Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-19, 2023

Summary of major experimental facilities constructed in SNL and KAIST for S-CO_2 power cycle commercialization

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1. Introduction

An S-CO_2 (supercritical CO_2) power conversion system is gaining attention as the next generation energy conversion system for nuclear power, concentrated solar power, and waste heat recovery. The S-CO_2 power system is a Brayton cycle that uses supercritical carbon dioxide as a working fluid, and it has good compatibility with materials and utilizes compact turbomachinery. Research works on the S-CO_2 power system is ongoing due to their ability to operate at competitive efficiency at moderate temperature heat source. Power cycle layouts using recuperators and recompressors have been suggested to improve system efficiency, and efforts to validate these layouts are being made around the world. KAIST is also putting significant efforts to demonstrate the competitiveness of an S-CO_2 power system in line with global trends.

This paper summarizes the S-CO_2 experimental facilities constructed in Sandia National Lab (SNL) of the US and KAIST of S. Korea to compare what research works have been conducted in these two institutions. SNL has been recognized as a pioneer in this field illuminating many important research results to accelerate commercialization of the technology. KAIST have also tried to fill in the gaps which other institutions were not looking at the time, and also made an effort to independently assess, verify and validate important technologies for the S-CO_2 power cycle. These research works were all conducted around the facilities constructed by the two research institutions, thus this paper tries to summarize the major experimental facilities constructed in the two institutions to highlight recent achievements for realizing the technology.

2. SNL S-CO_2 Experimental Facilities

In 2008, Sandia National Lab (SNL) conducted the first operation of the Research Compression Loop. Fig. 1 shows Sandia's first S-CO_2 compressor research loop. It was successfully used for compressor performance map, seal and bearing tests, and condensation tests. [1]

Fig 1. S-CO_2 Compressor Research Loop (Top : 2008, Bottom : 2011)

The other test loop is Heated Unrecuperated S-CO_2 Brayton Loop (Fig 2). SNL also developed the Split-flow S-CO_2 Recompression Brayton Loop (Fig.3) for research on system split flow. **[2]**

Fig 2. S-CO_2 Heated Unrecuperated Test Loop

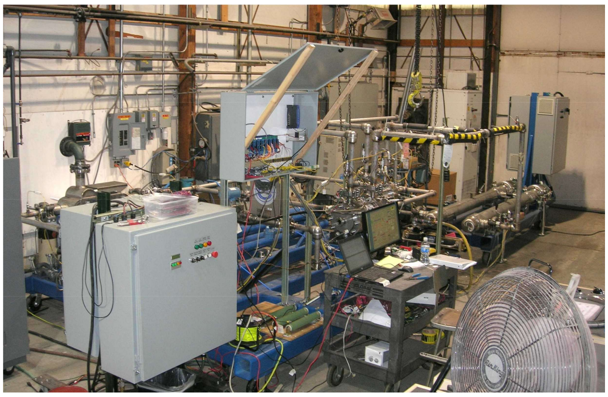

Fig 3. Split-flow S-CO_2 Recompression Brayton Loop

Fig. 3 is the Recompressed Closed Brayton Cycle loop. This loop features 1 MW heater-class Brayton cycle with one Turbine-Alternator-Compressor (TAC). [3] The loop was later improved by SNL as shown in Fig. 4. The improved loop is the 1 MWth experimental loop with a 780 kWth heater, two installed TACs, and three extremely efficient PCHE recuperators. [4]

