature into the heater about 600 °C. The thermal power is 600 MW [5]. The cycle was optimized for the best parameters with thermal power 600 MW.

Thermal Power	600 MW
Compressor Efficiency	68 %
Turbine efficiency	79 %
Recuperator effectiveness	90 %
Compressor inlet temperature	34 °C
Turbine inlet temperature	550 °C

Table 1. Parameter of the GFR S-CO$_2$.

5. The S-CO$_2$ cycle for DEMO2 fusion reactor

In the case of the fusion reactor, the Re-compression cycle is used as the first. The heat sources are arranged behind [6]. However, the layout of the Re-compression cycle can be designed differently. The heat sources can be situated to other streams [7]. The different layout of the S-CO$_2$ power cycle can be a benefit for the heat transfer and net power of cycles.

A Demonstration Fusion Power Plant (DEMO) represents the first fusion power station capable of producing electricity and operating with a closed fuel-cycle. Two DEMO design options are currently investigated, in an attempt to identify a realistic range of possibilities: a near-term DEMO1 and an advanced design concept DEMO2. DEMO1 is the concept based on reliable technology deliverable in the term of 20 years from now, and it is planned to work in the pulse operation mode. DEMO2 based on advances in the physics basis deliverable on a longer term is expected in the steady-state operation mode [8]. The DEMO2 power plant based on the steady-state fusion power reactor is analysed in this study.

The DEMO2 fusion reactor has several different heat sources. The main heat sources are the Blanket, first wall, and divertor. Each of them operates on different temperatures and powers.

The Preheating S-CO$_2$ cycles may be more suitable for DEMO2. A layout of the Preheating cycle is shown in Figure 6. The Preheating cycle has benefit for the pinch point mitigation as well as the layout of Re-compression cycle.
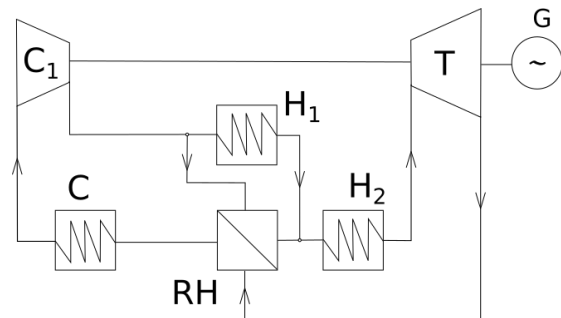

Figure 6. Preheating cycle.

The Table 2 brings parameters of the analyzed fusion reactor DEMO2 model [9]. Thermal power of the fusion reactor DEMO2 is 4109 MW. The blanket has the thermal power of 3887 MW. The thermal power of the divertor and the first wall is 222 MW. The blanket and first wall are cooled by helium, the divertor is cooled by water. The high-grade reactor outlet temperature is projected to 500 °C. The low-grade reactor outlet temperature is projected to 160 °C. The turbine inlet temperature is 475 °C.

Consequently, the analyzed fusion reactor DEMO2 has two different heat source. The Preheating cycle uses the heater H1 for high-grade primary heat (first wall and blanket). Second heater H2 is used for low-grade secondary heat (divertor).

Thermal Power	4109 MW
Primary (high-grade) heat	3887 MW
Secondary (low-grade) heat	222 MW
Compressor Efficiency	68 %
Turbine efficiency	79 %
Recuperator effectiveness	90 %
Compressor inlet temperature	34 °C
Turbine inlet temperature	475 °C

Table 2. Parameter of S-CO$_2$ for fusion reactor DEMO2.

6. Result of GFR reactor and DEMO2 fusion reactor

The thermodynamic calculation was done for Precompression cycle and Preheating cycle. The calculation was performed using programming language Python. The codes of cycles have been written in Python. Properties of pure CO$_2$ and mixtures are embedded into the Python. Source of gases and mixtures properties is NIST Reference Fluid Thermodynamic and Transport Properties database, Version 9.1. [10].

