The Application of Supercritical CO_2 Power Cycle to Various Nuclear Systems

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1. Introduction

A supercritical CO_2 (S-CO_2) Brayton cycle is recently receiving significant attention as a promising power conversion system in wide range of energy applications due to its high efficiency and compact footprint. The main reason why the S-CO_2 Brayton cycle has these advantages is that the compressor operates near the critical point of CO_2 (30.98℃, 7.38MPa) to reduce the compression work significantly compared to the other Brayton cycles [1-4]. In this paper, various applications of supercritical CO_2 power cycle to nuclear systems will be presented and summarized.

2. Application Examples

2.1 Large LWR

Initially, the APR-1400 was first modified as a co-generation plant with existing steam power conversion system by the KAIST research team [5]. In this concept, 10% of steam which passes through the high pressure turbine (HPT) section of APR-1400 was redirected to the low pressure turbine for desalination. The KAIST research team studied an applicability of the S-CO_2 Brayton cycle by substituting the steam cycle low pressure turbine section. The concept of substituting steam cycle low pressure turbine section with the S-CO_2 power cycle showed some benefit and potential to outperform the first design.

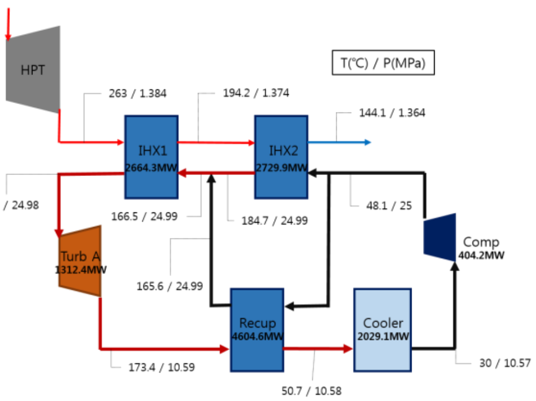

Fig. 1. Performance of S-CO_2 cycle for APR-1400 low pressure steam turbine substitution

Furthermore, the concept of replacing the entire steam cycle of APR-1400 with the S-CO_2 Brayton cycle was evaluated. The preliminary design of the S-CO_2 Brayton cycle operating under APR-1400 condition showed some promises as well.

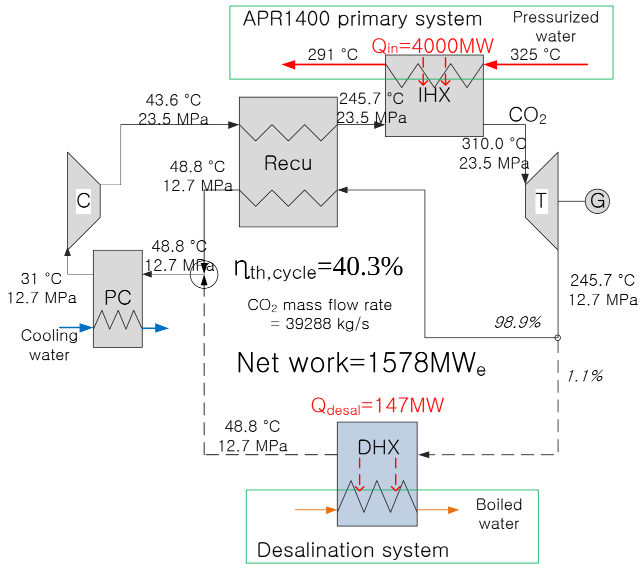

Fig. 2. Simple recuperated S-CO_2 cycle for APR-1400 condition with desalination

2.2 Water-cooled Small Modular Reactor

A small and medium size water-cooled nuclear reactor (SMR) has been gaining interest due to its wide range of application such as electricity generation, seawater desalination, district heating and propulsion. Another key advantage of a SMR is that they can be transported from one place to another mostly by maritime transport due to its small size, and sometimes even through a railway system. Therefore, the combination of a S-CO_2 Brayton cycle with a SMR can reinforce any advantages coming from its small size if the S-CO_2 Brayton cycle has much smaller size components, and simpler cycle layout compared to the currently considered steam Rankine cycle. As an example, SMART (System-integrated Modular Advanced ReacTor), a 330MWth integral reactor developed by KAERI (Korea Atomic Energy Institute) for multipurpose utilization, is considered as a potential candidate for applying the S-CO_2 Brayton. In consideration of SMART condition, the turbine inlet pressure and size of heat exchangers were analyzed.

