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Potential Improvements of Supercritical CO2 Brayton Cycle by Modifying Critical Point of CO2

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1. Introduction

A Sodium-cooled Fast Reactor (SFR) is one of strong candidates for a next generation nuclear reactor. However, the conventional design of a SFR concept with an indirect Rankine cycle is subjected to a sodium-water reaction, which can deteriorate the safety of a SFR. To prevent any hazards from sodium-water reaction, a SFR with the Brayton cycle using Helium or Supercritical Carbon dioxide (S-CO2) as working fluids can be an alternative approach to improve the current SFR design.

As in a helium cycle, there has been an investigation to modify thermo-physical properties to increase the efficiency of the cycle and reduce the size of turbomachineries. Particularly, He-Xe or He-N2 binary mixture were successful to decrease the stages of turbomachines due to the increment of molecular weight of gas mixture than that of pure helium [1,2].

Similar to the case of helium, CO2 has a potential to modify its thermo-physical properties by mixing with other gases. For instance, it was reported that critical point of CO2 can be shifted by mixing with different gases [3, 4]. Since, the efficiency of a S-CO2 cycle is limited to the critical point of CO2, the shift in critical point implies that there is a possibility of improving the cycle efficiency than the current design. This paper presents the results of a preliminary analysis to identify the effects of CO2 critical point modification on the Brayton cycle performance.

2. Potential improvement of S-CO2 Brayton cycle

S-CO2 Brayton cycle is one of the most promising power conversion cycles for SFR or Gas-cooled Fast Reactor (GFR). To simplify the analysis, this paper will limit its discussion to the simple Brayton cycle. The cycle is consisted of a heat source (herein, Intermediate Heat Exchanger, IHX), a turbine, a compressor, a recuperator, and a precooler. Conceptual design of the cycle is shown in Fig. 1.

There are some key advantages of S-CO2 cycle. The size of turbomachinery in S-CO2 cycle is much smaller than those in Helium cycle. Furthermore, high efficiency can be achieved with low turbine inlet temperature and simpler cycle configuration. Moreover, sodium-CO2 reaction is less critical than sodium-water reaction [5].

However, the S-CO2 Brayton cycle is more sensitive to the compressor inlet temperature than other Brayton cycles. This is because heat rejection temperature is just above the CO2 critical temperature, and when excessive cooling is at present in the precooler the cycle performance can deteriorate very quickly. In other words, critical point acts as a limitation of the rejection temperature due to huge variation of properties of CO2 near the critical point. In general, lowering rejection temperature of thermodynamic cycles can increase the efficiency, but S-CO2 cycle is limited in this case. Therefore, it can predict that changing the critical point of CO2 with a small modification can result in a significant improvement of the total cycle efficiency.

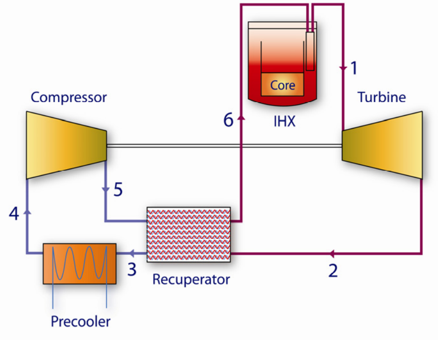

Fig. 1. Simple Brayton cycle diagram

To evaluate the effect of shifting the critical point on the S-CO2 simple Brayton cycle, we referred to the report written by V. Dostal at MIT [6]. The cycle maximum temperature is at 823.15K, maximum pressure is at 20MPa, turbine pressure ratio is around 2.55, and inlet temperature and mass flow rate of cooling water are 300.15K, and 9400kg/s respectively. Temperature and pressure of each cycle point is presented in Fig. 2. In Fig. 2 the critical point of CO2 is also shown to demonstrate how S-CO2 cycle lowest temperature point is close to the critical point.

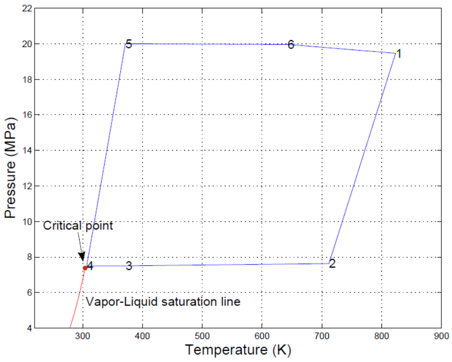

Fig. 2. Pressure vs. temperature diagram of S-CO2 simple Brayton cycle

To evaluate the change of the critical point on the cycle, we have modified the property of CO2 from NIST table [7]. As a simple hypothetical analysis, all properties of CO2 (density, heat capacity, enthalpy, and so forth) were shifted with respect to the critical temperature while maintaining the same value. It should be noted that in a real gas mixture, not only the critical point changes but all other thermo-physical properties vary with concentration of species. However, in this paper we have assumed that only critical point of CO2 is changed.

