POWER--CONVERSION CYCLES FOR SODIUM--COOLED FAST REACTORS

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A PhD level submission

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Summary

Recently, CO_2 has gained wide attention as an alternative to water working fluid in power conversion cycles of a sodium-cooled fast reactors. Since the maximum temperatures of the second loop sodium are relatively low, it is important to optimize the corresponding power conversion cycle. Various Brayton gas-cycles are discussed in the paper along with the calculations of efficiencies. Helium is considered as an alternative to CO_2.

1. Introduction

Sodium-cooled Fast Reactor (SFR) is the only one of six Generation-IV concepts to be implemented so far. The current operating reactors are represented by BN-600 in Beloyarsk, Russia and Monju in Tsuruga, Japan. Both reactors employ two sodium loops (to prevent possible leakage of radioactive sodium to power conversion cycle, and to have a buffer loop between low pressure sodium (0.1 – 0.3 MPa) from high pressure water (12 – 16 MPa)). Sodium reacts exothermally with water at any temperatures, therefore any leaks in a sodium-water Heat eXchanger (HX) may lead to serious damage of the former. This is a major reason for seeking an alternative working fluid for use in SFR. Moisseytsev and Sinicki [1] investigated various CO_2 power conversion cycles attached to a sodium-cooled Advanced Burner Test Reactor (ABTR). They compared double recompression cycles with and without reheat and intercooling. They found that there was no appreciable increase in thermodynamic efficiency of the cycle compared to the recompression, or so-called Feher, cycle. In [1], realistic considerations of pressure drops and efficiencies of HXs were made. For the maximum temperature of 470°C corresponding to the ABTR design, they obtained about 39.1% efficiency. Since CO_2 flow splitting was made in all cycle options considered in [1], we present the analysis of efficiency of a cycle with two-stage compression with intercooling and regeneration and two-stage compression with intercooling and reheat. Secondary Na inlet/outlet temperatures and mass-flow rates correspond to those at the Monju reactor. It is necessary to mention that Dragunov et al. [2] analysed efficiency of BN-600 reactor and compared current power conversion cycle with those cooled by supercritical water and CO_2. They obtained the highest efficiency of 52.7% for the idealized supercritical-water Rankine cycle. Turbine inlet temperature was 505°C in their calculations.

2. Cycles

To simplify the analysis, 100% efficiencies of all equipment components were assumed. This allows for a top estimate of the efficiency. The first of the two cycles is shown in Figure 1.

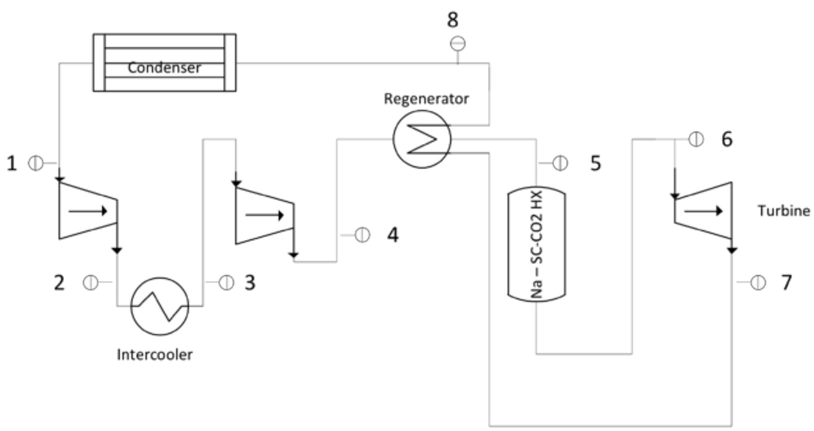

Figure 1. Two-stage compression with intercooling cycle.

Parameters of CO_2 at each of the points are given in Table 1.

Table 1. Parameters of CO_2 at different point of cycle shown in Figure 1.