The calculation of the GFR S-CO$_2$ cycle was performed according to the parameters included in Table 2. The cycle was optimized for the best results. The results of the GFR Re-compression cycle are
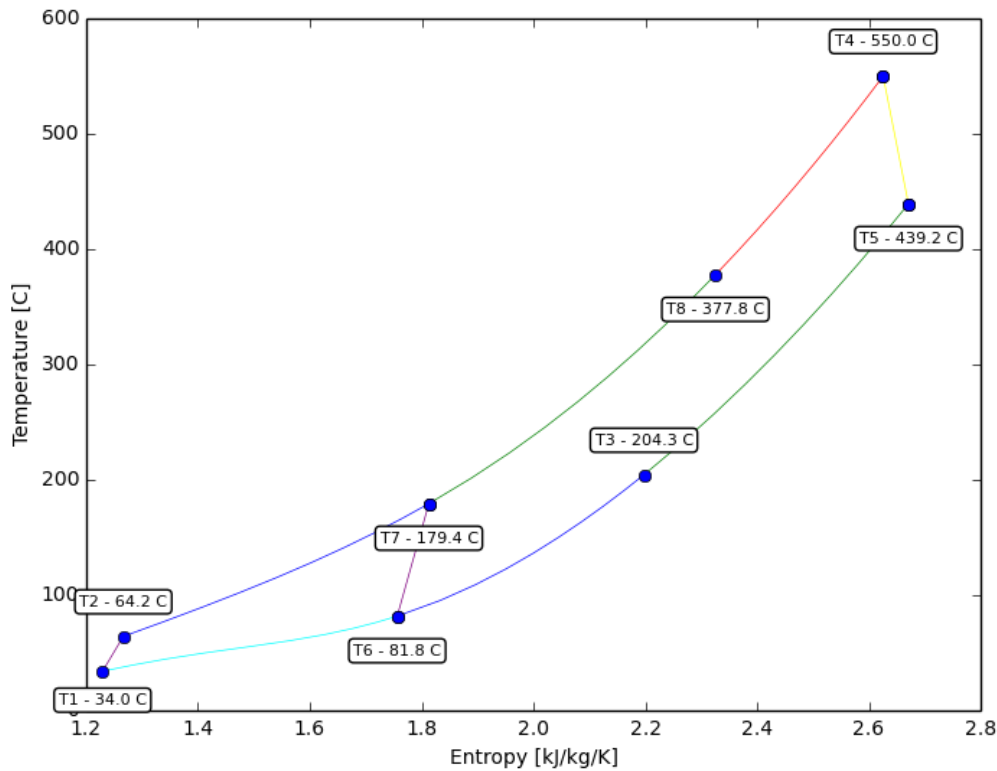
FIGURE 7. T-S diagram of the GFR Re-compression cycle.

shown in Table 3. The Figure 7 shows a T-S diagram of the cycle.

According to the Table 3, the total net power of Re-Compression cycle is 201 MW. The cycle efficiency is 33.56 % and the mass flow is 2730 kg/s.

Cycle efficiency	33.56 %
Turbine power output	324.98 MW
Compressor no.1 in. power	89.44 MW
Compressor no.2 in. power	33.84 MW
Compressor input power	123.28 MW
Added heat	600.98 MW
Removed heat	399.28 MW
Regenerative heat	1249.15 MW
Mass flow in LTR (cold s.)	2299.89 kg/s
Mass flow in Com. no.2	430.1 kg/s
Mass flow ratio	0.842
Net power	201.69 MW
Mass flow	2730.0 kg/s
Pressure ratio	2.8
Pressure no.2	34.0 MPa

TABLE 3. Result of GFR Re-compression cycle.