The shift in critical point results in different enthalpy value for the same pressure and temperature point, and therefore different cycle thermodynamic efficiency. The efficiency does not vary linearly which is shown in Fig. 3 due to non-linearity of CO2 enthalpy change with respect to temperature and pressure.

Fig. 3 shows the cycle efficiencies by changing the critical temperature with temperature and pressure point of the S-CO2 simple Brayton cycle. It is readily shown that the decrease in the critical temperature of CO2 has positive effects on the cycle efficiency.

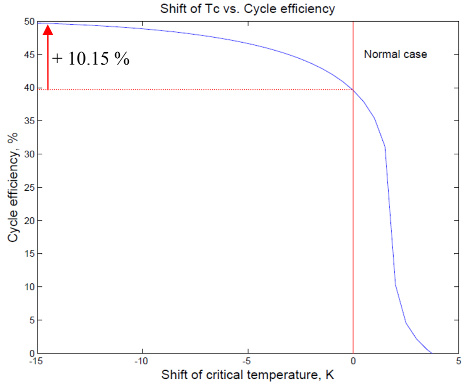

Fig. 3. Cycle efficiency vs. shift of critical temperature

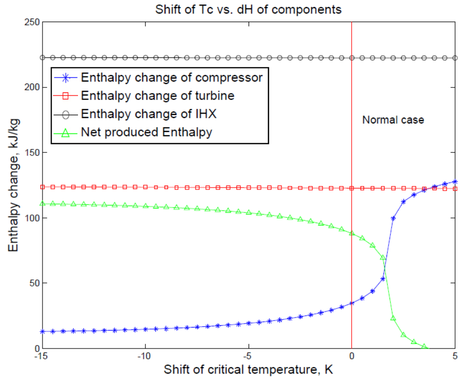

Fig. 4. Enthalpy change of each components in a S-CO2 Brayton cycle vs. shift of critical temperature

This is due to reduction of the compressor work which is clearly shown in Fig. 4. In this calculation, mass flow rate of the cycle is assumed to be a constant so that only enthalpy variation is affecting the output consumed or produced work. Variations of enthalpy in the IHX and the turbine are negligible with respect to the critical point modification. This is contrast to the enthalpy change in the compressor. The enthalpy change in compressor is reduced due to the small density variation with respect to pressure change when the operating fluid temperature becomes larger than the fluid critical point. Thus, it can be concluded that 15K critical temperature shift can be projected to 10% improved cycle efficiency due to reduction in the compressor work consumption, as shown in Fig. 3.

3. Conclusions and Further works

This work has demonstrated that the S-CO2 cycle, which is one of most promising future energy conversion cycles, can be potentially further improved by altering the fluid thermo-physical properties. Furthermore, it was also suggested that one of the possible directions to increase the cycle efficiency with small amount of effort: lower the critical temperature point. Therefore, we will try to identify desirable real CO2 gas mixture for the cycle through a thorough screening process.

In order to assess the newly identified coolant, robust cycle design tool has to be developed in parallel. Various layouts of S-CO2 Brayton cycles and gas mixture cycles will be studied to optimize cycle and mixture composition. The newly suggested optimized cycle will be then specifically designed for a nuclear power conversion or other energy conversion devices with the developed tool.

4. Acknowledgement

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REFERENCES

[1] M. S. El-Genk, J.-M. Tournier, Performance analyses of VHTR plants with direct and indirect closed Brayton cycles and different working fluids, Progress in Nuclear Energy, Vol. 51, pp. 556-572, 2009.
[2] M. S. El-Genk, J.-M. Tournier, Noble gas mixtures for gas-cooled reactor power plants, Nuclear Engineering and Design, Vol. 238, pp. 1353-1372, 2008.
[3] J. Ke, M. Poliakoff, The Critical Point of CO2 + N2: An Experiment Inspired by “Notes and Records”, Notes & Records of the Royal Society, Vol. 59, pp. 171-174, 2005.
[4] V. G. Martynets, N. V. Kuskova, E. V. Marizen, and V. F. Kukarin, Critical line of (xenon + carbon dioxide), The Journal of Chemical Thermodynamics, Vol. 31, pp. 191-195, 1999.
[5] A. Moisseytsev, J. J. Sienicki, Investigation of alternative layouts for the supercritical carbon dioxide Brayton cycle for a sodium-cooled fast reactor, Nuclear Engineering and Design, Vol. 239, pp. 1362-1371, 2009.
[6] V. Dostal, M. J. Driscoll, P. Hejzlar, A Supercricial Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, 2004.
[7] Lemmon, E.W., Huber, M.L., McLinden, M.O., NIST REFPROP, Version 8.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2007.