Point	*T*, °C	*P*, MPa
1	32.0	7.75
2	45.0~~4.95~~	12.45
3	32.0	12.45
4	41.0~~0.98~~	20.00
5	268.4~~36~~	20.00
6	480.0	20.00
7	362.1~~08~~	7.75
8	41.0~~0.98~~	7.75

Parameters of CO_2 entering first stage of compression were chosen to be slightly above the critical point. Pressure at the turbine inlet was chosen somewhat arbitrarily to be 20 MPa.

Mass-flow rate of CO_2 ~~was found to be.~~for this cycle 886.7 kg/s. Thermodynamic efficiency of the cycle was found to be 41.~~45~~5%

An alternative layout which includes reheat of sodium is shown in Figure 2.

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Comment [TP1]: Intermediate Pressure = sqrt(P1*P2) =sqrt (7.75*20) =12.45

Comment [O2]: Pth = 231.778 MW

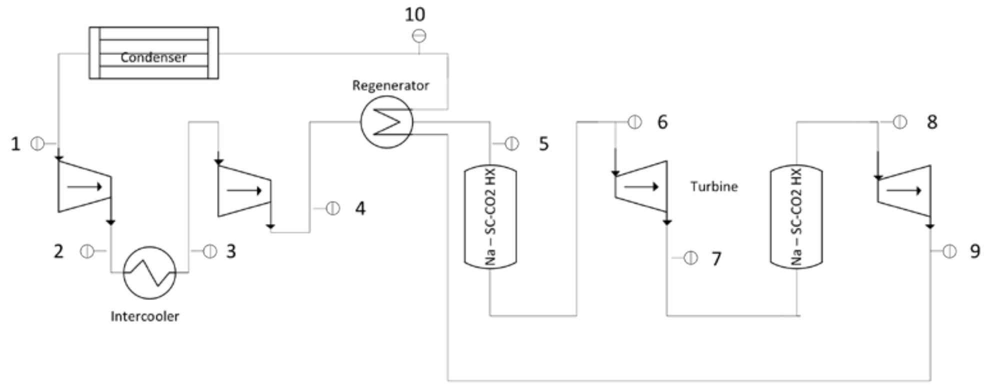

Figure 2. Two-stage compression with intercooling and reheat cycle.

Parameters of CO_2 entering first stage of compression were chosen to be the same as in the previous case. Mass-flow rate of CO_2 was found to be 867.2 kg/s. Thermodynamic efficiency of the cycle was found to be: 42.~~66~~7% (3% increase in efficiency compared to the previous case). The comparison of T-s diagrams for both cycles is presented on Figure 3. It is easy the amount of work added by implementing reheat and using an additional stage of turbine from this figure.

Comment [TP3]: This is correct. I get 42.74% efficiency

Table 2. Parameters of CO_2 at different point of cycle shown in Figure 2.

Point	***T*, °C**	***P*, MPa**
1	32.0	7.75
2	45.0~~4.50~~	12.45
3	32.0	12.45
4	41.3~~3~~	20.00
5	303.0~~2.96~~	20.00
6	480.0	20.00
7	417.0~~6.92~~	12.45
8	480.0	12.45
9	422.1~~4~~	7.75
10	41.3~~3~~	7.75