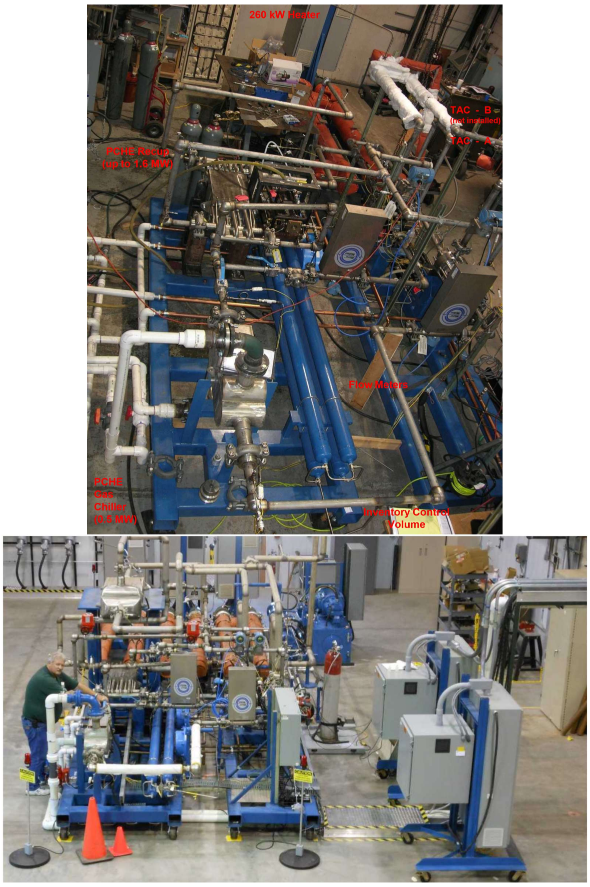

Fig 4. Split-flow S-CO_2 Recompression Brayton Loop (Top : 2011, Bottom : 2014)

In addition to the S-CO_2 Brayton cycle test loop, SNL has constructed many experimental facilities to investigate various following technical issues. [5]

1. Bearings Test Rig
2. Natural Convection Loop
3. Optical Diagnostics Lab
4. Burst and Fatigue Rig
5. Heat Exchanger Rig
6. Compressor/Seal Test Loop
7. Low-Pressure Brayton Loop
8. Dry Natural Circulation Loop.

3. KAIST S-CO_2 Experimental Facilities

The SCO2PE (S-CO_2 Pump Experimental Facility) is a loop-type experimental facility that was in operation from 2011 to 2020. Utilizing this device, KAIST developed in-house codes including KAIST-TMD for turbomachinery, KAIST-HXD for heat exchanger design, KAIST-CCD for closed cycle design, and KAIST-OCD for off-design performance evaluation. These codes were mostly validated with experimental data obtained from SCO2PE. Furthermore, GAMMA+ code originally developed by KAERI was improved independently and validated with experimental data obtained from SCO2PE.

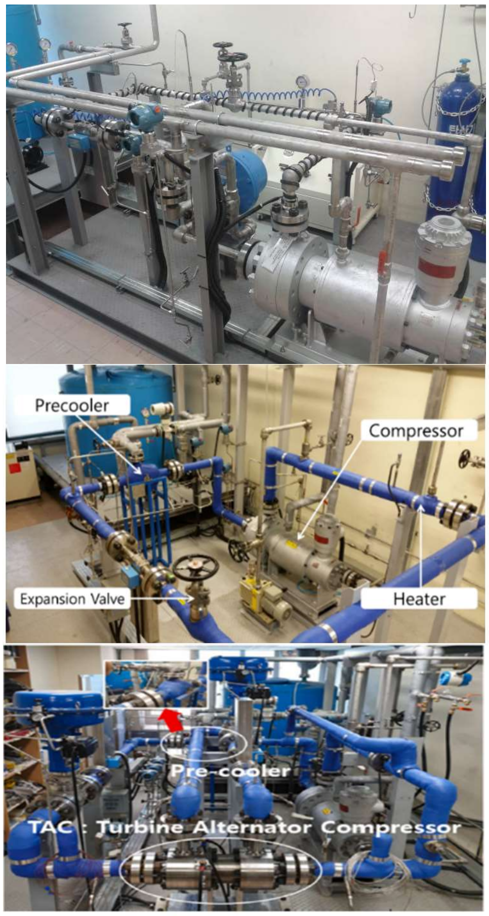

Fig 5. SCO2PE Facility
(Top: 2011, Middle: 2016, Bottom: 2020)

The KAIST research team is currently finalizing the ABC (Autonomous Brayton Cycle) loop system, which is a facility re-designed and constructed from SCO2PE. Since 2021, the ABC Loop has been operating to comprehensively verify the S-CO_2 power system, which is designed to explore beyond SCO2PE operational limit. ABC loop is equipped with a PCHE-type recuperator, heater, and Active Magnetic-Bearing (AMB) supported turbomachinery. [6]

The AMB supported turbomachinery has a ball-bearing system for back-up and turbine and compressor are attached to a single shaft acting as an alternator. The ABC loop can now test a full power cycle operation and tests data for heater, turbine, and recuperator can now be obtained from the loop.

