

Installation of the Supercritical CO₂ Compressor Performance Test Loop as a First Phase of the SCIEL facility

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The Supercritical CO₂ Brayton cycle power generation system is presented as a promising alternative to the present Rankine cycle. The S-CO₂ Brayton cycle is one of the candidates for the next generation nuclear power plants since the S-CO₂ Brayton cycle has relatively high efficiency and compactness. KAERI has been installing a Supercritical CO₂ Brayton Cycle Integral Experiment Loop (SCIEL) to develop the element technologies for the S-CO₂ turbomachinery and compact heat exchanger with KAIST and POSTECH joint research team. Operation and control test will be also conducted to develop the operation logic in the S-CO₂ system. For actual outcomes, final goal of the SCIEL is to demonstrate the simple recuperated cycle layout with a series of recuperation process. Currently, the compressor performance test loop is completed its installation as a first phase of the SCIEL, which has a 100kW S-CO₂ compressor (72,000rpm, 6.4kg/s, pressure ratio 1.8).

1. Introduction

The steam Rankine cycle has been utilized as the power conversion system of the current water-cooled reactors for more than 60 years. It has demonstrated a good efficiency and system reliability when the reactor operating temperature is below 350°C. However, the next generation reactors generally operate in higher temperature condition compared to the water-cooled reactor system. Among various Brayton cycles, S-CO₂ cycle is considered as a promising alternative to the present Rankine cycle with the benefits of competitive efficiency, simple layout and compact system size. S-CO₂ cycle can especially replace violent sodium-water reaction with milder sodium-CO₂ reaction which can potentially enhance safety and economy of the Sodium-cooled Fast Reactor (SFR) system at the same time.

To demonstrate and assess the theoretically proposed S-CO₂ cycle performance, the integral test loops of S-CO₂ cycle are necessary. Several research groups including Sandia National Lab (SNL), Bettis Atomic Power Lab (BAPL) and Institute of Applied Energy (IAE) constructed the small scale test loops for the design targets. To develop the element technologies and establish the control logics of S-CO₂ cycle for the SFR application, SCIEL is designed by the joint research team of Korea Atomic Energy Research Institute, (KAERI), Korea Advanced Institute of Science and Technology (KAIST) and Pohang University of Science and Technology (POSTECH). This paper provides the review and

comparison of existing S-CO₂ test facilities and the design consideration and of SCIEL.

2. SCIEL design and current status

2.1. Reviews of existing S-CO₂ test facilities

Since Dostal et al. revitalized the S-CO₂ cycle concept for the next generation reactor applications, various applications of S-CO₂ Power cycle including the nuclear, renewable energy and fossil fuel applications are suggested [Dostal et al., 2004, Cha et al., 2009, Johnson, 2011, Ma, 2011]. However, the advantages of S-CO₂ cycle are purely evaluated from the theoretical thermodynamic cycle analysis based on fluid property databases. To validate the predicted performance, several research institutes constructed the integral test loops of S-CO₂ cycle.

The layout of SNL IST is the recompressing cycle which is generally regarded as the most efficient layout in S-CO₂ cycle [Dostal et al., 2004, Feher, 1967]. The target turbine inlet temperature is 500oC which matches well with the mild temperature heat sources including SFR, CSP and fuel cells. Besides, the designed turbine inlet temperature of BAPL IST is 300oC. S-CO₂ cycle shows competitive performance not only in the mild temperature range (450-650oC) but also in the low temperature range (~300oC) application when the system size is strictly limited [Yoon et al., 2012]. The layout of BAPL IST is the recuperated cycle without recompressing process. The power turbine is separately designed for the flexible power control. The other characteristic of BAPL IST is utilizing the intermediate heat exchanging loop with the organic fluid for the heating process.

Compared to the test facilities mentioned above, IAE test facility was designed for the small scale. In the early design status, the recompressing layout was considered but it was discarded due to the small flow rate [Utamura et al., 2012]. The layout is recuperated cycle with a series of recuperation process. The power output was limited due to the windage losses in the rotor.

The design specifications are listed in Table 1.

The common feature of S-CO₂ turbomachinery from the existing test facilities is Turbine-Alternator-Compressor (TAC), which the turbine and compressor are connected with a single shaft. The main advantage of TAC is that the compressor rotates via the mechanical work transferred from the turbine and the motor requirement is reduced. This technology is a derivative of Brayton cycle technologies. However, the main characteristic of S-CO₂ cycle is the small compressor work as the fluid becomes more like an incompressible fluid. Therefore, the innovative turbomachinery such as a single set of compressors can be considered for the future test facilities.