The Calculation of S-CO$_2$ cycle for DEMO2 was performed for two cycle. The first cycle is the Re-compression cycle and the second cycle is Preheating cycle. The calculations were performed with the parameters from the Table 2. The cycles were optimized

for the best results. The result of the DEMO2 Re-compression cycle is shown in the Table 4. The layout of heat sources corresponds to the Figure 2. The heat source H is split into two heat sources arranged serially. According to the Table 4, the total net power of the Re-Compression cycle is 1251 MW. The cycle efficiency is 30.45 %. However, the mass flow for this case is very high and achieves of 20 250 kg/s.

Cycle efficiency	30.45 %
Turbine power output	2013.02 MW
Compressor no.1 in. power	719.62 MW
Compressor no.2 in. power	42.41 MW
Compressor input power	762.03 MW
Added heat	4108.83 MW
Removed heat	2857.84 MW
Regenerative heat	8340.95 MW
Mass flow in LTR (cold s.)	19 589.33 kg/s
Mass flow in Com. no.2	660.66 kg/s
Mass flow ratio	0.967
Net power	1250.98 MW
Mass flow	20 250.0 kg/s
Pressure ratio	2.6
Pressure no.2	34.0 MPa

TABLE 4. Result of DEMO2 Re-compression cycle.

The Figure 8 shows the T-S diagram of the DEMO2 Re-compression cycle. The result of the DEMO2 Pre-
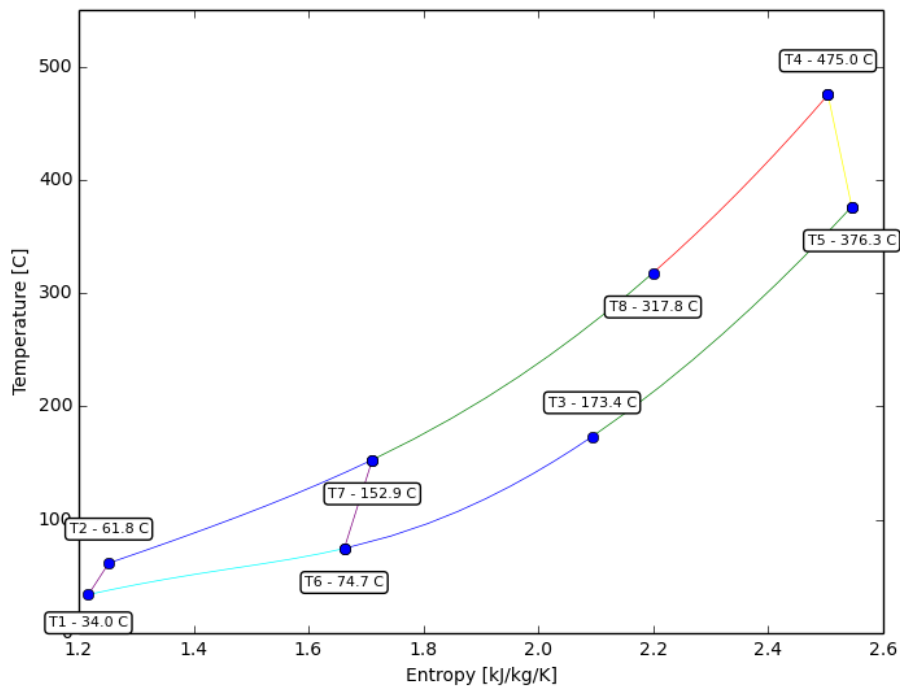
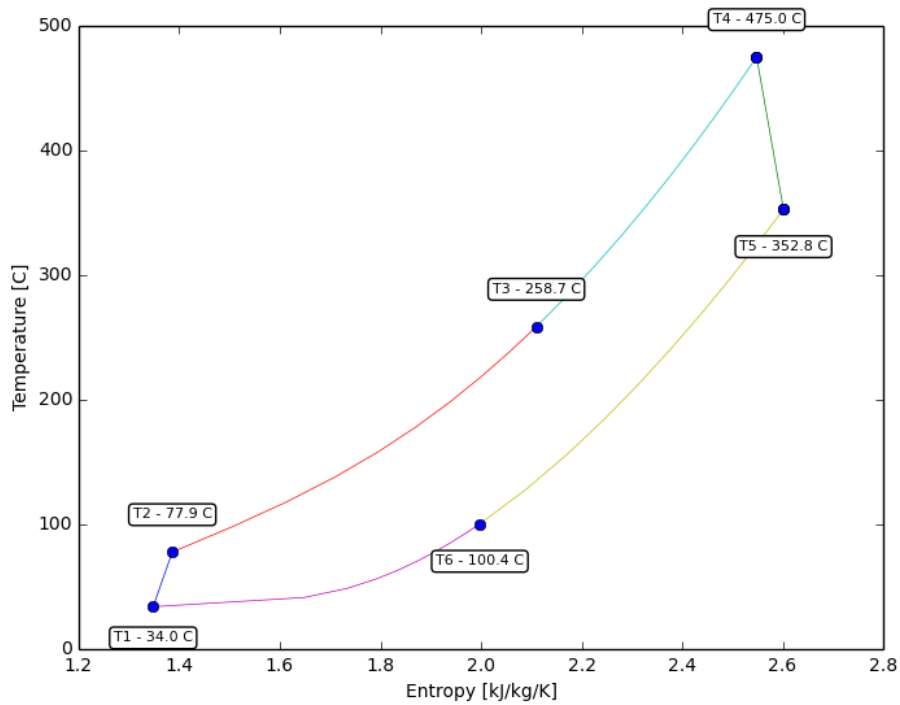FIGURE 8. T-S diagram of the DEMO2 Re-compression cycle.