According to the cycle evaluation, the maximum cycle efficiency under 310℃ is 30.05% at 22 MPa of the compressor outlet pressure and 36% of flow split ratio with 82 m^3 of total heat exchanger volume while the upper bound of the total cycle efficiency is 37% with ideal components within 310℃. The total volume of turbomachinery which can afford 330MWth of SMR is less than 1.4 m^3 without casing.

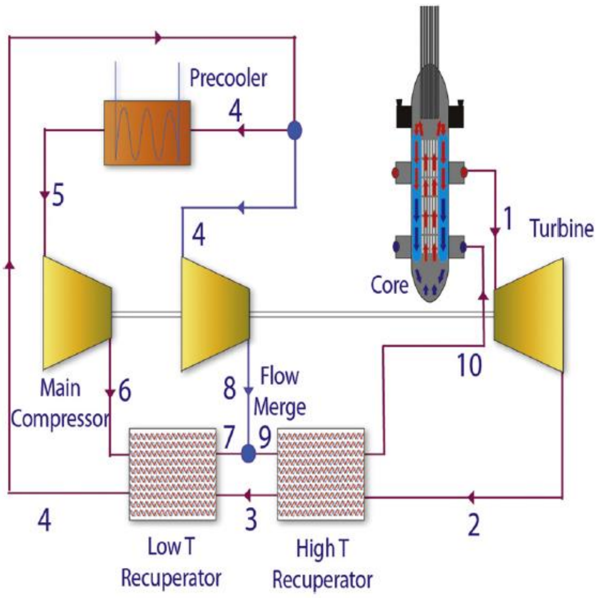

Fig. 3. S-CO_2 cycle coupled with SMART

2.3 Sodium-cooled Fast Reactor (SFR)

The existing SFR designs with steam power cycle have to carefully consider the potential consequence of vigorous Sodium-Water Reaction (SWR) which can damage the reactor system. Therefore, some of SFR designs incorporated detectors and steam generator protection systems including a double wall steam generator for the protection and mitigation of sodium-water reaction to ensure the safety of SFR from SWR. Some research works indicate that the small sodium leaks can be controlled and mitigated by utilizing waveguide sensor visualization technology designs or sodium water reaction pressure relief system for the sodium flow inspection.

Even though several SFR designs make an effort to prevent or reduce the impact of SWR, arguments related to SWR have been one of the major issues when adopting or proceeding with SFR developments in some countries. Many previous researchers suggested to utilize a closed Brayton cycle technology as an alternative option to SFR power conversion system [7-9]. By selecting an inert or less active gas with sodium, SWR can be substituted with much milder or no reaction with sodium.

From the previous study [4], it was identified that S-CO_2 cycle is the most preferable closed gas Brayton cycle for achieving the highest efficiency for a small modular SFR application. Furthermore, the S-CO_2 power cycle can be composed with turbomachinery with the simplest configurations. This eventually results in the most compact cycle size. Thus, the S-CO_2 power cycle has a great potential of improving safety and economy of SFR.

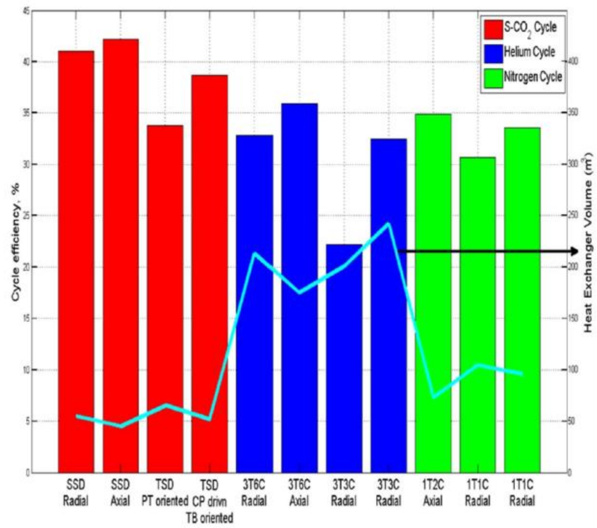

Fig. 4. Performance of various closed Brayton power cycles for SFR application.