Table 1. The comparison of existing S-CO₂ integral system loops [Wright et al., 2010, Clementoni et al., 2013, Utamura et al., 2012]

	SNL	BAPL	IAE
Turbomachinery feature	2 - TAC	1 - TAC, 1 - turbine	1 - TAC (2-recuperator)
Cycle layout	Recompressing Fig. 1	Recuperated Fig. 2	Recuperated Fig. 3
Heat, kW	780	834.9	160
Efficiency	31.5	14.7	7
Mass flow rate, kg/s	3.5 (target) / 2.7 (achieved)	5.35 (target) / 3.54 (achieved)	1.1 (achieved)
Turbine Inlet Temperature, °C	537 (target) / 342 (achieved)	300 (target)	277 (achieved)
Pressure ratio	1.8 (target) / 1.65 (achieved)	1.8 (target) / 1.44 (achieved)	1.4 (achieved)
Rotating speed, x 1000 rpm	75 (target) / 52 (achieved)	75 (target) / 55 - 60 (achieved)	69 (achieved)
Turbine efficiency, %	86 (turbine - 1) / 87 (turbine - 2)	79.8 (PT) / 79.7 (C-driving TB)	65
Compressor efficiency, %	67 (MC) / 70 (RC)	60.8	48

2.2. SCIEL design consideration

As the S-CO₂ cycle is considered as the promising candidates for the SFR power conversion system, KAERI designed S-CO₂ Integral Experiment Loop (SCIEL) with KAIST and POSTECH. The generated data from SCIEL will be utilized to simulate the steady and transient state of S-CO₂ cycle and establish the control logics for the operation scenarios such as part load operation and loss of power operation. For SCIEL design process, KAERI, KAIST and POSTECH are responsible for the overall system, turbomachinery and heat exchanger, respectively. The design parameters and layout are summarized in Table 2 and Figure 1, respectively.

As the design pressure ratio is high, the two-stage of compression and expansion process is considered. As CO₂ behaves more like an incompressible fluid, the compressor work is reduced and therefore splitting compressor and turbine by having two separate shafts layout was considered for the SCIEL design. By utilizing the low pressure turbine (LPT) and low pressure compressor (LPC), the simple Brayton cycle can be demonstrated. For the high pressure ratio operation, the high pressure turbine (HPT) and the high pressure compressor (HPC) will have TAC configuration. The SCIEL can

be constructed step by step as the compressor and turbine are not mechanically connected. Thus, two turbomachinery operate at different rotating speed. To balance the thrust loads of LPC, the twin-impeller configuration is considered and some portion of the compressed CO₂ flows to the precooler directly via bypass line.

For the heat exchanger such as recuperator and precooler, the promising candidate is the Printed Circuit Heat Exchanger (PCHE) which has been widely used for the S-CO₂ cycle research. The operational temperature and pressure of PCHE are wide and the compactness is high. For the SCIEL design, a series of PCHEs will be utilized to recuperate heat. Further researches for the alternative option to PCHE will be performed in the future.

The T-s diagram of SCIEL is compared with the SNL design in Figure 2.

Table 2. SCIEL design parameters

Target T.I.T, °C	500	Cycle layout	Recuperated
Target C.O.P, MPa	20	Target C.I.T, °C	33.2
Target C.I.P, MPa	7.78	Recuperator total effectiveness, %	85
Turbine efficiency, %	85	Heater / Precooler ΔP, kPa	100 / 150
Compressor efficiency, %	65	Recuperator HS / CS ΔP, kPa	100 / 150