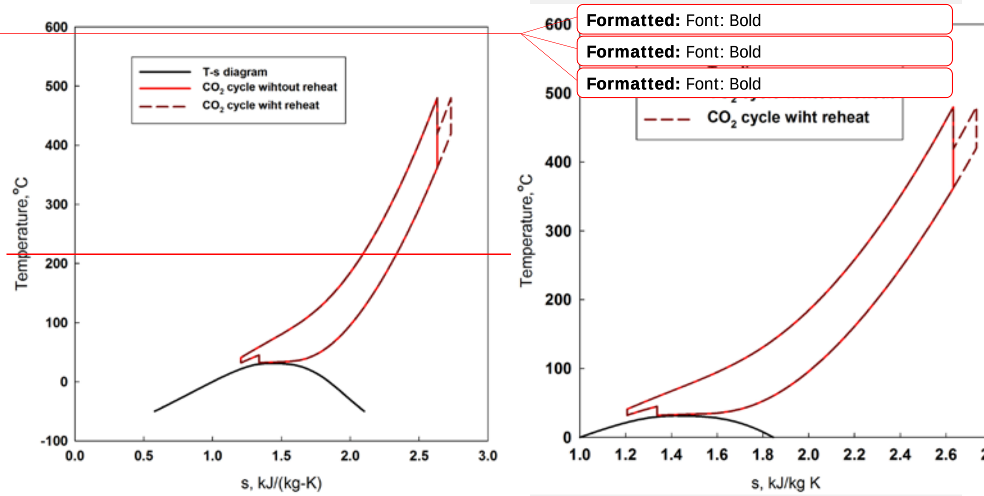

Figure 3. T-s diagram for the considered SC CO_2 cyc

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3. Helium as a working fluid

As it was mentioned in introduction, vigorous exothermic reaction between water and sodium at any temperatures pushes for search for alternative working fluid in the power conversion side of a SFR. It turns out that CO_2 also reacts exothermally with Na, though at higher temperatures. Simon et al. [3] conducted calorimetric studies to study the kinetics of Na – CO_2 reaction. They revealed that a fast global reaction, which can be interpreted as auto-combustion of CO_2 in sodium, starts at a temperature higher than 500°C. Miyahara et al. [4] conducted a number of experiments to study the reaction behaviour between Na and CO_2. Parts of their experiments were simulating a leak of CO_2 to Na in different points of a Na-CO_2 HX (characterized by a combination of different temperatures of Na and CO_2). They came to the conclusion that Na – CO_2 is an exothermal reaction that becomes continuous beyond a threshold temperature, which is between 250 – 300°C. It should be noted that in [3] they also found that Na – CO_2 reaction occurs at temperatures below 500°C and is characterized by an induction time. Therefore, we decided to compare the efficiency of the mentioned above cycle when chemically inert helium is used instead of CO_2. Since the critical state of helium is very low, at pressures of the order of 1 MPa, all of its thermophysical properties are nearly constant. It is worth mentioning that helium has a very high value of specific heat, which is comparable to that of water. Therefore, we arbitrarily chose 1 MPa as the lowest pressure in the cycle and 2.58 MPa as the highest pressure (to preserve pressure ratio of the CO_2 cycle). Table 3 shows the states corresponding to the two cycles, mass-flow rates and thermodynamic efficiencies.

Table 3. Parameters of He at different points of cycle shown in Figures 2 and 3.

Point	***T*, °C**	***P*, MPa**	***T*, °C**	***P*, MPa**
1	32.0	1.00	32.0	1.00
2	95.7~~65~~	1.61	96.0~~5.99~~	1.61
3	32.0	1.61	32.0	1.61
4	95.6~~3~~	2.58	95.3~~1~~	2.58
5	242.4~~4~~	2.58	349.3~~0~~	2.58
6	480.0	2.58	480.0	2.58
7	242.4~~3~~	1.00	350.6~~55~~	1.61
8	95.6~~3~~	1.00	480.0	1.61
9	–~~-~~	–~~-~~	349.4~~37~~	1.00
10	–~~-~~	–~~-~~	95.3~~2~~	1.00
Mass-flow rate, kg/s	187.9		171.6	
Efficiency, %	46.4~~1~~%		51.0%	

Comment [TP4]: This is correct! I get 51.03% using my MATLAB script! I guess Helium is a miracle fluid!
I will check the single stage one tomorrow (thursday)

A comparison of T-s diagrams for CO_2 and He cycles with reheat is shown in Figure 4. Value of specific entropy was set to zero at the compressor inlet to have a proper absolute comparison of changes in the values of specific entropy. We can see a huge difference between the amounts of work produced per unit mass of both fluids.