2.4 High Temperature Gas-cooled Reactor (HTGR)

A High Temperature Gas-cooled Reactor (HTGR) system was generally designed and planned to be constructed in a medium size reactor (around 600MWe power output) in the past. More recently, the potential of very small modular type HTGR with a special attention given to the power conversion system was evaluated [3]. Since HTGR is generally known for the best system to achieve passive safety while it is relatively easy to adopt an air-cooled Brayton cycle for a power conversion system, HTGR can be quite advantageous for a small modular reactor application.

However, as the size of the power system decreases the consisting component performance usually degrades and the final effect on the total system performance was not seriously studied before for a small size HTGR system. Considering the size of the SMR system, a simple recuperated Brayton cycle for helium and S-CO_2 was used as a reference power conversion system. The thermal efficiency was calculated for various turbomachinery efficiencies because the turbine and compressor efficiencies in such a small scale power cycle with helium and S-CO_2 are not guaranteed to be high like in a large power system. As a result, the cycle performances of the S-CO_2 cases are generally higher than those of the helium cases at similar turbine inlet temperature except for the cases of when very high turbomachinery efficiency can be guaranteed. In case of heat exchanger size comparison, the volume of helium cycle cases are highly related to efficiency of turbomachinery, while the volume of S-CO_2 cycle is quite indifferent to turbomachinery efficiency due to its narrow optimal pressure ratio variation when the turbomachinery efficiency varies.

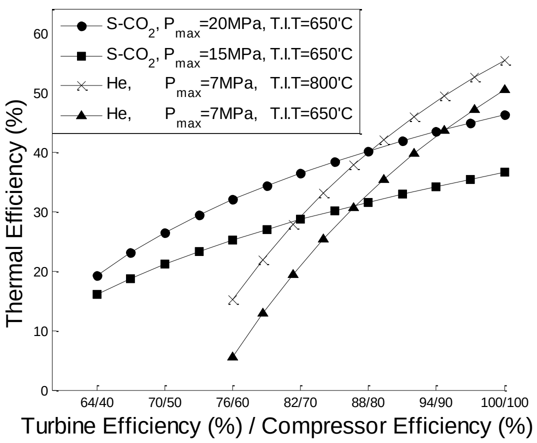

Fig. 5. Performance of S-CO_2 and helium closed Brayton power cycles for small modular HTGR application.

2.5 Small Modular Gas-cooled Fast Reactor

Most of the small modular reactor (SMR) concepts developed in the past have compact size and a longer life reactor core than the conventional nuclear power plants. However, these concepts have not achieved the full modularization including power conversion system. Recent study suggests an innovative concept of a reactor cooled by supercritical state carbon dioxide.

A reactor core with uranium mono-nitride fuel controlled by drum type control rods was designed. The core has long life (20 years) without refueling or reshuffling as well as inherent safety features. The reactor can be used as a distributed power source and replace outdated fossil fuel power plants for small cities. Moreover, the S-CO_2 Brayton cycle as a power conversion system was proposed to achieve compact and lightweight module. Due to compact core and power conversion system, the entire system can be contained in a single module. The target of the system is to be able to transport a single core and power conversion system module via ground transportation. In order to meet this target single module's total weight is minimized in the order of 100 tons. The external size of a module is less than 7m in length and 4m in diameter. It produces 12MWe electricity from 36MWt reactor core.