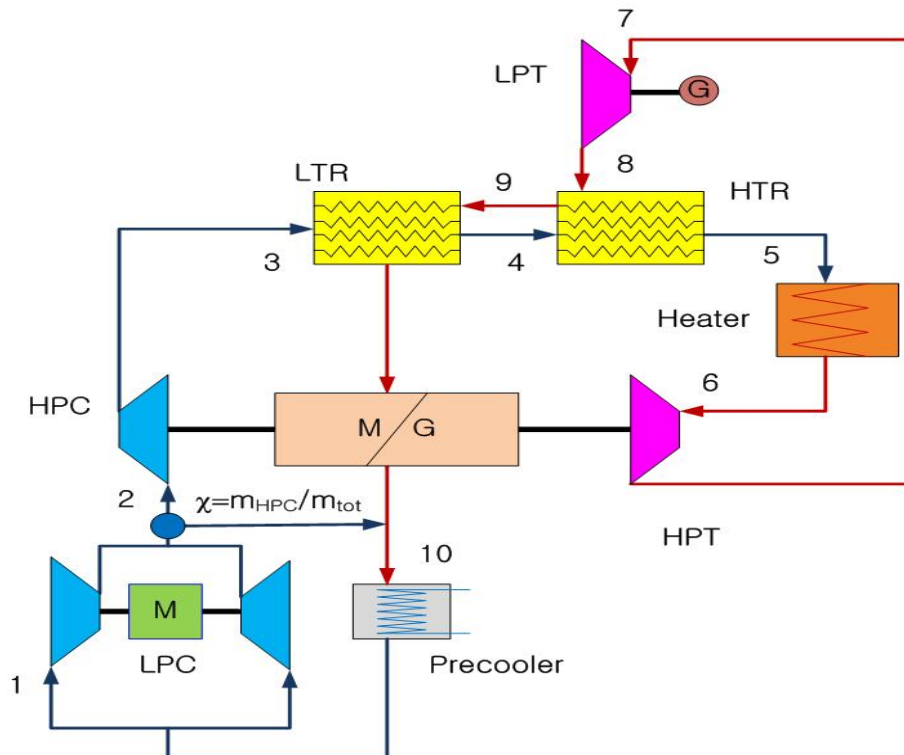


Figure 1. The recuperated layout of SCIEL

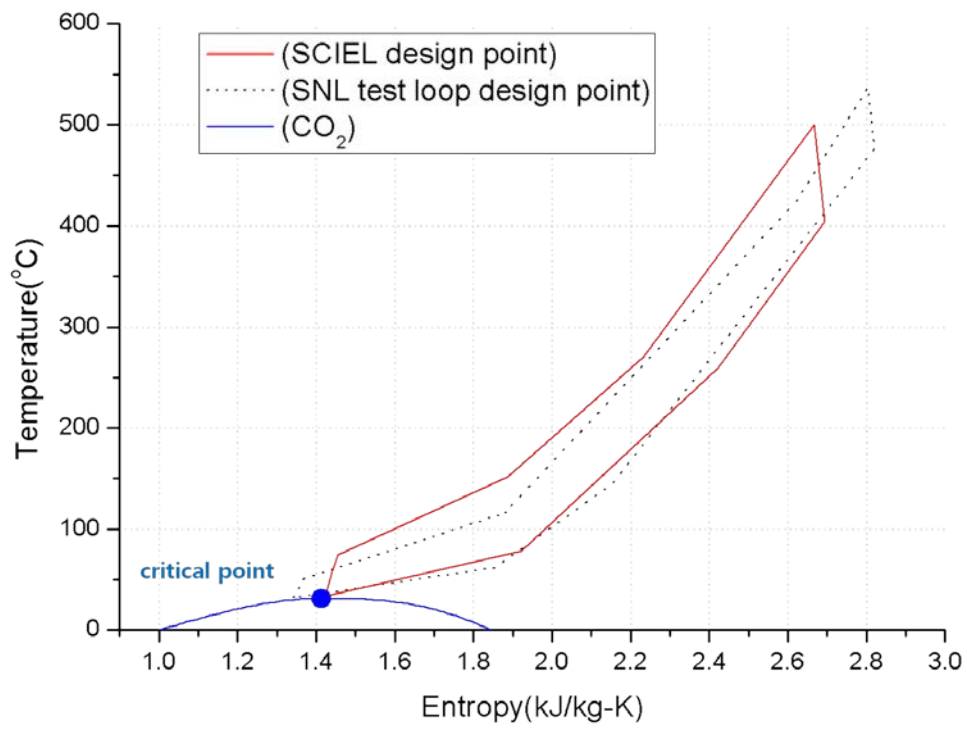


Figure 2. The T-s diagram of SCIEL and SNL test loop

2.3. SCIEL current status and preliminary experiment



Figure 3. The picture of SCIEL building (outside)