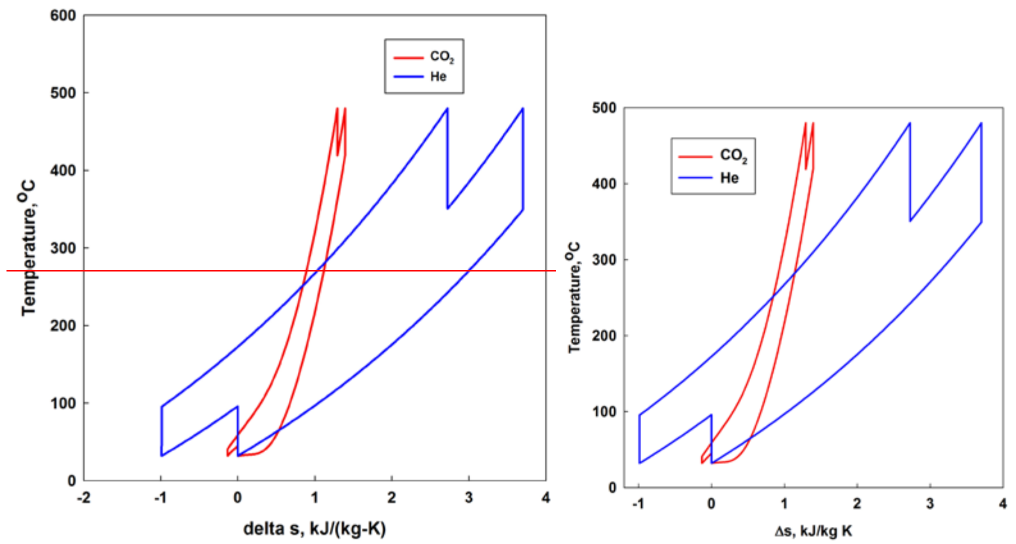

Figure 4. T-s diagrams for CO_2 and He cycles with reheat.

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4. Conclusions

Calculation of thermal efficiencies of the power conversion side of a SFR were made. Temperatures and mass-flow rates of sodium corresponding to that of the secondary sodium loop of Monju reactor were used. CO_2 and He were considered as alternative working fluids to water. For the cycle with recompression, thermal efficiency of the idealized "He-cycle" was found to be 46.4%, which is higher than that of idealized "CO_2-cycle" by 12.0%. For the cycle with recompression and reheat, thermal efficiency of the idealized "He-cycle" was found to be 51.0%, which is higher than that of idealized "CO_2-cycle" by 19.5%. Though He turbines have not been developed yet and using He may be challenging due to it expected ingress into turbine bearings, He-based power conversion cycle offers very high efficiencies at relatively low turbine inlet temperatures (480°C).

5. Nomenclature

~~T temperature, °C~~
P pressure, Pa
s specific entropy, J/~~(~~kg K~~)~~
T temperature, °C

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Abbreviations and Acronyms:

HX	Heat eXchanger
SC	SuperCritical
SFR	Sodium-cooled Fast Reactor

6. References

[1] Moisseytsev, A. and Sienicki, J., 2009. Investigation of Alternative Layouts For The Supercritical Carbon Dioxide Brayton Cycle For A Sodium-Cooled Fast Reactor, *Nuclear Engineering and Design*, 239, pp. 1362-1371.

[2] Dragunov, A., Saltanov, Eu., Bedenko, S. and Pioro, I., 2012. A Feasibility Study on Various Power–Conversion Cycles for a Sodium–Cooled Fast Reactor, Proceedings of the 20th International Conference on Nuclear Engineering (ICONE–20), July 30 − August 3, Anaheim, California, USA, Paper #55130, 10 pages.

[3] Simon, N., Latge, C., and Gicquel, L., 2007. Investigation of Sodium – Carbon Dioxide Interactions With Calorimetric Studies, Proceedings of ICAPP, May 13-18, Nice, France, Paper #7547, 8 pages.

[4] Miyahara, S., Ishikawa, H., and Yoshizawa, Y., 2011. Experimental Investigation Of Reaction Behaviour Between Carbon Dioxide And Liquid Sodium, *Nuclear Engineering and Design*, 241, pp. 1319-1328.