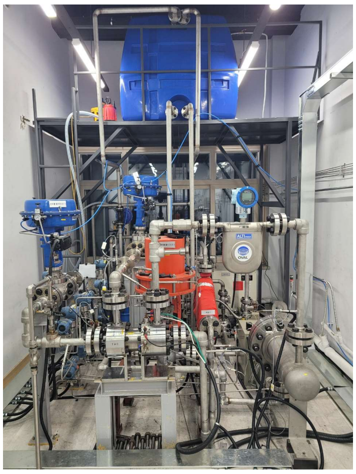

Fig 6. ABC Loop

AMB system is tested under S-CO_2 conditions for the first time, thus a separate AMB test rig is also attached to the ABC loop to experiment AMB operation. This test rig has assisted to design and understand how AMB operates under the S-CO_2 power cycle conditions. [7]

Fig 7. AMB Test Rig

In the near future, the ABC loop will be used for more comprehensive validation of concepts and ideas, which were not possible with the SCO2PE loop. Currently major research works are focused on improving and developing system control strategy to enable autonomous operation of the S-CO_2 power cycle operation. Ultimately, while SCO2PE remained at the research stage, the ABC loop will serve as a cornerstone for practical validation towards the commercialization of S-CO_2 power conversion systems.

There is also an S-CO_2 critical flow test facility in addition to the ABC loop system. In the compressor, critical flow of S-CO_2 can occur due to rapid pressure drop in seals. Computational simulations and experimental verifications were performed to understand the physical phenomenon of critical flow in the S-CO_2 turbomachinery environment. [8]

Fig 8. S-CO_2 Critical Flow Test Facility

4. Future Works at KAIST

SNL is considered as the pioneer in the S-CO_2 power cycle research area and constructed many important facilities to resolve technical issues in the field. KAIST is also trying to construct a similar experimental capability but focusing on different technical aspects and issues. The S-CO_2 power cycle field is now approaching early commercialization stage, and it requires more wide range of data and technical validation. Therefore, not only the validation of lab scale experimental loop is necessary and essential, but also industrial scale facility has to be operated and the technology has to be proven in larger scale.

The following issues are remaining yet as significant issues to be addressed in the future research works.

1. S-CO_2 loss model for turbomachinery design and analysis
2. Physical interpretation of subcritical and supercritical CO_2 behaviors while considering turbulence
3. Quantification of S-CO_2 property error near the critical point
4. Understanding the two-phase flow effect within the heat exchanger
5. Full demonstration of proving AMB competitiveness

6. Obtaining optimal control strategy for autonomous control of the system

KAIST is focusing its effort to address these issues in the S-CO_2 power cycle research. In particular, AMB test rig, which is an effective technical choice to scale up the power cycle with simplicity is unique research topic handled in the institution. KAIST will continuously improve its in-house simulation capabilities and conduct a research on developing small modular reactor using the S-CO_2 power cycle technology. Furthermore, the research direction will be now more focused on scaling up and commercialization of the S-CO_2 power cycle by collaborating with various energy industries.

ACKNOWLEDGEMENT

This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2022-00143652).

REFERENCES

[1] ORRELL, A. Sandia's Roles in the Global Nuclear Energy Partnership. In: . B.m. 2008.

[2] VERNON, M. Advanced Power Conversion Systems Development at SNL. 2010.

[3] GUSEK, B. Supercritical CO2 Main Compressor Performance Measurements. 2009.

[4] PASCH, J. Supercritical Carbon Dioxide Closed Brayton Cycle: Development and Applications. 2014.

[5] MENDEZ CRUZ, C., B. LANCE, and G. ROCHAU. *sCO_2 Power Cycles Summit Summary, November 2017* [online]. SAND2018--3545, 1435490, 662495. 2017 [accessed. 30. March 2023]. Retrieved from: doi:10.2172/1435490

[6] BAEK, J.Y., J.J. LEE, and J.I. LEE. System Modeling of KAIST S-CO2 ABC Test Loop. 2022.

[7] KIM, D., S. BAIK, and J. LEE. Instability Study of Magnetic Journal Bearing under S-CO2 Condition. *Applied Sciences* [online]. 2021, vol. 11, no. 8, p. 3491. ISSN 2076-3417. Retrieved from: doi:10.3390/app11083491

[8] LEE, J.J., J.Y. BAEK, and J.I. LEE. Study on supercritical CO2 critical flow through orifices under power cycle operating conditions. *The Journal of Supercritical Fluids* [online]. 2022, vol. 190, p. 105756. ISSN 08968446. Retrieved from: doi:10.1016/j.supflu.2022.105756