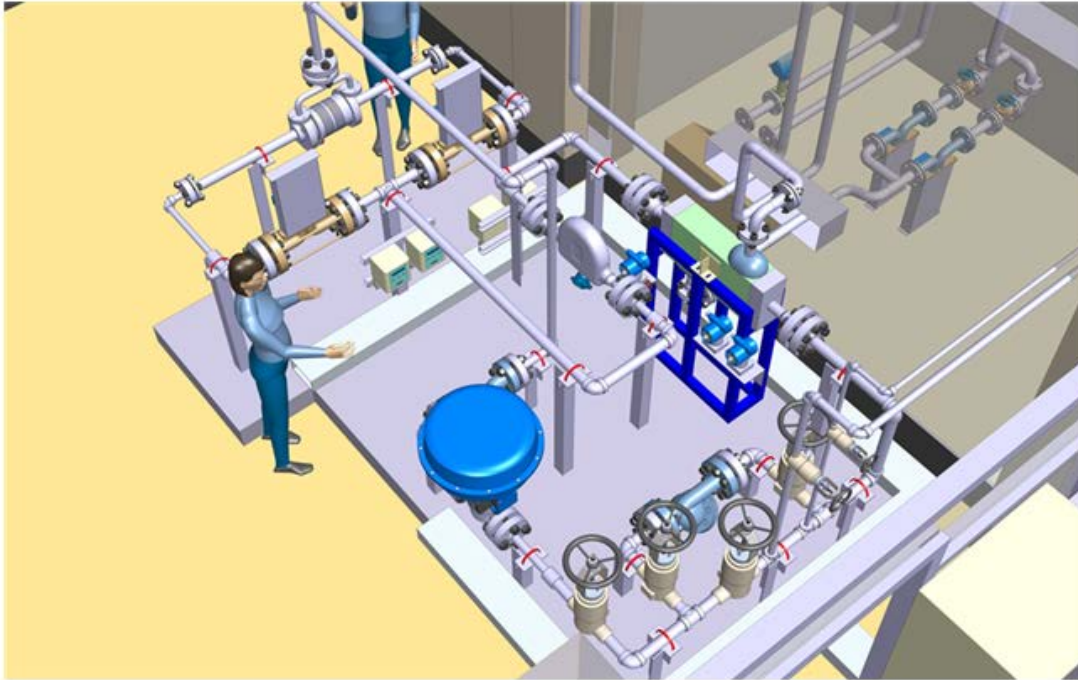


Figure 4. 3D view of SCIEL

SCIEL is being constructed in KAERI. The capacity of the cooling system shown in Figure 3 is 610kW. The inventory and cooling system is located outside of the main component building. Figure 4 shows the 3D view of current SCIEL facility.

Low pressure compressor (LPC) was designed and manufactured for the pressure ratio of 1.8 and total mass flow rate is 6.4kg/s. The motor requirement of LPC is 100kW and the rotating speed is 72,000 rpm. The preliminary experiments of LPC was performed with the current configuration of SCIEL. To measure the precise mass flow rate in the compressor inlet side, the Coriolis mass flow meter and a density meter were installed. The PCHE type pre-cooler was installed.

Some preliminary data and discussion regarding the data will be presented in the symposium.

3. Summary & Future works

For the mild temperature (450-650°C) heat source application, S-CO₂ cycle is gaining a lot of interests. S-CO₂ cycle is also considered as the promising candidate of SFR power conversion system. To validate the predicted performance, several research institutes developed the integral system test loops. To test different approach in turbomachinery and operating conditions, KAERI designed and constructing the S-CO₂ cycle Integral Experiment Loop (SCIEL) with KAIST and POSTECH.

The common characteristic of S-CO₂ turbomachinery from the test loops is the Turbine Alternator Compressor (TAC) feature which is widely used in the gas Brayton cycle technology. However, the single S-CO₂ compressor can be designed as CO₂ behaves more or less an incompressible fluid

near the critical point. Since the compressor and the turbine are split, SCIEL can be constructed step by step.

The layout of SCIEL is recuperated cycle without recompressing process. As the pressure ratio is higher than existing test loops, two stage of compression and expansion processes are considered. As for the turbomachinery, a low pressure compressor (LPC), a low pressure turbine (LPT) and a TAC type high pressure compressor (HPC) and high pressure turbine (HPT) were designed, being manufactured and tested. To balance the thrust loads near the critical point, twin impeller type LPC is designed and being tested. More detail of the facility and some preliminary data will be presented in the symposium.

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