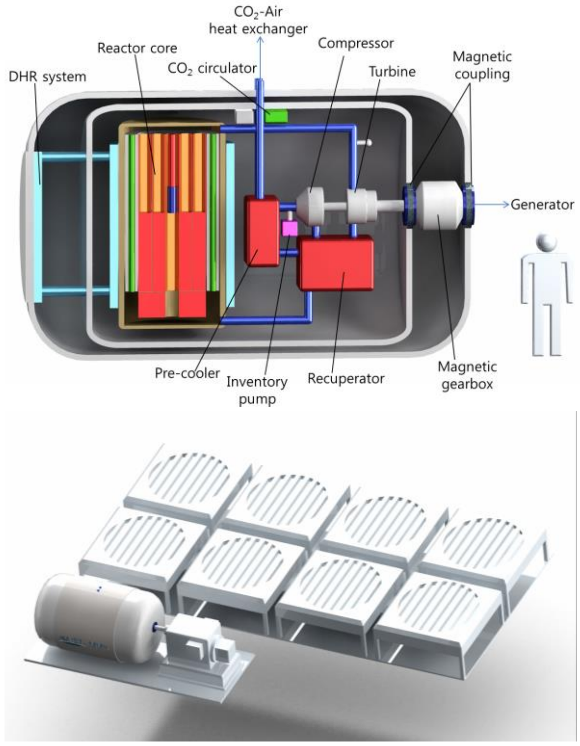

Fig. 6. Schematics of S-CO_2 cooled small modular gas-cooled fast reactor

3. Conclusions

The S-CO_2 cycle can achieve relatively high efficiency within the mild turbine inlet temperature range (450–850℃) compared with other power conversion systems. The main benefit of the S-CO_2 cycle is the small size of the overall system and its application includes not only the next generation nuclear reactors but also conventional water-cooled reactors too.

Various layouts were compared and the recompression cycle shows the best efficiency. The layout is suitable for application to advanced nuclear reactor systems. To evaluate the S-CO_2 cycle performance, various countries constructed and demonstrated S-CO_2 integral system test loops and similar research works are ongoing in Korea as well. However, to evaluate the commercial S-CO_2 power systems, development of a large scale (> 10 MW) prototype S-CO_2 system is necessary. The research activities are focused on a large scale S-CO_2 power system and various foreign research institutions and Korean researchers are attempting to realize the future power system that can significantly transform the nuclear energy industry around the world.

REFERENCES

[1] V. Dostal, P. Hejzlar, M.J. Driscoll, The supercritical carbon dioxide power cycle: comparison to other advanced

power cycles, Nuclear Technology, Vol.154, pp. 283–301, 2006.

[2] H. J. Yoon, Y. Ahn, J. I. Lee, Y. Addad, Potential advantages of coupling supercritical CO2 Brayton cycle to water cooled small and medium size reactor, Nuclear Engineering and Designing, Vol. 245, pp. 223-232, 2012.

[3] S. J. Bae, J. Lee, Y. Ahn, J. I. Lee, Preliminary studies of compact Brayton cycle performance for Small Modular High Temperature Gas-cooled Reactor system, Annals of Nuclear Energy, Vol. 75, pp. 11–19 (2015).

[4] Y. H. Ahn, J. I. Lee, Study of various Brayton Cycle Designs for Small Modular Sodium-Cooled Fast Reactor, Nuclear Engineering And Design, Vol.276, pp. 128-141, 2014.

[5]Y. H. Jung, Y. H. Jeong, J. Choi, A. F. Wibisono, J. I. Lee, H. C. No, Feasibility study of a small-sized nuclear heat-only plant dedicated to desalination in the UAE, Desalination, Vol.337, pp. 83-97, 2014

[6] W. W Lee, Y. H. Jung, Y. H. Jeong, J. I. Lee, Studies of S-CO_2 power cycle application for a large PWR with a desalination capability, ICAPP 2015, ANS, Nice, France, 2015.

[7] Cha, J. E., Lee, T. H., Eoh, J. H., Seong, S. H., Kim, S. O., Kim, D. E., Kim, M. H., Kim, T. W., Suh, K. Y., Development of a Supercritical CO2 Brayton Energy Conversion System Coupled With a Sodium Cooled Fast Reactor, Nuclear engineering and technology, Vol.41, 1025-1044, 2009

[8] Zhao, H., Peterson, P. F., Multi reheat helium Brayton cycles for sodium cooled fast reactors, Nuclear Engineering and Design 238, 1535-1546, 2008

[9] Alpy, N., Cachon, L., Haubensack, D., Floyd, J., Gas Cycle testing opportunity with ASTRID, the French SFR prototype, Supercritical CO_2 Power Cycle Symposium, 2011