FIGURE 9. T-S diagram of the DEMO2 Preheating cycle.

heating cycle is shown in the Table 5 and the T-S diagram of the cycle is shown in the Figure 9. The layout of heat sources corresponds to the Figure 6. The heater H1 was used for high-grade primary heat, the heater H2 was used for low-grade secondary heat.

According to the Table 5, the total net power of Preheating cycle cycle is 1145 MW. The cycle efficiency is 27.87 %, and the mass flow for the Preheating cycle is 14 040 kg/s.

Cycle efficiency	27.87 %
Turbine power output	1727.14 MW
Compressor input power	582.005 MW
Added heat	4108.54 MW
Removed heat	2963.41 MW
Regenerative heat	4125.79 MW
Mass flow in HEX	13 338.0 kg/s
Mass flow in H2	702.0 kg/s
Mass flow ratio	0.95
Net power	1145.13 MW
Mass flow	14 040 kg/s
Pressure ratio	3.4
Pressure no.2	28 MPa

Table 5. Result of the DEMO2 Preheating cycle.

7. Conclusion

The results from the Table 3 represent the suitable results for the GFR designing with Re-compression cycle. Improvement of the parameters is possible by future research.

The results of the S-CO$_2$ cycle for the fusion reactor show the effect of the use of multiple heat sources. The Re-compression cycle is better than the Preheating cycle according to the Table 4 and Table 5. However, it is obvious that this advantage is valid only for the net power. The critical disadvantage of the Re-compression cycle is the mass flow of about 20 000 kg/s. The mass flow of the Preheating cycle is lower in comparison with the Re-compression cycle.

Designing and optimization of the S-CO$_2$ cycles are of great importance for fusion energy. The Preheating cycle is a convenient cycle for utilization of low potential heat, and such cycles are suitable for exploitation of the multiple heat sources of the fusion power reactor like analyzed DEMO2.

Further research of the S-CO$_2$ power cycles for the fusion power reactors will be focused on the detailed comparison of the S-CO$_2$ power cycle and on the development of the new modifications of the S-CO$_2$ power cycle, which will take into account the fusion reactor multiple heat source design.

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